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THE WORLD RIFT SYSTEM

Report of
Symposium,
Ottawa, Canada
4-5 September, 1965

GEOLOGICAL SURVEY OF CANADA

PAPER 66-14

DEPARTMENT OF MINES AND TECHNICAL SURVEYS



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THE WORLD RIFT SYSTEM

Report of a symposium held in Ottawa 4-5 September, 1965, under the sponsorship of the International Upper Mantle Committee with financial assistance from UNESCO

Edited by T. N. Irvine

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

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FOREWORD

The World Rift System was first recognized as a major tectonic element of the earth only a dozen years ago. Many parts of the system had however been known and studied for decades.

The Symposium was planned as a survey of the World Rift System area by area, and subject by subject. Invitations were extended to participants only three months in advance of the Symposium, and I am very grateful to the contributors for their fine lectures and papers prepared at such short notice. I am also grateful to the Geological Survey of Canada for the excellent arrangements made for the symposium meetings and in the preparation of this symposium volume, and to T.N. Irvine for assuming the task of editing this volume. I wish to thank the Upper Mantle Committee for the opportunity to plan the program at this Symposium.

Bruce C. Heezen
Chairman,
Commission on the World Rift System.

INTRODUCTION

During the period September 2-9, 1965, three symposia were held in Ottawa in conjunction with meetings of the International Upper Mantle Committee. Their titles were: Drilling for Scientific Purposes; The World Rift System; and Continental Margins and Island Arcs. This volume contains the papers presented during the sessions on the World Rift System, and the resulting recommendations. An earlier volume devoted to Drilling for Scientific Purposes has been published as Geological Survey of Canada Paper 66-13 and a final report on Continental Margins and Island Arcs will appear as Paper 66-15.

The World Rift System was highlighted as a symposium subject because it is the theme of one of three international programs selected by the Upper Mantle Committee at its meeting in Moscow in May, 1964 for emphasis as part of the Upper Mantle Project. It is significant in this connection that the concept of a world-encompassing rift system is relatively new. As was pointed out by Professor B.C. Heezen during the symposium, the existence of such a system has been recognized only in the last 15 years even though it is now generally considered to involve about one quarter of the earth's surface. In view of this novelty, vastness and undoubted importance, it was considered an opportune time for scientists studying the Rift System in different parts of the world to meet, "compare notes" and become familiar with one another's methods of study, findings, and interpretations. The program of the Ottawa symposium was therefore designed to bring together the authorities on the different parts of the World Rift System, and theorists from the specialized disciplines involved in its study, to summarize the current knowledge of this important feature and formulate goals for future work.

The present volume follows fairly closely the program of the symposium which is contained in Appendix I. There are twenty-eight papers, twenty-two of which deal with the nature and development of the rift system on a regional basis. Particular emphasis is given to the junction of Asia and Africa, the Indian Ocean, the Mid-Atlantic, and western North America. Five other papers relate to the rift system as a whole, covering specific features and more general concepts of origin. Some papers are, for various reasons, reported in abstract form only. The final section of the volume is a record of the session dealing with proposals, recommendations and discussion arising from the papers. The recommendations finally approved by the Upper Mantle Committee are presented immediately after this introduction. A list of the participants in the symposium is given in Appendix II.

The discussion following individual papers and the record of the session on resolutions and recommendations are taken from taped records and from the notes of appointed reporters. The remarks of the speakers

have been edited to varying degrees, and wherever possible the written versions of the proposals submitted by the delegates in the general session have been substituted for those presented orally. Some speakers have had an opportunity to examine and revise their remarks, but this has not been practical in every case; therefore if cases of misrepresentation of remarks arise, the editor may be held responsible.

The symposium and this report were made possible through the generous cooperation of numerous people and agencies. The United Nations Educational, Scientific and Cultural Organization and the International Union of Geological Sciences provided financial assistance toward the travel of participants and the preparation of the final publication. The Department of Mines and Technical Surveys and the National Research Council sponsored the meeting and entertained the guests. J.M. Harrison furnished the overall direction and coordination.

The speakers, of course, provided the stimulus to the sessions and followed through with patience and cooperation to the final typing of their manuscripts. B.C. Heezen designed the program and contacted the speakers, and C.H. Smith organized the local arrangements. W.H. Poole, A.R. Larochelle and E.F. Roots acted as reporters, while P.J. Hart, A.S. MacLaren, E.R. Niblett, Mrs. B.F. Thomas and many others kept the sessions running smoothly and attendees in good spirits. Miss F.C. Aitkens assisted in assembly of the manuscripts. Particular thanks go to Mrs. M.A. Shanks, Mrs. B. Richard and Mrs. M.M. Finn for their efforts in preparing the typescript of the report.

T.N. Irvine

Ottawa,
June, 1966

RESOLUTIONS AND RECOMMENDATIONS ON THE WORLD RIFT SYSTEM

The following recommendations arising from the symposium on the World Rift System were prepared and approved by the International Upper Mantle Committee on September 9-11, 1965. The detailed proposals and discussions on which these recommendations are based are contained in the final section of this volume.

1. The study of the World Rift System is one of the primary objectives of the Upper Mantle Project. Therefore a Commission has been formed to provide liaison between the Working Groups of the Upper Mantle Committee concerned, to coordinate proposals, and promote research on the structures of the world rift systems.

2. Detailed surveys of the Mid-Oceanic Ridge and Rift System in different parts of the ocean should be carried out and, where possible, should be connected with continental surveys of similar nature.

   2.1 Junctions of oceanic ridges with continental areas are of special significance. Gravity and magnetic anomaly patterns across transitional zones between rift valleys on land and the median structure of ocean ridges may clarify their relationship.

   2.2 The identification, mapping and dating of topographic and magnetic lineaments in oceanic areas may throw light on the history of the ocean floor.

   2.3 Dating of volcanic and tectonic activity related to the rift valleys and the ocean ridge systems is required, as well as geological studies on land and at sea.

3. Comparable studies of the continental rifts are needed to decide whether they differ from oceanic rifts and, if so, whether the differences arise from physical differences in the mantle or from the different responses of continental blocks and ocean floor to the same underlying physical mechanism.

4. The Upper Mantle Committee endorses national and regional joint endeavours. As an example, it may be mentioned that some countries have initiated collaborative studies of large areas, as for instance the countries of Central America through the Committee on Geophysical Sciences of the Pan American Institute of Geography and History, the East African Geophysical Committee, and the Nordic countries respectively.

5. Field studies should be accompanied by theoretical and laboratory studies of processes in the upper mantle which might cause the observed phenomena.

6. The total thickness of the sediment layer is only a few tens of metres over a wide belt which includes the Mid-Oceanic Ridge and Rift System and adjacent abyssal hills; a knowledge of the regional distribution of age and composition of the basal sediments and underlying rock layer would greatly add to our knowledge of the development of the Mid-Oceanic Ridge and Rift System and of the upper mantle processes beneath this large earth feature. Present techniques in sediment coring make it possible to obtain suitable samples with only slight modifications of present practices. Therefore the Upper Mantle Committee recommends that a program of total sediment coring be instituted and carried out across the full width of the Mid-Oceanic belts of thin sediment cover.

7. It is recommended that the next symposium on world rift systems be held in conjunction with the General Assembly of the International Union of Geodesy and Geophysics in Switzerland (1967).

GRAVITY OBSERVATIONS OF THE DEAD SEA RIFT*

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and

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Abstract

The Dead Sea Rift zone has been explored by means of a gravity survey. The interpretation of the data shows that the Dead Sea Rift may be different from the East African and Red Sea Rift types. The results show that the Jordan River Valley overlies the contact between the continent represented by Arabia to the east and the ocean to the west. The thinner oceanic crust continues across the Levantine coast and terminates at the Dead Sea. After the regional gravity anomaly is removed under the assumption that the two blocks are in contact, no significant residual remains. Thus the Dead Sea Rift is very likely a bearing surface for the motions associated with the formation of the Red Sea.

INTRODUCTION

The structure and the mechanism of formation of the Dead Sea Depression has been the subject of considerable conjecture. It has been described as a graben bounded by thrust faults as the result of compressional stresses resulting in a "ramp" valley (Willis, 1928). It has been described as a graben bounded by normal faults as the result of tensile stresses in an E-W direction by Picard (1931, 1943) and others. Finally it has been described as a rift fault with left-lateral movement; this region has been presumed to participate in the northward motion of Arabia away from Africa and the formation of the Red Sea (Dubertret, 1932, and others). The details of the various hypotheses will not be presented here. Excellent summaries are given by Quennell (1959) and Freund (1965).

---

*Publication Number 476, Institute of Geophysics, University of California, Los Angeles.

A recent accumulation of geologic evidence has tended to support the last of these hypotheses. Correlations of rocks and other geologic evidence indicate a left-lateral motion of from 80 km to 140 km (Quennell, 1956, 1959; Lloyd-Morris, 1960; Freund, 1961, 1965).

All of the conclusions based upon geology have been made without the corroboration of concrete geophysical evidence across the Dead Sea Rift zone. The state of stress and absence or presence of equilibrium falls directly within the province of geophysical studies. Geophysical evidence in nearby regions includes gravimetric data (Lejay, 1938) from pendulum observations which, with the single exception of a station at Jerusalem, covered the territory to the north of the present nations of Israel and Jordan. In addition submarine gravity measurements have been made in the Red Sea and in the Eastern Mediterranean (Girdler and Harrison, 1957; Girdler, 1957). Finally, regional gravimetric surveys of parts of both Jordan (Lloyd-Morris) and Israel (Nettleton, unpublished) have been made in the course of petroleum explorations. Approximately one-third of Jordan has been covered in these surveys but the published map is without careful elevation control and nowhere does it cross the rift zone. Only in the region from Amman to the Syrian border does the gravity map describe the east side of the rift zone as far west as the Jordan River. For political reasons, a traverse of the Dead Sea Rift is possible today only in part of Jordan, a region having a north-south extent of about 100 km.

The gravity measurements over the East African Rift zone by Bullard (1936) showed a significant gravity minimum over the rift portions of the otherwise compensated East African Plateau. The gravimetric data in the Red Sea show marked high positive values which indicate a thinning of the crust; this has been interpreted to mean that part of the Red Sea has an almost oceanic type of structure and that the Red Sea is very likely a feature produced by tensile stresses. Gravity observations of the Dead Sea Rift could show the relationship of this feature to the Red Sea and East African Rifts.

PRESENT INVESTIGATION

In December, 1960, during the course of an archaeological expedition, we had occasion to carry out two gravity traverses across the Jordan River north of the Dead Sea. The surveys were carried out along the two main highways which cross the rift zone north of the Dead Sea. Gravimetric data were obtained with a Worden gravimeter obtained from the Department of Geodesy and Geophysics of Cambridge University. A magnetic profile was also taken at most of the same stations with a proton magnetometer obtained from the same source.

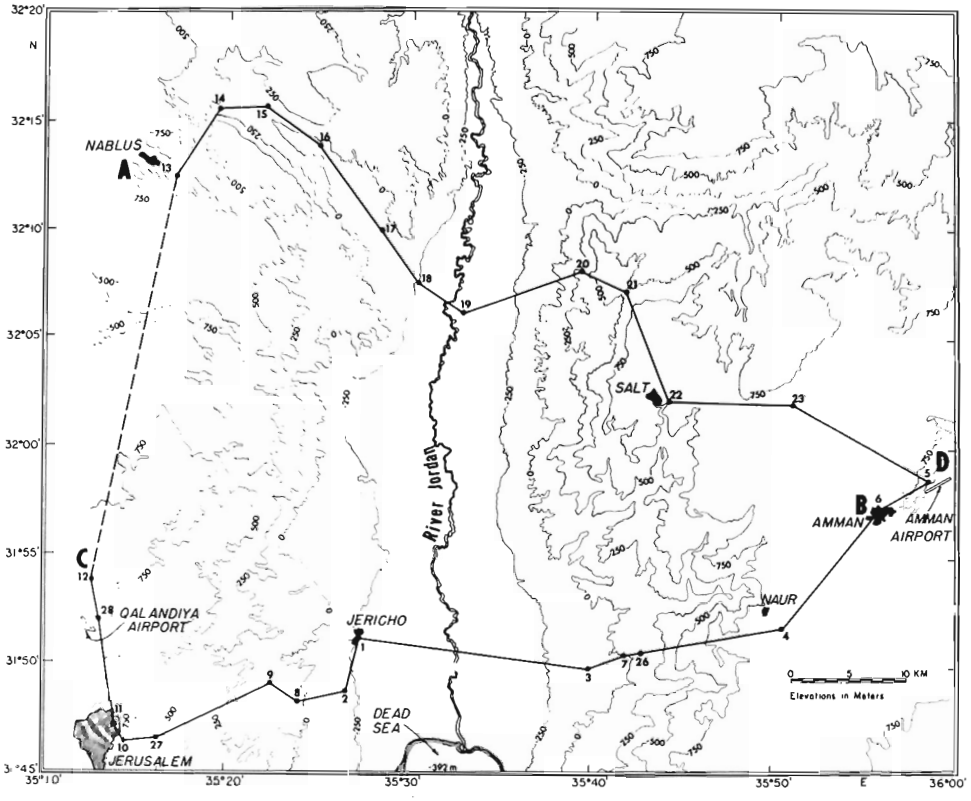


Figure 1. Topographic map of Jordan River Valley showing gravity stations.

A topographic map of the area with pertinent cultural features and showing the stations occupied during our survey is presented in Figure 1. A closed gravity loop connects all the stations. For purposes of later description the data are divided into two parts: the lines AB and CD correspond to traverses from Nablus to Amman and from Jerusalem airport to Amman airport, respectively. The missing segment in the graphical representation is represented by a dashed line in the figure although our data are continuous across this gap. The two lines trend generally W-E. As will be seen later the line connecting Jerusalem and Nablus will play an important role in the interpretation; a portion of this line has been appended to the line CD and does not follow the general trend of geography. The contours in Figure 1 are taken from British Army topographic maps of the Palestine Series.

Results of the data reduction for the two traverses are shown in Figure 2. In the upper part of the diagram the elevations along the two traverses are shown. The horizontal scale is approximate and has a rough correspondence to distance between stations; the horizontal scale has been selected to permit comparison between corresponding parts of the two traverses. A station was occupied at the Jordan River only on the line AB; the elevation profile for the line CD is indicated by a dashed segment across the river. The elevation of the Jordan at the crossing of line CD is, of course, lower than at AB. Location names are those of the nearest geographic features identifiable on the topographic maps and are intended only for identification; all stations are on the highways.

Also shown on Figure 2 are the results of the magnetic survey. There is little correlation of magnetometer reading with elevation. This can be taken to mean that any basaltic basement underlying the sediments is far from the surface under both the Jordan River Valley and the plateaus on either side.

The proximity of our southern line to the Dead Sea itself should be noted. The Dead Sea reaches its greatest depth at the northern end approximately 1,400 feet below the surface. This could produce a negative anomaly on the southern (CD) line. Freund (personal communication) has indicated that sedimentation is likely to be smaller at the Jordan crossing of line AB than at the crossing with line CD. Drilling in the Lisan Peninsula of the Dead Sea has shown several kilometres of rock salt to be present. Deep sedimentation is found south of the Dead Sea.

Elevations were obtained from two portable barometers carried with the other instruments. Absolute elevations at the two airport weather stations are published. The southern line (CD) crosses sea-level at a marked place along the Jerusalem-Jericho road. The weather was relatively clear and uniform during the times that the surveys were made;

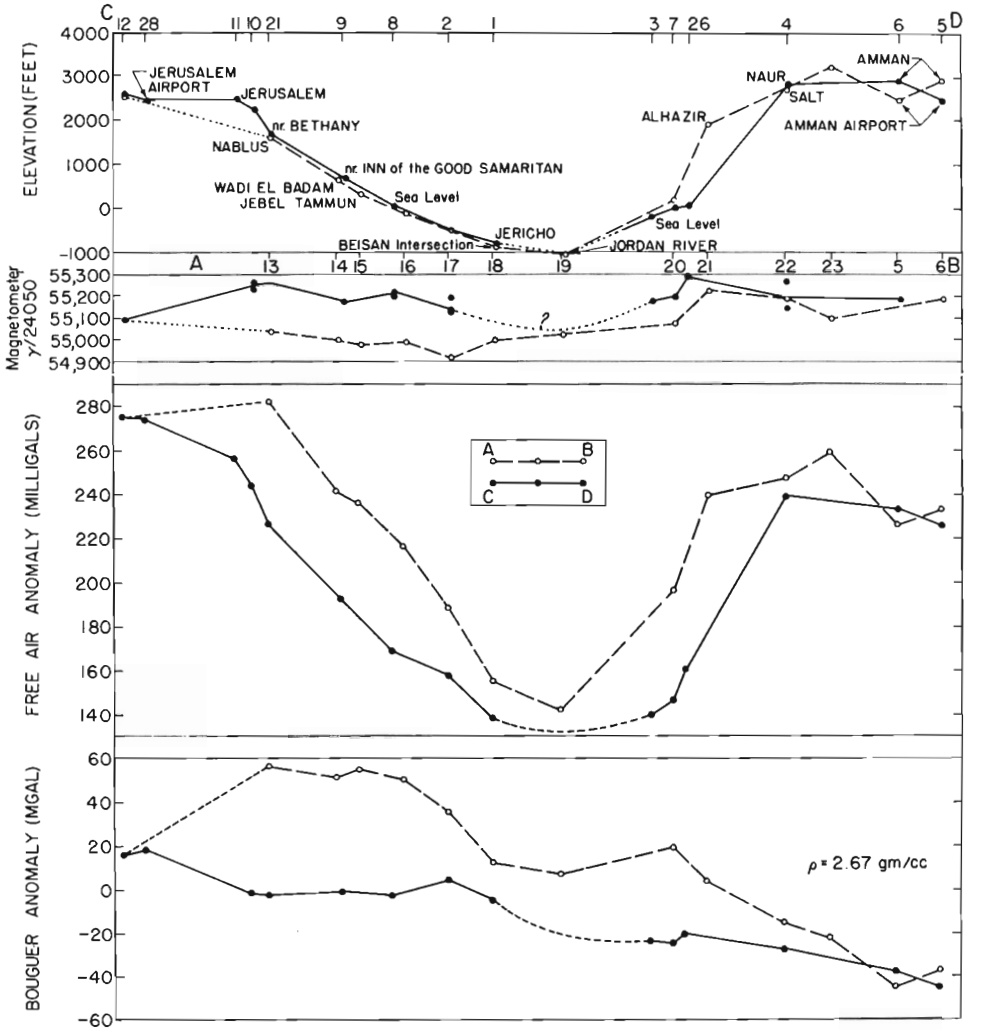


Figure 2. Data reduction showing elevations, magnetic, free air and Bouguer anomalies for the lines AB (dashed) from Nablus to Amman and CD (solid) from Jerusalem to Amman.

corrections to the elevations have been made from published barometric data for stations in the vicinity. We anticipate errors due to elevation are not more than two milligals. The barometers were inoperative at elevations lower than 500 feet below sea-level. For stations in the Jordan River Valley below this elevation, elevations were obtained from the topographic maps. Here the topographic gradient is not large; we anticipate that inaccuracies in elevation due to using maps will not be greater than two milligals.

The last sets of traces in Figure 2 show the free air anomalies and the simple Bouguer anomaly (ρ = 2.67 gm/cc) computed without taking into account topographic corrections other than elevation. The gravity values are adjusted to a Bouguer anomaly of +1 mgal for Jerusalem (station 11) in accord with Lejay's pendulum value. It should be noted that our station was at the National Hotel; Lejay's station was in the Pontifical Bible Institute. The difference in Bouguer anomaly for these two sites is assumed to be small. The free air anomalies are well correlated to elevation. A summary of our data is presented in Table I.

An examination of the Bouguer anomalies for the two surveys shows that the two regions on either flank of the Jordan Valley do not have identical structures. In fact Jerusalem is 38 milligals more positive than Amman; Nablus is 93 milligals more positive than Amman. Thus before searching for features pertaining to the rift zone itself one must remove the regional trend due to the east-west asymmetry across the graben.

The data of Girdler et al.show large negative but substantially equal Bouguer anomalies on either side of the Gulf of Aqaba. Thus the east-west asymmetry across the Jordan Valley may have been equilibrated at the junction of the Dead Sea Rift with the Red Sea. From the gravity data of Lejay the east-west asymmetry is maintained for several hundred miles to the north of the Dead Sea. The gravity data of Lejay, corrected for topography by Bourgoin (1948), have been used in the European gravity map constructed by deBruyn (1955). deBruyn has used, in addition, the Eastern Mediterranean data collected by Cooper et al. (1952) to compile his gravity map. A portion of his Bouguer anomaly map, corrected and amended by our data, is shown in Figure 3. The east-west gravitational asymmetry across the Dead Sea and its extension to the north, already noted, can be seen.

From Figure 3 it can be seen that the positive gravity anomalies of the Eastern Mediterranean sweep undiminished across the Levantine coast; high positive gravity anomalies are found inland from the Mediterranean almost as far as the Dead Sea Rift and the northward extension of the rift. The positive gravity anomaly along the western flank of the Dead Sea Rift becomes more pronounced as one proceeds southward toward Nablus and begins to diminish to the south of Nablus in the direction of Jerusalem (Fig. 4). On the other hand the gravity values in the Transjordan block to

TABLE I

Station	Location	Elevation (ft.)	Free Air (mgal)	Bouguer (mgal)	Magnetic (γ /24050)
LINE A - B					
13	Nablus (Jacob's Well)	1578	110	+56	138
14	Tubas Rd.	594	71	+51	99
15	Jebel Tammun	270	64	+55	83
16	Khirbat Beit Hasan	-191	44	+50	87
17	Shunat al Masna'a	-550	16	+35	21
18	Beisan Rd.	-891*	-17	+12	101
19	Damiya, River Jordan	-1070*	-30	+7	124
20	Ain Khuneizir	133	24	+19	177
21	Es Subeihi Rd.	1849	67	+4	323
22	Ain El Jadur, Salt	2660	75	-15	294
23	Suweilih	3190	87	-22	196
5	Amman (Marka) Airport	2514	54	-44	-
6	Amman (Jarash Rd.)	2870	61	-37	292
LINE C - D					
12	Al Bira	2546	103	+16	186
28	Jerusalem (Qalandiya) Airport	2461	102	+18	-
11	National Hotel, Jerusalem	2445	84	+1**	-
10	Bethlehem Road	2195	72	-2	333, 363
27	2 miles east of Bethany	1654	54	-2	357
9	1 mile west of Good Samaritan Inn	623	20	-1	271
8	Sea Level Sign	-5	-3	-2	297, 313
2	Jericho-Amman Crossroads	-535	-14	+5	225, 292, 236
1	Winter Palace Hotel, Jericho	-851*	-34	-6	-
3	Near Sea Level	-247	-32	-23	280
7	Near Sea Level	-34	-25	-24	298
26	Near Sea Level	110	-11	-15	392
4	Naur	2863	67	-27	248, 372
6	Amman (Jarash Rd.)	2870	61	-37	-
5	Amman (Marka) Airport	2514	54	-44	292

* elevation from topographic maps

** adopted value from Lejay

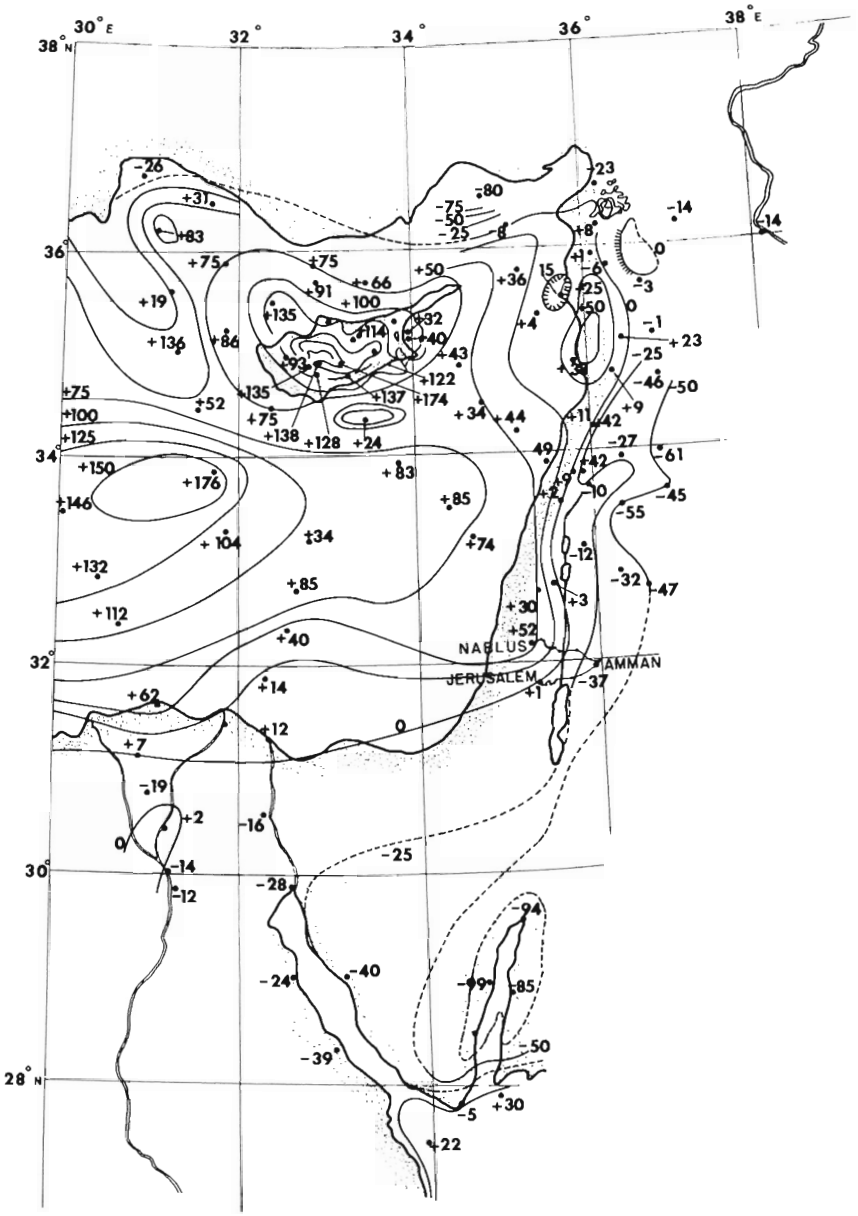


Figure 3. Bouguer anomaly map for the eastern Mediterranean and the Dead Sea Rift region.

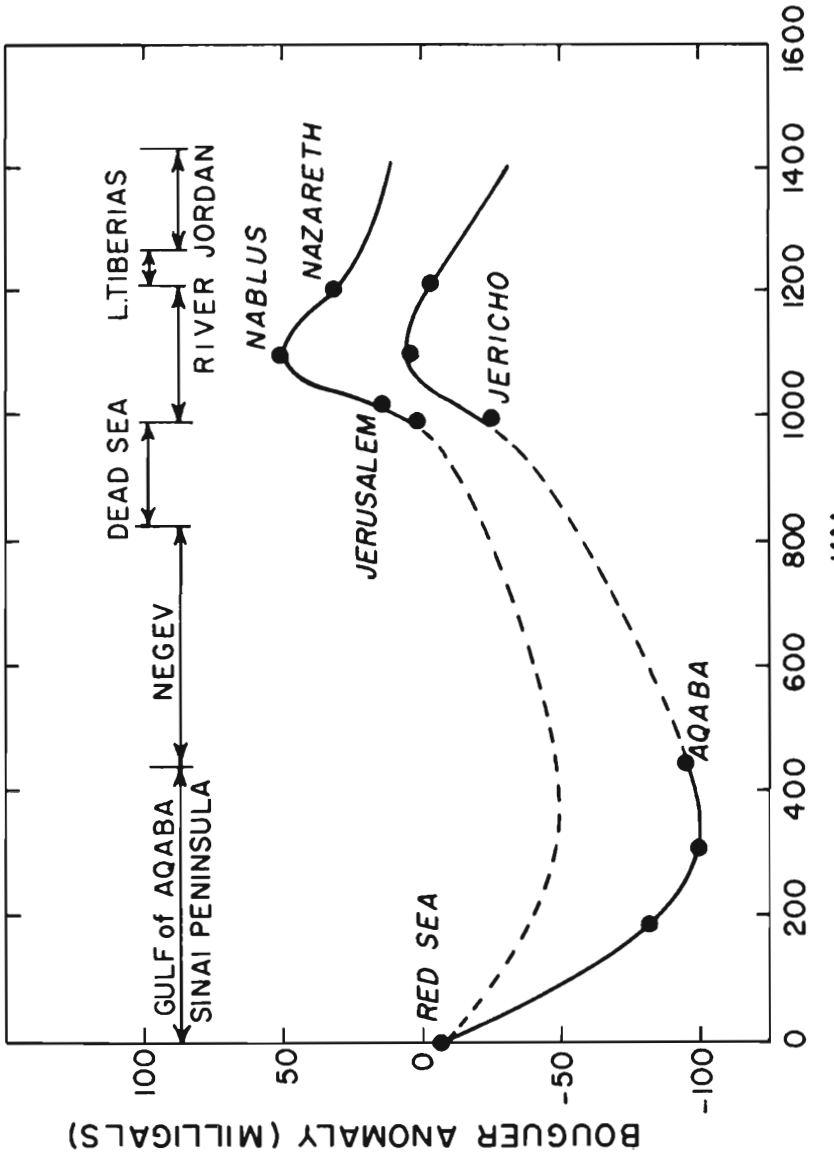


Figure 4. Bouguer anomaly in the Rift bottom and along the western edge of the Rift zone.

the east of the Dead Sea Rift seem to be uniformly about 30 to 40 milligals negative. The gravity values along the western flank are uniformly significantly larger than in the rift floor.

INTERPRETATION OF THE DATA

To begin our interpretation we assume that the Transjordan block has a more-or-less constant crustal thickness in a north-south direction to the east of the Dead Sea Rift in the latitudes of our traverses. On the other hand the continuous connection of the high positive anomalies to the west of the rift with the positive values in the Eastern Mediterranean makes it seem plausible that the thin crust of the Mediterranean extends under the land at least as far as the Dead Sea Rift and is thinner than the crust on the east side of the rift. We assume therefore that the crust on the west side of the rift is thinnest in the neighbourhood of Nablus and thickens as one proceeds south toward Jerusalem. It can be seen from Figure 3 that the high positive gravity anomalies in the Eastern Mediterranean disappear at about the latitude of Jerusalem. South of the latitude of Jerusalem the Dead Sea Rift and the Mediterranean coast diverge. If the conjecture is correct that the positive gravity anomalies west of the Jordan River Trench are associated with the extension of the positive values from the Eastern Mediterrranean, then a gradual gradient to large negative gravity anomalies at the Gulf of Aqaba is consistent with the absence of interaction with the Mediterranean to the south of the Dead Sea. Thus the two blocks on opposite sides of the Dead Sea south of the latitude of Jerusalem probably have crustal bottoms that dip to the south and approach a common thickness at the Gulf of Aqaba, with the western block having the greater dip.

An attempt can now be made to remove these large-scale geographic trends in gravity from the data in the two traverses by means of a simple theoretical model. We introduce a semi-infinite horizontal sheet of mass at an arbitrarily chosen depth of 30 km. The edge of the sheet is presumed to run north-south and parallel to the rift valley. The sheet extends westward and represents the mass corresponding to the gravity anomaly between the two plateaus on opposite sides of the valley. The sheet is placed in an otherwise homogeneous half-space and permits us to calculate the gravitational profile to be expected from a block fault model of crusts of differing thickness abutting in a vertical plane containing the edge of the sheet. The strength of the sheet is a variable for each of the gravity stations in the survey. The strength for any station is chosen so that the theoretical values for the sheet fit two interpolated points on lines 30 km to the east and west of the Jordan. The eastern value is obtained by a linear interpolation to the latitude of the station between the Bouguer values at stations 4 and 23;

the western value is governed by a similar interpolation between the Bouguer values at stations 11 and 13.

We place the edge of the sheet under the Jordan River, more or less in the centre of the Rift Valley. The valley is narrow and not much freedom of position is possible in an east-west direction. The data, when reduced, leave as residuals the curves shown in Figure 5. There is substantially no residual gravity anomaly on either line. All residuals but one are less than 10 milligals; errors of this order of magnitude are possible in the interpolation procedure used above. The computational result only verifies what is evident by inspection of the Bouguer anomalies of Figure 2; the east-west asymmetry is resolved in a horizontal distance of the order of the crustal thickness. It thus seems likely that the rift zone is, in the main, in isostatic equilibrium. If the sheet is placed at 20 km depth, the residuals are altered by no more than $1\frac{1}{2}$ milligal due to the method of adjusting the strength of the sheet.

We see no direct evidence for extensive sedimentation on this model. Small positive residuals are observed at either side of the Jordan River bottom. The zero value of residual at the river itself may be the result of small amounts of sedimentation; hence the Bouguer anomaly after reduction could be fortuitously almost zero. Unfortunately we have no gravity station at the Jordan River on our southern line C-D. The curves of the residuals for both lines are remarkably similar in the vicinity of the river bottom although the maximum residuals are small and are perhaps not to be considered as significant.

The large negative Bouguer values in the Gulf of Aqaba are inconsistent with our data in the Jordan Valley to the north of the Dead Sea. Two explanations of this inconsistency are possible. One is that extensive sedimentation of low density material has taken place in the Gulf of Aqaba. The replacement of 5 km of material of density 2.67 gm/cm^3 by material of density 2.0 gm/cm^3 would result in a 120 milligal negative anomaly. As noted above, drilling at the south end of the Dead Sea has shown several kilometres of salt to be present. The west wall of the Dead Sea at Sodom is a salt formation hundreds of feet high. However, we have not found these extensive light sediments as far north as station 19.

Another possiblity is that the crust is indeed thicker at the Gulf of Aqaba with a significant root. This might be the case if the Gulf and the surrounding region represent a feature arising from compressional stresses. If this is the case, the Gulf of Aqaba may be a hinge for the relative motion of the Arabian Peninsula away from the African continent. This leads to the following tentative picture for the large-scale mechanics. The Red Sea has been opening under tensile stresses; as the Arabian Peninsula rotates counterclockwise, it pivots about the Sinai Peninsula,

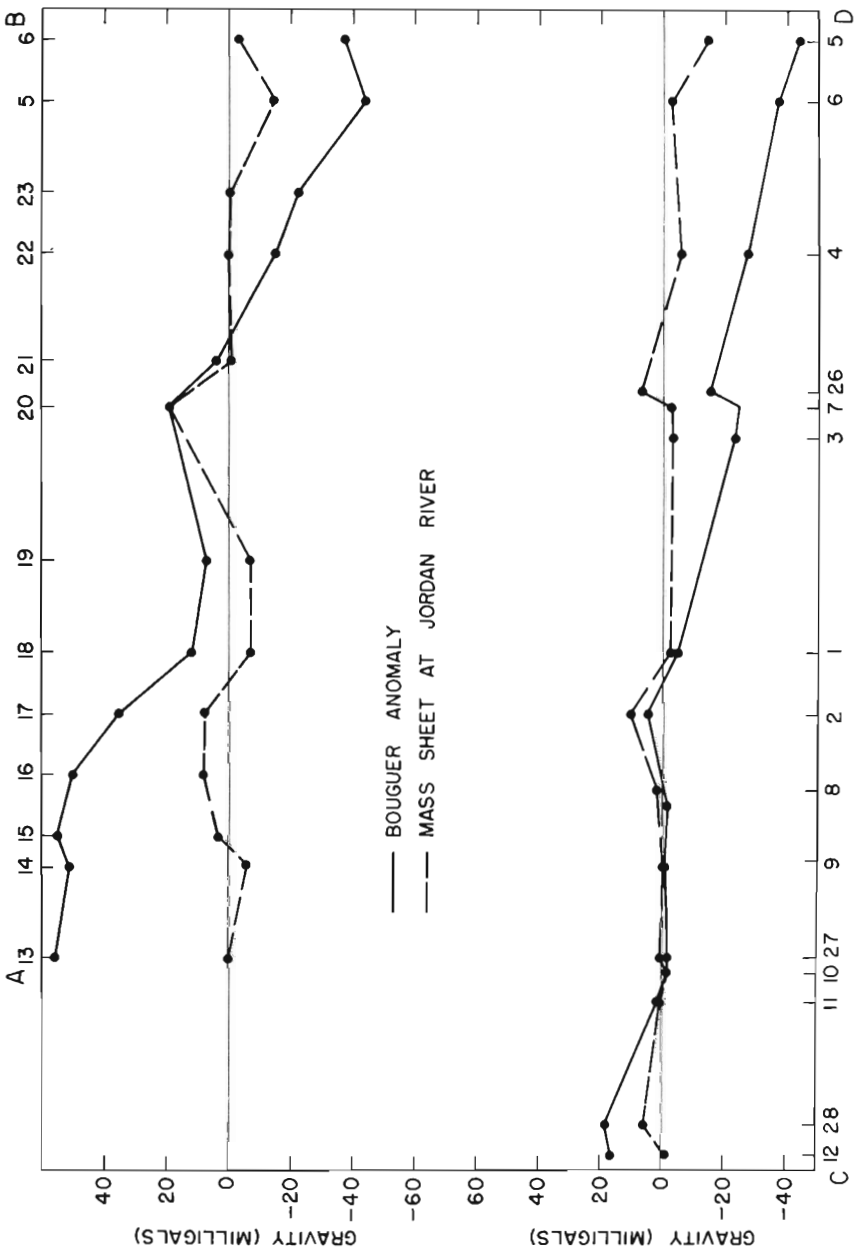


Figure 5. Bouguer anomaly for the two lines plus residual after effect of massive half-sheet to west of Jordan River is removed. Half-sheet is placed at 30 km depth.

exerting enough compressional stresses at the bearing surface of the Gulf of Aqaba to depress the crust and produce large negative gravity anomalies. During the process of rotation, drag at the hinge caused fracture of the hinge and the creation of the Gulf of Suez; no direct data have been taken in the Gulf of Suez.

Tests of the two hypotheses for the problem of the Gulf of Aqaba can be constructed. Gravity measurements to determine the depth of the Aqaba anomaly should be made by measurements on the adjacent land masses; if the negative values extend on to the Sinai Peninsula and its Arabian image for some distance then the compression hypothesis will be preferred. Exploration should be made to see if positive gravity anomalies are found in the Gulf of Suez to test the conjecture of friction at the Gulf of Aqaba. Finally if the compression hypothesis is valid, rotation of geologic features in the Aqaba Graben should be found. The Tiran Islands at the mouth of the Gulf represent an outcrop of Mid-Gulf material; these should be explored for possible rotation in a counter-clockwise direction.

Independent of the mechanics of the Gulf of Aqaba, it is now possible to construct the large-scale mechanics of the structural features to the north. The Arabian plateau slides northward along the Dead Sea Rift in primarily left-lateral strike-slip motion using the thinner Mediterranean crust to the west as a bearing surface. The rift is formed without the need for the introduction of large tensile stresses. Hence the gravity anomalies need not be large in the Dead Sea Rift. Irregularities in linearity of the bearing surface can cause local accumulation of matter where the two blocks override each other or absence of surficial matter where the two blocks separate (Freund, unpublished). This is especially the case for the brittle surface materials; at greater depth the plastic nature of the rocks would permit the two blocks to remain in contact.

CONCLUSIONS

Whichever of the two hypotheses for the Gulf of Aqaba is found to be appropriate (we favour the compression hypothesis), the results of our investigations show the following: the Dead Sea Rift, from the Dead Sea northward, is the western continental margin for Arabia. The geologic evidence indicates that left-lateral strike-slip motion has taken place along the discontinuity. It is reasonable that this motion should have taken place at the continental margin since this is the point of structural weakness. The absence of a significant gravity anomaly across the fault indicates that the rift has formed without significant stresses. Thus the graben may be a surface feature associated with the separation of the eastern and western blocks under the strike-slip motion. It would seem plausible that the

geographic orientation of the continental margin on the west has been a significant factor in controlling the direction of motion during the opening of the Red Sea Rift.

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DISCUSSION

Dr. L. Picard (Israel)

May I ask you to compare the eastern and western blocks? According to you, the Arabian Plateau has a thinner crust than the western block.

Dr. L. Knopoff (U.S.A.)

No. The western block is thinner; the Arabian Plateau is thicker.

Dr. Picard

Well, that is exactly the opposite of what we know from our geological data. As one goes westward, all the sedimentary masses above the Precambrian and older rocks become thicker and thicker. Why, I can't tell you, it is simply a fact of observation in the field.

Dr. Knopoff

Nablus is 87 mgal more positive than Amman.

Dr. R.W. Girdler (U.K.)

Can we say whether the density used in computing the anomaly of 2.67 might be altered? If so we might get a negative gravity anomaly, perhaps as large as 150 mgal over the rift valley. There is an anomaly of 150 mgal.

Dr. Knopoff

There is a large free-air anomaly but not a large Bouguer anomaly. The density would have to be too low to produce a large negative Bouguer anomaly over the rift.

Dr. Girdler

Do you think that the large Bouguer anomaly is due to the effect of two blocks in contact?

Dr. Knopoff

Yes.

Dr. V.A. Magnitsky (U.S.S.R.)

This broad communication is very interesting. I'm not too familiar with the geography of this region, but if I understand the previous communication, the oceanic crust overlaps the Mediterranean Coast. This observation should extend to the north as well. Now that we have some gravity profiles in the region of Jerusalem, it seems to me that the crucial gravity experiment by which we can solve these problems is to obtain, not one or two gravity profiles, but extensive gravity profiles across the rift to the north. A comparison of the gravity field in these places can prove or deny the explanation offered by Freund and Knopoff. Is it possible to obtain these gravity data in the rift zone to the north?

Dr. Knopoff

The only data which exist at present, that I know of, are the early pendulum data of Lejay. These are very sparse. No detailed profiles are available.

Prof. T. Sorgenfrei (Denmark)

I want to put the question as to whether there are other geophysical surveys in the general area. I'm thinking of seismic surveys taken, for instance, in connection with prospecting work. Are there any other data which could help us in the interpretation? Dr. Picard has mentioned the geology. I think that if we had better coverage in the areal sense, then we might be able to combine the data in a better way than we have today. Are there more data available?

Dr. Knopoff

I assume some data have very likely been collected from exploration surveys for petroleum but they are not available in the literature.*

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*Note added in proof: The thesis by Lloyd-Morris represents a report of partial coverage of parts of Jordan by oil prospecting methods.

Dr. G.A. Thompson (U.S.A.)

I have learned from Dr. Freund that there are very thick low density sediments in the bottom of the Jordan Rift. Now these would produce quite a large negative Bouguer anomaly. If Bouguer anomaly is absent and the low density sediments are known to be there, then can there not be a large high density mass under the rift zone?

Dr. Knopoff

A deep high density mass would produce a broad positive anomaly which is not observed in the residuals. One can conclude that the Dead Sea Rift is too narrow a feature to be compensated in the manner you suggest.

THOUGHTS ON THE GRABEN SYSTEM IN THE LEVANT

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Abstract

The Levant graben system is a north-south system extending from the border of Syria and Lebanon to the Gulf of Aqaba. Its major faults are commonly masked by parallel and en echelon faults, and many transverse and diagonal faults extend into and cross the system. This pattern results in curved fault scarps, and in a series of smaller "sub-graben" that are the locations of Pleistocene and Recent Lakes. Some of the transverse faults show apparent transcurrent movement and have caused small displacements of Recent sediments, but the graben system as a whole shows principally dip-slip movements of Pleistocene age, the last major movements having taken place during Middle Pleistocene times.

Negative gravity anomalies in the areas of the Gulf of Aqaba and the Kara-su valley apparently reflect the presence of thick accumulations of sediments in the fault trough and along its edges. It has been estimated that there is about 30,000 feet of fill to the south of the Dead Sea, and a recent drill-hole encountered more than 10,000 feet of Pleistocene clastics alone.

Basaltic volcanic rocks were erupted along the graben system (in both the down-faulted trough and its marginal blocks). They occur in "continental" plateau-type flows and appear to have been erupted from open fissures under tensional conditions. They would not seem to support the idea of large transcurrent movement along the fault system.

Large wrench (transcurrent) faults do occur in the Arabian Precambrian shield, but they are of Precambrian age and generally trend northwest-southeast.

DESCRIPTION OF THE LEVANT GRABEN SYSTEM

The term Rift Valley, can be misleading since many of the mega-faults or geo-sutures that have been called rifts have dominantly strike-slip movement (e.g. the San Andreas and Great Glen faults) and do not constitute "valleys of subsidence with long steep parallel walls" as the term was originally defined by Gregory (1894). Suess' name Graben for this type of fault-bordered regional depression is preferable and should be maintained.

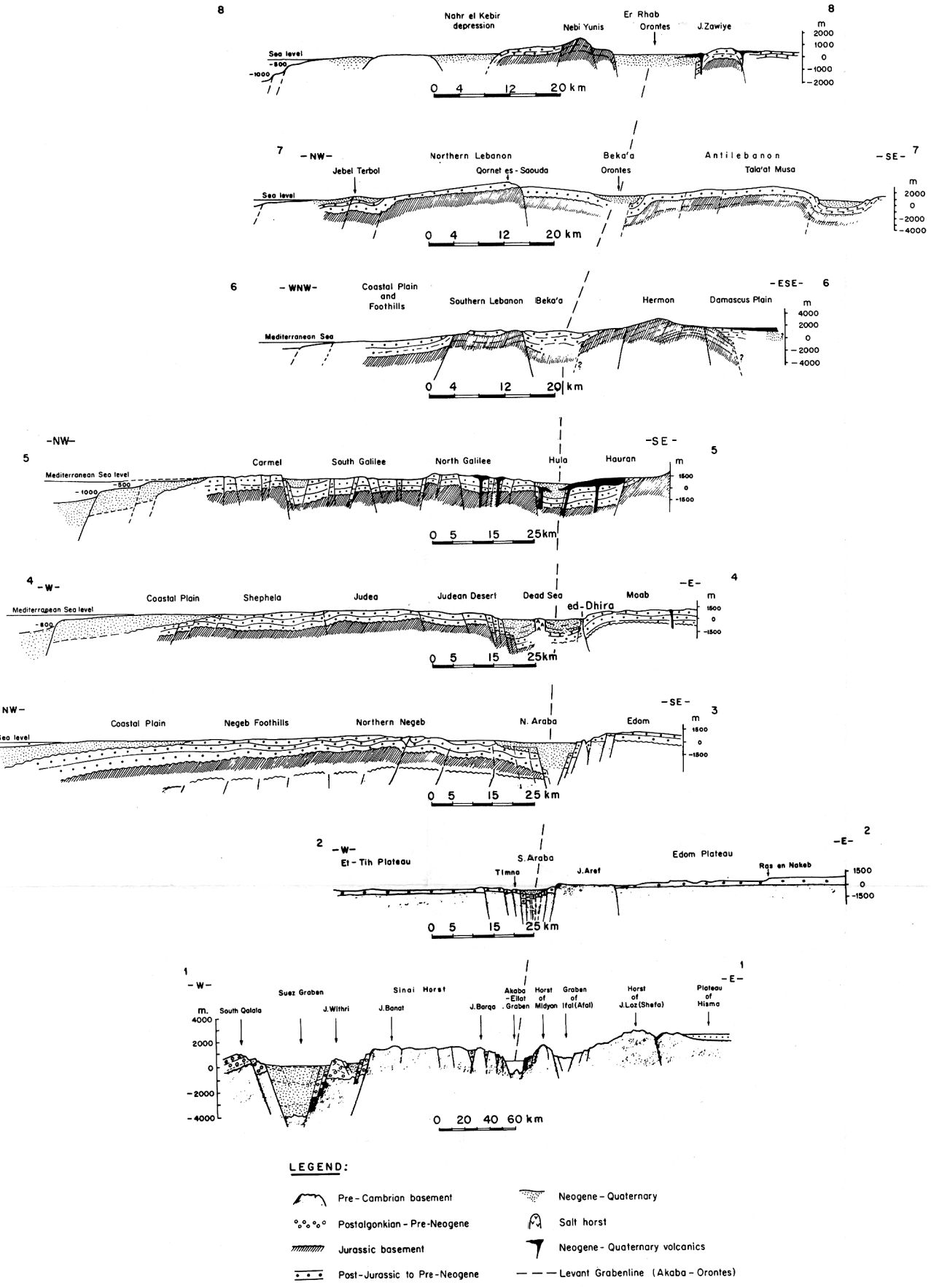


Figure 2. Geological cross sections through the Levant graben system.

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In the Levant graben system (Fig. 1) the main border faults, which are meridionally directed, are of Pleistocene age. They are commonly hidden by smaller faults and (or) en echelon faults having genuine gravitational (dip-slip) character (55° average dip). Transverse and diagonal faults cut the adjacent horsts and may penetrate or even (albeit less commonly) cross the graben. These intersecting sets of faults, whose morphological effect is the formation of curved fault scarps, are the principal structural feature of the sedimentary cover on the horsts and the graben borders. (They are particularly well developed and well studied in Galilee.) By contrast the more crystalline Precambrian massifs of Sinai and Midian (where the southern end of the Levant graben system splits or "splays out" into many faults) shows several minor graben wedged into the crystalline basement and trending parallel to the main Aqaba-Elath graben (Fig. 2, cross section 1). The structure here bears much similarity to that on the southern part of the Rhine Valley graben system.

The fractures that cross the Levant graben system between Antitaurus and the Red Sea have divided it into a series of sub-graben. These are represented by Aqaba-Elath Gulf; South and North Araba Valley; the Dead Sea and the southern Jordan Valley; the Tiberias Lake depression; Hula Valley; Er-Rhab; and Kara-su. The sub-graben have also influenced the formation of the Pleistocene and Recent lakes. On the geological maps (Dubertret, 1953, Picard, 1959) the larger transverse faults crossing the mountains of northern Israel and Lebanon in NW-SE or, more rarely, E-W directions appear to have slight horizontal (strike-slip) displacement, maximum displacements being of the order of a few kilometres, although it must be admitted that field investigations have not detected strike-slip striae or appreciable mylonitization on the exposed fault scarps.

Strike-slip fractures crossing the Araba and southern Jordan graben obliquely were assumed by Quennel from the study of air photos. They appear to be of very small displacement, and since they cut the younger Pleistocene fans and Lisan beds, are also of relatively recent age.

In spite of the minor dimensions of the apparent transcurrent faults which cross the upwarps of the Levant and occasionally approach its graben system, a comparison of their structure to those of suboceanic wrench faults may perhaps be permissible. As Heezen's "Tectonic chart of the World" (Heezen, 1962, Fig. 19) clearly demonstrates, the gigantic wrench faults of the ocean basins are consistently transverse to the suboceanic swells, and terminate at the meridional graben depression that characterizes the crestal part of the swells. Thus the combination of "equatorial" wrench faulting with associated regional upwarps and swells and "meridional" tensional graben faulting appears to be a universal tectonic pattern[1].

[1]Van Bemmelen (1965) apparently had a similar idea in mind when he hypothetically (in his Fig. 3) extended the wrench faults crossing the Indian oceanic swells into the graben system of the East African uplift.

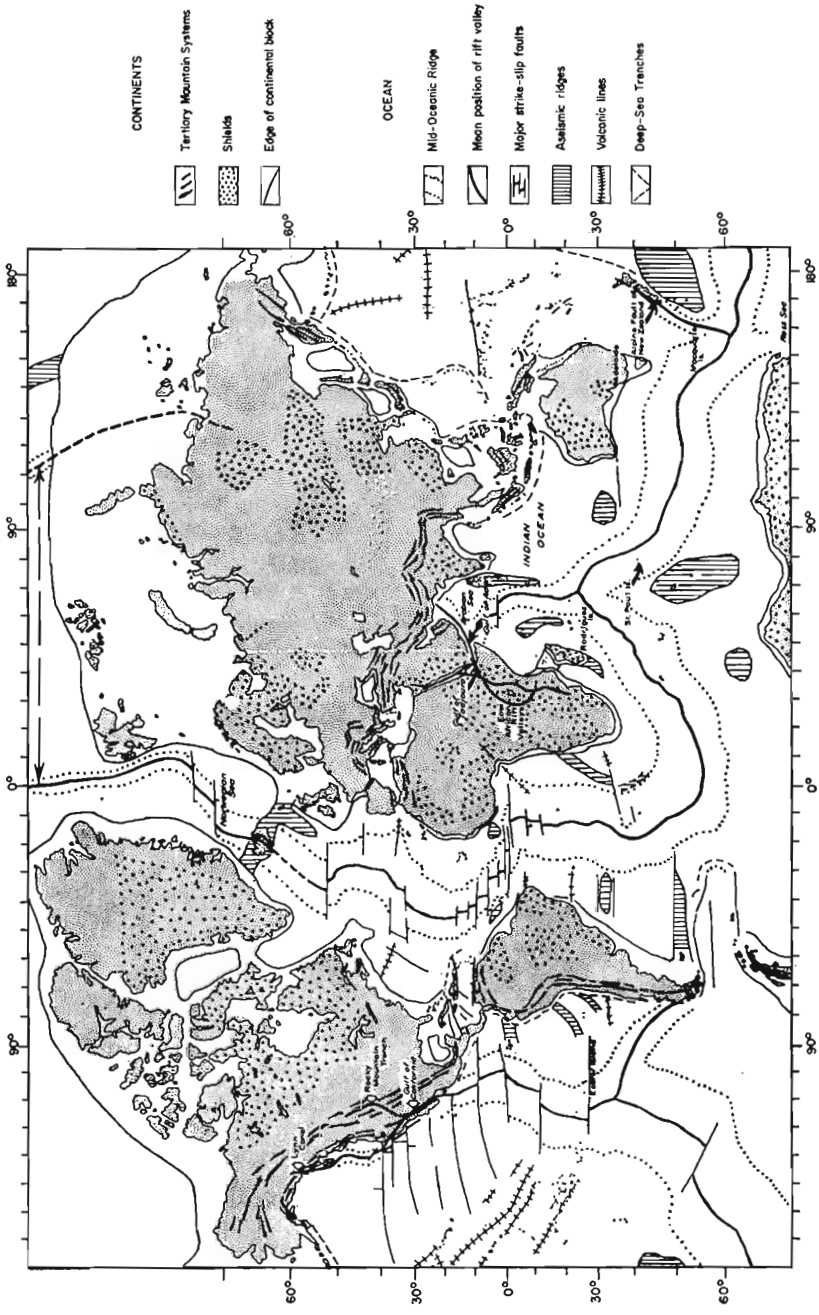


Figure 3. Tectonic chart of the world. After Heezen, 1962, Figure 19.

The Pleistocene age of the Levant graben system is definitely proven by the fact that the graben faults extend into and through Neogene formations. There are other faults having Neogene (Galilee), Jurassic (Negeb, Lebanon) and Precambrian ages, but we find no indication that they have caused meridional graben features earlier than the Levant graben system.

The principal fault depressions preceding the Quaternary period are of a different trend. They consist of Neogene subsidence areas that originated along NW-SE ("Erythrean") or NE-SW ("Alexandretta") lines and formed a number of marine Neogene gulfs and inland seas, in particular those of Alexandretta in Turkey; of Tripoli in the Lebanon; of Haifa-Emek in northern Israel; of the coastal plain of southern Israel (up to Beersheba?); and lastly of the Gulf of Suez and the Red Sea. Large portions of these Neogene bays are now covered by the Mediterranean Sea as a result of Quaternary downfaulting along the eastern Mediterranean. The latter faulting is evidenced by steep submarine slopes, primarily at and between the 500 m and 1000 m contours of the sea bottom. The western extensions of fault-controlled promontories on the mainland (e.g. Carmel and Beirut) are also apparent in the submarine topography as distinct nose-like projections in the bottom contours.

However, the most important Oligocene or early Miocene down-faulting is associated with the large Erythrean graben marked by the Gulf of Suez (length, 300 km; width, 80 km) and the Red Sea (length, 2000 km; width 350 km). This graben system separates the Arabian and Sinai Peninsulas from the African continent and is (geographically speaking) outside the Levant graben system. The succeeding Pleistocene taphrogeny has strongly affected the Neogene sedimentary deposits in the graben system: in the Suez graben, a series of minor faults and "endemic" fold structures has been developed parallel to the Erythrean graben trend; and in the Red Sea, a "graben-in-graben" feature has been produced. The renewed stretching and deepening caused by the Pleistocene tensile fracturing may well explain the rise of basic magma along the axis of the Red Sea graben as has been postulated on the basis of the large positive gravity anomalies (over 100 mgls) measured there (latest discussion in Drake and Girdler, 1964).

Only a few gravity measurements have been made in the sub-graben between the Gulf of Aqaba and the Kara-su Valley, but these have all revealed negative anomalies: e.g. Port of Aqaba, -94 mgls (Girdler, 1958); Tiberias south, -27 mgls, and Hula north, -20 mgls (Ginzburg, 1960); Beka'a, -25 mgls (de Bruyn, 1955; Bourgouin, 1945); and Amik, -36 mgls (Yüngül, 1951). Since these Levant graben valleys have an average width of only 10 km, they have not provided much room for lateral dispersal of Quaternary sediments (as compared to the Red Sea graben, which is 30 times broader), and this may be the reason for the great thickness of their

Quaternary sedimentary fill. For example, a recent "wild cat" oil well in the northern Araba remained in clastic alluvial fillings to a depth of 10,000 feet; and Nettleton (in a private report in 1947) inferred from gravity surveys made in the same area that the sedimentary accumulation was at least 30,000 feet thick. The existence of negative gravity anomalies has been known for many years (Krenkel, 1925), and the author (Picard, 1931) has suggested that they are caused by the "heaping of sial sediments". However, geophysical data on the Levant graben system are still too few and too sporadic to permit a final diagnosis on the subject despite the comments of De Bruyn (1955), Bourgouin (1945-1948), and de Cizancourt's (1945-1948). Positive anomalies may be expected in sections of the Levant graben system, although they probably are not as high as those of the Red Sea.

Basaltic volcanism is widely distributed in the Erythrean and Levant regions. In the Tiberias region, the basaltic effusions are partly of Neogene age and are linked with diagonal NE or NW faulting (Schulman, 1962; Wakshal, 1965; Saltzman, 1964). Even more impressive are the Quaternary eruptions that have spread lava over large sections of the Hejaz, Hauran and Orontes regions. Dubertret (1929) noticed that, in the Hauran, the lavas are related to approximately north-south eruption lines. In other regions such as that between the Dead Sea and Hula, and that in the Er Rhab, the Quaternary lavas either flowed into, or were intruded into the graben. In any event, their association with plateau volcanism having "continental" olivine-basalt kindreds points to open tensional fissuring rather than to wrench faulting of a more "sealed" character.

COMMENTARY

We must now return to the problem of the significance of transcurrent or wrench faults in the Levant graben system. This problem was originally considered almost a hundred years ago (Lartet, 1869), and has been raised again in recent efforts to explain the mechanics of the graben system. Quennel (1958, 1959) and Freund (1965) both believe there is a hundred or more kilometres of horizontal displacement along the main graben faults. Quennel held that this shifting took place mainly in the Quaternary, whereas Freund believes it started in the Upper Cretaceous and continued until relatively recent times. Freund also believes that this strike-slip faulting has produced the network of folds and upwarps (Krenkel's Syrian arc) spread over the entire Levant region and northern Egypt (Fig. 1).

As a supplement to the author's previous comments on this subject, his "Thoughts on the Graben system of the Levant" may be summarized as follows: the meridional rupture zone constituting the Levant graben system and extending for more than 1000 km from the Red Sea to the Antitaurus foreland (Fig. 1) is a younger branch of the East African graben

chains of Quaternary age. The influence of the Neogene Erythrean fault system is evident in the Levant countries in the form of a number of diagonally transverse faults (Picard, 1954; Vroman, 1961), some of which have been revived in the Quaternary. Where these transverse faults enter and cross the Levant graben system, they have divided it into sub-graben. Some of the transverse faults may be of transcurrent character (see also Sitter, 1962), but they are of minor size and displacement. The sub-graben (Fig. 2) either have the classic form of a graben with faults on both borders (the most symmetrical examples are the Aqaba-Elat sub-graben and, to a lesser degree, the Hula and Tiberias sub-graben), or they are asymmetrical (e.g. in the Araba Valley and the Dead Sea, the eastern horst block has risen higher; and in the Beka'a and Orontes Valleys, the western block shows greater uplift). In extreme cases of graben asymmetry, half-graben are developed – thus pre-Quaternary formations have been downwarped in an easterly direction in the northern Araba, and in a westerly direction in the Beka'a. However, it is noted that border faults may exist on the downwarped side of asymmetrical sub-graben; their existence is masked by younger sediments but may commonly be inferred from cross-sections. In the better developed sub-graben that have been studied, the main border faults and their accompanying step faults are of a gravitational, tensional type. Reverse (thrust) faults at the graben margins are very rare; they are attached, as in the case of the ed Dhira fault at the south end of the Dead Sea (cross-section 4, Fig. 2), to the borders of strongly asymmetric anticlines such as are generally found outside the graben area in the steep flanks of the upwarps in northern Sinai, Negeb, Judaea, Galilee, Lebanon and Anti-Lebanon designated in Figure 1, "major monoclinal flexures" (see also geological cross-sections in "Atlas of Israel"). Despite many observations in both the sedimentary cover and the crystalline Precambrian outcrops along the Levant graben areas, no significant shatter belt of crushed or mylonitized rocks has been discovered. Considering that a horizontal displacement of more than 100 km is argued for by supporters of a wrench fault origin for the Levant graben system, it is certainly surprising that striking shatter belts like those occurring along the Great Glen fault (where the shifting has been of a similarly large magnitude) have not been found. It is even more difficult, for reasons to follow, to accept the idea that the postulated meridional line of transcurrent faulting should have caused the development of a fold pattern in a regional foreland that comprises the enormous area extending from northernmost Syria to the Nile delta. The reasons are: (1) Many of the folds are transversely or obliquely cut by major and minor faults of the Levant graben system, to say nothing of the related Pleistocene downfaulting that occurred in the Mediterranean shelf area and which has destroyed many fold ranges now covered by the sea. (2) It is difficult to understand why, if the folding is an effect of the transcurrent faulting, the strike-slip movements that are assumed to have continued until the Holocene have not wrinkled and folded the almost undistrubed, well bedded Upper Pleistocene (Lisan) formations of the Jordan-Dead Sea graben region. Where minor folds occur in this region,

they are of post-Villafranchian age (Picard, 1965) and definitely a phenomenon of vertical graben subsidence in response to gravitational forces ("endemic graben tectonic"; Picard, 1943). Furthermore, the strike of these small folds is totally different from the large folds of the "Syrian arc" system. (3) The Quaternary basaltic volcanic rocks (those having "continental" kindreds) occur in both the horsts and the graben and would appear to indicate tensional opening of feeding fissures rather than a compressional shearing accompanying wrench faulting.

Finally, it is interesting to note (although this is not absolutely basic to our discussion) that the regionally important faults known to occur in the crystalline Precambrain basement of Midian and Western Arabia (e.g. the Nadj fault of Brown and Jackson, 1960) trend for the most part in a NW-SE (Erythrean) direction parallel to the Precambrian orogenic belt, and not in the meridional direction of the Levant graben system. Moreover, nowhere do these faults continue into Palaeozoic-Mesozoic cover beds.

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RED SEA SEISMIC REFLECTION STUDIES[1]

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Abstract

Seven continuous seismic reflection profiles were made across the main trough of the Red Sea north of 17°N latitude. These were accompanied by short-pulse echo-soundings and measurements of the total intensity magnetic field and the free-air gravity anomaly.

The horst-and-graben structure of the Gulf of Suez continues southward beneath the western marginal zone of the main trough at least as far as latitude 20°05'N. Deformation of sediments in the grabens indicates fault activity during and after deposition. Short-pulse echo-soundings reveal several episodes of faulting, probably Pleistocene, in the top 20 metres of sub-bottom sediments in the Gulf of Suez.

The main trough between the shelves of the Red Sea can be divided into mildly deformed marginal zones and a deeper, intensely fractured axial zone. Sedimentary sequences in places over 1.8 km thick are found in the marginal zones. Sediment-filled depressions in the western marginal zone at latitudes 18° and 25°N appear to be basins partially closed at their eastern margins by buried blocks of crystalline basement. A strong reflector 0 to 500 metres below all zones of the main trough is postulated to be an unconformity of late Miocene or early Pliocene age. If this postulate is correct, the following can be stated about ages of deformation in the main trough: (1) Most of the deformation in the axial zone appears to have taken place in two periods, one before the beginning of the Pliocene, and the other in late Plio-Quaternary times. These periods of deformation were separated by a period of tectonic quiescence during the early part of Plio-Quaternary time. (2) In the marginal zones, horsts and sediment-filled grabens similar to those of the Gulf of Suez were formed before the Pliocene, and lie buried beneath little-disturbed sediments of Pliocene and younger age.

Recently deposited layered sediment ponds exist in the north and south ends of the Red Sea.

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INTRODUCTION

This paper is concerned primarily with the structure beneath the floor of the Red Sea, determined by continuous seismic reflection profiling (Hersey, 1963). During March 1964, R/V Chain, en route eastward for the International Indian Ocean Expedition, made ten crossings of the axial part of the Red Sea north of latitude 17°N. Continuous seismic profiles, believed to be the first in the region, were made on seven of the crossings (Fig. 1). Gravity, magnetic, and high-resolution echo-sounding observations were made on all ten crossings. Five of the reflection profiles were run across or closely paralleled positions of refraction profiles made in 1958 aboard R/V Atlantis (Woods Hole Oceanographic Institution) and R/V Vema (Lamont Geological Observatory) in order that the reflection measurements might be correlated with the refraction results reported by Drake and Girdler (1964).

INSTRUMENTATION AND DATA PROCESSING

The sound source used for the continuous seismic profiling was an underwater spark, produced by discharging the stored energy of a 1920 μfd capacitance charged at about 8kv. Reflection measurements were taken every ten seconds. The receiver was a Chesapeake Instruments hydrophone array, consisting of five hydrophones in line, ten feet apart, that was towed about 500 ft. behind the ship. The combined output of the five hydrophones connected in parallel was preamplified and fed via the tow cable to additional amplifiers aboard ship. Signals from the array were then recorded on Precision Graphic Recorder (PGR) and magnetic tape. Variable bandpass filters were used when required before the signals were recorded on the PGR, but no filter was used before the magnetic tape recorder. The tapes were then played back at later times through filter-bandwidths not previously used. Ship speeds during profiling were 7-9 knots.

The free-air gravity anomaly and total-intensity magnetic-field measurements presented here with the interpretations of the seismic reflection data are preliminary results obtained from a LaCoste-Romberg sea gravimeter and a Varian proton-precession magnetometer, respectively. They were computed by a shipboard IBM 1710 computer (Bernstein and Bowin, 1963).

RESULTS

The chart of the Red Sea (Fig. 1) shows the ship's track and the locations of seismic reflection profiles described in this paper, and the location of the refraction profiles described by Drake and Girdler (1964).

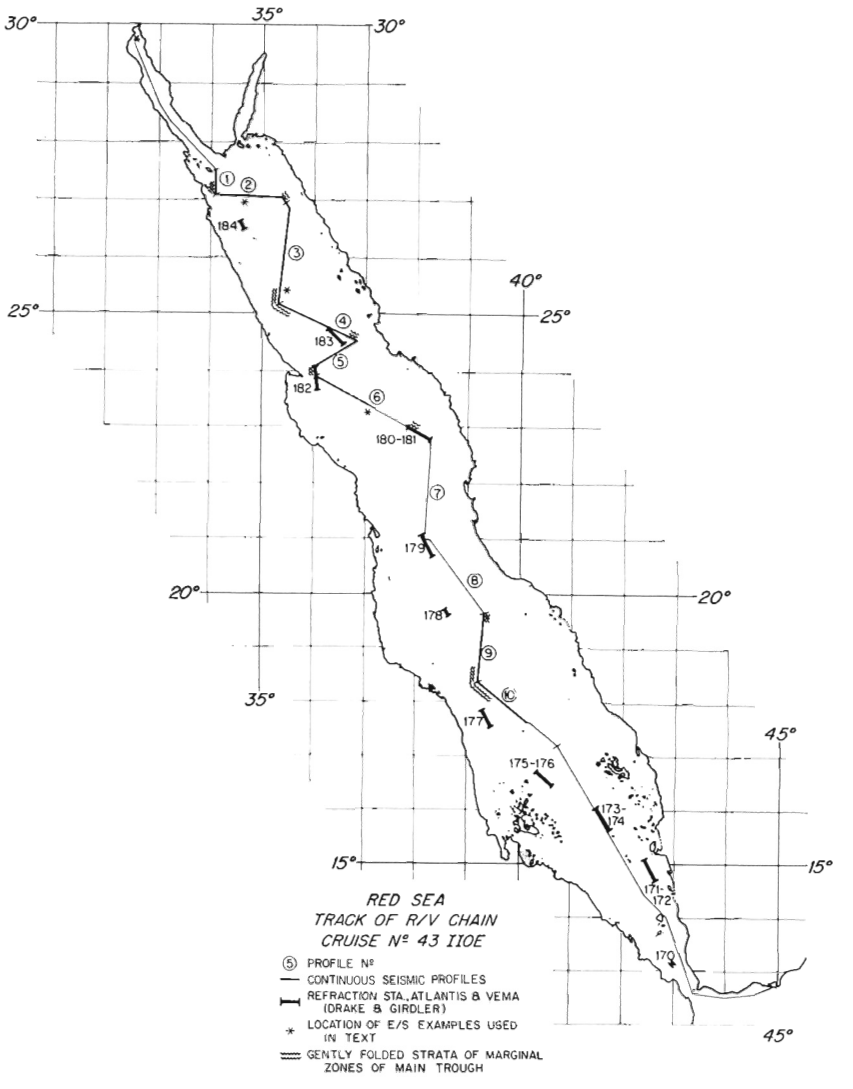


Figure 1. Track of R/V Chain and locations of observations in the Red Sea.

Examples of the seismic profiles recorded by the PGR are given in Figures 2-4. The apparent configuration of reflectors from the reflection profiles is shown by means of line drawings in Figures 2 and 5-16 together with profiles of total intensity magnetic field and free-air gravity anomaly. Bathymetry only is given for those crossings where seismic reflection profiles were not taken. In the line drawings, corrections have been made for varying ship and recorder speeds to bring the tracings to a common horizontal scale. The vertical scale is a time scale whose spatial equivalent varies with the compressional wave velocity of the materials traversed by the sound. Bathymetric scales are based on the assumption that the speed of sound in water is 1500 m/sec. The vertical exaggeration of the bathymetry is about 20:1, and of the configuration of the sub-bottom layers, somewhat less. The exaggeration in the reproductions of original records (Figs. 2-4) is about the same.

In the line drawings, solid lines indicate continuously received and well-correlated echoes (in this case "correlation" refers to how well successive measurements compare with one another in travel time and signal shape); broad lines indicate strong reflections and broken lines indicate interrupted and poorly correlated reflections. Ambiguities may exist where many reflecting horizons are closely spaced in depth. Closely spaced interfaces may be clearly identified at one point in a profile and at another appear to merge and form a single prominent reflecting horizon; in such case the interpretations may show more than one solid line joining a broad line.

ECHO SOUNDINGS

High-resolution echo-sounding records were made on all the tracks by using intense, short (0.2 millisecond) 12-kcps pulses. Sections of records are shown in Figure 17 (for their positions see Fig. 1).

DISCUSSION

The terminology of Drake and Girdler (1964), somewhat amplified, is used for physiographic regions of the Red Sea in the following discussion. New terms which are introduced below are the "axial zone" and the "marginal zones" of the main trough. The former is not to be confused with the axial trough, a previously defined term for a distinct region.

Three physiographic regions of the Red Sea are apparent: the coastal shelves, the main trough, and the axial trough (Fig. 18a; Drake and Girdler, 1964; Heezen and Tharp, 1964; Admiralty Chart C6359, 1965). The shelves slope gently from the shores to depth of 300 to 600 metres. The

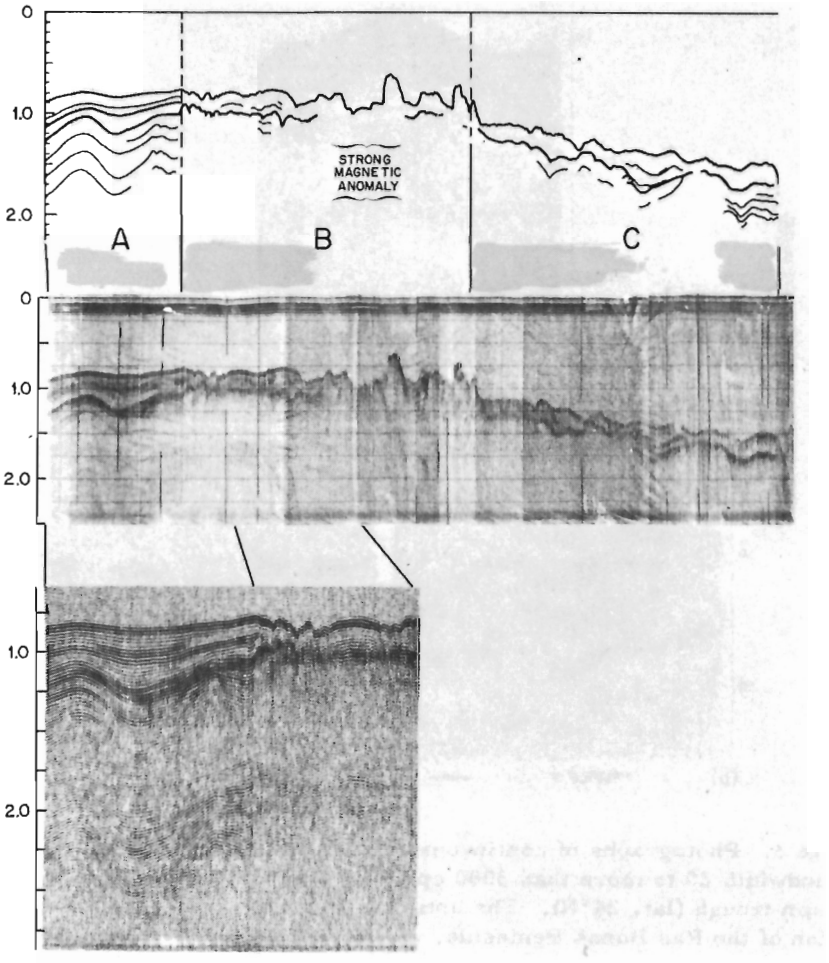


Figure 2. Western half of Profile 4: (top) line-drawing interpretation; (middle) seismic reflection record, recording bandwidth 37.5 to 300 cps; (bottom) section of reflection record, recording bandwidth 37.5 to 75 cps. A. Gently folded strata of western marginal zone. B. Acoustically opaque ridge which trends across the Red Sea. C. Axial zone of the main trough.

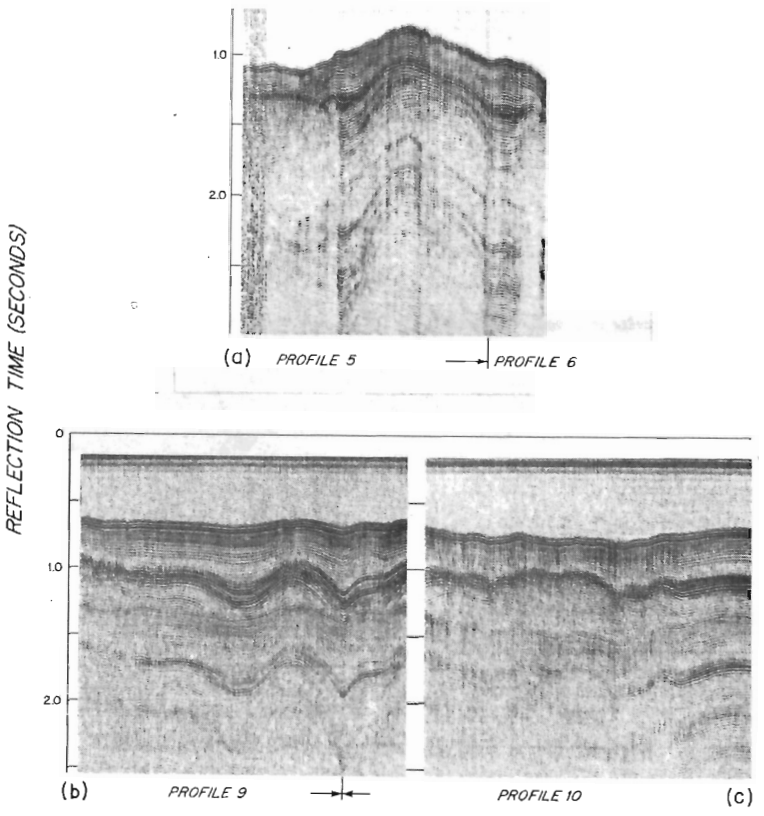


Figure 3. Photographs of continuous seismic reflection records. Recording bandwidth 20 to more than 3000 cps. (a) Western marginal zone of the main trough (lat. 24°N). The anticline is probably the submarine extension of the Ras Banas Peninsula. A sequence of reflectors beneath the anticline, 0.9 to 1.5 seconds below sea-level, is cut off abruptly on the north (left) side, possibly along a steeply dipping fault. Reflectors below the sequence are multiples. The strong reflector 0.25 seconds below the sea floor is postulated to be the Miocene-Pliocene contact. (b) Strata beneath the broad embayment in the western shelf at 18°N. The strong reflector at 0.9 seconds at the south end (left) laps up onto acoustically opaque substrata. (c) The central part of the profile shows an opaque unit, apparently a horst, below the strong reflector at 1.0 secs below sea-level. The strong reflector continues across a sediment-filled graben to the right (south-east) of the horst.

irregular broken floor of the main trough varies from 600 metres to more than 1,000 metres deep. This trough is 100 to 150 kilometres wide north of latitude 20°N, but becomes generally narrower southward. Between 23° and 26°N isolated deeps occur in the main trough. South of 23°N a continuous deep, the axial trough, is developed within the main trough. In places the axial trough is more than 2,000 m deep and greater than 20 km wide. It is incised by deeps that appear to trend parallel with the axis (Swartz and Arden, 1960). South of 19°N, the depth of the axial trough decreases, the shelves widen, and the main trough narrows. At 17°N, the axial and main troughs become indistinguishable.

The Red Sea reflection profiles discussed here cut only the main and axial troughs. The shelves were not investigated. Profile 1 (Fig. 8) runs along the boundary between the shelf and the main trough. Profiles 2-6 (Figs. 8-12) cut the trough, and Profiles 7-10 (Figs. 13-16) cut both the main and axial troughs.

Profile 1 (Fig. 8) is parallel to the margin of the main trough just south of the Gulf of Suez, and Profile 2 cuts across the north end of the main trough. Information from surface geology and exploratory wells just north of Profile 1 shows that this region is one of elongated horsts of crystalline basement and grabens filled by Tertiary sedimentary rock. The controlling faults trend north-northwest (Said, 1962, Figs. 25, 26 and 47). This structural picture is supported by the reflection profiles. Profile 1 extends 35 km south from a point near Shadwan Island. Two grabens filled with layered rock at least one kilometre thick lie between three horsts of crystalline basement or older more consolidated sedimentary rock. The northern horst is probably the southern continuation of a basement high passing beneath Shadwan Island (Said, 1962, Fig. 25). The northern graben may be a continuation of the graben beneath Tawila Island (ibid, Figs. 26 and 68) that, some 40 km north, is known to be filled with about 4 km of post-Eocene strata. The southern graben of Profile 1 appears again as the deep western graben of Profile 2. Deformation within the grabens indicates reactivation of the boundary faults and of other faults in the underlying basement during and after deposition.

Examination of the shape of the sea floor and sub-bottom reflectors of the profiles over the main trough (Figs. 8-12, Profiles 2-6) reveals that this trough is generally divisible into three zones – namely, a deep axial zone of rugged floor and intense sub-bottom deformation, and shallower marginal zones of more gentle topography and milder deformation, which bound the axial zone to east and west. Examples of reflection profiles across places where the boundary between zones is abrupt are shown in Figure 4. The transition from one zone into another is not in all places so sharp and unequivocal, however. Parts of Chain's track underlain by the gently folded strata of the marginal zones are shown in Figure 1, and the

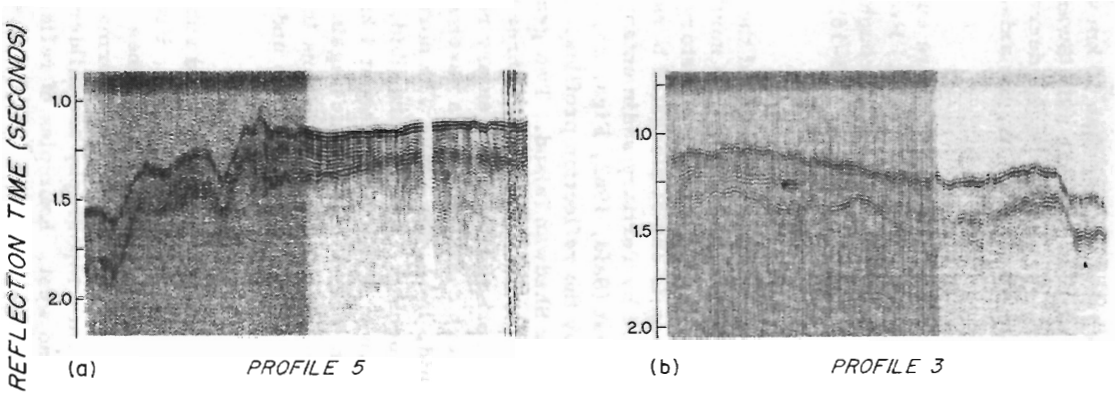


Figure 4. Continuous seismic reflection profiles across the transition between the marginal and axial zones of the main trough. (a) Near lat. 24°N. Strata of the western marginal zone appear to crop out on the fault scarp which marks the boundary. (b) Near lat. 27°N. The strong reflector beneath the eastern marginal zone appears about 450 metres (0.3 secs) deeper in the axial zone (sections viewed from the north).

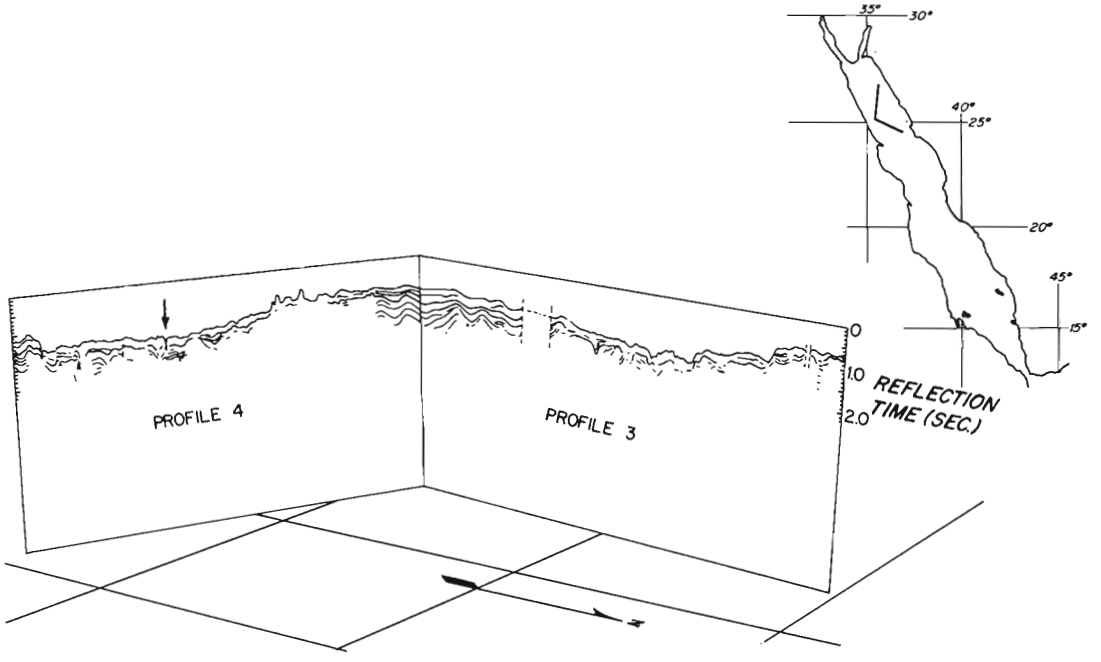


Figure 5. Panel diagram showing seismic reflection Profiles 3 and 4 of northern part of the main trough of the Red Sea, showing a basin beneath the western marginal zone (centre) and two sections through the axial zone. Note narrow axial deep below arrow.

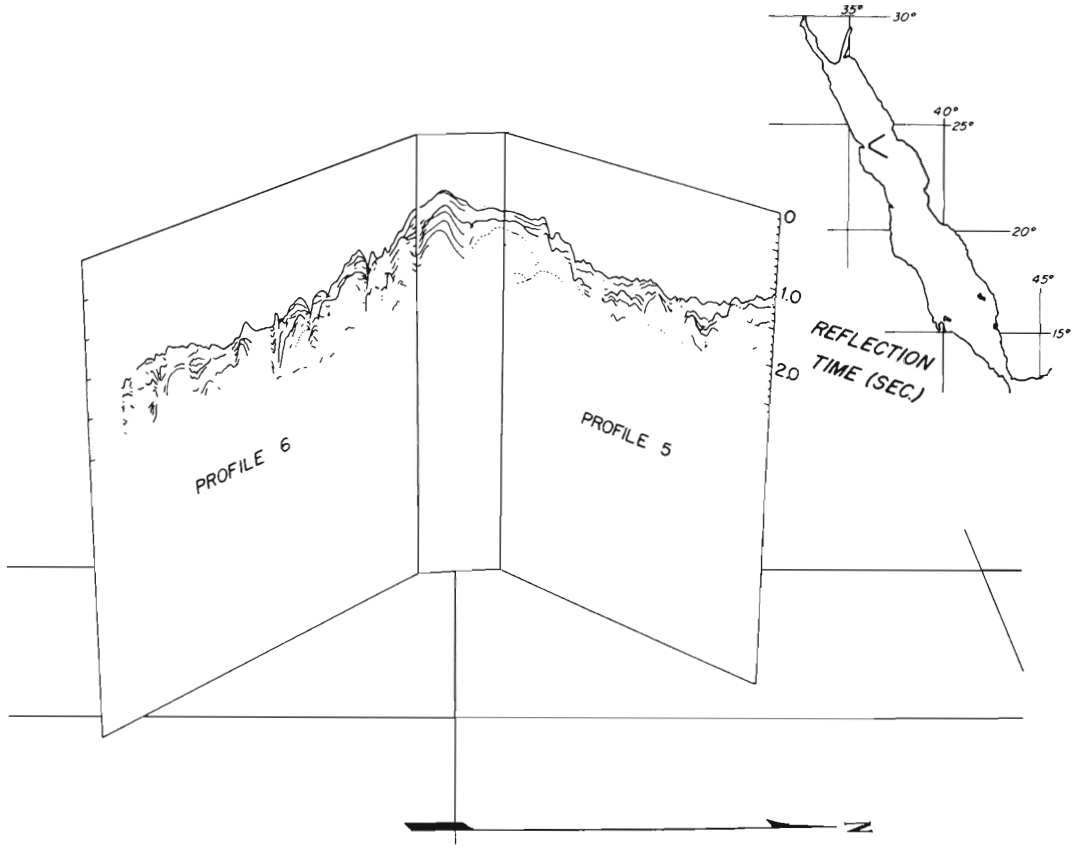


Figure 6. Panel diagram of seismic reflection Profiles 5 and 6 across the seaward extension of the Ras Banas Peninsula (centre) near St. John's Island, and across the axial trough in two places.

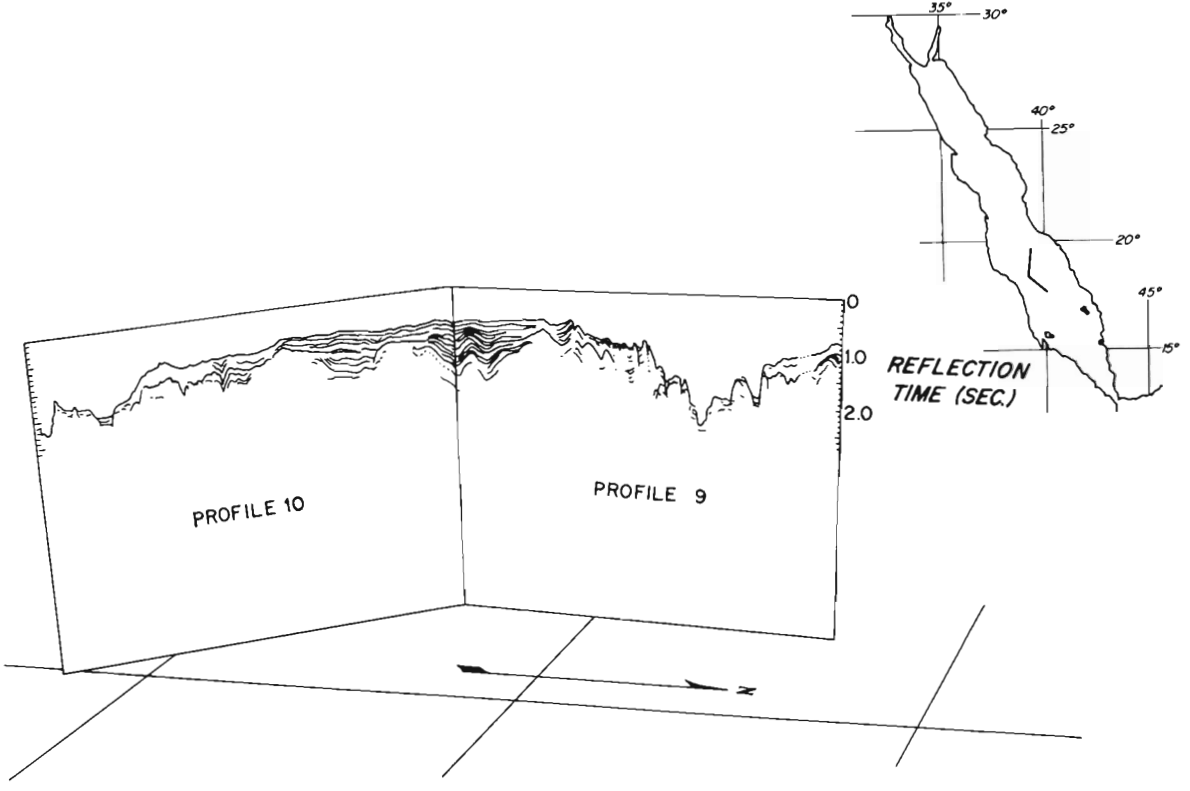


Figure 7. Panel diagram of seismic reflection Profiles 9 and 10 in the southern part of the Red Sea showing gently folded strata of the marginal zone of the main trough under a broad re-entrant into the western shelf (centre of diagram) and two cuts across the axial trough.

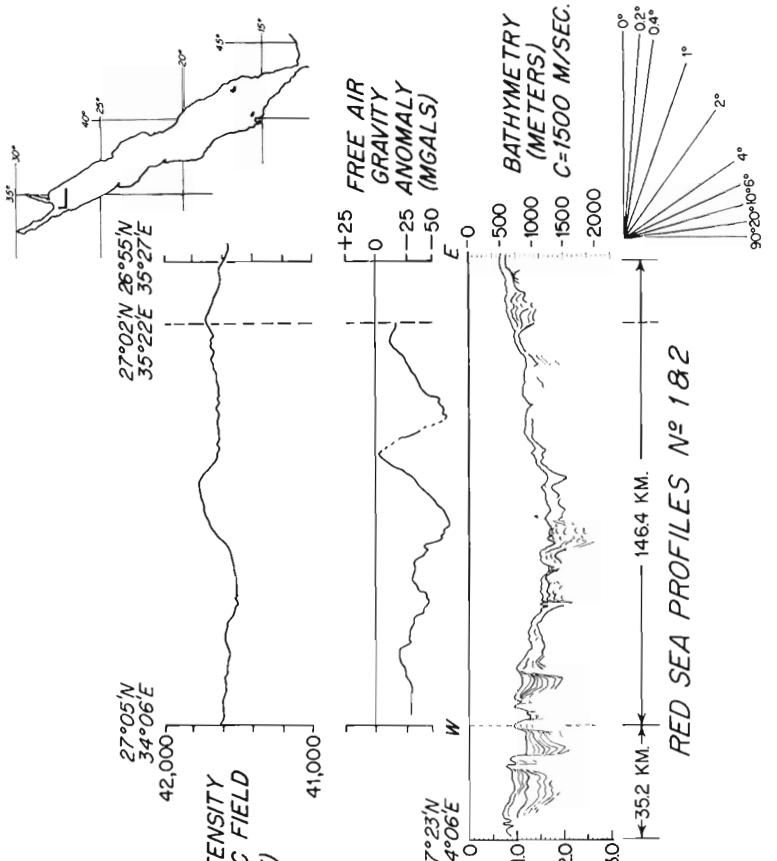


Figure 8. Profiles 1 and 2: seismic reflections, bathymetry, gravity and magnetics (course changes indicated by vertical dashed lines).

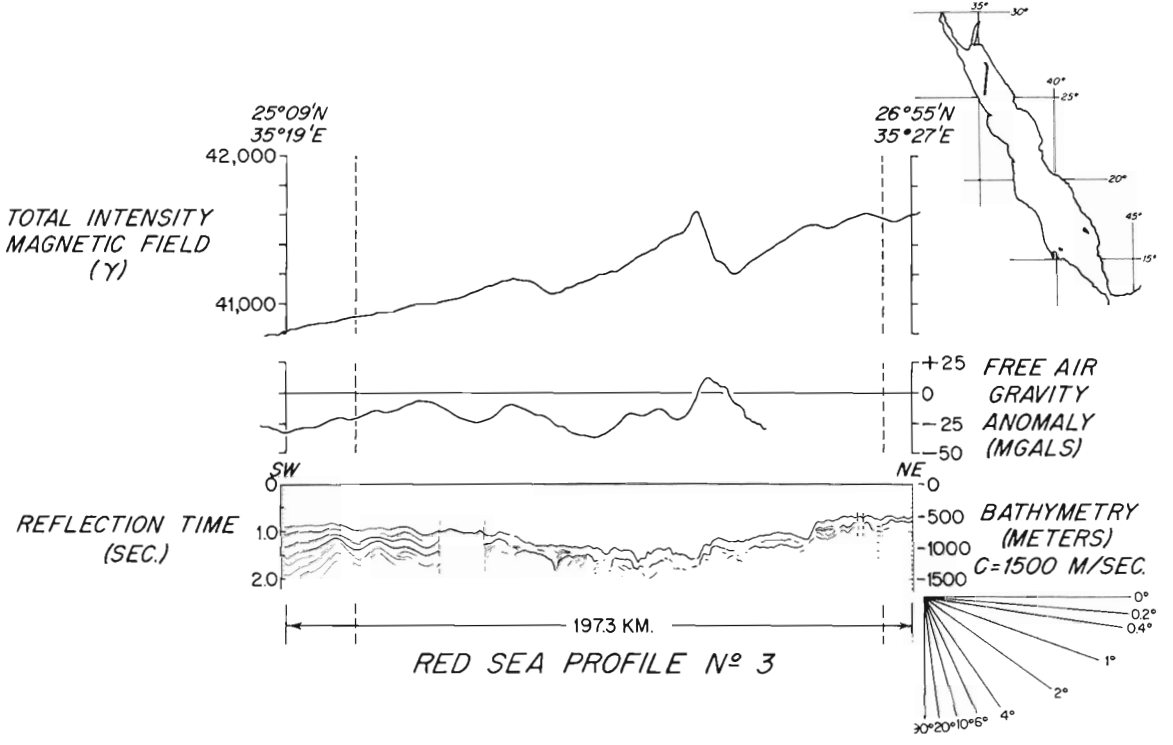


Figure 9. Profile 3: same as in Figure 8.

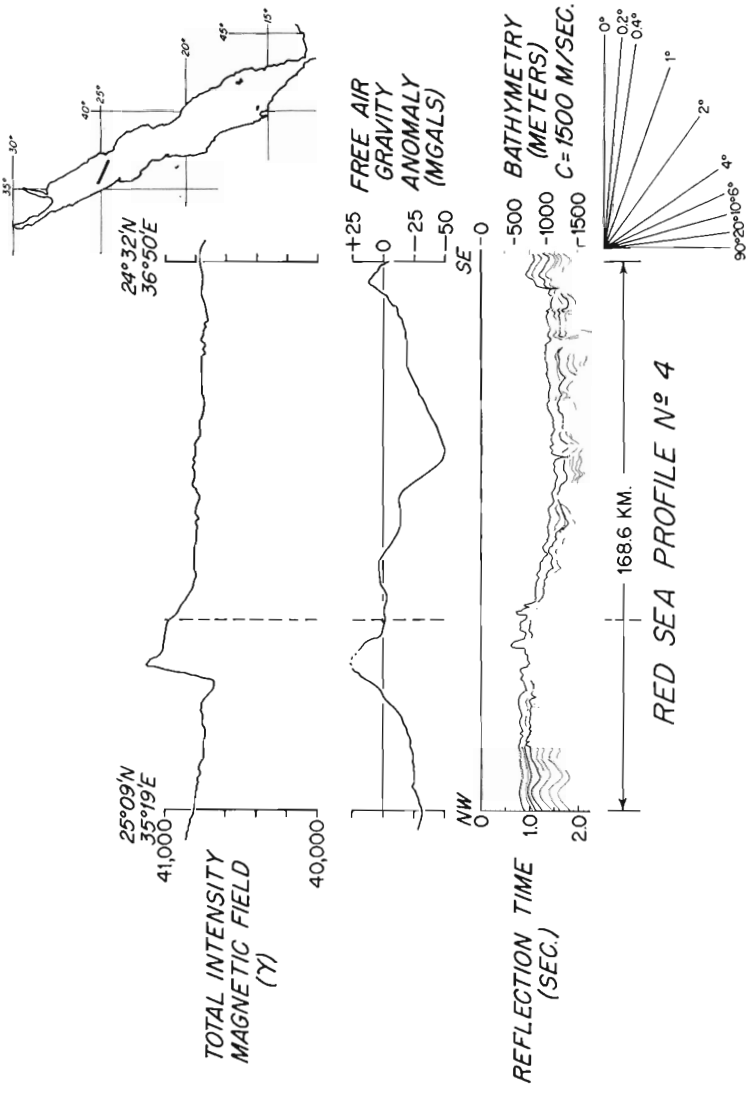


Figure 10. Profile 4: same as in Figure 8.

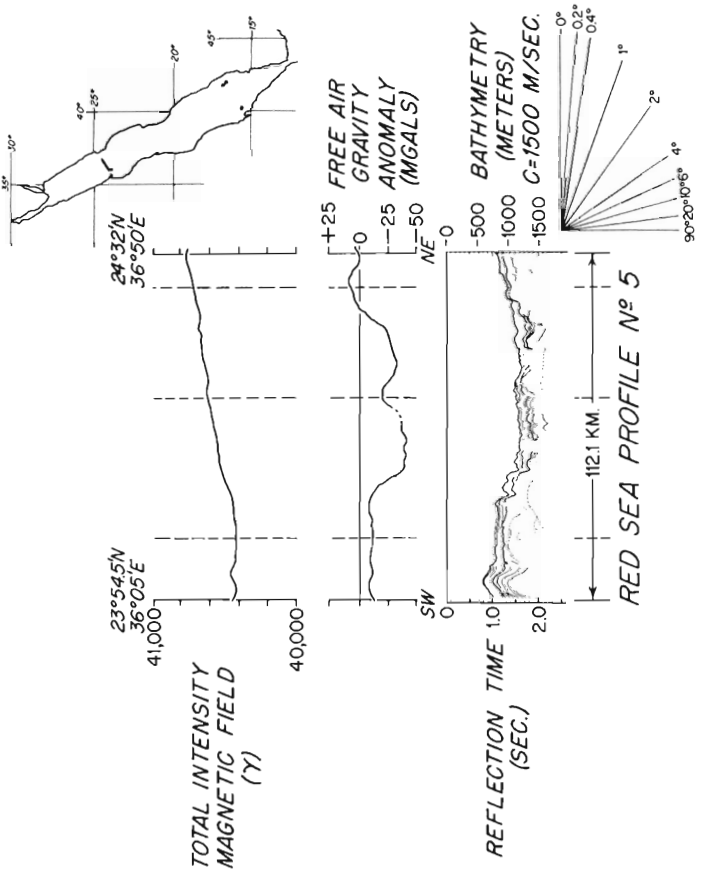


Figure 11. Profile 5: same as in Figure 8.

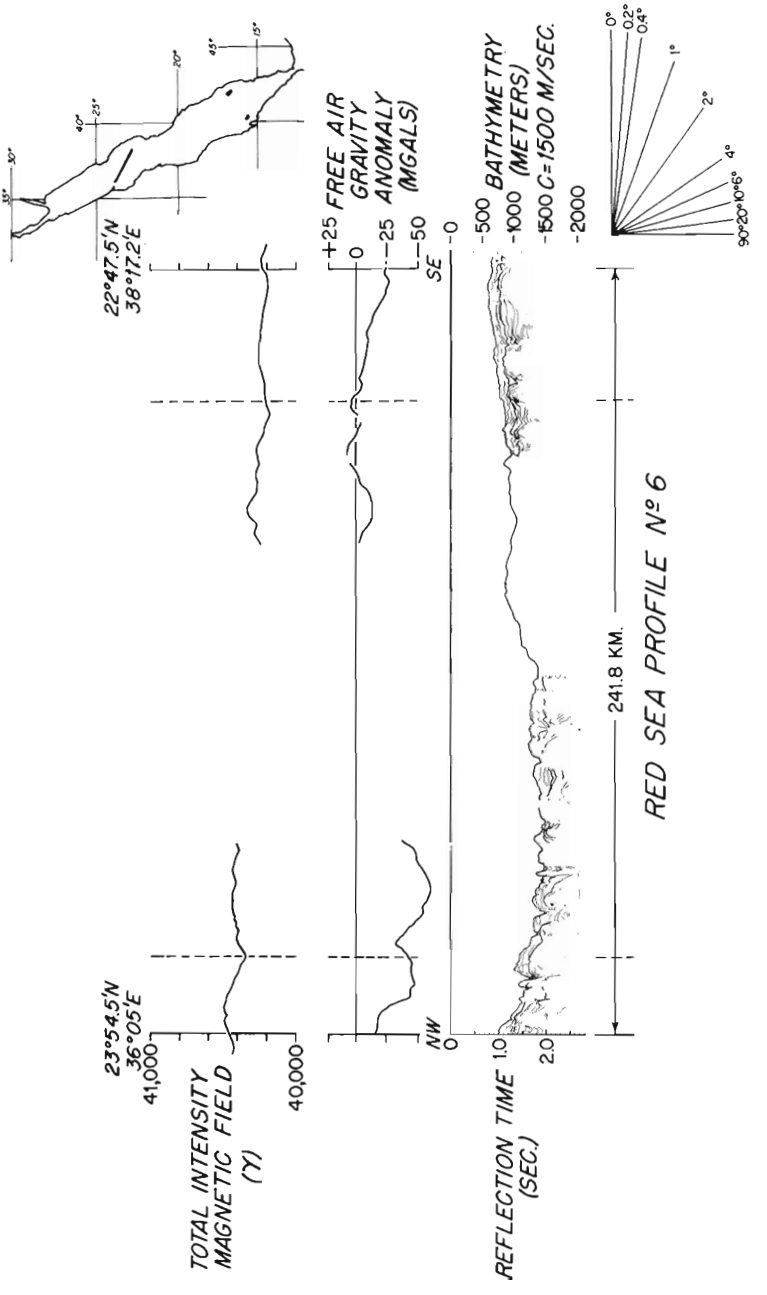


Figure 12. Profile 6: same as in Figure 8.

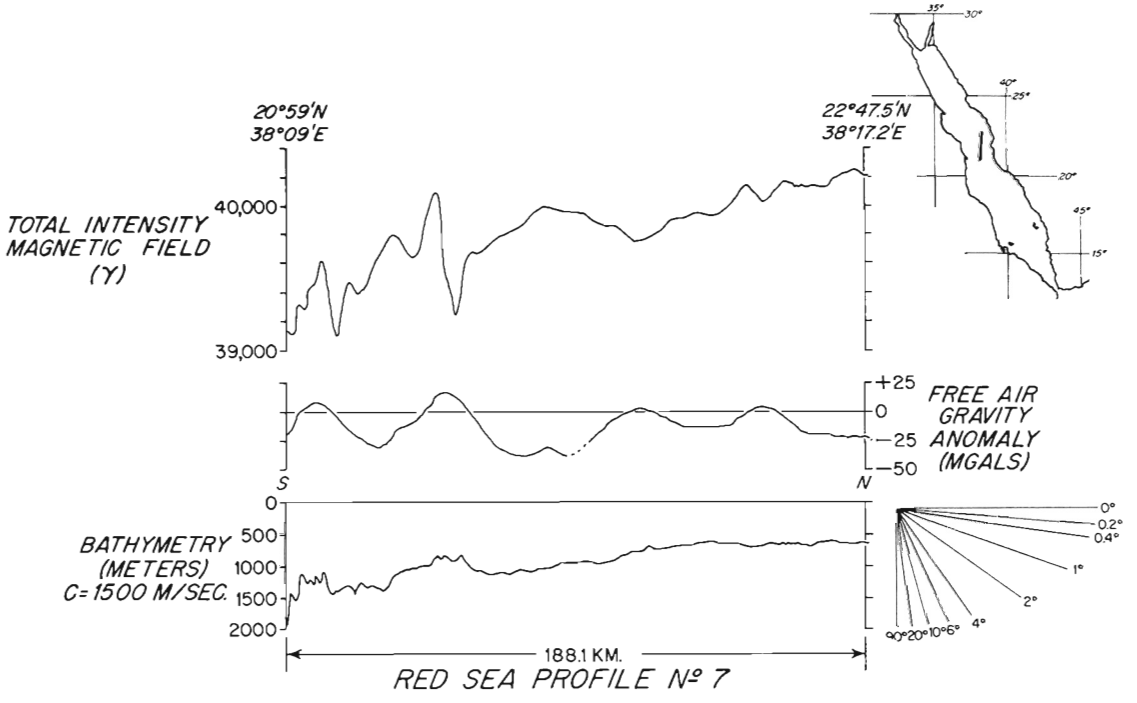


Figure 13. Profile 7: Bathymetry, gravity and magnetics (course changes indicated by vertical dashed lines).

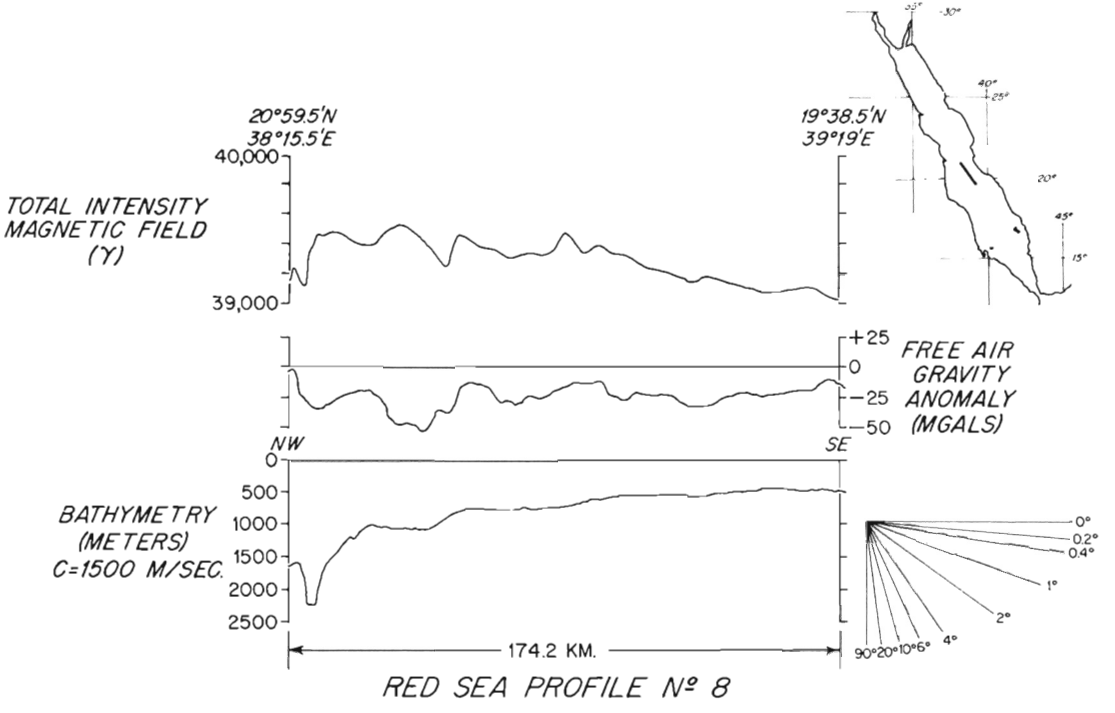


Figure 14. Profile 8: same as Figure 13.

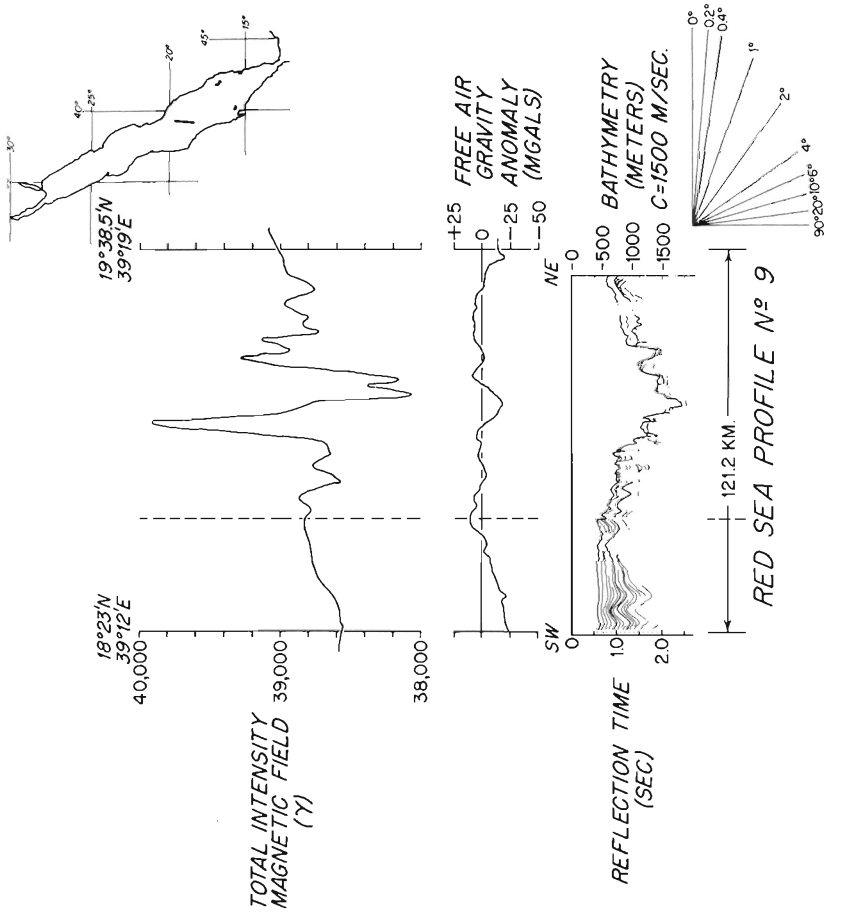


Figure 15. Profile 9: same as in Figure 8.

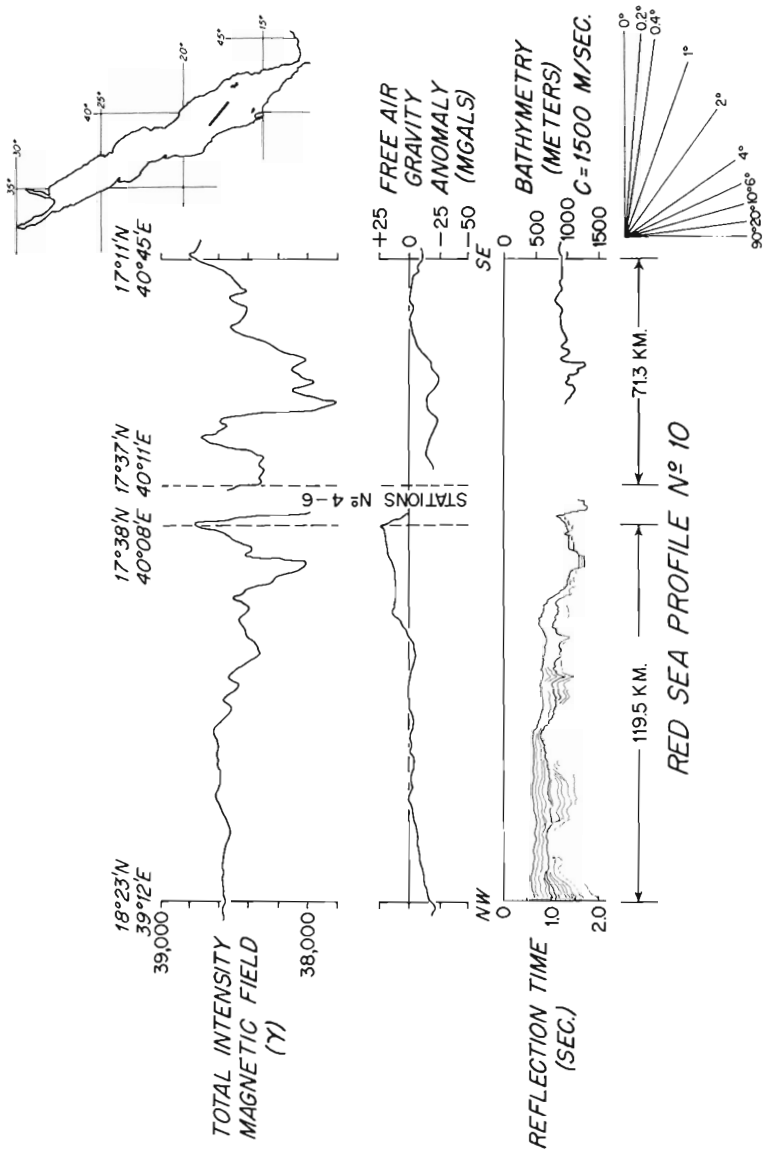


Figure 16. Profile 10: same as in Figure 8.

approximate boundaries of the axial zone in Figure 19. The central part of Profile 2 (Fig. 8), through the axial zone of the main trough, shows distorted, laterally discontinuous sequences of reflectors, this being evidence of many faults. A marked free-air gravity high near the eastern margin of the axial zone may be the result of much greater differential movement of basement blocks and consequent variations in thickness of semi-consolidated superficial material in this locality than is apparent from the reflection profiles. On the other hand, it may instead mark an intrusive igneous body at depth, though the associated magnetic anomaly is small compared with those farther south in the axial trough (cf. Figs. 13-16).

Profile 3 (Figs. 5 and 9) cuts obliquely across the main trough. At its southwest end, penetration was obtained into a sequence of gently folded strata which also appear at the northwest end of Profile 4 (Figs. 5 and 10). In the latter profile, penetration is less beneath an area of relatively rugged bottom to the southeast of the folded strata. This area forms part of an irregular northeast-trending ridge shown on Admiralty Chart C6359. An extension of the ridge forms the northern side of an isolated deep in the axial zone. High free-air gravity anomalies coupled with a magnetic anomaly over this ridge indicate that it is an upfaulted basement block, or an intrusive mass, or perhaps both. It seems to form the southern side of a sediment-filled depression (Fig. 5). There is a suggestion on Profile 3 that sedimentary strata in the depression also shallow to the north before they reach the axial zone. Thus the depression may be a closed basin.

One strong reflector (about 1.5 sec below sea-level at the west end of Profile 3) beneath the western marginal zone appears to be a surface of mild unconformity. A similar though rougher reflector is present beneath the axial zone in both profiles, although there the attitudes of beds above and below it are more divergent. Similar strong reflectors appear in all the other reflection profiles, beneath both marginal and axial zones of the main trough (Figs. 3 and 4), but not beneath the axial trough in Profile 9 (Fig. 15). It is postulated here that all the above-mentioned strong reflectors are one and the same, and that this one strong reflector is a surface of unconformity, dating from the end of the Miocene or the beginning of the Pliocene and representing a period when blocks in the axial zone were differentially elevated, depressed and tilted, and sediments beneath the marginal zones were more gently warped over faults in the underlying crystalline basement. The argument supporting this postulate is as follows. The depth of the reflector beneath the sea bottom varies between zero and 0.5 seconds under both axial and marginal zones of the main trough. If a compressional wave velocity appropriate for unconsolidated sedimentary rock is assumed (that is, about 2 km/sec), the thickness of rock above the reflector is 0 to 500 m. The Red Sea refraction results of Drake and Girdler (1964) (Fig. 18b) indicate that in most places a layer of material of about

this thickness and velocity overlies rock of higher velocity that they assume comprises consolidated sediments and evaporites beneath the shelves and main trough, and lava flows and sediments beneath the axial trough. There is evidence from exposed and subsurface geology of the margins of the Red Sea (Said, 1962; Sestini, 1965, USGS Map I-270A) that tectonic activity at the end of the Miocene or the beginning of the Pliocene terminated the deposition of a Miocene succession of limestone, evaporite and clastic rock. Pliocene and Pleistocene deposits, mainly clastic sediments and reef limestones, overlie the Miocene succession. The thickness of the post-Miocene deposits in the Gulf of Suez varies from 0 to 1.6 km (Said, 1962, p. 279). On the coast south of the Gulf of Suez, near Q'seir, the Pliocene succession is about 100 m thick (Said, 1962, p. 117), and beneath the Sudan coast, it is known to be as thick as 400 m (Sestini, 1965, p. 1465). Thus the thickness of the post-Miocene sediments on the margins of the Red Sea is similar to that of the rocks above the strong reflector, and to that of the unconsolidated material of the refraction profiles. Hence it is postulated that the strong reflector is a discontinuity which resulted from tectonic activity at the end of the Miocene.

Post-Miocene deformation in the western marginal zone is indicated in Profile 5 (Figs. 3a and 11), which approaches St. John's Island from the northeast, and shows simultaneous folding of the postulated Miocene-Pliocene unconformity and of the sequence below it. In Profile 5 there is a rough correspondence, between western marginal and axial zones, of the number and separation of weaker reflectors above the unconformity. To explain this and similar correspondence found in Profiles 2-4 (Figs. 8-10), it is postulated that during the Pliocene a blanket of sediments extended across the main trough without such a marked break as is now apparent between marginal and axial zones (photographs of the original records illustrating the break are shown in Fig. 3), and that the present broken and tilted structure of the axial zone is in part post-Pliocene.

Profile 6 (Fig. 12) shows that considerable deformation, pre-unconformity and thus presumably pre-Pliocene, took place beneath the eastern marginal zone north of Jidda. Post-Pliocene deformation is indicated by the roughness of the unconformity and discontinuity and variable dip and thickness of beds above it.

The southern end of Profile 7 and the northeastern end of Profile 8 (Figs. 13 and 14) for which there are no reflection data, show strong magnetic anomalies over the axial trough and eastward similar to those of Profiles 9 and 10. The latter (Figs. 15 and 16) are crossings of the region in which the axial trough is well developed, where strong linear magnetic anomalies were found by Drake and Girdler (1964) and Allan (1964). The positive free-air gravity anomaly of Profile 9 agrees generally with the measurements of Vening Meinesz (1934) and of Girdler and Harrison (1957).

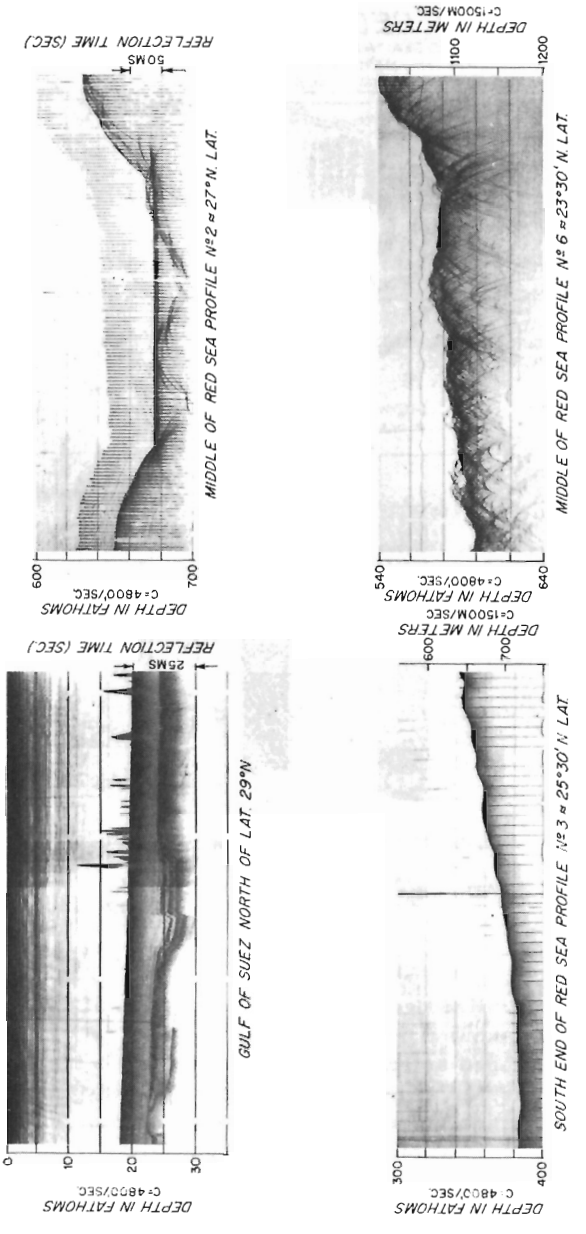


Figure 17. Echo-sounding records showing surficial sediment structures and bottom roughness.

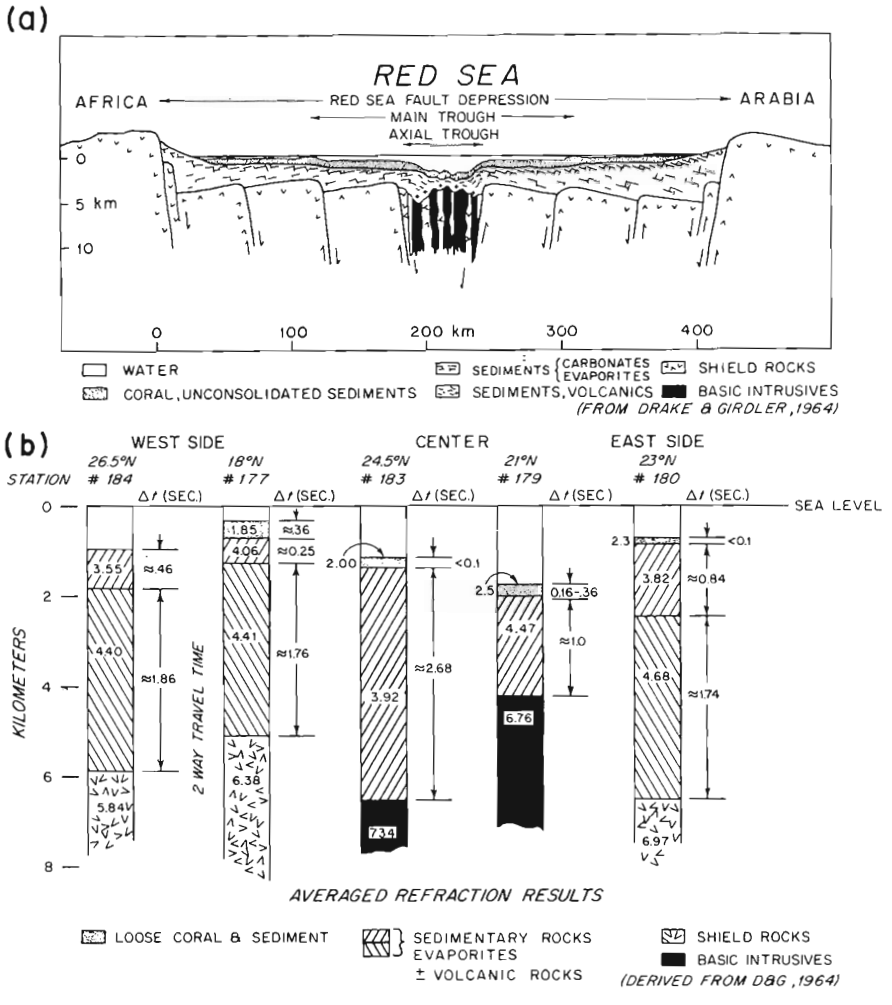


Figure 18. (a) Generalized geological cross section of the Red Sea, from Drake and Girdler (1964).
(b) Averaged seismic sections of the main trough. Depth in kilometres at left; approximate two-way travel times through each layer at right of each column; seismic velocities in kilometres per second within each column.



Figure 19. Chart of the Red Sea illustrating the boundaries of the axial zone of the main trough, and the trends of the successive segments of the axis of the sea. (Bathymetric contours taken from British Admiralty Chart C6359 with some modifications based on soundings of R/V Chain.)

The southwest end of Profile 9 (Figs. 7 and 15) shows the structure beneath a broad re-entrant or embayment into the western shelf, that to the north and south is wide and shallow (Admiralty Chart C6359). The free-air anomaly becomes increasingly negative towards the centre of this embayment in Profile 9, and also in Profile 10 which cuts obliquely across the seaward margin of the embayment. The gently folded strata which underlie the embayment appear to thin northeastwards in Profile 9 (Figs. 3b and 15) and lap up onto a buried block of acoustically opaque material that presumably consists of consolidated sedimentary or crystalline rock. The upper surface of the block has an apparent dip of about 1.5° south-southwest. If it is assumed that the azimuth of the true dip is normal to the axis of the trough, the value of the true dip of the block surface is something over 2° southwest. Farther northeast, Profile 9 makes an oblique cut across a narrow southern extension of the main trough and the axial trough. Laterally restricted stratified sequences exist beneath the former (Fig. 15, left centre), as they do in the better developed sections of the main trough to the north. In contrast, beneath the axial trough, equally thick sequences of several parallel reflectors are not seen.

In Profile 10 (Figs. 3, 7 and 16) the unconformity discussed above and postulated to date from the beginning of the Pliocene extends beneath the floor of the embayment across the tops of acoustically opaque volumes of rock and intervening depressions filled with stratified, gently folded material. The near parallelism of this profile with the main structural trends prevents confident interpretation of the sub-bottom structure. Most likely the latter consists of horsts and grabens bounded by faults which, judged by the low relief of the unconformity, have moved little since the latter was formed.

HIGH FREQUENCY ECHO SOUNDINGS

The sea-floor in the echo sounding record from the Gulf of Suez shown in Figure 17, upper left, varies between 18 and 20 fathoms in depth. The "spikes" above the bottom are reflections from schools of fish. Below the floor, penetration of up to 27 milliseconds (about 20 metres) was achieved. A complex sequence of events is indicated, as follows:

1. Deposition of the material now below the lowest reflector on the left hand side of the record.
2. Erosion or faulting to form the buried hill on the same side of the record.
3. Deposition of the material between the lowest and the next layer.

4. Formation of the depression in the centre part of record, probably by faulting, possibly assisted by fluvial erosion.
5. Deposition of a layered sequence up to 10 metres thick in the depression.
6. Renewed faulting of the basement to distort the layered sequence.
7. Deposition of about 10 metres of acoustically transparent material above the layered sequence.

This part of the Gulf of Suez is shallow enough to have been above sea-level during the Pleistocene. Thus, some of the layers seen in the record may be of sub-aerial or fluviatile origin. The faulting mentioned in 2, 4 and 6 above is probably Pleistocene in age.

The two echo-sounding records reproduced on the right hand side of Figure 17 come from the axial zone of the main trough of the Red Sea. The upper record shows a sediment pond near the northern end of the sea in which some 5 metres of layering is apparent. Other sediment ponds in the axial trough were crossed in the south (Figs. 15 and 16), but few, if any, occur in the middle latitudes of the sea. The lower record is made up of numerous parabolas each representing a small reflecting area, an indication of a very rugged floor, unmasked by recent sediment accumulation. This record is to be contrasted with the smoother, acoustically opaque bottom underlain by the gently folded strata of the western marginal zone of the main trough (Fig. 17, lower left).

CONCLUSIONS

1. On the basis of the relative depth and ruggedness of the sea floor, and the degree of deformation of the sub-bottom reflectors, the main trough of the Red Sea can be divided into an intensely deformed axial zone flanked by mildly deformed marginal zones.

2. Sedimentary sequences in the mildly deformed zones are in places over 1.8 km thick.

3. A strong reflector 0 to 500 metres below all zones of the main trough is postulated to be a discontinuity, in some places an unconformity, of late Miocene or early Pliocene age. On the assumption that this postulate is correct, the following can be stated about ages of deformation in the main trough.

(a) The similarities in the reflecting characteristics and the number of Post-Miocene strata beneath the axial and marginal zones in some

regions is taken to indicate that most of the intense deformation of the axial zone of the main trough occurred in two periods, one before the beginning of the Pliocene, and the other in late Plio-Quaternary times. These periods of deformation were apparently separated by a period of tectonic quiescence during the early part of Plio-Quaternary time.

(b) Pre-Pliocene horsts and sediment-filled grabens similar to those of the Gulf of Suez lie buried beneath layers of little-disturbed Pliocene and younger sediments under the eastern marginal zone around latitude 23°N, and under the western marginal zone around latitude 18°N.

4. Sediment-filled depressions in the western marginal zone at latitudes 18° and 26°N appear to be basins partially closed at their eastern margins by buried blocks of crystalline basement.

5. Layered sediment ponds exist in the north and south ends of the Red Sea.

6. The horst-and-graben structure of the Gulf of Suez continues southward beneath the western marginal zone of the main trough of the Red Sea at least as far as latitude 20°05'N. Deformation of the sediments in the grabens indicates fault-activity during and after deposition. Short-pulse echo soundings reveal several episodes of faulting, probably Pleistocene, in the top 20 metres of sub-bottom sediments in the Gulf.

ACKNOWLEDGMENTS

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GRAVITY AND MAGNETIC MEASUREMENTS IN THE RED SEA

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SUMMARY

Following a preliminary magnetic survey of the Red Sea by HMS DALRYMPLE in 1959 and the seismic refraction and magnetic work carried out by VEMA in 1958, R.V. ARAGONESE made a detailed gravity, magnetic and bathymetric survey in November 1961. The results of this survey were presented at the Ottawa meeting.

The survey included a total of 53 transverse crossings of the Red Sea. Charts of bathymetry, total magnetic field, anomalous magnetic field and Bouguer gravity anomalies were presented both for the whole sea and, in more detail, for the area of large anomalies in the southern half of the sea. The bathymetric chart has been produced recently by the British Hydrographic Office.

Where the axial trough is more fully developed, it was shown that the magnetic anomalies reach amplitudes of 1000-1500γ while the Bouguer gravity anomaly reaches +150 mgal. The lateral extent of the anomalies coincides with the width of the axial trough. The magnetic anomalies die out north of latitude 23°N whereas the Bouguer gravity remains positive almost up to the Gulf of Aqaba although its amplitude is less than that over the axial trough.

There is a dramatic change in the character of the anomalies on entering the Gulf of Aqaba. The Aqaba rift is less than 25 km wide, reaches a depth of 2000 m, shows little magnetic anomaly but the Bouguer gravity anomaly reaches -100 mgal.

It was concluded that:

(a) the axial trough in the southern Red Sea is the result of tensional forces and the anomalies reflect the presence of basic intrusive material which has risen through a series of cracks. The width of the trough may represent the separation of Arabia from Africa;

(b) the Gulf of Aqaba is underlain by a great thickness of light sediments. The change from positive Bouguer anomaly in the northern Red

Sea to negative Bouguer in the Gulf of Aqaba is abrupt. In contrast to the Red Sea, the Gulf of Aqaba may represent the result of compressional forces causing transcurrent faulting.

DISCUSSION

V.A. Magnitsky (U.S.S.R.)

What do you think causes the strong negative Bouguer anomaly in the Gulf of Aqaba?

Dr. Allen

I think there must be a very large thickness of sediments under the Gulf of Aqaba. And if, as Dr. Knopoff suggested earlier, there was some sort of stress couple set up somewhat north of the Gulf of Aqaba – in the hinge as Dr. Freund calls it – then you can, I think, relate the tensional forces causing the axial rift in the Red Sea to the compressional zone in the Gulf of Aqaba causing the Sinai Peninsula and the large thickness of sediment under the Gulf of Aqaba. To put it more simply, the forces in the Gulf of Aqaba region were compressional forces, those in the southern Red Sea were tensional.

L. Knopoff (U.S.A.)

Is there not a possibility that the Gulf of Suez might be a tensional feature associated with the system of forces you are suggesting?

Dr. Allen

I wish I could say yes or no, but the geophysical evidence is indefinite.

Dr. Knopoff

Are there no gravity data for the Gulf of Suez?

Dr. Allen

We have two profiles. They show a positive Bouguer anomaly.

F.K. North (Canada)

It has been postulated that the reason for the great positive gravity anomaly in the Red Sea is the rise of basic material into the central rift zone. Is it not possible that a certain minimum amount of extension will have to take place in such a rift system before that rise would be possible? The difference in gravity anomalies between the Gulf of Aqaba and the Red Sea might then be due to the fact that the Gulf of Aqaba has not yet undergone sufficient extension for that rise to take place. When the Red Sea Rift first started it would have a large negative gravity anomaly, as the Gulf of Aqaba has now. Similarly, if extension continues, the Gulf of Aqaba will eventually acquire a large positive anomaly. So the two gravity anomalies would be due to the same origin, which would seem to be more likely than that one is the result of compression and the other the result of tension.

THE ROLE OF TRANSLATIONAL AND ROTATIONAL MOVEMENTS IN THE FORMATION OF THE RED SEA AND GULF OF ADEN

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Abstract

A revised model for the amount of crustal separation in the Red Sea and Gulf of Aden is given. The model is based on a northward movement and anticlockwise rotation of the Arabian Peninsula, the evidence for these movements being briefly reviewed. The amount of crustal separation is calculated for various parts of the Red Sea and Gulf of Aden, and the separation is examined in the light of available geophysical data. It is found that there is no geophysical evidence which opposes the amount of crustal separation proposed. Critical experiments to test the hypothesis are given and a possible mechanism for the movement of Arabia is discussed.

INTRODUCTION

There can be little doubt that the Red Sea represents a region of crustal separation. This may be deduced from the presence of positive gravity anomalies, large magnetic anomalies and the presence of material with seismic velocity of 7 km/s at shallow depths beneath the deep axial trough. There is, however, some doubt about the actual amount of crustal separation in the light of geophysical evidence at present.

Drake and Girdler (1964) favoured a crustal separation which is determined by the areal extent of the large magnetic anomalies. This was mainly based on an interpretation of the structure in the southern part of the Red Sea where, at that time, most geophysical data were available. The southern part of the Red Sea is in some respects atypical in that the shelves on either side are covered by large thicknesses of evaporites and by coral reefs. These tend to obscure the underlying structures.

There is now a case for examining an alternative model based on the measured transcurrent movement along the Dead Sea-Aqaba rift in the north. A movement of 90 to 100 km has been determined along this rift and could imply a crustal separation of 60 to 67 km in the most northerly part of the Red Sea. This is about equal to the distance between the 500 fathom (914 m) contours, i.e. the depth which Bullard and others (1965) found gave the best 'least squares' geometrical fit for the continents around the Atlantic.

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In addition, the Red Sea fault depression widens towards the south at an angle of approximately 7° and so the amount of crustal separation becomes correspondingly wider.

These movements imply a northward translation of Arabia together with an anticlockwise rotation. This communication examines the implications of this possibility.

EVIDENCE FOR TRANSLATIONAL MOVEMENT OF ARABIA

Several writers (e.g. Dubertret, 1932; Quennell, 1958; Freund, 1965; and De Sitter, 1962) have presented geological evidence for transcurrent movement along the Dead Sea fault system. The direction of motion is consistent with a northward movement of Arabia. The impressive feature of this work is that different lines of evidence by different workers all give the same order of magnitude for the amount of displacement. The evidence includes measurements of the displacements of two separate facies types of the Turonian; marine Jurassic strata; Cambrian limestone facies; Precambrian igneous rocks; manganese and copper deposits; and tectonic features. The best estimate (Freund, personal communication) for the amount of displacement is 90 km. In addition, secondary structures observed on either side of the fault system are those to be expected from transcurrent motion and provide supporting evidence. It is noted that as the displacement of the Precambrian and Cambrian is of the same magnitude as the displacement of the Lower Turonian, the major movement must be post-Turonian. The Dead Sea rift has therefore formed since the Upper Cretaceous, with a small amount of extension and a large amount of transcurrent motion.

EVIDENCE FOR ROTATIONAL MOVEMENT OF ARABIA

The evidence for an anticlockwise rotation of Arabia has been reviewed by Girdler (1963). Part of the evidence is that the main Red Sea fault trough widens towards the south (Fig. 2). Measurements north of 24°N where the margins of the trough are straight give a divergence of 6 to 7°, suggesting an anticlockwise rotation of Arabia of this amount. Similar deductions may be made from the divergence of the main fault trough of the Gulf of Aden and from various features of the bottom topography in the northern part of the Red Sea.

Further, the region of large magnetic anomalies which commences at 24°N parallels the shores and widens towards the south, and a similar region of magnetic anomalies along the centre of the Gulf of Aden widens towards the east. The anomalies are most probably associated with a fracture zone and it seems that the areal extent of this zone is a consequence of the rotational movement.

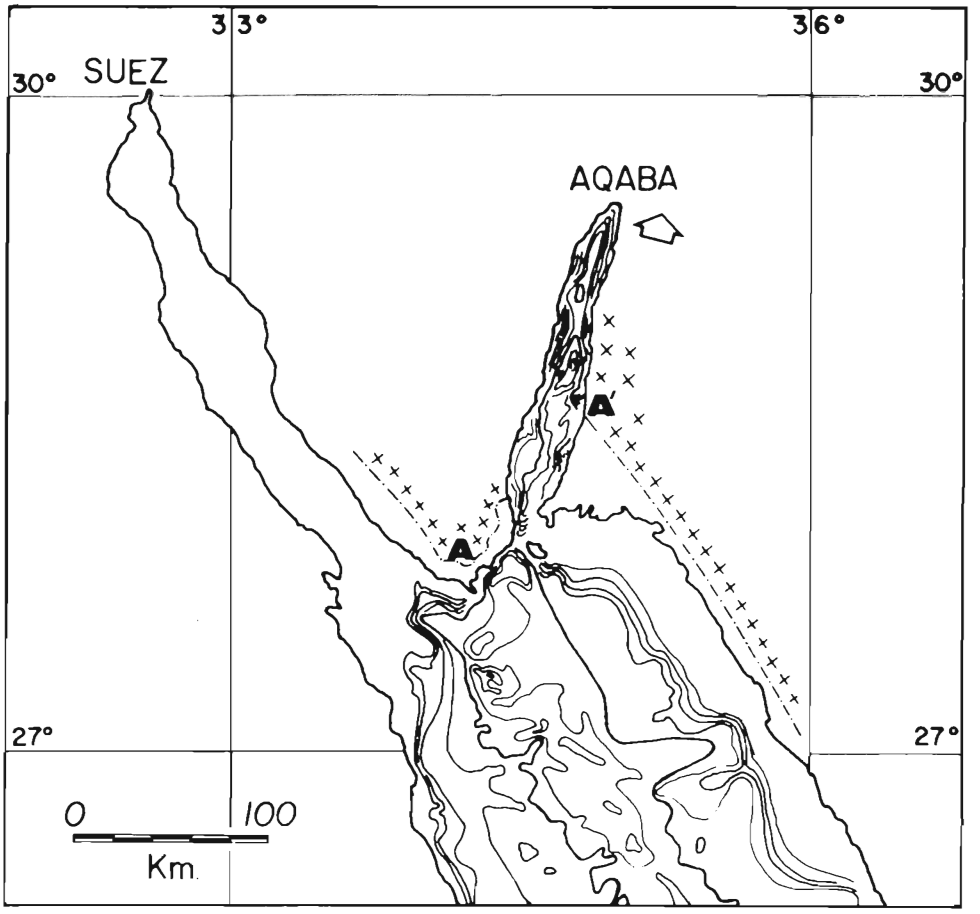


Figure 1. Sketch map of the most northern part of the Red Sea and the Gulfs of Suez and Aqaba showing the displacement of the Precambrian shield. The bathymetry (contour interval, 100 fathoms) is taken from Hydrographic Office Chart No. C6359.

Lastly, palaeomagnetic measurements on the Aden Volcanics (Irving and Tarling 1961) give a mean declination of N 6.9°W ± 3.8°. This result is consistent with an anticlockwise rotation of Arabia subsequent to the cooling of the rocks.

There are therefore independent lines of evidence for an anticlockwise rotation of Arabia of 7° in addition to the northward translational movement. These movements imply that there should be compressional features north of the Dead Sea and these are found in the folds of the Zagros-Taurus Mountain Range.

TRANSLATIONAL AND ROTATIONAL MOVEMENTS OF ARABIA IN RELATION TO CRUSTAL SEPARATION IN THE RED SEA AND GULF OF ADEN

The question arises as to whether it is reasonable to extrapolate the 90 km of movement observed along the Dead Sea rift to regions further south. Figure 1 is a sketch-map of the most northern part of the Red Sea. The bathymetry is shown together with the outcrops of Precambrian shield rocks in Sinai (west of the Gulf of Aqaba) and Saudi Arabia (east of the Gulf of Aqaba). Geological maps show the Precambrian to be displaced about 85 km (A-A', Fig. 1). It therefore seems that the horizontal displacement has affected the most northern part of the Red Sea.

This is also supported by the bathymetry. Deep water (depth greater than 1 km) extends right up to the Sinai Peninsula and the contours south of the Gulf of Suez suggest structures in line with the Gulf of Aqaba. If a figure of 100 km is assumed for the amount of movement parallel to the Dead Sea-Gulf of Aqaba, the amount of extension at right angles to the axis of the Red Sea in the most northern part is found to be 67 km. This distance is about equal to the distance between the 500 fathom (914 m) contours. The figure of 100 km was taken as a convenient working number and allows for a small amount of extension in the Gulf of Suez rift.

From the geological map of the Arabian Peninsula (U.S.G.A. and Arabian Oil Co., 1963), there appears to be no fault system of the magnitude of the Aqaba-Dead Sea system until the Gulf of Aden is reached. The assumption will therefore be made that a 100 km translation of Arabia played a part in the opening up of the whole of the Red Sea and the Gulf of Aden.

The amounts of crustal separation in the Red Sea and Gulf of Aden are now calculated assuming a northward translation of Arabia of 100 km and an anticlockwise rotation of 7°. The results are given in Tables 1 and 2 and illustrated in Figure 2.

Table 1 (Red Sea)

Latitude	A (km)	B (km)
27°N	100	67
24.5°N	152	102
22°N	204	136
19°N	256	171
16.5°N	308	206
14.5°N	360	241

A = amount of separation in direction of movement (approximate)
B = amount of separation perpendicular to the axis of the Red Sea (approximate)

Table 2 (Gulf of Aden)

Longitude	A (km)	B (km)
45°E	163	153
46.5°E	189	178
48.5°E	214	201
50°E	239	224

A = amount of separation in direction of movement (approximate)
B = amount of separation perpendicular to the axis of the Gulf of Aden (approximate)

In Figure 2, the lengths of the arrows represent the amount of separation required in the direction of movement. An interesting feature is that the amount of separation in the southern part of the Red Sea is just compatible with the topography. It has been previously noted (e.g. Girdler, 1963) that a shore-to-shore fit of the Red Sea is impossible because of the geology of the Afar area of Ethiopia. However, there are enough recent volcanics in this region (e.g. the Aden Volcanics of Pliocene age) to make possible the amount of separation shown.

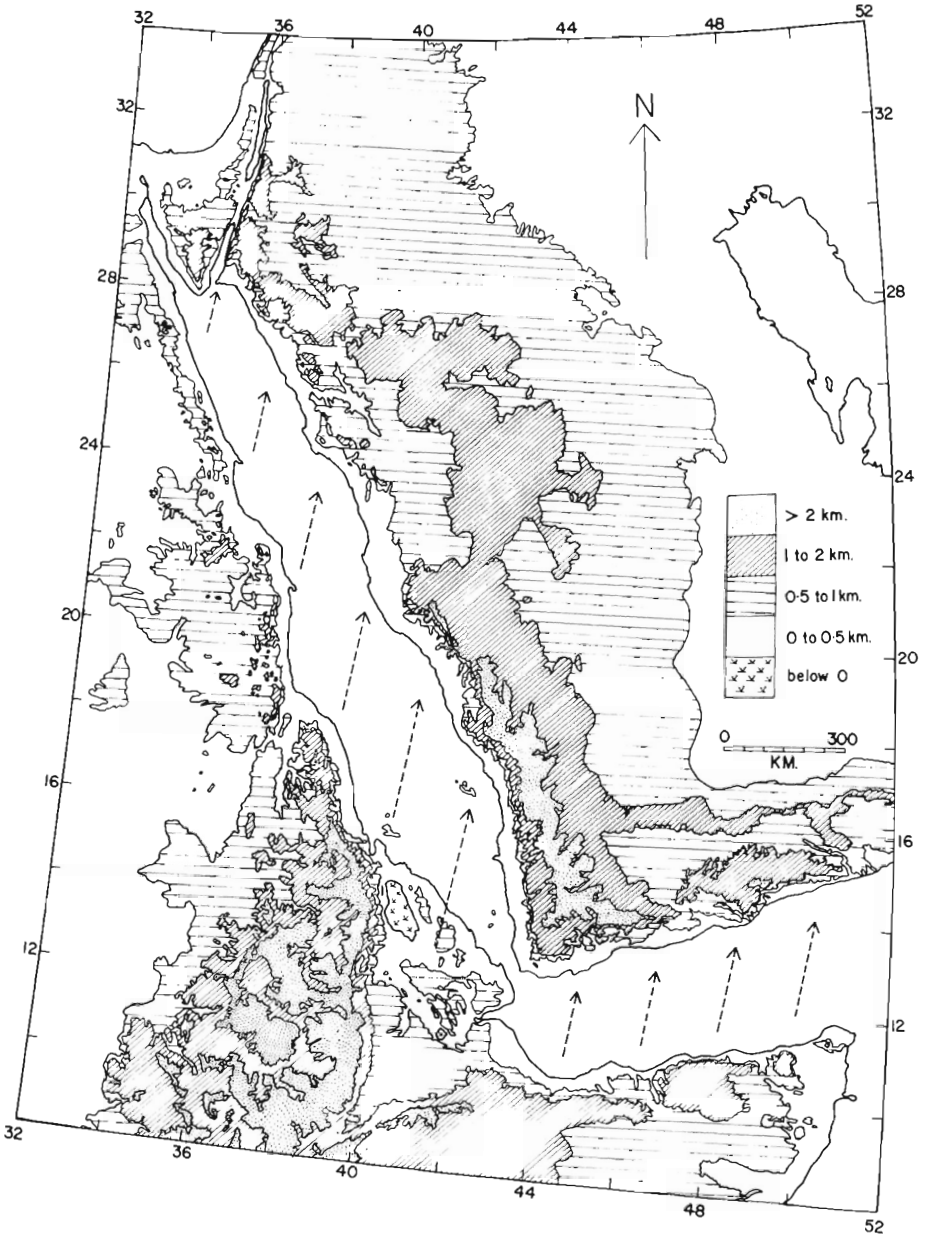


Figure 2. Topographic map of the Red Sea area. The lengths of the arrows represent the amount of crustal separation assuming a northward translation of Arabia of 100 km and an anticlockwise rotation of 7°.

COMPATIBILITY OF THE SUGGESTED CRUSTAL SEPARATION WITH PRESENT GEOPHYSICAL DATA

It is now important to establish whether the proposed crustal separation shown in Figure 2 is compatible with the results of geophysical work carried out in the Red Sea. The new model will be examined in relation to seismic refraction data, gravity and magnetic anomalies.

(i) Seismic refraction data

Figure 3 summarises the seismic refraction profiles given by Drake and Girdler (1964) and shows the profiles in relation to the bathymetry. For clarity, details of some of the uppermost sedimentary layers have been omitted from some profiles. The velocities of the lower layers fall into two groups: 7.08 ± 0.21 km/s and 5.92 ± 0.24 km/s[1]. The former are close to the velocities found near the crests of the oceanic ridges and are considered to be new oceanic material and the latter are interpreted to be downfaulted shield rocks. In general, the higher velocities occur beneath the deeper water, and the lower velocities, beneath the shelves. The division is not completely clear cut as at Profile 180, a velocity of 6.97 km/s is found to the east of the main trough where the water depth is only 0.7 km and at Profile 177, a velocity of 6.37 km/s (which is a velocity frequently found in layer 3 of the oceans) is found beneath the shallow shelf where the water depth is 0.36 km.

In the north, Profile 183 in the middle of the Red Sea at 25°N has a velocity of 7.34 km/s and is consistent with the proposed separation. A critical test is whether this velocity continues northwards to south of the Sinai Peninsula. Unfortunately, Profile 184 is just at the western limit of the amount of separation required where one might expect to find either velocities 7.08 or 5.92 km/s. In fact, the velocity is 5.84 km/s. The seismic results are therefore not inconsistent with the amount of crustal separation proposed but provide little supporting evidence.

(ii) Gravity anomalies

Allan and others (1964, and this symposium) and Plaumann (1963) have confirmed that nearly the whole length of the Red Sea from 15°N to Sinai is associated with positive Bouguer gravity anomalies. The Bouguer anomaly reaches 150 mgals over parts of the deep axial trough. In contrast, in the Gulf of Aqaba, where the water depth is similar to that of the northern part of the Red Sea, negative Bouguer anomalies of -80 to -90 mgal are

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[1]The plus-or-minus values are standard deviations.

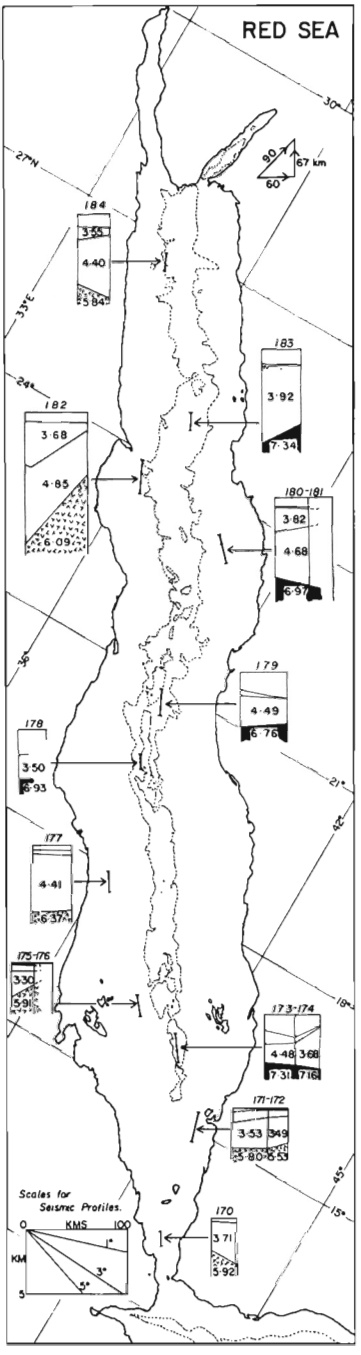


Figure 3. Map of the Red Sea showing bathymetry (contour interval, 500 fathoms) taken from Hydrographic Office Chart No. C6359 and seismic refraction profiles from Drake and Girdler (1964).

found. The gravity profile at 16°N has been interpreted by Girdler (1958) who proposed the presence of intrusive material with a density contrast of +0.2 g/cm^3 at a shallow depth. It is further thought that the anomaly is related to the material with seismic velocity 7.3 km/s occurring at a depth of 4 km. The new gravity maps of the Red Sea show the anomaly to be unusually narrow at this latitude. This is probably associated with the build-up of large thicknesses of light sediments on the margins in this region. Further north, the anomaly widens and the fact that it continues as far as Sinai (although becoming less in amplitude) implies that nearly all the centre of the Red Sea is underlain by denser material. The new gravity data therefore tend to support the amount of separation shown in Figure 2.

(iii) Magnetic anomalies

Previously, the magnetic anomalies which reach amplitudes of 1200 gammas over the centre of the Red Sea were interpreted as being due to the basic intrusive material with seismic velocity 7.08 km/s (Drake and Girdler 1964). The region of magnetic anomalies does not extend into the northern part of the Red Sea (i.e. north of 24°N), and therefore this interpretation must be revised if the crustal separation is assumed to extend to Sinai. The only way of doing this is to relate the magnetic anomalies to the lower velocity materials. This was earlier thought to be unreasonable because of the very high intensities of magnetization required to explain the amplitudes of the anomalies when the magnetic material is restricted to the much smaller volume (i.e. to a layer with a thickness about 3 km). However, since this earlier interpretation, Cox and Doell (1962) and Ade-Hall (1964) have made many measurements of the intensities of magnetization of oceanic basalts and submarine lavas and have found surprisingly high intensities. Their work indicates that the intensities for basic rocks previously thought to be reasonable from data in the rock magnetism literature can be easily increased by factors of from 3 to 10.

The seismic velocities of this layer are difficult to interpret (Drake and Girdler 1964). The material overlying the 7.08 km/s layer has a mean velocity of 4.12 ± 0.45 km/s and a mean thickness of 2.76 ± 1.47 km. The material overlying the 5.92 km/s layer has a mean velocity of 3.96 ± 0.55 km/s and a mean thickness of 3.12 ± 1.34 km. There is therefore little significant difference in the velocities of material overlying the intrusive zone and shield rocks. The velocities are appropriate for sedimentary rocks, evaporites or volcanic materials. There is now no evidence to oppose the interpretation that the magnetic anomalies over the centre of the Red Sea are caused by volcanic material in the 4.12 ± 0.45 km/s velocity layer and it seems a strong possibility that a considerable volume of this material is responsible for the magnetic anomalies.

A similar interpretation has been arrived at for the interpretation of the magnetic anomalies over the mid-Atlantic Ridge (Heirtzler and Le Pichon 1965). They also prefer to attribute most of the anomalies to the upper oceanic crustal layer (Layer 2 of the oceans) with seismic velocities ranging from 3.7 to 5.8 km/s overlying velocities of the order 7 km/s.

CRITICAL EXPERIMENTS FOR FUTURE WORK

Although there is a considerable amount of geophysical data now available in the Red Sea area, some critical experiments are needed to test the amount of crustal separation proposed in Figure 2. The following are suggested.

(i) Long seismic refraction profiles are needed in the centre of the most northern part of the Red Sea to establish the northern extent of the 7 km/s layer.

(ii) An aeromagnetic survey over the region where the Red Sea and Gulf of Aden rifts meet is greatly needed to elucidate the complex structure of that area and establish the relative amounts of recent volcanic materials and ancient Precambrian rocks.

(iii) Further gravity and seismic refraction investigations in the Gulf of Aden are required to establish relationships of the gravity and magnetic anomalies to the crustal structure.

The computer determinations of epicentres by Sykes and Landisman (1964) show that nearly all the seismic activity is concentrated along the central part of the Gulf of Aden and southern part of the Red Sea. This suggests an association of the magnetic anomalies with a fracture zone that is still forming and being filled with volcanic rocks. The region of positive gravity anomalies is much more extensive than this and it may be that two or more phases of extension have occurred in the Red Sea and Gulf of Aden.

POSSIBLE CAUSE OF TRANSLATIONAL AND ROTATIONAL MOVEMENT

The crustal separation discussed here involves the northward movement and anticlockwise rotation of the whole of Arabia. It is difficult to envisage a mechanism for the movement of a landmass of this size without resorting to the hypothesis of mantle convection.

It is of interest that the most impressive negative anomaly of the recent analyses of free air gravity from satellite data and surface observations occurs over the Arabian Sea (e.g. Guier and Newton 1965,

Izsack 1963, Uotila 1962). This indicates a region of low density in the upper mantle and could locate a region of uprising convection as suggested by Runcorn, thus providing a mechanism for the movement of Arabia. There is some support for this from the heat flow data, 115 of the 140 measurements in this area listed by Lee and Uyeda (1965) being higher than the world mode of 1.1×10^{-6} cal/cm^2/s, but a careful statistical treatment of the observations is required.

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DISCUSSION

Dr. D.C. Krause (USA)

I like the idea of the combination of fracturing and faulting as an origin for the rift very much, but I was just reading the abstract of a paper presented at the A.G.U. meeting in Dallas, Texas (A.G.U. Trans., 46, 544) by Bill Strange of the Smithsonian Astrophysical Observatory in which he claims to have been unable to find a relation between satellite gravity data and heat flow data.

Dr. Girdler

As I've mentioned, I have examined the data from Lee and Uyeda's paper on heat flow in this regard. One would expect to find an overall background of high heat flow in the northwestern part of the Indian Ocean, and one finds that 115 out of the 140 observations listed are higher than the world mode of 1.1×10^{-6} cal/cm^2/sec. This may not be confirmatory, but it suggests that there is a correlation for this area. I am sceptical of the harmonic analysis of heat flow and hence the correlations between the harmonic analysis of heat flow and gravity data because of the large heat flow anomaly obtained over Africa where there are no observations at all!

THE GULF OF ADEN, IN RELATION TO THE RED SEA AND THE AFAR DEPRESSION OF ETHIOPIA

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Abstract

The mid-ocean ridge system has been suggested as the locus of the generation of new oceanic crust, resulting from the separation of continental blocks. In the NW Indian Ocean, the Carlsberg Ridge meets the Afro-Arabian continental mass at the Gulf of Aden, thereby linking it with the African Rift valley system and the Red Sea.

Some authors have explained the Gulf of Aden as a graben formed by vertical movement only, whereas others have been impressed by the congruity of the coastlines and have suggested predominantly horizontal drift movement of the continental blocks. Recent geophysical evidence in the Gulf of Aden has shown that the crustal structure is more similar to an oceanic than a continental crust, thereby supporting the idea of an origin by continental separation. The evidence may be summarized as follows:

(a) The topography shows a central rough zone running the whole length of the Gulf of Aden, which is associated with an earthquake epicentre belt, high linear magnetic anomalies, and high heat flow. This is a logical continuation of the Carlsberg Ridge.

(b) The crustal structure, determined by seismic refraction stations combined with gravity profiles, is oceanic, except that beneath layer 3, the mantle velocity is low and is associated with low density. The base of this low density layer is 40 km., comparable to that found beneath the mid-Atlantic Ridge.

(c) NE-SW transform faults can be followed across the Gulf and indent the edge of the continental shelf. A good fit is obtained by matching shelf edges at the 500 fm. line, and predrift (i.e. pre Miocene) geological features are continuous across the reassembly.

The suggested reassembly involves superposition of the Yemen on a large part of the Afar depression of Ethiopia in the pre-Miocene, and a large closure of the southern Red Sea. It is suggested that a large part of the Afar depression might be new basaltic crust resulting from the continental split, and that the Danakil Alps are a fragment left between the two separating continents. The reassembly can be tested by palaeomagnetic measurements.

INTRODUCTION

The mid-ocean ridge system is thought by many to be the surface expression of upper mantle movements and, possibly, the locus of generation of new suboceanic crustal material. Where a limb of this system approaches a continental margin, it is important to know the effect it may have on a continental block. The Gulf of Aden, the Red Sea and the Rift valleys of Africa are clearly connected in some way with the Carlsberg Ridge in the NW Indian Ocean (Fig. 1). Matthews (1965) has shown that the Carlsberg Ridge is a typical mid-ocean ridge and that its axis is displaced southeast of Socotra by the Owen fracture zone. A continuation of the ridge further north into the Gulf of Aden has been established on the basis of topography, the earthquake epicentre belt, and magnetic anomalies. Through the Gulf of Aden, therefore, the connection is established with the Red Sea and the African Rift valley system.

However, although the Red Sea, the Gulf of Aden and the African Rift valleys may have been produced by a common subcrustal mechanism, their physical characteristics differ considerably. The Red Sea is flanked on land by high cliffs, now erosional but probably originally fault controlled. The underwater shape of its south end consists of a central axial trough, some 2,000 m deep and 50 km wide, bordered for 150 km on either side by water that commonly is less than 100 m deep. The shallow shelves are dotted with coral reefs and islands, the biggest of which are Dahlak Islands on the west side and Farisan Islands on the east side of the axial trough. Further north the shelves are narrower and are separated from the axial trough by water of intermediate depth.

By contrast, the Gulf of Aden is very much deeper, except at its extreme western end. Recent data obtained during the International Indian Ocean Expedition have enabled the main physiographic features of the Gulf to be outlined and its crustal structure to be determined (Laughton, 1966). Figure 2 shows how the Gulf can be divided, on topographic data, into: (a) continental shelves and slopes; (b) a main trough and basins whose depth increases from about 2,000 m at 46°E to 4,000 m at 56°E; and (c) a central rough zone of echelon ridges and valleys with a relative relief of 2,000 m. At the western end of the Gulf, this zone merges into an E-W trough running into the Gulf of Tadjura in a region where there is little contrast between the continental shelves and the main trough. The central zone shows a series of offsets, the largest of which is between Ras Alula and Ras Fartak at 52°E. These offsets are reflected on the continental margins by offsets of the continental shelf edges. They are examples of "transform faults" recently described by Wilson (1965).

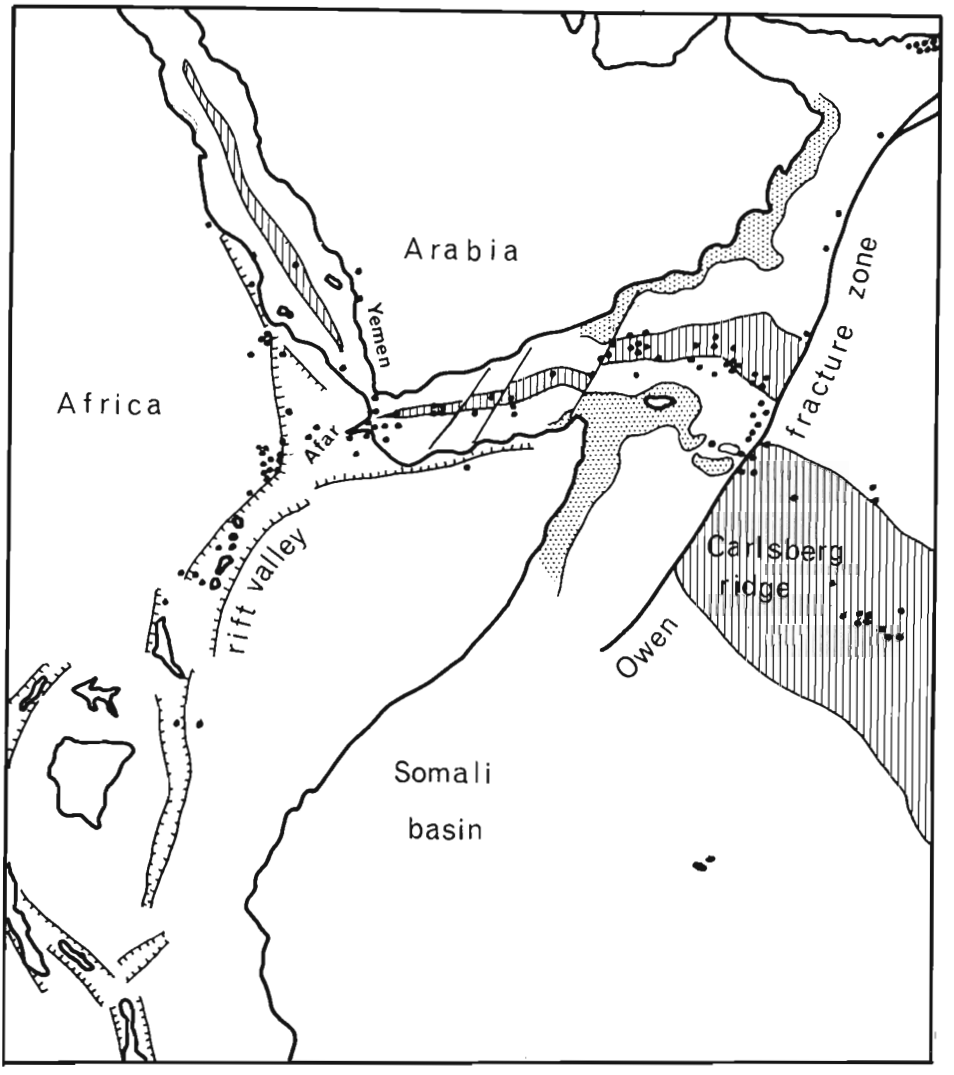


Figure 1. Physiographic sketch map showing relation between the Carlsberg Ridge, the Owen fracture zone and the Gulf of Aden. Dots show shallow earthquake epicentres: shading shows magnetic seamounts of the Carlsberg Ridge, the central rough zone of the Gulf of Aden, and the axial trough of the Red Sea: stippling shows non-magnetic seamounts and continental margin near Socotra.

THE GULF OF ADEN

The geophysical data obtained in the Gulf of Aden suggest that the structure is more similar to an oceanic crust than to a continental crust. These data are described in detail in Laughton (1966) and will only be summarized here.

The central rough zone is in many ways similar to a mid-ocean ridge. Sykes and Landisman (1964) have redetermined the position of recent earthquake epicentres with an accuracy of 10 km; the epicentres all lie within the central rough zone and are particularly concentrated along the Alula-Fartak trench, and along the Tadjura trough. High values of heat flow have been measured right across the Gulf with peak values of 6 microcal/sq cm/sec in the centre (Herzen, 1963; Sclater, 1966). The axis of the central rough zone is marked by relatively large magnetic anomalies ($>300\ \gamma$) showing an E-W lineation; those at the western end have been described by Girdler and Peter (1960).

All the above types of features are associated with the mid-ocean ridge system. The chief differences lie in the echelon lineation of the ridges in the Gulf, which contrast with the parallel lineations of the Carlsberg ridge; and in the absence of a clear median valley in the Gulf, except at its western end. Transform faults are apparently common in the mid-ocean ridge systems (Wilson, 1965).

In the main troughs on either side of the central zone, there are magnetic anomalies of $\pm$ 100 γ whose trends have not been established. However, they are conspicuously absent on the Socotra shelf, suggesting a difference in basement rock type.

Seismic refraction data have been obtained by Nafe, Hennion and Peter (1959) at five stations distributed along the Gulf in both the main trough and the central rough zone. Two of these stations reached a high velocity layer, and all of them showed a similar structure above it (Fig. 3). Beneath a variable thickness of sediments, there is a layer with velocity 3.9-4.6 km/sec beneath which is a basement showing 6.4-6.9 km/sec. At two stations, the base of the lower layer velocity was determined at about 10 km below sea level, and a high velocity layer of 7.5-7.8 km/sec was found. Nowhere was a granitic-type velocity of 5.6 km/sec found.

The above section is similar to that found under ocean basins but differs in the following respects: (a) the water depth is typically 2 km, not 5 km; and (b) the sub-basement velocity is lower than the usual 8.1 km/sec of the upper mantle.

Continuous gravity profiles through the Gulf of Aden and across the Socotra continental shelf and into the Somali basin have been combined

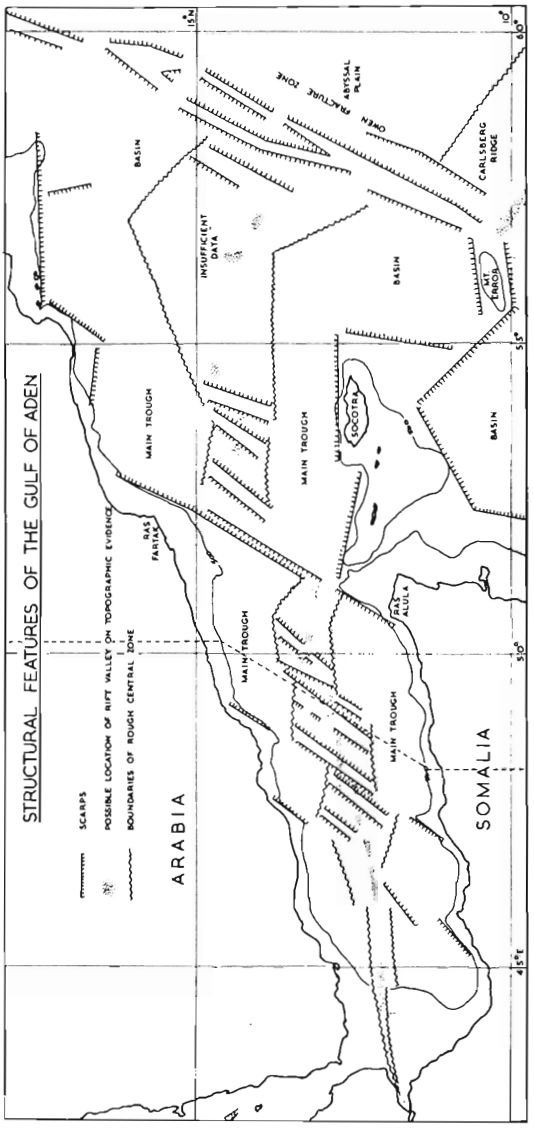


Figure 2. Structural features of the Gulf of Aden (from Laughton 1966).

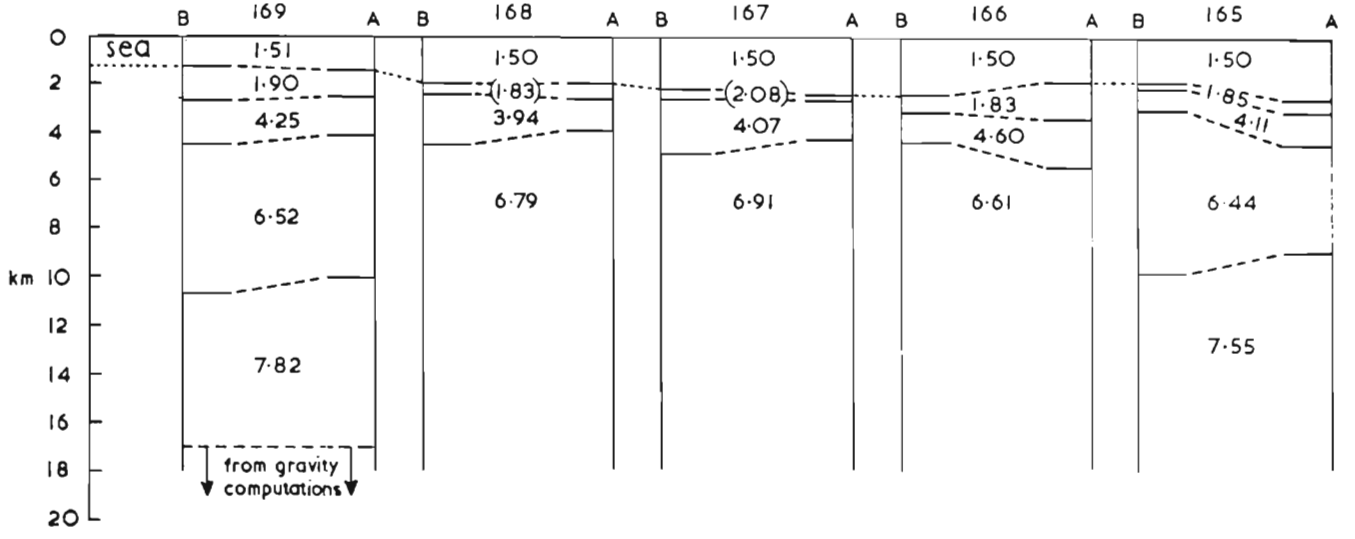


Figure 3. Crustal layering in the Gulf of Aden obtained by seismic refraction stations of VEMA and ATLANTIS 1958 (by courtesy of Dr. Nafe, Lamont Geological Observatory).

with the seismic data to provide additional structural information. Assuming a standard continental section (Worzel and Shurbet, 1955) for the Socotra continental shelf, which is consistent with a typical oceanic section for the N. Somali basin, the gravity data can be used to determine the base of the anomalously low mantle velocity layer below the Gulf (Fig. 4). The depth of 39 km between densities of 3.15 and 3.30 gm/cc is similar to that found beneath the mid-Atlantic ridge (Talwani, Le Pichon and Ewing, 1965), although the latter ridge does not have a 6.7 km/sec layer beneath its crest.

The seismic and gravity data suggest, therefore, that the crust beneath the Gulf of Aden could not have been formed as a downfaulted block of continent unless the entire crust had subsequently been modified in thickness and in physical properties. All the geophysical data point to the conclusion that the Gulf has resulted from the separation of the continental masses of Arabia and Africa and the formation of new oceanic crust from a juvenile and highly active mid-ocean ridge. If such a separation occurred, it must have taken place along the edges of the continental shelves, which can be approximated by the 500 fm (1,000 m) contour. Figure 5 shows the way in which the geological picture can fit across a reconstructed Gulf of Aden, prior to the Miocene.

The fit of the pre-Miocene geology and evidence for the date of separation is discussed in Laughton (1966), but the main features are summarized here:

(a) The congruity of shelf edges and the guide lines of the transform faults allows the position of fit to be well located. The coast-lines approach to within 50-80 km.

(b) There are many similarities between the late Mesozoic and Tertiary succession of sedimentary rocks of Arabia and Somaliland, although the details of the stratigraphy suggest that the two coast-lines were never closely adjacent (Beydoun, 1961). The western boundaries of the Eocene sea match better in this reconstruction than in their present position.

(c) The north and south areas of exposed Precambrian basement in the western part do not overlap.

(d) The major "Red Sea trend" fault system in Yemen and Somalia predates the opening of the Gulf of Aden and can be traced as a more or less continuous band of faults across the closed Gulf.

(e) The Mukalla arch of uplifted and eroded Jurassic sediments (Beydoun, 1960) can be matched in Somalia.

(f) The Wadi Hadramaut in Arabia developed during middle Eocene and should therefore have cut across the reconstructed Gulf. There is evidence of such a cut in the high plateau south of Bender Cassim in

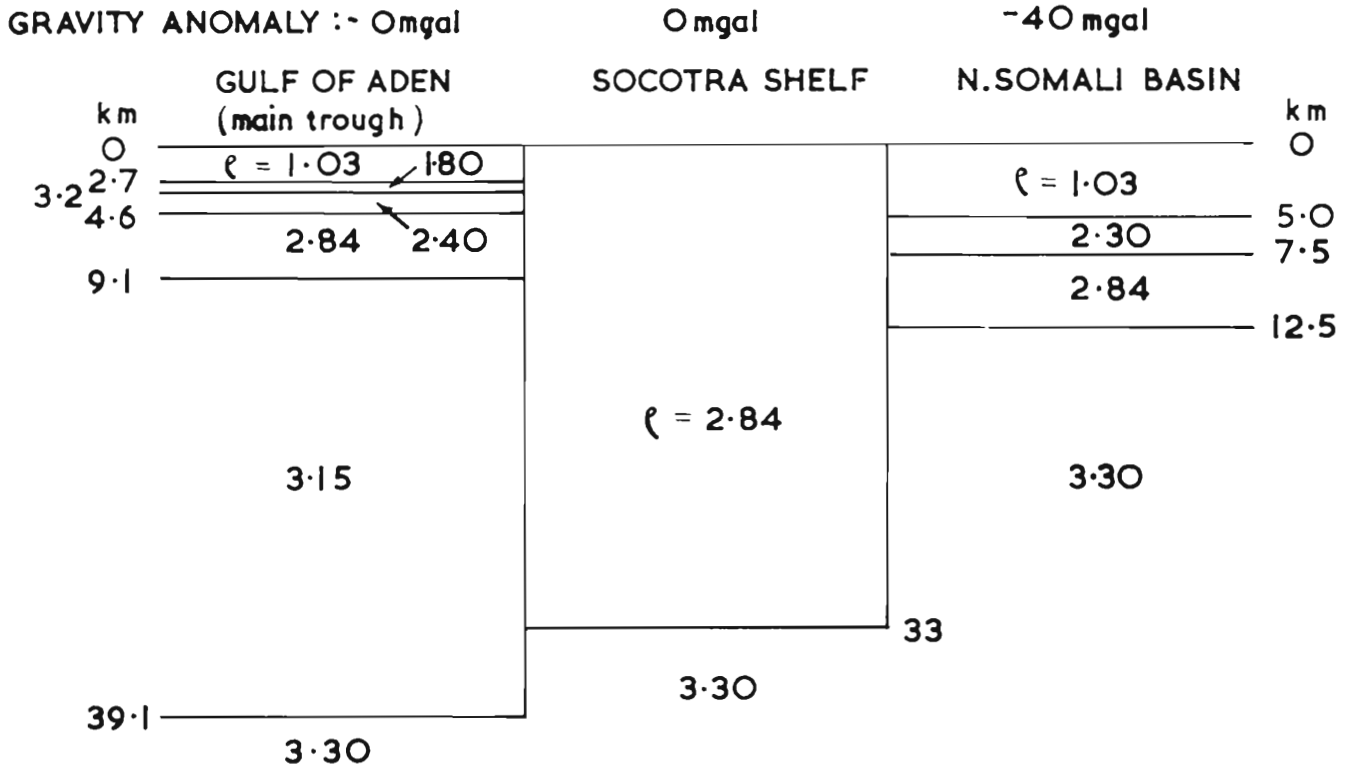


Figure 4. Crustal sections of the Gulf of Aden, the Socotra Shelf and the Somali Basin derived from seismic refraction and gravity data.

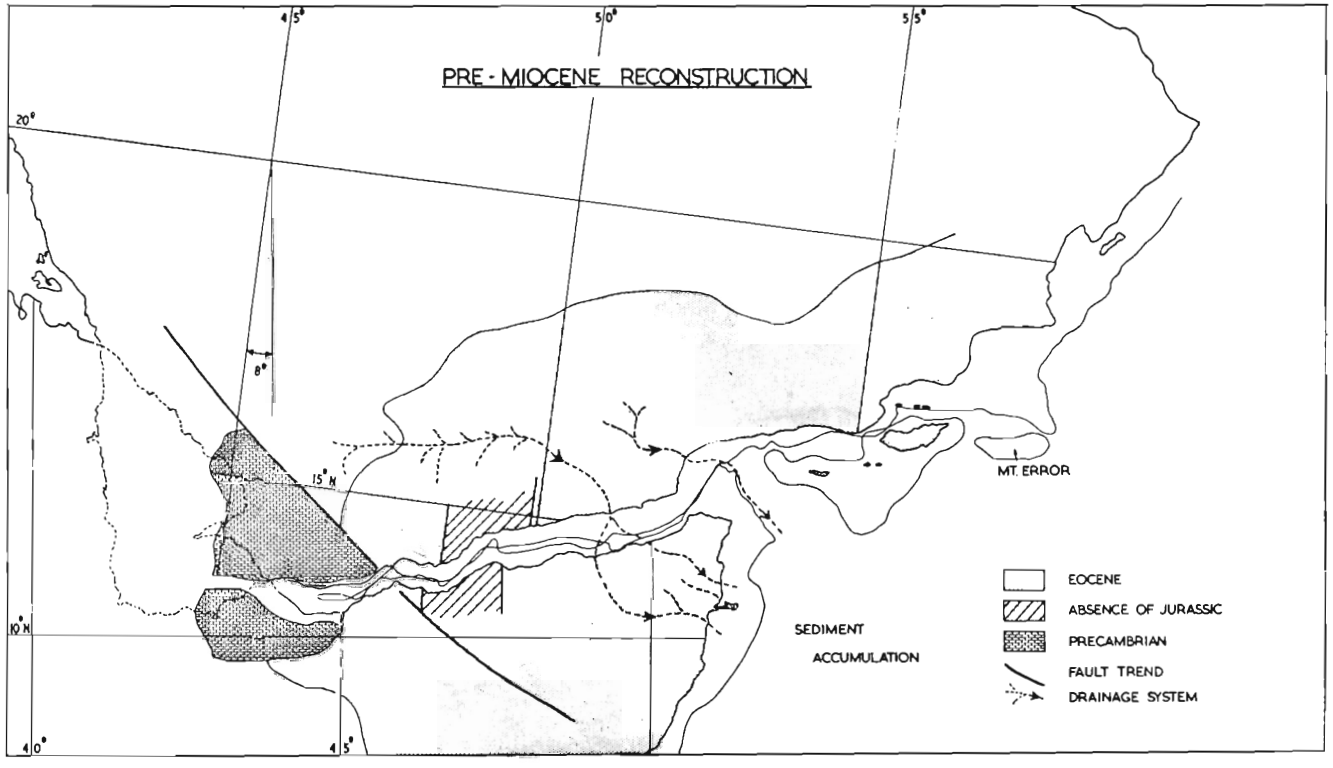


Figure 5. Pre-Miocene reconstruction of the Gulf of Aden (from Laughton 1966).

Somalia, and of estuarine and lagoonal sediments of Miocene age filling in a long and broad valley reaching up to this cut from the east coast of Somalia near Ras Hafun (Azzaroli, 1958).

This description has taken no account so far of the overlap of the Yemen onto the Afar depression of Ethiopia, the Danakil Alps, or of the results obtained by other workers on the geological development of the Red Sea. The Red Sea will be considered first.

THE RED SEA

Drake and Girdler (1964) have made a geophysical study of the Red Sea, and further geophysical surveys have been made by T.D. Allan of SACLANT, La Spezia (unpublished). These studies include bathymetry, magnetics, gravity and seismic refraction measurements. The axial trough of the Red Sea has a positive Bouguer gravity anomaly and linear magnetic anomalies parallel to its length. The seismic stations may be classed according to their results as: (a) shallow (depth 400 m); (b) deep (depth 1,000 m); and (c) intermediate (depth 400-1,000 m). In the southern part of the Red Sea, there are only shallow and deep stations. The shallow stations were characterized by a basement velocity of 5.6-6.4 km/sec, whereas in the axial trough deep stations, the velocity range was 6.7-7.4 km/sec. Drake and Girdler interpret the geophysical data as indicating that the Red Sea has been formed as a tension feature, the axial trough representing the lateral separation of Arabia and Africa (Fig. 6); beneath the axial trough basic intrusives give rise to its magnetic anomalies and maintain it in isostatic equilibrium (Fig. 7). The shallow and intermediate depths of the remainder of the Red Sea are interpreted as down-faulted and tilted continental blocks covered, first by carbonate sediments and evaporites, and later, by coral and unconsolidated sediments.

The rotation of Arabia relative to Africa implied by the opening of the axial trough about a fulcrum in the Sinai Peninsula is 3-4°, and the opening at 15°N is about 60 km. These figures should be compared with those obtained from the Gulf of Aden, which suggest a rotation of Arabia relative to Africa of 8° about a fulcrum in the Eastern Mediterranean, giving rise to an opening of 250 km at 15°N. If Arabia has moved as a single undistorted block, the data from the Red Sea and the Gulf of Aden are mutually inconsistent and need further examination.

The south end of the Red Sea axial trough tapers to nothing at 14°N, as does the Tadjura trough at the west end of the Gulf of Aden. Both show similar dimensions and are characterized by earthquake activity and strong magnetic anomalies. In Laughton (1966), the suggestion is made that the growth of the Tadjura trough was the last of three phases of movement that tended to separate Arabia and Africa, the first and second phases giving

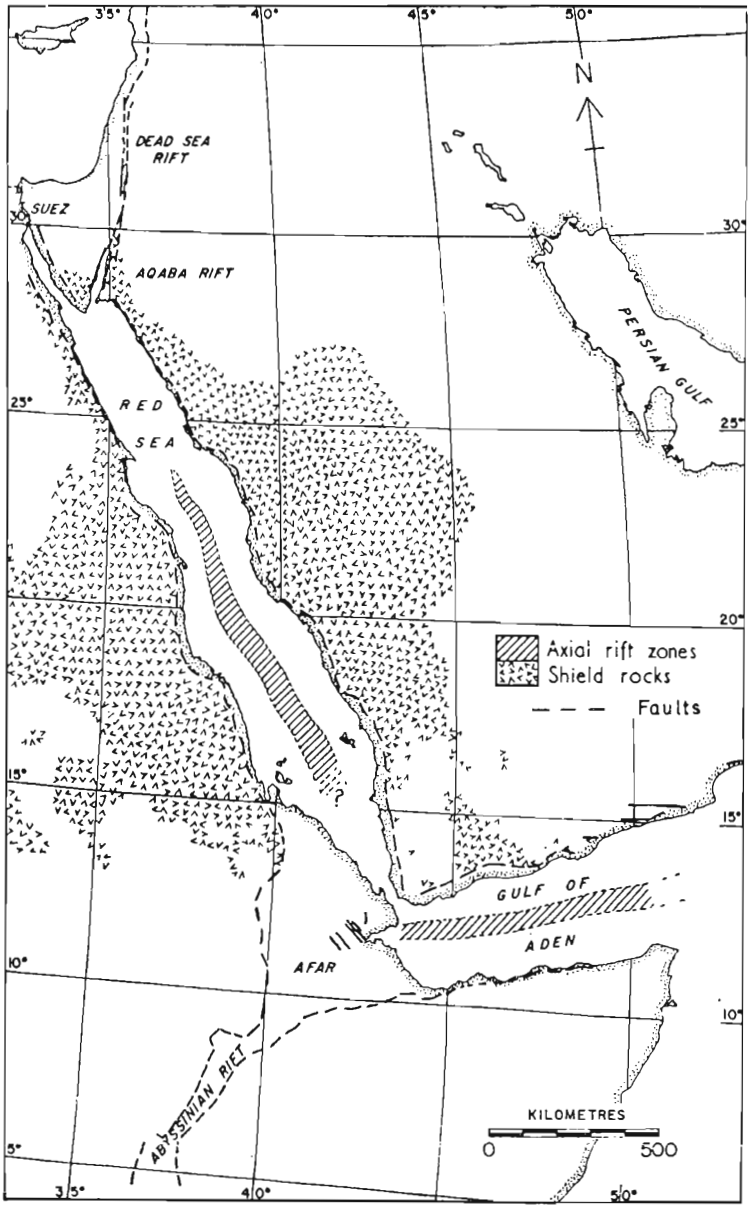


Figure 6. Structural map of the Red Sea area, showing the axial rift valley and region of continental separation (shaded) inferred by Drake and Girdler (from Drake and Girdler 1964).

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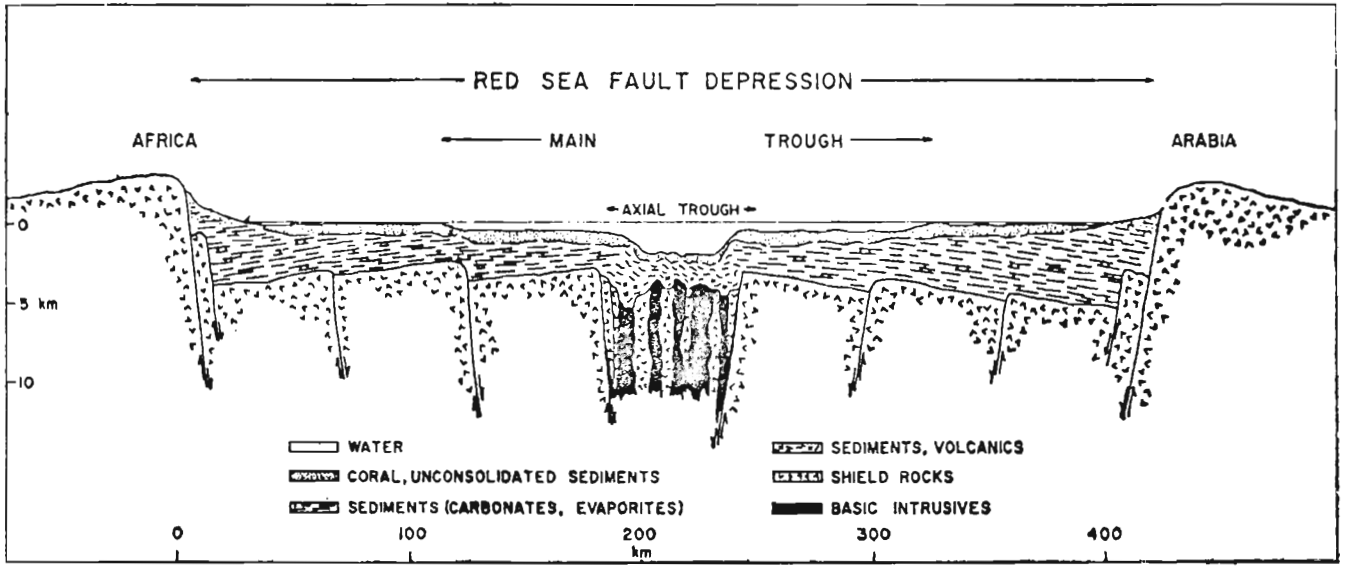


Figure 7. Structural section of the northern part of the Red Sea inferred from geophysical data (from Drake and Girdler 1964).

rise to the main trough and the central rough zone respectively. It is possible that the axial trough of the Red Sea represents a final phase of opening, and that during earlier phases, a large part of the Red Sea (thought by Drake and Girdler to be downfaulted continental crust) was in fact previously formed oceanic crust. The main geophysical arguments against this are the shield-rock velocities obtained for the basement at seismic refraction stations 175, 176 and 177 situated in shallow water to the west of the axial trough in the vicinity of Dahlak Islands. Of the five high velocity lines determined (176 was not reversed), four fall in the range 6.28 to 6.52 km/sec, and at station 175 where 5.64 km/sec was obtained, there was considerable dip. It is possible that these velocities should be attributed to basic rocks rather than shield rocks, or at least to rocks containing substantial proportions of basic intrusions. This would permit a much greater separation than the 60 km suggested by the axial trough.

In the southern part of the Red Sea, the magnetic and gravity fields have not been adequately surveyed on either side of the axial trough owing to the hazards of navigation, and so it is not known whether they are consistent with a 250 km opening at 15°N prior to the formation of the axial trough. If pronounced magnetic anomalies are not found here, their absence could be attributed to a reduction of magnetization by intensive shearing accompanying the separation of the continents.

THE AFAR DEPRESSION, THE DANAKIL ALPS, AND THE YEMEN

The lowland country in the funnel at the north end of the Ethiopian Rift valley has not yet been discussed in the interpretation of either the Red Sea or the Gulf of Aden development. The movement of Arabia deduced from both areas is such that, prior to drift, part of the Yemen was superimposed on what is now emerged land. On the basis of the Red Sea data, the overlap is relatively small, but it is significant because of the high terrain on either side of the Straits of Bab el Mandeb. The Gulf of Aden data indicate that the overlap is large, involving the superposition of the Yemen over a large part of the Afar depression (Fig. 5). The interpretation of the geology and deep structure of this region is therefore crucial to test whether either or neither of the two movements of Arabia postulated above are real. A summary of the geology is presented in Figure 8, based on the Geological Map of Africa (UNESCO, 1963) and on recent work of Mohr (1961).

The Afar depression is bounded on its western side by the great scarp of the Ethiopian Plateau, and on the south by the scarp of the Somali Plateau. On the northeast side lie the Danakil Alps extending from the Gulf of Zula to the Gulf of Tadjura. The most recent work on the geology of Ethiopia (Mohr, 1961) describes the area as follows:

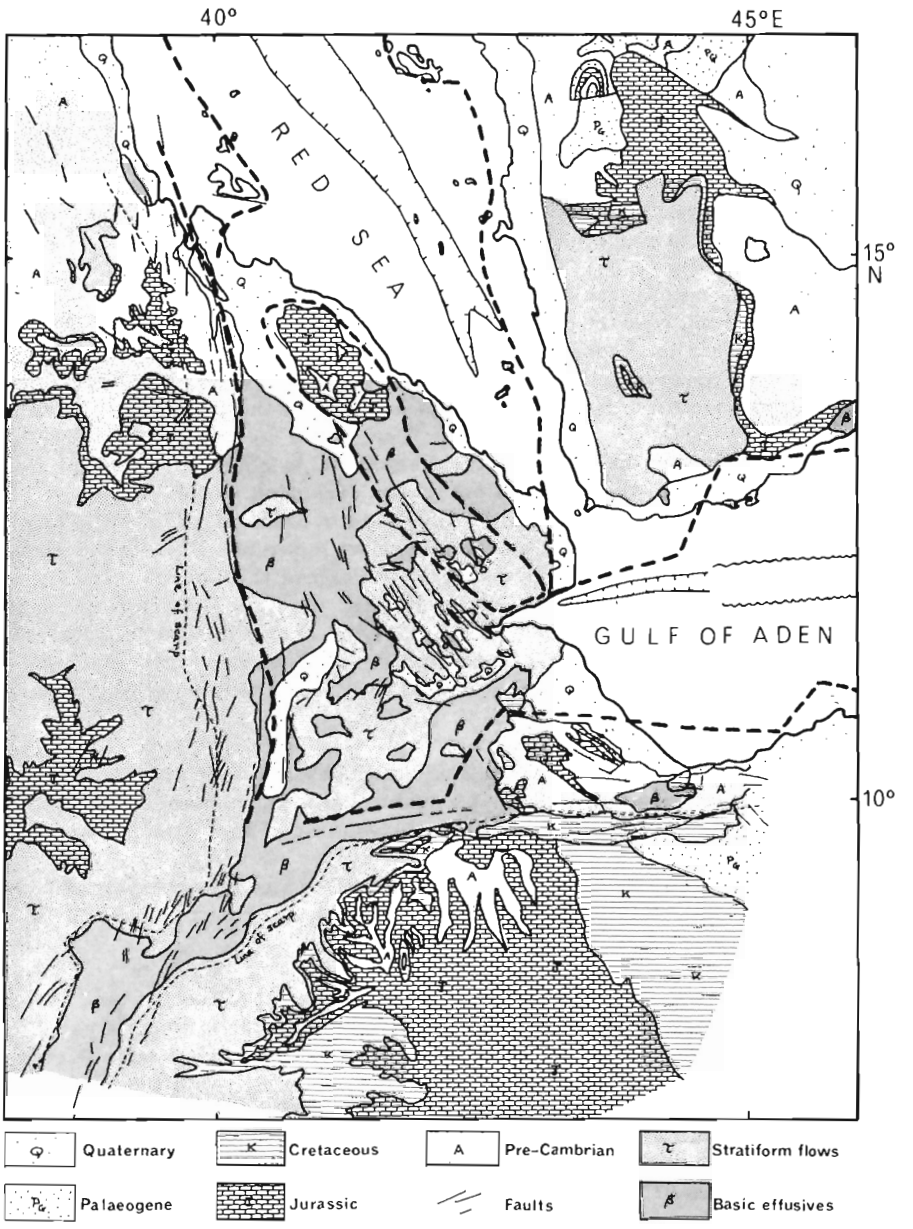


Figure 8. Geological map of the Afar region of Ethiopia based on 1963 edition of the Geological Map of Africa (ASGA-UNESCO) and Mohr (1961). Heavy dashed lines indicate edges of separated continental blocks which are fitted together in Figure 9.

"This immense downfaulted region, much of which lies below sea-level, has a geography and geology which even today are known only in the barest outline, and this is especially true of the inhospitable interior. Almost nothing is known of the faulting of the floor of internal Afar. Around the periphery of the Salt Plain [in the northern apex] faulting is associated with recent outpourings of immense quantities of fissure-basalts which have tended to smooth out any irregularities of the floor surface caused by older faulting.....In Western Afar faulting of the floor trends parallel to the scarp of the Ethiopian Plateau....."

Mohr presents a map of the faults which has been included in Figure 8. Except in the southern part of the area, these converge toward the northern apex. The present positions of the bounding escarpments to the west and south do not represent the major fault lines of the depression but lie some 40-50 km farther out, being the result of erosion of the high plateau country.

The northern end of the Danakil Alps consists of an uplifted horst sloping gently to the sea in a northeast direction and having an extremely denuded scarp on its southwest side overlooking the Salt Plain. The horst consists mainly of Jurassic rocks with patches of exposed Precambrian basement. The southwest-facing scarp of the horst meets the west-bounding scarp of the Afar depression and continues north to form the main western boundary fault zone of the Red Sea near the Gulf of Zula. Mohr believes the Salt Plain to be "the infilled form of a tectonic trough whose faulting, particularly along the eastern margin, is strongly developed and very recent in age".

The Danakil Alps continue southeasterly but consist of immense piles of volcanic rocks perhaps obscuring a continental basement. The mountain range is terminated by the E-W fault of the Gulf of Tadjura.

Within the Afar depression itself, no sedimentary rocks older than Quaternary have been described, most of the area being covered by basic effusives and stratified lava flows.

On the Arabian side of the junction of the Red Sea and the Gulf of Aden in the Yemen, the geological map shows stratified lava flows lying on top of Cretaceous and Jurassic sediments, which in turn rest on a Precambrian basement. It is not clear whether the cliffs behind the coastal plain represent the position of a boundary fault, or whether as in Ethiopia, they have been eroded back from this line. However, there seems little doubt that the Yemen is largely a continental mass connected to the Arabian continent.

Thus, if Arabia has moved, since the Miocene, the distance suggested by the Gulf of Aden data, then the Yemen represents the continental piece that fitted where the Afar depression now is, and a large part of the crust beneath the Afar region must have formed since the drifting occurred.

The absence of any old continental rocks in the area and the immense quantities of basaltic lavas tend to support this idea.

There is, however, the problem of the Danakil Alps which are certainly in part, and possibly completely continental. Figure 9 shows how these might be a fragment of continent which, at one time, was parallel and adjacent to the west bounding fault of the Afar depression. In Figure 9, the fit of the overlap has been determined by the fit of the Gulf of Aden. There is room for the Danakil Alps between the Ethiopian highlands and the Yemen. The Farisan Islands appear between the Dahlak Islands and the Danakil Alps.

As the opening took place, the Danakil Alps were swung anticlockwise, remaining nearly attached to Ethiopia at their northern end and to the Yemen at their southern end. Thus the tapering off of the Red Sea and its axial rift at their south end is compensated by an opening of the Afar depression southwest of the Danakils. The trend of the faults in the Afar is not inconsistent with this idea.

Some predictions based on the above hypothesis, by which it can be checked, are as follows:

(a) The palaeomagnetic directions obtained from, say, the Jurassic rocks, or from pre-Miocene volcanic lavas should give the following rotations relative to Ethiopia: (1) Danakil Alps, 35° anticlockwise; (2) the Yemen, 8° anticlockwise. These rotations could be measured. Irving and Tarling (1961) have already measured an anticlockwise rotation of 6-9° for the Aden volcanics, but these rocks may not be representative of the Arabian continental mass.

(b) The crustal structure beneath the southern end of the Red Sea should be similar to that beneath the Afar depression. In particular, there should be evidence of a pattern of magnetic anomalies in the centre of the Afar depression resembling that over the axial trough of the Red Sea. An aerial magnetic survey could map such a pattern. Gravity and seismic surveys would be needed on land to determine the thickness of the lavas, and to see if they are underlain by shield rocks. The relatively positive Bouguer anomaly found over the northern end of the Ethiopian Rift valley (Girdler, 1958) suggests a considerable thinning of the crust in that area.

(c) The Gulf of Zula and the Salt Plain define one of the major initial fault zones along which separation started. Geophysical data might throw more light on this.

(d) The geometrical operation whereby Arabia is moved as an undeformed unit to close the Red Sea and the Gulf of Aden requires a pivot point somewhere in the Eastern Mediterranean. The opening up of these

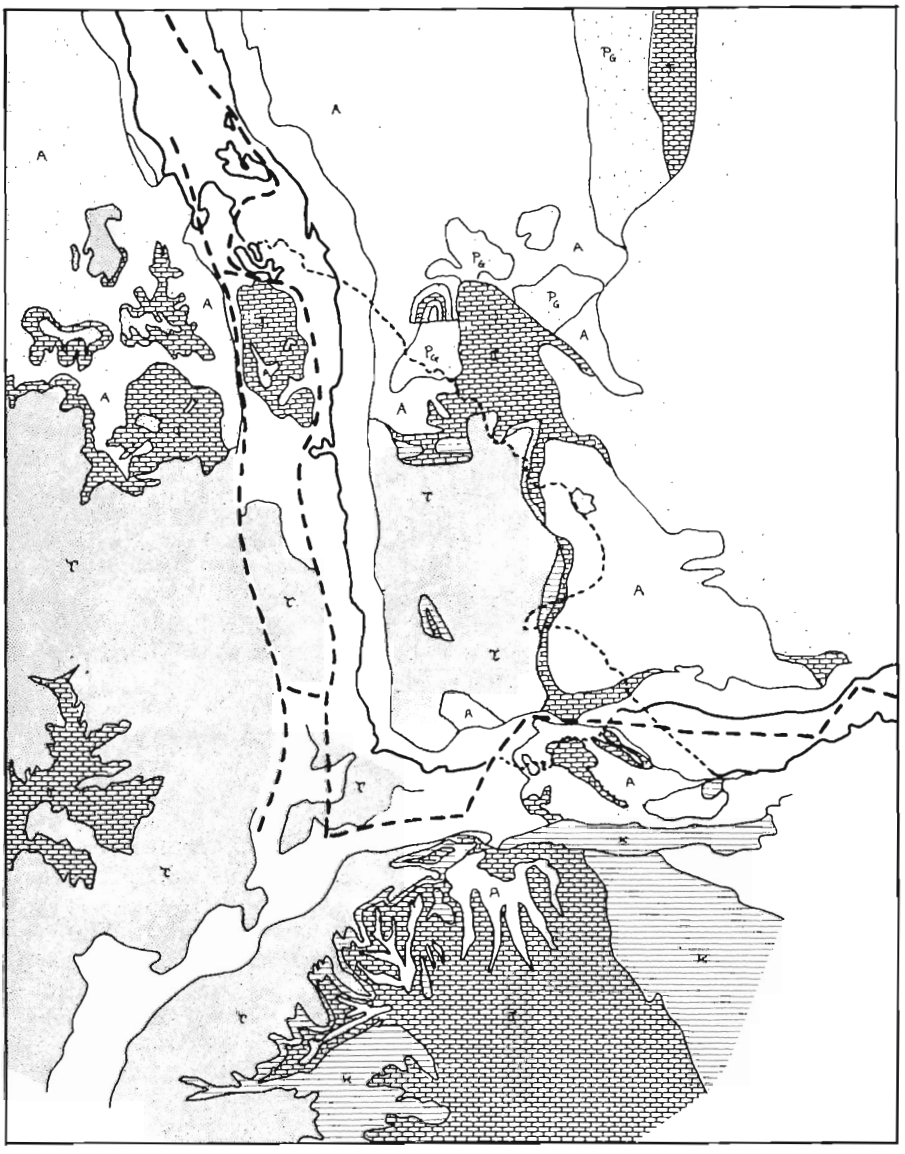


Figure 9. Pre-Miocene reconstruction of the Yemen and Ethiopia. Heavy dashed line indicates line along which separation will take place.

features in this way implies considerable left lateral shear along the Gulf of Aquaba-Dead Sea Rift. Quennel (1958) has described such a shear of 107 km, and this has been further examined by Freund (1965).

In conclusion, the geophysical data obtained from the Gulf of Aden and from the Red Sea both suggest relative horizontal movement between Arabia and Africa, but by different distances and angles. Both involve some overlap of the Yemen onto the Afar depression. The geology of the Afar region and the Danakil Alps can be interpreted to allow the large overlap suggested by the Gulf of Aden data in pre-Miocene times, provided the Danakil Alps can be rotated by 35° during the separation. Considerably more geophysical and geological data are required in this critical area before the problem can be resolved satisfactorily.

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DISCUSSION

Dr. D.C. Krause (U.S.A.)

I find the ideas expressed here very interesting. They can, as a model, be applied to other areas. For example, the Gulf of California bears a lot of similarity except that there is a strong strike-slip component as well, and I think that many of the features in the central Atlantic Basin can also be developed on the same model.

Dr. T.D. Allan (U.S.A.)

I am curious as to the southward extension of the Axial rift zones of the Red Sea. You have ended them with a question mark.

Dr. Laughton

The idea I have is that the separation of the continental crust along the Red Sea is continuous but is nullified at the south end of the sea by the formation of the triangular block of Afar.

Dr. W.F. Whittard (U.K.)

What happens to the seismic structure at the western end of the Gulf of Aden. Does the rift zone bifurcate or change in trend?

Dr. Laughton

The westernmost seismic stations we have are just southeast of Aden. The structure there appears to be similar to all other stations in the Gulf of Aden. There does not seem to be a change in the seismic structure from east to west. Now possibly if we went even further west toward the junction with the Red Sea, and I think this is a particularly critical area to investigate, we may find some transition from oceanic to continental crust. Perhaps this is the region to test Dr. Beloussov's idea of oceanization of continental crust. We do have a transition from oceanic structure up the axis of the Gulf of Aden to something that we believe to be continental, and this transition is not marked by a continental margin as we normally think of continental margins.

SOME COMMENTS ON THE RIFT IN ETHIOPIA

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University College, Addis Ababa, Ethiopia

The Red Sea, the Gulf of Aden and the Central Ethiopian Rift join in the Afar region of Ethiopia and French Somaliland. This important area is not well known geologically. At present, there is no Geological Survey in Ethiopia, and no detailed geological mapping is being done on a systematic basis. The primary responsibility of the Ministry of Mines in Addis Ababa is concerned with locating new, and developing known mineral deposits in Ethiopia. The U.S. Mapping Mission is completing aerial photographic coverage of Ethiopia, but the topographic maps necessary for geological-geophysical studies are still to be made.

The Central Ethiopian Rift, which trends N30°E, may be related to the direction of foliation in the schists and gneisses of the basement complex. Recent age determinations on the basement complex in southern Ethiopia divided the rocks into two groups. The younger group (400-500 m.y.) trends slightly east of north; and the older group (600-750 m.y.) trends north and northwest. The younger group is closest to the Rift but is covered in the immediately adjoining area by Mesozoic marine sediments and Tertiary volcanic rocks.

The Rift began to develop in the Miocene or perhaps slightly earlier. It cut across the Arabo-Ethiopian swell (a 2,500 + m uplift) but probably not along the axis. The Rift is generally bounded by parallel faults which commonly form steps and tilted blocks. Downwarping is also noted along the western margin. In the area just west of the major Rift escarpment, there is a narrow graben extending for several hundred kilometres north from Addis Ababa. In 1961, a series of earthquakes was associated with this graben at Karakore (about 250 km. north of Addis Ababa). Surface expressions of the earthquakes consist of numerous landslides, and a surface "crack" about 5 kilometres long in unconsolidated sediments. The maximum vertical displacement on the latter break was 2 metres.

Uplift of the Ethiopian Plateau has continued through the Recent. This is indicated by (1) raised wave cuts (about 2 metres uplift) in the reefs of the Dahlak Islands; (2) incised stream gravels; and (3) tilting of Recent lake beds in southern Ethiopia (they are tilted up towards the Rift at an angle of 15-20 minutes). The lake beds are similar to others near Addis Ababa which contain hand axes and similar implements, and mammal bones. If the tilting is real, C^{14} age studies may reveal its rate.

For additional information on the Ethiopian Rift, the reader is referred to Mohr and Rogers (1965); this paper includes a summary of geophysical works done by Pierre Gouin and Paul Mohr of the Geophysical Observatory, University College, Addis Ababa.

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THE RIFT VALLEY CRATON

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Abstract

Three sets of master lineaments in the East African rift valley terrain combine in pairs to outline a polygonal cratonic plate. Numerous details of the structural features of the terrain suggest that the rift valley habit dates back at least to the Proterozoic, and possibly earlier. A size-age graph speaks of orogenic evolution, the oldest rocks being the finest mosaic pattern.

The rift valley terrain of East Africa is an elliptical block about 16 x 12 degrees. The centrepiece is a subsided block, and the oval uplands surrounding it are concentrically bisected throughout most of their annular length by the main rift valley arcs.

This is an ordered pattern but of a complexity that is not easily reconciled with the concept of convection currents. It would be still more difficult to invoke convection currents to explain the implied progression in time from a fine pattern to a coarse one.

The rift valley block can be regarded as a craton surrounded by cratons of roughly similar size and shape, forming part of a mosaic which covers Africa.

A cause-and-effect relationship is postulated between the dropping of a crustal block and the uplift of neighbouring blocks. The cause of the dropping is one of the big remaining problems.

INTRODUCTION

The Rift Valley controversy — tension versus compression — has become rather quiescent of recent years chiefly because of a paucity of new data, and not because any clear concept of rift valley tectonics has emerged from the conflict. The one noteworthy advance seems to be an increasing usage of the term "vertical tectonics" with its implication that the relative ups and downs between contiguous crustal blocks are somehow a reflection of the vagaries of the mantle. It is this that brings the rift valley

terrain into the Upper Mantle Project discussion. The crustal plates adapt themselves to the upper mantle regardless of whether the earth is expanding or contracting, and regardless of whether the crust of earth is in tension or compression. Those controversial issues, although perhaps not satisfactorily solved, are not germane to the discussion when we talk in terms of vertical tectonics whose processes are conceived to take up the slack either way.

The 20 mile thickness of the crust is almost negligible with relation to the 1,000 mile length of the terrain — a mere 2 per cent — so one can think in terms of plane geometry marred only by the curvature of the earth. The hade of a fault is not going to alter the pattern appreciably.

The present paper aims to show something of the study of form and pattern as a tool, on the legitimate assumption that the crust is in harmony with what lies underneath, in which case rhythmic patterns in the crust may have a message about what lies underneath, namely the upper mantle.

One of the unique things about the rift valley terrain is the relative completeness of the exposed structural pattern with a horizontal datum, the 4,000 foot plateau of Africa against which vertical tectonics can be measured, both as uplifts and subsidences.

The typical rift valley of East Africa has been described in its cross-section as the "dropped keystone of an arch". This may not be a good analogy mechanically because an arch converts gravity into compression which would prevent the keystone from dropping. The description, however, does correctly convey the impression that the uplifted rims of the rift valley are sloping away from the dropped block. Generally the rims are around 7,000 feet in elevation, compared to the 4,000 foot elevation of the plateau. The description is also apt in its implication that the main rifts longitudinally bisect upland country. Lake Victoria is bracketed by the arcuate rift valleys whose concavities face the lake.

This is our starting point in a terrain where vertical tectonics announce themselves clearly and precisely, with a Miocene datum plane just mentioned. The downs and the ups are not merely relative: with the 4,000 foot datum they are close to being absolute.

THE DOMINANT TRENDS

Northeast Set (Fig. 1)

The northeast set of lineaments is exemplified by the Somali coast which, when extended to the southwest, aligns closely with the Ruaha and Luangwa Valleys. The Lake Albert trend falls into this group, and between them, evenly spaced, are two less conspicuous lineaments, one of which is the extension of the Upemba rift in the Congo, also a Bukoban line. At the northwest extremity of the rift valley terrain, a granitized zone marks the truncation of the broad Kibali trend. From the completeness of the truncation, it can be inferred that the truncating lineament is an important one.

Thus we have two master lineaments 10 or 12 degrees apart, with three or perhaps four sympathetic but smaller lineaments.

Northwest Set (Fig. 1)

The southern end of Lake Tanganyika combines with the Ubendian and Rukwa to make a broad and conspicuous trend. The Aswa line, which with its mylonites has attracted considerable attention, heads for the crux of Mount Elgon, beyond which it continues as that phenomenal feature the Yatta Plateau (of which more later). The northeasterly extremity of typical rift valley country is marked by a geological break of (inferred) considerable magnitude but is largely hidden by the Ghazal basin, the Rudolf volcanics and the deltoid-shaped Juba Lowlands. In a long strip, 1,000 miles long and 60 miles broad, no Precambrian rocks crop out, and this is deduced to be a master break, also trending in a northwest direction. Likewise, it is 12 degrees from the Rukwa line.

Meridional Set (Fig. 2)

From the edge of the Congo tectonic basin to the meridional eastern edge of the shield is $12\frac{1}{2}$ degrees. The intermediate lineaments of this set between the master lineaments are rather intermittent. In the southern portion of the East African terrain between Lake Victoria and Mbeya, a north-northeast trend is conspicuous, at the expense of the meridional trend. The main lineaments of this set, the Kivu-Edward line and the Tunduru-Mombasa line, are spaced similarly to other master breaks.

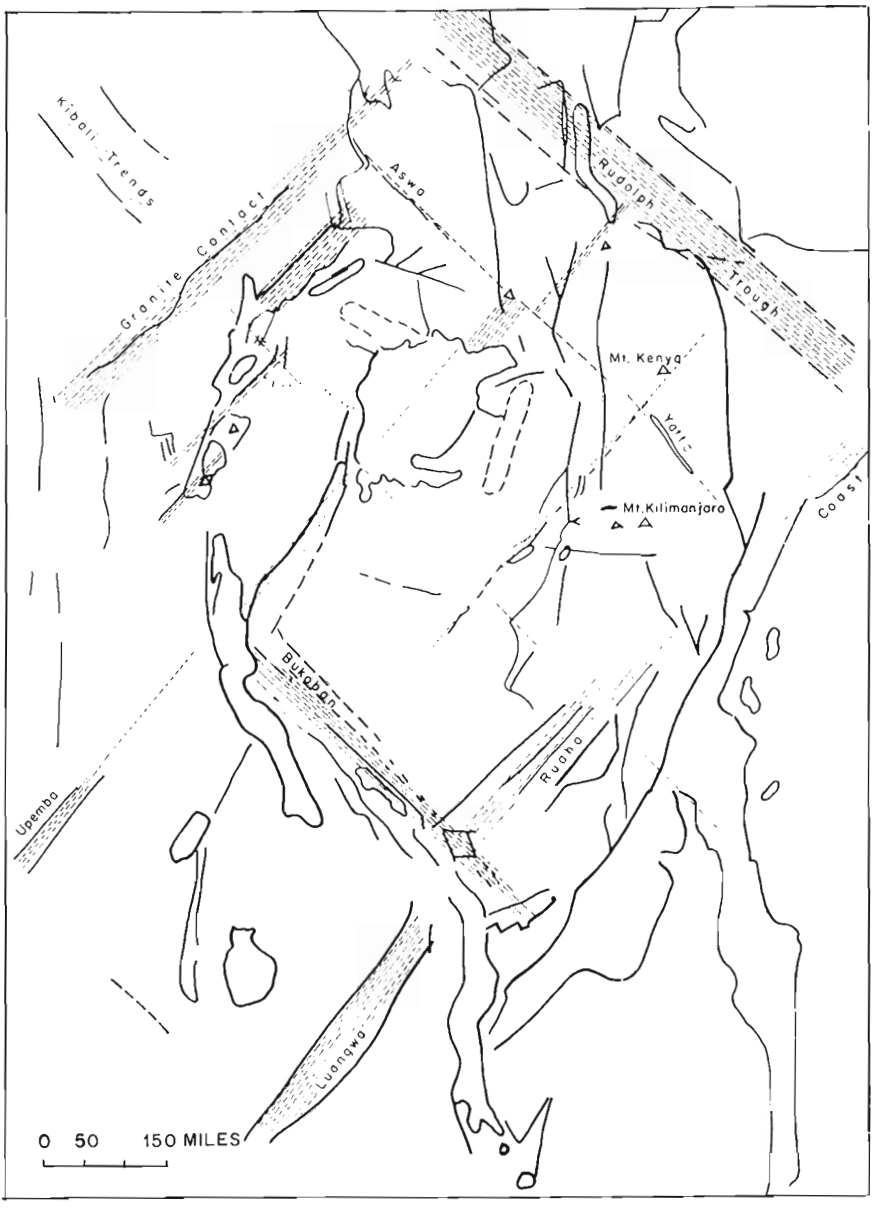


Figure 1. Northeast and southwest-trending lineaments.

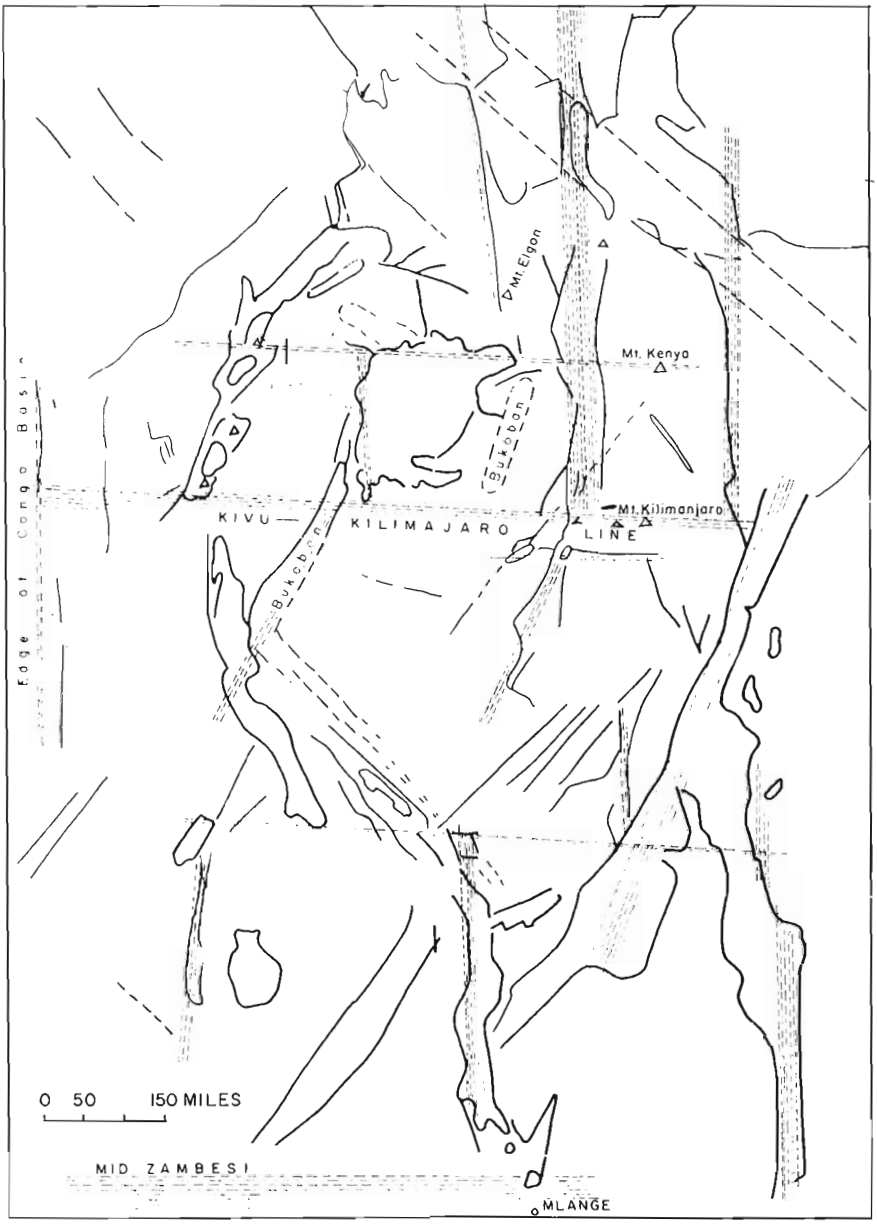


Figure 2. Lineaments trending north-south and east-west.

The three pairs of major breaks combine to outline a polygonal block. Within this polygonal block, the minor lineaments combine to constitute the fragmentation pattern of the block as a whole.

East-West Set (Fig. 2)

A fourth set of lineaments, the east-west, is not very conspicuous within East Africa, but the mid-Zambezi depression which aligns with the Mlanji horst suggests that it does exist. Alignments of volcanoes (e.g. Kilimanjaro-Meru-Kivu) tend to support this, but the trend has not the importance of the other three.

SOME TYPICAL DETAILS OF THE RIFT VALLEY TERRAIN

1. Meandering of the Major Rifts

Some of the rift valleys, accentuated by the lakes they contain, are "straight" in the broad view, but in detail they go around corners with the parallelism of the walls unimpaired. There are some pinchings and swellings giving the range of width of 20 to 40 miles, but these irregularities are emphatically not due to horizontal movement along the line of the rift. Had such occurred, it would be easy to diagnose.

The axis bisecting the lake is usually zigzagged left-right-left, but there are exceptions where an arc instead of a zigzag negotiates a cross structural feature such as the Mahari Peninsula. The arc is composed of three segments angling right in succession. The segments of the bisecting axis are usually a little more than the width of the rift.

In order to demonstrate that the averaging of the axis of a meandering line is a lawful procedure, the general arc of the Western Rift is compared to other structural forms in its neighbourhood in Figure 3.

The detailed meanderings, however, from their size and shape would appear to be related to the Archaean pattern as exposed in the Dodoman, Nyanzian and Sebakwian (Rhodesia) areas. Thirty to sixty miles is the amplitude of sinuosities in the coarser patterns.

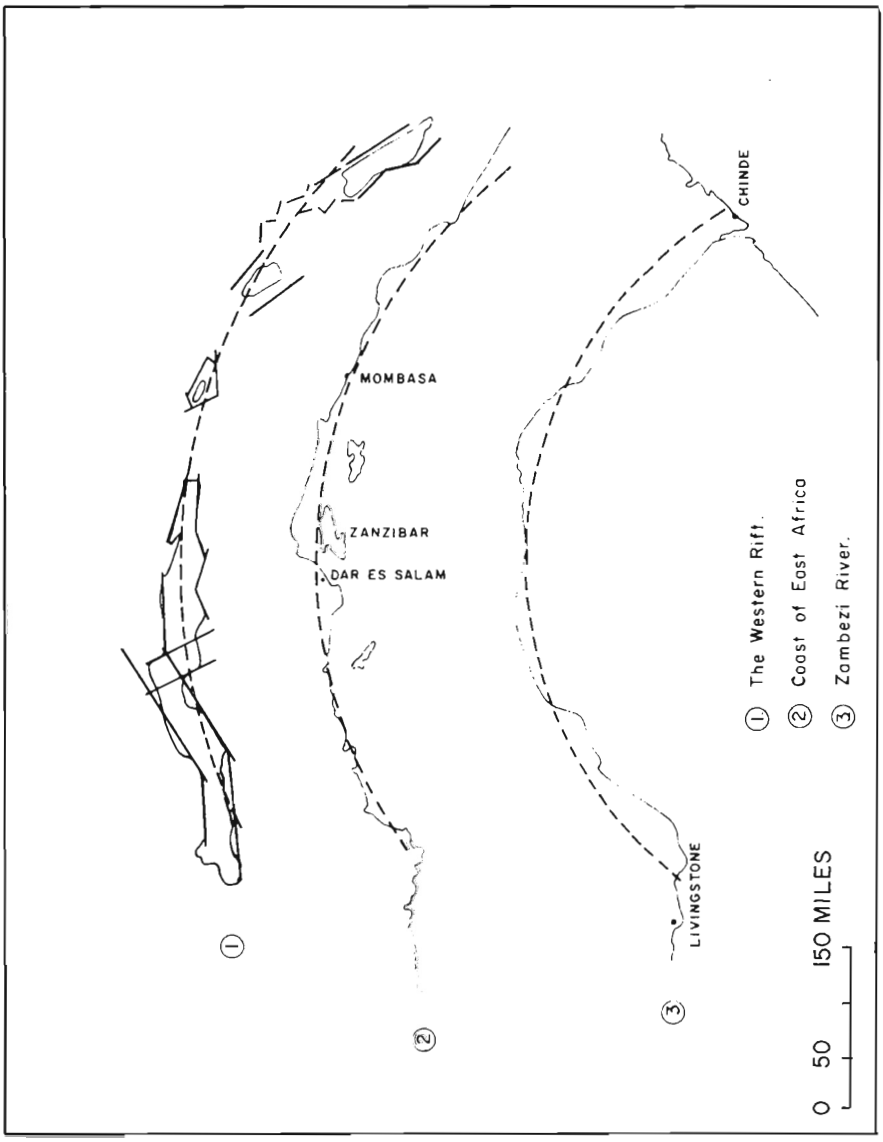


Figure 3. Similar forms.

2. A River Breaking Out of its Rift

The course of the Ruaha outside of the Ruaha rift (Fig. 4) is important as an indication of the fundamental pattern of small nodular blocks round which the river swings. That the river marks an important structural weakness is evident, otherwise the river could never have succeeded in breaking out of the rift valley it occupies in the upper reaches. The pattern of its deeply cut sinuosities is quite in keeping with the width of the rift as an interval of structural significance, again with its ultimate origin seemingly of great age.

3. En Echelon Rifts

An example of this is the Rukwa Valley parallel to the Tanganyika Valley, with a horst between of about 40 miles width. As the Tanganyika Valley fades out, so the Rukwa becomes prominent, with an overlap of the same order as the distance between the two lakes. The en echelon faults may indicate a warping rather than a wholesale movement of a block, but there is usually evidence of a multitude of smaller faults when the greater faults are missing.

4. Subsidiary Rifts

In addition to those 30 mile rifts which, if not the master lineaments, are at least the master rifts, there are numerous subsidiary rifts which do not seem to serve any visible purpose, nor to add sensibly to the pattern. Although perfect rifts in miniature (some no more than 16 miles long and 6 miles wide, such as Rufunsa), they do not seem to tie into the broader pattern with any meaningful link.

They are mentioned to indicate the degree of complexity.

5. Equidimensional Depressions

These can be described as rift valleys that do not go anywhere. One occurs near the centre of an uplifted mass of gently dipping gneisses. The Ruaha River makes use of the depression for a distance of about 18 miles. The depression could not have been caused by drainage, nor by folding; it is simply a dropped block.

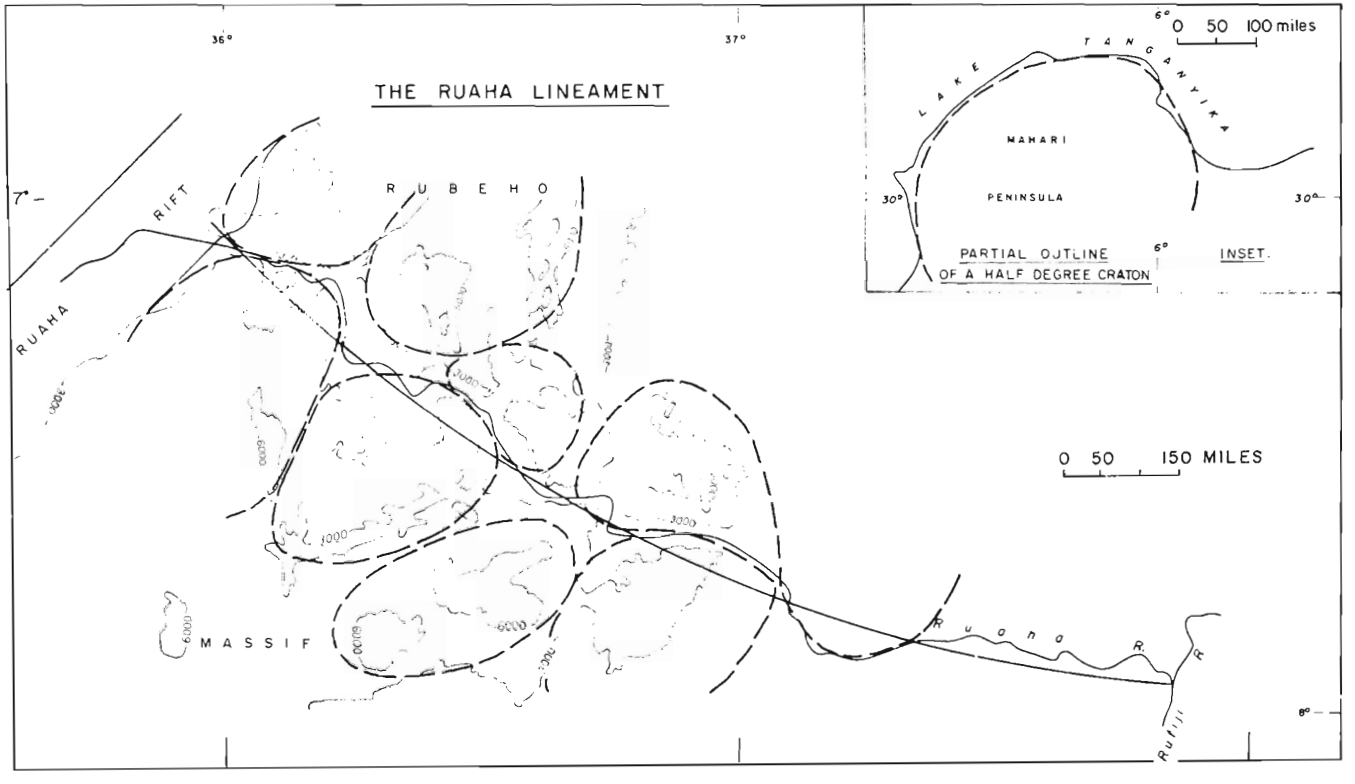


Figure 4. The Ruaha River breaking through the upland country bounding the Ruaha rift. The arcuate stretches of the river suggest the Nyasa scale of mosaic, and the topography tends to bear this out. The sharper bends of the river coincide with fragmentary interstitial remnants. The structural control of the river is not to be doubted.

The Ngorongoro "crater", 12 miles in diameter, has usually been considered volcanic in origin. It is virtually surrounded by volcanic cones of 10,000 or 11,000 feet elevation. The volcanic effusion conceivably gave rise to a void into which the block dropped. "A space to break against" is one of the unsolved problems of rift valley tectonics, and of small equidimensional rifts in particular.

The small size of these downdropped blocks would indicate that we are not dealing with isostatic adjustments. There is no reason whatever to believe that the density of the dropped block differs from that of neighbouring blocks.

6. Horsts Bounded by Rifts

A horst shares the acute angle of a bifurcation, because without the intervening horst there would be no bifurcation. An elegant example of the grand scale is the Sinai Peninsula. Another is Kariba, another the Mafingi mountain block. The latter, composed of quartzite correlated with Muva, might be the infilling of a discrete basin, later uplifted.

The acute-angled structure is an unstable structure in contrast to the obtuse angles that combine into arcuate boundaries of the more stable crustal units.

7. The Isolated Horsts of Eastern Tanganyika

The block mountains of usually gently dipping gneisses sticking up sharply from the lowlands, e.g. Uluguru, Nguru and Usambara have a common length of 40 miles. Structurally they are akin to rift valleys, but in reverse (Fig. 5).

Here again the relatively small size of the horsts together with their composition suggests pure vertical tectonics.

8. The Yatta Plateau

This is a narrow ridge, 175 miles long with a curious 135 degree kink at either end. The ridge is composed of Tertiary lava and is capped by flat-lying flows. The length and the irregularities can be matched by all sorts of features in the rift valley terrain (Fig. 6). If these numerous

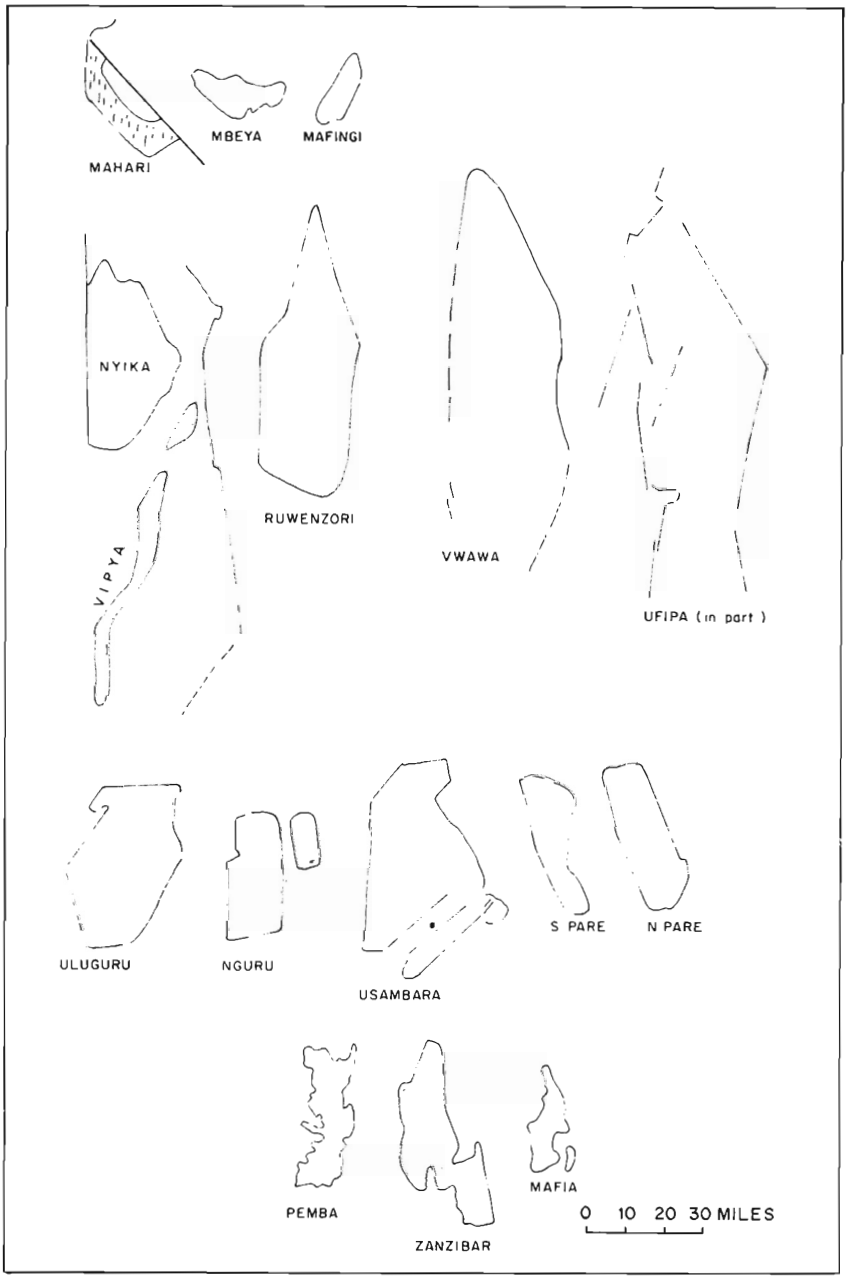


Figure 5. Comparison of sizes of block mountains and related features.

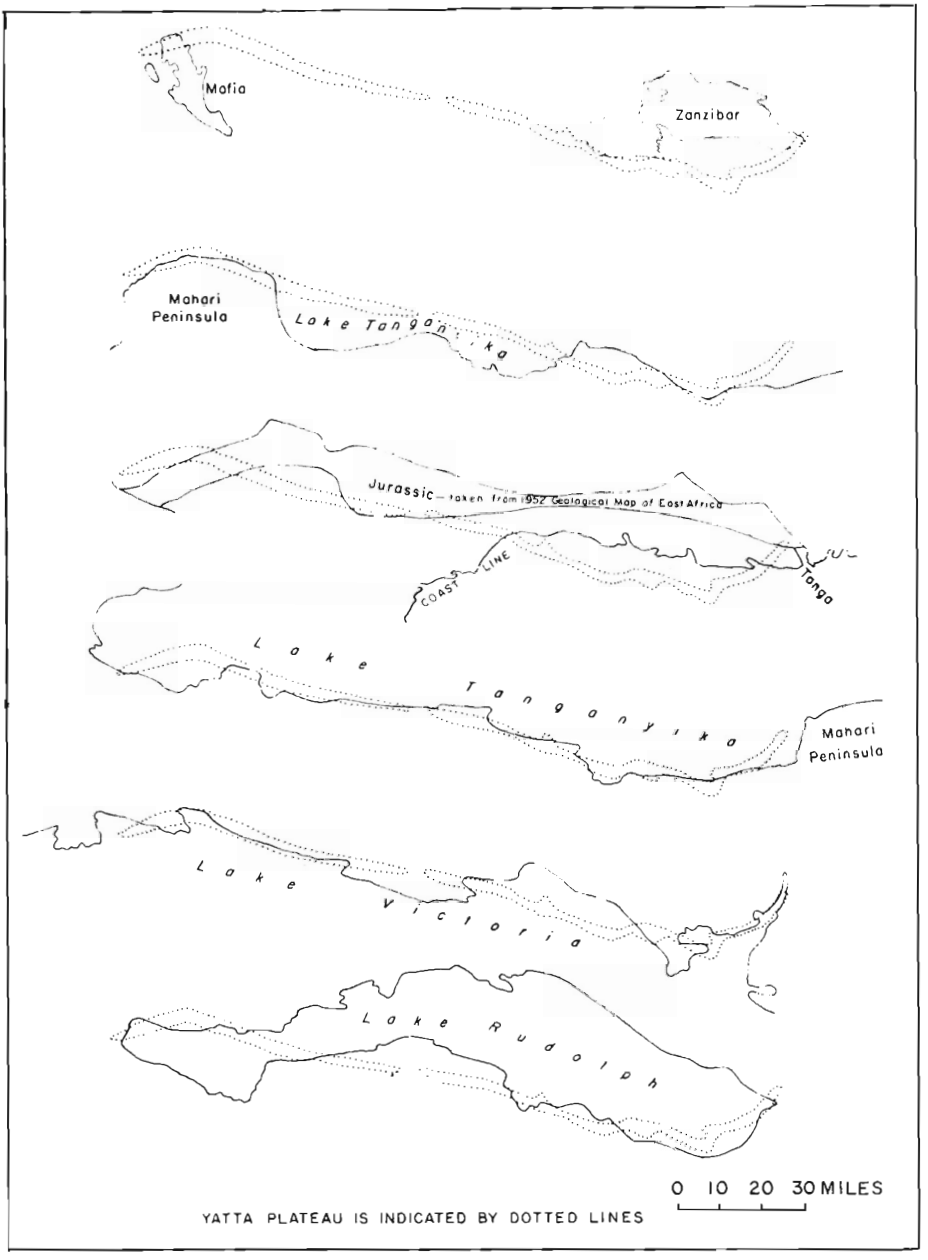


Figure 6. The geometric character of the Yatta Plateau, and some similar land forms.

coincidences are not fortuitous, one may deduce structural control of the Yatta, but it is still not adequately explained.

9. The Mbeya Crux

Mbeya Mountain, a basement block of 9,400 feet elevation, is the crux of four converging rifts (Fig. 7). It is not difficult to conceive of a block on rift axes being loosened by deepseated faulting and finding itself free to move vertically independently of adjacent blocks. The prominent relief is caused by pure measurable uplift in contrast to the dropped blocks of the rifts.

10. The Bukoban Ranges

The series of prominent hills of Bukoban sandstone and conglomerate trends intermittently parallel to Lake Rukwa. Coarse conglomerates with cobbles several inches in diameter indicate substantial relief during deposition, and the alignment of the range indicated a depositional trough. An inward dip confirms this view. The rift valley habit thus appears to have begun at least in the Proterozoic.

The Bukoban range east of Lake Victoria is better preserved than in the Rukwa. The former is plotted in Figure 8 with the south end of Lake Tanganyika superimposed. The similarity is striking enough to suggest that the depositional troughs were rift valleys of Proterozoic age.

SIZE-AGE PATTERNS

The Dodoman-Nyanzian pattern is utterly characteristic of the Archaean, where sedimentary rocks are wrapped around "gregarious batholiths" (Macgregor, 1951) in Rhodesia. The batholiths characteristically are 30 to 60 miles in diameter (Fig. 9).

The Middle Precambrian remnants are appreciably larger, between 2 and 3 degrees in diameter. The Bukoban, which is Proterozoic or slightly later, covers larger areas, and so on up the time scale. The terrain is big enough to put the orogenic evolution concept to the test, and a convincing size-age curve results (Figs. 10 and 11).

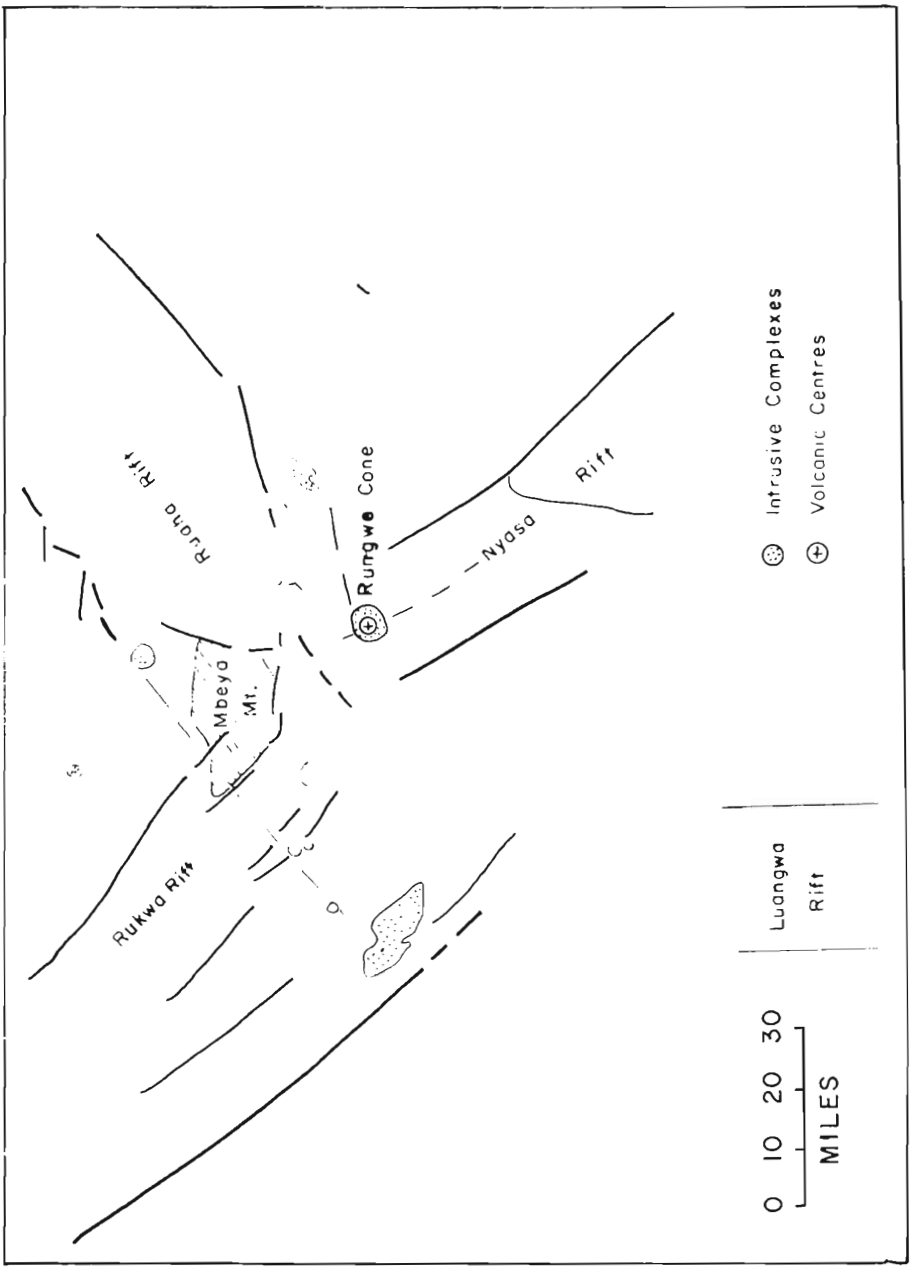


Figure 7. The Mbeya environs.

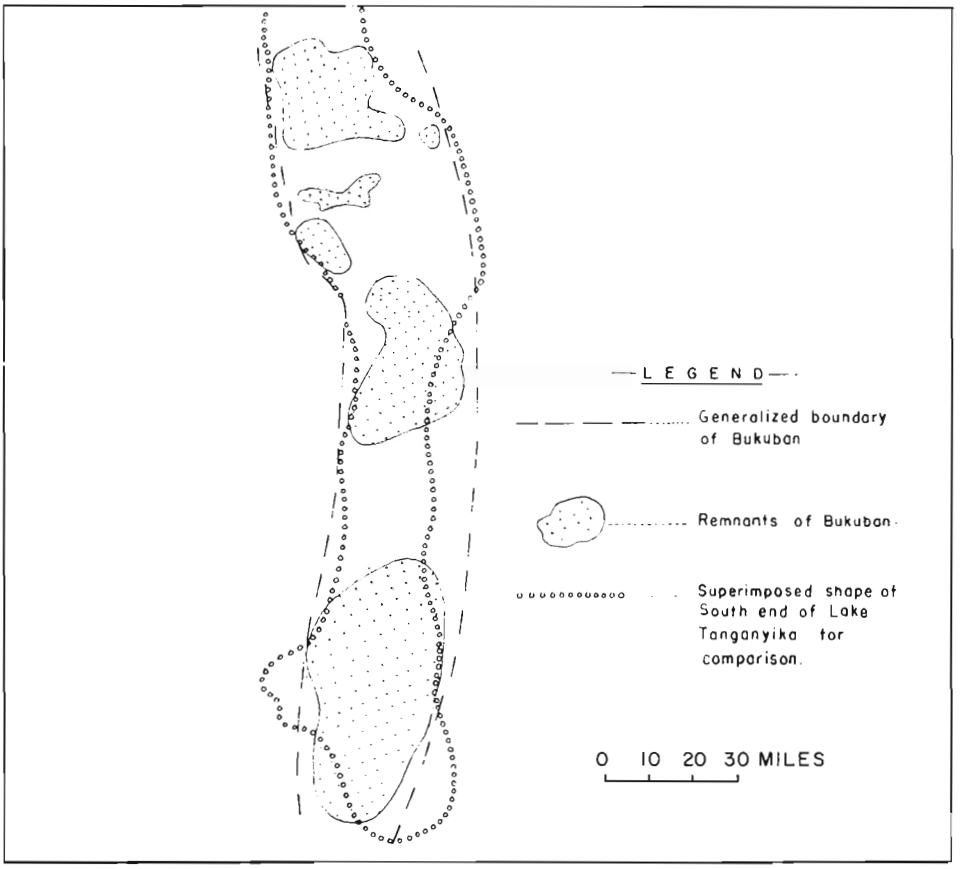


Figure 8. The Bukoban east of Lake Victoria with the south end of Lake Tanganyika superimposed.

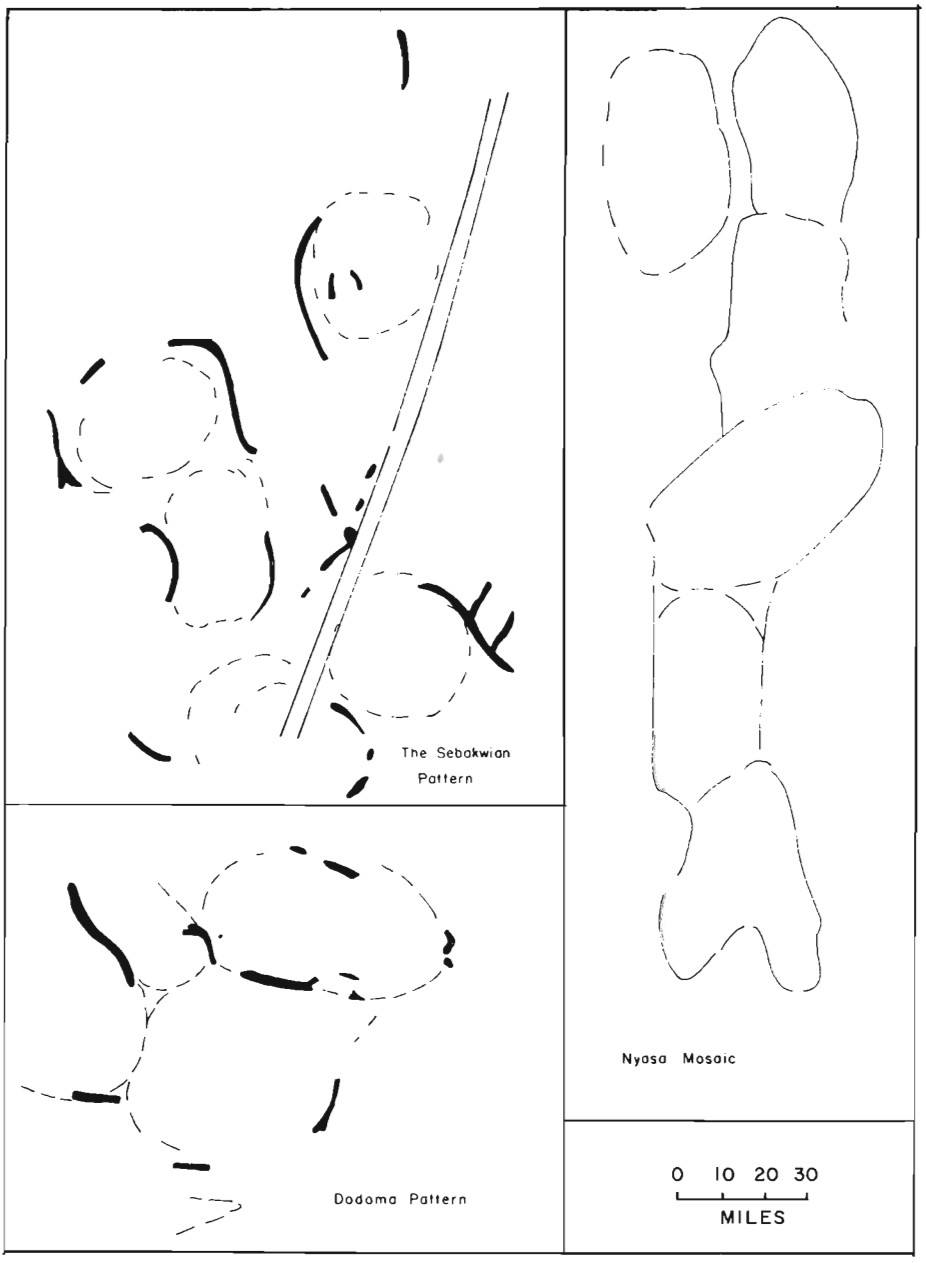


Figure 9. A comparison of patterns.

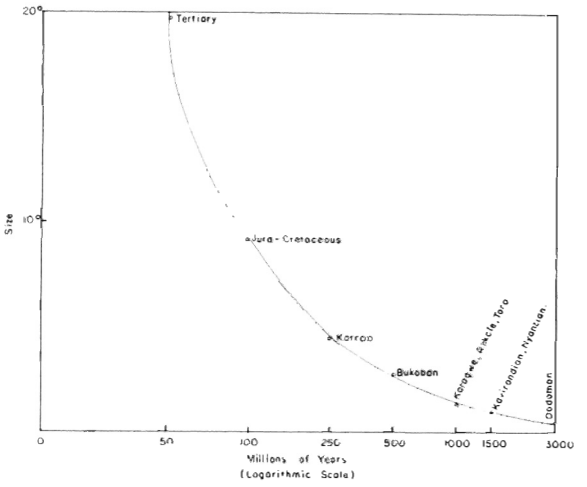


Figure 10. Size-age curve for several African structures.

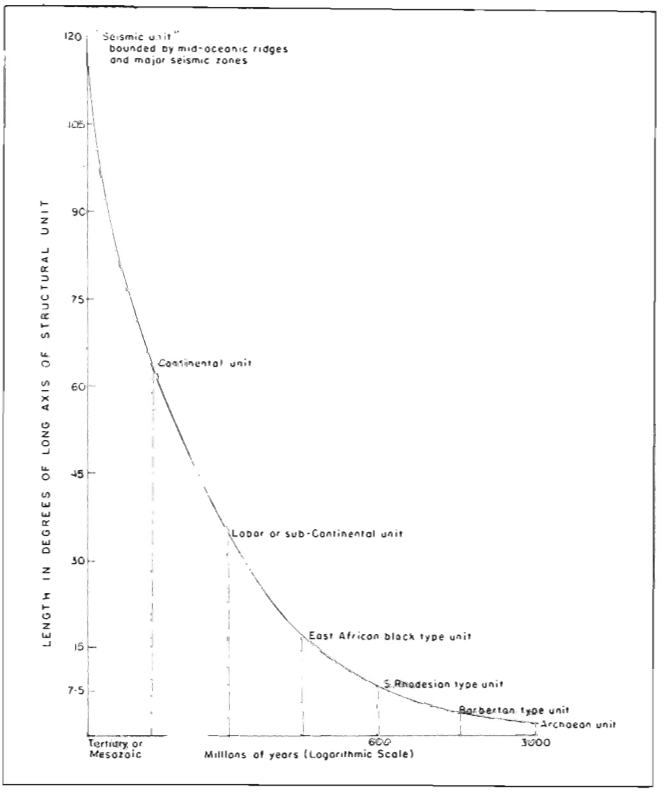


Figure 11. A world-size age curve showing the place of the East African structural unit in the heirarchy.

MOSAIC ANALYSIS OF EAST AFRICA

In the subdivision of any crustal plate, the presence of a centre-piece structurally distinguishable from its neighbours is very often a useful clue, especially if it has an angular outline whose angles are likely to mark the boundaries of the surrounding segments.

In Lake Victoria (Fig. 12), whose shore at least locally has been proved to be structurally controlled, we have an excellent example of an equidimensional block which presumably has dropped. From its shores are radiating sutures, which not only separate segments of unlike geology, but which also tie in to distinctive breaks in the rift valley closure.

The mosaic within the Victoria basin is fairly homogeneous as to size of unit, but to the southward, a coarser mosaic pattern is evident of which the Masai block and the Dodoma block are representative. There is a lowland area around Tabora comparable to Lake Victoria, but it is not so precise in its boundaries.

It will be noted that the lineaments defined earlier are conspicuous in the boundaries of the subunits of the terrain. Indeed it is the lineaments that make the subdivision possible.

THE UNITY OF THE RIFT VALLEY TERRAIN

The unity of the rift valley terrain in East Africa can best be seen in the sudden changes in the type of geology, or in the juxtaposition of a comparable block. It is in fact a block surrounded by other rigid blocks or crustal fragments, namely (see Fig. 12):

1) to the west, the dropped floor of the Congo basin,
2) to the northwest the Kibali truncation,
3) to the north and northeast the Ghazal basin, the Abyssinian volcanics and the Somali block,
4) to the east the Juba trough and the lowland coastal area,
5) to the southeast, the Tunduru break and the Mocambique block, and
6) to the southwest the Bangweulu block.

The upland zone is arcuate like the rift valleys that roughly mark the centre line throughout much of the perimeter. The upland areas meet at their southern end, where the two arcuate features converge towards Mbeya Mountain. At the northern end, the upper Nile, while not visibly a rift, occupies a valley whose course relates itself to the rift pattern and not

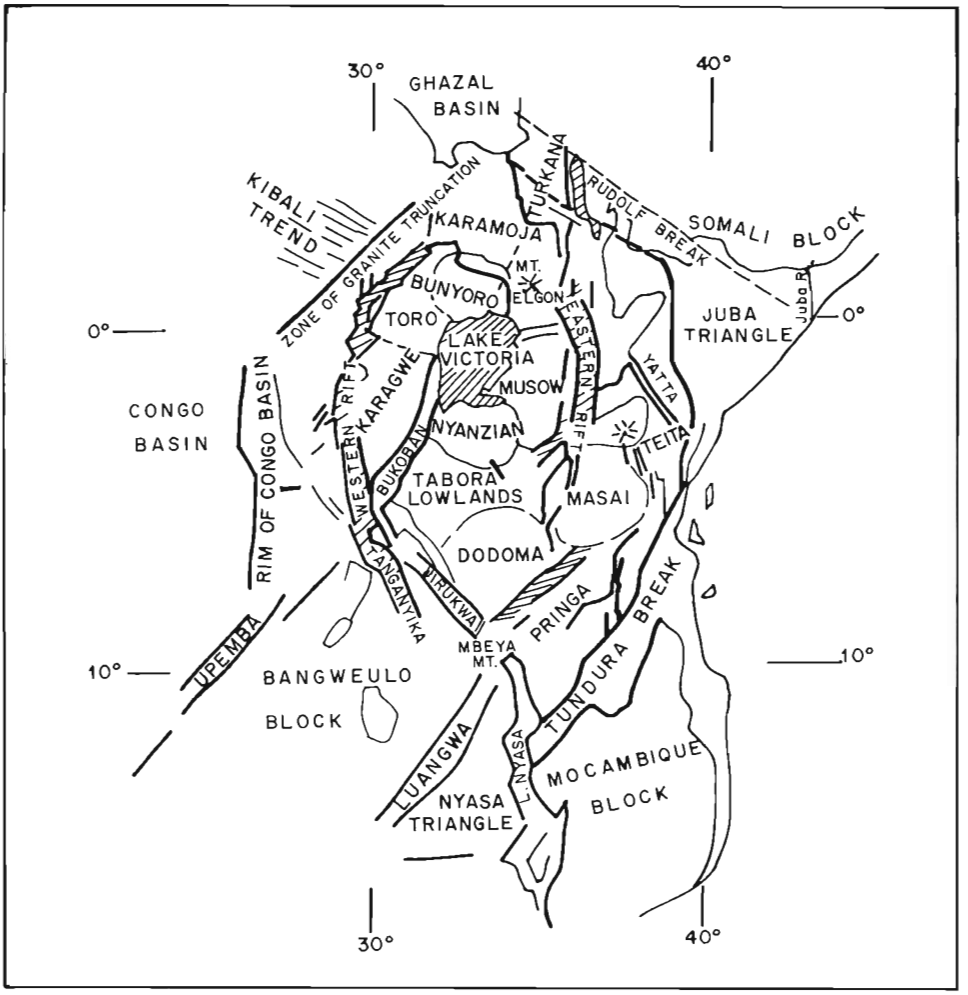


Figure 12. Mosaic analysis of East Africa.

to any normal drainage pattern. Its structural control is clearly evident; throughout most of its length it is heading for Mt. Elgon, which completes the closure.

The closure of the two major rift systems accentuates the unity of the terrain embraced by rift valley arcs, a unit of much the same size and shape as the Rhodesian craton.

It is necessary, however, to attempt to define the ultimate limits of the craton, which must include all the upland areas bisected by the two major rifts. For the greater part of its length, it is a topographical break which coincides to a large degree with the six master lineaments already described. To the block outlined almost entirely by the rift valleys themselves, we merely add a frame or outer rim which extends as far as the topographical declivity. The Bangweulu block adjoins the rift valley terrain without leaving room for a frame. Here, however, the rift zone is several times its normal width in the en echelon zone. The gaps in the closure, or irregularities in the frame, may be gaps in our geological knowledge.

Even though locally the boundaries are more vague and arbitrary than one would like, the topographical map alone pronounces this to be a structural unity, measuring 16 degrees in its long dimension and about 11 or 12 degrees in its short dimension.

THE RIFT VALLEY CRATON AS A MODEL

A demonstration that this is a common size and shape of a structural unit can be conducted quite simply with the help of a transparent dome on a geological globe. The size and shape can be matched quite accurately by the Guiana shield, the Gulf of Mexico basin, the West Australian shield, the Baltic shield — in fact on every continent, including other examples in Africa (notably the South African craton bounded by the Limpopo, Makarikari and Ghanzi).

Using the East African craton as a type unit, Africa may be subdivided into a mosaic of about 15 units that are fairly homogeneous as to size and shape (Fig. 13): three for the West African craton, four for Southern Africa, four for the Arabian-Edyptian block. The Congo basin proper is another such block but its Precambrian rim seems composed of longitudinally split units. Madagascar appears to be an elegant example of a split unit (Fig. 14), the straight, faulted east coast representing the centre line. It is important to note that the axial line is something more than a geometrical convention. Here, it is a geological reality.



Figure 13. Mosaic analysis of Africa. Rift Valley Craton as a model.

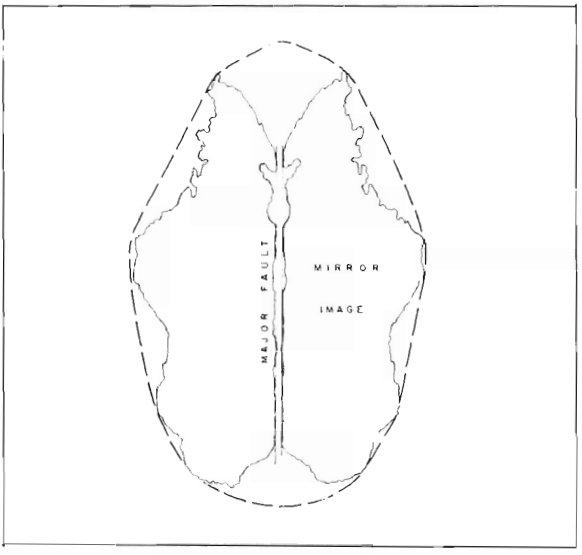


Figure 14. Madagascar, a unit split on its long axis.

Another test of the legitimacy or otherwise of the reality of the East African craton: a structural map of East Africa or South Africa on tracing paper is folded along the line which allows the South African block to be superimposed as a mirror image on top of the Rift Valley craton. The symmetry lies precisely midway between the Kasai lineament and a parallel lineament which transects Africa with a mopani belt. This line stands out plainly on a vegetation map (Fig. 15).

The Rift Valley craton, far from being unique in shape and size, is ubiquitous. It is however unique in the elegant exposure of its internal structure with concentric tendencies round a depressed or sunken heart. Subsided elements comparable in size to Lake Victoria are: the granitic heart of the Bushveld; the Rand basin; the Basutoland uplands; and the Damara basin.

We are entitled or almost impelled to look for a comparable frame to the South African unit. The Cape fold-mountains, the Lebombo, the Limpopo depression, the Ghanzi ridge, all seem appropriate boundaries for such a unit. Even though evidence of rifting is sparse, the structural style is comparable.

The Rift Valley craton, in terms of vertical tectonics, is a roughly oval-shaped terrain with a collapsed centrepiece and an uplifted rim bisected by a linear depression, the whole being bounded by a major break, commonly in the form of a declivity where it abuts a contiguous craton.

CONCLUSION

The Rift Valley terrain is a unique exposition of vertical tectonics, with the African 4,000 foot plateau as a datum level against which to measure the uplifts and the subsidences. These movements of blocks, absolute as well as relative movements, make an ordered pattern. An oval-shaped upland area is bisected concentrically by a sharp depression which constitutes the main rifts.

The pattern contains elements of a wide range scale in which the Archaean makes the finest pattern, and the youngest rocks the coarsest, but the imprint of the oldest pattern is commonly discernible in the younger rocks, and even in the shape of the rift valleys themselves, where the 30 mile width predominates.

The structural pattern is an ordered pattern, but of a complexity that is difficult to reconcile with convection currents. Still more difficult would be the reconciliation of an evolutionary tectonic pattern with

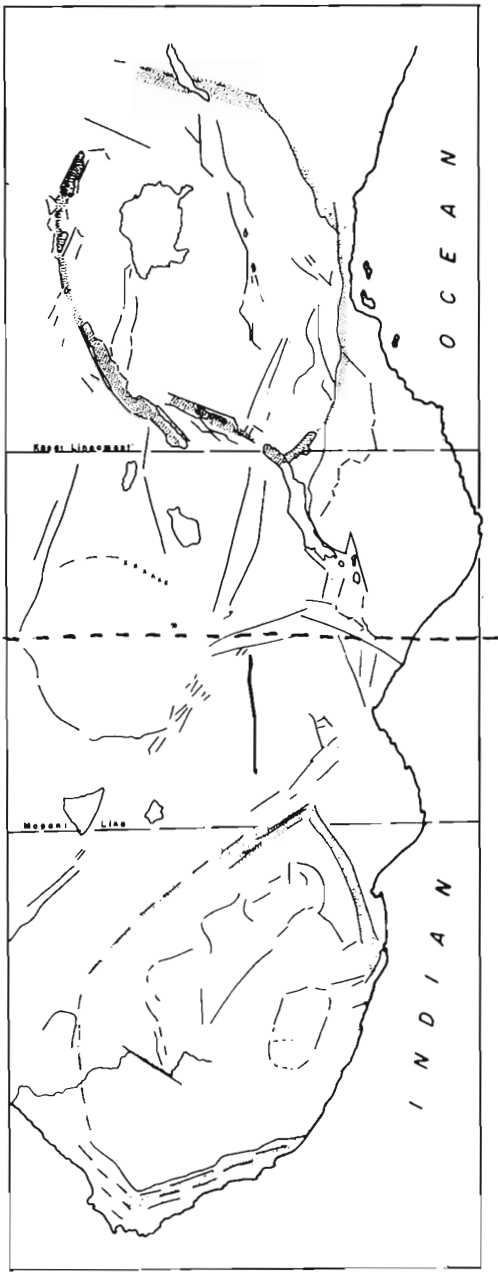


Figure 15. Symmetry around an axis of unknown significance midway between two continental lineaments. The mirror image of the rift valley block is reflected in the Transvaal-Eastern Cape block.

an evolutionary convection system. The earliest tectonic pattern, the Archaean, is a fine mosaic pattern entirely compatible with the concept of a thin crust. The imagination boggles at a correspondingly fine convection pattern.

The present approach fails to answer the vital question: what caused crusted blocks to drop? But, with the empirical knowledge that blocks did drop, a cause-and-effect relationship between subsidence and uplift seems logical.

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DISCUSSION

V.V. Beloussov

Some may think that such investigations are a little formal, but I think they represent a very important direction of thinking and study. At the Moscow University, one of my assistants undertook the same type of study. We tried to statistically compare the size and shapes of basins and platforms of different ages, and there appeared to be some preferred sizes although the relation of size to age is not simple. We do not know the mechanism which produced the basins — it may be some kind of convection current, but I personally do not believe it is simple convection. It seems to me more probable that there is some kind of differentiation of material at depth resulting in the uplift of light material and depression of heavier material. In principle, the mechanism is very near to that of convection currents. If this is so, the size of these basins may indicate the depth of origin of the controlling processes, because there is a correlation between the size of such basins and the depth of the process which may have caused their formation. But I would like to ask you about one difficulty which we met in our work. What size do you use when you measure eroded basins? If one takes the area presently covered by sedimentary rock, one could be wrong because the sedimentary rocks might have extended over a wider area. This is a major difficulty which may lead us to mistakes. Thus, we may obtain results which are interesting but not realistic.

B.B. Brock

Thank you Dr. Beloussov. You have raised a very large question which cannot be answered except in general terms. A structural mosaic whether coarse or fine is composed of an assemblage of cratons, of which the depressed ones constitute tectonic basins. One particular one in South Africa, the Rand Basin, is preserved virtually intact and, since the rim of the basin is exceptionally well exposed by drilling and by crosscuts, this allowed the development of a set of criteria for the recognition of the proximity of the edge of a tectonic basin. These criteria are widely applicable to tectonic basins generally, and have proved useful in mosaic analyses. This seems hardly the place to enlarge on the subject.

V.A. Magnitsky

What are the average dimensions of these blocks?

B.B. Brock

The East African block, comprising the Rift Valley block plus its rim, is 16 by 12 degrees. The Rift Valley block, that is the cratonic element bounded by the two arcuate rift systems, has a counterpart in the Southern Rhodesian craton bounded by the Zambezi and Limpopo depressions. It measures roughly 7 degrees by 5, which is a widespread cratonic size.

THE NORTHERN END OF THE CARLSBERG RIDGE

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Abstract

This paper briefly reviews present information of the Carlsberg Ridge between the Owen Fracture Zone and the Gulf of Aden. In this region, the ridge closely resembles the Mid-Atlantic Ridge at the mid-latitudes of the North Atlantic. A median valley is generally clearly developed, and magnetic profiles across the ridge typically show a large negative anomaly at its crest, small irregular anomalies over its flanks, and large broad anomalies over the adjacent foothills and abyssal plains. There does not appear to be a consistent pattern of free-air gravity anomalies associated with the ridge; a simple two-dimensional Bouguer correction removes local anomalies, leaving a smooth decrease of positive Bouguer values over the swell, and it thus appears that the broad features of the ridge are isostatically compensated.

The median line of the Carlsberg ridge, as based on magnetic anomalies and bathymetry, follows the belt of earthquake epicentres, and between the equator and the Owen Fracture Zone there is a relatively close association of high heat flow values with the median line. High heat flow values are ubiquitous in the Gulf of Aden, where they probably indicate more active volcanism in the gulf as compared to the rest of the ridge system.

A detailed survey of an area at the crest of the ridge near 5°N showed that two seamounts flanking the median valley are reversely magnetized, and this led to the suggestion that the gross features of the magnetic anomaly pattern can be simulated by a model in which strips of the upper part of the oceanic crust have alternately normal and reversed bulk magnetization. If the earth's magnetic field has recently been subject to alternations of polarity, such strips could be formed by the injection of swarms of basaltic dykes parallel to the median line, provided that the probability of dyke injection decreased normally (and steeply) with increasing distance from the axis. It is important to test this hypothesis by seeking for magnetic lineations over the flanks of ridges and such a test is being attempted along part of the Mid-Atlantic Ridge.

INTRODUCTION

The material summarized here is not new, much of it having been presented at discussions of the International Indian Ocean Expedition in London and New Delhi during the autumn of 1964, and most of it having been published in the Philosophical Transactions of the Royal Society of London. It represents the work of several English submarine geologists, most of whom were members of the late Dr. Maurice Hill's group in Cambridge; I would mention in particular Dr. A.S. Laughton, and Dr. and Mrs. F.J. Vine.

Earthquake epicentres in the northwestern Indian Ocean are plotted in Figure 1. The present paper is concerned with the Carlsberg Ridge, which is the part of the mid-ocean ridge situated north of the equator. Along the Carlsberg Ridge, as elsewhere, the trend of the crest of the ridge proves to be adequately represented by the epicentre belt. As shown in Figure 1, it extends from a kink just southeast of Socotra into the Gulf of Aden where it merges with a diffuse group of epicentres at the northern end of the Ethiopian rift valley. Figure 1 also shows tracks along which profiles of bathymetry, gravity and magnetics are available (Anonymous 1963, 1964, and in press).

CHARACTERISTICS OF THE CARLSBERG RIDGE

Bathymetric profiles across the Carlsberg Ridge all show that it has its greatest relief near its crest, and in this respect, it is more like the Mid-Atlantic Ridge than the East Pacific Rise (c.f. Menard 1964, Figs. 6,7). The Carlsberg Ridge is a broad swell, some 2 km high and 1,000 km wide, surmounted by elongated seamounts. It does not become significantly narrower toward its northern end where it approaches the Afro-Asian continental block. Seven profiles out of nine show a prominent median valley, and bathymetric charts compiled on a scale of 1:1,000,000 by Dr. A.S. Laughton from soundings collected by the British Admiralty provide good evidence (at least at the northern end of the ridge where the track density is greatest) that the median valley is a continuous, if frequently disrupted, feature. Dr. B.C. Heezen has drawn attention to the similarity between profiles across the median valley and across the East African Rift. There is also a similarity in scale between the profiles of the Carlsberg Ridge swell and those across the post-Miocene "rise-to-the-rift" evident in Kenya (Saggerson and Baker, 1965).

Magnetic anomaly profiles across the Carlsberg Ridge all show a similar pattern (Matthews, Vine and Cann, 1965; Matthews, 1966). At the crest of the ridge directly above the median valley, wherever the valley can be recognized, there is a prominent negative median anomaly which commonly is flanked by a few other large anomalies. The anomalies over the flanks of the ridge are relatively small and narrow, but those over the lowest foothills and the adjacent abyssal plains are large and broad. This

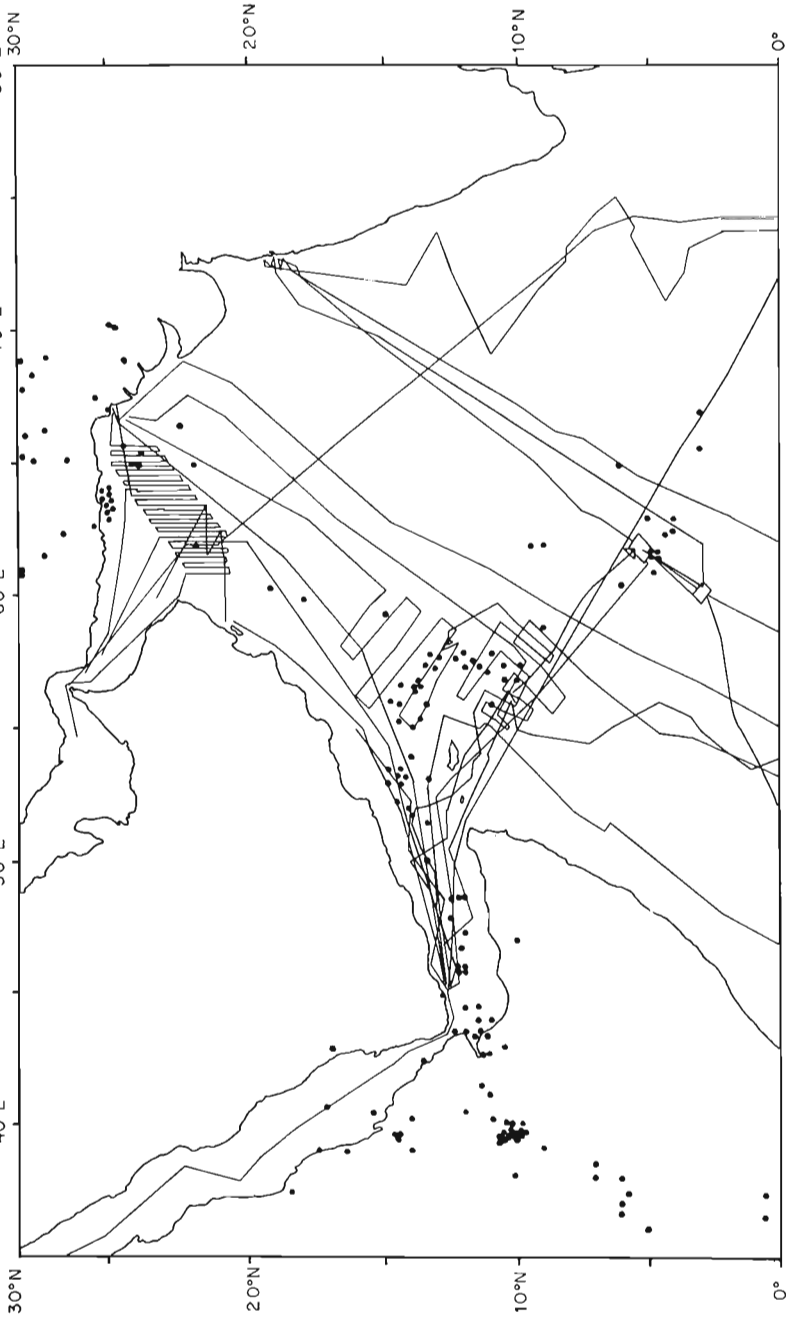


Figure 1. Tracks of British ships in the northwest Indian Ocean during the International Indian Ocean Expedition. The dots are earthquake epicentres recorded up to 1965.

pattern is closely similar to that described recently by Heirtzler and Le Pichon (1965) for the Mid-Atlantic Ridge.

Gravity profiles show no significant regional change in free-air anomaly between the flanks and the crest of the ridge. Even a simple two-dimensional Bouguer correction does much to smooth out the local free-air anomalies associated with individual topographic features, leaving a smooth decrease of positive Bouguer values over the swell. Thus it appears that the broad feature of the ridge is compensated, although individual seamounts (and the median valley) are not.

A combination of bathymetric and magnetic profiles has permitted the identification and plotting of the line of the median structure of the ridge and the recognition of four displacements along minor fracture zones north of the equator (Fig. 2). Three of the displacements, which are 30 miles or less in magnitude, occur in areas where the density of soundings is sufficient to allow the production of fairly detailed bathymetric contour charts (Matthews, 1966, Fig. 3; and Matthews, Vine and Cann, 1965), and in these places it is clear that even such small displacements are associated with substantial valleys cutting across the crest of the ridge.

At a point about 200 miles southwest from Socotra, the Carlsberg Ridge is truncated by a major fracture zone, the Owen Fracture Zone (Matthews, 1963, 1966), and between the truncated end of the ridge and Socotra are several very large non-magnetic seamounts that are clearly different in character from the strongly magnetized volcanic seamounts along the ridge. It is interesting to speculate that the non-magnetic seamounts are fragments of a disrupted Oman-Baluchistan fold range. The apparent displacement on the Owen Fracture Zone is 170 miles right lateral. The pattern of epicentres (Fig. 1) and the available magnetic anomaly profiles strongly suggest that the mid-ocean ridge continues northward from the Fracture Zone in the way indicated in Figure 2, but additional surveys are needed in this area.

Sclater (1965, 1966) has reviewed the observations of heat flow along the northern part of the Carlsberg Ridge and has demonstrated that there is a relatively strong association of high heat flow values with the axis of the ridge.[1] Measurements in the Gulf of Aden are all high; this indicates that at the present time there is more volcanic activity in the Gulf of Aden than on the Carlsberg Ridge.

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[1] Von Herzen and Vacquier (1966) have shown that the correlation is less strong south of the equator.

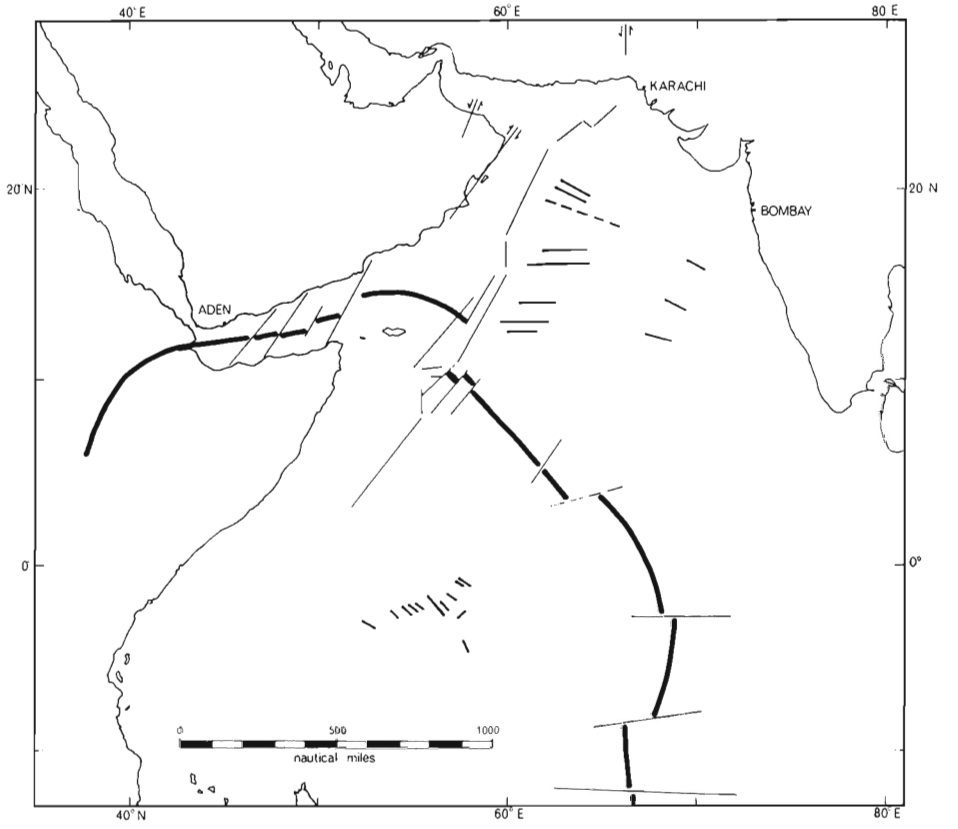


Figure 2. Linear features in the northwest Indian Ocean. The heavy line is the axis of the mid-ocean ridge; the short bold lines are magnetic lineations (see text); the thin lines are faults.

In November, 1962 a detailed survey of a one degree square astride the crest of the Carlsberg Ridge was made near 5°N by H.M.S. OWEN, and in September, 1963 station work was carried out in the same area by R.R.S. DISCOVERY. The survey (Anonymous, in press) shows an unmistakable lineation of topography and magnetic anomalies parallel to the axis of the ridge (Matthews, Cann and Vine, 1965). From the results of the magnetic survey, Vine was able to demonstrate that the median valley must be underlain by a normally magnetized block with steep sides and that at least one seamount adjacent to the median valley is reversely magnetized (Cann and Vine, 1966). The magnetic anomalies within the surveyed area can best be simulated by alternately normal and reversely magnetized blocks (or, of course, by more and less strongly magnetized blocks) within the crust. Recognition of this fact led to the speculation that the oceanic crust might be expanding away from the crest of the ridge as a result of the injection of dyke swarms at the crest of the ridge, and that these dyke swarms would have alternately normal and reverse thermo-remanent magnetization if the earth's field is subject to periodic reversals (Vine and Matthews, 1963). To check this hypothesis we must determine the net direction of magnetization of as many seamounts as possible and search for magnetic lineations. Whatever may be the truth of the hypothesis, there can be no doubt that the search for linear magnetic trends in the oceans (like those superbly demonstrated off the west coast of North America) is important.

The existence of lineations along the mid-ocean ridge parallel to its crest is beginning to be established. Detailed magnetic surveys of the crest of the Mid-Atlantic Ridge near Iceland and near 45°N are reported elsewhere in this volume by Talwani, Le Pichon and Heirtzler, and by Loncarevic, Mason and Matthews. Detailed surveys made on the flanks of the Mid-Atlantic type ridges are still regrettably rare. A detailed survey of an area about ten miles square on the eastern flank of the Mid-Atlantic Ridge at 45°N, 25°W shows a striking elongation of topography parallel to the trend of the ridge, but the evidence of magnetic lineation in this direction is less good (Matthews, in press). The same conclusion might be drawn about an area about 35 miles square on the lower southwest foothills of the Carlsberg Ridge shown in Figure 3, a and b. This area was surveyed by H.M.S. Owen along lines spaced one mile apart in November 1962 (Anonymous, in press).

Since detailed surveys are so rare, we are forced to seek for correlations between more widely spaced profiles. One rather simple way of doing this is to make cut-out models of magnetic anomaly profiles, after removal of a regional trend, and to erect the models above a suitable bathymetric contour chart. Correlations between adjacent tracks in the northwest Indian Ocean are shown in Figure 2. The group southwest of Karachi are well established, but they are not parallel to the closest part of the Carlsberg Ridge. The group northeast from the Seychelles are also well established, and they do run parallel to the Carlsberg Ridge.

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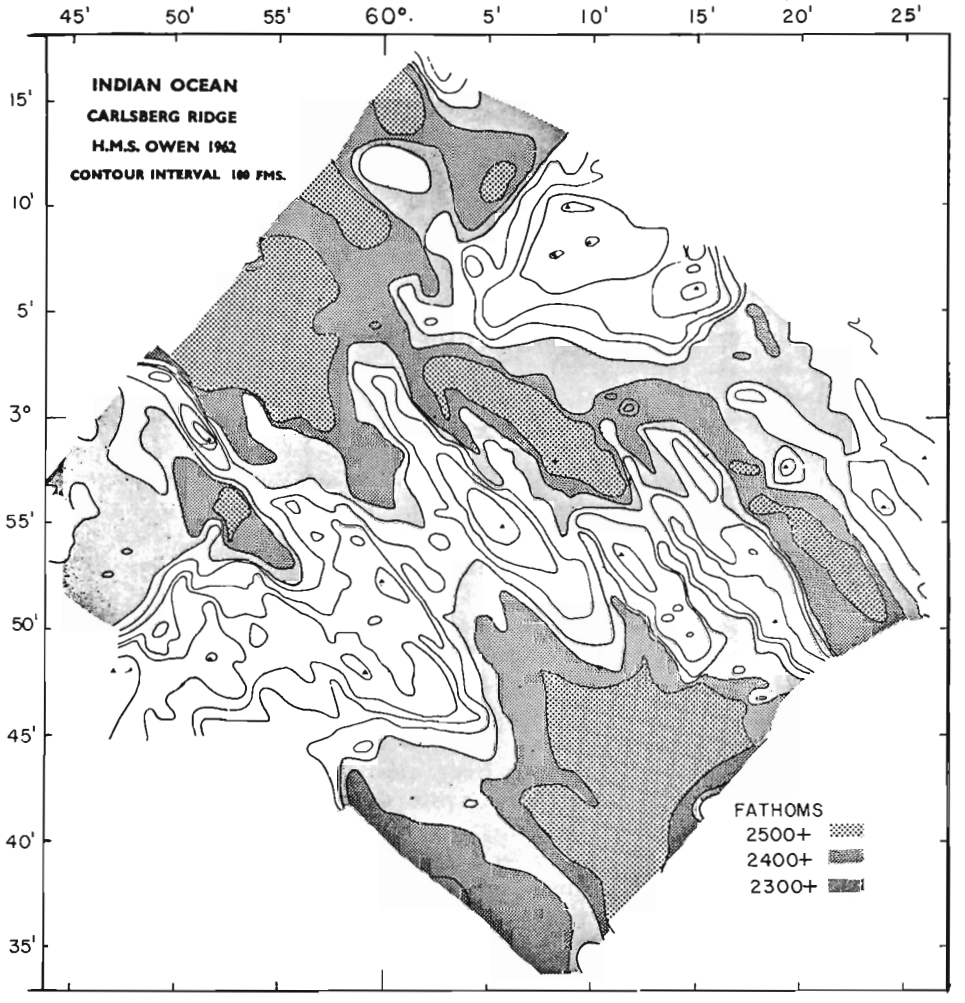


Figure 3a. Bathymetric contours of an area on the foothills of the Carlsberg Ridge. Contour interval 100 fathoms.

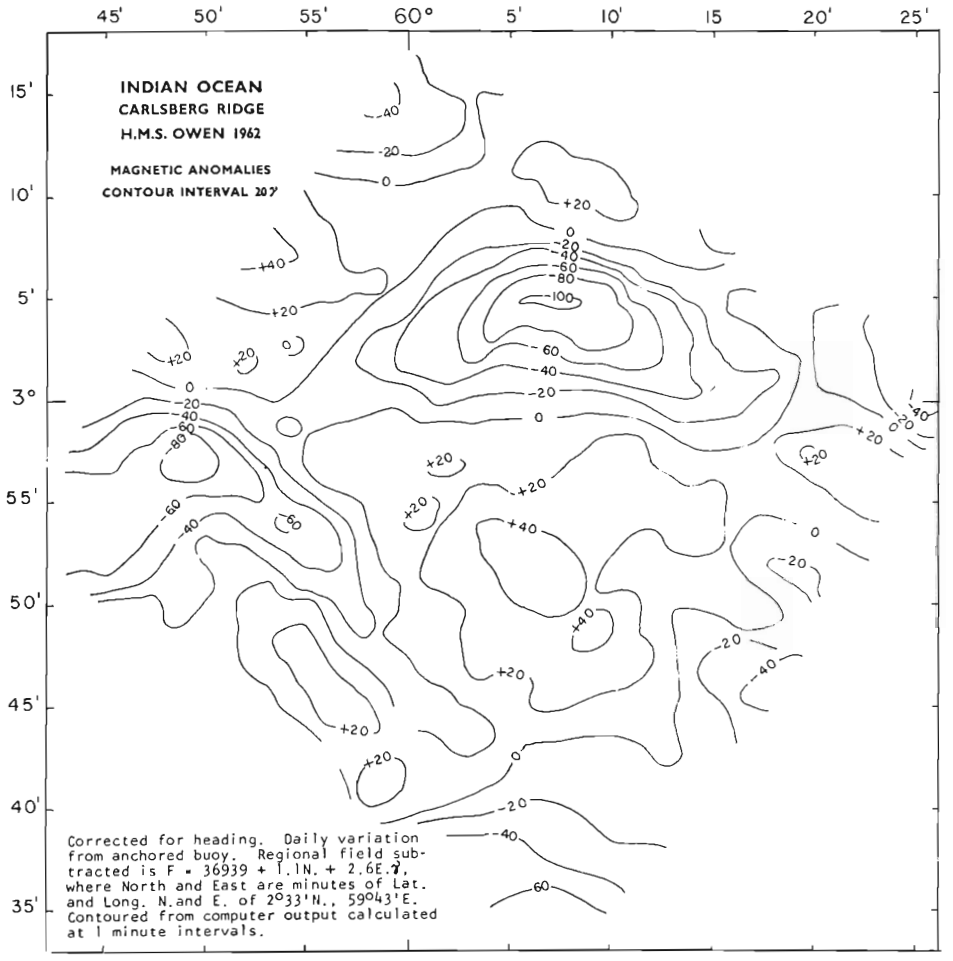


Figure 3b. Magnetic anomaly contours (total field) of the same area as Figure 3a. Contour interval 20 γ.

COMPARABLE LINEATIONS IN THE ATLANTIC

Preliminary results of a study of the kind mentioned above are shown in Figure 4 for part of the eastern North Atlantic. The figure shows the coastline of western Europe and the 100 fathom line. The heavy dots are earthquake epicentres recorded by the International Seismological Summary and the United States Coast and Geodetic Survey for the period 1950-1964. Topographic lineations (major scarps, ridges and troughs) are taken from unpublished 1:1,000,000 contour sheets prepared by Dr. A.S. Laughton; the heaviest continuous line is the median valley of the Mid-Atlantic Ridge, and the shorter heavy continuous lines represent other major topographic lineaments. The thin lines show tracks along which magnetic profiles have been taken by Cambridge groups during the period 1956-1965, some tracks having been omitted in the interest of clarity. The dotted lines show magnetic lineations tentatively identified by correlations between adjacent tracks. Only the lineations in the Bay of Biscay and in the area of a comparatively detailed survey near 43°N, 20°W are well established. The magnetic lineations on the continental shelf west of Brittany were reported by Hill and Vine (1965).

COMMENT

The compilation of maps of this kind is a proper objective for the Upper Mantle Project. Since the major topographic features of the deep ocean seem to be in isostatic equilibrium, maps of major lineaments should be related to the present distribution of density in the upper mantle, or to the depth of the base of the oceanic crust. If the linear magnetic anomalies are really due to the magnetization of dyke swarms and fissure eruptions within the oceanic crust, a map of magnetic lineations may contain information about ancient directions of tension in the oceanic crust. Thus we have the possibility of mapping ancient stress fields. This duality of age may be the reason for the apparent crossing of magnetic and topographic lineations in some areas of the North Atlantic.

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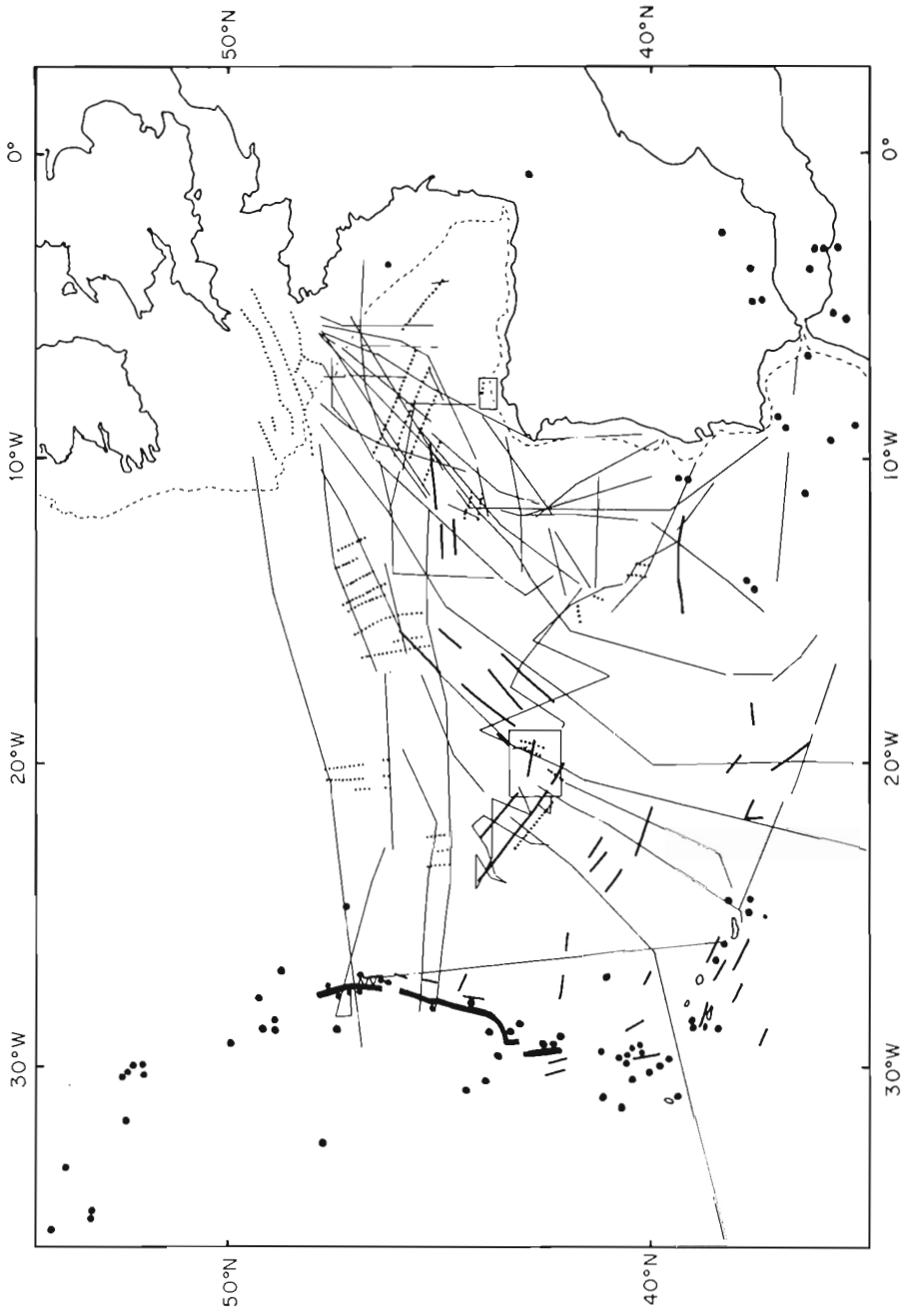


Figure 4. Crossed lineations in the North Atlantic (see text).

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THE MEDIAN RIDGE IN THE SOUTH CENTRAL INDIAN OCEAN

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Abstract

Ships participating in the International Indian Ocean Expedition 1960-65 have provided well-controlled and precise bathymetric data on the median ridge in the central and southern Indian Ocean. Three areas of the Mid-Indian Ocean Ridge are discussed: 1) the generally-north-trending segment east of the Mascarene Plateau, between the Equator and the latitude of Rodriguez; 2) the southeast-trending ridge just southeast of its intersection with the branch passing south of Africa; and 3) in some detail, the vicinity of St. Paul-Amsterdam. In all three areas, a ridge frequently displaying a rift valley has been subjected to cross-fracturing and offsets of tens to hundreds of miles. These data suggest (1) that a topographically-expressed rift valley is locally but not universally developed, and (2) that large east-northeast-trending fractures, and minor north-northwest-trending faulting, have disrupted, expanded, and complexly offset the simpler structure.

INTRODUCTION

My presentation will extend the discussion of the nature of the Mid-Indian Ocean Ridge to the region well southeast of the Carlsberg Ridge just described by Drummond Matthews. Intensive exploration has been carried out recently by ships participating in the International Indian Ocean Expedition 1960-65. Nearly all IIOE ships were equipped with precision echo-sounders; many also towed magnetometers, and some were equipped with continuously-recording gravimeters. Within the IIOE, Scripps Institution sent three major expeditions to the Indian Ocean; the discussion below will draw most heavily on SIO data.[1] Most of the conclusions will be based on topographic evidence from three areas (in ascending order of detail):

1) east of the Mascarene Plateau, the median ridge between the Equator and the latitude of Rodriguez;

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[1]Field work was supported by Grant G-22255 of the National Science Foundation and by contracts with the Office of Naval Research.

2) southeast of Rodriguez, the southeast branch of the inverted "Y" of the median ridge system;
3) the narrow discrete ridge in the vicinity of St. Paul and Amsterdam Islands.

TOPOGRAPHY OF THE MEDIAN RIDGE BETWEEN THE EQUATOR AND 21°S

South of its complex juncture with the northwest-trending Carlsberg Ridge near the Equator, the Mid-Indian Ocean Ridge has an overall N-S trend that is closely reflected in earthquake epicentre plots. Here the next major feature to the east is the Chagos-Laccadive Plateau; between the rises, the seafloor is more than 4,000 metres deep. South of 10°S, the seafloor deepens eastward into one of the Indian Ocean basins.

A striking feature of this portion of the median ridge is the absence of a through-going central rift valley or cleft. Depths locally shoal to 3,000 or rarely to 2,000 metres, the latter as pinnacles in the central portion of the ridge. Such peaks sometimes are bordered or separated by local deeps of more than 4,000 metres. A NNE-trending median deep does seem to be developed a few hundred miles northeast of Rodriguez, and another trends NNW to the east-southeast of Saya de Malha.

The dominant topographic trend modifying the generally-north-trending ridge is expressed in a series of east-northeast linear deeps. Some traverse the ridge completely and extend well westward, perhaps to modify the shape of the Mascarene Plateau. More frequently, they are 75-300 kilometres in length. The most spectacular, deepest and best studied of these features is Vema Trench near 9°S (Heezen and Nafe, 1964) which, in common with several other cross-fractures, is bordered by parallel ridges.

Based on these data, the north-trending ridge, at depths of 2,500-4,000 metres, locally displays a rift valley; more often the ridge seems cut and quite obviously offset or canted along the east-northeast fractures. Earthquake epicentre plots show clusters of activity near some of the apparent offsets, but the correlation is not definite. A major east-west-trending fracture zone and left-lateral offset of the median ridge in the vicinity of Rodriguez Island and the Rodriguez Ridge has been postulated (Heezen and Tharp, 1965). Certainly, the ridge is generally shoaler north of 20°S than to the south, and a large left-lateral offset here may be compensated by several right-lateral offsets along the deeps to the north.

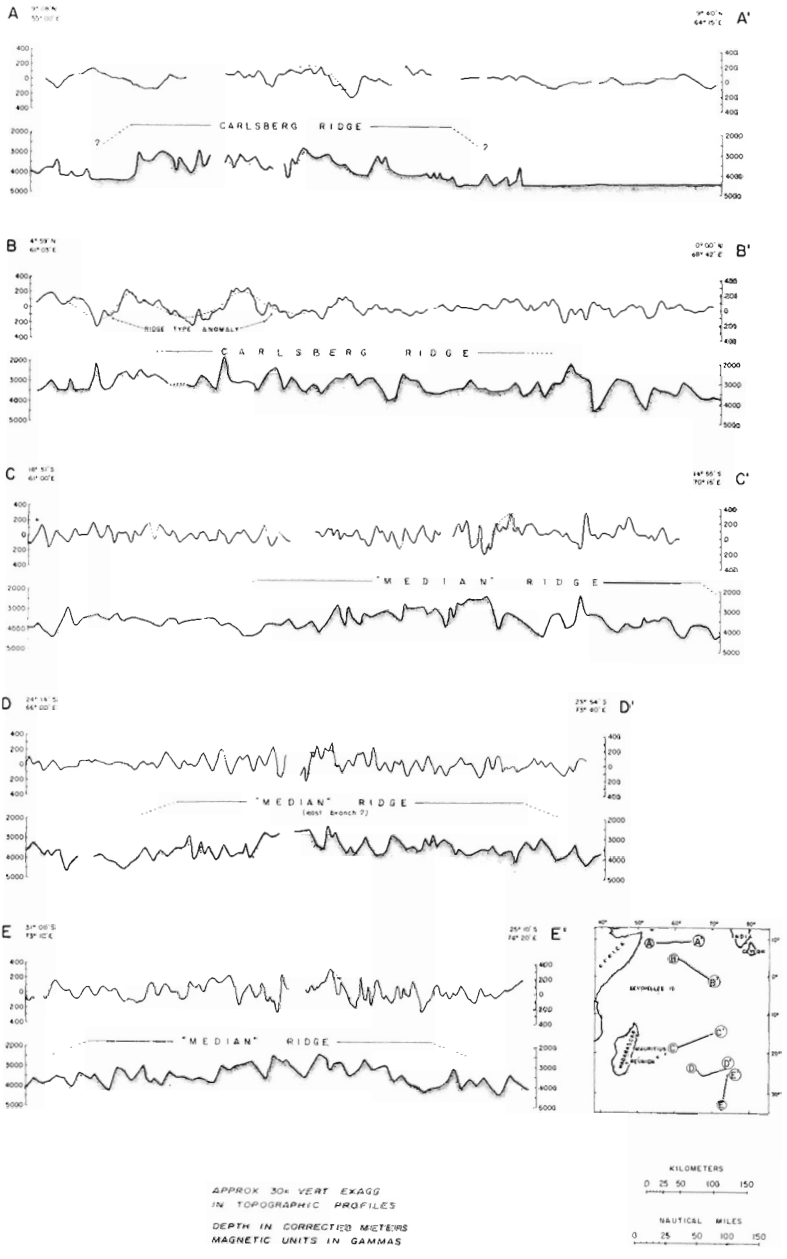


Figure 1. Magnetic (upper) and generalized topographic (lower) profiles on the northwestern and central portions of the Mid-Indian Ocean Ridge, after Raff (1964, unpublished).

Topographic data are not conclusive as to the presence of this fracture zone either just north or just south of Rodriguez Ridge. [1]

Figure 1, after Raff (1964, unpublished), shows that even where an obvious rift is not expressed topographically, a "ridge anomaly" commonly is present in the magnetic intensity profile. Such a magnetic axis was used by Von Herzen and Vacquier (1966) to help determine the ridge "crest" in interpreting heat flow variations in these latitudes. These authors suggest that, where the ridge magnetic anomaly is lacking, the ship's track probably passed near a displacement of the ridge axis. Figure 2, of more detailed topography, suggests that within the central 125-250 kilometres of the ridge irregularities are longer in period and tend to be rather larger than on the flanks. This central band might be termed a "rifted zone". The second profile crosses the system near the junction of the so-called "Y". One perhaps may distinguish both the southwest and southeast branches here; two groups of epicentres can be recognized. The lowermost profile will be discussed below but here serves to show how the narrow steep-sided ridge at St. Paul-Amsterdam compares in scale and definition with the more usual Indian Ocean ridge crossings.

THE SOUTHEAST BRANCH OF THE MEDIAN RIDGE, AT 22°-25°S

Petrologic and topographic data from a 350,000 km^2 area on the southeast branch of the ridge system has been reported by Engel, Fisher and Engel (1965). Several SIO tracks and one LGO line cross this part of the ridge system. The region is not markedly seismic at present. It does show heat flow rather higher than the average oceanic value, and a "ridge magnetic anomaly" is present. Topographically, it is extremely irregular in an east-west and, apparently, in a north-south direction; again there are larger peaks and troughs near the central portion of the ridge. There are almost no sedimented depressions; physiographically, the region appears very young. No simple "rift valley" has been correlated through the area. As in the region discussed above, there are linear deeps trending in an easterly direction, at least in the eastern part of the area.

Three dredge hauls on the eastern flank and one near the middle of the ridge complex produced rather uniform low-potassium tholeiitic

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[1] The discussion above is based on impressions from work in preparation with Bruce Heezen and Leonard Johnson of Lamont Geological Observatory. Final interpretation of newly-acquired bathymetric data is still under negotiation.

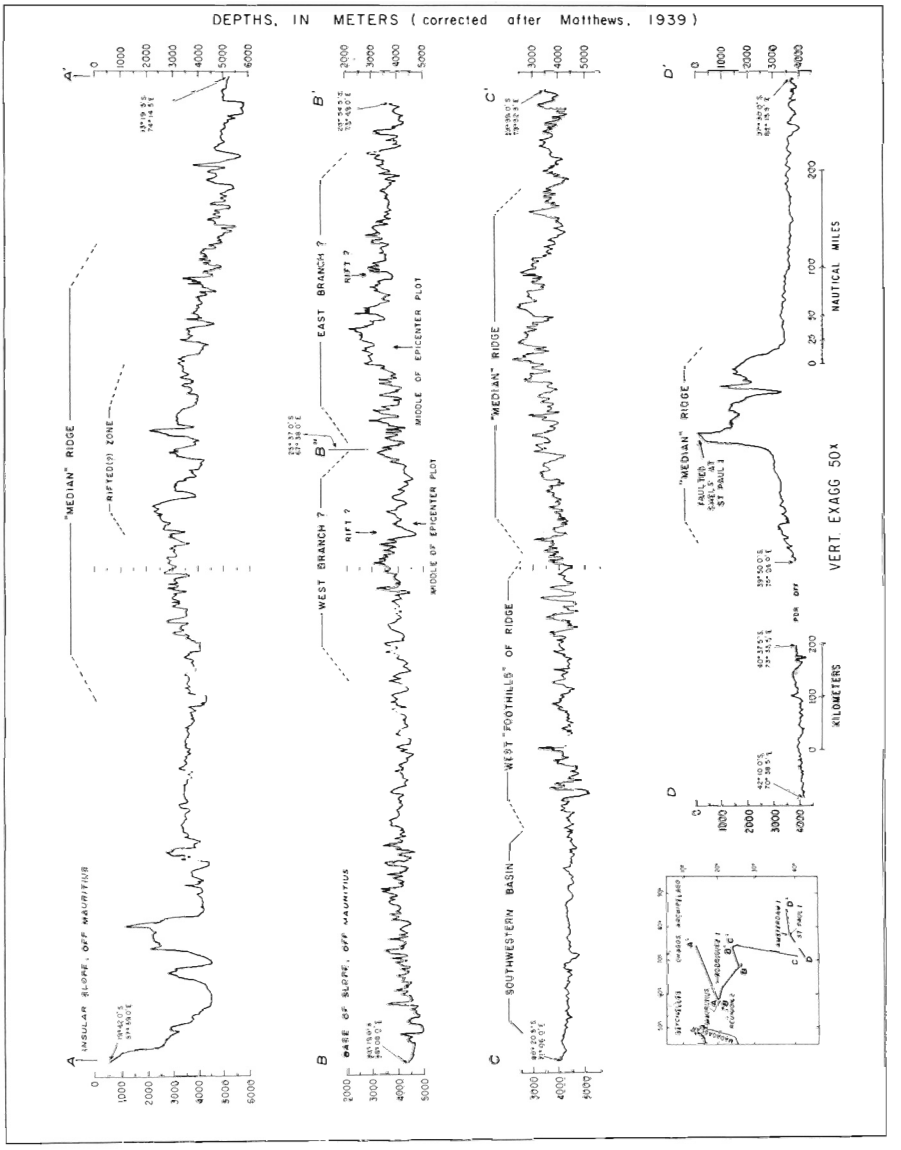


Figure 2. Topographic profiles on the median ridge, central Indian Ocean.

basalts. No ultrabasic or metamorphic rocks were found even in the haul closest to the "crest" or "rifted area" as selected on magnetic grounds.

THE MEDIAN RIDGE IN THE VICINITY OF ST. PAUL-AMSTERDAM

On Expeditions MONSOON (1960-61) and LUSIAD (1962-63) SIO research vessels made fairly detailed investigations of the median ridge at 35°-40°S (Fig. 3). The ships carried out topographic, gravity, magnetic and, to a limited extent, seismic refraction studies near the basic volcanic islands of St. Paul and Amsterdam (Fig. 4).

Nearly all that we know about these islands in a geological sense stems from work by Ferdinand von Hochstetter who was the geologist on the Austrian NOVARA Expedition of the late eighteen-fifties. Von Hochstetter spent 18 days on St. Paul and one on Amsterdam in 1858. He reported (1866) that the bulk of the rock on St. Paul (as on Amsterdam) is a vesicular, medium-to-fine-grained labradorite basalt, although on St. Paul a local occurrence of rhyolite is the oldest exposure. The present cratered landscape attests the recency of volcanism; hot springs, fumaroles and warm ground exist on the northern part of the island. Von Hochstetter noted that a landslide or displacement along a northwest-southeast fault had removed the eastern fourth of the island and allowed the sea to enter the principal crater. Basing his conclusions on soundings close inshore, he opined that the now-absent portion had merely slumped. One aim of the 1960 and 1962 exploration was to locate the missing fragment to determine the direction and magnitude of motion along the possible rift.

Detailed, closely-controlled runs radially and spirally about St. Paul permitted the construction of a topographic chart (Fig. 5). It reveals very obvious flow lobes at depths of 250-350 metres west and south-southeast of the island and that the present, fresh-appearing principal crater caps an almost equilateral (except on the northeast) submarine pile. There are narrow shelves cut around St. Paul.[1] The northwest-trending, post-volcanism fault scarp postulated by von Hochstetter is recognizable to a depth of nearly 1,000 metres. It is here suggested that the flattish submarine rise 15-16 km northeast of St. Paul is the portion now missing from the present island base, perhaps an eastern lobe analogous to those intact west and south of St. Paul. If so, there has been about 12 km of separation or possibly 18-20 km of lateral offset on the fracture in geologically-recent time.

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[1] SIO exploration around Amsterdam (Fig. 4) was not sufficiently inshore to detect such shelves. Amsterdam seems to be a much steeper cone with a proportionately greater subaerial development.

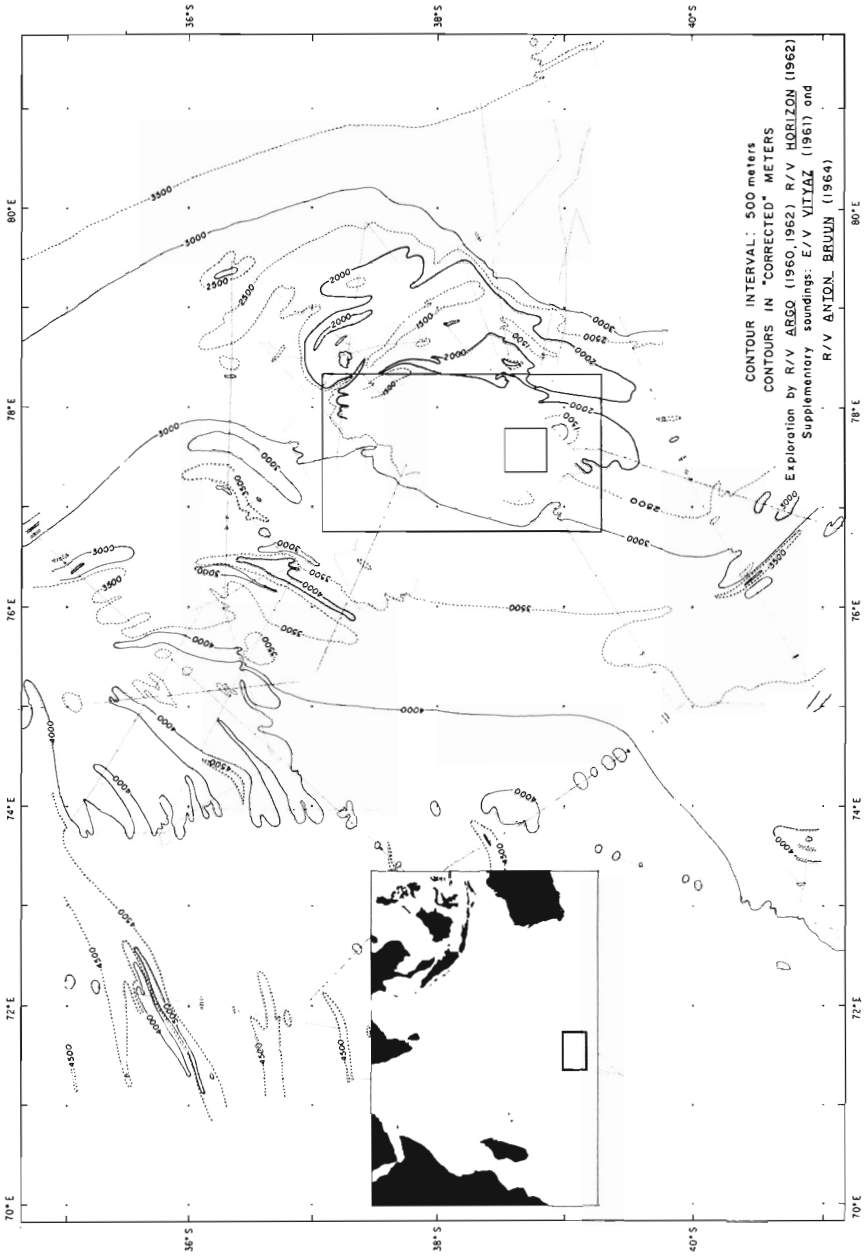


Figure 3. Topography of the median ridge near Amsterdam-St. Paul. The large vertical rectangle is shown in detail in Figure 4, the inner square in Figure 5.

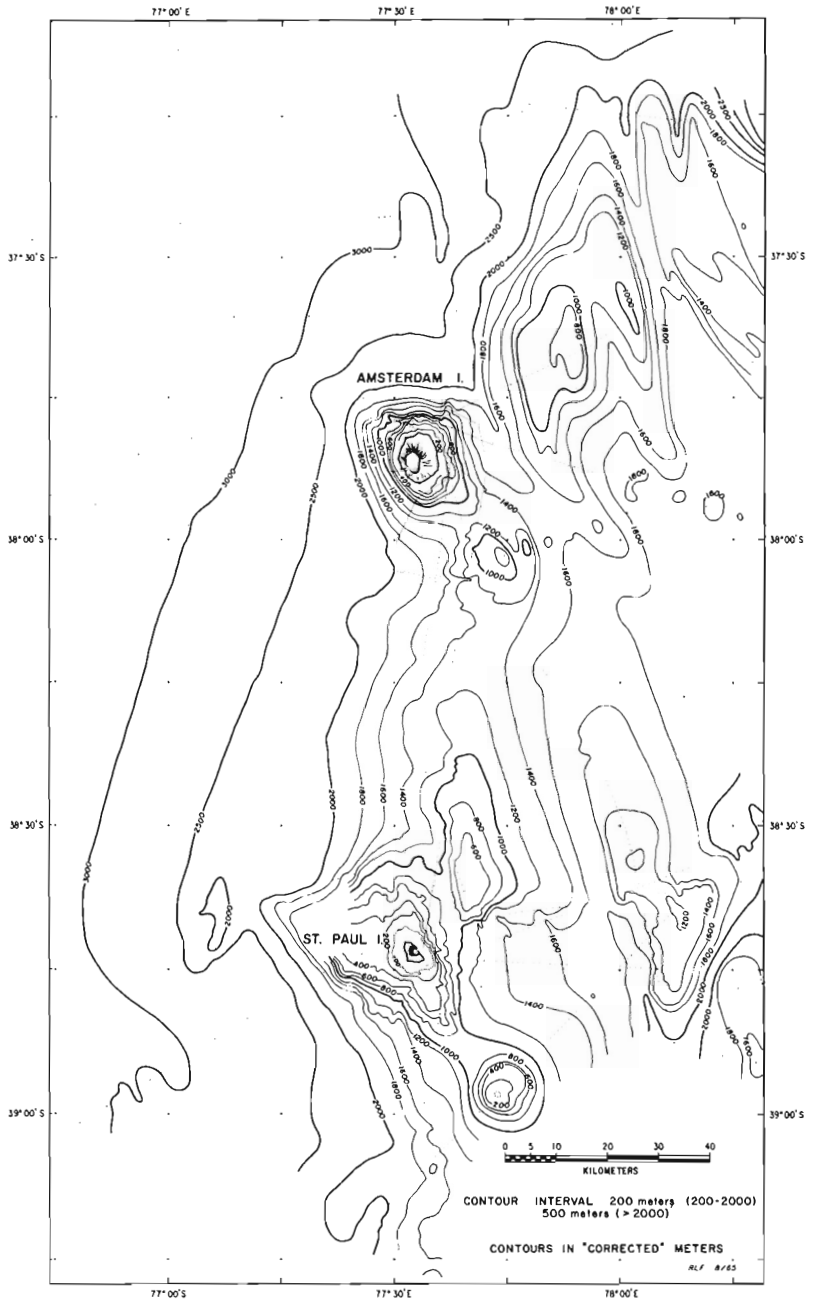


Figure 4. Submarine topography, Amsterdam-St. Paul.

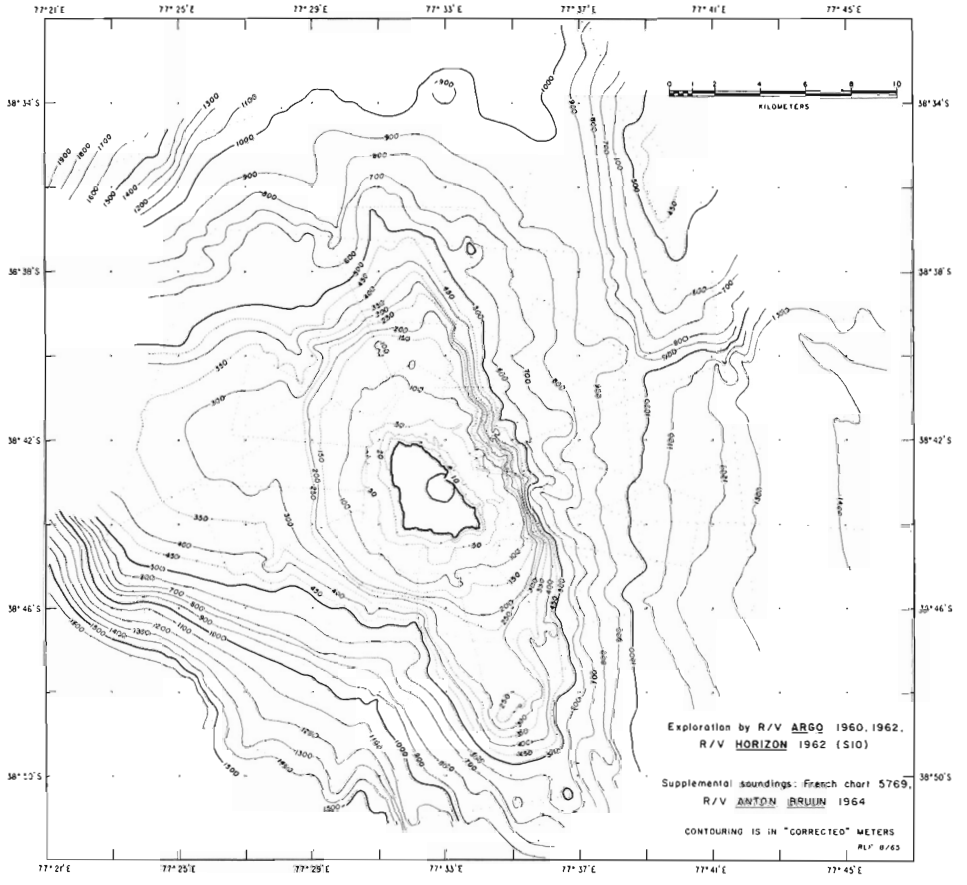


Figure 5. Submarine topography, St. Paul Island.

Returning to the St. Paul-Amsterdam chart (Fig. 4), one sees that exploration has established neither the shape nor the eastern extent of the shoal area. Southeast of St. Paul, there is a very shallow (70 metre) pinnacle that appears terraced (see Fig. 6, E-E') and probably was a third volcanic islet not long ago. North and to the east of St. Paul-Amsterdam, there are north-northwest-trending deeps and ridges that may represent en echelon faulting. Three or perhaps four slivers or blocks appear within the figure; cumulatively, there may have been several tens of kilometres of recent offset near St. Paul-Amsterdam.[1] Earthquake plots show clusters of shallow-focus activity in this region.

From very sketchy exploration to date and from earthquake epicentre plots, south of 42°S, the Mid-Indian Ocean Ridge trends west-northwest; north of 35°S, it trends north-northwest. The intervening area is seismically rather active. Although the northeast sector has not been well-explored, one may speculate that, from 36°-40°S (Fig. 3, Fig. 6), a generally north-trending and scarp-bounded simple ridge has been complexly faulted. Movement along the fractures resulted in some expansion of the ridge and in the development of sinuosity. In view of the obvious cleft shown east of St. Paul on Figure 2, one may expect a central rift valley. The 3,350-metre deep pictured in Figure 2 (and in Fig. 6, D-D') lies within a narrow north-northeast-trending furrow between the 2,000-metre contours (Fig. 3). One crossing of the ridge (Fig. 6, G-G') shows a narrow 2,600+ metre deep about 100 km south of St. Paul that may be correlated with the furrow, suggesting a line of separation or activity. On this southern profile, both the magnetic and topographic relief are considerably subdued east of the deep.

Two profiles on the upper right portion of Figure 6 lie almost parallel to the overall trend of the median ridge. They were shooting runs for seismic refraction studies by Russell Raitt of SIO. On H-H', on the western flank of the ridge, the steep slopes and wide flat basin appear due to step-faulting on border fractures. The seismic receiving position for the profile lay within this deep; there was marked crustal asymmetry on the two sections of the run, but the travel-time plots appear consistent. Preliminary interpretations of this work (Raitt and Shor, 1963, abstract; 1964, unpublished) furnish additional evidence of major faulting through the crust at the median ridge. Very thin crust and normal mantle velocity were observed on the western flank of H-H'. At I-I', near the crest of the ridge, a crustal thickness of 7-9 km, a rather low mantle velocity and an abrupt thickening

[1] More careful examination of magnetic records obtained by Argo and Horizon may reveal patterns of "subdued" magnetic topography similar to that reported by Matthews et al. (1965) and used by those authors to trace a fault zone crossing the Carlsberg Ridge. The interpretation above is based on topography alone.

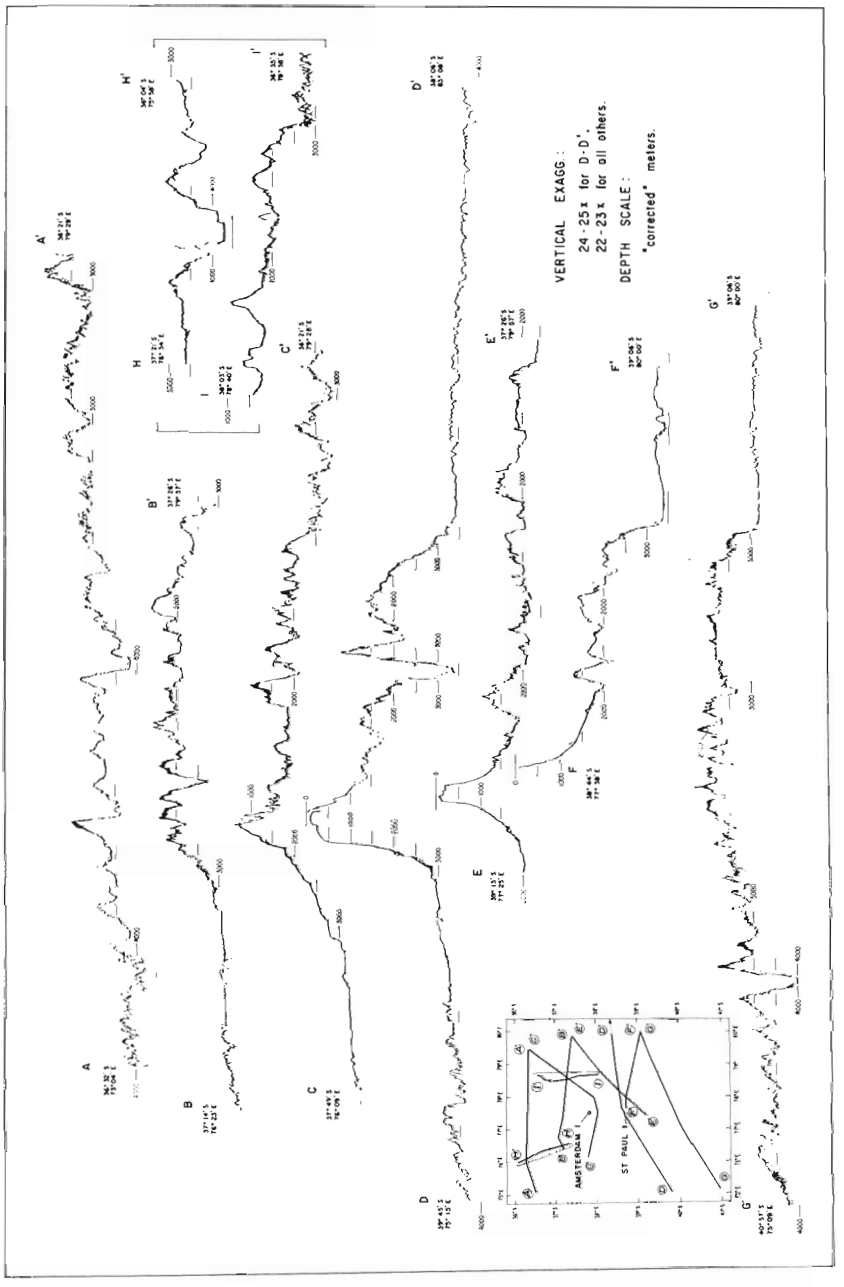


Figure 6. Bathymetric profiles near Amsterdam-St. Paul traced from Precision Depth Recorder tapes.

(relative to H-H') of the 6.7 km/sec layer was observed. Raitt's LUSIAD stations in the basins west of the ridge characteristically showed thinner crust and shallower depth to mantle than did those east of the ridge; the boundary, H-H' to I-I', is very marked. However, a planned station on the eastern flank comparable to H-H' was not carried out, and possibly a thin crust is present there as well.

CONCLUSION

In conclusion, then, these recent data indicate that, in all three ridge areas discussed above, a well-defined shallow "crest" and crestal "rift valley" are not obviously developed. Most bathymetric cross-sections show one or more striking deeps. Sometimes the "rifted zone" so-defined can be matched to a magnetic "ridge anomaly" and lies on the crest drawn from epicentre plots. Frequently, especially between the Equator and 21°S, the deeps can be traced across and beyond the ridge; in such cases, they mark cross-fractures along which the simpler ridge has been offset tens to hundreds of kilometres. Several such major cross-fractures can be correlated with clusters of seismic activity on epicentre plots. Local deeps and ridges, especially well-developed near St. Paul-Amsterdam, occur subparallel to the over-all ridge trend and give evidence of lateral motion, and some expansion, along the ridge.

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DISCUSSION

V.V. Beloussov

There is the ridge across the southwest Indian Ocean. What is the chance that the ridge extends to the plateau of the Maldives — Laccadives and to the volcanics in India?

R.L. Fisher

At one time we thought that plateau might be a continuation of the southwest ridge, with an X east of Rodriguez. However, they do seem to be separate. T.J.G. Francis and George Shor have just completed a seismic refraction study of the plateau and its possible continuation north.

F. Roots

Would you care to comment on that, Dr. Heezen?

B. Heezen

(gesturing toward the Heezen-Tharp Physiographic Diagram of the Indian Ocean) — Our interpretation is shown right there. They are very different features, of different age, and certainly not related today.

D. Matthews

We also wondered about this. It seems there is some continuation magnetically and topographically, but they are not related structurally.

RESULTS OF UPPER MANTLE PROJECT STUDIES IN THE INDIAN OCEAN BY THE RESEARCH VESSEL "VITYAZ"

G.B. Udintsev, Institute of Oceanology
Academy of Sciences, U.S.S.R.

Abstract

The 36th cruise of the ship VITYAZ was part of a program of studies related to the International Upper Mantle Project and the International Indian Ocean Expedition. Its route and scientific activities are reviewed. On the basis of the data obtained, together with earlier data, the major tectonic features of the Indian Ocean are briefly described. They include: the ocean basin floors or monocratons; oceanic ridges having block structure (i.e. the aseismic ridges); modern geosynclinal zones including the oceanic marginal trenches; the folded belts of island arcs and deep marginal basins; and the Indian Mid-Ocean Ridge. The data are considered on terms of Hess' hypothesis on the origin of the mid-ocean ridges.

INTRODUCTION

The study of the oceanic regions of the earth is an important aspect of the International Upper Mantle Project. The program of studies encompasses not only the investigation of the general tectonic divisions of the ocean bottom as revealed by a complex of geological and geophysical information, but also special studies of zones where the interaction between the crust and upper mantle is most active, and where the processes occurring in the upper mantle of the earth are most spectacularly in evidence.

The World Rift System of the mid-oceanic ridges, and the continental margins and island arcs are included in the list of zones which have priority in the Upper Mantle Project. When the Meeting of the International Upper Mantle Committee in Moscow (May, 1964) recommended the study of these zones, it did so on the basis of considerable information on the geological structure of the rift zone of the oceans. Notable contributions to the study of rift zones have been made by B. Heezen, M. Ewing, J. Ewing, H. Menard, R. Raitt, G. Shor, A. Laughton, M. Hill, J. Wiseman, R. von Herzen, V. Vacquier, P.L. Bezrukov, and other researchers. Important concepts concerning processes occurring in the rift zones of the ocean, formulated some time ago by H. Hess (1954, 1962), should also be pointed out; these concepts comprise a rational working hypothesis which correlates well with almost all the facts obtained at the present time.

THE 36th CRUISE OF THE "VITYAZ"

The above studies served as a basis for outlining the most important problems in the study of the oceanic rift zone during the Upper Mantle Project. Among the expeditions which have taken part in these researches is the Soviet Expedition on the ship VITYAZ. This expedition was organized by the Institute of Oceanology, Academy of Sciences of the U.S.S.R., in cooperation with a number of other scientific institutions, including the Institute of Physics of the Earth, Academy of Sciences of the U.S.S.R. The expedition was the 36th cruise of the VITYAZ and the fourth voyage in the program of the International Indian Ocean Expedition. Its main purpose was to conduct geological-geophysical researches on the different tectonic zones of the Indian Ocean, including studies of bottom topography, oceanic sediments, and the bed rocks of the ocean floor and oceanic islands. Also planned were: studies of the magnetic field of the earth and its gravitational field; seismic experiments and studies of the thickness of the sedimentary cover of the ocean floor; measurements of heat flow from the earth's interior; and several other projects. According to methods of observation, two types of data can be distinguished: (1) those collected en route to and from areas of detailed surveys; and (2) detailed surveys on polygonal areas located over representative parts of the different tectonic zones of the ocean bottom.

The expedition sailed for five months, from October 5, 1964 to March 6, 1965 (Fig. 1). The VITYAZ started the cruise from Vladivostok, crossed the Japan Sea, the East China Sea, the Philippine basin of the Pacific, and the South China Sea, and it then visited Singapore Harbour. It then passed through the Strait of Malacca, entering the Andaman Sea where the first detailed survey was made over a polygonal area of the deep basin in this sea (Fig. 2). From there, the VITYAZ crossed the continuation of Sunda Trench where it is buried by sediments and reached the Bay of Bengal from the Andaman Sea through Coco Pass (Fig. 3). In the central part of Bay of Bengal, a second polygon was surveyed (Figs. 4, 5, 6). Then the VITYAZ visited Colombo, Ceylon. After leaving Colombo, it went south to the equator where a third polygon (Fig. 7) was investigated. Continuing southward, latitude 8°S was reached, and a fourth polygon (Fig. 8) was surveyed. The second, third, and fourth polygons are located over the ocean bed of the Bay of Bengal and the Central Basin of the ocean. Turning to the northwest, the VITYAZ reached the submarine Maldive ridge and surveyed a fifth polygon. After that, atoll Addu (Maldive Islands) was visited. Following a route to the southwest, the VITYAZ reached the northwestern branch of the Mid-Indian Ocean Ridge (also known as the Arabian-Indian Ridge or the Carlsberg Ridge; Fig. 9), and observations were carried out in a sixth polygon over the rift zone of this ridge (Figs. 10, 11, 12). From there, the VITYAZ headed west to the Somali basin on the Madingley-Rise Plateau, where it carried out work on a seventh polygon. Then Port Victoria on the

Mahe Island (Seychelles) was visited. The expedition then proceeded southward, and in the Mascarene basin, work was carried out on an eighth polygon (Figs. 13, 14). Tromelin Island was then visited in order to make geological collections, and Port Louis on the Mauritius Island was visited. The next geological collection was made on Rodriguez Island, from where the VITYAZ headed southwest and established a ninth polygon in the Madagascar basin over the lowest part of the slope of the southwestern branch of the Mid-Indian Ocean Ridge (the West-Indian Ridge) (Fig. 15). After it crossed the ridge in a southeastern direction, it surveyed a tenth polygon in the rift zone of the ridge (Figs. 16, 17, 18). Passing the Crozet basin, the VITYAZ approached the Central Indian Ridge, and the Expedition made geological collections on New Amsterdam and St. Paul Islands, which are located in the rift zone of this ridge. Then proceeding slightly to the north, the VITYAZ did research on an eleventh polygon which also is located in the rift zone of the Central Indian Ridge (Figs. 19, 20, 21).

Turning to the east, the VITYAZ sailed to the submarine West-Indian Ridge where a twelfth polygon was surveyed. And then the latitudinal traverse of the eastern part of the ocean was ended at Freemantle Harbour, Western Australia. Continuing in a northwestern direction, the VITYAZ crossed the West-Indian Basin and reached the East-Indian Ridge (also known as the Ninetyeast Ridge) where research was done on a thirteenth polygon (Fig. 22). After that, we proceeded to Bali Strait, and on the way, the expedition made geological collections on Christmas Island. Continuing through Bali Strait, the VITYAZ left the Indian Ocean, passed Macassar Strait, and entered the Celebes Sea; it then passed to the south of Mindanao Island to the Philippine Sea of the Pacific. On the way back to Vladivostok, we visited Tokyo to attend scientific meetings with our Japanese colleagues.

During the voyage, responsibility for collection of data was distributed as follows: topography of the ocean floor, V.F. Kanaev; bottom sediments, Yu.A. Bogdanov and E.I. Romankevich; bedrock of the ocean floor, V.I. Chernyshova; seismic refraction and reflection studies, Yu.P. Neprochnov; magnetic researches, M.F. Mikhno; and the study of heat flow from the earth's interior, G.B. Udintsev and E.A. Lubimova.

GEOLOGICAL AND GEOPHYSICAL FEATURES OF THE INDIAN OCEAN

As the result of the above work, the expedition obtained an extensive sample of information characterizing different tectonic zones in the Indian Ocean. The author had made previous attempts to define the tectonic divisions of this ocean while preparing a compilation for the International Tectonic Map of the World. He has drafted the maps of the tectonic structure of the ocean shown in the "Tectonic Map of Eurasia"

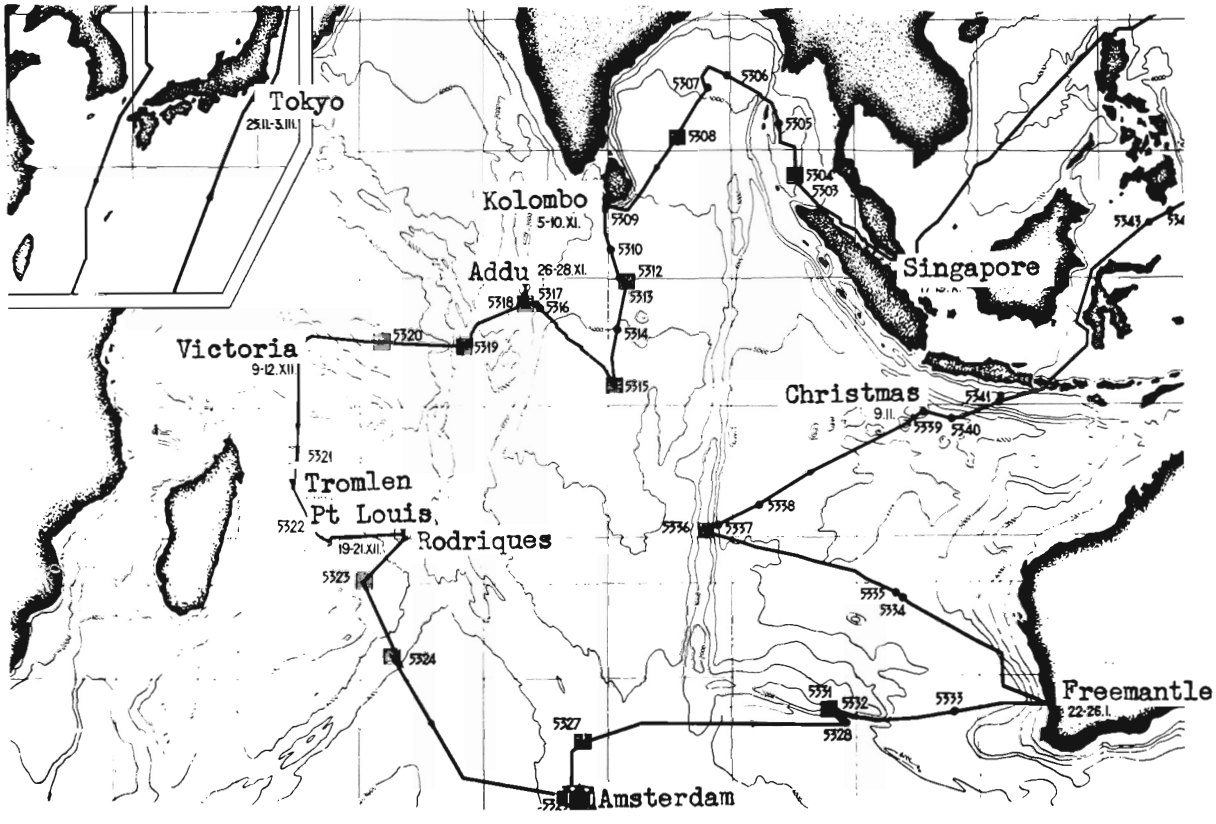


Figure 1. 36th cruise of the VITYAZ in the Indian Ocean. Figures show the numbers of stations. Squares indicate polygons. The names of landings and ports of anchorage are indicated with dates. The bottom relief is shown by schematic isobaths every 1000 m according to the map "Indian Ocean" at 1:15 000 000.

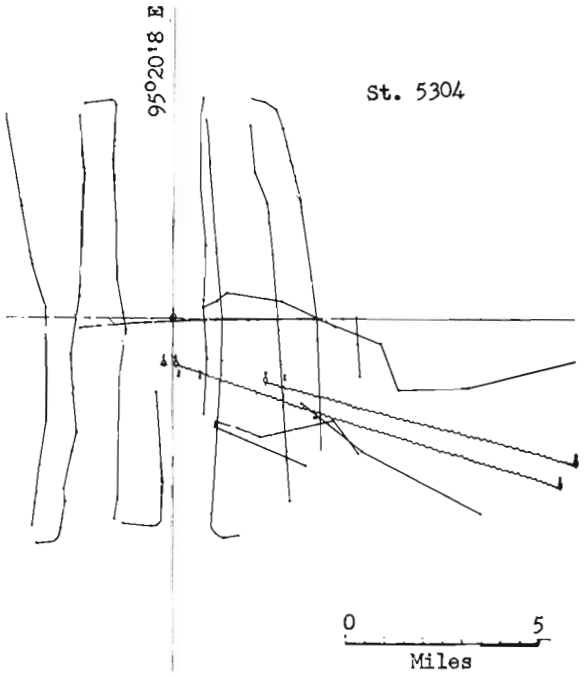


Figure 2. The scheme of works on station 5304

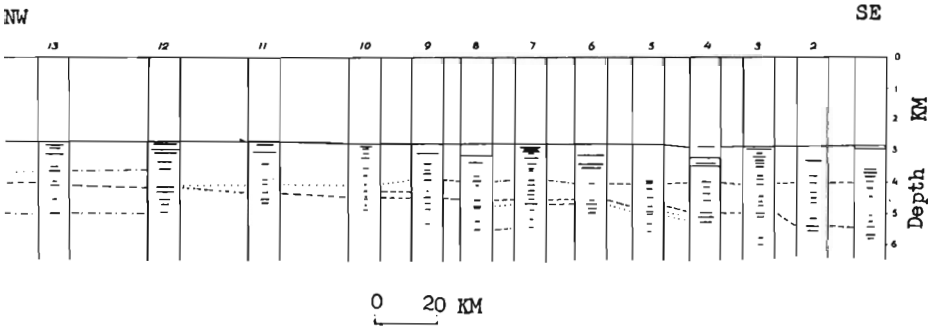


Figure 3. Seismic cross-section through the northern end of the Sunda trench (preliminary data by J.P. Neprochnov).

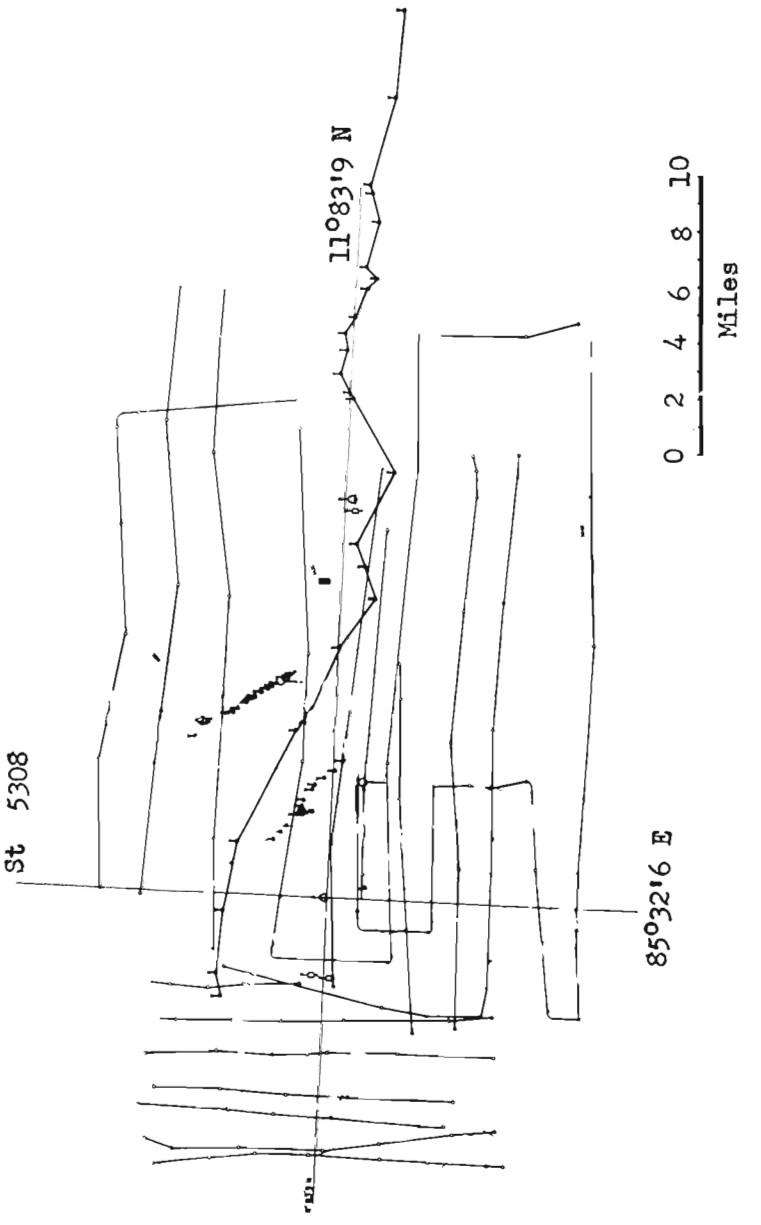


Figure 4. The scheme of works on station 5308.

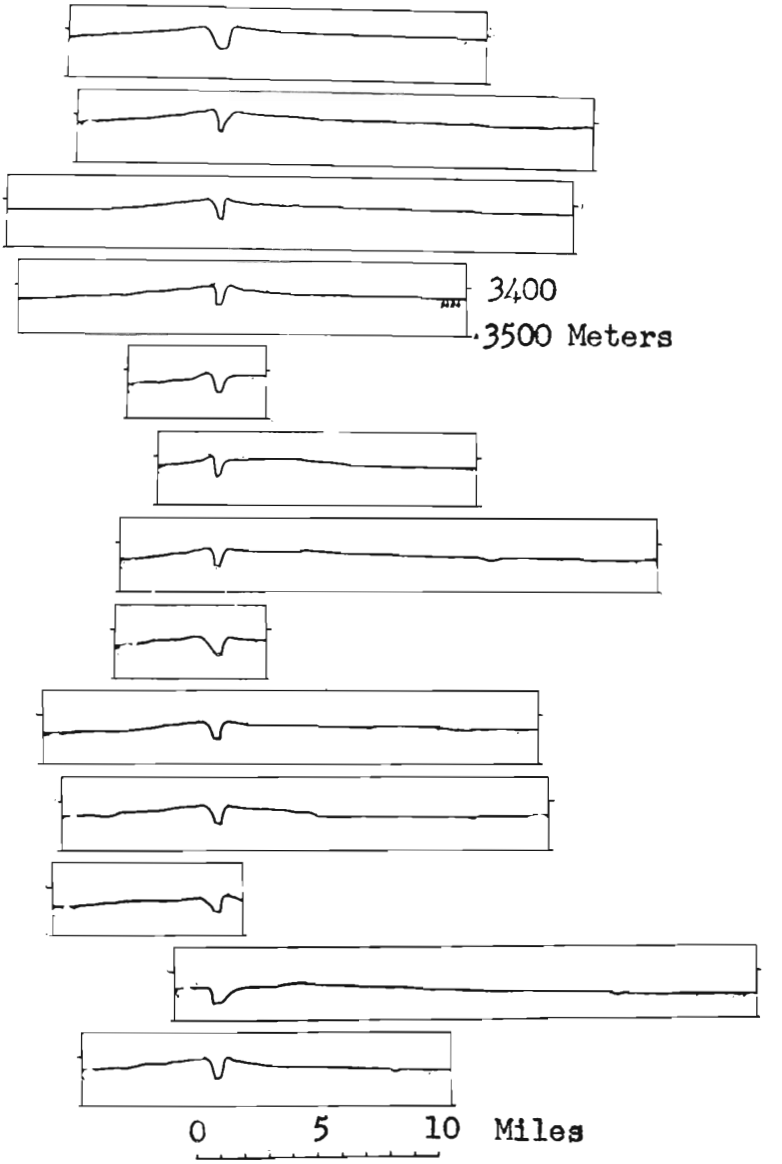


Figure 5. The profiles of the valley of suspension stream on station 5308 (by V.F. Kanaev).

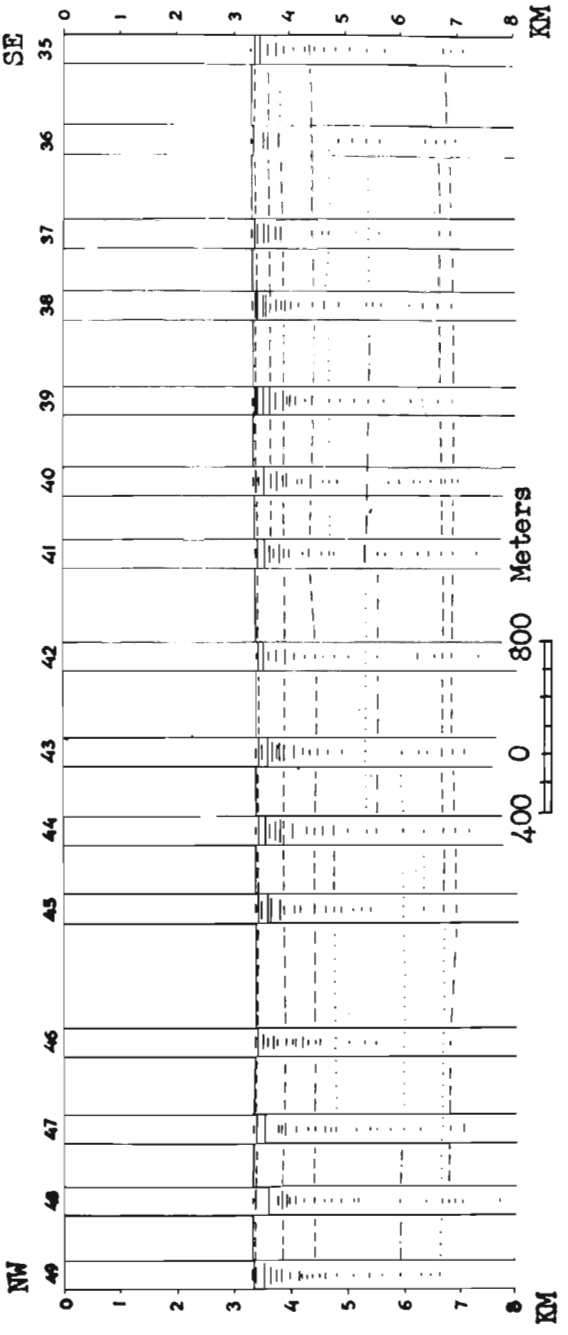


Figure 6. Seismic profile of the sedimentary layer on station 5308 (preliminary data by J.P. Neprochnov).

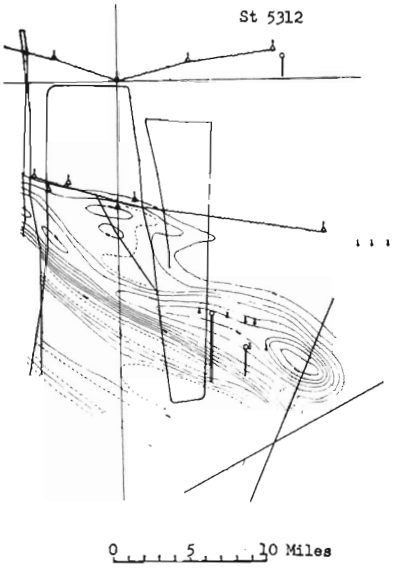


Figure 7. The scheme of works on station 5312 (preliminary bathymetry by V.F. Kanaev).

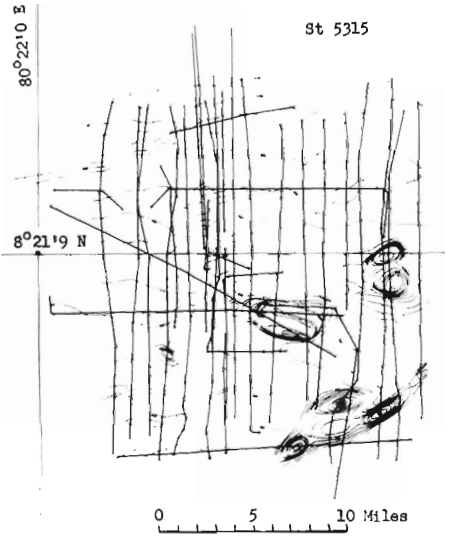


Figure 8. The scheme of works on station 5315 (preliminary bathmetry by V.F. Kanaev).

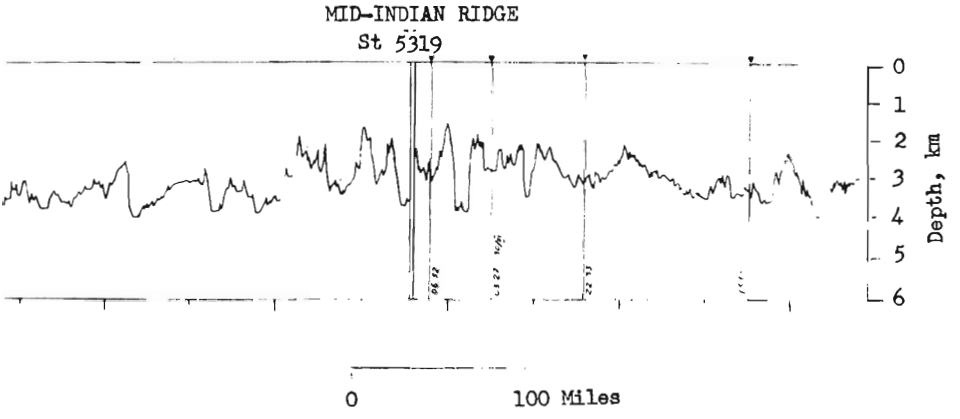


Figure 9. The profile of the Arabian-Indian ridge in the region of station 5319 (by V.F. Kanaev).

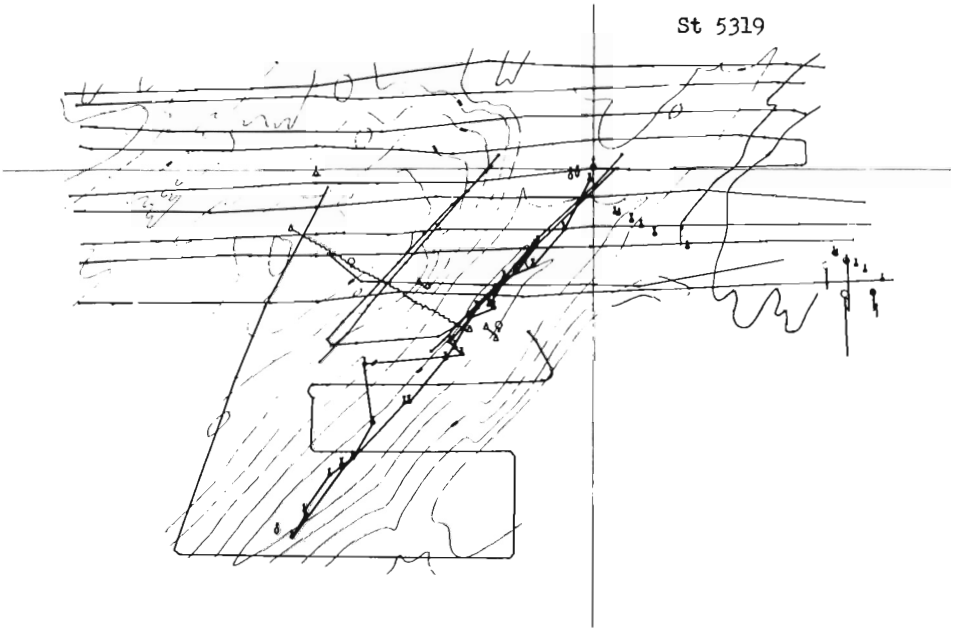


Figure 10. The scheme of works on station 5319 (preliminary bathymetry by V.F. Kanaev).

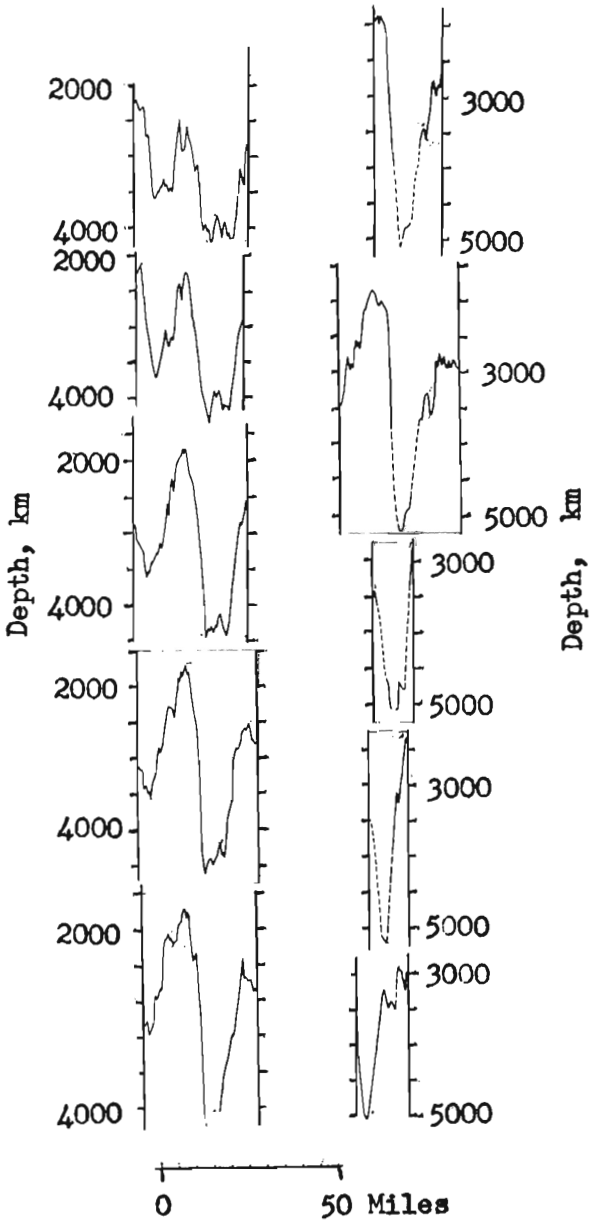


Figure 11. The profiles of the rift valley on station 5319 (by V.F. Kanaev).

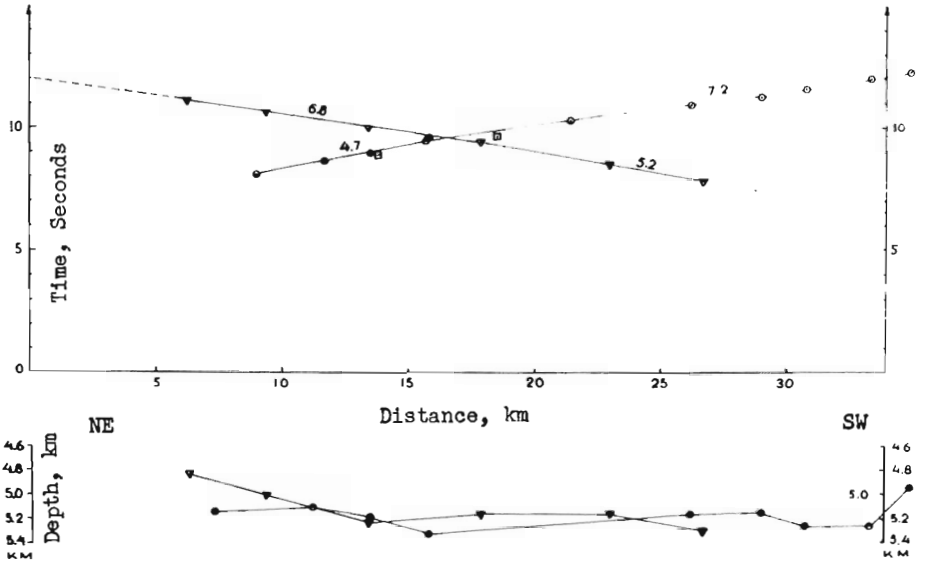


Figure 12. The travel-time plot station 5319 (preliminary data by J.P. Neprochnov).

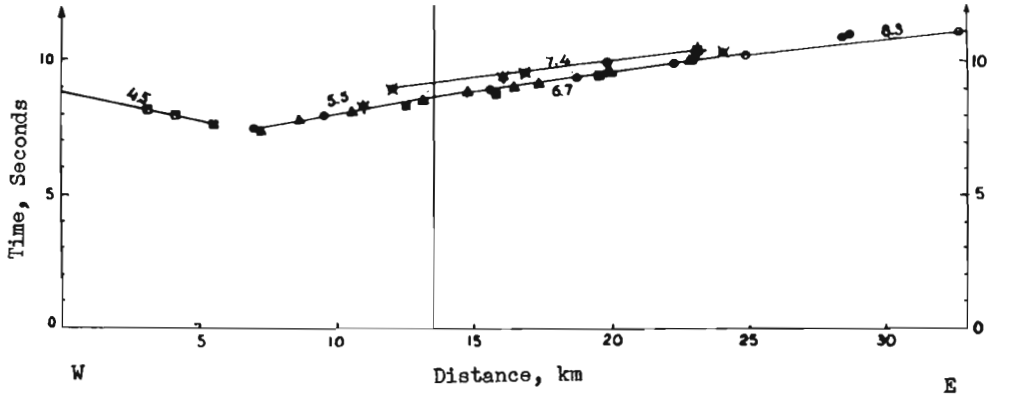


Figure 13. The travel-time plot station 5321 (preliminary data by J.P. Neprochnov).

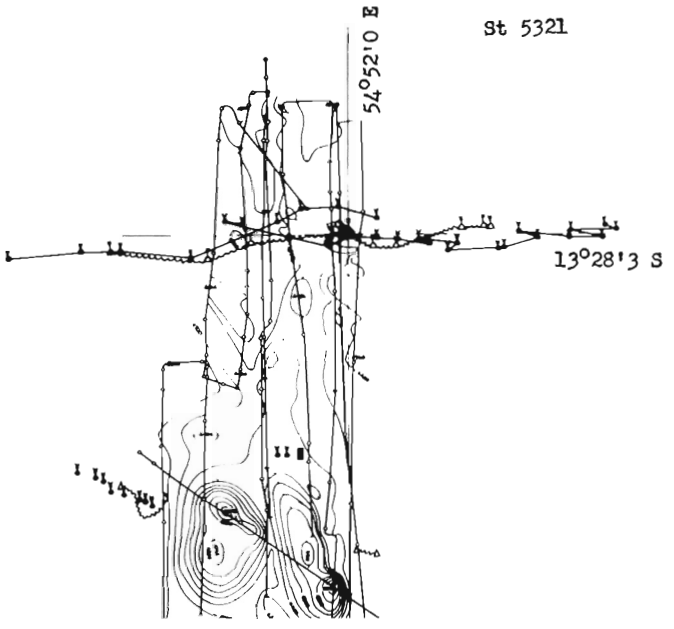


Figure 14. The scheme of works on station 5321 (preliminary bathymetry by V.F. Kanaev).

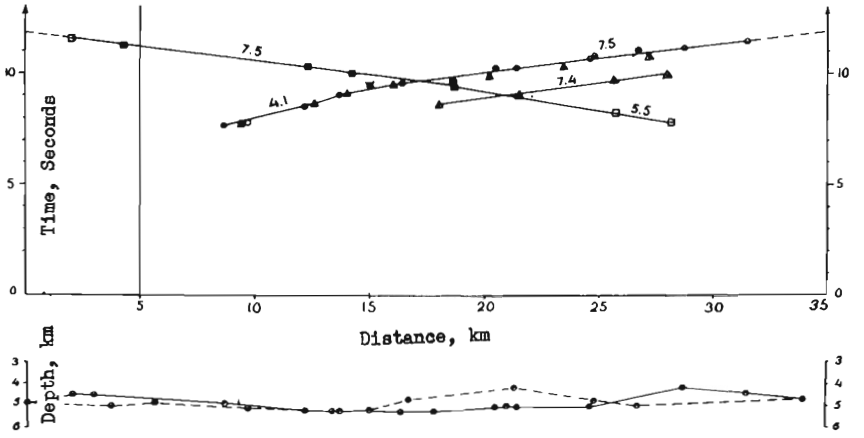


Figure 15. The travel-time plot, station 5323 (preliminary data by J.P. Neprochnov).

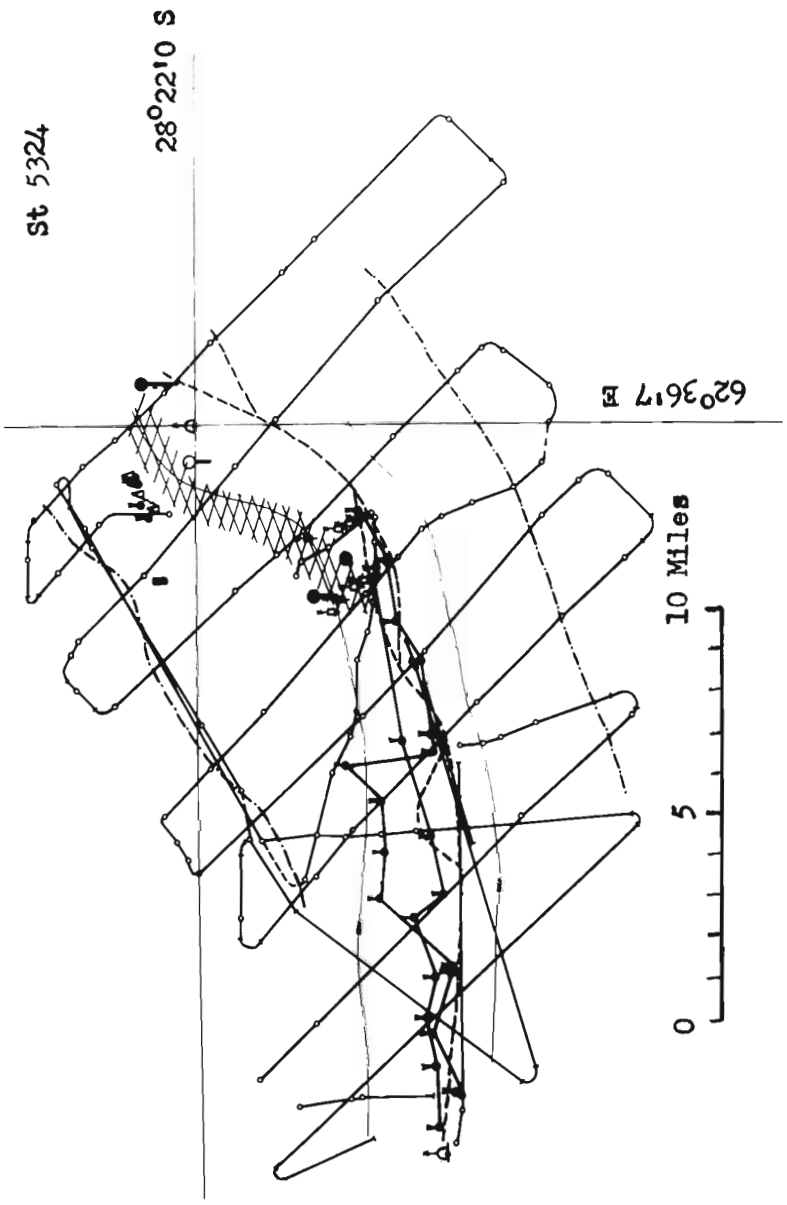


Figure 16. The scheme of works on station 5324.

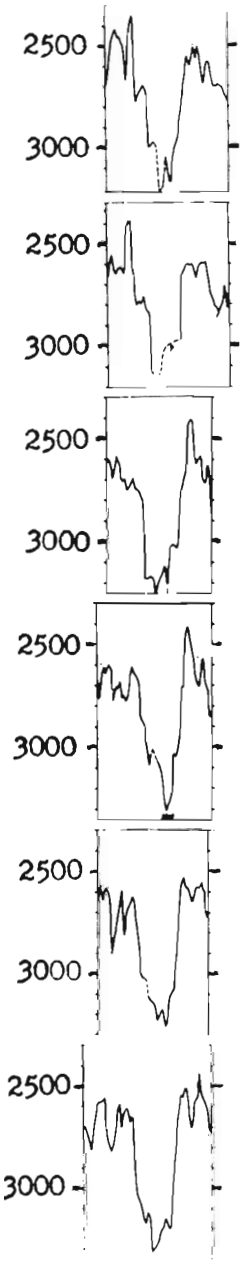


Figure 17. The profiles of the rift valley on station 5324 (by V.F. Kanaev).

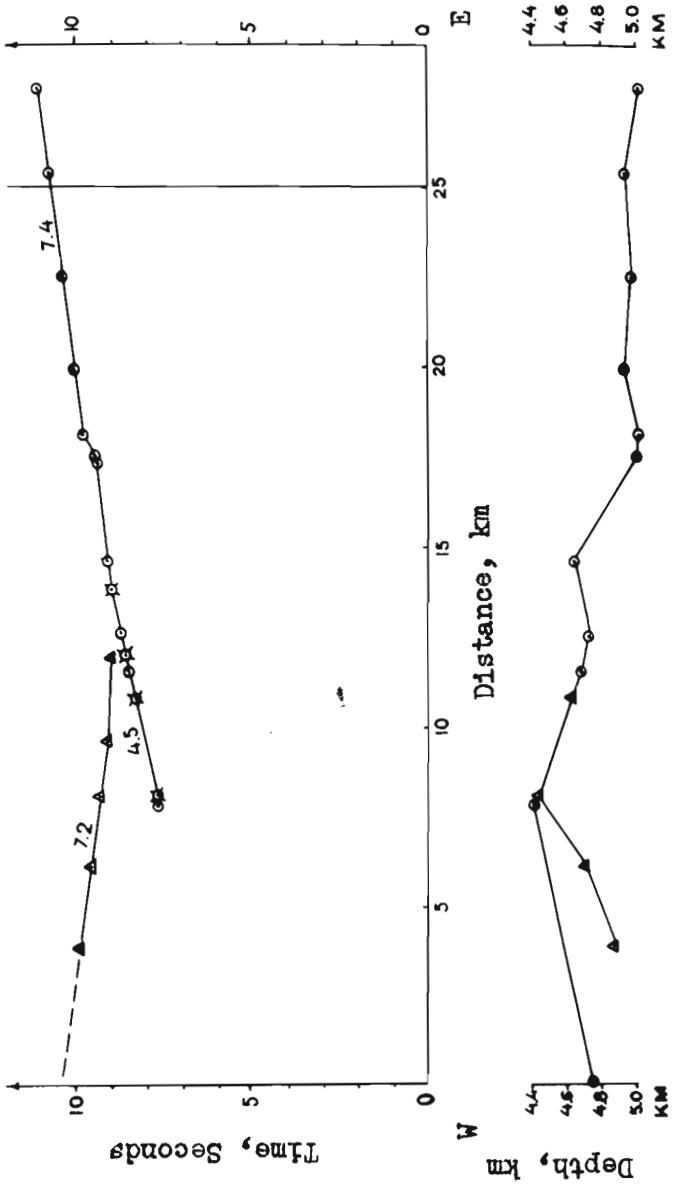


Figure 18. The travel-time plot, station 5324 (preliminary data by J.P. Neprochnov).

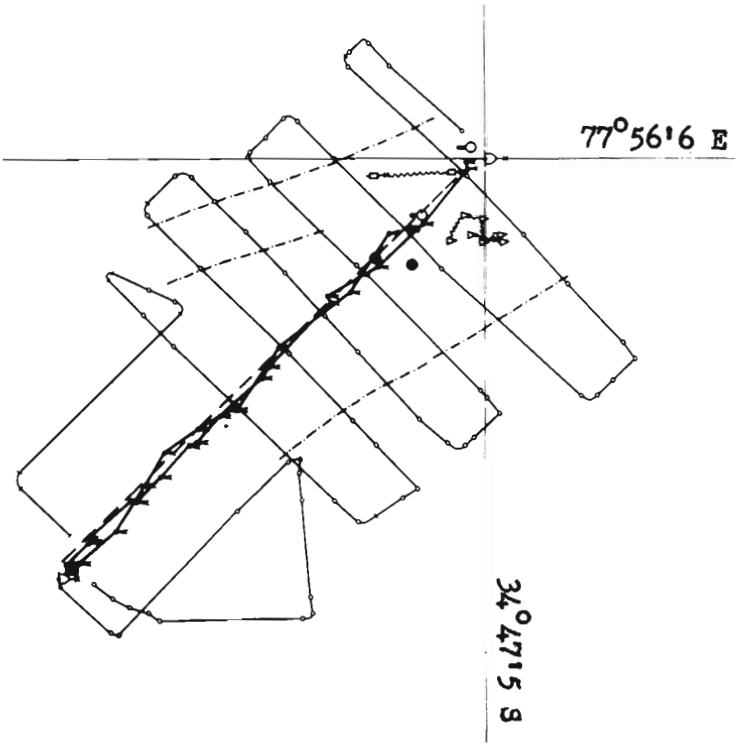


Figure 19. The scheme of works on station 5327.

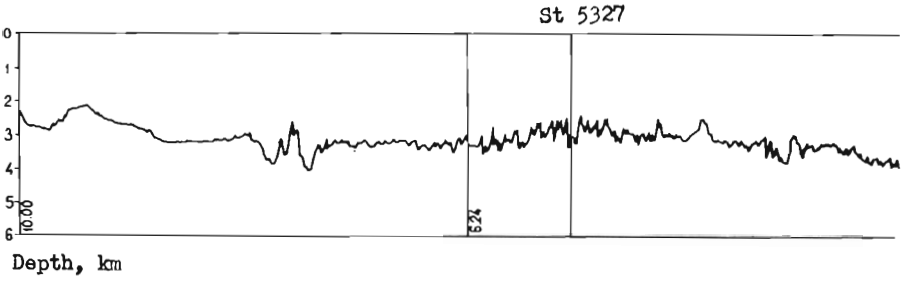


Figure 20. The profile of the Central-Indian ridge in the region of station 5327 (by V.F. Kanaev).

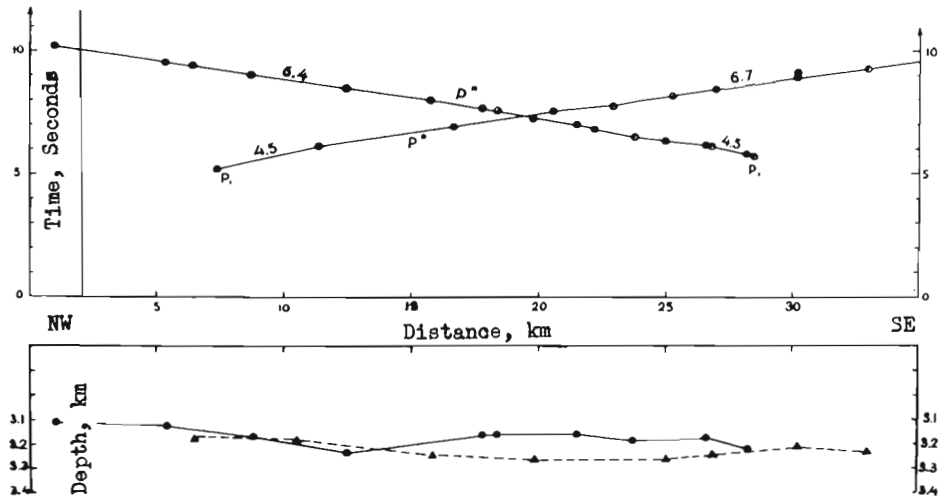


Figure 21. The travel-time plot, station 5327 (preliminary data by J.P. Neprochnov).

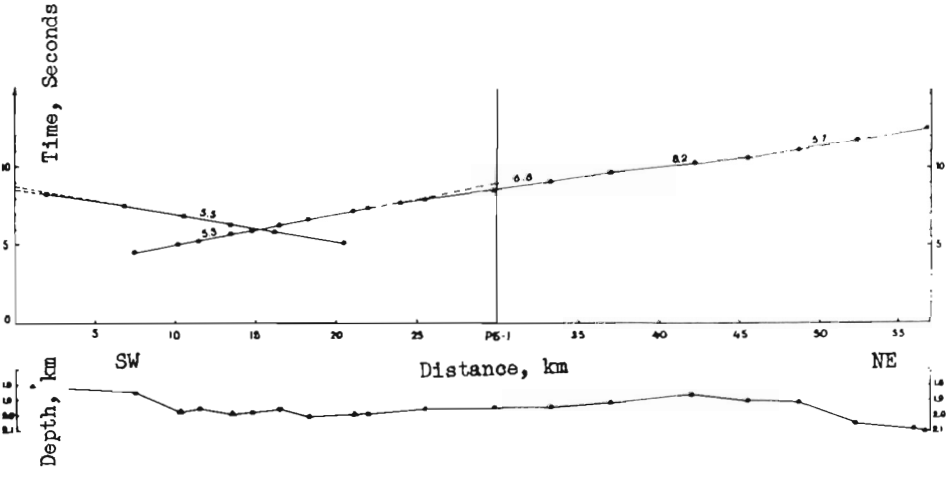


Figure 22. The travel-time plot, station 5336 (preliminary data by J.P. Neprochnov).

(1964), and on the map of tectonics of the world in "Physico-geographical Atlas of the World" (1964). The tectonic maps of V.V. Beloussov (1961) and of other authors should also be mentioned, but they made lesser allowance for the results of oceanic researchers. Notable also is the recent "Physiographic Diagram of Indian Ocean" compiled by Heezin and Thorp (1964). There are now many more data available for solving the problem of the tectonic divisions of the Indian Ocean. These data are a basis for distinguishing between different types of structures using the combined geological and geophysical characteristics of the crust. It is probable that their further study will be useful in developing concepts on the fate of the continent of Gondwana.

According to the data collected both previously and recently, the major tectonic features of the investigated parts of the Indian Ocean appear to be the following (Fig. 23):

(a) The Ocean-basin floor or monocratons. These are the most stable parts of the oceanic platforms (or thalassocratons), their main movements being vertically downward. Monocratons are analogous to geocratons or continental platforms of different ages in regions that did not pass through geosynclinal development during the last stages of geological history. The monocratons of the Indian Ocean have different ages, some of them having developed rather recently in the place of ancient continental platforms, while others have existed for a long time. The gravitational field within the monocratons is characterized by high positive Bouguer anomalies, and their magnetic field is of an unstable nature. They show a heat flow from the earth's interior approximately equal to the heat flow on continental platforms. The earth's crust underlying the monocraton is composed of a so-called "basalt" layer, 4-6 km thick, overlain by the "second" or "overbasalt" layer, 1-3 km thick. The cover of unconsolidated sediments is distinctly variable in thickness – from 100-200 m to several tens of metres, and at some places, it is absent. However, near the continental margins, the thickness of this cover increases to 1.5-2.5 km. The top of the upper mantle is characterized by seismic P-wave velocities on the order of 8.1-8.3 km/sec.

(b) Oceanic ridges having block structure, or aseismic ridges. These are high narrow uplifts which tower over the monocratons by thousands of metres. Their length is much greater than their width, and the margins are very nearly linear – in some cases, strikingly linear. They are structures of the horst type. Very typical are the structures of "asymmetric ridges", which present a combination of an upthrown ridge and a downthrown edge of a plate. Volcanism is commonly associated with block ridges, and consequently it is difficult to decide which part of them is formed by block dislocation, and which part by volcanic processes. The crustal structure comprises a relatively thin (several hundreds of metres) cover of

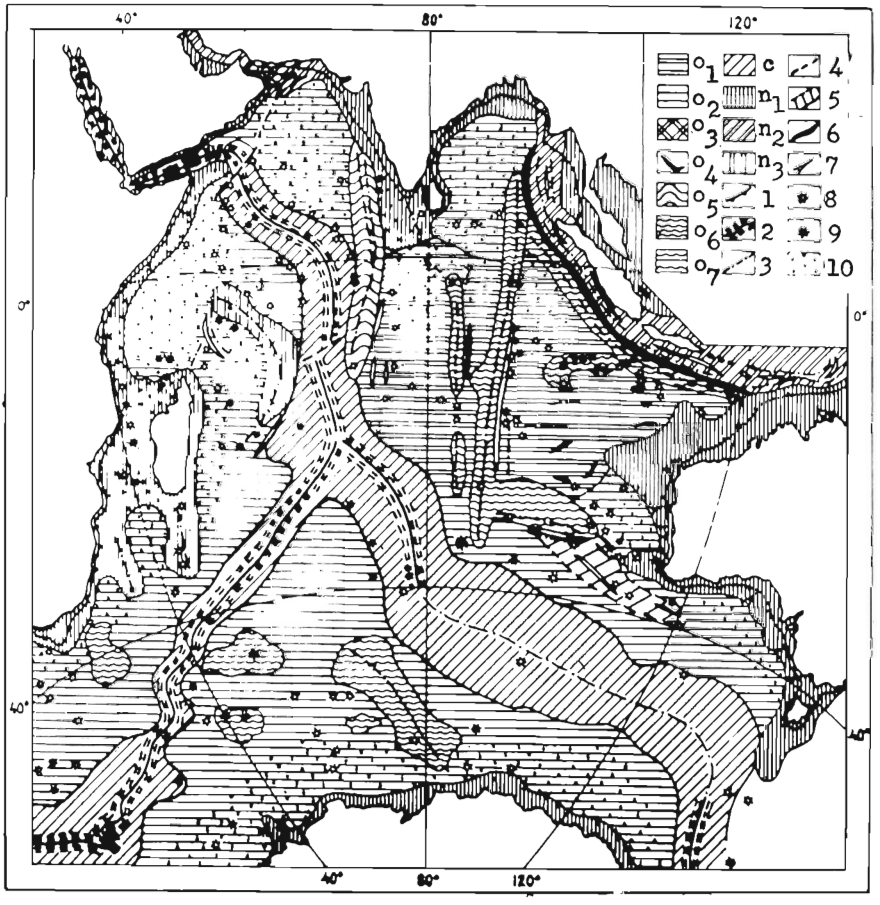


Figure 23. The tectonic scheme of the Indian Ocean (by V.F. Kanaev and G.B. Udintsev).

Legend:

o_1 - ancient monocratons
o_2 - young monocratons
o_3 - marginal geosynclinal zones
o_4 - marginal oceanic trenches
o_5 - aseismic ridges built by corals
o_6 - aseismic ridges built by volcanoes
o_7 - marginal swells
c - Mid-oceanic ridges (geotaphrogens)
n_1 - submarine margins of continental platforms of different age
n_2 - submarine parts of Cenozoic folding systems
n_3 - microcontinents
1 - continental shelf margin
2 - rift zone
3 - axes of swells and ridges
4 - faults
5 - fault zones
6 - fault-type trenches on the ocean floor
7 - submarine canyons
8 - submarine volcanic cones
9 - submarine volcanic cones with islands
10 - thick sediments

unconsolidated sediments; a considerably thicker cover of consolidated sediments or coral layer; a "second" layer, 2-4 km thick; and the "basalt" layer, 4-7 km thick. Positive Bouguer gravity anomalies are associated with the ridges, and high total-intensity magnetic anomalies occur along their "marginal faults". Data on the existence of roots under these ridges are dubious, and the age of the ridges is uncertain. They could be either the remnants of ancient continental platforms, or typical oceanic structures.

(c) Modern geosynclinal zones, including oceanic marginal trenches, folded belts of island arcs and deep marginal basins. These large structures are crustal folds complicated by numerous faults and fractures and characterized by abrupt gravitational and magnetic anomalies. The bottoms of the geosynclinal basins and trenches are regions of intensive accumulation of sediments. The degree of compensation of these depressions is different depending on local physico-geographical conditions. The thickness of the sedimentary cover reaches 1.5-2.5 km at some places, and it almost compensates the warping of the northern part of the Sunda trench lying on the continuation of the Ante-Himalayas foredeep. Different parts of the Sunda Island Arc are, evidently, in different stages of geosynclinal development. Of interest is the outer folded ridge on the Sunda Island Arc; similar ridges are present along many previously studied island arcs.

(d) The Indian Mid-Ocean Ridge. The structure of this rift zone is of the greatest interest because its various geological and geophysical characteristics have been determined simultaneously with the collection of samples of magmatic rocks. The rift zone has a rather complicated topography with sharp ridges and deep valleys. The slopes of the rift valleys are either uncovered or just slightly covered by sediments, but their bottom is filled with a sedimentary-volcanogenic layer of 2.0-2.5 km thickness having seismic P-wave velocities of about 5.0 km/sec. Beneath this layer the rocks have velocities 7.0-7.2 km/sec, and the morphology of the rift valley indicates the possibility that these are exposed on the slopes. A marked minimum in the total intensity magnetic field is observed in the heat flow from the earth's interior.

Samples of vitrified basaltic lavas and baked foraminiferal sandstone were obtained from the bottom of the valley and ridges of the rift mountains. The basalts consist of laths of plagioclase and large ophitic grains of pyroxene with inclusions of olivine. Samples of mafic and ultramafic rocks were obtained from the slopes of the rift valley. The mafic rocks are represented by basalt and coarsely crystalline gabbro composed of labradorite and diallage. Among the ultramafic rocks, peridotite (harzburgite) showing different degrees of serpentinization, and the serpentinite formed from them, are predominant. Dunites and chromitites were found in lesser quantities. The mineralogy of the ultramafic samples is characterized by the presence of magnesian olivine accompanied by

enstatite and, more rarely, by augite. Chromite and picotite are ubiquitous admixtures. All samples show serpentine pseudomorphs after the primary minerals. The surfaces of the samples show gliding planes, and traces of dynamometamorphism are also evident in strained olivine crystals and in the serpentine structure.

COMMENTARY AND CONCLUSIONS

We consider it reasonable to suggest that the ultramafic rocks obtained in the rift valley are slightly changed material from the upper mantle of the earth. Their mineralogical composition correlates completely with the modern concept that the upper mantle constitutes the residue after basalt has been removed by zonal melting of an initial material similar in composition to stoney meteorites. The present sample should correspond, not to the local apophyses far detached from the major body of the mantle, but to the roof of an uplifted arch of the mantle caused by the formation of the Mid-Indian Ocean Ridge. This uplift is indicated by the near-surface location of the boundary of the layer with seismic velocities of 7.0-7.2 km/sec under the bottom of the rift valley.

As was shown by Hess (1962) seismic velocities of this magnitude at small depths should correspond to ultramafic rocks at low pressures (in comparison with the usual position of upper mantle rocks), comparatively high temperatures,and in a highly serpentinized dynamometamorphosed condition. It is known from laboratory measurements that ultramafic rocks influenced by these factors do show velocities of the order of 7.0 km/sec, and even lower. All of them are present in the rift zone of the Mid-Indian Ocean Ridge, and although it is difficult to know which has the deciding influence, each of them provides the possibility of explaining the observed velocities. For this reason we have designated the boundary defined by them as the Mohorovicic discontinuity (Fig. 24).

The rise of matter from the upper mantle to the surface, and the accompanying dynamometamorphism and serpentinization of the ultramafic rocks are most active in the modern rift zone. This is a process of outward squeezing of the rocks, in contrast to the outflow of basalt lavas melted as the result of the process of zonal melting. However, the influence of the rising of upper mantle material is not limited to the modern rift zone. The divergence of convection currents in the upper mantle beneath the rift zone should cause extension of the crust over the whole region of the mid-oceanic ridge. As a result, the zone of outcrop of the ultramafic rocks and their serpentinization products is stretched, and this causes the formation of a specific type of crust in the region of the ridge. This is confirmed by the observations on the flanks of the Indian Ridge.

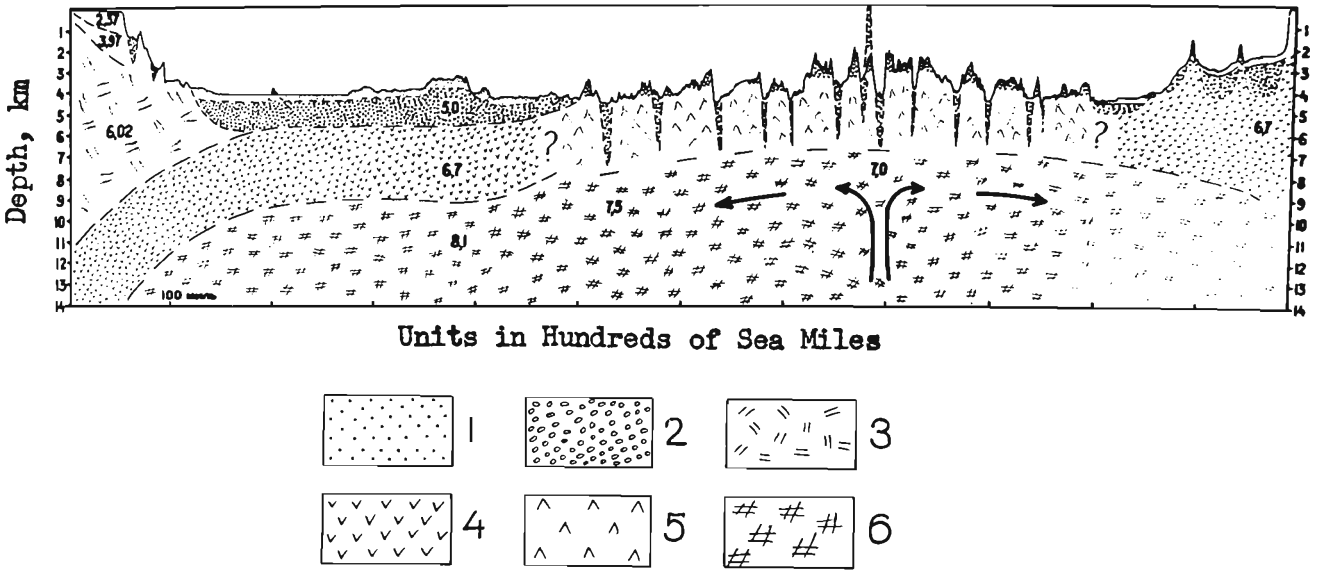


Figure 24. Schematic profile of the earth's crust across the Mid-Oceanic Ridge of the Indian Ocean according to the summarized data obtained by B. Heezen, M. Ewing, R. Fisher, R. Herzen, V. Vacquier, R. Raitt, G. Shor, M. Hill, T. Frensis, F. Davis, A. Laughton and according to the results of the work of the 36th cruise of the VITYAZ.

Legend: 1 - loose sediments
2 - "second" seismic layer of the earth's crust
3 - "granite" layer of the earth's crust
4 - "basalt" layer of the earth's crust
5 - lifted, serpentinized and dynamometamorphosed rocks of the upper mantle
6 - the upper mantle of the earth

The numbers show the velocities of propagation of seismic waves in km/sec. The arrows show the direction of supposed convection movements of the matter of the upper mantle. The vertical scale – the depths in km; horizontal – distances in sea miles (100 miles – 185.2 km).

The rift zone, where outcrops of ultramafic rocks now seem probable, is one of the remarkable features of the earth's structure. The mid-oceanic peridotite and greenstone of the belt represent a parallel to the greenstone belts of the island arcs at the peripheries of the oceans. In general, as noted by Heezin, Hess, Bullard and others, the mid-oceanic ridges are peculiar tectonic zones. It seems to us that they are comparable to geosynclinal belts in scale and importance, and we suggest that they be called geotaphrogens (based on the term taphrogenesis from the Greek word taphros--ditch). This term,which was introduced some time ago by Suess, is meant to emphasize the leading role of extension and faulting in the formation of the structure of the rift zone.

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DISCUSSION

H. Kuno (Japan)

I would make a comment on the differences in the seismic velocities in the rocks you collected from the Indian Ocean. We have determined the P-wave velocity of an olivine nodule from Yanu Crater in Japan. This nodule has a very distinct lineation shown by parallel array spinel and pyroxene crystals. We determined velocities both parallel and perpendicular to the lineation at room temperature and 10 kilobars pressure. The velocity parallel to the lineation was about 9 km/sec; that perpendicular to it was about 8 km/sec. These figures are about the same as you observed. I would think that the lineation in the nodule was controlled either by shearing movement (i.e. deformation) or by a convection current within the mantle. If we detect a difference of 1 km/sec between velocities along a certain direction in the mantle and perpendicular to it, then it may in part reflect the direction of the convection current. This is one possibility.

M. Talwani (U.S.A.)

What was the thickness of the abyssal plain sediments, and what was their age?

Dr. Udintsev

The sediment column under the abyssal hills was very much thicker than we usually get in this type of abyssal hills. Just off the continental margins, the thickness ranges from 200 m to 2 km. In the central part of the plains it may be 10-20 m. The average is about 50-60 m. We found an outcrop of Tertiary rocks on the hills; I do not remember its exact age at the moment.

F.K. North (Canada)

I'd like to ask if the second polygon in the Bay of Bengal was over the Ganges Delta? And if so, do they know yet what the thickness of sediments is in the Bay of Bengal?

Dr. Udintsev

Yes, the second polygon was exactly on the edge of the Ganges Fan. The thickness of the sediments was approximately 2 1/2 km.

THE BAIKAL RIFT ZONE

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Abstract

The Baikal rift zone is a linear system of grabens extending for 2500-3000 km from northwestern Mongolia to South Yakutia. It comprises a series of intermontane basins and mountain ranges representing a chain of grabens. The grabens are imposed on a basement of largely Archean rocks, but their form is principally controlled by Proterozoic and Caledonian faults. Some of these faults are locally occupied by lenses of ultramafic rocks. The morphology of the grabens is asymmetric – they have steep northern or northwestern slopes caused by large active faults, whereas their opposite slopes are more gradual. The depressions contain sediments of Oligo-Miocene, Pliocene and Pleistocene ages, and the nature of these sediments shows that the region evolved from a relatively flat terrain marked by large lakes and swamps. The total thickness of the sediments is about 5000-6000 m, and the amplitude of crustal displacement has been about 5000-7000 m. The earlier stages of downwarping were accompanied by the eruption of trachybasalt lavas. Geophysical information is briefly reviewed.

GEOLOGICAL CHARACTERISTICS

The Baikal rift zone, a linear system of grabens, extends for 2500-3000 km from northwestern Mongolia through the mountains of East Siberia to South Yakutia (Fig. 1). It is curved twice, but its predominant strike is northeasterly. The system comprises intermontane depressions of different sizes and the mountain ranges between them. The depressions, which occur one after another, represent a chain of grabens that branches in its northern part.

To the south, the system probably ends in two large transverse depressions – Darhat and Hubsugul – directed perpendicularly to the western latitudinal wing of the general system. The eastern wing, also formed by almost latitudinally directed elements, extends to the middle part of the course of the Olekma River and to the western part of the Stanovoi range. There is some evidence that this wing may have extended farther to the east in recent times, into the region of the upper part of the Aldan River.

The depressions are formed on the crest line of general arched uplift. Therefore the Baikal rift zone is characterized by high

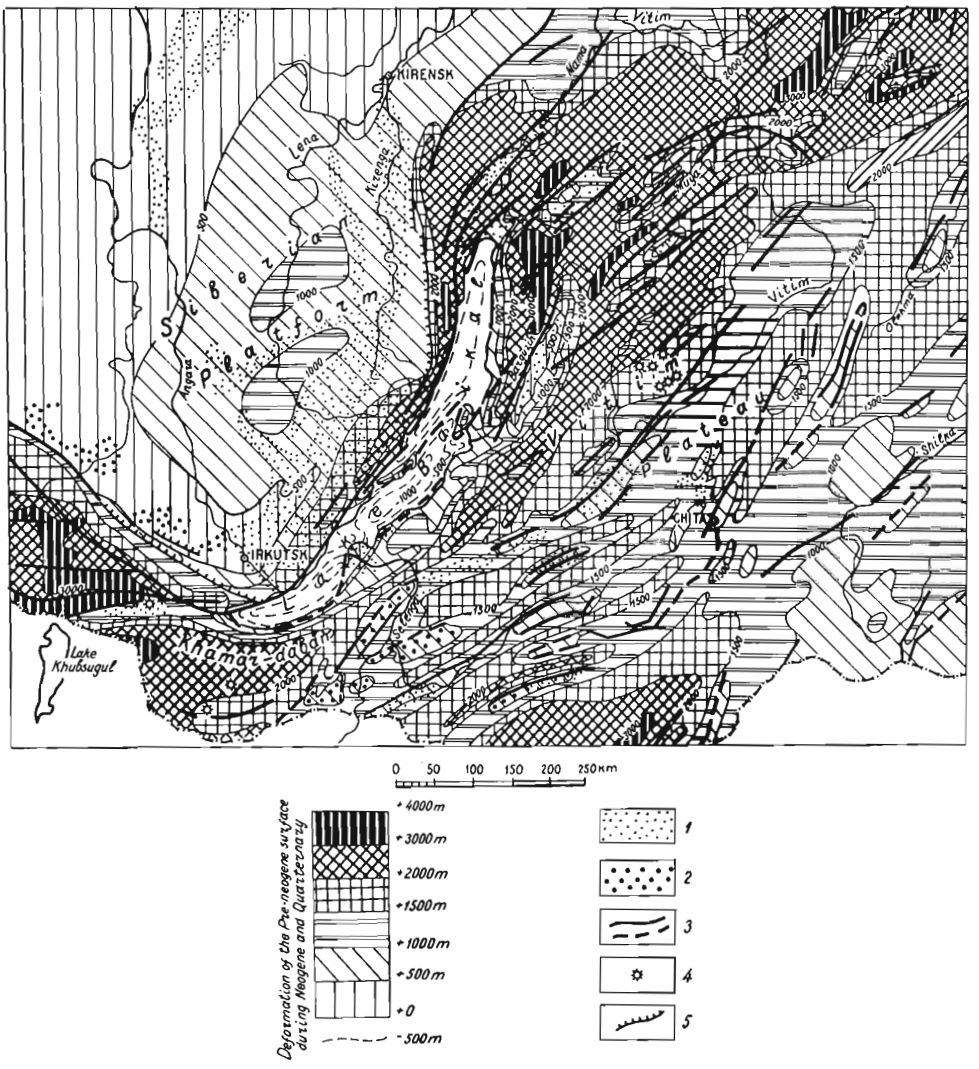


Figure 1. The map of modern tectonics of the Baikal Mountain region (isolines show modern altitudes of the Neogene peneplain).

1. Region of the Neogene-Quaternary accumulation
2. Region of considerable Quaternary accumulation
3. Recent faults (defined and supposed)
4. Recent flexures
5. Dead volcanoes (Neogene and Quaternary)

elevations in mountain ranges very close to depressions. It shows a maximum of geomorphic contrasts and of geophysical anomalies. Statistical data collected during the last 100-150 years show that the level of seismic activity is also very high, and earthquakes of magnitude 7.8 are known to have occurred in the zone.

The Baikal chain of grabens is situated in an ancient heterogenetic folded zone. The latter, in its middle part, consists of the edge of the epi-Proterozoic platform. Its western wing consists of a part of the epi-Caledonian platform, and the East and South Baikal regions comprise more ancient blocks, where folding of a geosynclinal type was not later than Archean.

The zone of the grabens is sharply asymmetric in relation to the general structure pattern of the Irkutsk amphitheatre. Except for some large and very ancient faults that were active from the beginning of the late Proterozoic and which occur along the whole internal curve of the Irkutsk amphitheatre, the principal grabens are connected only to the eastern wing of the amphitheatre. Farther to the east the grabens trend approximately parallel to the south edge of the Siberian platform; they are not affected by local changes in the direction of the Precambrian tectonic structures that cross them.

The relation of the Baikal rift zone to the inner structure of its ancient base is not simple. The depressions are imposed on scattered blocks of the Archean rocks, the external outlines of which do not conform to their inner structures. On the other hand, the grabens of the Baikal system are better controlled by the late Proterozoic and Caledonian structures, particularly by faults of those ages. The zone of grabens is not connected with any single deep fault. There is a complicated system of faults, the most important being those which constitute the shortest connection between neighbouring grabens.

The morphology of grabens is asymmetric. The asymmetry is represented by a greater steepness along northern or northwestern slopes, which are generally formed by large active faults. The opposite slopes are less steep, and the role of the faults in their development is less important.

The mountainous or hilly uplifts within the depressions are transverse or diagonal. They are formed by bifurcated faults. A good example of these is the tectonic block represented by the Island Olhon in Lake Baikal.

In addition to the Precambrian, and to a lesser degree the Cambrian metamorphic rocks, there are some Jurassic continental sediments in the basement of the rift zone.

The sediments filling depressions of the Baikal type are generally unfossiliferous continental deposits of Oligo-Miocene, Pliocene, and Pleistocene ages. The lowest beds could possibly belong to the Paleocene, but they are not exposed in surface outcrops, and borings have not reached them. The Oligocene-Miocene sediments are predominantly sandstones, gravels, silts and clays but fresh-water limestone, diatomite and charcoal or lignite beds occur locally. The contact of the sediments with the crystalline rocks at their base is depositional, and the basement rocks are generally weathered. There are no appreciable changes in the composition of the sediments, either vertically or horizontally. The sediments are fine-grained, and contain some chemical and organic materials. The paleogeographic conditions of their formation were sharply different from modern conditions, the sediments having been deposited in large shallow lakes, swamps and rivers on a flat terrain. The constitution of the Pliocene sediments expresses the instability of the conditions of their formation, and their plant-fossils indicate that the climate had become colder. The Upper Pliocene and Pleistocene sediments are wholly confined to modern intermontane depressions. Well developed among them are marginal psephytic sediments. The total thickness of sediments in the depressions, as defined by geophysical work on the delta of the Selenga River, is 5000-6000 metres; part of the section measured by a boring is 3000 metres thick.

The Cenozoic sedimentary beds form shallow synclines, which are essentially horizontal in their central parts, but which show small folds at places along their margins. It is possible to distinguish two major units in the overall section of sediments corresponding to two different tectonic regimes or cycles. The lower unit reflects an early stage of downwarping of the basement rocks and the beginning of basaltic volcanism; the upper unit was formed during the orogenic period (from beginning of Pliocene to recent times), when oscillatory movements of earth's crust became stronger and geomorphic conditions approached modern ones. As shown by the lithologic composition and the distribution of the sedimentary formations, the upper unit corresponds to the filling of troughs, which developed concurrently with the accumulation of the sediments.

Eruptions of trachybasaltic lava began in the Miocene and continued until the Recent. They were mainly concentrated outside the bounds of the grabens, and volcanic plateaux and even some buttes have been deformed by warping and faulting.

Different structural models for the Baikal depressions have been proposed by different specialists. Modern versions suppose the combination of linear or isometric up-and down-warping, and longitudinal and transverse normal faults, most of which follow deep ancient faults. There is no distinct strike-slip component in the movement of the large

faults. According to the results of the investigations of the Cenozoic sediments, the geological history of the Baikal rift zone began in the Miocene and continued until recent times. During this time, there took place a gradual transformation of a vast flat area into the present terrain of deep fault-bounded depressions. A substitution of more and more active faulting for plastic deformation was the main line of development of the rift zone during the late Pliocene and Pleistocene. The transformation of the primary shallow basins into symmetrical or asymmetrical grabens proceeded simultaneously with a broad, more general uparching of the region.

The total amplitude of uplift and subsidence during the late Cenozoic was 5000 m in some places (Tunkinsky depression) and as much as 7000 m (South Baikal).

GEOPHYSICAL CHARACTERISTICS

Geophysical investigations are still insufficient to throw much light on the deep structure of the Baikal rift zone, or on the physical conditions of the origin and development of its grabens. The magnetic field of the Baikal region somewhat to the south of the northern foothills of the Baikal mountains and the East Sayan range is generally negative and strongly differentiated, and it clearly reflects the structural pattern revealed by geological mapping. There are some narrow local zones of positive anomalies, which are believed to be caused by thin lens-shaped masses of ultramafic rocks occurring along deep faults. An ultramafic belt extending along the western shore of Lake Baikal coincides with long ancient faults bordering the rift zone. It produces a strong linear magnetic anomaly with the same gradient at both sides, which shows that the Western (Obruchevsky) fault and the boundaries of the ultramafic bodies are steeply dipping or subvertical.

The gravity field of the Baikal rift zone is not well known, but the general field of the Baikal region is established. Several authors have proposed models of the region, and a combination of seismological and gravimetric data has lead to the conclusions that the earth's crust is thicker in the Baikal region as compared to the inner part of the Irkutsk amphitheatre, and that the Moho discontinuity is tilted towards Lake Baikal. Present seismological data do not elucidate vertical discontinuities in the earth's crust.

Bulmasov (1960) believes that the thickness of the crust is greatest (70-80 km) beneath the Baikal and Bargusin depressions, where pronounced negative free-air anomalies measured are dominant. Above some mountain ranges, both the free-air and isostatic reduction anomalies are mainly positive. Bulmasov believes that all of the region surrounding

the Baikal and other neighbouring grabens is unbalanced, and that isostatic anomalies are continuing to grow here, thus restraining modern uplift of the mountains and subsidence of the grabens. Other geophysicists suppose lesser thicknesses for the crust and simpler forms for the Moho surface; they believe the anomalies under Baikal are local, being caused by large thickness of unconsolidated Cenozoic sediments lying within Baikal depression.

CONCLUSIONS

From this compilation of the available geological and geophysical data on the structural depressions of the Baikal rift zone, it is possible to draw some conclusions (see Fig. 2). The importance of plastic deformation is admitted by all authors, but undoubtedly the main elements of the rift zone are connected with ancient deep faults. The most controversial point is the nature and type of the faults involved in the formation and development of the zone. Almost all investigators believe that they are not overthrusts, but some authors consider the western boundary of the Baikal depression to be a steep reverse fault coinciding with a deep Precambrian fault inclined toward the Irkutsk amphitheatre. In this case, the eastern margin of the Baikal depression is formed by normal faults. This model of the structure of the Baikal depression is the well-known combination of rift (eastern part) and ramp (western part). Most investigators accept the rift model of the structure of Baikal depression and its satellites as the best one on the basis of both geological observations and seismological data. A considerable instrumental study of the epicentres of shallow and intermediate earthquakes has shown that these commonly coincide with the traces of faults discovered by geological methods.

Special investigations of the mechanisms of local earthquakes have shed light on the nature of the strain in the earth's crust in the Baikal region. It is known that horizontal and transverse (to general strike of tectonic lines) tension and vertical compression are predominant beneath the Baikal depression and everywhere in the eastern part of the rift zone. By contrast, the western part of the rift zone and the hypocentres of earthquakes in Mongolia indicate the reverse distribution of strain.

Vertical movements in the rift zone are still continuing to generate frequent strong earthquakes. Many thermal springs occur along the traces of faults and are probably connected with a shallow layer of high temperatures in the earth's crust.

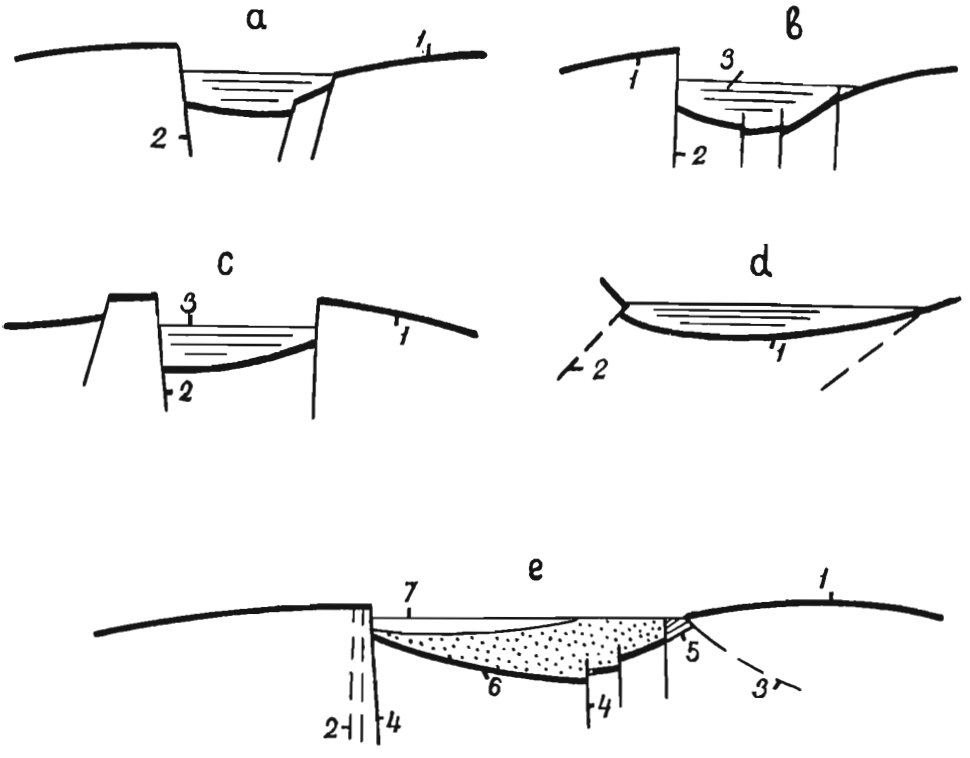


Figure 2. Models of the structure of the Baikal depression:
a) according to N.A. Florensov (1953)
b) according to K.V. Pshennikov (1954)
c) according to V.V. Lamakin (1955)
d) according to Bulmasov (1961)

Legend:
1. Deformed surface of crystalline basement
2. Faults
3. Sediments and the water in the lake

e) a current version of the structure of the Baikal depression:

Legend:
1. Surface of the Pre-Cenozoic basement
2. Zone of ancient deep fault
3. Late-Mesozoic reversed fault
4. Rift forming faults
5. Jurassic deposits
6. Cenozoic deposits
7. Waters of the lake.

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FAULT BLOCKS AND RIFTS IN SOUTH AUSTRALIA[1]

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Abstract

The pattern of faulting in the South Australian rift area is described and is related to the continental pattern of lineaments outlined by E.S. Hills. Although the framework is an ancient one, the faults have been active in the late Cenozoic, and indeed, their development continues.

TEXT

Although the Australian rifts are most obviously manifested in southern South Australia, a pattern of faulted blocks of which the rifts are an inherent part extends over the entire continent. This continental tectonic framework is expressed in long, continuous, rectilinear or gently arcuate structures called lineaments which are the traces of steeply dipping faults and joints, as well as warp axes, and which are fundamentally of great antiquity although subject to recurrent movements. They determine the major features of Australian topography, display limited trend-ranges, and according to some authorities, they are part of a global pattern.

In South Australia, the rift system is most marked about the Mt. Lofty-Flinders Ranges, and at the eastern margin of the West Australian Shield (Fig. 1). Although the Ranges are represented on topographic maps as having curved outlines, in reality, they consist of a series of juxtaposed blocks principally delineated by NW-SE and SW-NE trending faults and warps, although in some areas N-S and E-W trends are apparent. To the west of the upland backbone, which has an offshoot in the south in the horst block of Yorke Peninsula, a number of rift valleys are arranged like an inverted and distorted Y. In the south, the two arms of the Y, the Spencer and St. Vincent Gulfs, are inundated by the ocean. The western side of the Spencer Gulf (the eastern margin of Eyre Peninsula) is delineated by the Lincoln fault zone, which trends SW-NE but within which are important faults trending N-S. This zone continues to the NE beyond the head of the Gulf and can be

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[1]Contribution No. 66-1, Rensselaer Polytechnic Institute, Troy, New York.

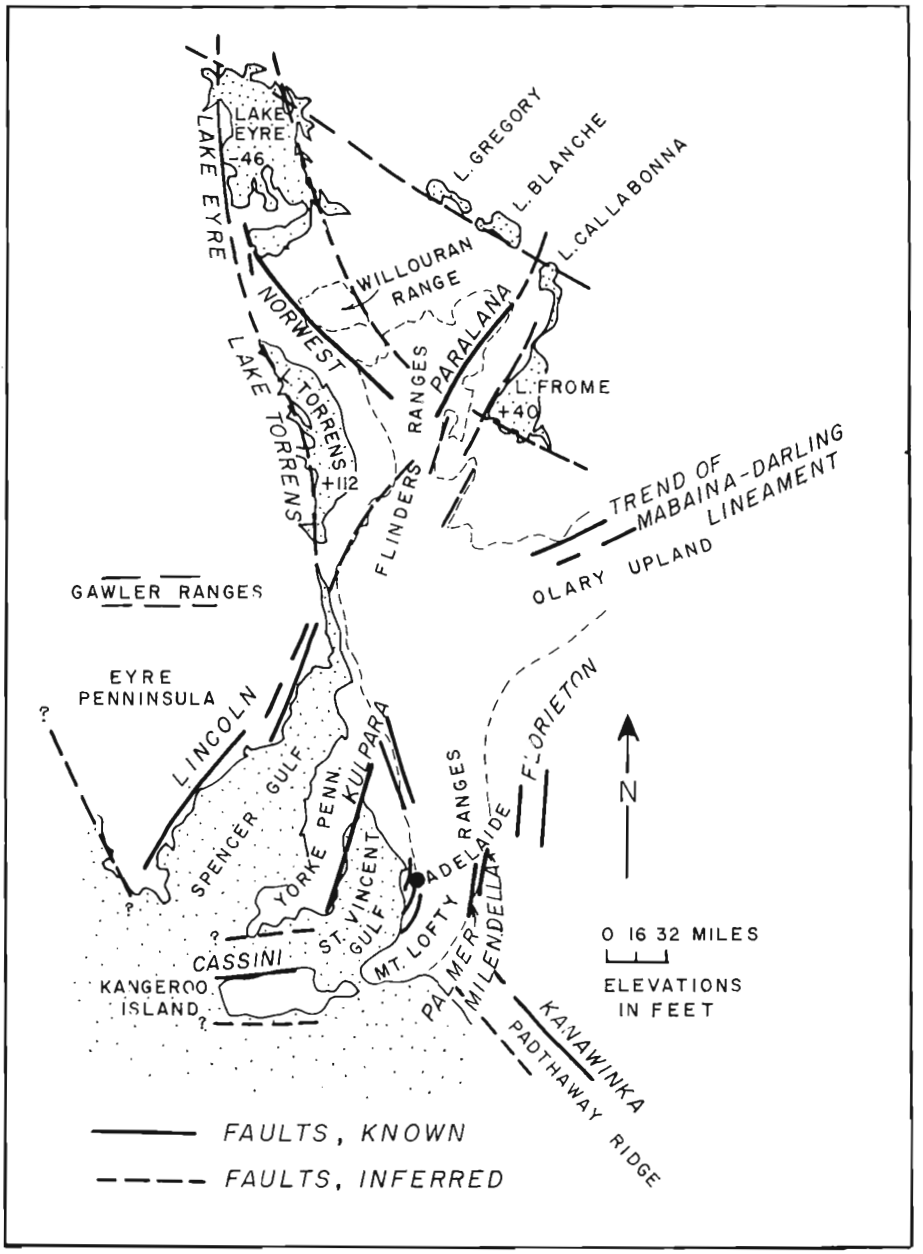


Figure 1. Sketch map of the principal faults in the vicinity of Adelaide.

traced into the Flinders Ranges where, in the northeast for example, it appears as the Paralana fault demarcating the upland from the Lake Frome basin. Yorke Peninsula is similarly outlined by faults, the Kulpara fault on its eastern side being particularly well expressed topographically. On the eastern margin of St. Vincent Gulf, a series of gently arcuate fault blocks dip southwesterly beneath the waters of the inlet, and in the intervening fault block depressions — the Adelaide, Noarlunga and Willunga basins — there has been spasmodic deposition since early Tertiary times. The faults, which are arranged en echelon, together comprise a strong N-S trending zone of displacement which is repeated many times within the Mt. Lofty block, and which is paralleled in the eastern side of the upland by a complex of dislocations (including the Florieton, Milandella and Palmer faults) that define the border between the horst block and the Murray basin. In the south of the Gulfs region, in southern Yorke Peninsula and on Kangaroo Island E-W faulting is important in delineating upland and lowland, land and sea.

To the north of the Gulfs area, the single stem of the Y is represented by the Lake Torrens depression. The western edge of the depression is delineated by a single, arcuate N-S trending fault zone; the eastern is more complex and involves a number of important zones but essentially forms a lowland embayment between the NNW-SSE trending Norwest fault, and the NE-SW trending Lincoln-Paralana fault. The fault trough, which is now occupied by the Lake Torrens salina (112 feet above sea level) and by desert plains, was the scene of freshwater sedimentation in the middle Tertiary. Still farther to the north, in a large westerly extension of the Great Artesian Basin, is the lowest part of the Australian Continent — the bed of Lake Eyre, a salina about 3,600 square miles in area and 46 feet below sea-level. Not only is the whole Lake Eyre depression a negative tectonic area, but the Lake Eyre salina itself appears to be a downfaulted block. The western margin of the Lake is, disregarding minor crenulations due to stream erosion, a remarkably rectilinear feature. On the bed of the lake, mound springs display alignment along N-S lines; earth tremors are restricted to the neighbourhood of the western scarp; and Wopfner has suggested that the gypsite which caps the western escarpment of the lake basin is the same formation which occurs at shallow depth beneath the bed of the salina. Moreover, this postulated major fault lines up with fractures to the south. Thus subsidence, rather than deflation, appears to be primarily responsible for the Lake Eyre salina.

Other major salinas, including Lake Frome (about 40 feet above sea-level), either lie along, or are to a significant degree defined by, faults of the lineament pattern (Fig. 1).

Thus the central N-S zone of South Australia, essentially at the margin of the Shield, comprises a series of positive and negative faulted or

warped blocks, some of them long and narrow and of the horst and graben type, and others having a more complex pattern.

In eastern South Australia, in the Olary upland and Murray basin, strong lineament trends (many of them the terminations of structures strongly developed in adjacent States) determine the major geomorphological features. The Anabama-Darling lineament, for example, continues in the ENE-WSW trend of the Olary and its regional structures, and the course of the Murray owes much to lineaments in the underlying bedrock. The Padthaway ridge (or horst), separating the Murray basin with its late Mesozoic and Tertiary marine sediments from the Southern Ocean, trends NW-SE, is only shallowly covered by unconsolidated deposits (so that granitic rocks, for example, are exposed) and is in part at least defined by faults.

To the west of the Mt. Lofty-Flinders upland, the whole of Eyre Peninsula is part of the rectangular Gawler block, the borders of which trend NW-SE and NE-SW. The Eucla basin, containing Cretaceous and Tertiary marine sediments, is bounded on the NE by the lineament defining the SW edge of the Gawler block, and on the NW, it is probably bounded by another strong structural trend which turns NNE-SSW and which is paralleled by sections of the West Australian south coast. In the far NW, the Everard, Musgrave, Mann and other ranges form part of the E-W structure that is so distinctive a feature in central Australia. But there is an obvious and marked concentration of major faults within and bordering the upland backbone of South Australia, and immediately to the west, at the margin of the Shield. This is the South Australian rift zone.

In most areas the nature of the faulting is not clear. The Norwest and Paralana faults are thrust faults, and although those in the Adelaide area are generally regarded as normal, there is some evidence that, locally at least, they are of reverse type. A theory of the mechanics of faulting on the South Australian rift area has been elaborated by O'Driscoll (1962), but much geophysical work remains to be done in the area.

The framework of lineaments is ancient, but there is ample evidence and suggestion of recent displacement of the fault blocks. For example:

(a) Earthquakes and earth tremors commonly occur in the vicinity of known faults.
(b) Many fault escarpments are so little dissected and have receded so little that the faulting must have occurred in geologically recent times.
(c) This argument can in some areas be substantiated stratigraphically. From evidence exposed on the western side of the Mount Lofty Ranges near Strathalbyn, Horwitz (1960) has argued that the faulting is

post-Miocene. In the Adelaide area, Glaessner (1953) has been able to demonstrate several phases of dislocation, including one of Pliocene or later age. Near Whyalla, marine Pliocene sediments were deposited at the base of the Lincoln fault zone escarpment. The possible displacement of Pleistocene gypsite at the western margin of Lake Eyre has already been mentioned.

Other possible demonstrations of recent and continued dislocation, for example in the Adelaide and the Gulfs areas, are uncertain because of difficulties in distinguishing between tectonic and eustatic effects, but in all probability, the rift system in South Australia is continuing to develop.

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THE MEDIAN ZONE OF ICELAND

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Abstract

The paper summarizes the results of recent geological and geophysical studies that serve to describe the median zone or central graben of Iceland, or bear on the problem of its origin.

The median zone is a shallow graben of Plio-Pleistocene age about 250 km wide in its southern part and 120 km wide near its northern end. It is mainly filled by the so-called palagonite formation, which is a mixture, partly of subaerial and subglacial eruptions (palagonite breccias and pillow lavas), and partly of glacial, fluvial and eolian deposits. The median zone divides the Tertiary basalt plateau into two areas. The plateau consists of a pile of tholeiitic and olivine basalt flows having a total thickness (above sea-level) of about 10,000 m. A striking contrast in landscape between the plateau basalt areas and the median zone is mainly due to external conditions; the chemical composition of the erupted materials is the same. The median zone is characterized by extraordinary volcanic activity and great numbers of tension fissures. The volcanism has been continuous from the Tertiary through Pleistocene and Postglacial times, and is distinctive in its linearity.

Seismic refraction measurements show a layer of palagonite formation (P-velocity, 2.8 km/sec) and two layers of plateau-basalts (P-velocities, 4.2 and 5.1 km/sec), with an aggregate thickness of about 3 km. These are underlain by a layer with a P-velocity of 6.3 km/sec, which is also found beneath the plateau-basalts of the Faroe Islands, but not along the mid-Atlantic ridge north and south of Iceland. Opinions still differ as to the nature of the 3 km/sec layer, but it probably can be revealed by drilling because, in one area, it is at a depth of only 0.6 km.

Geological and geophysical research work in Iceland has shown that the oldest rocks are at the eastern and western sides of the country, and it has recently been postulated that they have been carried hundreds of kilometres apart by crustal drift. The postglacial rate of drift may be 1-2 cm/year.

INTRODUCTION

By way of an introduction to this paper, I would emphasize its compilatory character. The paper attempts to briefly summarize the results of the geophysical and geological research that has been carried out in Iceland by Icelandic as well as foreign scientists during the last decades, and which has a bearing on problems related to the median zone of Iceland (also known as the mid-Icelandic graben, or the central graben). My part in this research is very small.

Interest in this zone has increased since the discovery of the rift valley of the mid-Atlantic ridge in 1953 because the zone is apparently a surface exposure of the submarine rift and therefore more accessible to study. The question is: How typical a part of the mid-Atlantic rift zone is the mid-Icelandic zone?

GEOLOGICAL FEATURES OF THE MEDIAN ZONE

When looking at the geological setting of Iceland, two facts stand out as most important. One is the country's central position within the Thulean or North-Atlantic plateau basalt province, and on the submarine Wywille Thomsons Ridge, which runs from East-Greenland to the British Isles (Fig. 1). The other, already mentioned, is that the country is crossed by the mid-Icelandic rift zone. Iceland is therefore like Gallia in Caesar's time – divisa in partes tres.

The east and west parts of Iceland are built mainly of Tertiary plateau basalts (Fig. 2) which now cover about 50 per cent of its area or about 50,000 km^2. The plateau basalts to the east have, during the last 10 years, been thoroughly studied by G.P.L. Walker of Imperial College in London and his collaborators (Walker, 1959 and later). Walker has found that a succession of tholeiitic and olivine basalt flows forms about 85 per cent of the volcanic pile above sea-level, the total pile having a thickness of about 10,000 m. Acid and intermediate rocks and detrital beds form the rest. In general, the basalts dip inward at an average of 8° near sea-level, and at about 4° at the mountain summits 1,000 m or so above sea-level (Fig. 3). The dip is towards the median zone, which is a shallow graben bounded partly by fault-scarps and partly by warpings and having a maximum down-throw of less than 1 km. To the north, the graben is simple and about 120 km wide. To the south, it is more complex (Fig. 4) and about 250 km wide. The youngest plateau basalts which are down-faulted or warped into the graben are the so-called grey basalts or Graue Stufe, belonging to the magnetic periods N_1, R_1 and N_2. Van Bemmelen and Rutten (1960) regard the graben as post-Willafranchien, but there is some evidence that the down-faulting began at least as early as the Upper Pliocene (Bárdarson 1926).

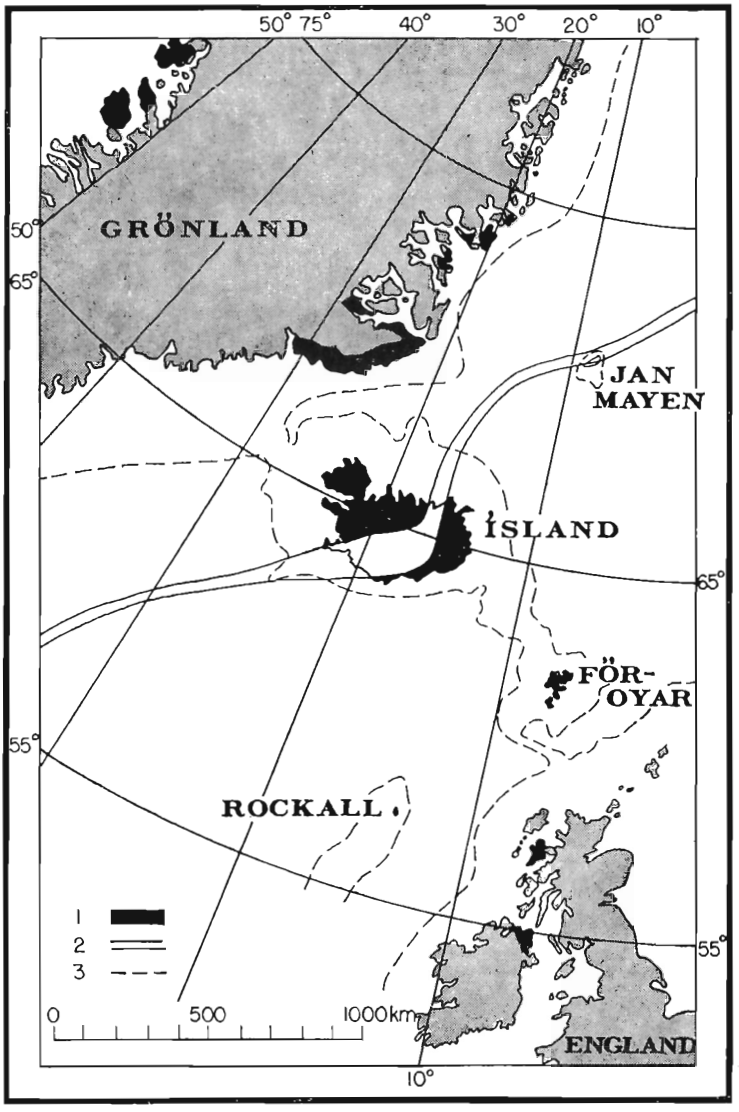


Figure 1. The North Atlantic Tertiary volcanic regions and the mid-Atlantic rift zone. 1. Tertiary basalts. 2. Mid-Atlantic rift zone. 3. 600 m depth contour. (From Thorarinsson, 1964; based on Richey, 1935.)

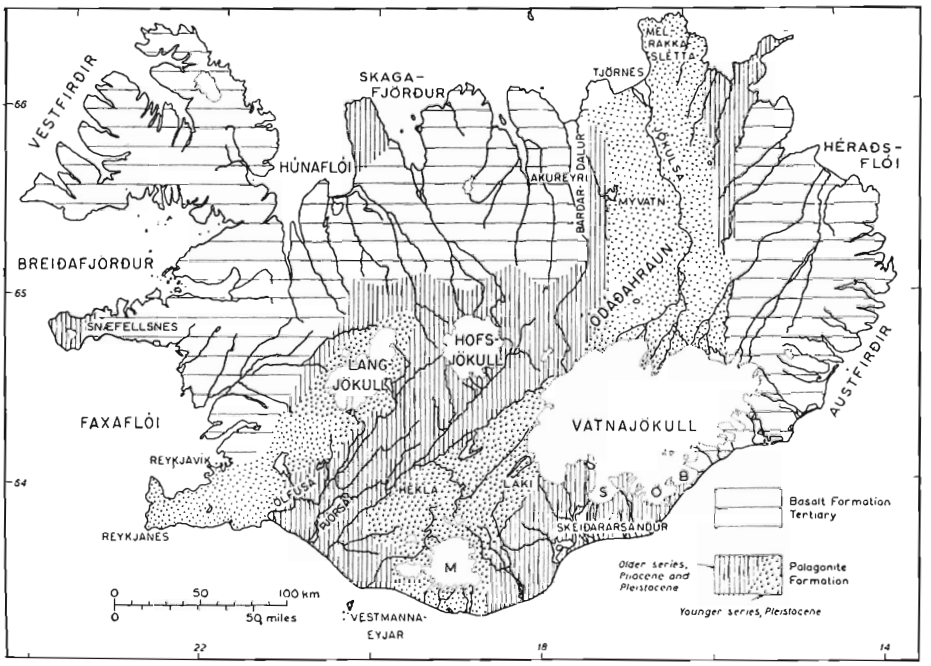


Figure 2. The bedrock formations of Iceland. (From G. Kjartansson in Askelsson et al. 1960.)

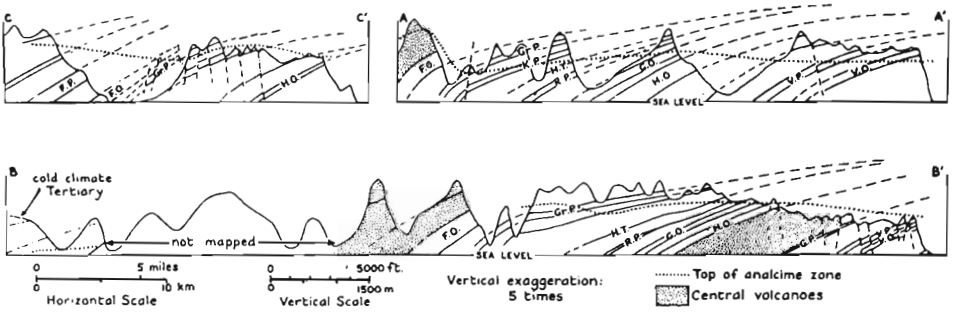


Figure 3. Sections through the basalt lava pile in E. Iceland. (From Walker, in Bodvarsson and Walker, 1960.)

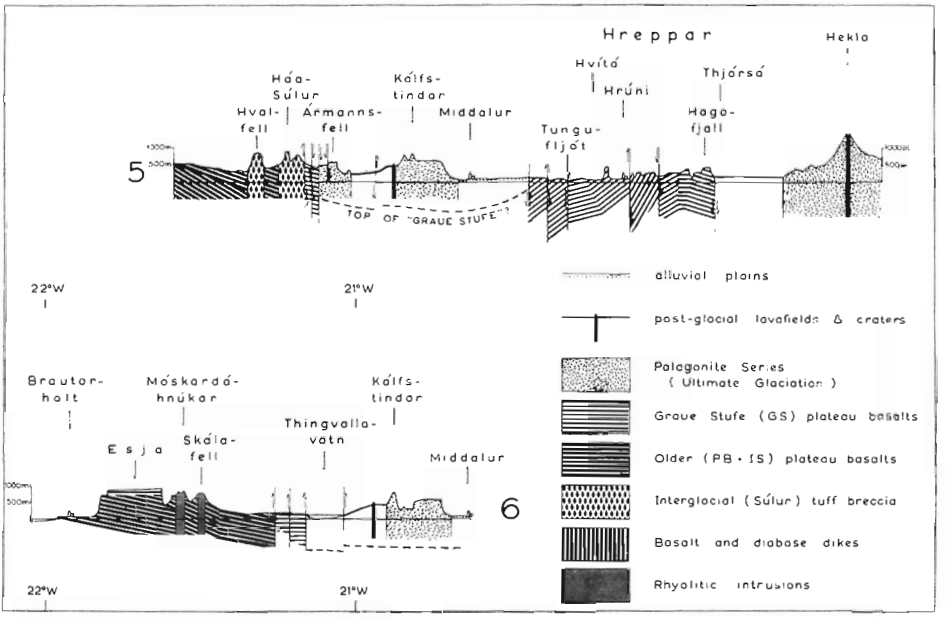


Figure 4. Sections through the southwestern part of the mid-Iceland graben. Vertical exaggeration, x5. (From Bemmelen and Rutten, 1960.)

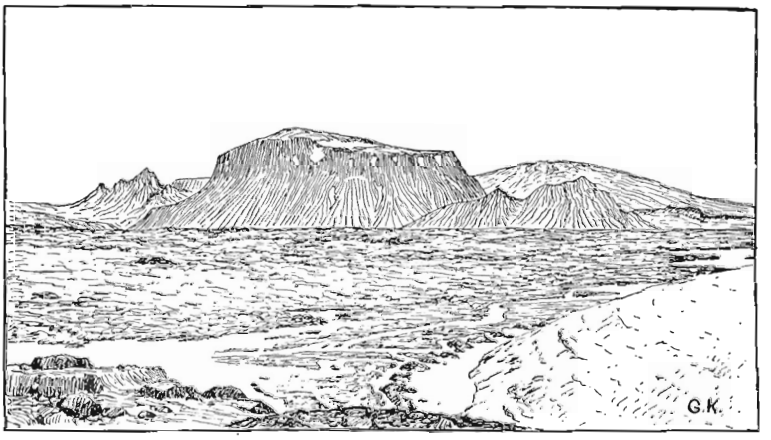


Figure 5. Three types of Icelandic volcanoes viewed from the south side of Langjökull. In the middle, a tablemountain; (Hlödufell) to the right, a shield-volcano (Skjaldbreidur); to the farthest left, and in front of Skjaldbreidur, ridges (Skridutindar and Thórólfsfell). (From G. Kjartansson in Áskellson et al, 1960.)

The mid-Icelandic graben is more or less filled by so-called palagonite formation (Fig. 3), which is a complex mixture partly of subglacial and subaerial eruptives and partly of glacial, fluvial and eolian deposits. The most common and characteristic rock, however, is a brownish tuff breccia rich in the hydrated basalt glass known as palagonite. Pillow lavas and pillow lava breccias are also very common.

There is little doubt that the entire median zone and limited areas to its west were more or less volcanically active during the Pleistocene glacial and interglacial periods, and that this activity was a direct continuation, without interruption, of the Tertiary activity that formed the plateau basalts. The chemical composition of the rocks also is essentially the same. The striking difference in landscape between this area and the Tertiary basalt plateaus is due to external conditions: viz., the repeated covering of the country by the Pleistocene ice-sheets which blanketed the volcanic activity. Thus the median zone is not only a supramarine part of the mid-Atlantic rift zone, it is also an area where relatively recent volcanism has taken place under conditions rather similar to those along the submarine parts of the ridge.

The main types of subglacial volcanoes are the steepsided table mountains formed by repeated central eruptions. During ice free periods, the same eruptive centres built up shield volcanoes of the Hawaiian type. Long serrated ridges developed during glacial times correspond to the postglacial crater rows (Fig. 5).

The postglacial volcanism is limited to narrower belts (Fig. 6), covering about one-third of the country. The width of the belt is 45 km in its northern parts, and the aggregate width of the two belts in the south is 150 km. These belts are divided by the so-called Hreppar Formation which forms a horst of Plio-Pleistocene age. In addition, there is postglacial volcanism on Snæfellsnes and in Öræfajökull.

The postglacial volcanic activity was continuous with the Pleistocene activity, the only change in external conditions being in those parts of the country that are now free of ice. The table mountain activity has become shield volcano activity, and instead of serrated ridges, we now have crater rows. Two features especially characterize this zone. One is the extraordinary productivity of its volcanism and the manifoldness of the volcanic edifices and related phenomena. About 200 volcanoes have been active during Postglacial time, of which about 30 have erupted during the last 1,000 years (Fig. 7). About one-third of the lava produced on earth during the last 500 years was produced in this limited area, and one may find nearly every type of volcano existing on the face of our globe.

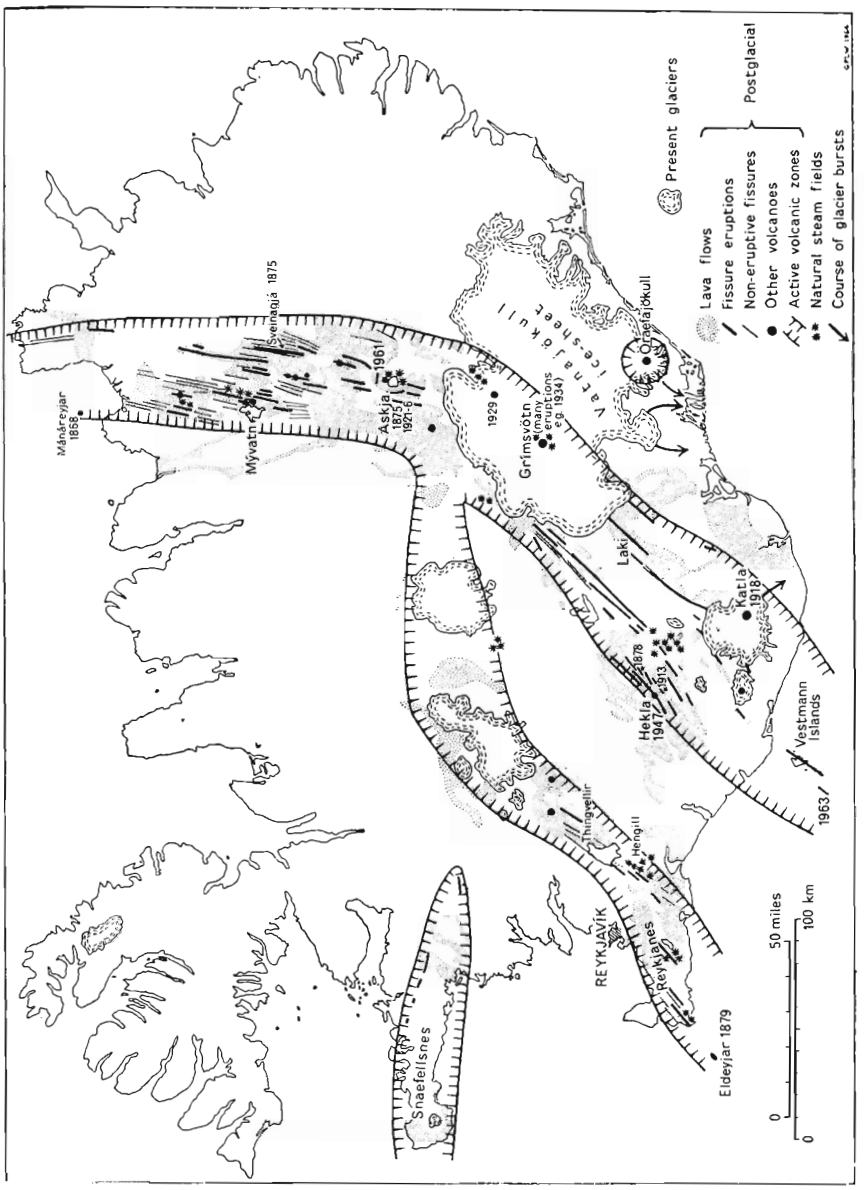


Figure 6. Map of Iceland showing the postglacially active volcanic zones and the distribution of postglacial volcanoes and their products. (From Walker, 1964.)

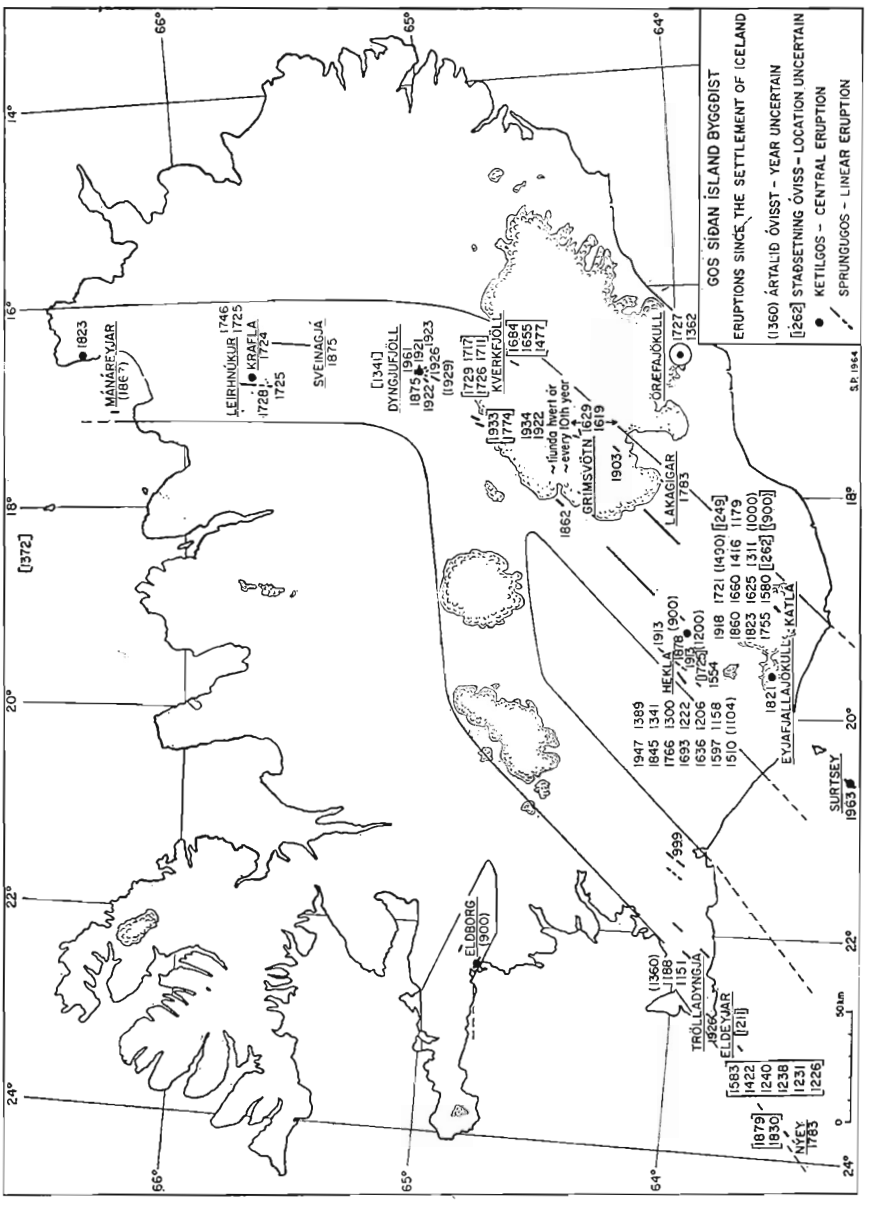


Figure 7. The historical volcanism in Iceland. (From Thorarinsson, 1964.)

The other characteristic feature is the enormous number of fissures within the zone. Many have produced lava but many have not. The verical displacement along the fissures is generally small and commonly negligible; horizontal displacement has not been detected. The fissures are clearly tensional. They have parallel trends, in a NE-SW direction in southern Iceland, and in a N-S direction in northern Iceland; and they thus meet in central Iceland with an angle of about 120°, the same angle that we find when, for example, permafrozen ground splits into tundra polygons, or when basalt is jointed.

Figure 8 is a map of the southwesternmost part of the Reykjanes Peninsula where the mid-Atlantic rift zone reaches shore. Another striking part of the rift zone in southern Iceland is the Thingvellir graben (Fig. 9). This graben is less than 9,000 years old and is still in statu nascendi. In 1789, the lava plain within the graben to the east of Almannagjá subsided about 65 cm during an earthquake. The graben is bounded on both sides by step faults. The highest fault scarp is that of Almannagjá, which has a vertical displacement of about 40 m. Numerous tension rifts run through the lava flows on the floor of the graben.

Figure 10 shows part of the rift zone in northern Iceland. It is characterized by very narrow grabens, some only a few hundred metres wide although tens of kilometres in length. Some of the grabens may be termed linear calderas because they have formed by subsidence of a crater row and a strip of land along both sides of the row. Figure 11 shows part of the Mývatn Gjástykki rift system, and Figure 12 is a section through the same system somewhat farther south.

The volcanic eruption which has been going on off the south coast of Iceland since 1963 has clearly demonstrated the close relation between the crater rows, the shield volcanoes and the table mountains. The eruption started as a fissure eruption, but the activity soon became concentrated in the central part of the fissure and developed into a central eruption. If it had occurred on land, this eruption would have built a shield volcano, but as it was, it built up a socle of tephra and pillow lava, and it started a shield volcano activity when the socle was high enough that the sea no longer had access to the vent. The result is a table mountain, the Island of Surtsey. The activity in the table mountain ceased last May, but no sooner had it ceased than the fissure opened at another place 0.6 km ENE of Surtsey, where the eruption continued and is still going on.

GEOPHYSICAL FEATURES OF ICELAND

We now turn to geophysical studies of Iceland and its median zone. T. Einarsson (1954) has made a gravimetric map of Iceland. The

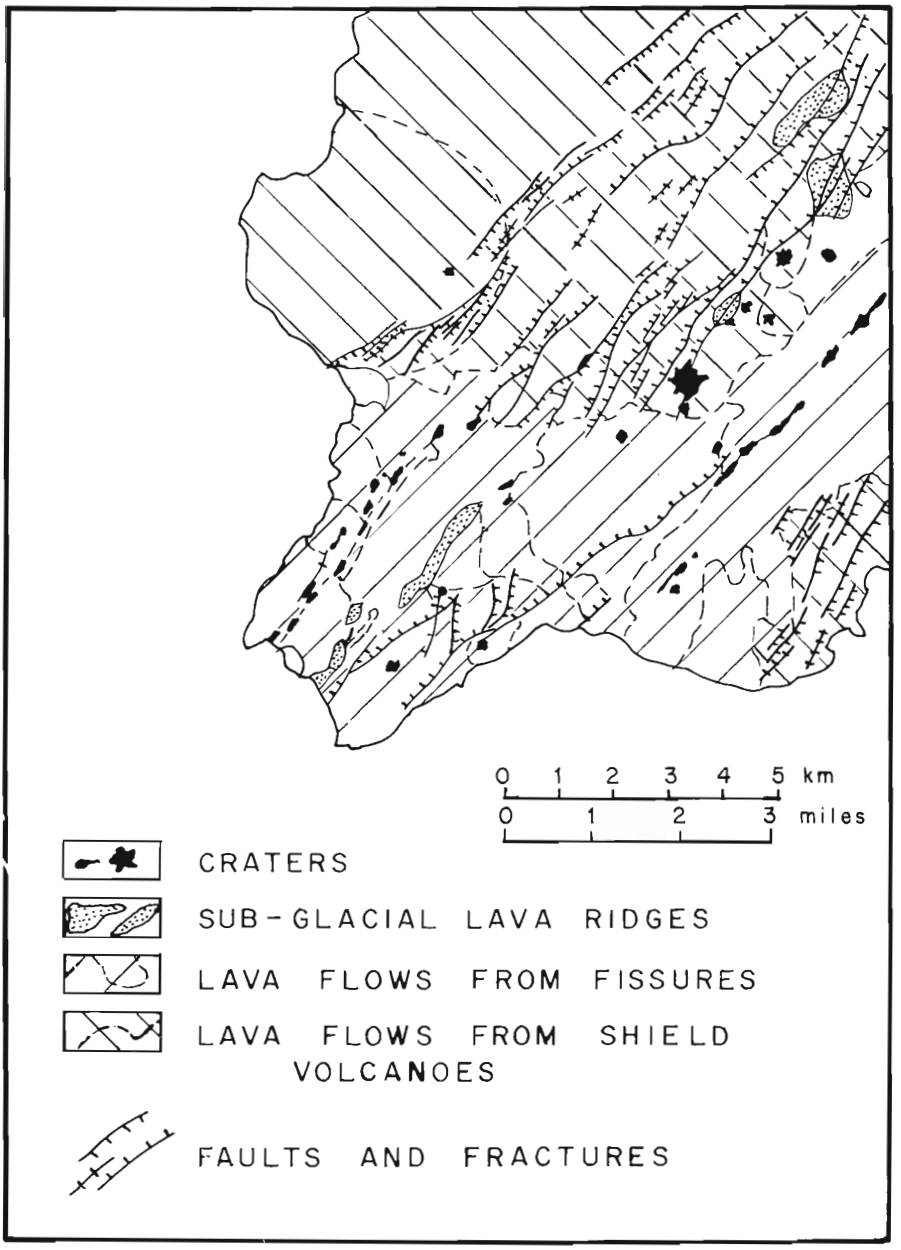


Figure 8. Geological map of the southwesternmost part of the Reykjanes peninsula. (Drawn by Jón Jónsson.)



Figure 9. The western part of the Thingvellir graben. View to the north. Almannagjá to the left. Photo by S. Thorarinsson.

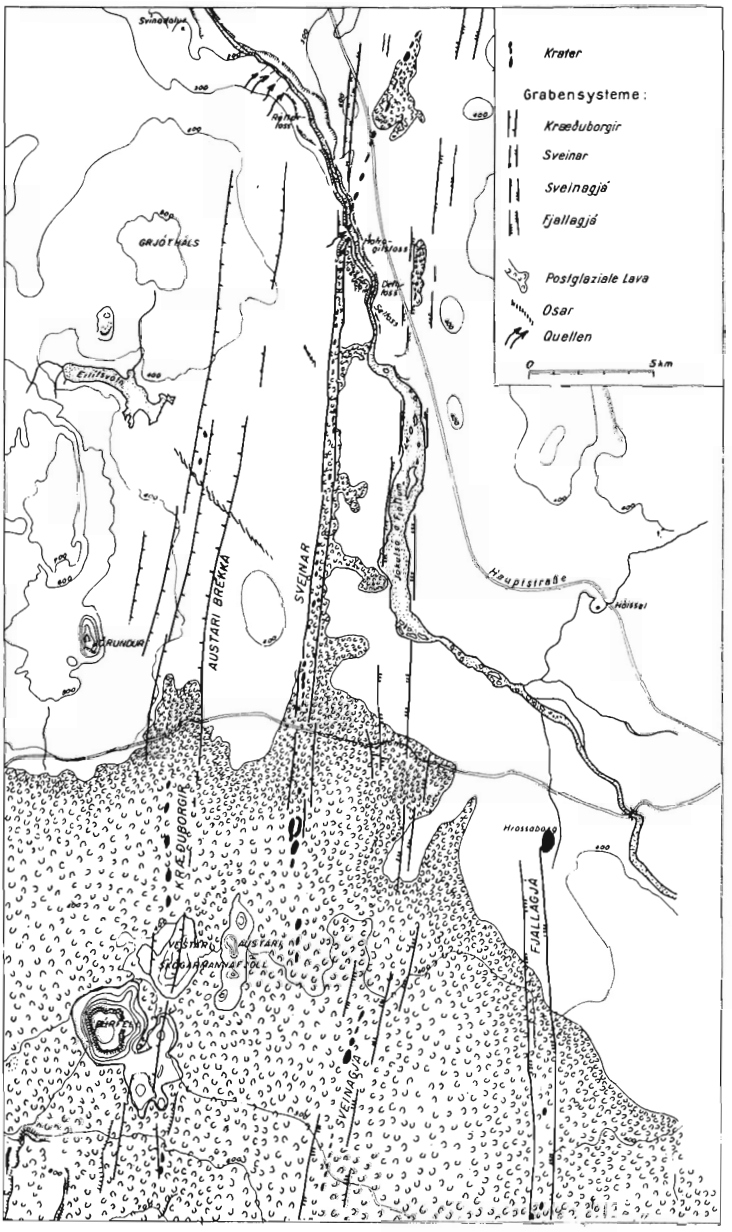


Figure 10. Graben systems and crater rows in the Jökulsá area, Northern Iceland. (From Thorarinsson, 1960.)



Figure 11. Part of the rift system of Mývatn, North Iceland. South is to the top of the photograph. (U.S. Air Force.)

Bouguer anomaly field is rather regular, having roughly the shape of a bowl with a minimum of -35 milligals in the central area and a maximum of +40 to +60 milligals in the coastal areas. Einarrson (oral communication) regards the shape of the gravity field as evidence against widening of Iceland.

Seismic refraction measurements in Iceland were started by Båth and Tryggvason who measured a profile northeastward from the Reykjanes area, but not directly crossing the median zone (Båth 1960; Tryggvason and Båth, 1961). This work,which is an important contribution to the geophysics of Iceland, has been continued by G. Pálmason, the present Director of the Department of Natural Heat in Reykjavík. Pálmason has measured numerous refraction profiles in many parts of the country and combined the results with magnetic and gravimetric measurements (Pálmason 1963). Figure 13 shows his W-E profile of North Iceland which is perpendicular to the graben. A layer of palagonite formation with a P-velocity of 2.8 km/sec is underlain by two layers of plateau basalts having P-velocities of 4.2 and 5.1 km/sec and an aggregate thickness of about 3 km. These rocks rest on a layer with a P-velocity of 6.3 km/sec which, according to Båth and Tryggvason, has a maximum thickness of 16 km beneath Iceland and is underlain by a layer with a P-velocity of 7.4 km/sec. Tryggvason (1962) concludes from dispersion of surface waves that the 6.3 km/sec layer extends for hundreds of kilometres outward from Iceland.

Recent seismic refraction studies in the Faroe Islands by Pálmason show essentially the same structure that he found in Iceland (Fig. 14). A sequence of plateau basalt flows having a total stratigraphic thickness of 3,000 m has similar velocities to the Icelandic ones (3.9 km/sec in the upper part of the upper basalt sequence, and 4.9 in the rest of the pile both above and below a lignite unit which had hitherto been regarded as marking the main division in the basalt formation). The basalts are underlain by a 6.4 km/sec layer. It is thus probable that this layer underlies the entire Wywille Thomsons ridge, but a layer of this velocity is not shown beneath the mid-Atlantic ridge in the most recently presented seismic-gravity models (Le Pichon et al., 1965; Talwani et al., 1965).

A very comprehensive study of natural heat in Iceland has been carried out since the second world war under the leadership of G. Bodvarsson, the former Director of the Department of Natural Heat. The study is based on numerous drill-holes (the deepest of which is 2,200 m) combined with geophysical research.

From measurements made in the drill-holes, Bodvarsson has determined conductive heat flow to be 3.2-3.6 μ cal/cm^2 sec, and the heat transport by thermal activity to be 1.0 μ cal/cm^2 sec. Thus the total heat transport is 4.2-4.6 μ cal/cm^2 sec, or nearly four times the global average. This is also higher than the average maximum recently measured over the

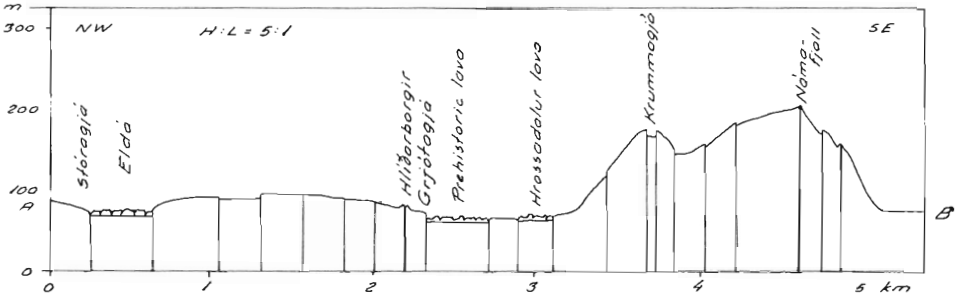


Figure 12. Section showing late-glacial and postglacial faults (thin vertical lines) and lava producing fissures (thick lines) east of Reykjahlíð in the Mývatn area, North Iceland. (From Thorarinsson et al, 1960.)

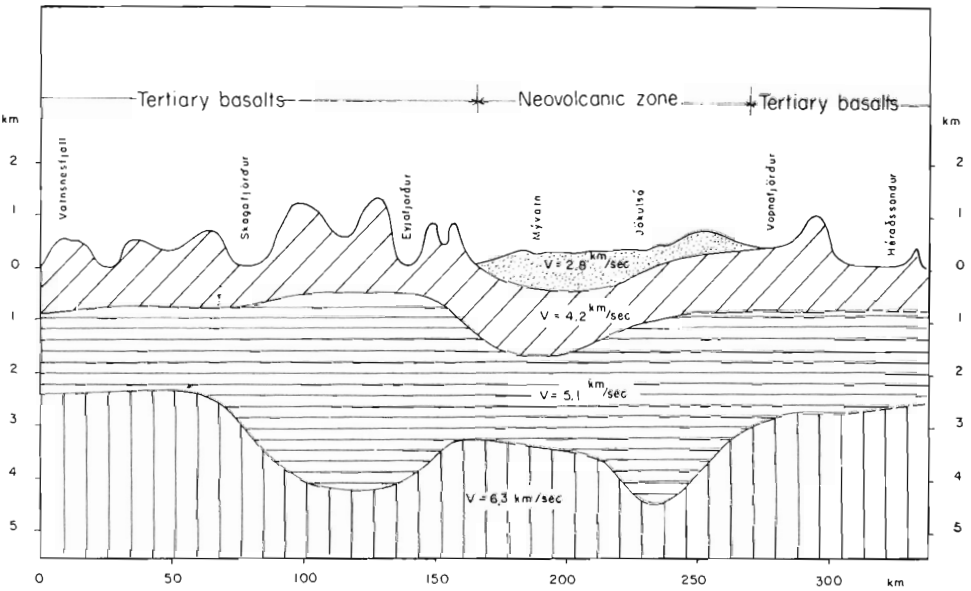


Figure 13. Schematic structure section (W-E) through North Iceland. (From Pálmason, 1963.)

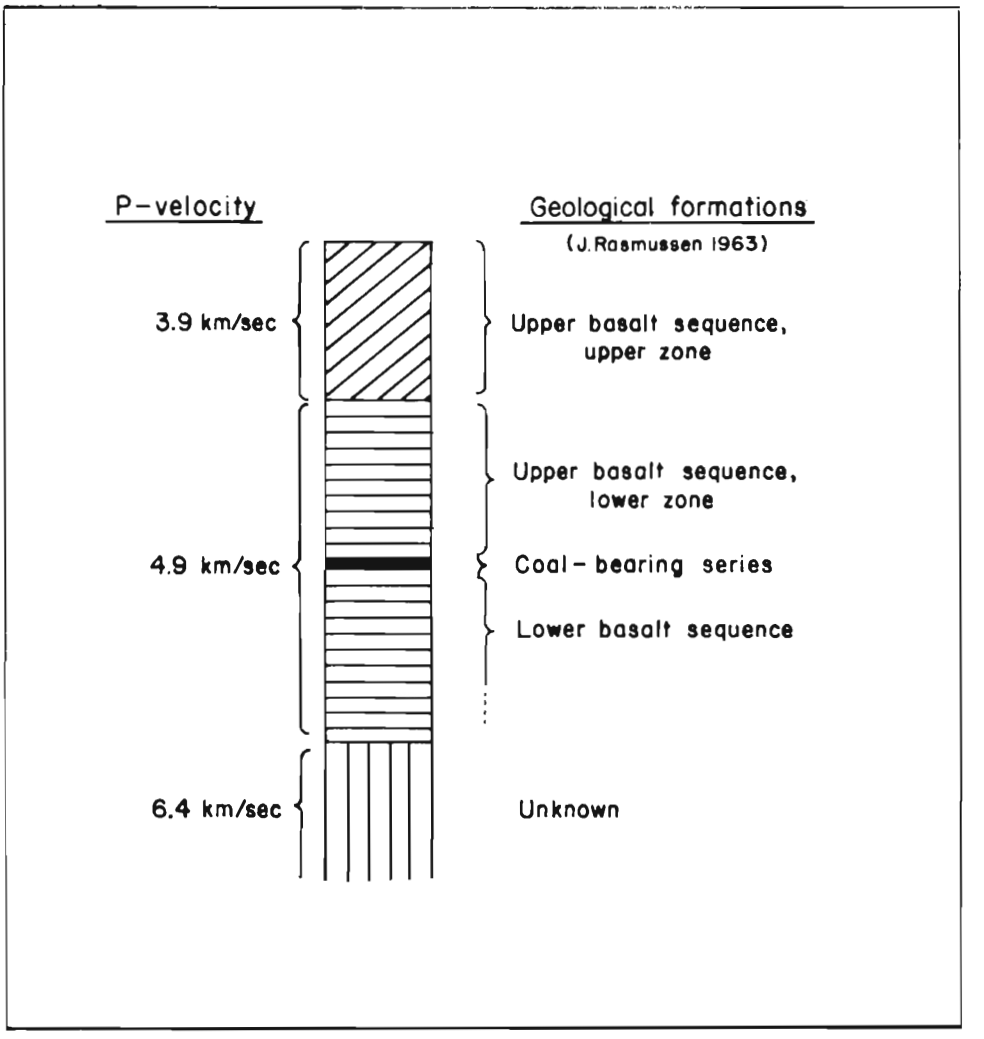


Figure 14. Correlation of seismic velocities and geological formations in the Faeroe Islands. (From Pálmason, 1965.)

East Pacific Rise at 10°N (Langseth et al., 1965). I may add that the most recent measurements of the heat flow in Iceland, made in a 1565 m bore-hole on Heimaey, Vestmann Islands, show a somewhat lower conductive heat flow (Pálmason, oral communication), and there is reason to think that the average heat flow in Iceland is similar to that on the mid-Atlantic ridge (3.3 μcal/cm^2 sec; Langseth, oral communication).

Bodvarsson assumes that the anomalous heat flow beneath Iceland is mainly due to more or less continuous intrusion of magma into the crust in amounts of about 0.1 km^3/year. According to Walker's estimates, quoted by Bodvarsson in their joint paper, an average of 0.025 km^3 of magma has reached the surface annually in postglacial times, or only about one fourth of the material injected into the crust. I may comment that, according to my estimates unknown to Bodvarsson, an average of about 0.04 km^3/year has reached the surface. Bodvarsson's gravity-seismic model of Iceland is shown on Figure 15. He interprets his layer D (Pálmason's layer 3) to be a mixture of plateau basalts and injections of higher velocity material. To explain his model, he assumes a continuous widening of Iceland by injections of new material into the central area.

CRUSTAL EXTENSION IN ICELAND

The idea that the median rift zone of Iceland indicates that the country is being torn apart by tensional forces was first expressed in print in 1929 by N. Nielsen. In 1938, a German expedition measured the width of the North Iceland graben by precision triangulation. The measurements were to be repeated after 10 years to determine if the graben zone was still widening, but they were not redone until this summer and the results are not yet known. Van Bemmelen and Rutten (1955) also considered the graben to be an effect of tensional movements, but contrary to the idea put forward by Nielsen (1929) and Bernauer (1939) that it is a feature of great regionality, they regarded it as reflecting gravity pull on a restricted scale related to the tectonic high of Iceland. They believed that, at the end of the Tertiary, Iceland stood as a horst above surrounding basins. This created a stress field, and the tensional stresses in the top resulted in the formation of swarms of fissures which then acted as pathways for basalt and eventually led to the collapse of the horst.

G.P.L. Walker has recently published some interesting observations on this problem in joint authorship with Bodvarsson (Bodvarsson and Walker, 1964). His conclusions, which were reached independently and on purely geological grounds, were similar to those of Bodvarsson in regard to the widening of Iceland.

Walker found in eastern Iceland that, in one traverse of 37 km, there were 450 dykes with an aggregate thickness of 2.3 km. In another traverse of 53 km, there were 1,000 dykes with an average thickness of 3 m. He believes that injection of dykes is the main process resulting in crustal extension in Iceland and he has tried to calculate that extension. As noted above, he found the stratigraphic thickness of the supramarine pile of rocks in eastern Iceland to be 10,000 m. He also states that the strata generally dip toward the west and become thinner up dip (cf. Fig. 3) so that the original surface was probably not more than 500 m above the present summit surface. Because of the down-dip thickening of the strata, only a slight extrapolation below sea-level increases the thickness of the pile enormously, and Walker considers 20-30 km to be a reasonable total stratigraphic thickness for the basalt. He estimates that to feed all this basalt, dykes with aggregate thickness of about 400 km are needed. Further, he has found many strato-volcanoes in eastern Iceland, the oldest of which are farthest to the east. Thus, he reaches what he calls a steady state hypothesis: viz., that the belt of active volcanoes in Iceland has remained approximately uniform during the Tertiary and Quaternary, with a width of only a few tens of kilometres and a constant intensity of activity. He suggests that the oldest rocks on the east and west have been carried apart by crustal drift caused by dyke injections having an aggregate thickness of about 400 km, and that the dip of the Tertiary lavas is due to successive stacking of flows on one side of the older ones.

Walker has also tried to calculate the present rate of tearing apart of the median zone. Assuming that the open fissures are surface manifestations of dykes that did not reach the surface, he finds that the rate of formation of dykes during the last few thousand years averages 6 mm/year and is thus sufficient to produce several hundred kilometres of crustal drift since the beginning of the Tertiary.

Walker's views, which are on line with views earlier expressed by Tuzo Wilson (1963), are certainly important because they are based on very thorough field work. I would make only three comments on them. Firstly, instead of considering the widening to be due to dyke injection, and the open fissures as being the surface manifestations of this process, I would rather think of tensional fissuring as the primary feature and the dyke injection as a geological consequence. Secondly, from my studies of the graben area in northern Iceland (and provided that the open fissures are surface manifestations of dykes, an assumption not yet proved), I would estimate that the rate of postglacial widening was at least double Walker's estimate, or 1-2 cm a year; thus only 20-30 million years would be needed for a crustal drift of 400 km and not the entire Tertiary period. Thirdly, I would point out that even a rate of widening as large as my estimate cannot account for the difference between the widths of the belts of glacial and

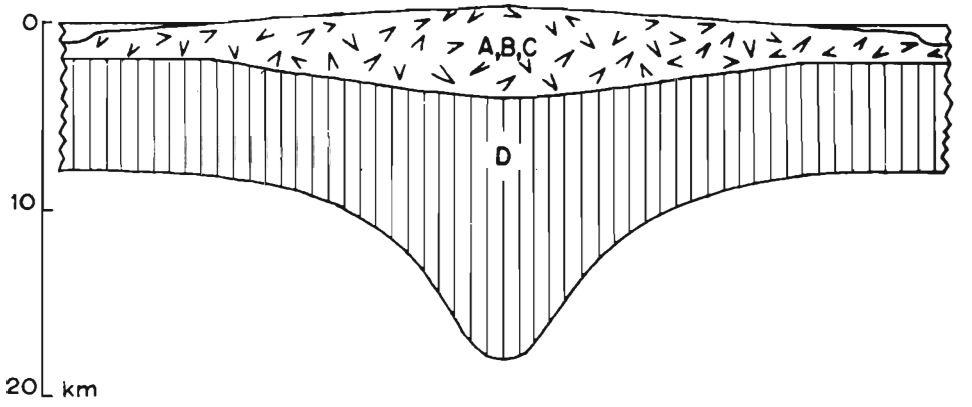


Figure 15. Bodvarsson's seismic gravity model of the structure of Iceland. (From Walker and Bodvarsson, 1964.)

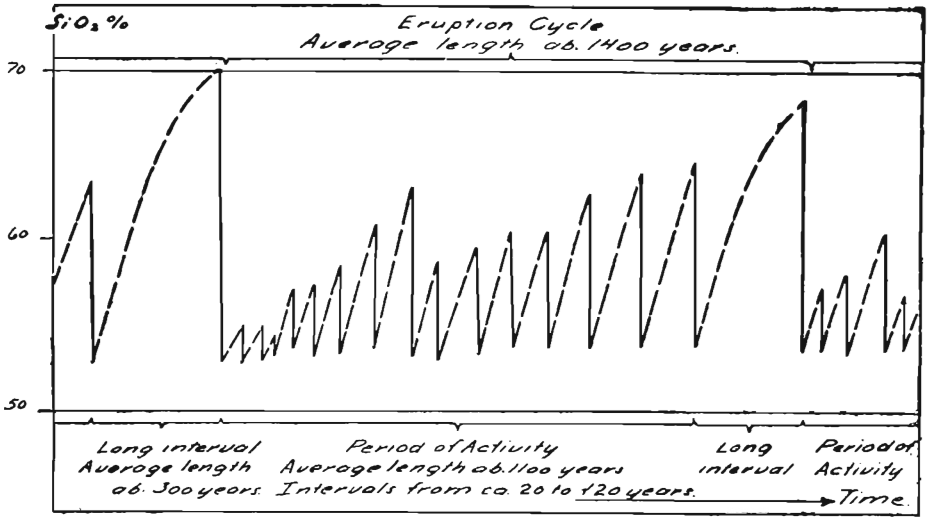


Figure 16. Schematic diagram of a typical Hekla eruption cycle and period of activity. (From Thorarinsson, 1955.)

postglacial volcanoes; there has certainly been a considerable narrowing of the active belt during the last million years or so.

VOLCANOLOGICAL AND PETROGRAPHIC STUDIES

There is also a volcanological and petrogenetic approach to the problems discussed above which deserves consideration.

It has long been known that basalt is the predominant rock in Iceland. According to Thoroddsen's geological map, acid rocks (rhyolites) cover less than one per cent of the country's area, and the map shows no intermediate rocks. It has therefore been stressed by some geologists – for example, van Bemmelen and Rutten (1955) – that there is a miscibility gap between basalts and rhyolites. However, recent petrographic work (Walker, 1959, 1962, 1963; Sigurdsson, 1965; Sigvaldason, unpublished; and others) and volcanological and tephrochronological studies (Einarsson, 1950; Thorarinsson, 1954, 1958, 1959) have modified the above picture. The postglacial eruption history of Hekla, Askja and other strato-volcanoes in Iceland has shown that not only have these volcanoes periodically produced a great amount of rhyolitic material, mainly tephra, but also andesitic and dacitic material, thus bridging the gap between the rhyolites and basalts. At least three per cent of postglacial eruption products in Iceland are acid (Thorarinsson, 1959). Walker (1959) found that in the Reydarfjördur area in eastern Iceland six per cent of the lavas were acid and three per cent were andesitic. He also demonstrated the existence of extensive welded acid tuffs (Walker, 1962; cf. also Dearnly, 1954; and Tryggvason and White, 1955).

The tephrochronological studies of Hekla and other postglacial volcanoes has revealed that, from a petrogenetic point of view, there are mainly two types of volcanoes in Iceland. One is the mass producing fissures and shield volcanoes typified by Laki and Skjaldbreidur; these have produced basalt of practically the same composition for the whole of Postglacial time, and are presumably fed by a deep-seated, uniform magma source. The other type is the strato-volcano such as Öræfajökull, Askja and Hekla, which are fed by separated magma chambers at shallow depths, and in which there is evidence of differentiation between eruptions. Hekla is the best studied and the most striking example of this differentiation process, the SiO_2 content of the initial products of each eruption being nearly a linear function of the duration of the preceding period of repose (Fig. 16).

Walker and his collaborators have now found in eastern Iceland many Tertiary strato-volcanoes of the same type as the postglacial ones (Walker, 1963).

Since the discovery of the acid Krablite on the Krafla volcano more than a century ago, many geologists have assumed that an acid layer is present beneath the plateau basalts of Iceland, and some petrographers still hold to this opinion and consider the rhyolites to have formed, at least in part, by fusion of this sialic substratum. Van Bemmelen and Rutten (1955) have done so, basing their assumption on the absence of intermediate rocks, which as was already mentioned is incorrect. Walker finds it difficult to explain the great amount of acid rocks in eastern Iceland without the existence of sialic substratum and T. Tryggvason (1965) who has studied some acid xenoliths from Hekla and other postglacial volcanoes also seems to favour this view. He is inclined to explain the bowl-shaped low in the gravity field as the result of a sialic layer, and he attributes the P-velocity of layer 3 to sialic rock densely cut by basalt dykes. He quotes Noe-Nygaard (1940) as being of the opinion that the present height of Iceland may be due to acid masses beneath the plateau basalt cover.

Other petrographers such as G. Robson (unpublished paper) and Sigurdsson (1965) would rather interpret the acid rocks as solely the result of gravitational fractionation of a parent basalt magma. Sigurdsson points out that the relatively great amount of rhyolitic rocks found above sea-level may be due to concentration of the acid material in the uppermost parts of the basalt bulk because of its lower specific gravity. He mentions a strong argument for the opinion that the basalts and rhyolites are consanguineous; viz., according to unpublished results by Moorbath, the Sr^{87}/Sr^{86} ratios of the basalts and rhyolites are the same. This, and Pálmason's statement that Poissons ratio is about the same (about 1.27) for the 6.3 km/sec layer and the plateau basalts are in my opinion the strongest arguments against a sialic substratum.

Recently, it has been shown (Engel and Engel, 1964; Engel, Engel and Havers, 1965) that tholeiites with low values of K, Ti and P are predominant on the submerged parts of the mid-Atlantic ridge, whereas volcanic islands on the ridge are built of alkali basalts. It was mentioned earlier that tholeiitic basalts are common in Iceland, but they appear richer in alkalies than those typical of the submerged ridge and thus of a more continental type. Consequently, although Scheinmann (1964) is not correct in stating that Iceland differs from all other parts of the mid-Atlantic ridge by producing tholeiitic basalts, Iceland does differ in this respect from other islands along the ridge. Scheinmann regards the Icelandic tholeiites as a proof of the existence of continental subcrustal material not yet completely replaced by an oceanic crust, whereas Engel, Engel and Havers regard the tholeiitic magma on the submerged ridge as a primary magma from which the alkali basalt is derived.

There is still one fact to be mentioned which is significant in this discussion. During the last eruption of Hekla, there was a large drop

in the SiO_2 content of the tephra ejected during the Plinian initial phase of the eruption. This phase started with the mass production of greyish brown soda rhyolite (SiO_2 content, 63 to 62 per cent) but changed after about half an hour to the production of dark brown dacite (SiO_2 content, about 57 per cent). This change was abrupt, and it seems to speak against gravitative crystal fractionation, which is more likely to lead to a gradual change in the composition. Rittmann (1962) regards the abrupt change as absolute proof of a sialic roof above Hekla's magma chamber.

Thus the opinions of volcanologists as well as petrographers still differ with regard to the nature of the substratum of the plateau basalts in Iceland, and the results of seismological research are not yet conclusive. We need more knowledge about the 6.3 km/sec layer, and fortunately, it seems now possible to gain that knowledge without too frightening a cost. Pálmason's thorough measurements have revealed that, in one limited area in northern Iceland, the surface of that 6.3 km/sec layer is at only 600 m depth. A core drilling to about 1,000 m depth would, in all probability, add a lot to our knowledge of this layer. Such a drill-hole would cost about $30,000. With the expressed hope that this sum can somehow be raised, I end my paper.

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MID-ATLANTIC RIDGE BETWEEN 45°N AND 46°N[1]

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and

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Abstract

Detailed surveys of contiguous areas made by RRS DISCOVERY II in 1960 and CSS HUDSON in 1965 have made it possible to compile maps of bathymetry, total field magnetic anomaly and gravity anomaly which cover an area approximately 50 x 20 miles along the crest of the Ridge. Within the surveyed area, the median valley and the associated belt of large positive magnetic anomalies are continuous and display a striking lineation in direction 020 degrees. Minor features, revealed by closed contours are developed en echelon and have an elongation of about 4:1. Trench floor sediments were not observed but several minor ponded sediment basins were seen on the flanks. Near the northern end of the area the valley is partially blocked, apparently by confluent flows from two unusually large volcanoes standing on either side of the valley. Underwater camera photographs showed pillow lavas, and olivine basalts and dolerites were dredged near this point.

Magnetic anomalies within the surveyed area can be simulated by a two dimensional model in which steeply dipping contacts separate blocks of rock having different magnetization. These blocks could be entirely within the volcanic layer extending to a depth of 5 km below sea level, but the central block, immediately underlying the median valley, must be much more strongly magnetized than those adjacent to it. The free air gravity anomaly shows a strong resemblance to topography and largely disappears when the Bouguer anomaly is calculated, indicating that the intrusive body immediately underlying the median valley is not significantly different in density from the rocks beneath the elongated sea mounts overlooking the valley. Small variations in the Bouguer anomaly indicate that there is an increase in density in northwest direction across the survey area.

The mechanism by which the valley was formed remains obscure although it is thought to be a volcanic, rather than tectonic feature.

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[1]For the complete paper, see the Canadian Journal of Earth Sciences, 3, 327-349.

THE DEVELOPMENT OF EUROPEAN RIFTS

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Abstract

The purpose of this paper is to call attention to the fact that many rifts in Europe are marked by en echelon faults. These structures developed at an early stage and prove that horizontal movement contributed to the formation of the rift. All rifts investigated by the writer trend north-northeast and exhibit right-hand movement. In the Oslo graben, down-faulting began in Permian times; in the Rhine graben, vertical movements commenced in the lower Oligocene and are continuing at the present.

INTRODUCTION

The most important European rift system is the so-called Mittelmeer-Mjoesen Zone of H. Stille, a rift system which extends, according to this conception, from the Mediterranean Sea to Mjoesen Lake north of Oslo in Norway. The best known parts of this system are the Rhine graben and the Oslo graben, each about 300 km long and 30 to 40 km wide. The most interesting part of the Oslo graben is the Oslo Fjord which is a graben in itself. The boundary faults of the Oslo Fjord are excellently exposed over a distance of about 20 km in walls up to 100 m high. The west and east coasts of the fjord consist of Precambrian gneisses, but the islands between them are composed of Ordovician and Silurian limestones and slates. The faults along the shore are encrusted with a blastomylonite which is overlain by a breccia containing fragments of blastomylonite comprising Cambrian and Ordovician rocks and, locally, Permian volcanic rocks. This indicates, as W.C. Broegger pointed out almost 80 years ago, that two phases of motion are involved. The first phase took place before the Permian, and the second happened after Permian volcanism.

DEVELOPMENT OF THE OSLO FIORD GRABEN

The west coast of the Oslo Fjord between Slemmestad and Naersnes is a pinnate fault with a horizontal en echelon arrangement of separate shear planes (Fig. 2). The development of these border faults occurred in the following manner. First, feather joints and feather fissures

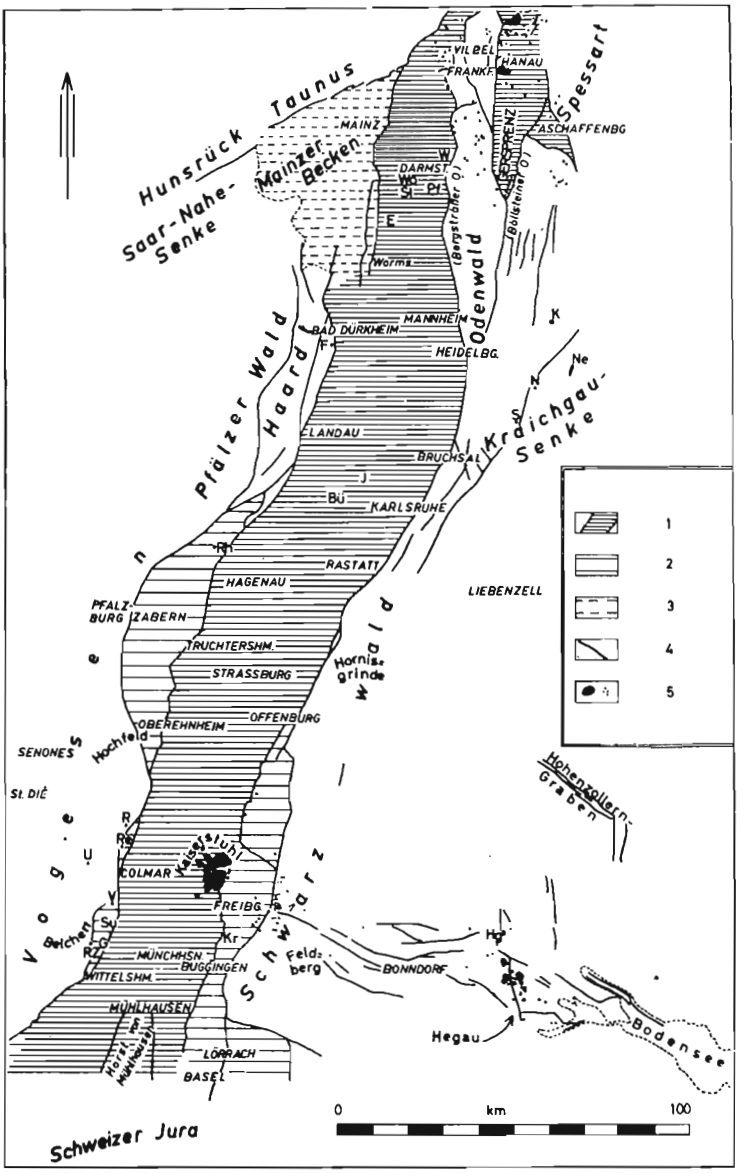


Figure 1. Graben and troughs of the Mittelmeer-Mjoesen Zone according to R.v. Zwerger.

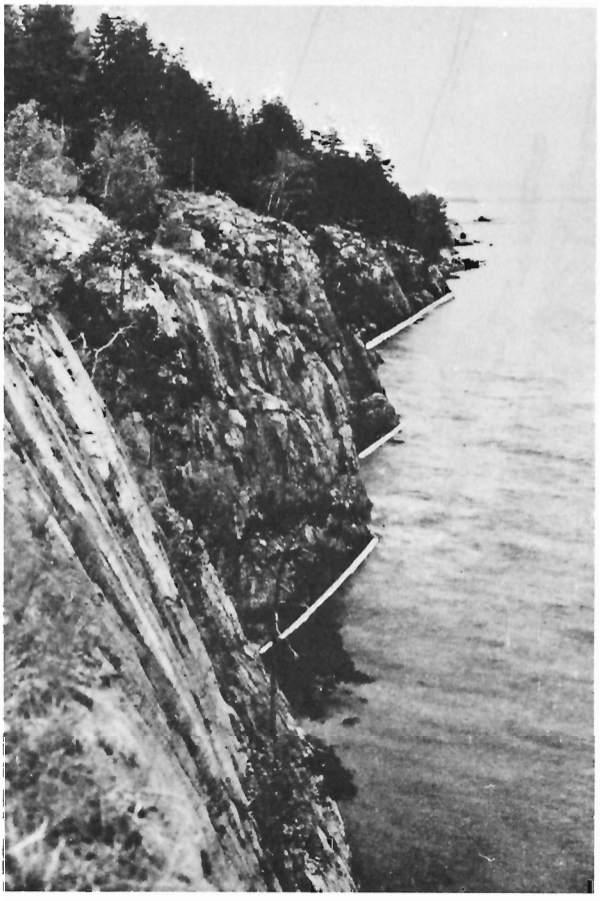


Figure 2. En echelon faults on the west coast of the Oslo Fjord south of Slemmestad.

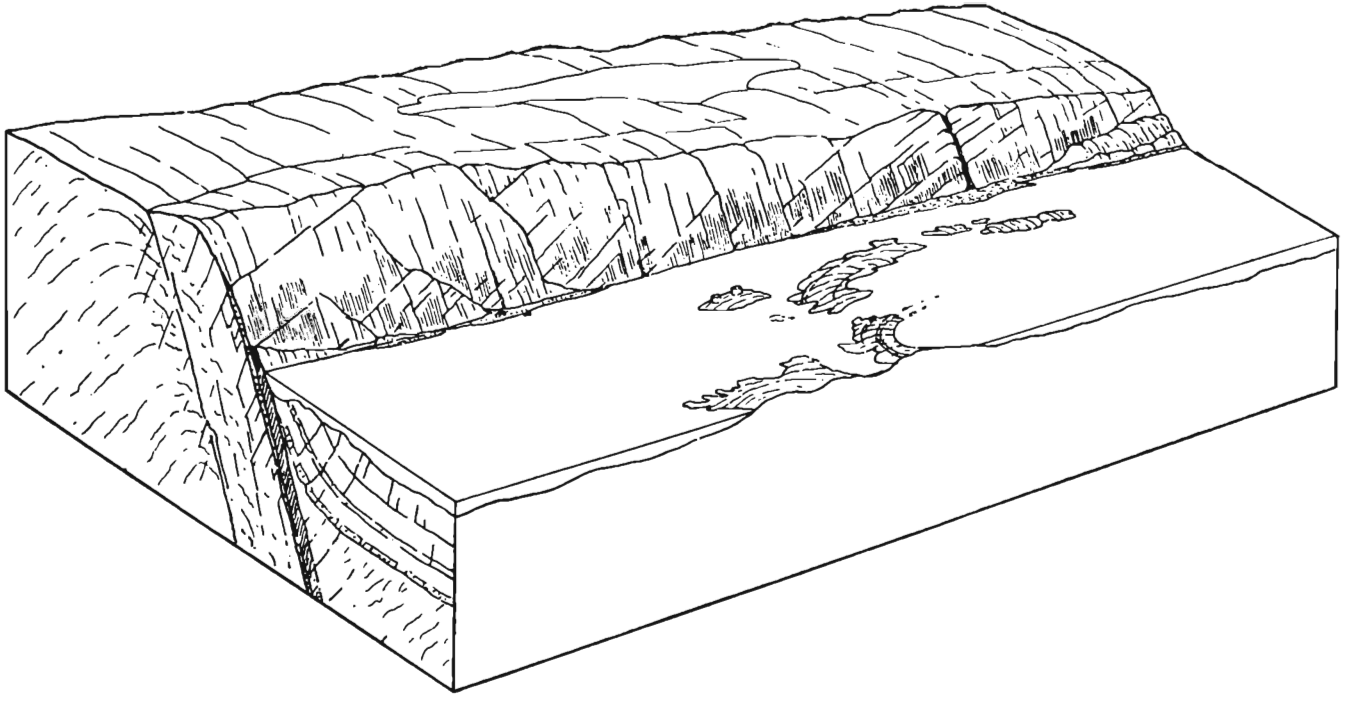


Figure 3. The fault on the east coast of the Oslo Fjord and the drag of the Ordovician beds of the Ildjernet Islands, which is attributed to a dextral movement along the fault. After H. Cloos.

came into being as the result of rotational strain set up by differential movements of the adjoining blocks. As the movements progressed, the fissures were changed into pinnate faults along which mylonites and ultramylonites were formed. These mainly horizontal movements took place before Permian magmatism. After the consolidation of the igneous rocks, probably at a much later date, the wrench faults were converted into dip-slip and oblique-slip faults and a new friction breccia was formed which covers the older blastomylonite and masks the en echelon structure of the faults. In contrast to the blastomylonites and the faults having pronounced en echelon structure, which are clearly proven to be pre-Permian, it is usually assumed that the dip-slip faults of the graben became active at the time of the intrusion of the Permian igneous rocks. This may be true for a part of these movements, but the relief and frequency of earthquakes in the Oslo Fjord indicates that tectonic movements are continuing at the present time. It is impossible that the steep slopes of the fjord coasts could have survived 200 million years of denudation. It is more probable that the faults were revived in the Tertiary at the time of the formation of the Norwegian Channel in the Skagerrak, the latter being a graben of Tertiary age. This sequence of events has a counterpart in the Rhine graben.

NATURE OF THE RHINE GRABEN

The downfaulting of the Rhine graben began in the Lower Oligocene and continued to the present time. This is shown by the Pliocene and Pleistocene sediments in the graben, and by the earthquakes in the region. The subsidence is generally 2500 – 5000 m. The boundary faults are exposed in only a few places; they are normal faults with mean dips of 60 - 70°. The graben also trends in north-south to north-northeast, the so-called rhenic direction.

Although the Rhine graben is a young structure, there are on both flanks blastomylonite zones having rhenic strikes which are much older (specifically, Carboniferous). These zones cut Carboniferous granites and are overlain by undisturbed Permian beds. Horizontal lineation and drag structures in the bordering schists indicate horizontal movements. Thus we have here a variscan shear zone which has determined the direction of the Tertiary graben. These features are in accordance with those of the Oslo Fjord, and the Rhine graben and the Oslo graben can be looked upon as equivalent constituent parts of one geological unit, the Mittelmeer-Mjoesen Zone of H. Stille. This zone originated in North and Central Europe as a large variscan shear zone cutting the variscan strike at an acute angle, but when tensional stresses became effective in the Cenozoic, it was transformed into a graben zone.

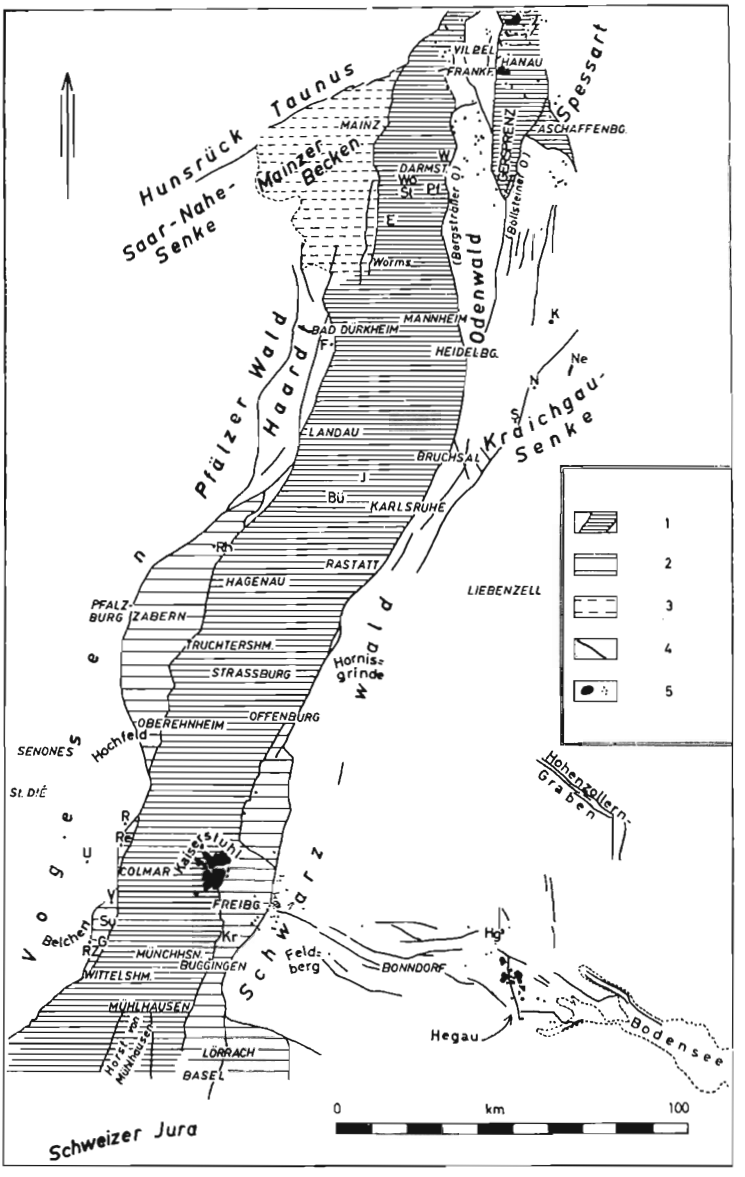


Figure 4. The Rhine graben. After H. Murawski.
1. Inner graben: Tertiary and Pleistocene. 2. Foothills zone: Mesozoic. 3. Undisturbed Tertiary. 4. Main faults. 5. Tertiary volcanites.

CONCLUSION

I would like to conclude this paper with a question. All the strike-slip and oblique-slip faults of the Oslo region, which I have studied, show dextral displacements. These are caused by the oblique-slip faults like those which bound the Leine graben, in which Göttingen is situated 1,000 km south of Oslo, and which also is regarded as a component of the Mittelmeer-Mjoesen Zone. Since the en echelon faults are the result of rotational strain, the question suggests itself: Has there perhaps been a clockwise rotation in Europe? This possibility is emphasized if one considers the displacement along the Great Glen fault in Scotland, and on the wrench fault which, according to E. Kusnetzov, occurs in the Middle Urals.

DISCUSSION

H.P. Laubscher (Switzerland)

I wish to point out that the Oslo graben system is not different from any of the other rift systems (including the Red Sea graben) in that it is not strictly unidirectional but is composed of faults in many directions. The fact that there is a series of parallel structures on one side of a given part of the graben shows that there was a consistent movement on this unit at one stage, but I don't think that the whole graben should be explained exclusively by this particular movement. There is clear evidence that the Rhine graben was established very early, and that later, lateral movement took place along its border. I don't think that one can conclude too much from the presence of faults that could have resulted from rotational movement.

Professor Bederke

En echelon faults of the same direction and corresponding sense of motion exist on both sides of the Oslofjord graben.

G.A. Thompson (U.S.A.)

It is interesting to point out that in the Oslo graben, where there are no Tertiary sediments of low density, the Norwegian gravity map shows no gravity anomaly. I wish to indicate that the gravity anomaly in front of the graben may indicate that the graben provides an isostatic control.

L. Picard (Israel)

Have the en echelon faults been observed in crystalline rocks or sedimentary rocks, or both?

Professor Bederke

In both types.

Professor Picard

This is very interesting because I have never observed en echelon faults in crystalline rocks. A common explanation is that en echelon faults reflect marked differences in the plasticity of adjacent rocks.

GEOLOGICAL AND GEOPHYSICAL STUDIES IN THE GULF OF FONSECA-NICARAGUAN DEPRESSION AREA, CENTRAL AMERICA

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Abstract

Geological and geophysical work done in the last few years in the Gulf of Fonseca-Nicaraguan Depression area of Central America indicate that its volcanic-tectonic origin involved a long process of repeated eruption emergence and subsidence, culminated by its complete rise above sea-level during Tertiary-Quaternary times. Two structural features appear to have controlled this process: (a) an east-west mountainous salient of very old age extending from central Guatemala across Honduras into northern Nicaragua, esignated as nuclear Central America; and (b) the Costa Rica-Panama spur of upper Tertiary-Quaternary age, an extension to the west of the western branch of the Andean-Cordilleran in Colombia which extends across Panama, ending in western Costa Rica. Between these masses lies a lowland of irregular relief, criss-crossed by faults of complicated origin and pattern, but following a general northwest to southeast trend from southeastern Guatemala to central Costa Rica (the latter being more elevated than the rest of the lowland). This lowland is characterized by abundant volcanoes (about 40 still active), geothermal sources, and continuous earthquakes. For the purpose of this report, the area of study is divided into two parts: the Gulf of Fonseca, opening on the Pacific Ocean; and the Nicaraguan Depression occupied by the Chinandega Plain to the west, and the Managua and Nicaragua Lakes in its central and eastern parts where structural and tectonic evidence suggests a "rift-like" pattern. It is necessary therefore to combine crustal and Upper Mantle studies to obtain a better knowledge of the origin and evolution of this area.

INTRODUCTION: A REVIEW OF PREVIOUS WORK

Almost thirty years ago, in 1936, the Pan American Institute of Geography and History began a program of geological and geophysical studies in three countries of the Central-American Isthmus (Guatemala, El Salvador and Honduras). Under the direction of Ing. Pedro C. Sánchez, the first Director of the P.A.I.G.H., gravimetric and magnetometric investigations were undertaken which gave rise to several reports (Ruíz, E., 1937; Sánchez, P.C., 1937; Vaca Alatorre, A., 1937). Other structural and

tectonic characteristics (mainly seismic and volcanic) of southern Mexico and northwestern Central-America, were also observed and described by Ing. Sánchez in later papers in which he concluded that, as a geomorphic unit, "Central-America extended from Parallel 19° in the Mexican Republic to the Atrato Depression, in the Isthmus of Darién" (Sánchez, P.C., 1942a, b).

Further geographic and geologic studies were made in the same area by Dr. Federico K.G. Müllerried, Professor of Palaeontology in the National Autonomous University of Mexico, as an extension of previous work in the tropical zone of southeastern Mexico (Müllerried, 1938; 1939a, b; 1940; 1942a, b, c; 1945). This work reflected the ideas of the famous German explorer Karl Sapper (see Maldonado-Koerdell, 1958). Between 1940 and 1950, a great development in cartographic and exploratory work took place in the Central-American countries, including geological and geophysical studies and the training of experts in field and laboratory work by the National Cartographic Agencies under the stimulation and cooperation of the Pan American Institute of Geography and History and the Inter-American Geodetic Survey (the latter having headquarters at Fort Clayton, Canal Zone, Panama).

In 1952, during the first phase of Project 29 of the OAS — Evaluation of Natural Resources in the Americas, the Pan American Institute of Geography and History renewed its efforts in the Central-American countries, with emphasis being placed on physical and biological aspects. In September of that year, a Mission of Experts under the direction of Prof. Dr. Jorge A. Vivó, geographer, with a geologist, an agronomer, and a biologist, visited the Central-American countries; they compiled information on natural resources and produced a series of reports under the general title Los Estudios sobre los Recursos Naturales en las Américas (Simonpietri and others, 1953).

Other ideas were discussed in the "Conclusions and Recommendations of the Mission of Experts of the Caribbean Area of Project 29 of the Program of Technical Cooperation of the OAS" (Vivó and Maldonado-Koerdell, 1956) which referred in part to problems of geologic and geophysical exploration. In the same period, Prof. Angel Rubio of the University of Panama published his opinion on the proper geographic location of the territory of that country with respect to the Central-American Isthmus, along with views and comments of other specialists (Rubio, 1955), while various contributions on the same area are given in other P.A.I.G.H. reports (Simonpietri, 1956; Marquina, 1961).

Another advance in the knowledge of the physical characteristics of Central-America was made possible by a grant from the Geological

Society of America in aid of the compilation of a "Geological and Paleontological Bibliography of Central-America" (Maldonado-Koerdell, 1958, in Spanish and English). Previous contributions on the Quaternary sediments in El Salvador and on the Triassic stratigraphy and fossil plants of Honduras in the vicinity of the Gulf of Fonseca (Maldonado-Koerdell, 1953a, b) had already indicated the importance of this area (and of the nearby Nicaraguan Depression) and the need for further studies.

Later on, as part of the work of Mission 105 of the OAS sent to Honduras at the petition of its Government to investigate various aspects of the program of Agrarian Reform in that country, a more complete exploration of the Gulf of Fonseca area (Maldonado-Koerdell, 1961a) allowed the presentation of a project of study to the First National Coastal and Shallow Water Research Conference, held in Los Angeles, California in October of 1961 (Maldonado-Koerdell, 1961b) and the Interamerican Conference on Marine Science held in Miami, Florida in November, 1962. As a conclusion of many seasons of field and laboratory work in the Central-American Isthmus, the author published an account on the "Geohistory and Paleography of Middle America" (Maldonado-Koerdell, 1964, in English).

Gravity measurements in the six Central-American countries, which resulted in the establishment of a first order base network connected with absolute stations in the world network in Mexico City and in the Canal Zone of Panama, were made during the International Geophysical Year, 1957-1958 and the International Geophysical Cooperation Program in 1959 and subsequent years (Monges Caldera, 1960, 1963a, b; Monges Caldera, and others, 1963). For a group of studies on the seismicity of the west coast of North- and Central-America, Dr. Rudolf Schulz, Seismologist of the former National Geologic Survey of El Salvador, now Center of Geotechnical Studies, prepared a report on the seismicity of the region, describing its tectonic conditions and its great crustal and subcrustal instability (Schulz, 1963).

In November and December of 1964, a submarine gravity survey was made of the Gulf of Fonseca by a group from the Institute of Geophysics of the National Autonomous University of Mexico, the National Cartographic Agencies of Guatemala, El Salvador, Honduras and Nicaragua, and the Inter-American Geodetic Survey with the economic support of the UNESCO and the Pan American Institute of Geography and History, as a continuation of the previous gravity work on land in the same area. Members of this group were: Ings. J. Monges Caldera, of Mexico; Haroldo Duarte Villela, of Guatemala; José González and José Bustamante, of El Salvador; Ulises Martinez, of Honduras; Francisco Hansen, of Nicaragua; and Roman Geller, of the J.A.G.S. The results of their work will soon be available with a reinterpretation of gravity values, Bouguer anomalies, and other data.

In October of 1964, the U.S. Navy Oceanographic Office, as part of Project MAGNET of the World Magnetic Survey, in its Phase NAVOCEAN, conducted an aeromagnetic survey over the Gulf of Fonseca and the surrounding areas to determine declination and inclination, and the total vertical, and horizontal intensities of the magnetic field. They produced a preliminary report and map for the tenth Pan American Consultation Reunion on Cartography in Guatemala City in June and July of 1965 (O'Neill, 1965). A monograph on the terrestrial magnetic values of the Central American Isthmus by Ing. Haroldo Duarte Villela, of the National Geographic Institute of Guatemala, with descriptions of stations, magnetic values and other data was also presented on that occasion (Ministerio de Comunicaciones y Obras Públicas, 1965).

A preliminary geohydrological survey of the coastal plain of Honduras along the Gulf of Fonseca was also carried out during three weeks in February of 1965 by Ing. Rodolfo del Arenal C., of the Institute of Geophysics of the N.A.U.M., with emphasis being placed on the geomorphological factors acting on the establishment of stream nets and associated problems. Other programs of geological and geophysical scope are planned for the Gulf of Fonseca-Nicaraguan Depression area in future years that are particularly concerned with the study of the crust of the earth and, if possible, the Upper Mantle.

RESULTS AND IMPLICATIONS OF PREVIOUS WORK

There seems to be no doubt about the physiographic boundaries of the Middle-American region (as it is now called) postulated many years ago, when it was defined as a continuous tract from southern Mexico to northwestern Colombia. Unity and close relationships of geological and geophysical traits, and a well defined geological history and palaeogeography characterize this terrestrial link between North and South America, notwithstanding certain environmental diversities in the areas, and in their past behaviour (Fig. 1).

In this respect, it may be said that two structural masses developed through a long volcanic-tectonic history in the Central-American Isthmus proper have guided (and still guide) the geological and geophysical processes of that bridge. These are: (1) Nuclear Central-America, consisting essentially of an east-west mountainous salient extending from central Guatemala across Honduras to northern Nicaragua; and (2) the Costa Rica-Panama spur, a prolongation to the west of the western branch of the Andean Cordillera, across the Isthmus of Darien (Fig. 2).

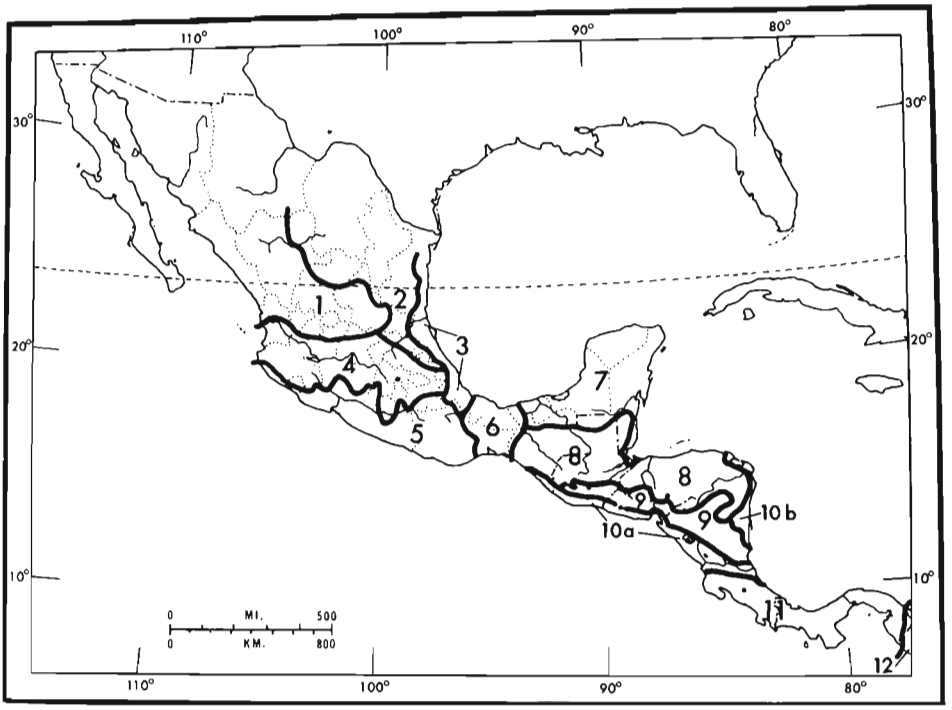


Figure 1. Principal Geological Provinces of Middle America (after A.J. Eardley, 1951, p. 586). 1) Sierra Madre Occidental; 2) Mexican Plateau; 3) Gulf Coastal Plain; 4) Volcanic Province of Southern Mexico; 5) Sierra Madre del Sur; 6) Isthmus of Tehuantepec; 7) Coastal Plain of Yucatan Peninsula; 8) Sierras of Northern Central America; 9) Salvador-Nicaraguan Volcanic Province; 10a) Pacific Ocean Coastal Plain and Nicaraguan Depression; 10b) Caribbean Sea Coastal Plain; 11) Costa Rica-Panama Isthmus.

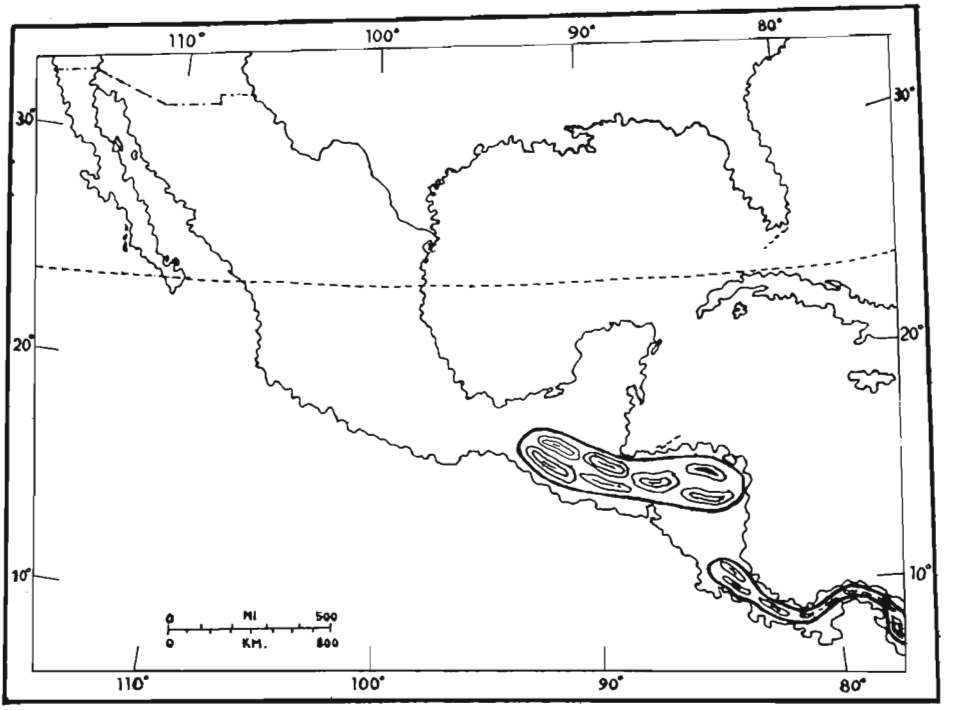


Figure 2. Tectonic-volcanic structural areas of the Central-American Isthmus. To the north is the Nuclear Central-American mountainous salient; to the south, the Costa Rica-Panama spur.

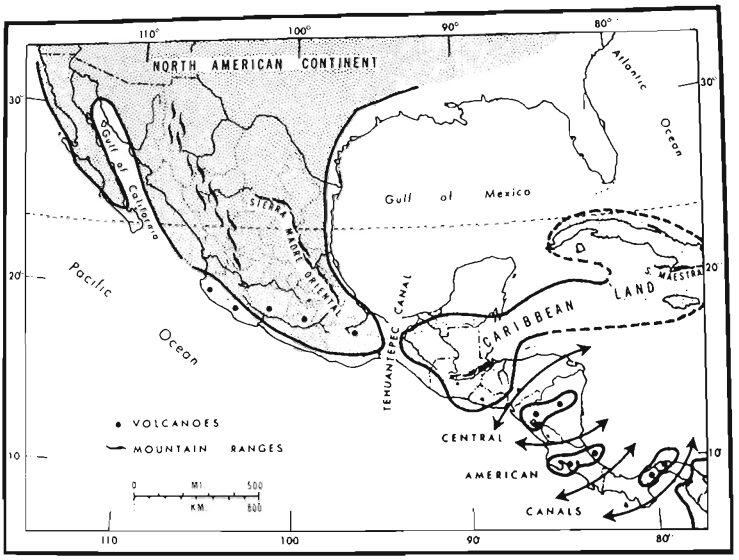


Figure 3A. Tertiary paleogeography of Middle America and adjacent areas. Oligocene-Lower Miocene.

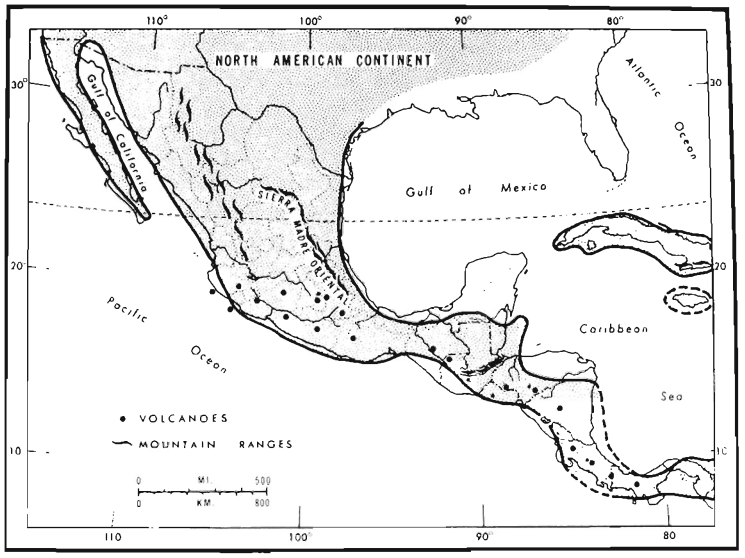


Figure 3B. Tertiary paleogeography of Middle America and adjacent areas. Miocene-Pliocene.

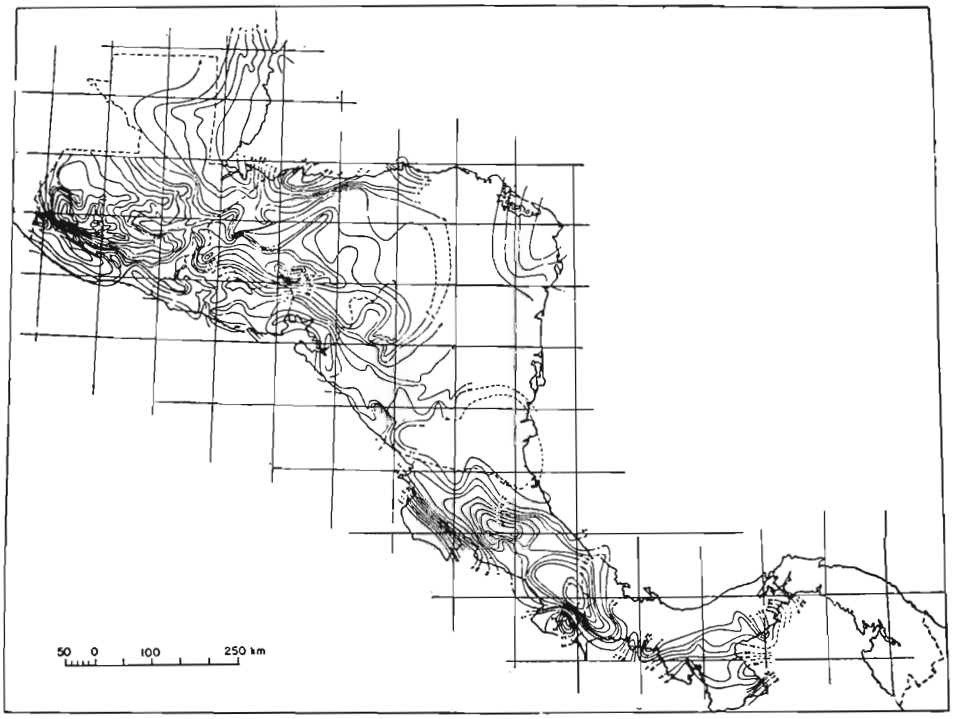


Figure 3C. Map of the Bouguer gravity field of Middle America. Compare with Figure 3A.



Figure 4A. Location of active volcanoes in Central America. Guatemala and El Salvador (After Bullard, 1957).

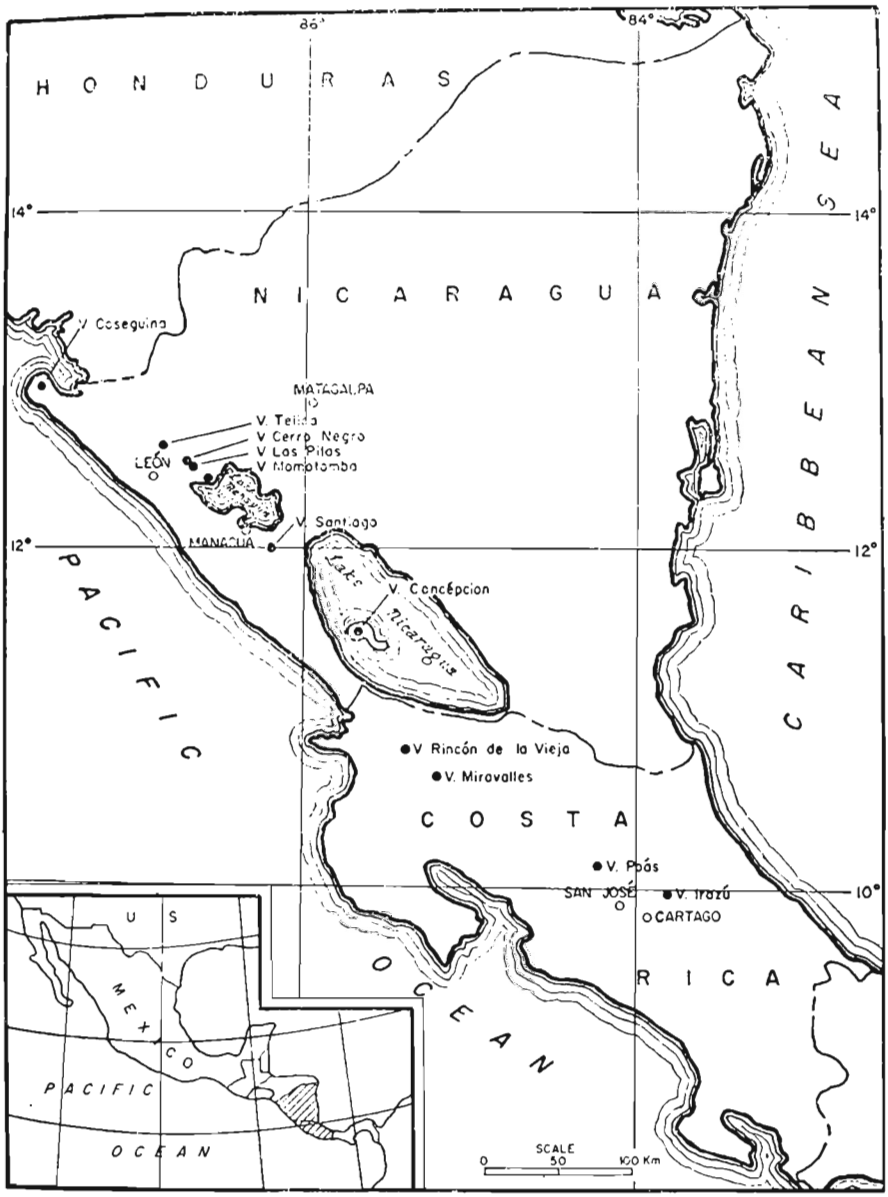


Figure 4B. Location of active volcanoes in Central America. Nicaragua and Costa Rico (After Bullard, 1957).

In Jurassic-Cretaceous times, there was a marine passage-way between these two structural masses, interrupted by volcanic islands which were forerunners of the elevation of the land mass now forming south-western Costa Rica, the southern half of Nicaragua, the southern slopes of Honduras, most of El Salvador, and southeastern Guatemala. The elevation of this landmass was marked by the appearance and disappearance of sea canals during the Tertiary, and total emergence of land in the Quaternary. Gravity values and the distribution of Bouguer anomalies seem to confirm this interpretation, although there is still a need for more work in many areas, and for a better integration of geophysical information with the geological evidence, especially that on igneous petrology (Fig. 3).

In the same geologic epochs (i.e. the Tertiary and Quaternary), a long volcanic chain was established in the Central-American Isthmus, which is now marked by some hundreds of extinct and active volcanoes between Guatemala and western Panama. It has been demonstrated from a palaeogeographic view-point that there were at least three northwest-southeast rows of volcanoes, the first and oldest now sunk below the continental shelf and talus, the second or middle intercalated with geologic structures along the southern coast of the isthmus, and the third and youngest having more than 40 active peaks and forming a formidable barrier of igneous activity on land at a certain constant distance from the coast (Fig. 4).

In spite of advances made in the study of Central-American volcanology, it still has many unknown or little appreciated aspects, especially those related to the emplacement of deep crustal (and/or sub-crustal) materials. Among other phenomena, an abundance of geothermal sources indicates the strength and extent of igneous processes in the Central-American Isthmus; these hold much promise for practical applications and invite research to better our knowledge and explanation of them (Fig. 5).

There is also the set of structural and dynamic conditions manifested by seismic phenomena which link past and present suboceanic processes along the continental shelf and in the Pacific Ocean and Caribbean Sea basins. The Central-American Isthmus is well known for its numerous and violent earthquakes (on many occasions associated with volcanic activity) marking the presence of longitudinal and (or) transverse alignments, and shallow or deep foci (Fig. 6).

It is also important to consider the results of the aero-magnetic survey conducted over the Gulf of Fonseca (and adjoining areas of the Nicaraguan Depression to the southeast) in conjunction with the gravity and seismic maps (Figs. 7-9). All three clearly indicate that both the Gulf of Fonseca and the Nicaraguan Depression deserve thorough study with regard to their structural and dynamic traits; the studies should include

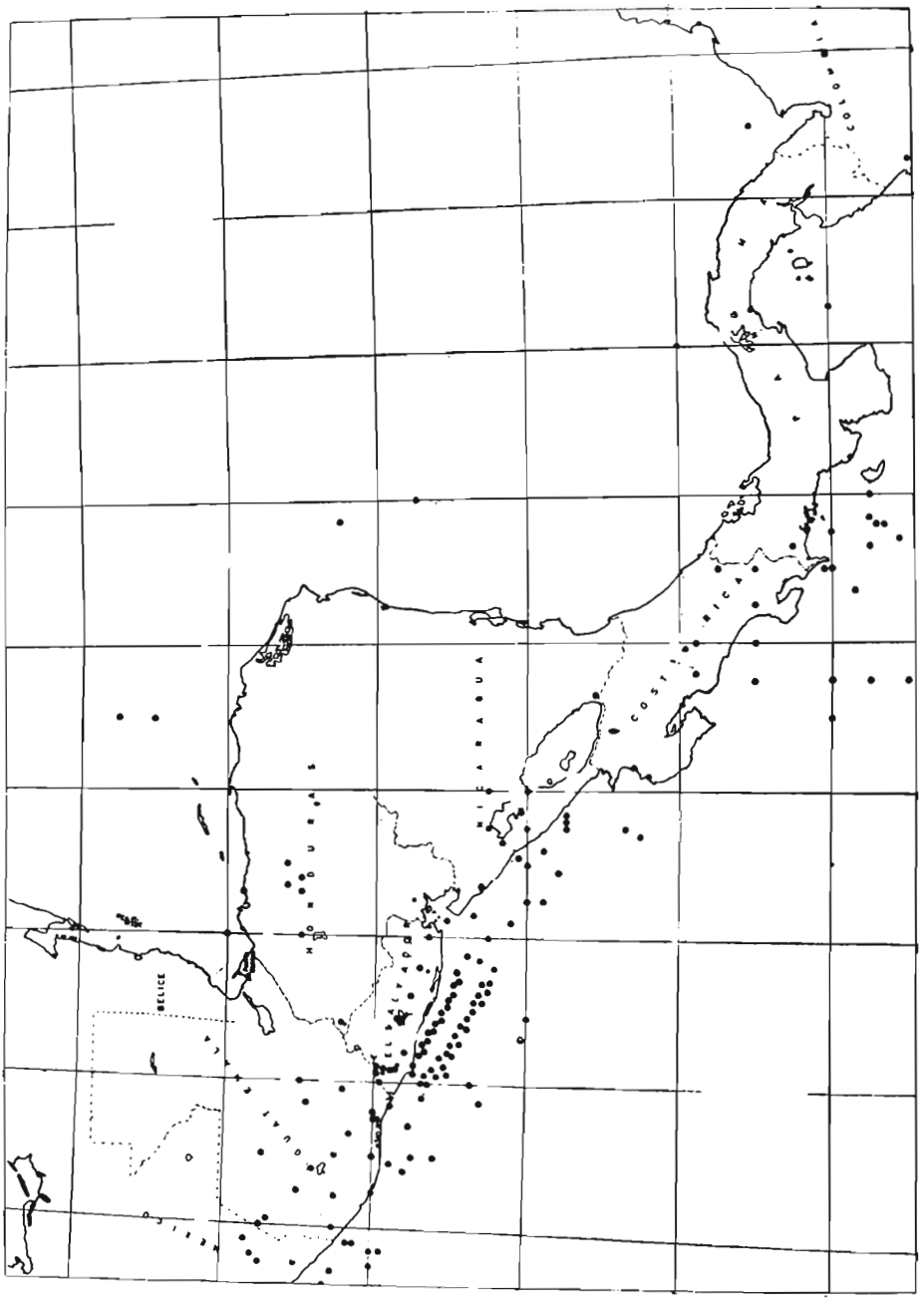


Figure 5. Map of the earthquake epicenters of Central America.

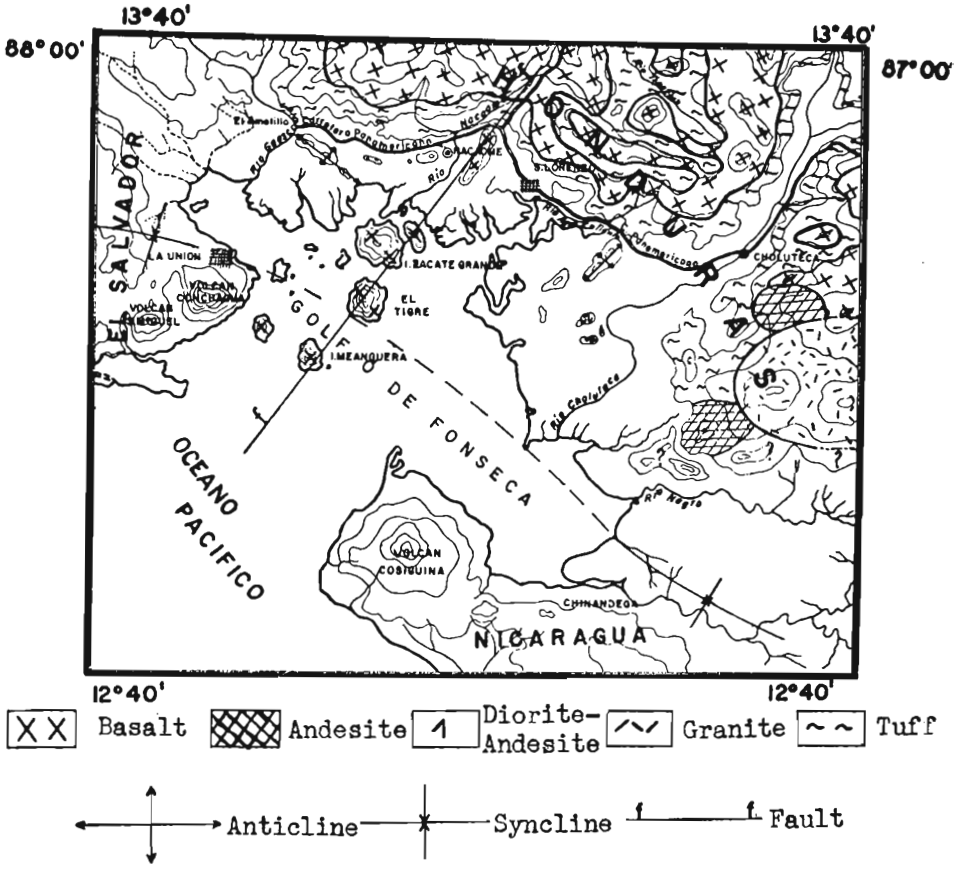


Figure 6. Geological sketch map of the Honduran part of the Gulf of Fonseca.

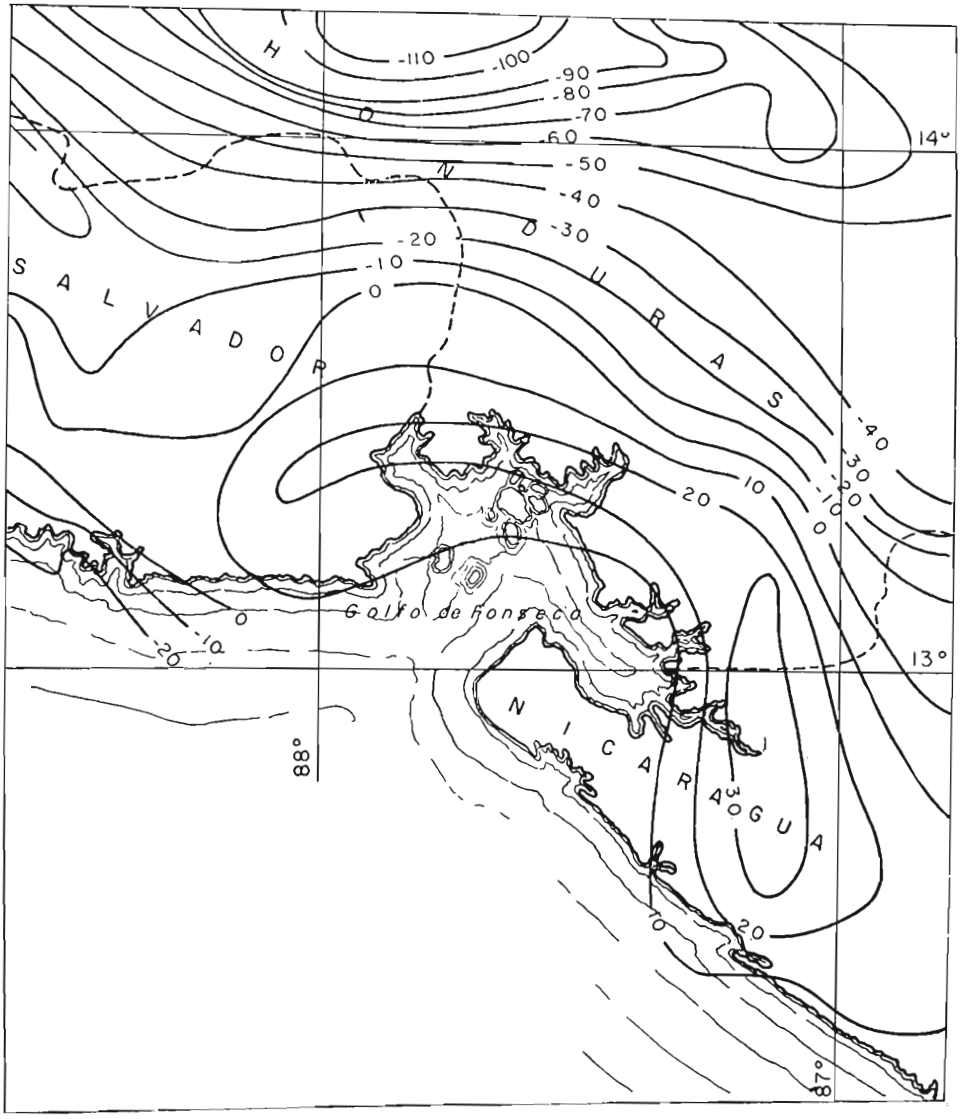


Figure 7. Map of the Bouguer gravity field around the Gulf of Fonseca. Contour interval, 10 milligals.

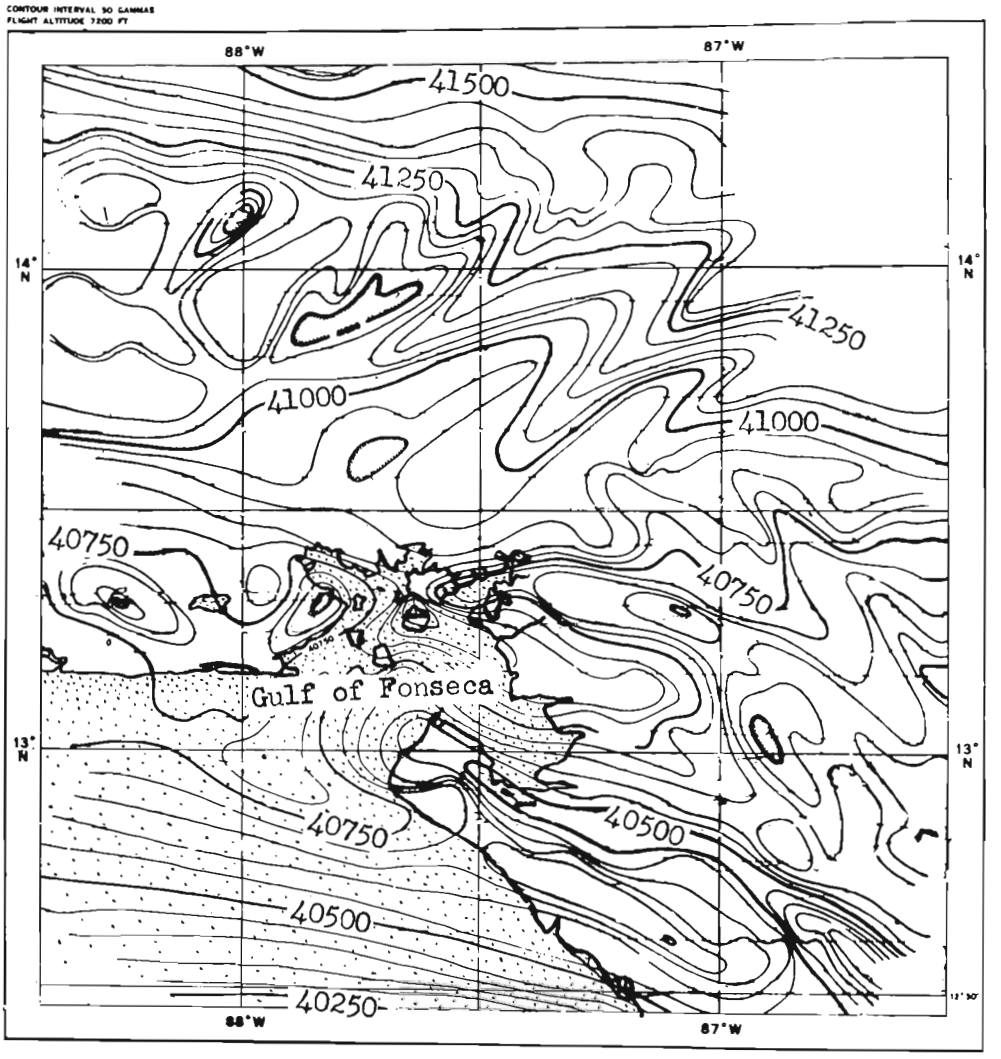


Figure 8. Aero-magnetic Map of Gulf of Fonseca with Total Intensity Contour Lines (prepared by U.S. Navy Oceanographic Office in 1964).

investigations of the continental shelves of the Pacific Ocean and the Caribbean Sea and the deeper crustal (and subcrustal) levels.

There is no need to go far back into the geological history and palaeogeography of the Central-American Isthmus to appreciate that the Gulf of Fonseca and the Nicaraguan Depression hold the key to the explanation of many of the obscure points of geological and geophysical structure of the isthmus. Furthermore, its exploration is only beginning, and there is still much to be done toward taking advantage of the progress which has been made in techniques such as seismic exploration in lakes (as in the recent study of the Great Lakes of North-America by the Carnegie Institution), measurement of earth-tides, volcanological recordings, deep drilling, etc.

In this respect, it should be mentioned that a proposal has been put forward to establish a volcanological observatory in the Nicaraguan Depression area. Such an observatory should add greatly to our knowledge of the many important features described above. The proposed position of the observatory is equidistant from the two ends of the Central-American Isthmus and has easy communication in case of emergency. The observatory will not only be a centre for the recording and analysis of eruptive events and associated phenomena, but it will also serve for the training of specialists in various types of geophysical studies and as a centre for the stimulation and coordination of research.

The Central-American Isthmus, in particular the Gulf of Fonseca-Nicaraguan Depression area, should also be utilized for Upper Mantle studies in view of its distinctive characteristics. A program of field and laboratory work could be integrated and executed in the future with the assurance of having the complete approval and cooperation of the agencies that have participated in one way or another in previous phases of the geological and geophysical exploration of the region.

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THE SAN ANDREAS SYSTEM, CALIFORNIA AND MEXICO

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Abstract

The surface trace of the San Andreas fault is a 500-mile, essentially continuous, lineament resulting from Recent ground movements (extending from Pt. Arena southeastward to San Gorgonio Pass). The San Andreas zone comprises those faults which are semiparallel and surface connected to the San Andreas fault (an 800+ by 30 mile belt). Many other northwest trending right-lateral slip faults of the San Andreas set and some east-northeast trending left-lateral slip faults of the Garlock set comprise the San Andreas system (a 1000+ by 300+ mile belt). This appears to be a strain system of north-south shortening and east-west relative extension, with local upward relief. The San Andreas zone is characterized by at least several tens of miles of cumulative right-lateral slip since Miocene time and perhaps several hundreds of miles since Cretaceous time.

The San Andreas zone, at least as far south as the north end of the Gulf of California, is a shear or compressional structure. However, if the zone extends farther southeast, it may become a rift or tensional structure with a cumulative right-slip component commensurate with the tens to possibly hundreds of miles of post-Mesozoic displacement on the zone in California. Furthermore, it may be that a relatively northward moving upper mantle current along the western margin of the North American continent is responsible for the San Andreas fault system. In any case, knowledge of the San Andreas fault zone is important to an understanding of the dynamic history of the earth.

INTRODUCTION

The San Francisco earthquake of 1906 focused attention on the association of earthquakes with faulting, and in this case, with movement on the San Andreas fault, or so-called rift. It also stimulated the elastic rebound concept of earthquakes and demonstrated lateral, or strike-slip,

movement on faults. Although rift[1] is probably a misnomer for the San Andreas, it may be the excuse for my participation in this symposium. However, I suppose that more is known about the San Andreas than most other major fault zones of the earth — particularly since much of it can be mapped on the basis of surface geology whereas so many faults are concealed by alluvium or water, or are mapped by geophysical techniques. Therefore, this brief statement concerning the San Andreas and associated faults in California and northwestern Mexico may be of some interest to you, and some contribution to the subject of this symposium.

SAN ANDREAS FAULT SYSTEM

The accompanying map (Fig. 1) of portions of California and Mexico, and the adjacent shelf, continental borderland and Pacific basin, shows approximate surface positions and extents of some of the more obvious major faults of the region. Many important faults are not shown for various reasons, but especially because they have not yet been mapped (e.g., in basement terrains, alluviated areas or below the sea).

However, you can see that this is a relatively highly faulted area, and as far as known, all of these faults have been active in late Tertiary to Recent geologic time and may all (or essentially all) belong to a single strain system. This I will take the present liberty of calling the San Andreas Fault System. The system appears to be typified by right-slip on northwest trending faults and by left-slip on some of the east-northeast trending faults.

The San Andreas Fault, shown by the double line, is the fault responsible for the San Francisco earthquake. Its type locality is at San Andreas Lake (an elongated topographic depression, or rift feature, just south of San Francisco, resulting from Pleistocene to Recent displacements on the fault), and it extends approximately 500 miles across the map as an essentially continuous lineament resulting from geologically late ground movements.

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[1] According to Webster a rift is an opening made by splitting. And a rift valley is an elongated depression between faults. Therefore if the term rift is applied in geology, a genetic connotation (splitting or depression) is implied. However, since the sense of slip on faults is seldom known the term rift (for dip-slip and/or pulling apart) is seldom justified. Furthermore, some American writers, contrary to those in most other countries, use rift for fault zones with strike-slip displacement (e.g., San Andreas Rift). Also rift is used in both a geomorphic and a tectonic sense. Therefore the term is ambiguous and of doubtful value in geologic terminology.

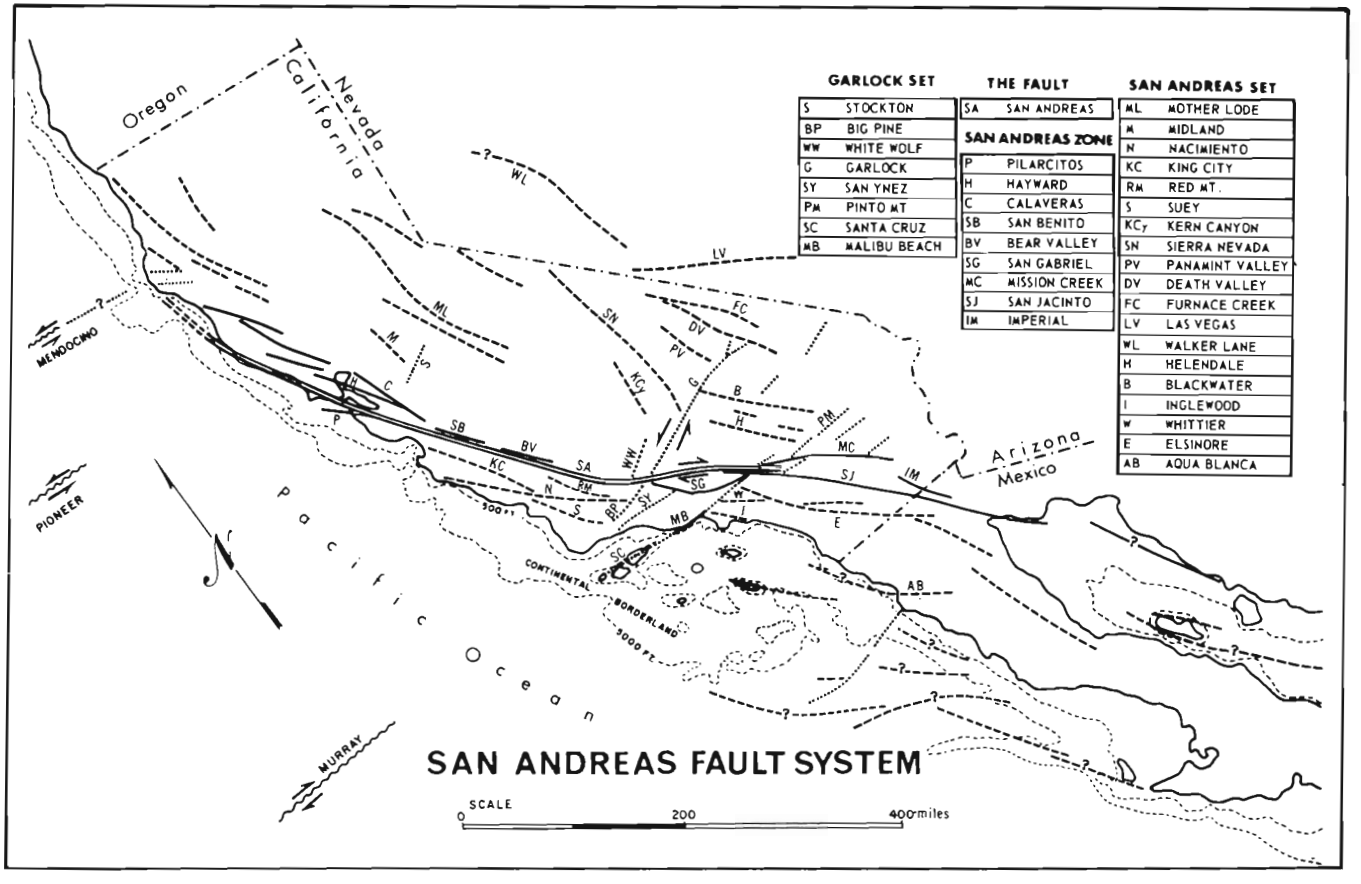

GARLOCK SET
S STOCKTON
BP BIG PINE
WW WHITE WOLF
G GARLOCK
SY SAN YNEZ
PM PINTO MT
SC SANTA CRUZ
MB MALIBU BEACH
THE FAULT
SA SAN ANDREAS
SAN ANDREAS ZONE
P PILARCITOS
H HAYWARD
C CALAVERAS
SB SAN BENITO
BV BEAR VALLEY
SG SAN GABRIEL
MC MISSION CREEK
SJ SAN JACINTO
IM IMPERIAL
SAN ANDREAS SET
ML MOTHER LODE
M MIDLAND
N NACIMIENTO
KC KING CITY
RM RED MT.
S SUEY
KCy KERN CANYON
SN SIERRA NEVADA
PV PANAMINT VALLEY
DV DEATH VALLEY
FC FURNACE CREEK
LV LAS VEGAS
WL WALKER LANE
H HELENDALE
B BLACKWATER
I INGLEWOOD
W WHITTIER
E ELSINORE
AB AQUA BLANCA
Oregon
Nevada
California
Arizona
Mexico
MENDOCINO
PIONEER
MURRAY
Pacific Ocean
CONTINENTAL BORDERLAND
-3000 FT
SAN ANDREAS FAULT SYSTEM
SCALE
0
200
400 miles

Figure 1

The faults which are semiparallel with, and have at least approximate surface connections to, the San Andreas fault (including the San Andreas fault) are here called the San Andreas Fault Zone. Some of the more important of these faults are: Pilarcitos, Hayward, Calaveras, San Benito, Bear Valley, San Gabriel, San Jacinto, and Mission Creek faults, which are shown by solid lines.

Other northwestward trending onshore and offshore faults which are, or are suspect of being, right-lateral slip faults of late Tertiary to Recent age are here, for the first time I believe, called the San Andreas Fault Set[1]. They are shown by dashed lines (the set includes the San Andreas zone and the San Andreas fault).

The faults marked by dotted lines, mostly trending east-northeast and some of which have been determined to be left-lateral slip faults, are included along with the San Andreas set as part of the San Andreas Fault System. These are here called the Garlock Fault Set. The eastward extent of the San Andreas system is unknown. It surely extends to the Walker Lane — Las Vegas Shear zone, and if the Rocky Mountain Trench is typified by right-slip (which I doubt), it could extend much farther eastward. It has been suggested that the system (and even the fault zone, if not the fault) extends into Alaska and much beyond the southern border of this map. Possibly, and for various reasons which I expect will be (or have been) brought out in this conference, the San Andreas system may (although I doubt it) extend westward beyond the continental borderland and into the Pacific Ocean basin to include the Mendocino, Pioneer, and Murray fracture zones.

Certainly the San Andreas fault system, extending over an area of at least 300,000 square miles, and comprising long, steep and deep faults, some of which are known to have cumulative strike-slip offsets of tens of miles, is important in any analysis of the tectonic history of the earth and thus should be pertinent to this symposium on rifts of the world.

SAN ANDREAS DISPLACEMENTS

Seismic, geodetic, and geomorphic evidences of right-lateral slip on the San Andreas fault are well known. Geologic map evidences of cumulative strike-slip of at least tens of miles on the San Andreas zone in

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[1]Fault set comprises faults of similar orientation or direction, occurring in a single geographic area during the same interval of geologic time.

this same sense have been described. Pleistocene gravel deposits of two facies occur in the Temblor Range-San Emigdio Mountains region to prove approximately fourteen miles of right-lateral slip. Upper Miocene stratigraphic facies have been offset at least another fifty miles. Lower Miocene and Oligocene rock facies now mismatch across the San Andreas fault by a distance of 150 to 175 miles. The distribution of Eocene and Cretaceous strata may indicate a cumulative right-lateral slip on the San Andreas zone of roughly 225 miles and 320 miles, respectively. And a contact between the Mesozoic Sierran and Franciscan basement rocks may be offset more than 350 miles[1].

Geodetic surveys indicate right-lateral creep along the San Andreas zone of approximately 2 inches per year. On the other hand geologic estimates of slip are as low as 0.2 inches per year[2] or 0.3 inches per year[3]. These rates and this discrepancy may be significant as controls on concepts of fault dynamics and seismic activity.

SAN ANDREAS CONTROVERSY

There are, perhaps properly, still divergent conclusions on both sense and amount of slip on the San Andreas fault zone since its inception. Obviously all workers subscribe to right-lateral slip of a few feet at the time of earthquakes (1906 and 1940) and up to nearly one mile since Pleistocene time (stream offsets). Vickerey (1925) was the first to suggest miles of strike-slip on a branch of the San Andreas (thirteen miles of right-lateral slip on the Sunol fault), and Noble (1926) proposed twenty-four miles on the San Andreas. Then Reed and Hollister (1936) and Taliaferro (1941) said there could be no strike-slip measured in miles on the San Andreas; whereas Hill and Dibblee (1953) and Crowell (1962) presented geologic evidence to indicate tens to possibly hundreds of miles of right-lateral slip on this fault zone. And now, Oakeshott (1964) argues against more than a few thousand feet of strike-slip and for large dip-slip displacements on the San Andreas.

Although I now have no doubt that the cumulative slip on the San Andreas fault zone has been at least tens of miles (since Miocene time — 13±

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[1]The 225-mile post-Eocene, 320-mile post-Cretaceous, and 350+-mile post-Franciscan-Sierran basement were offered as possibilities only, and should never have been stated in Life Magazine, certain text books, and elsewhere as facts.

[2]Sixty-five miles in 13 million years.

[3]Three hundred twenty miles in 70 million years.

million years ago), and perhaps even hundreds of miles since its inception (possibly in Cretaceous time — 70± million years ago), there are at least a few knowledgeable California geologists who disagree with these conclusions. However, it seems that the arguments against at least tens of miles of strike-slip on the San Andreas fault are based on: (1) failure to distinguish between fault separation and fault slip; (2) erroneous age or lithologic correlations of strata across the zone; and/or (3) innate prejudice against such movements.

Obviously the amount of strike-slip is not limited by gravitational forces, so that with consistent dynamics and plenty of geologic time, there is no reason why cumulative strike-slip on major fault zones should not be measured in hundreds of miles. Actually there is fairly strong evidence that such zones of faulting are rather common on the earth, and their presence may provide explanations of other geologic phenomena. Therefore the acceptance of large cumulative strike-slip on faults as a major tectonic phenomenon is apt to speed up our understanding of the deformational history of the earth. However, blind acceptance of large cumulative offsets and misquoting and using such figures out of context is unscientific, embarrassing to the original workers, and will most likely retard true understanding of earth dynamics. Also the extension of fault zones and/or regimes of deformation beyond their habitat, particularly easy on small scale maps and underwater, should be discouraged.

CONCLUSIONS

I now return to the map of the San Andreas fault system as a basis for discussing the faulting in this region within the context of this symposium on the World Rift System. Firstly, there appears to be a contradiction because the San Andreas fault zone is a shear zone rather than a rift, or pull-apart. The strain pattern of strike-slip faults and divergently trending folds indicates deformation under compression rather than tension. This pattern, including the east-west oriented Transverse Ranges folds and thrust-slip and reverse-slip faults, indicates north-south relative shortening of the crust — and thus a compressive component on the northwest trending San Andreas fault set. The preponderance of the northwest trending right-lateral slip faults suggests, in addition, a dynamic system of simple shear (rather than pure shear) whereby the northeastern Pacific basin is moving northerly relative to the North American Continent. The orientation in azimuth and the depth of the dynamic forces involved, or the origin of these forces, are as yet unknown. However, with more and better mapping of the strain pattern and deformational history in this and other regions of the earth, these forces, including their orientations and mechanisms, will probably be determined. If, as commonly supposed, upper mantle currents

are determined to be the cause of crustal deformation, it is not difficult to see how a shear zone like the San Andreas could extend into a region of tension, as has been postulated for it in the Gulf of California (Hamilton, 1961). But if so (which I doubt), the component of rifting has become greater than the component of shear, and if not, it should not be called a rift. And in this problem as in most others concerned with fault zones, the critical first step after discovering a fault zone is to determine (not assume) its sense of displacement.

In my opinion, geologic evidence has and will continue to contribute significantly to the history of deformation of the earth's crust. In this field, the most essential geologic control is knowledge of the geometry and history of deformation. And to get this understanding, the mapping of faults, with determinations of their senses of relative movement and cumulative amounts of displacement, is most critical (but for various reasons the importance of this concept has been largely ignored). Certainly the kinematics of fault displacements comes before dynamics of faulting, and knowledge of both must precede sound interpretations of the causes of crustal deformation.

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RIFT SYSTEM IN THE BASIN AND RANGE PROVINCE[1]

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Abstract

In 1961 the writer (in part after Heezen and Menard) postulated that the landward extension of the East Pacific Rise includes (1) the rift system passing through California, including the San Andreas fault zone, (2) the belt of grabens immediately east of the Sierra Nevada, and (3) the major rift system which branches off from the Gulf of California and extends through western Arizona, central Utah, southeastern Idaho, western Wyoming, western Montana, and British Columbia. The present paper reviews recent geophysical evidence that defines in more detail the rift system in the eastern part of the Basin and Range province. The rift system here is not a continuous rift valley but comprises belts of grabens which are in en echelon arrangement.

The Wasatch trench is a northward-trending belt of grabens about 160 miles long in north central Utah. Across the Wasatch trench in the North Ogden area, a combination of refraction and reflection seismic profiles and a gravity profile indicate that here the graben is about 13 miles wide and bounded on the west by at least two nearly parallel major faults, and on the east by at least three faults (including the one along the Wasatch front). The thickness of the valley fill in the graben is indicated to be as much as 6,000 feet by seismic results and 7,600 feet by the gravity data.

A gravity survey has demonstrated a major graben lying west of the Hurricane fault zone in southwestern Utah.

A gravity survey, supported in part by seismic refraction data, defines the Pilot-Grouse Creek rift belt in northwestern Utah that is at least 90 miles long and constitutes a major belt of grabens.

Long gravity and refraction seismic profiles across the boundary between the Basin and Range province and the colorado Plateau in Arizona and southwestern Utah indicate that the Mohorovicic discontinuity is at a depth of 25 to 30 km beneath the eastern part of the Basin and Range province and deepens to 40 to 45 km beneath the western and southwestern parts of the Colorado Plateau; and the low-density material, corresponding to the known anomalous low-velocity (7.6 to 7.8 km/sec) material at a depth of 25 to 30 km, conceivably extends to a depth of about 70 km beneath the

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[1] Contribution No. 75, Department of Geophysics, University of Utah.

eastern part of the Basin and Range province and probably wedges out eastward in the area under the western and southwestern parts of the Colorado Plateau. These latter results support the existence of a "mantle-crust mix" as postulated by the writer to exist under the Basin and Range province. It is believed that phase transformations at depth, including those that may occur within the mantle-crust-mix, are related to the current seismic activity along this great tectonic belt. To explain the possible mechanism of the tectonics characteristic of the Basin and Range province, a model assuming convection currents within the upper mantle, which were probably the main driving force of late Cenozoic volcanism and diastrophism in this region, is presented. To explain the San Andreas fault and the transcurrent faulting that has apparently moved into the Basin and Range province recently (Billings, 1960), change in the direction of the mantle convection currents is postulated.

INTRODUCTION

In dealing with the rift system in the Basin and Range province in this paper, I will first give a brief history of the concept of rift valleys in the Basin and Range province; then I will show some of the recent geophysical results bearing on the characteristics of these rift valleys; and finally, I will speculate briefly on the tectonic processes involved in their formation. I shall report mostly on features found in the eastern part of the Basin and Range province, as this is where my colleagues and I have done most of our work.

HISTORY

As shown in Figure 1, Heezen (1960) suggested a bifurcation of the rift system of the East Pacific Rise where it meets the North American continent. According to Maurice Ewing (1963, oral communication), the eastern branch was drawn so that it connected with the Rocky Mountain trench. Menard (1960, p. 1742) suggested that the plateau of Mexico, the Basin and Range province, and the Colorado Plateau were possibly related to the landward extension of the East Pacific Rise under western North America (Fig. 2), and I (Cook, 1961, 1962) suggested a possible trifurcation of the rift system (cf. Fig. 3) somewhat similar to that proposed independently by Heezen and Ewing (1961, Fig. 4). I drew the central branch of the rift system along the eastern side of the Sierra Nevada, and I used the expression "rift valleys of Utah" for the eastern branch because it is comparable to the rift valley systems of the Mid-Atlantic Ridge and the African continent[1]. The present discussion deals principally with the eastern branch of the rift system.

[1]It has however, become clear during these meetings that we have a problem in nomenclature because of the multiple meanings for the word "rift". An attempt to resolve this problem might be made a subject for a committee at the I.U.G.G. meeting in Switzerland two years hence.



Figure 1. Mid-ocean rift over East Pacific Rise and postulated bifurcation as rift enters North American continent. From Heezen (1960), with permission.

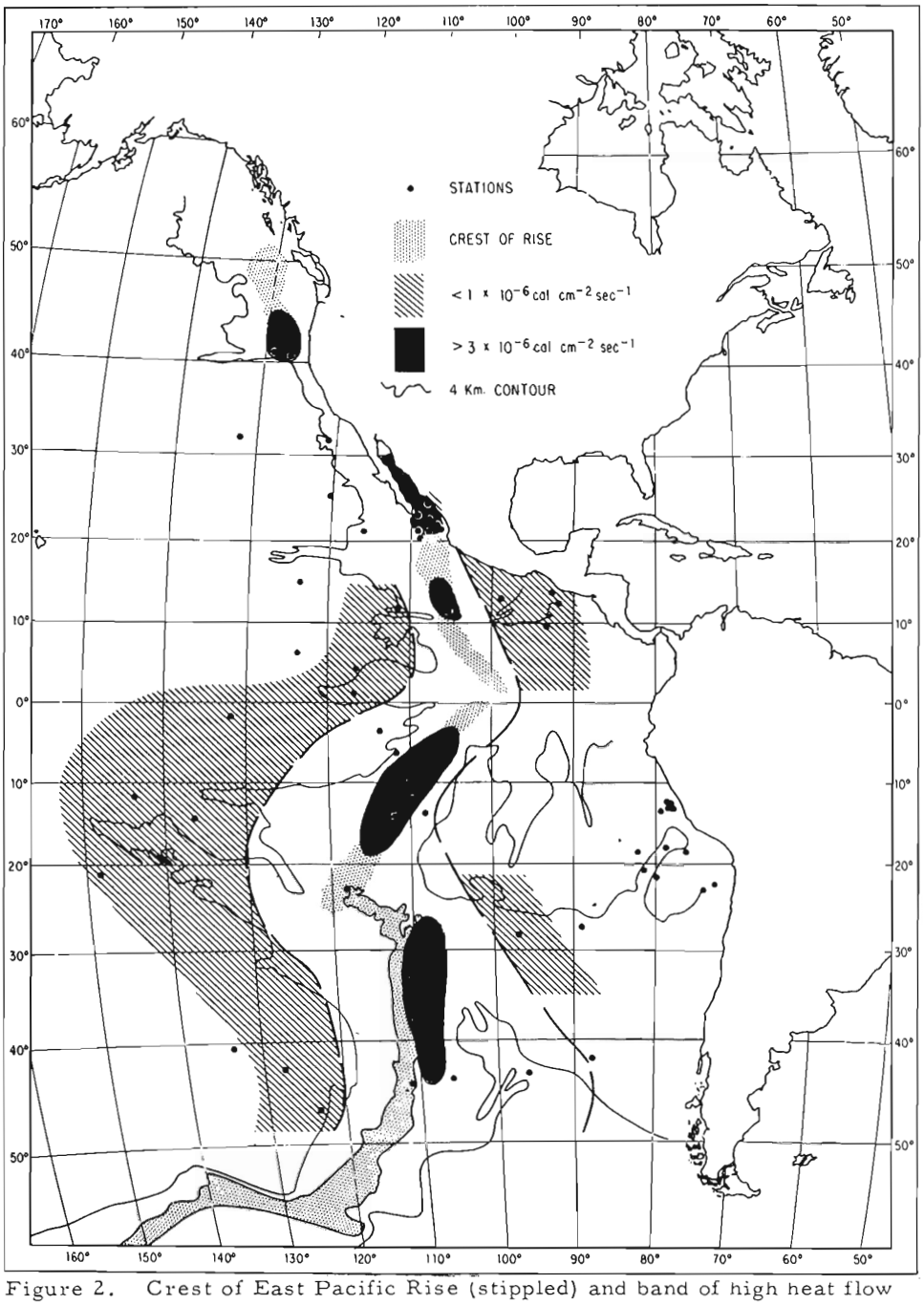


Figure 2. Crest of East Pacific Rise (stippled) and band of high heat flow (solid black), both of which appear to pass through western United States. From Menard (1960), with permission.



Figure 3. World mid-oceanic rift system over East Pacific Rise and postulated trifurcation as rift enters North American continent. Modified after Heezen (1960) and Heezen and Ewing (1961), and reproduced from Cook (1962), with permission of the publisher.

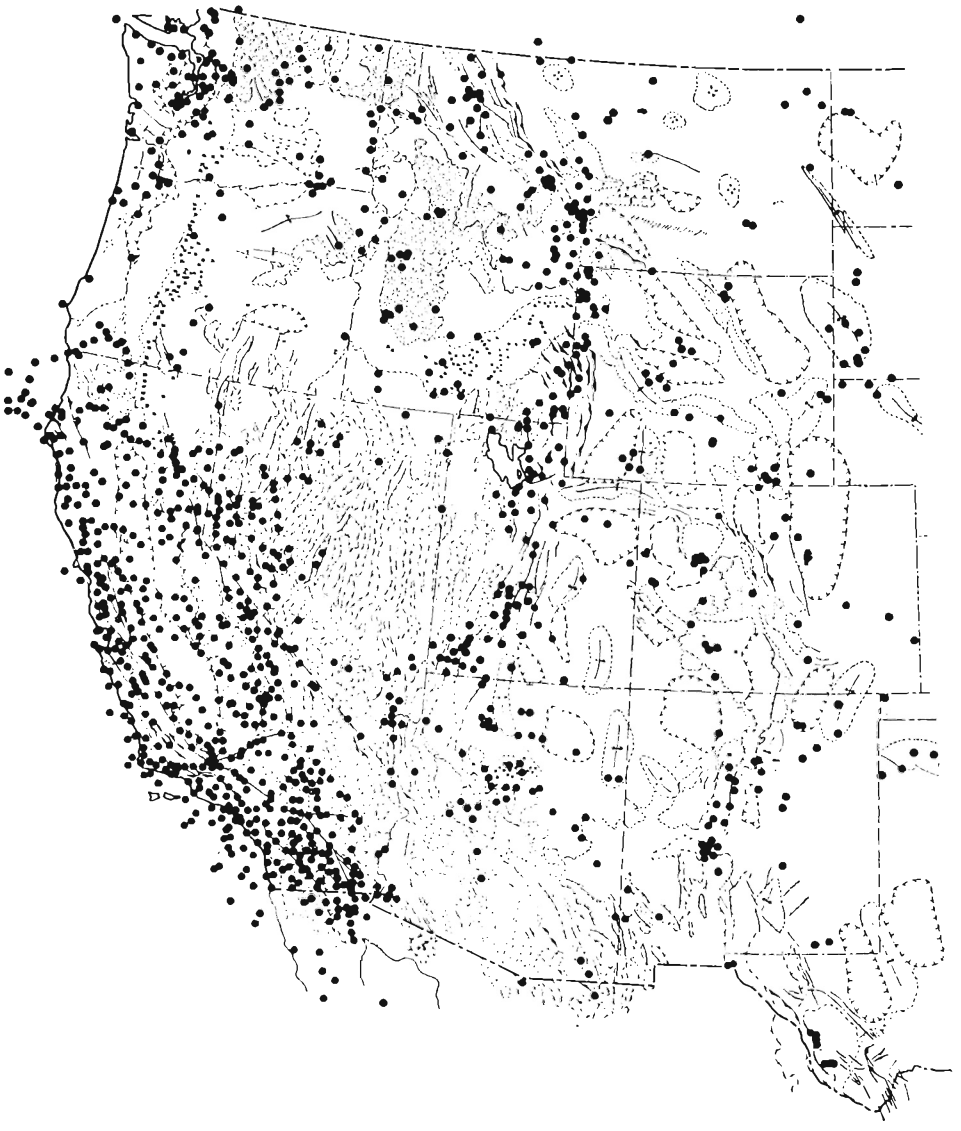


Figure 4. Relation of earthquake epicentres (through 1957) to tectonic structure in western United States. From Woollard (1958), with permission.

The active belt of seismicity in the eastern part of the Basin and Range province is well known. As shown on the maps of earthquake epicentres in Figures 4 and 5, this belt extends northward from the Gulf of California, through northern Mexico, western Arizona, central Utah, southeastern Idaho, western Wyoming, western Montana, and into British Columbia. The system of great trenches between Arizona and British Columbia (Fig. 6) essentially coincides with the seismic belt, and with the eastern branch of the rift system.

The Basin and Range province comprises a system of peculiar and roughly parallel mountain ranges and valleys bounded on the east and west (approximately) by the Wasatch Mountains and the Sierra Nevada. The fault-block structure of the ranges and valleys, both large and small, has long been known to be the dominant structure of the province. Gilbert (1874; 1875; 1890, 340-357; 1928, 1-2, 33, 61) originally recognized many of the great Basin and Range faults and studied the relationships between the great grabens and horsts in several areas, as for example in the Wasatch fault area in Utah. He postulated that the fault-block features were caused by both tensional and compressive forces, in which the block faulting is considered a surficial, more or less tensional, expression of deep folding (cf. Nolan, 1943, p. 184).

Figure 7 shows the framework of the late Cenozoic fault systems of the western United States, including enough of the Basin and Range normal faults to indicate the general direction of the tensional forces. The concentration of the longest and largest northward-trending faults essentially coincides with the eastern branch of the rift system, and with the system of great trenches. The belt of northwest-trending normal faults in Arizona near the boundary between the southern part of the Colorado Plateau and the Basin and Range province will be discussed later.

RECENT GEOPHYSICAL RESULTS

In the generalized geologic map of Utah shown in Figure 8, the heavy dark lines denote faults, and the previously mentioned major fault system extending through Utah and forming the eastern branch of the rift system is indicated. In southwestern Utah, several major north-south faults, such as the Hurricane fault, are found along the rift system, and in some areas, large grabens adjacent to these faults have been found by gravity surveys (Cook and Hardman, 1966). However, there is apparently an en échelon arrangement of the faults and grabens and not a continuous single rift valley. In northern Utah, there are also major north-south faults: e.g., the Wasatch fault which forms the steep escarpment known as the Wasatch front on the west side of the Wasatch Range. To the southeast of the Wasatch front is the Colorado Plateau, and to the west are the fault-block mountains

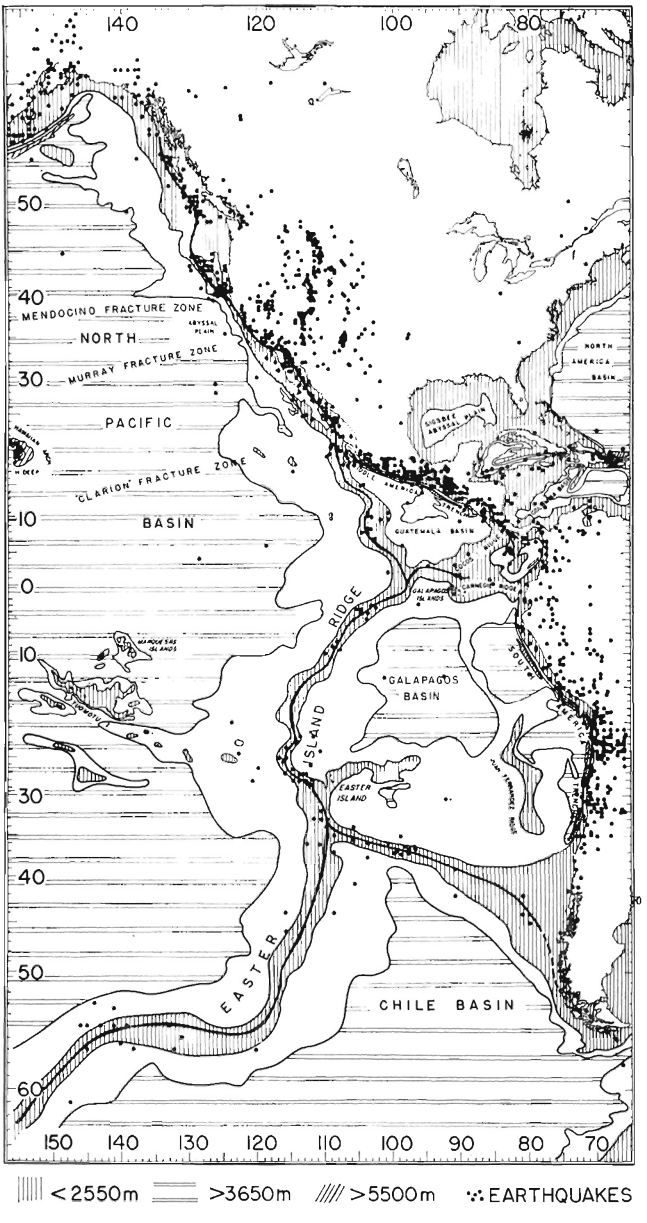


Figure 5. Bathymetry and seismicity of eastern Pacific. From Heezen (1962), with permission of the publisher.

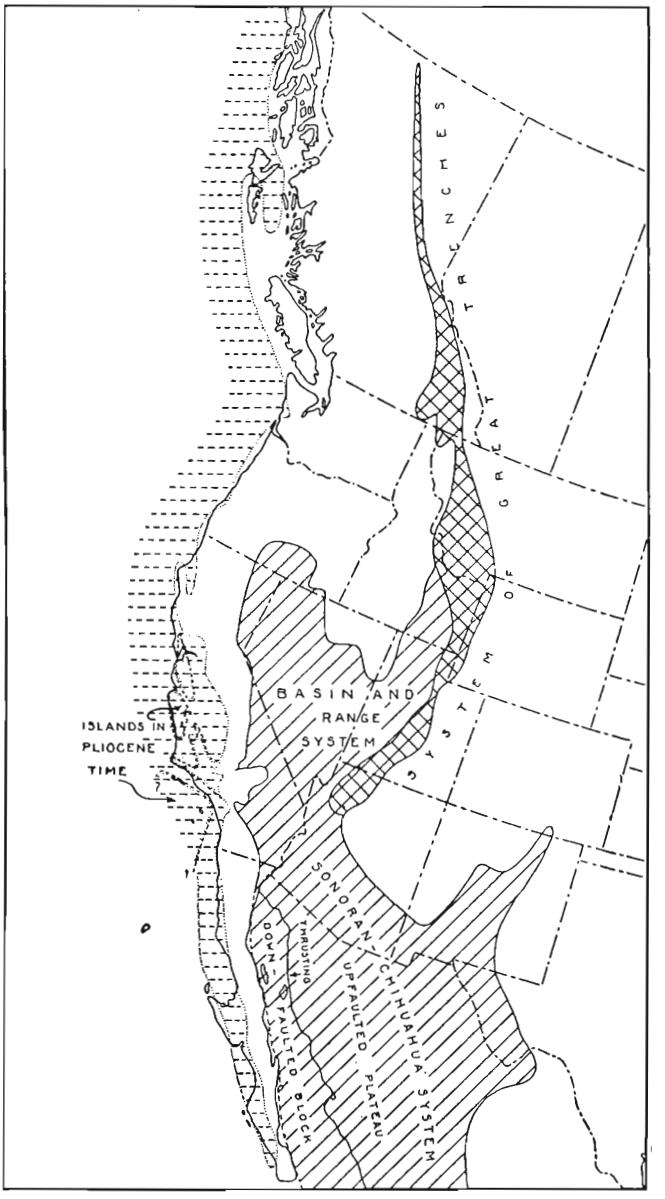


Figure 6. Tectonic map of western Cordillera showing Basin and Range and Sonoran-Chihuahua systems (obliquely ruled area) and system of great trenches (cross-ruled belt). From Eardley (1962, p. 494), with permission of the publishers.

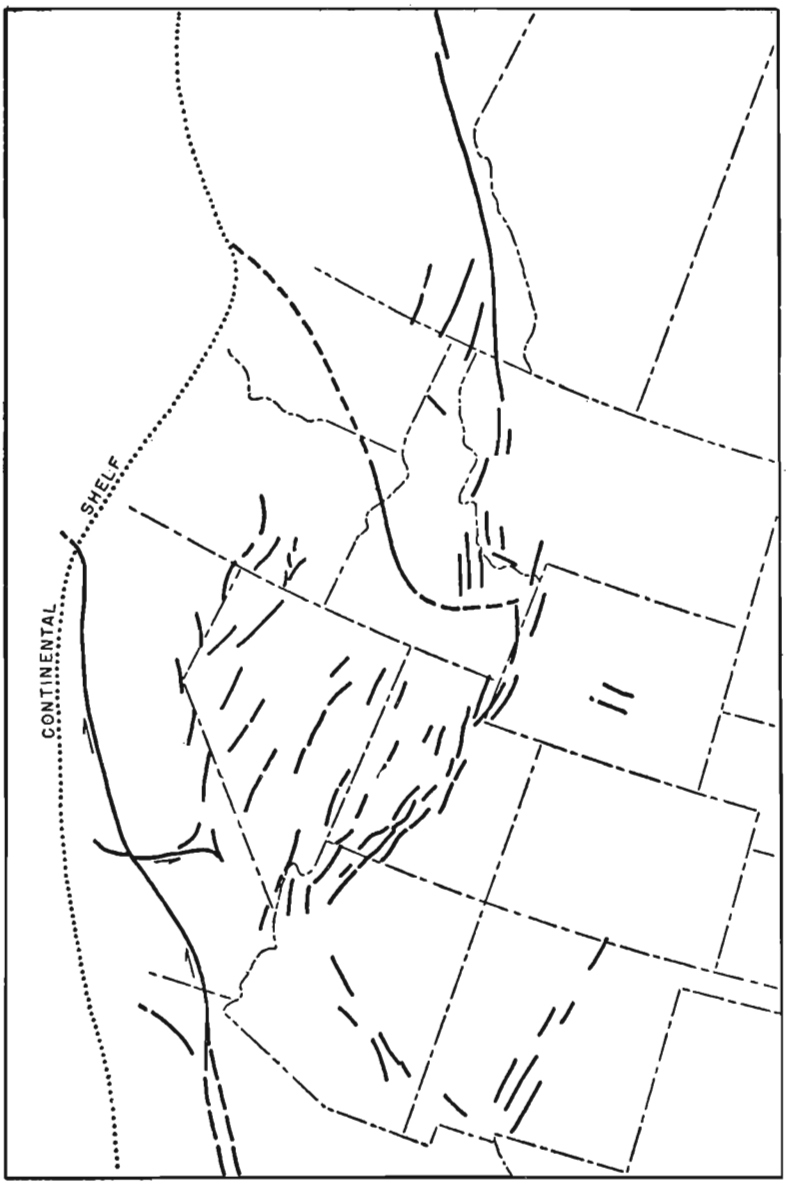


Figure 7. Framework of late Cenozoic fault systems in western United States. From Eardley (1962, p. 510), with permission of the publishers.

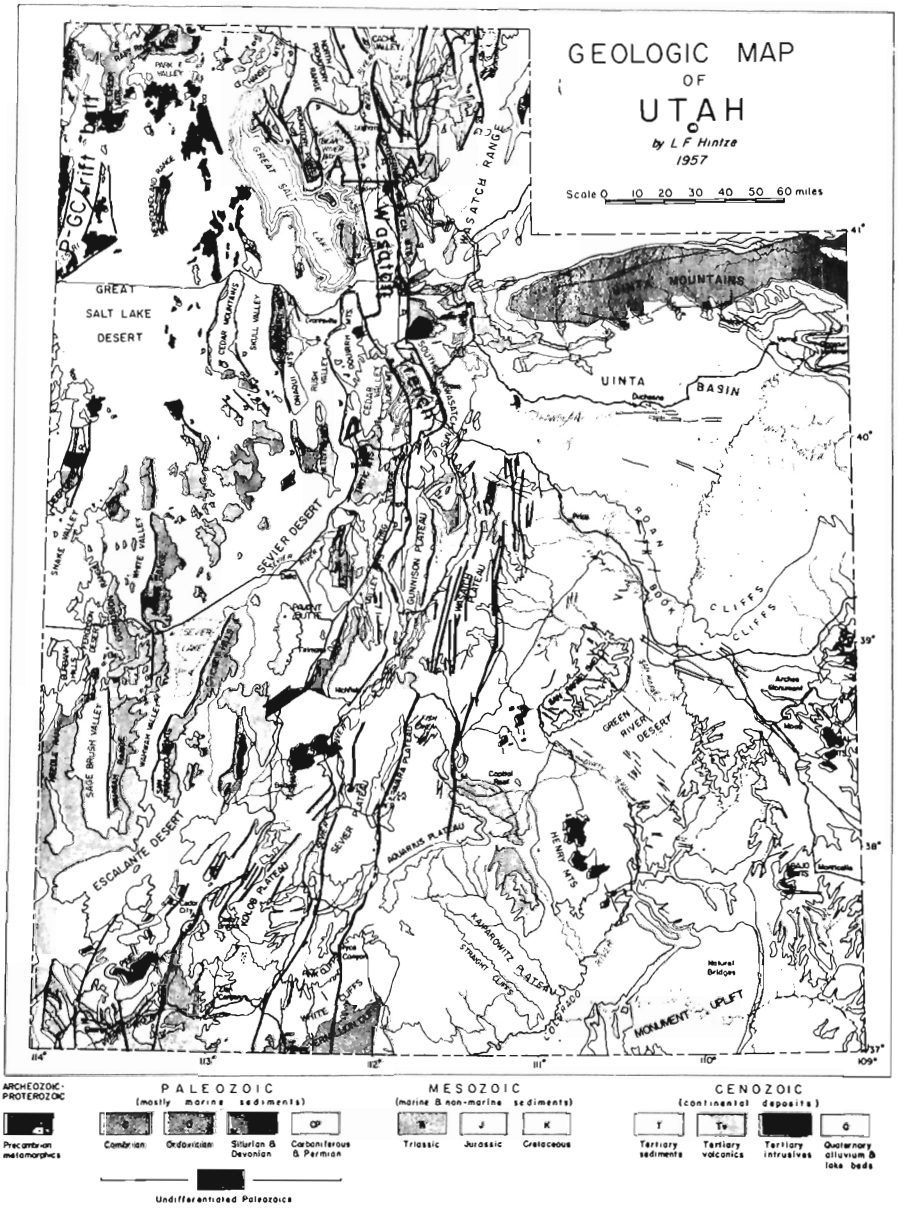


Figure 8. Geologic map of Utah. Modified slightly (by adding several major Basin and Range faults), and reproduced from Hintze (1957), with permission.

and valleys of the Basin and Range province. Our gravity work in Utah (Cook and Berg, 1956, 1958, 1961; Cook, 1962) has indicated a feature just west of the Wasatch front that we have designated the Wasatch trench. This trench comprises a series of great grabens that have been down-faulted relative to the Wasatch Mountains block (the latter being a great horst); it is now known to extend for a distance of about 160 miles along the west side of the Wasatch Range. The structure was originally recognized as a trough by Gilbert (1928, p. 33 and 62), and the gravity work has confirmed his interpretation and shown the trough to be much longer than he originally indicated.

Figure 9 shows an interpretive geologic cross-section across the Wasatch trench along a generally eastward-trending profile AA' (at approximately latitude 41°15'N in Fig. 8) just north of the city of Ogden, Utah. The section is based on data from a combination of refraction and reflection seismic surveys (Cook, Berg, and Lum, in press). These results indicate a minimum thickness of the valley fill [Cenozoic sedimentary and volcanic(?) rocks] of about 6,000 feet. Figure 10 shows an interpretive geologic cross-section along a gravity profile which, except for its eastern part, also coincides with profile AA'. The gravity profile extends between Little Mountain South and the Wasatch Range in the Ogden area. The interpretation is based on the residual Bouguer gravity profile which shows a total relief of about 40 mgal, and the three depths to bedrock indicated in the section are derived for density contrasts between the bedrock and the valley fill of 0.4, 0.5, and 0.6 gm/cc. For a density contrast of 0.6 gm/cc, the indicated thickness of the valley fill is about 7,600 feet, implying that the bedrock is about 2,500 feet below sea level. This indicates that the valley must be structural in origin.

The map in Figure 11 shows the results of a regional gravity survey of the northern Great Salt Lake Desert and adjacent areas in Utah, Nevada, and Idaho. The surveyed area lies 50 to 100 miles west of the Wasatch trench. The dots on the map are the gravity stations, and the contours are at intervals of 2 mgal. In the extreme western part of the surveyed area, the data indicate a northward-trending rift zone, designated the Pilot-Grouse Creek rift belt; this has been mapped along its length for 90 miles and it probably extends even farther to the north and south. Notably, the belt lies approximately 100 miles west of the Wasatch trench and is roughly parallel to it. It comprises, starting in the area just north of the town of Wendover (near the southwestern corner of the map) and proceeding northward, the Pilot Valley graben (this being about 35 miles long and 10 miles wide with a pronounced gravity low having a closure of about 24 mgal), and – after a local interruption by the Lemay Mountain horst – the Lucin graben, the Grouse Creek graben, and the Junction Valley graben.

Figures 12, 13, and 14 show gravity profiles and interpretive geologic cross-sections across the Pilot Valley, Lucin, and Junction Valley

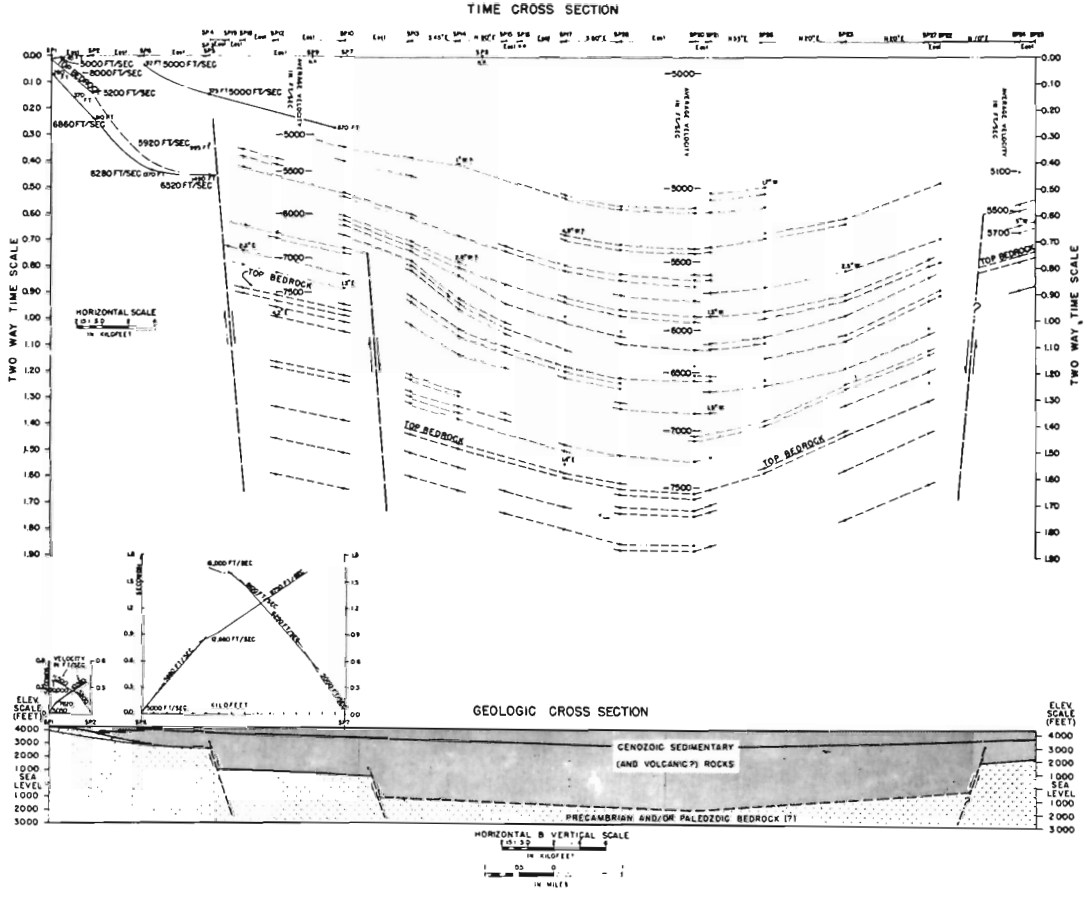


Figure 9. Refraction profiles, two-way time section of reflections and interpretive geologic cross-section based on seismic survey along profile AA' across Wasatch trench, Ogden area, Utah. From Cook and others (in press), with permission of the publisher.

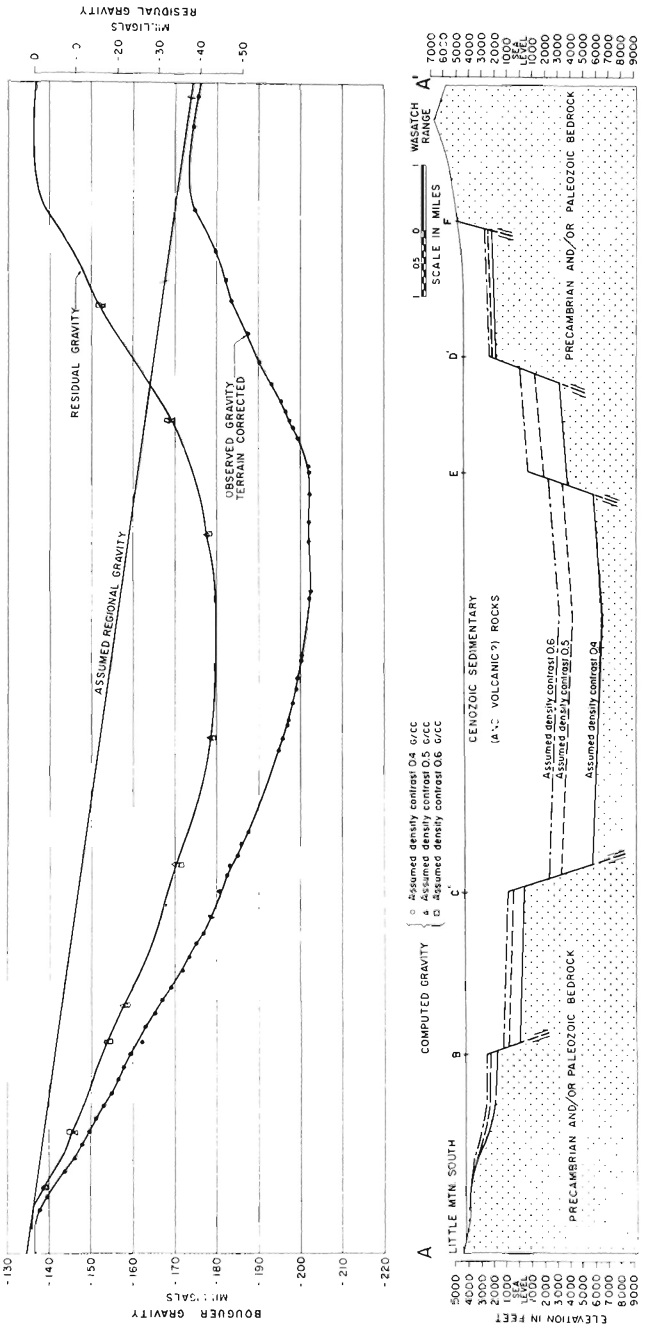


Figure 10. Observed Bouguer gravity, assumed regional gravity, and residual gravity (in milligals); and interpretive geologic cross-section along gravity profile AA' across Wasatch trench, Ogden area, Utah for three bedrock surfaces with assumed density contrasts of 0.4, 0.5, and 0.6 gm/cc, respectively, between valley fill and bedrock. From Cook and others (in press), with permission of the publisher.

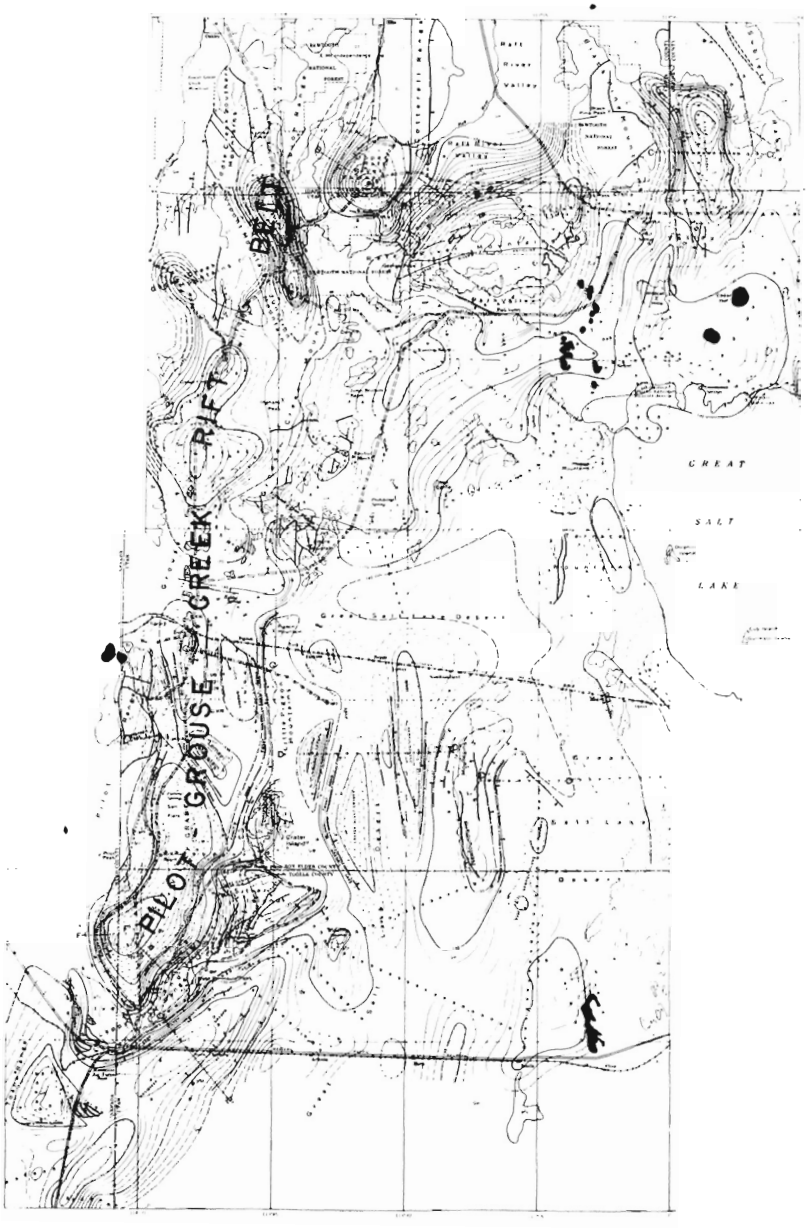


Figure 11. Bouguer gravity anomaly map of the northern Great Salt Lake Desert and adjacent areas in Utah, Nevada, and Idaho. Contour interval, 2 milligals. From Cook and others (1964), with permission of the publisher.

grabens, respectively. The density contrast between the bedrock and valley fill was assumed to be 0.5 gm/cc in each profile. It is emphasized that the geologic cross-sections should not be considered unique, but merely reasonable approximations. The indicated maximum thicknesses of the valley fill along the profiles are 5,300 feet in the southern part of the Pilot Valley graben, 7,000 feet in the central part of the Lucin graben, and 4,700 feet in the central part of the Junction Valley graben. At point B along the section across the Pilot Valley graben (Fig. 12), a north-south seismic refraction profile (Berg and others, 1961) indicated that the depth to the assumed pre-Tertiary bedrock is about 2,660 feet. At point A on the section across the Lucin graben (Fig. 13), a similar profile indicated that the depth to the assumed pre-Tertiary bedrock along the western part of the graben is about 2,200 feet.

To summarize the characteristics of the rift system in the eastern part of the Basin and Range province, it should be emphasized that the rift system is not one continuous rift valley but, rather, comprises individual belts of graben structures which are, in some places, parallel to each other, and in other places, intermittent with an en echelon relationship. In places, the total vertical displacement of the graben blocks relative to the adjacent mountain blocks may be 10,000-12,000 feet or more; and the bedrock that lies at the bottom of the valley fill may be as much as 2,500 feet below sea-level. These structural features of the Basin and Range province are strikingly similar to (1) the area of troughs and ridges in the East Pacific Rise (Menard, 1960, p. 1745), (2) the features in the area designated by Heezen and others (1959, p. 92) as the "Rift-Mountains Province" along the Mid-Atlantic Ridge, and (3) the rift valleys of Africa (Cook, 1962, p. 313 and 349). The rift valleys of Utah are especially comparable to the East Rift valleys of Africa [which seem less regular than the West Rift valleys of Africa, as judged from the descriptions of Gregory (1921) and Willis (1936)].

One of the most surprising results of crustal studies on continents in recent years is the fact that a thick layer of material with a compressional seismic velocity of 7.6 to 7.8 km/sec lies widespread beneath the Basin and Range province at a depth of about 25 km (Berg and others, 1960; Press, 1960; 1961; Diment and others, 1961; Cook, 1961; 1962, p. 326; Pakiser, 1963; Stuart and others, 1964). As shown in the cross-section in Figure 15c, this layer extends from the western portion of the Colorado Plateau across the Basin and Range province in Utah and Nevada, to the Sierra Nevada in California. The layer apparently extends down to a depth of about 72 km in the eastern part of the Basin and Range province. Because the material comprising this layer is apparently neither typical crustal-type rock nor typical mantle-type rock, I have suggested that it be designated as "mantle-crust mix" (Cook, 1962, p. 306). The material is considered to be intimately associated with the mantle, however, and accordingly forms a

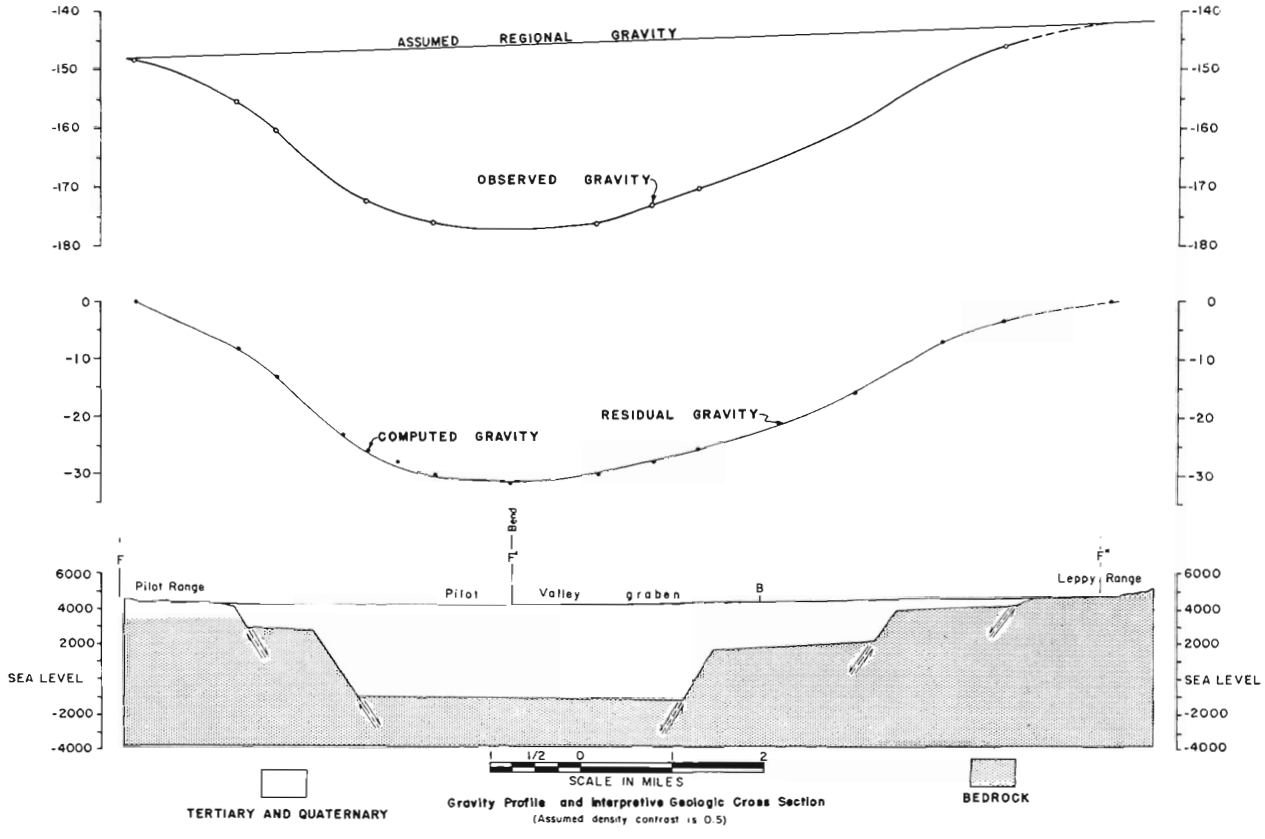


Figure 12. Gravity and interpretive geologic cross-section along profile F-F'-F" across Pilot Valley graben. Assumed density contrast is 0.5 gm/cc. From Cook and others (1964), with permission of the publisher.

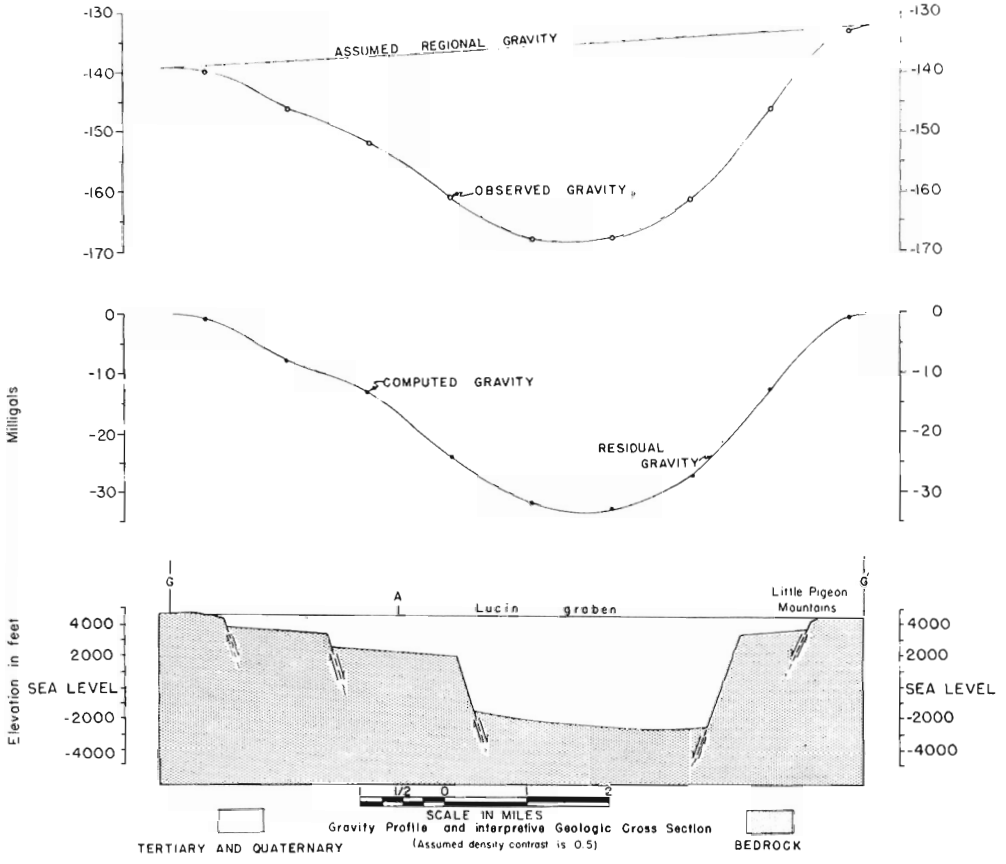


Figure 13. Gravity and interpretive geologic cross-section along profile G-G' across Lucin graben. Assumed density contrast is 0.5 gm/cc. Reproduced from Cook and others (1964), with permission of the publisher.

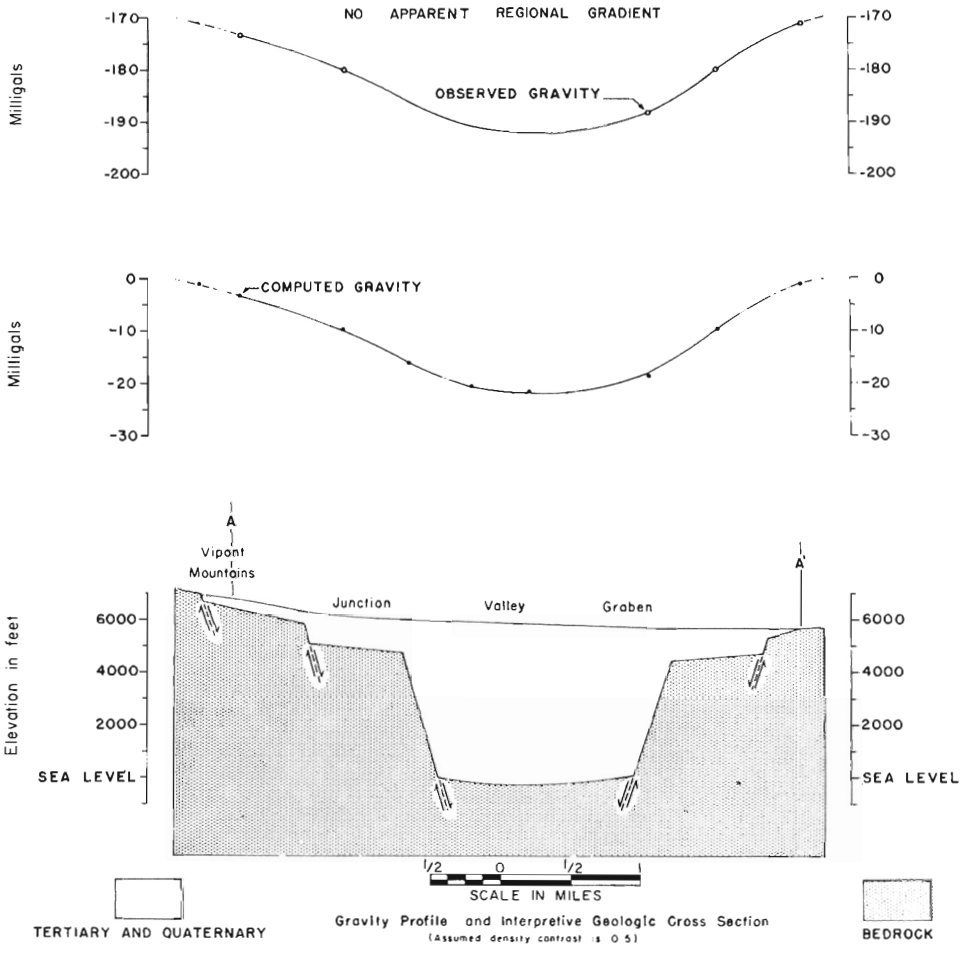


Figure 14. Gravity and interpretive geologic cross-section along profile A-A' across Junction Valley graben. Assumed density contrast is 0.5 gm/cc. From Cook and others (1964), with permission of the publisher.

lateral inhomogeneity in the uppermost mantle – that is, a lateral change of density in the uppermost mantle.

In recent years, to study the uppermost mantle, the Department of Geophysics of the University of Utah has been establishing long gravity profiles across the eastern part of the Basin and Range province and the western part of the Colorado Plateau. Our most recent work (Cook, Costain, Zimbeck, and Gray, 1965), which will be discussed briefly here, comprises long gravity profiles incident to the Transcontinental Geophysical Survey (part of the United States program for the International Upper Mantle Project). The discussion will deal with preliminary results along only one of two northward-trending gravity profiles that cross the boundary between the Basin and Range province and the southwestern margin of the Colorado Plateau in central Arizona. Large simple Bouguer gravity anomalies of as much as about 150 mgal relief were observed across the boundary. Using the earth crustal models for the general region as obtained from refraction seismic studies by the U.S. Geological Survey and the University of Utah, and assuming the velocity-density relationship of Nafe and Drake (Talwani and others, 1959, p. 1548), preliminary results were obtained which indicate that, with some minor exceptions, the Bouguer gravity anomalies correspond well with these models. In particular, the boundary between the two major layers at a depth of 25 to 30 km beneath the eastern part of the Basin and Range province deepens to 40 to 45 km beneath the western and southwestern parts of the Colorado Plateau; and the low-density material corresponding to the known anomalously low-velocity (7.6 to 7.8 km/sec) material at a depth of 25 to 30 km conceivably extends to a depth of about 70 km beneath the eastern part of the Basin and Range province and probably wedges out eastward and northeastward in the area under the western and southwestern parts, respectively, of the Colorado Plateau.

These results give added evidence that: (1) the mantle-crust-mix material exists beneath the eastern part of the Basin and Range province; (2) isostatic compensation goes to a depth of at least 70 km beneath the eastern part of the Basin and Range province; and (3) the average density of the mantle-crust-mix material under the Basin and Range province at depths of about 45-70 km is less than the average density of rocks at corresponding depths beneath the Colorado Plateau.

The general correspondence of (1) the large 150-mgal Bouguer gravity anomaly, (2) the deepening of the layer at 25 km to about 40-45 km, and (3) the wedge-out of the postulated mantle-crust-mix layer should be noted. Moreover, in this general region of south central Arizona, Eardley (1962, p. 510) postulates a great northwestward-trending strike-slip fault between the Basin and Range province and the Colorado Plateau.

The above-mentioned northward-trending gravity profile through Arizona and Utah extends across the region of south central Utah in which an apparent P_n velocity of 8.2 km/sec was reported by Herrin and Taggart (1962). Along this profile the periodic variation of their reported apparent P_n velocities from 7.5 km/sec in central Utah to 8.2 km/sec in south central Utah and then back to 7.7 km/sec in north central Arizona, would have resulted in a periodic amplitude of 40-80 mgal if the velocity-density relationship of Nafe and Drake (Talwani and other, 1959, p. 1548) were applied. However, no gravity anomaly of this magnitude was found that correlates with a P_n velocity of 8.2 km/sec in this region. In this respect our gravity results are in agreement with the conclusion of Healy and Ploger (1965) that the seismic refraction work of the U.S. Geological Survey does not support a P_n velocity of 8.2 km/sec in the south central Utah region (see also Ryall and Stuart, 1963).

Figures 16 and 17 show, respectively, the P_n velocities (Stuart and others, 1964, p. 184) and the contours of crustal thickness (Pakiser and Zietz, 1965) in the United States. In the Basin and Range province, the two large areas with upper mantle velocities less than 7.8 km/sec (Fig. 16) help to define the crestal part of the landward extension of the East Pacific Rise into the western part of the United States; and these two areas also indicate the great extent of the postulated mantle-crust mix. Figure 17 shows that the thickness of the earth's crust in almost the whole of the Basin and Range province is abnormally thin, namely less than 30 km. (In some places, it is as thin as 25 km.) The data in Figures 16 and 17 give supporting evidence that: (1) the Basin and Range province essentially coincides with the crestal part of the landward extension of the East Pacific Rise; (2) this landward extension of the East Pacific Rise has an abnormally thin layer of conventional crustal material, which is a characteristic feature of the East Pacific Rise itself (Menard, 1960, p. 1745); and (3) the mantle-crust-mix material of abnormally low velocity underlies the thin layer of conventional crustal material.

SPECULATIONS ON THE TECTONIC PROCESSES INVOLVED

Speculations will now be given on the probable tectonic processes involved in the formation of the rift system in the Basin and Range province. If the speculations are correct for this region, they will probably also apply to many of the other active tectonic belts of the earth which lie along the great world-encircling rift systems.

As shown in Figure 15b, I have taken Menard's (1960) convection cell, which he postulated beneath the East Pacific Rise, and projected it into the Basin and Range province (Cook, 1962, p. 327). Above the postulated rising convection cell is the region of inferred high heat flow and

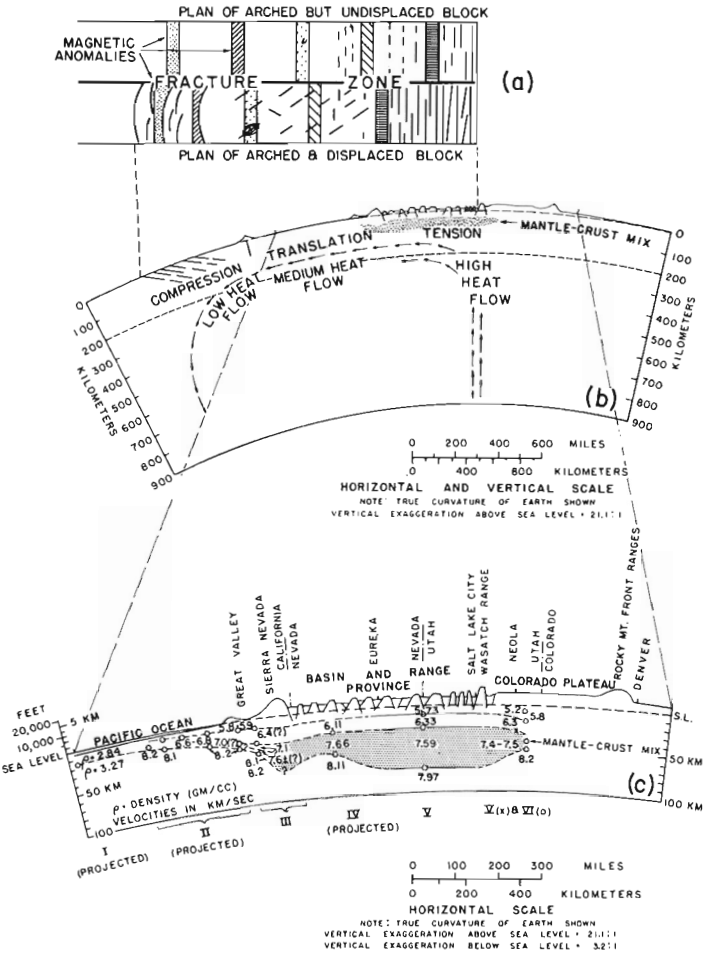


Figure 15. (a) and (b): Diagrammatic representation of convection-current hypothesis for the origin of various features associated with the western part of the United States (largely after Menard, 1960, as applied to East Pacific Rise). (c): Layering of the earth along generalized, interpretive cross-section across western part of United States; data along western part of section are projected long distances into the section. From Cook (1962), with permission of the publisher.

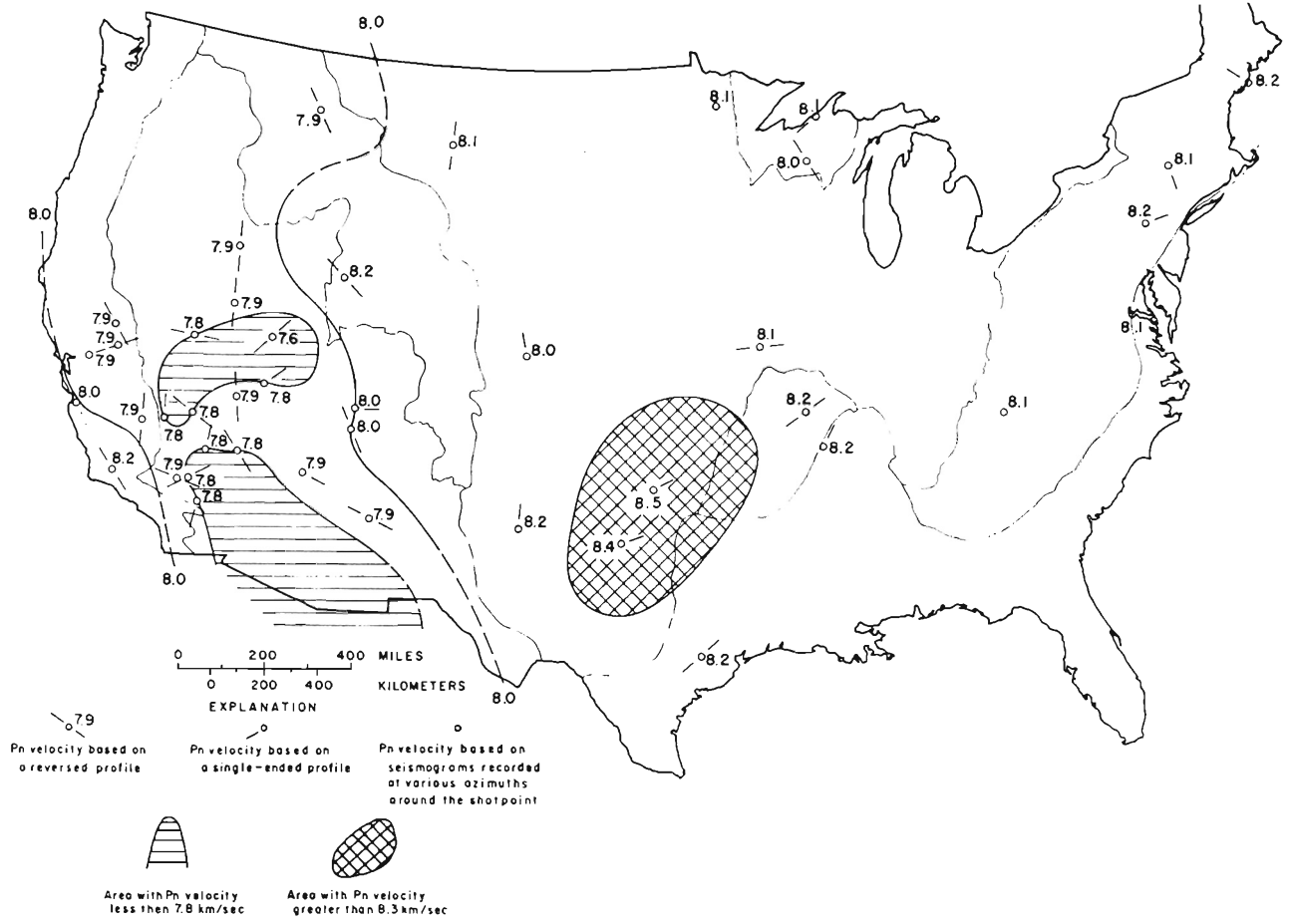


Figure 16. P_n velocities in the United States. Major physical division boundaries from Fenneman (1946). From Stuart and others (1964), with permission of the publisher.

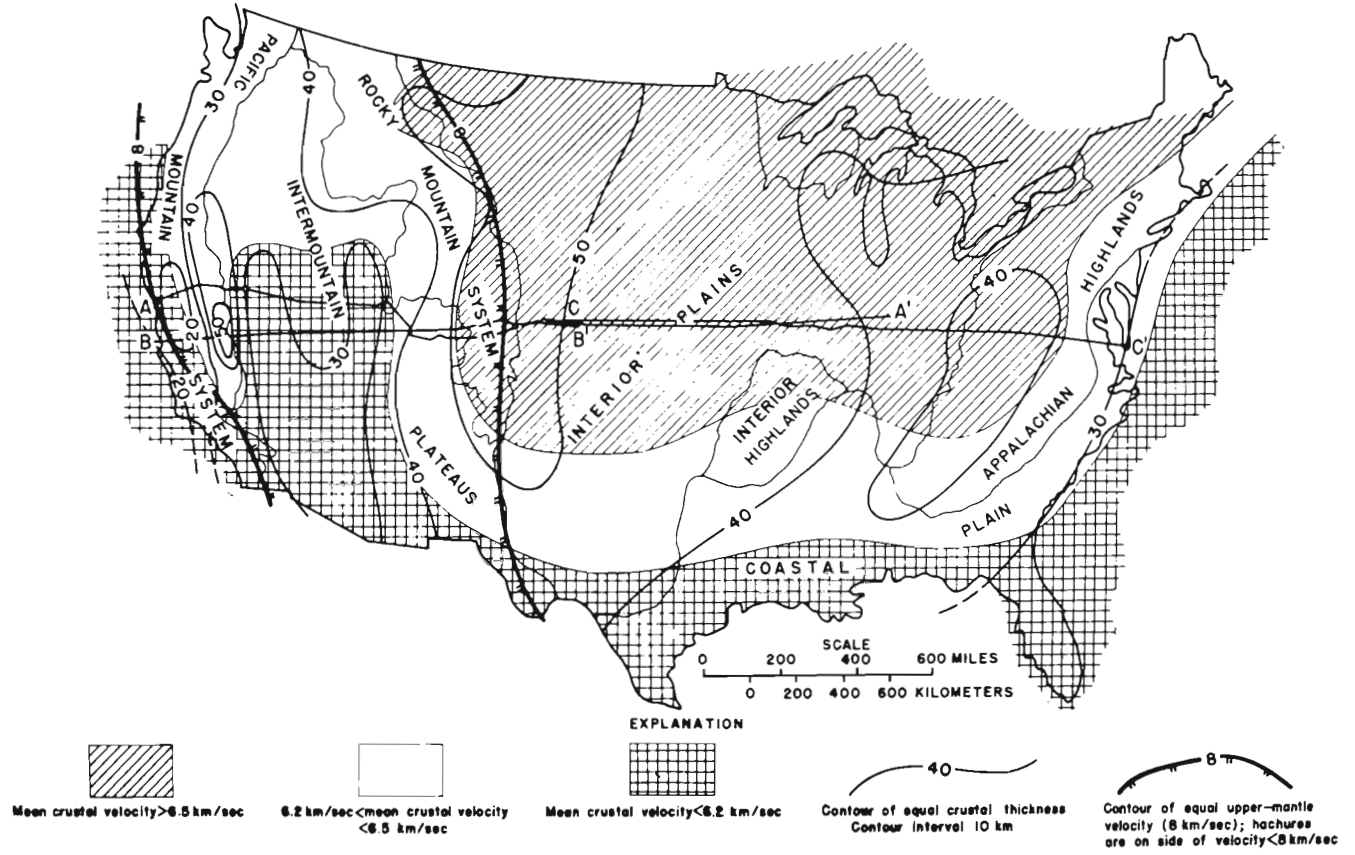


Figure 17. Crustal thickness; crustal and mantle velocities. From Pakiser and Zietz (1965) with permission.

of the tension, uplift, and lateral extension so characteristic of the Basin and Range province. Figures 15b and 15c show the postulated mantle-crust mix which probably extends between depths of about 25 and 72 km in the eastern part of the Basin and Range province (cf. Berg and others, 1960). The mantle-crust mix is postulated to have been formed in the zone marking the phase transformation from eclogite to basalt (or gabbro) with an expansion in volume. Or, of course, it may be serpentinized peridotite or the result of other phase transformations. However, if it is formed by a phase transformation, the concomitant expansion due alone to heat and a phase change is probably insufficient by itself to have caused the great uplifts and distensions of the overlying crust; accordingly, the convection current itself is probably the main driving force causing any large shift in the crust and uppermost mantle and, thus, has probably caused the uplift of the Mexico and Colorado plateaus, the Basin and Range province, and the great basaltic lavas and volcanic plateaus of the western United States.

In the model in Figure 15b, the top of the approximately horizontal limb (medium heat flow) of the convection cell in the region of translation (caused by drag forces exerted by the convection current on the rigid crust) is tentatively shown to be confined in the mantle to a zone between depths of 100 and 250 km below the earth's surface in order to make the zone conform (roughly) with the tentative limits of the low-velocity layer as given by Gutenberg (1959, p. 81, 84).

There are difficulties with the model shown in Figures 15a and 15b. The transcurrent faults (the Mendocino, Pioneer, and Murray faults) shown by Menard (1960) in his model for the East Pacific Rise have not as yet been proved to cross the Basin and Range province, and west of 130°W longitude, they are seismically dead. The convection cell along the profile shown in Figure 15b is in accord with the direction of left-lateral movement along the eastward-striking transcurrent Garlock fault of southern California (Smith, 1962, p. 87-88), which was mentioned in this symposium by Dr. Warren Hamilton; but the model does not explain the right-lateral movement along the San Andreas fault (Fig. 3). However, there is evidence suggested by Billings (1960, p. 363) on the basis of recent earthquake activity in the area of Fairview Peak-Dixie Valley, Nevada that right-lateral strike-slip movements of the San Andreas type are invading an area characterized by Basin and Range normal-fault structures. Accordingly the direction of the convection currents may have changed from those shown in Figure 15b.

Dr. George Thompson (this symposium) gives evidence of recent right-lateral transcurrent faulting in the Fairview Peak-Dixie Valley area as well as in the earthquake area immediately east of the Sierra Nevada. It should therefore be reemphasized that, because the above-mentioned transcurrent faults in the Pacific are now seismically dead, and

because the strike-slip movements along the San Andreas type (right-lateral) are probably now invading the Basin and Range province, the convection currents may have changed.

As a mechanism for producing faults with large strike-slip movements, Dr. J. Tuzo Wilson (1963, p. 90 and 93) has suggested the interaction of two mantle convection currents perpendicular to each other; and for the San Andreas fault region he showed a northward movement of the convection current lying west of the fault and a westward movement of the convection current lying east of the fault.

Figure 18 shows the possible direction and amounts (based on the widths of the lines) of distension and horizontal movements of the earth's crust in western North America as postulated by Eardley (1962, p. 510). The expansion fractures, which are distributed across the entire Basin and Range province, are concentrated along the western and eastern margins for purposes of illustration only. The San Andreas fault can be explained as the result of more rapid movement (to the northwest) of the crustal material (and hence convection currents) on the southwest side of the fault; and this process would result in oblique tensional rifting and the pulling-away of Baja California from Mexico to form the Gulf of California, as was suggested earlier by Hamilton (1961, p. 1315-1316). The formation of the Rio Grande graben or rift belt is also probably related to the extension and horizontal movement of the earth's crust in this region. A major northwestward-trending strike-slip fault across south-central Arizona at the southern margin of the Colorado Plateau has been postulated by Eardley (1962, p. 511; cf. Fig. 18, this paper), but the existence of this fault apparently has not yet been confirmed by field mapping. The trend of the postulated strike-slip fault would be parallel to the belt of northwestward-trending faults in Arizona (shown on Fig. 7), which are considered to be of the Basin and Range normal type. It should be recalled that the above-mentioned gravity anomaly having a total relief of about 150 mgal was found in this area along a northward-trending profile across the boundary between the Basin and Range province and the southwestern margin of the Colorado Plateau. However, any possible relationship between this gravity anomaly and the postulated major strike-slip fault remains to be resolved.

In conclusion, I would like to say that I think we need much more geophysical and geologic data to test better the working hypotheses incident to the problems of the world rift systems which have been presented at this symposium.

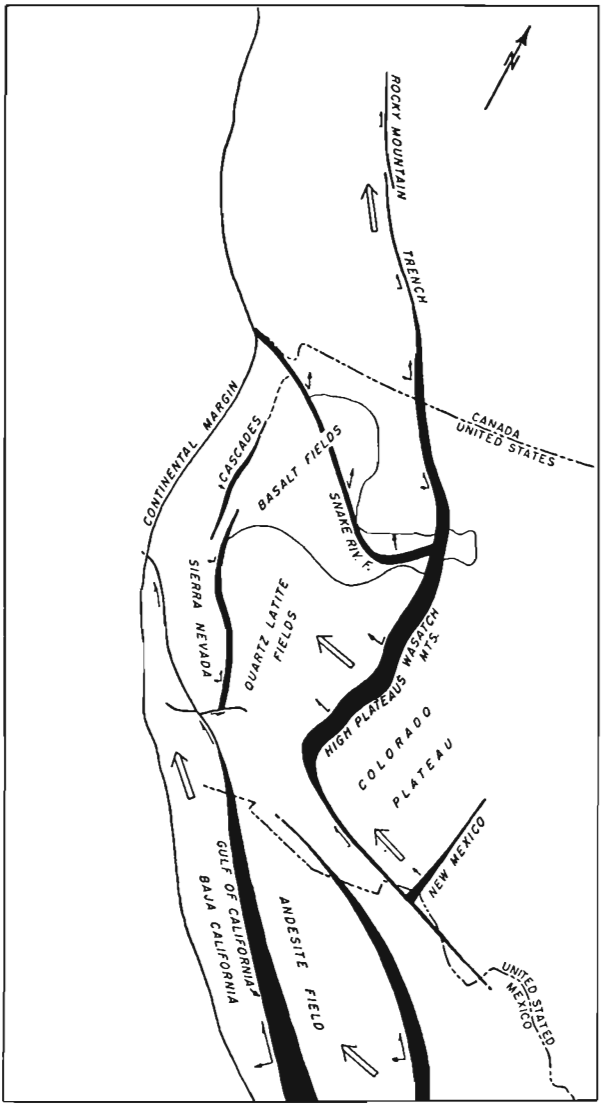


Figure 18. Diagrammatic map exploring the concept of extension and drift affecting western North America. Small arrows represent apparent vectors of movement. Large arrows represent apparent resultant direction of movement. From Eardley (1962), with permission of the publishers.

ACKNOWLEDGMENTS

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DISCUSSION

Dr. D.C. Krause (U.S.A.)

With regard to the work on the eastern margin of the rift zone, specifically along the Wasatch trench, do you have any idea whether that margin has been stable, say through Cenozoic time, or whether there has been a progressive eastward development of that margin?

Dr. Cook

I can only cite: (1) the work of Nolan (1943, p. 183), who states that faulting in the Basin and Range province as a whole has probably been in progress since early Oligocene time (about 36 million years ago), and that topographically expressed faults probably date back only to late Pliocene (less than about 13 million years ago) or early Pleistocene time (although there may have been still earlier movements along such faults); and (2) the work of Gilbert (1928, p. 10), who states that the faulting that caused the greater features of the present relief in the Wasatch fault area is clearly post-Eocene, but that the date of its beginning cannot yet be assigned. Gilbert also notes that although diastrophic changes have continued to the present time, only a small fraction are post-Pleistocene. The tuff in the Jordan Narrows unit, which is exposed in the southern part of Jordan Valley, Utah and which has been downfaulted into the grabens of the Wasatch trench, has been correlated tentatively with the Norwood tuff of early Oligocene age (Eardley, 1944, p. 845-846; Slentz, 1955, p. 25). Thus some of the faulting may be rather old. However, the faulting is continuing today, and there are

recent fault scarps – some probably only a few hundred years old at most – along the Wasatch trench. The Wasatch trench is seismically active today.

Dr. H. Kuno (Japan)

What kind of structure and rock arrangements do you postulate in speaking of mantle-crust mixtures?

Dr. Cook

We discussed the problem of the mantle-crust mix two years ago at the IUGG meetings in Berkeley. If the mantle-crust mix is caused by a phase transformation within active tectonic belts, there could be pockets of material, say of eclogite, within masses of basalt or gabbro (or vice versa) and this mantle-crust mix would not necessarily be one continuous layer all of the time (Cook, 1962, p. 346). It's a very interesting problem which, of course, justifies the Mohole.

Dr. Kuno

If eclogite pockets occur at some places within the mantle, we cannot distinguish such pockets from the surrounding peridotite because the seismic wave velocities of eclogite and peridotite are about the same. So I suggest that, at this particular region, several velocity values may be present in different depths in the upper mantle. The eclogite-gabbro transition probably lies well below the crust-mantle boundary. If we had pockets of gabbro below the Mohorovičić discontinuity, we would have the bulk velocity corresponding to that of a mixture of peridotite and gabbro. This velocity could be 7.6 to 7.8 km/sec.

Dr. H.H. Hess (U.S.A.)

Simply a higher temperature in normal mantle material would also decrease the seismic velocity, probably not as much as down to 7.5 km/sec, but it could bring it down to 7.8 km/sec. Raitt and Shor have measured seismic velocities where there's high heat flow, and have obtained the same sort of low velocities.

Dr. Cook

In 1962, I summarized the areas of the world which at that time were known to have seismic velocities of 7.4 to 7.7 km/sec in the uppermost part of the mantle; these areas comprised many active tectonic belts (Cook, 1962, p. 307-308). Since that time, similar low-velocity values in the uppermost mantle have been reported in other active tectonic belts, such as in the South Kurile Islands (Fedotov, 1963), Kamchatka (Kosminskaya and Riznichenko, 1964, p. 108-114), and northern Italy (Berckhemer and Hersey, 1965). Thus the 7.4 to 7.7 km/sec anomalously low velocities in the uppermost part of the mantle are characteristic of many active tectonic regions of the earth. Also in 1962, I estimated that the total area of these belts with such low velocities [which include mid-ocean

ridges, island arcs, and rift valleys (both oceanic and continental)], although still incompletely charted, is at least 10 per cent and may be 20 per cent, of the whole area of the earth (Cook, 1962, p. 348). It now appears that the value is closer to 20 per cent.

It should also be emphasized that in some of the active tectonic belts where deep refraction seismic soundings have been made, the low seismic velocity values extend to a great depth before normal upper-mantle velocity values of 7.8 to 8.3 km/sec are found. Beneath the South Kurile Islands region, for example, the refraction seismic measurements indicate a 7.7 km/sec layer that extends to a depth of 80 km (Fedotov, 1963).

Dr. D.H. Matthews (U.K.)

There is the related problem of abnormally high mantle velocities in areas that formerly were tectonically active but which are now inactive – e.g. the Darwin Rise in the Pacific, and the northern part of the Appalachians. Also, although it is tempting to postulate a rise in isotherms to account for low velocities in tectonically active regions, this implies a more uniform increase in heat flow than has been observed. The observed values are very spotty – there may be several high ones, but there are also many average and low ones. The high ones are not known to be related to velocity anomalies.

Dr. Cook

To my knowledge, the only published values of heat flow to date in the Basin and Range province are those taken by Dr. Robert F. Roy. They are as follows (in units of microcalories per cm^2 per sec): 1.9 and 3.5 (East Tintic mining district, Utah); 2.36 (western Nevada); and 2.1 (Mojave Desert, California) (Simmons, 1965). Because the Basin and Range province probably lies over the crestal part of the landward extension of the East Pacific Rise, it is expected that the average heat flow over this province will be larger than the world average.

THE RIFT SYSTEM OF THE WESTERN UNITED STATES

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Geophysics Dept., Stanford University
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Abstract

The rift system of the western United States was first recognized by G.K. Gilbert in 1875. It was later realized that the normal-fault complex was much more extensive than the Great Basin. Unless one wishes to lump together all of the tectonically active region, it seems reasonable to define the rift system as that part of the Cenozoic fault system characterized by lateral spreading or tensional strain.

The following conclusions may be drawn:

1. In some areas, especially near the margins of the rift system, there is an overlap in types of deformation, i.e. the normal faults have a strike-slip component, or (as in west Texas) broad anticlinal uplifts occur with the normal faults.
2. Present seismic activity does not coincide with the rift zone.
3. The region of anomalously thin crust and anomalous upper mantle correlates roughly but not exactly with the rift system.
4. Volcanism and heat flow show the closest correlation with the rift system, but more heat flow measurements are needed. Magnetic anomalies, which may also be thermally dependent, show promise and need further investigation.
5. Individual rifts may be underlain by igneous intrusions at a depth of 10 km or less.
6. Volume changes at the moment of large earthquakes are consistent at least qualitatively with elastic rebound theory.

EXTENT AND CHARACTERISTICS

Although he did not call it that, the rift system of the western United States was first recognized by G.K. Gilbert during the early geological exploration of the west (Gilbert, 1875). Gilbert found strong evidence that the Cenozoic mountains and basins of the internally draining Great Basin were not formed by folding as had been thought, but were created instead by intricate block faulting. It was later realized that the region of normal faulting extends far beyond the limits of the Great Basin, and the larger

region is commonly referred to as the Basin and Range Structural Province. It is the normal-fault complex of this region that I refer to as the rift system.

Stated another way, unless we wish to lump together all of the tectonically active region, it seems reasonable to define the rift system as that part of the Cenozoic fault system characterized by lateral spreading, i.e. extension or tensional strain. This does not mean that a component of strike-slip faulting may not be present also, but simply that the component of extension is essential. Defined in this way, the rift system is similar to the Iceland, the Oslo and the Rhine grabens, and to the African rifts, but it is dissimilar to the San Andreas fault system, which is characterized by past and present compression superimposed on strike-slip faulting. Gilbert himself confused the problem of the origin of the Basin Ranges. Perhaps influenced by the tectonic theories of his day, notably the shrinking earth hypothesis, he supposed that the normal faulting results from deep seated compression. However, extension is demonstrated clearly by geodetic measurements of strain increments at the time of large earthquakes along the rift system (Thompson, 1959, p. 224-226).

Figure 1 shows the extent of normal faulting – the rift system of the western United States – as compiled by Gilluly (1963, p. 158). The great faults forming the east escarpment of the Sierra Nevada are prominent. An active zone of large earthquakes in western Nevada converges southward with the Sierra Nevada faults. To the east, the faults near the west side of the Colorado Plateau are also active (Cook, 1966). Northward, the rift system narrows markedly and joins the Rocky Mountain Trench. Southward it diverges and includes a very broad region in Mexico.

It is noteworthy that there are some strike-slip movements in this region of predominant normal faulting. The Las Vegas shear zone in southern Nevada shows evidence of right-lateral strike-slip displacement (Longwell, 1950). The Owens Valley faulting in 1872 had a right lateral component although it was predominantly dip-slip (Bateman, 1961). The Dixie Valley-Fairview Peak earthquake of 1954 also had a right lateral component along part of the fault trace. The amount of strike-slip in these examples is small in comparison with the San Andreas system, and the strike-slip movements accompany extension in all the examples of recent faulting, whereas in the San Andreas system compression of Coast Range anticlines accompanies the present right-lateral shearing movement (Burford, 1965).

Figure 2 shows the epicentres of earthquakes between 1937 and 1957 as compiled by Woollard (1958, p. 1138). The two lines enclose the rift system shown on the preceding slide. The rift system cannot be defined by seismicity because the coastal region, where strike-slip faulting and compressional folding predominate, is obviously more active today.

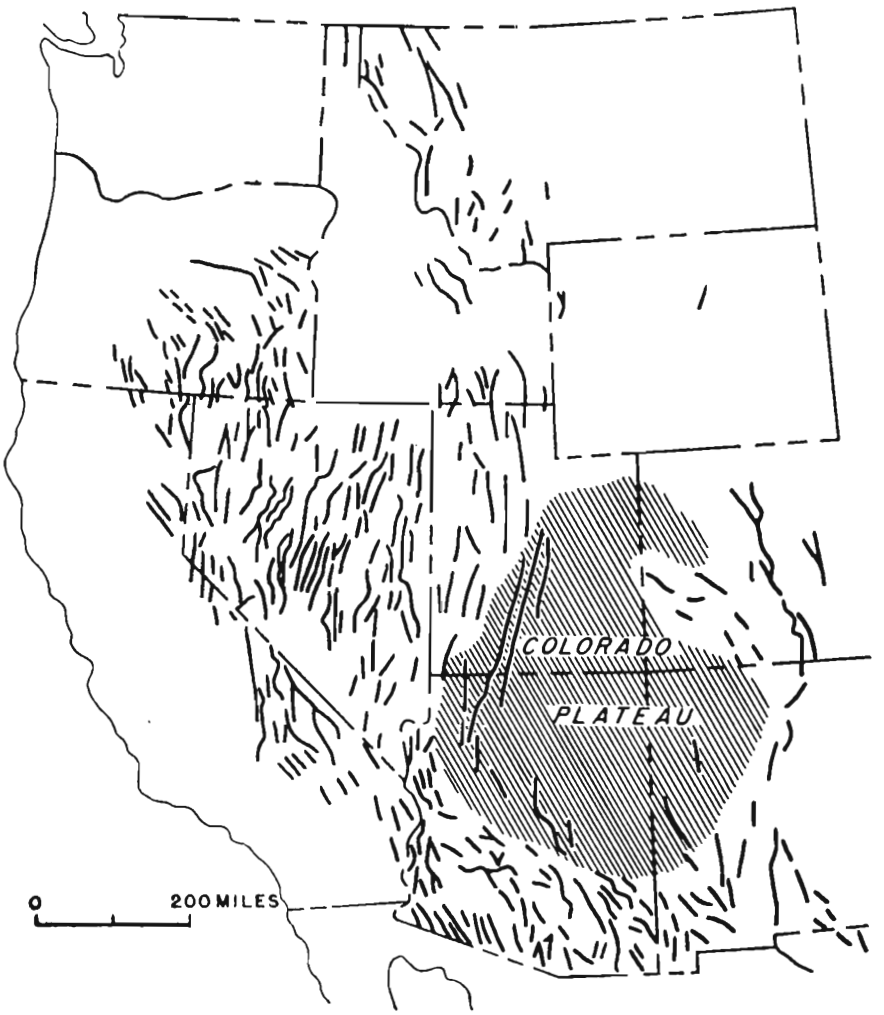


Figure 1. Cenozoic normal faults of western United States, from Gilluly (1963). The extent of normal faulting best defines the rift system.

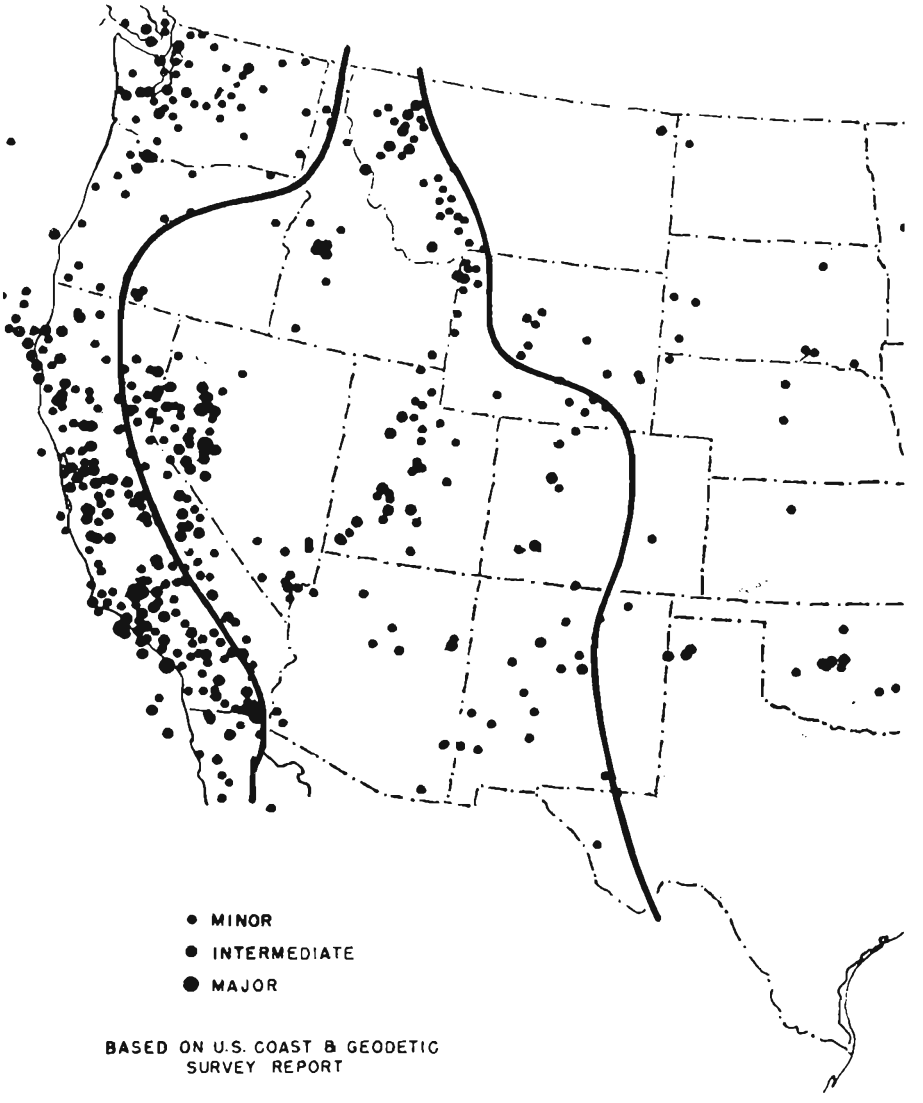


Figure 2. Earthquake epicenters, 1937 to 1957, from Woollard (1958). The two lines are approximate boundaries of the rift system shown in Figure 1. Part of the rift system appears seismically inactive.

Within the rift system some areas of intense normal faulting in the past are comparatively inactive today: e.g. southeastern Oregon, eastern Nevada, southern Arizona, and westernmost Texas. On the other hand, the Sierra Nevada front, the western border of the Colorado Plateau in Utah, and the Dixie Valley zone in western Nevada are highly active.

How does this fit into the oceanic rift system? Menard (1961, p. 53) suggests that the East Pacific Rise continues into the highland region of western North America. Ever since Ewing and Heezen (1956) first suggested that the rifts may be continuous on a world-wide scale, oceanographers have usually drawn the rift or its main branch through the Gulf of California and along the San Andreas fault. However, it seems more reasonable to include western Mexico with the Gulf of California in the rift zone, together with the whole broad zone of normal faulting to the north.

The Gulf should be included because of the evidence of lateral spreading concurrent with strike-slip faulting there (Hamilton, 1961). The continental borderland off southern California may also be a branch of the rift system, but it is not clear whether that area has undergone extension.

CRUST AND MANTLE

Several unusual properties of the crust and mantle are more or less closely associated with the rift zone of western United States.

First, the upper mantle velocity is anomalously low, and the crust is anomalously thin. Pakiser and Steinhart (1964, p. 137) have summarized the upper mantle velocities for the region. They show that the entire western area of the rift zone (the shaded area in their diagram) has a P_n velocity less than 8.0 km/sec. Neither the eastern nor the western boundary of this low velocity region corresponds exactly with the boundaries of the rift zone, but the geneneral correspondence with the broader highland region – the rise – is striking. The central part of the zone close to the rifts has the lowest velocity. A crustal section across the western side of the rise, computed by Thompson and Talwani (1964), shows that the area is isostatically balanced, but the crust is anomalously thin, and the upper mantle is anomalous in velocity and density. These anomalies extend over the whole of the seismically active area at this latitude and do not stop at the boundary of the rift zone along the eastern front of the Sierra Nevada. The thin crust and anomalous mantle correlate with the rise rather than the rift zone.

A second attribute of the rift zone is volcanism. The tectonic map of the United States shows this very well, and the world-wide association

of rifts with volcanism is widely accepted. The relationship is far from exact, however. Some areas of normal faulting are free of volcanics at the surface, and some volcanic areas have few normal faults.

Because of the regional Cenozoic volcanism, we expect the heat flow to be high, and recent measurements are bearing out the expectation (Lee and Uyeda, 1965). The high heat flow seems to be restricted to a narrower region than the anomalous mantle, but the details are not yet clear.

Magnetic anomalies within the rift zone differ from those elsewhere (Zietz, 1965). Broad anomalies that may have their sources in the lower crust or within the mantle are conspicuously absent. Zietz tentatively explains this observation in terms of a silicic crust and a hot upper mantle.

MODEL FOR A BASIN-RANGE RIFT

It is of interest to inquire into the subsurface structure and origin of a graben. Figure 4 shows diagrammatically a rift of fairly typical dimensions in the Basin Ranges. To take a specific example, it represents Dixie Valley, Nevada, reasonably well (Meister, 1965; Thompson, 1959). That valley widened 5 feet in the 1954 earthquake and one side sank 7 feet. The accumulated lateral spreading of this valley in all the earthquakes of the last 10 to 15 million years amounts to about 3 km. The geometry of faulting clearly requires sizable extension. A second notable fact is that the faults, which dip about 60°, converge at a depth of only about 10 km. Plastic flow of the rocks below this depth could account for regional spreading but could not readily account for localized dilation below the graben. A satisfactory explanation may be that an igneous intrusion or zone of intrusions dilates the lower crust beneath the graben, a suggestion which I published in 1959 (Thompson, 1959, p.222), but for which there is still no definite evidence. Numerous hot springs hint that the active valleys are thermally anomalous, and detailed heat flow studies might be especially enlightening. No magnetic anomalies diagnostic of a concealed intrusion have been found (Smith, 1965; Meister, 1965), but the volcanic rocks in this region are silicic, so that we should perhaps not expect a magnetic anomaly.

Turning again to the regional picture, if deep-seated plastic or convectional spreading is taking place on a broad scale, as suggested by the bottom arrows in Figure 3, it may be complementary to regional compressional deformation in the coastal region to the west, near the San Andreas fault zone (Thompson, 1960, p. 65).

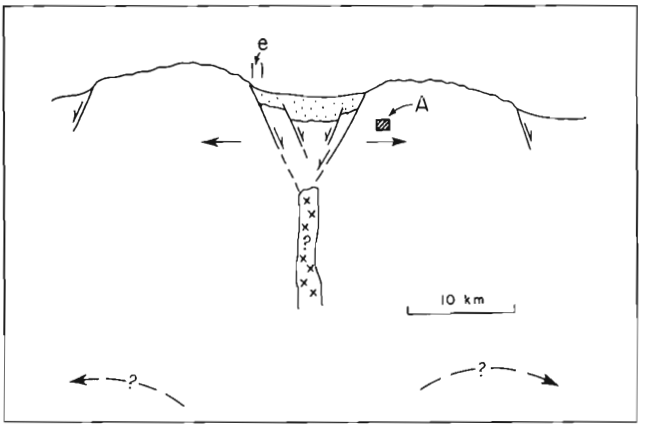


Figure 3. Sketch section of a graben in the Basin and Range province. Commonly the faults are unequally developed and the floor is tilted. The underlying dyke is hypothetical. Note the convergence of faults at depths about equal to the breadth of the graben. "e" is the horizontal extension on one fault; "A" is a small region shown in Figure 4.

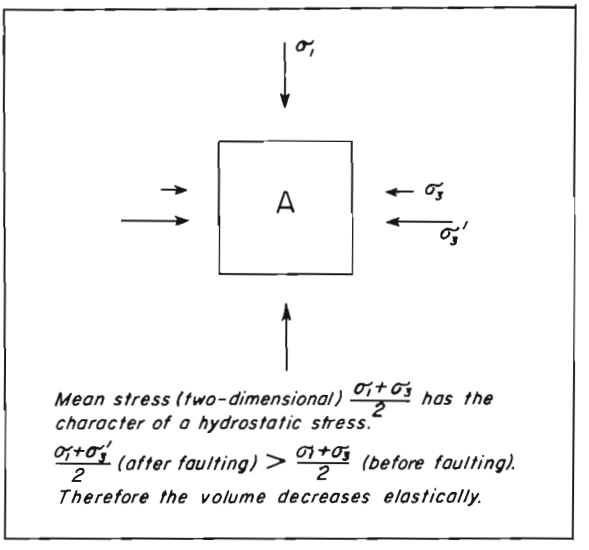


Figure 4. Stresses before and after an earthquake. The vertical principal stress, maintained by the gravitational load, remains constant but the horizontal principal stress (taking compression positive) increases. An elastic decrease in volume therefore allows the graben to drop during an earthquake.

ELASTIC REBOUND

If the detailed model has any validity, it should also account for the sudden subsidence of a graben block at the moment of an earthquake and the accompanying sudden lateral extension. In the example of the Dixie Valley earthquake of 1954, the elevation of the mountain blocks changed hardly at all, whereas the valley dropped as much as 7 feet. This asymmetry between the movement of the mountain and valley blocks demonstrates a serious inadequacy of present dislocation and strain theory, which neglects gravity and also assumes a perfectly uniform half space (Press, 1965). The horizontal strain jump at the time of the 1954 earthquake died off with distance from the fault, so that points distant, say 50 km, from the fault on either side moved little or not at all with respect to each other (Whitten, 1957). The observed relations can be understood if we assume the shallow crust was slowly distended elastically in the years preceding the earthquake. At the time of the earthquake these accumulated stresses were suddenly relaxed.

Consider the stresses in a small region "A", shown in Figure 4. The vertical principal stress, maintained by the gravitational load, remains constant during faulting. The horizontal principal stress, taking compression as positive, diminishes during strain accumulation up to the point of rupture. At rupture, the horizontal principal stress suddenly increases. The volume of "A" abruptly decreases, mainly in a horizontal direction, because of the abrupt increase in the mean stress. It is this abrupt elastic volume decrease in the adjacent mountain blocks that can permit the valley block to subside suddenly during an earthquake. At the surface a considerable volume disappears too quickly for it to be explained by plastic flow or movements of magma at depth. A check on this reasoning is available from the recent Alaskan earthquake, for a strike-slip or thrust movement should be accompanied by a decrease in the mean stress and a consequent increase in volume. The Alaskan data are in accord with this expectation; the volume of uplift appears to be roughly twice the volume of subsidence (Plafker, 1965), making a large net increase of volume.

CONCLUSIONS

1. The rift system of western United States is most logically defined by the Cenozoic normal faulting, which characterizes the region of lateral extension.

2. In some areas, especially near the margins of the rift system, there is an overlap in types of deformation, i.e. the normal faults have a

strike-slip component, or (as in west Texas) broad anticlinal uplifts occur with the normal faults.

3. Present seismic activity does not coincide with the rift zone.

4. The region of anomalously thin crust and anomalous upper mantle correlates better with the rise than with the rift system.

5. Volcanism and heat flow may show the closest correlation with the rift system, but more heat flow measurements are needed. Magnetic anomalies, which may also be thermally dependent, show promise and need further investigation.

6. Individual rifts may be underlain by igneous intrusions at a depth of 10 km or less.

7. Volume changes at the moment of large earthquakes are consistent at least qualitatively with elastic rebound theory.

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DISCUSSION

Dr. L. Picard (Israel)

The last two lectures have convinced me once again that the term "rift" calls for precise definition.

The San Andreas "rift" must be structurally distinguished from tensional grabens, and from the block faults of the Basin and Range province. The present horizontal shifting of the San Andreas fault would appear to be linked with the pressure of the Pacific coastal orogen that has the identical trend. Nevertheless the San Andreas rift may well have originated as a normal fault, but may later have been subjected to orogenic compression and horizontal displacement (as in the case of the reactivated Cevennes fault of the French Central Massif).

Wrench faulting of regional magnitude has also taken place along the Insurbian-Central Bakan-North Anatolian major thrust and shear zones of the Alpine orogenic belt. These geosutures of "lively" seismicity are dividing major tectonic units.

Years ago, Cloos emphasized that minor strike-slip movements commonly occur along fault planes of gravitational dip-slip character.

The young plateau-volcanism of the Western United States, outlined by Dr. Thompson, has its parallel in the Levant graben system.

CENOZOIC TECTONICS OF THE WESTERN UNITED STATES[1]

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Abstract

The Cenozoic structure of the western United States is here interpreted as the result of oblique rifting and fragmentation of the continental crust. Coastal California and Baja California – the long crustal sliver west of the San Andreas fault – have slid nearly 500 km northwestward past the interior, and the Gulf of California has opened in the lee of the moving block. The San Andreas apparently does not cut oceanic crust; the fault is limited to the continental crust, which is moving independently over the mantle. Oblique extension accompanied by lesser right-lateral faulting has produced the normal faulting of the Basin and Range province. The pre-Tertiary rocks of northern California and southwestern Oregon have pulled completely away from the pre-Tertiary crust of Nevada and Idaho, and the gap has been filled by Cenozoic volcanic rocks. The Snake River Plain is similarly a lava-filled rift produced in the lee of a northwest-drifting continental plate. The Cenozoic volcanic terrane of northwestern Oregon and southwestern Washington represents new volcanic crust, formed upon older oceanic crust, which is undergoing compressive deformation due to the lateral motion of the continental masses which bound it.

INTRODUCTION

The structure of the western United States is here described and interpreted in terms of a tectonic system in which the Pacific margin of the continent is moving rapidly northwards past the interior. Structures of extremely varied superficial aspect can be viewed within the moving framework of this tectonic system as but manifestations of a single pattern of continental motion. Such a tectonic system was proposed formally first by S.W. Carey (1958, p. 334-338), although other workers had suggested parts of it previously. Particularly important was the inference by Hill and Dibblee (1953) of great lateral faulting, the amount decreasing with decreasing age of the offset materials. Hamilton (1961) and Wise (1963) among others have expanded upon aspects of the tectonic system. Some older reports hinted at such a pattern of deformation.

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[1]Publication authorized by the Director, U.S. Geological Survey. A contribution to the Western Earthquake Belt Program.

This short paper is condensed from a longer report to be published elsewhere. Full presentation and evaluation of evidence are not possible in this small space, and only samples of the evidence are given. We state dogmatically things which we regard as demonstrated beyond a reasonable doubt, but we recognize that some geologists do not regard as convincing any evidence for great horizontal transport.

SAN ANDREAS FAULT SYSTEM

Coastal California is laced by numerous right-lateral strike-slip faults, trending northwestward subparallel to the coast in a belt 60 to 200 km wide. The through-going San Andreas fault (Fig. 1) is the most active break, and the whole set of faults is here referred to as the San Andreas fault system. Some minor members of the system are single breaks, but most of the major faults are zones up to a few kilometres wide of anastomosing nearly parallel breaks of varying age. Some breaks are moving now but others have been long inactive. Gouge and breccia are typically present along the faults, but mylonite and blastomylonite are exposed along some. Slivers between adjacent breaks are of rocks and deposits of all ages from middle Precambrian to Pleistocene; many slivers are clearly derived from nearby rock units, but many other slivers are of rocks with no counterparts outside the fault zones for long distances in either direction. Among the many descriptions of these and other features of the fault zones are those by Crowell (1952), Wallace (1949), and Waters and Campbell (1935).

Right-lateral surface offsets along various faults of the San Andreas system have occurred during 6 large earthquakes in the last 110 years, and horizontal displacements were as large as 10 m. Geodetic data demonstrate that the offsets during such major earthquakes release in elastic-rebound fashion part of the strain accumulated over regions extending far from the faults. Strain accumulates rapidly: for example, repeated triangulation in southeastern California demonstrates 0.5 to 1.2 m of right-lateral shear strain, distributed over a zone 120 km wide, within a 13-year period during which there was no faulting at the surface (Whitten, 1956, Fig. 3). Hundreds of lesser historic earthquakes along the faults have not been accompanied by surface faulting.

Displacements along the faults of the San Andreas system increase with age of the offset materials, as Hill and Dibblee (1953) emphasized. Stream channels, valleys, and other Quaternary erosional and depositional features show offsets increasing with age of the features. Upper Miocene materials are displaced at least 160 km on the San Andreas fault itself (Dibblee, 1962), and distinctive middle Eocene marine strata are offset about 260 km (Crowell, 1962). The contact between the Sierra Nevada

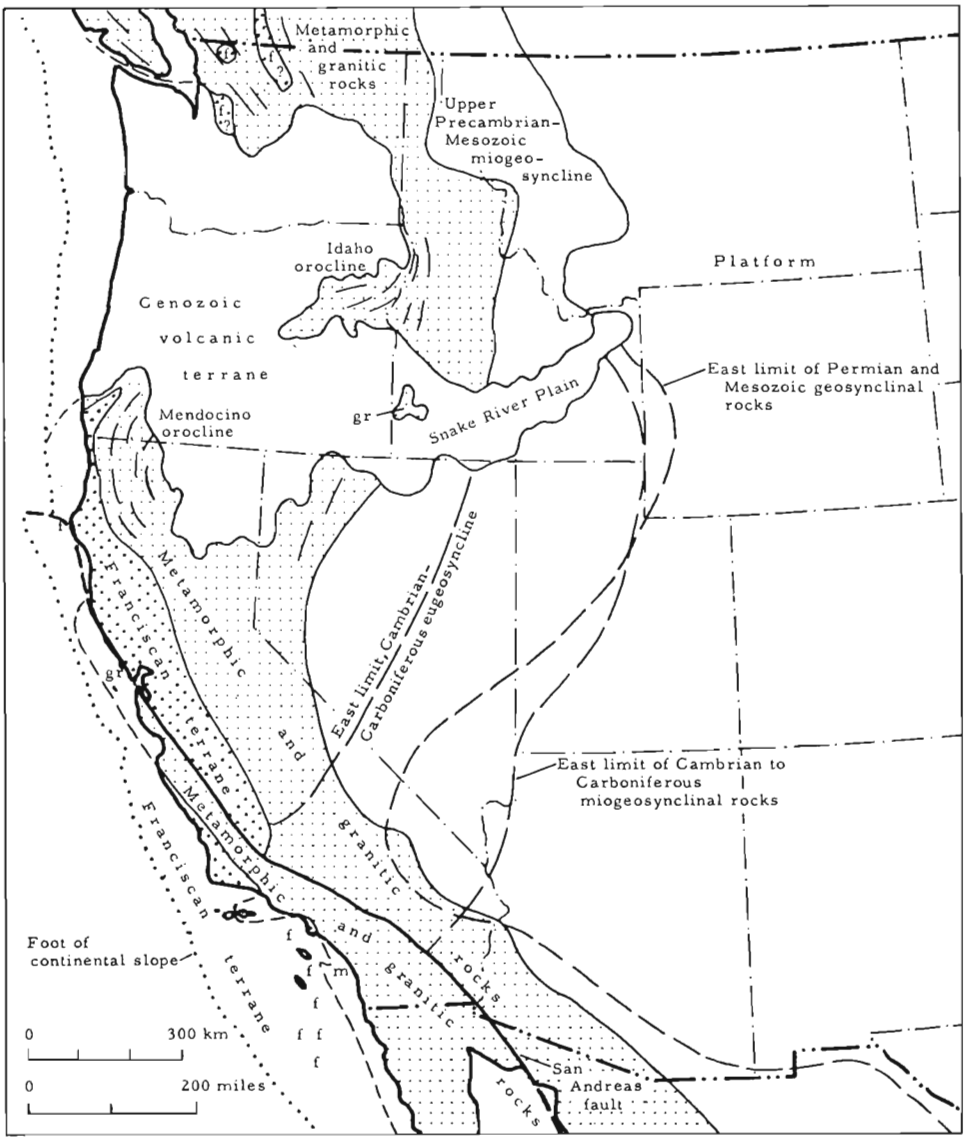


Figure 1. Major Paleozoic and Mesozoic complexes of the western United States. Small and offshore areas of basement rocks are marked by letters: f, Franciscan terrane (and similar rocks in Washington); gr, granitic rocks; and m, metamorphic rocks belonging to metamorphic-and-granitic terrane.

province of rocks metamorphosed and intruded by batholiths during Jurassic and Cretaceous time and the Franciscan terrane of generally nonmetamorphosed but highly deformed eugeosynclinal Jurassic and Cretaceous strata to the west has been offset about 500 km since Late Cretaceous time (Fig. 1; Hill and Dibblee, 1953).

There are many important faults within the San Andreas system. The Agua Blanca fault of Baja California offsets Quaternary gravels about 5 km and crystalline bedrock probably about 20 km (Allen, Silver, and Stehli, 1960, p. 467-469). The San Jacinto fault zone offsets Quaternary gravels at least 2 1/2 km, and a number of bedrock contacts about 25 km (R.V. Sharp, 1965, and unpub. Ph.D. thesis, Calif. Inst. Technology, 1964).

Faults of the San Andreas system trend longitudinally into the Gulf of California. Carey (1958), Hamilton (1961), Rusnak, Fisher and Shepard (1964), and others have shown that the Gulf was probably opened by the oblique tensional rifting of Baja California away from mainland Mexico. The width of the deep-water gap across the mouth of the Gulf, from Cape San Lucas to the geologically similar coast of Jalisco and Nayarit, is about 450 km, which defines the total offset on the motion system since the culminating intrusion of batholiths during middle Cretaceous time.

Baja California and its northward continuation, the Peninsular Ranges of southwestern California, have apparently moved obliquely away from mainland Mexico; the Gulf of California and its extension, the Salton Trough, formed where the previous continental crust was thinned and ruptured. (Older hypotheses of downwarping or downfaulting as an origin of the Gulf are disproved by the thinness of continental crust in its northern part, and by the strictly oceanic crust beneath the deep-water southern part.) Consistent with this pattern of oblique tension, the peninsula bears thin, little-deformed sections of Upper Cretaceous and Cenozoic strata. By contrast, the correlative rocks of the Transverse Ranges and Coast Ranges to the north occur in extremely variable sections in local basins and display repeated folding and thrust faulting along axes oblique at low angles to the San Andreas. The strike-slip motion has had generally a tensional component south of Los Angeles, but a compressional component north of it.

The strike-slip faults of the San Andreas system appear to be limited to the continental crust, and not to affect the mantle over which Baja California and coastal California are sliding northwestward. This interpretation if correct has profound implications regarding the mechanism of deformation. The rift topography of the Gulf of California ends at the mouth of the gulf, along a line trending southeastward from the tip of Baja California: the distinctive topography has formed in the lee of the drifting peninsula, but not in the open ocean farther south. Menard (1960) and others have speculated that the Gulf opened as the peninsula was carried passively

away from the mainland by mantle convection currents whose axis of divergence trends northward into the Gulf from the East Pacific Rise; the lack of rift topography south of the mouth of the Gulf refutes this conjecture.

The northern end of the San Andreas fault also provides evidence for the independent motion of crust over mantle. The fault trends along the shoreline from San Francisco to Cape Delgado, a few kilometres north of the 40th parallel. Beyond Delgado, the fault apparently arcs to the west and becomes the submarine north-facing Gorda Scarp. This curve is shown by submarine rift topography, the beheading of a submarine canyon, and a smoothly arcuate canyon that opens at the base of the scarp (Shepard, 1957). Epicentres of earthquakes are concentrated along the Gorda Scarp (Krause, Menard, and Smith, 1964, Fig. 5), which is about 1.5 km high and has an average slope of about 30° (op. cit. Fig. 3). Dredge hauls from the crest of the scarp 110 km offshore included serpentine and greenstone (op. cit., p. 248-249) indicating that the scarp bounds a block of Franciscan terrane, as would be inferred from the onshore geology. The San Andreas fault thus swings westward from a coastal trend to one directly offshore, and displaces the continental margin directly seaward; the Gorda Scarp is the margin of the high-standing block of continental crust. This north-facing scarp is directly continuous with the south-facing Mendocino Escarpment, which begins at the foot of the continental slope and continues westward for something like 2,500 km. The crossover occurs where the depth of the continental slope south of the Gorda Scarp becomes greater than the depth of the Mendocino Escarpment. The Mendocino structure apparently is seismically dead, but it probably marks a left-lateral strike-slip fault, along which a distinctive pattern of magnetic anomalies, and the westward-sloping ocean floor, have been displaced about 1,150 km (Vacquier, Raff, and Warren, 1961). San Andreas and Mendocino displacements are opposite and hence cannot be related, and yet the San Andreas turns directly into the Mendocino. These various features suggest to us that the narrow continental slice west of the San Andreas fault is riding over the crust of the Pacific Ocean, and that the northern point of this continental sliver was deflected westward as it encountered the south-facing Mendocino Escarpment on the ocean floor. About 100 km of displacement along the San Andreas has postdated this encounter, the balance having occurred before the coastal strip reached the scarp.

BASIN AND RANGE PROVINCE

East of the San Andreas fault system and the Sierra Nevada is the broad Basin and Range province (Fig. 2), whose obvious major structures of middle and late Cenozoic age are the dip-slip normal faults bounding the mountain blocks on one or both sides. There are also, however, important strike-slip and oblique-slip faults within the province, and the structure of

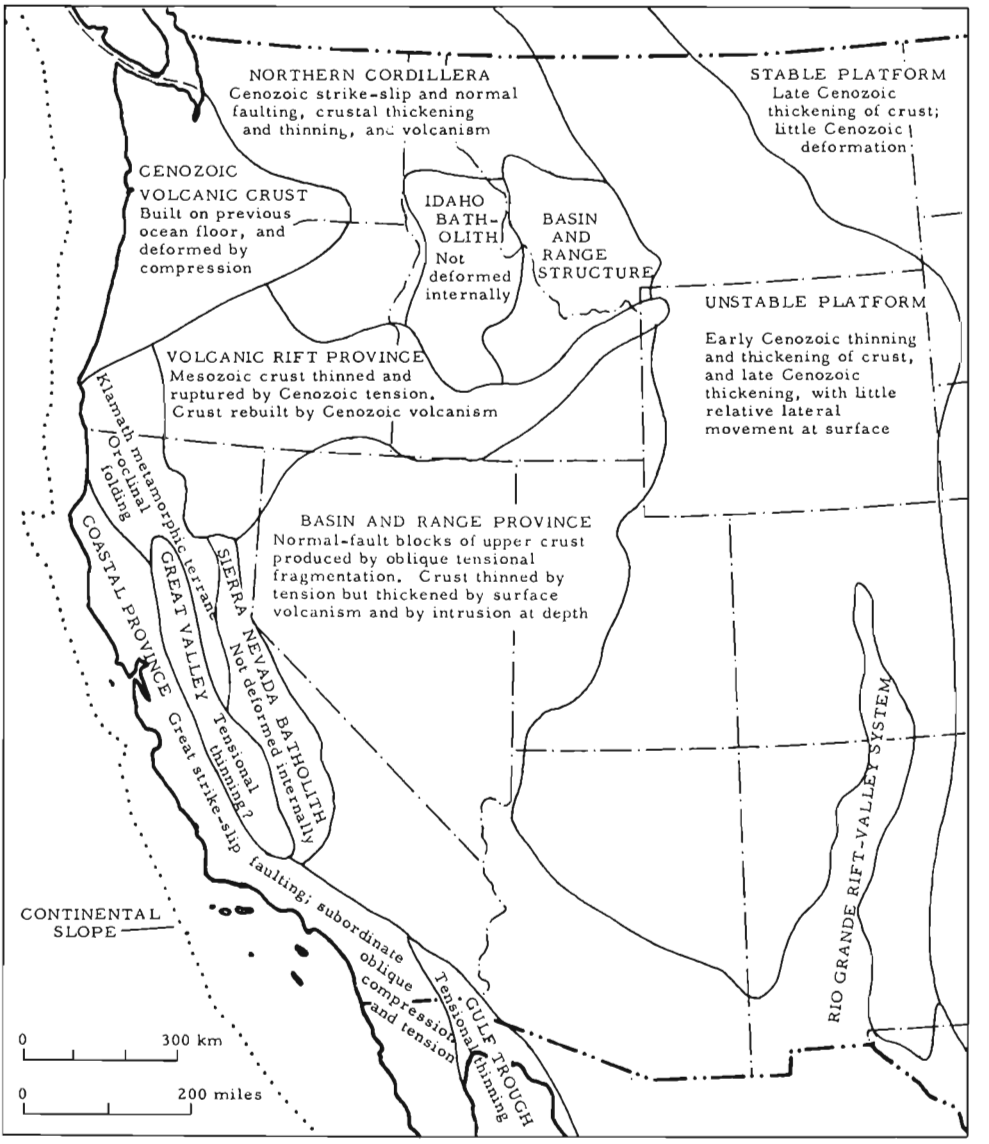


Figure 2. Cenozoic tectonic provinces in the western United States. Most deformation is interpreted as due to the northwestward movement of California relative to the continental interior. The proportions of oblique tension, oblique compression, and direct strike-slip motion vary widely, but all major movement is in the same right-lateral sense.

the region is best interpreted in terms of oblique, right-lateral extension. (We do not here consider the products of the Laramide orogeny of early Tertiary age.)

Two major right-lateral strike-slip faults are known in the Basin and Range province, where they are largely concealed beneath the alluvial fill of structural basins. The Death Valley fault (or Death Valley-Furnace Creek fault), the western of these two major known faults, offsets drainage and alluvial features. Facies and isopachs in the upper Precambrian and Lower Cambrian strata of the region strike generally south-southwestward, at a highangle to the fault, and are offset 80 km right-laterally by it (Stewart, in press). Stewart believes that the faulting gives way to oroclinal folding at least northwestward. The eastern major right-lateral fault is the Las Vegas fault which offsets, for example, isopachs of two Ordovician formations at least 40 km (Ross, 1964). This fault too gives way northwestward to oroclinal folding (Albers, 1964; Burchfiel, 1965) and lessened strike-slip faulting.

Two large earthquakes in west-central Nevada in December 1954 were accompanied by breaking of the surface by oblique-slip faults in a north-trending zone 80 km long (Whitten, 1957). Releveling and retriangulation of a survey network established shortly before the earthquakes demonstrated that blocks on opposite sides of the fault moved obliquely apart and that this pulling apart created a void into which the downdropped block collapsed. At least three other historic earthquakes in the Basin and Range province have been accompanied by right-lateral oblique or strike-slip faulting at the surface. Oblique extension, accompanied by strike-slip faulting, is apparently the cause of the normal faulting.

Basin and range blocks are typically each between 10 and 20 km wide. Ranges generally stand 500 to 1,200 m above flanking basins but extreme local relief exceeds 3,000 m. The bounding faults mostly dip 40° to 80° basinward (Gilluly, 1928). If the average near-surface dip of about 60° continues to the lowest depths at which the faults exist, then the major fault blocks can be viewed as horizontal prisms less than 15 km deep, beneath which level no normal faults are present. Moore (1960) concluded, however, from the general concavity in plan of most range fronts that the faults actually flatten at depth; if he is correct, the limiting depth of normal faulting should be less than 10 km.

Compressive structures of middle and late Cenozoic age in the Basin and Range province are limited to minor features that are apparently produced by gravity. The overwhelmingly dominant structures are tilted normal-fault blocks whose geometry requires regional extension (for example, Lombardi, 1964). The amount of displacement postulated depends upon assumptions of fault behaviour at depth (see for example, Thompson,

1959) and of the volume of volcanic additions to the upper crust, but a cross-strike component of extension of 50 km appears to us to be a minimum value and 200 km or even more appears likely across the northern part of the province, where volcanic rocks form most of the exposed bedrock and hence have greatly augmented the continental crust. The brittle fracturing which produces the fault blocks is limited to the upper part of the crust, and a smoother flow process must operate in the lower crust.

The pattern of normal faulting is interrupted by very large masses of granitic rocks. The Sierra Nevada batholith stands as a west-tilted block 600 km long, bounded on the east by normal faults, that resisted the crustal fragmentation which produced the normal faults. The tectonic belt which includes the Sierra Nevada and Idaho batholiths (Figs. 1, 3) is broken into many young fault blocks where, as in northwestern Nevada and southeastern California, the masses of granitic rocks are smaller.

The left-lateral Garlock fault arcs eastward across southern California from the San Andreas fault. The Garlock shows abundant physiographic evidence of Quaternary movement, and it offsets distinctive upper Mesozoic dykes 65 km (Smith, 1962). The Garlock and Death Valley faults merge and mutually deflect each other (Jahns and Wright, 1960); but the Garlock does not continue east beyond the Death Valley zone, nor does it appear farther southeast in a position offset along the Death Valley fault. South of the Garlock is the Mojave Desert of generally old, low mountain blocks, largely buried by basin deposits in the west. North of the Garlock fault is a region of high and exceedingly active fault-block ranges – the Sierra Nevada, Argus, Panamint, and Black Mountains. The Garlock thus has the position and relative offset required by the explanation that the block faulting to the north is due to crustal extension, for the fault marks the south end of the currently stretching mass, although the amount of displacement is too large to account for by this mechanism alone. There are also other northeast-trending left-lateral faults in southern California. Some have been interpreted to have large horizontal displacements, and others are known to have only small displacements. These left-lateral faults may generally represent offsets between blocks being jostled by drag within the regional right-lateral northwest-trending shear system.

The Rio Grande rift-valley system (Fig. 2) is a narrow belt of middle and late Cenozoic normal-fault ranges and grabens that trends northward for 750 km across the unstable platform of New Mexico and Colorado. Most of the belt consists of a single series of aligned troughs, bordered on one or both sides by normal-fault ranges whose dimensions are similar to those in the Basin and Range province. Volcanism has been widespread along the belt, which is similar structurally and topographically to parts of the rift-valley systems of East Africa.

STRUCTURE NORTH OF THE VOLCANIC RIFT PROVINCE

The Basin and Range province grades northward into the volcanic terrane of northeastern California and southern Oregon and Idaho, which are part of what we term the volcanic rift province (Fig. 2). The middle and late Cenozoic structures of the southeastern part of the region north of this volcanic terrane are similar to those of the eastern part of the Basin and Range. The Hebgen Lake earthquake of 1959 in southwestern Montana was accompanied by as much as 7 m of dip-slip downdropping along normal faults but there was virtually no compensating elevation above prior altitudes (Myers and Hamilton, 1964); this apparently requires a mechanism of gravitational collapse following crustal extension. Large normal-fault blocks break the region east of the Idaho batholith but not the batholith itself (Hamilton, 1963). A zone of right-lateral faults trending west-northwestward from near the northeast corner of the Idaho batholith offset large upwarps, major folds and faults, and mineralized areas about 25 km between middle Cretaceous and middle Miocene times (Wallace, Griggs, Campbell, and Hobbs, 1960).

Structures such as those noted fit a pattern of right-lateral rifting. The Idaho batholith may be drifting slowly northwestward as an unbroken mass, in the lee of which the Snake River depression is produced by tensional thinning of the crust. The batholith block is bounded on the north by right-lateral faults, and its displacement is taken up eastward by distributed tension represented by the normal faulting of southwestern Montana and adjacent Idaho. Tension operates also at the west margin of the batholith to produce the normal-fault belt there. The total horizontal shift increases westward.

THE MENDOCINO AND IDAHO OROCLINES

The rocks of the Klamath Mountains of northwestern California and southwestern Oregon were metamorphosed during late Mesozoic time to form belts that now curve through an arc of 90°, from a northwest strike in California to a northeast one in Oregon (Fig. 1). Carey (1958) termed this arc the Mendocino Orocline. A reverse arc – Carey's Idaho Orocline – occurs in northeastern Oregon and western Idaho, where the northeast-striking structures swing sharply to a northerly and then northwesterly strike. Carey attributed the two arcs to folding in plan of an initially straighter orogenic system.

Palaeomagnetic data give some support for Carey's suggestion. The palaeomagnetic bearing of lower and middle Eocene volcanic rocks in western Oregon, in the northeast-trending terrane, lies far clockwise from that expected (Cox, 1957), and if this discrepancy is due to oroclinal folding,

most of the rotation of the Mendocino orocline postdates the early Eocene. The Miocene lavas about the southern half of the Idaho orocline show a counterclockwise rotation of about 20° in palaeomagnetic declination: about a third of the rotation of that orocline apparently has occurred in Pliocene and Quaternary time (Watkins, 1965).

The late Cenozoic tectonic pattern also indicates crustal shift in the sense required by Carey's explanation. Only rocks of Cenozoic age – and largely volcanic rocks and volcanogenic sediments – occur within the large region of northwestern Oregon and southwestern Washington enclosed within the west side of the Z structure defined by the two oroclines. All known and projected occurrences of pre-Tertiary rocks lie east of this region (compare Figs. 1, 2), and the volcanic terrane west of the Idaho orocline apparently is a Cenozoic addition to the continent, built upon pre-Tertiary oceanic crust. These Cenozoic rocks are deformed by tight to open compressive folds (for example, Waters, 1955), and at least in the Coast Ranges by thrust faults (for example, Snavely and others, 1958, p. 84-93), which trend northeastward in Oregon and northwestward in Washington. This deformation may be due to closing of the arc by tightening of the oroclines.

VOLCANIC RIFT PROVINCE

If the Mendocino and Idaho oroclines were now connected, beneath the Cenozoic volcanic rocks of southeastern Oregon, by a continuous belt of pre-Tertiary metamorphic rocks, then the oroclinal-folding concept would require that the Sierra Nevada and Klamath terranes have moved approximately 600 km northwestward relative to the interior States. Strike-slip faults with this aggregate displacement would have to pass through the southern part of the Basin and Range province, and enough is known about this southern region to make it highly improbable that this much offset can be attributed to strike-slip faults within it. Evidence such as that noted in preceding sections nevertheless indicates that the arcs may indeed be oroclinal folds. The relationships are easily explained if the oroclines have been broken apart, the Klamath Mountains region having been rifted away from the Idaho region, and the volcanic terrane of northeastern California and southern Oregon and Idaho having filled in the gap left by disruption of the pre-Tertiary crust.

This interpretation can be supported in detail for the Idaho part of the volcanic terrane, the Snake River Plain. The surface of the Snake depression is far lower than that of the flanking highlands of pre-Tertiary rocks, and yet the depression is filled deeply by upper Cenozoic volcanic and sedimentary materials. Seismic-refraction data indicate that low-velocity ("granitic") continental crust is probably wholly lacking beneath the western

part of the plain (Hill and Pakiser, 1963). The Snake River plain may have formed as a tensional rift in the lee of the northwest-drifting plate of the Idaho batholith.

The volcanic rocks of southeastern Oregon and northeastern California are like those of the new-continental terranes of the Snake River plain and of northwestern Oregon and southwestern Wahington, and all may have formed similarly upon thinned continental crust, or upon subcontinental materials in tension rifts through the crust. Published seismic-refraction (Dehlinger, Chiburis, and Collver, 1965) and deep-resistivity (Cantwell and others, 1965) data suggest that here also "granitic" continental crust is lacking, and that the thick crust present is wholly volcanic and largely basaltic.

Figures 2 and 3 illustrate the interpretation that the pre-Tertiary rocks of southwestern Oregon were much closer to those of northeastern Oregon before rifting and oroclinal folding of the separated segments of the belt. Similarly, the Idaho batholith is interpeted as having been much closer to the Sierra Nevada batholith than the present distance between them.

SUMMARY AND CONCLUSIONS

We interpret the Cenozoic structure of the western United States to have been produced largely by the movement of the coastal regions northwestward past the continental interior. Strike-slip faulting and oblique tensional rifting of the continental plate have been the main manifestations of this motion although oblique compression has been important locally.

The faults of the San Andreas system have had an aggregate right-lateral displacement of 450 or 500 km since middle Cretaceous time. A third of this displacement has occurred since Miocene time, and more than half since the Eocene. Whether the remainder occurred entirely within early Tertiary time, or represents both Late Cretaceous and Tertiary motion, is not certain. The Gulf of California has been opened by oblique tension across the southern part of the system, whereas compressive structures have formed simultaneously in coastal California north of Los Angeles.

The middle and late Cenozoic block faulting in the Basin and Range province represents fragmentation of the upper crust in response to oblique tensional rifting. Right-lateral fault zones with offsets of tens of kilometres each occur in the western part of the province. Cenozoic volcanism has added much crustal material, particularly in the north. A narrower block-fault rift zone is the Rio Grande valley system of tensional

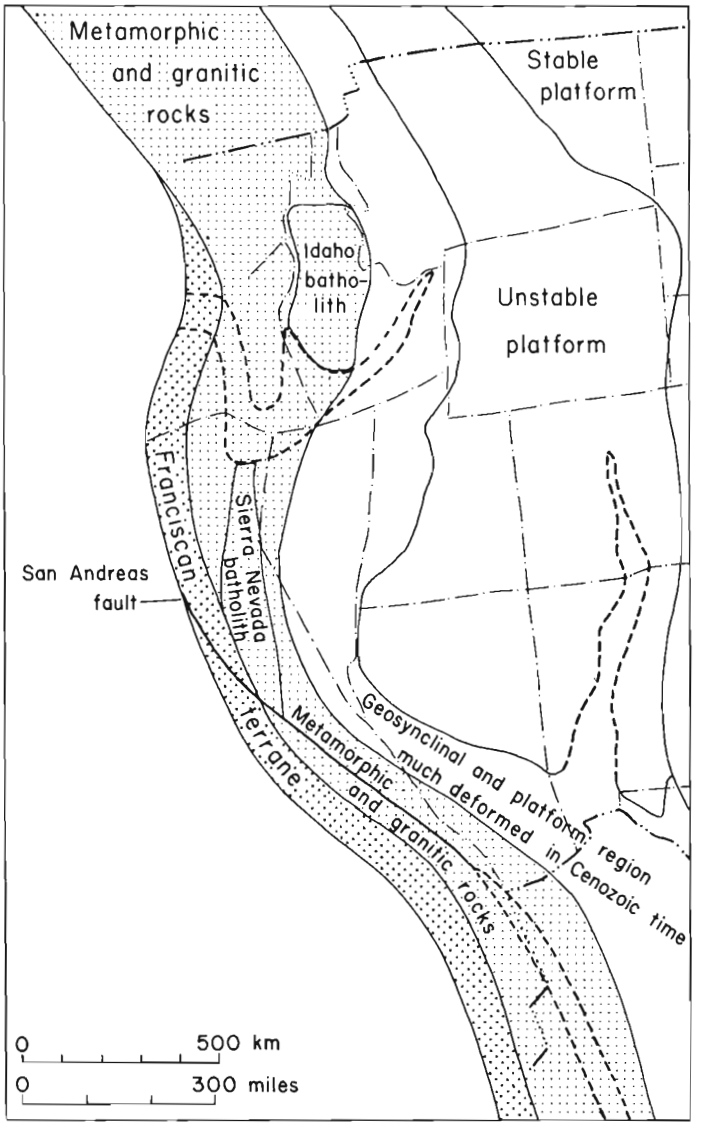


Figure 3. Paleogeographic map of the western United States at the beginning of Tertiary time. The distortion of State and National boundaries (compare with Figs. 1 and 2) represents deformation within Cenozoic time. Boundaries of subsequent rift zones are marked by heavy dashed lines.

grabens in New Mexico and Colorado, which are in many ways analogous to the rift valleys of East Africa.

The Cenozoic volcanic terrane of southern Oregon and Idaho and northeastern California formed by the filling with new basaltic crust of continental thickness a rift zone in which the Klamath Mountains and Idaho batholith regions have pulled away in different oblique right-lateral directions from the continental interior. Drag of the Klamath region produced the Mendocino orocline. The crystalline terrane of northeastern Oregon has pulled partly away from the Idaho batholith, forming the Idaho orocline. Most and perhaps all of the displacement on these oroclinal and rift features developed within Cenozoic time. The volcanic province of northwestern Oregon and southwestern Washington was built upon pre-Tertiary oceanic crust.

All these provinces are being actively deformed now, and the changes are rapid enough that they should be measurable by differences between repeated triangulation surveys a few decades apart.

The Basin and Range province has a high regional altitude and a nearly normal continental crustal thickness despite the great extension it has undergone. Volcanic, subcrustal, and intrusive mechanisms must have thickened the crust at the same time that tension thinned it. The possible subcrustal mechanisms are perhaps related to those which have thickened the crust of the little-deformed Colorado Plateau and Great Plains provinces within late Cenozoic time (see Gilluly, 1963, p. 155-157).

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THE ROCKY MOUNTAIN TRENCH

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Abstract

The Rocky Mountain Trench is a chain of valleys of unlike character extending along the Canadian Cordillera for about 1,600 kilometres. The southern and northern parts consist of block-fault valleys with consequential erosional links; they were initiated in early Tertiary or, in the north, latest Cretaceous time. Other segments are completely erosional valleys excavated along major fault zones and in adjacent strata naturally vulnerable to erosion.

The length of the Trench, the linearity of major segments of it, and its orientation relative to Cordilleran trends have encouraged speculation that it contains a strike-slip fault, but there is cogent evidence that the block-fault segments at its ends do not contain major strike-slip faults. The problem of harmonizing local evidence with hypotheses based on grander patterns of continental tectonics is complicated by the fact that the Rocky Mountain Trench traverses allochthonous terrains. The southern Canadian part traverses a terrain emplaced across its line in about Paleocene time by thrust faulting above an apparently passive Basement. Farther north the Trench traverses rocks whose last important relative eastward transport was in late Cretaceous to Paleocene time. This, and the contrast between the continuity and length of the Trench as compared to the diversity of its segments, leads to the further speculation that the Trench may mark an old, deep fracture zone that has reasserted itself through the allochthonous veneer.

INTRODUCTION

The Rocky Mountain Trench is a valley about 1,600 kilometres in length that extends from near latitude 47°N in Montana through British Columbia to the Liard Plain just north of latitude 59°N (Fig. 1). Structures that may be related to the Trench continue northward to latitude 61°N, at which point they are slightly southwest of structures related to the Tintina Trench. The latter Trench continues northwesterly across the Yukon Territory and into Alaska. Below the southern part of the Rocky Mountain Trench, which is akin to the valleys of the Basin and Range Province, is a transverse zone of faults known as the Lewis and Clark line.

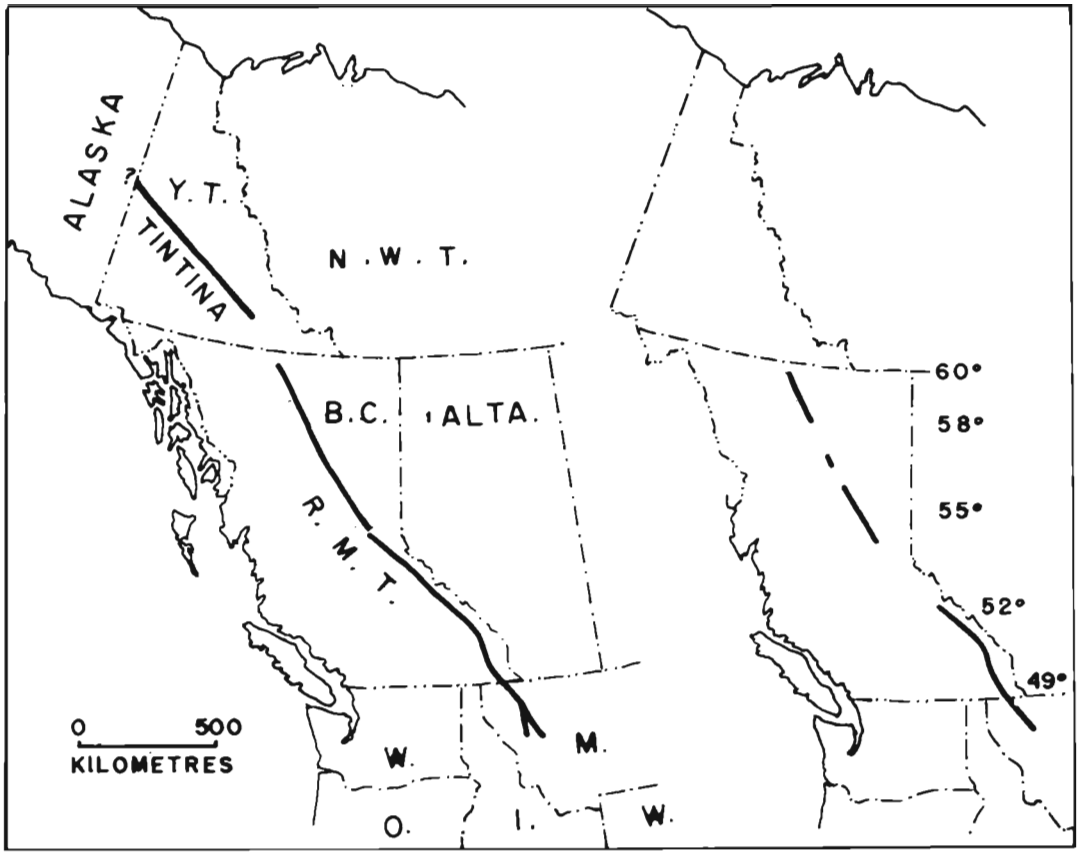


Figure 1. Maps of the Rocky Mountain Trench showing its extent (left) and the parts geologically mapped at one inch to four miles or larger as of 1965 (right).

Although some segments of the Rocky Mountain Trench are block-faulted structural depressions akin to rift valleys in the East African sense of "rift" used in the announcement of this symposium, much of it is a fundamentally erosional feature.

The Trench is typically steep-sided and 1,000-2,000 metres deep. For much of its length it has a distinct floor, commonly 5-13 kilometres wide, but in a few sections it is narrow and almost V-shaped. The floor is generally mantled with detritus, much of which is thick and concealing. Some sections of the Trench – in particular those believed to have originated by block-faulting – are distinctly asymmetrical in cross-section, one wall (typically the eastern or Rockies wall) being steep and linear (Fig. 2) whereas the other is less abrupt and more irregular. Sections that are simply erosional are more symmetrical and, commonly, more sinuous.

The Trench floor has gentle longitudinal gradients and the divides between north- and south-flowing streams are inconspicuous. The size of the Trench is independent of the sizes of the streams that it contains, some sections occupied by only small streams being larger than others carrying major rivers. At places there is physiographic evidence for reversals in the direction of drainage.

The whole of the Trench has been intensively glaciated, and this has modified its shape to a varying extent. Even as far south as 49°N, the ice was at least 1 1/2 kilometres thick.

The Trench is not a locus of volcanism or igneous intrusions (there is no "Finlay River volcanic field", contrary to Eardley, 1962, p. 586). Nor is it distinctively active seismically in Canada according to present knowledge (W.R.H. White, Dominion Observatory, oral communication, 1965) although minor earthquakes have occurred along or near its southernmost part.

Modern geological maps are available for about 60 per cent of the length of the Trench (Fig. 1), and work is in progress on a further 15-20 per cent. The main gaps are between 53°N and 54°N, and from 56°N to 58°N; in these areas published information is chiefly limited to old route-descriptions. About a third of the map coverage, all in the south, is at a scale of 2 miles to the inch or larger; the remainder represents reconnaissance work of varied character published at 4 miles to the inch.

Published geophysical data are few. There are aeromagnetic maps of the floor and west side of the Trench between latitudes 54°N and 56°N (Geological Survey of Canada, 1963-64). A reconnaissance regional gravity survey by Garland and Tanner (1957) was relatively more detailed in the Trench between latitudes 49°N and 50°45'N, and this has since been

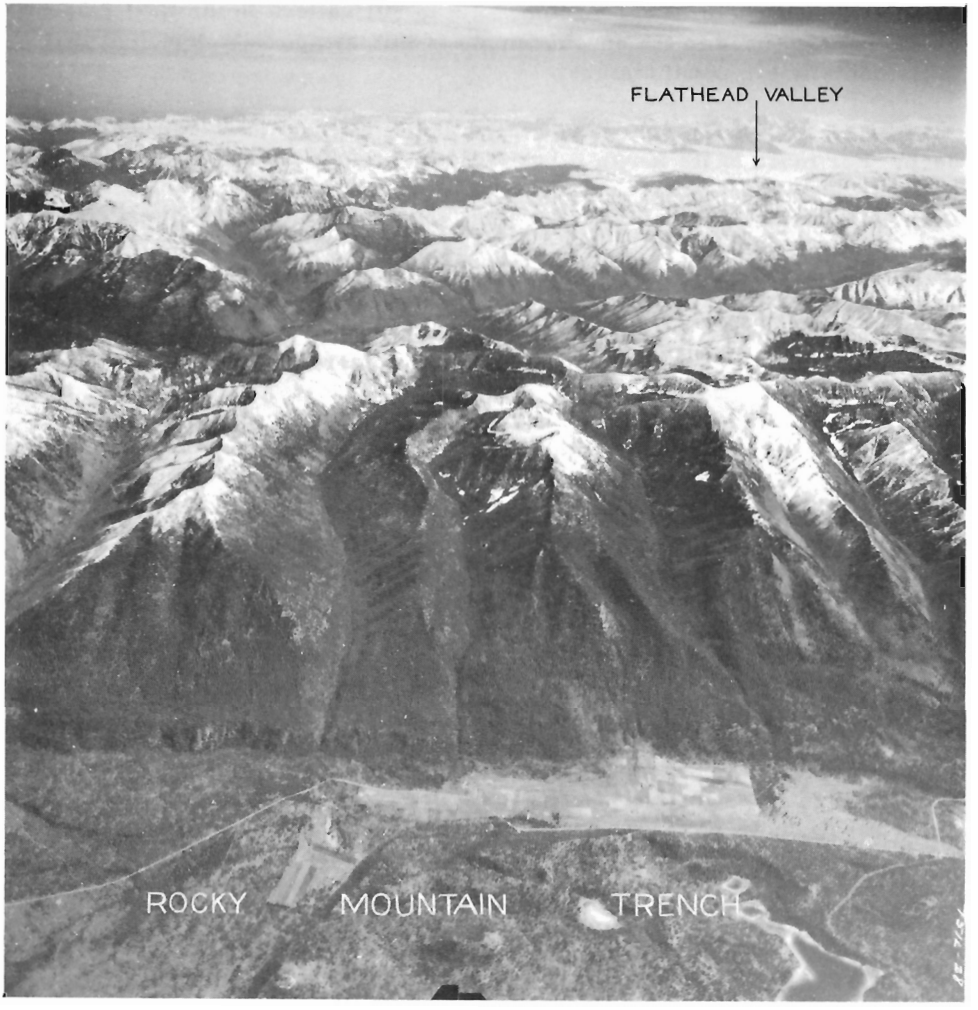


Figure 2. Looking across the east wall of the Rocky Mountain Trench near latitude 49°N. The Flathead Valley (cloud-filled) is in the right background. Both valleys have normal faults along their east edges, and the east wall of the Rocky Mountain Trench exhibits the combined effects of a fault-line scarp, truncation by Pleistocene ice, and erosion by glacial meltwater stream at its base. National Air Photo Library photo T51L-28.

augmented by a survey near 49°30'N by Garland, Kanasewich and Thompson (1961). Seismic profiles across the Trench near latitude 49°15'N, the southern limit of the gravity survey by Garland, Kanasewich and Thompson, have been reported on by Lamb and Smith (1962) and Bally, Gordy and Stewart (1965).

Figure 3 shows the regional setting of the Rocky Mountain Trench. It is aligned with the gross northwesterly structural grain common to this part of the Cordillera, and it defines the west boundary of the Canadian Rocky Mountains. In detail, however, it is at an angle to structures on both sides, especially the complex ones to its west. In northern British Columbia, structures west of the Trench commonly have a more westerly trend than the Trench; in southern British Columbia, they are more northerly. The discordance of the Trench with respect to the rocks to its east is generally small, the trends in the Rockies being only slightly more westerly than the Trench.

The region to the west of the Trench is largely underlain by eugeosynclinal sedimentary rocks, volcanic rocks, and plutonic and high grade metamorphic rocks. The region to the east is characterized by relatively unmetamorphosed shelf sediments, although higher grades of metamorphism do occur near latitudes 52°N and 57°N. The sketch in Figure 3 shows the approximate limit of the eugeosynclinal facies. It is evident that the Trench is roughly parallel to a long-continued, but fluctuating eugeosynclinal boundary, but it tends to be on the cratonic side, especially at its ends. Particularly significant is that the dominant northwesterly structural grain of the region reflects tectonic transport across this direction; thus, in central and southern British Columbia at least, the original eugeosynclinal boundaries must have been considerably farther from the line of the Trench than are the present facies boundaries, and some strata now east of the Trench were originally deposited to west of it.

That the continuity of the Trench is in distinct contrast to its lack of uniformity will be apparent from the following notes on certain of its sections.

NOTES ON SPECIFIC SEGMENTS OF THE ROCKY MOUNTAIN TRENCH

The Trench near latitude 58°N

The part of the Rocky Mountain Trench north of latitude 58°N has been studied by Gabrielse (1962, 1963) who finds that it strikes slightly more northerly than the structural trends in the Rocky Mountains on its east, and distinctly more northerly than the trends in the Cassiar Mountains on its west side. Folds on both sides are overturned toward the northeast. The

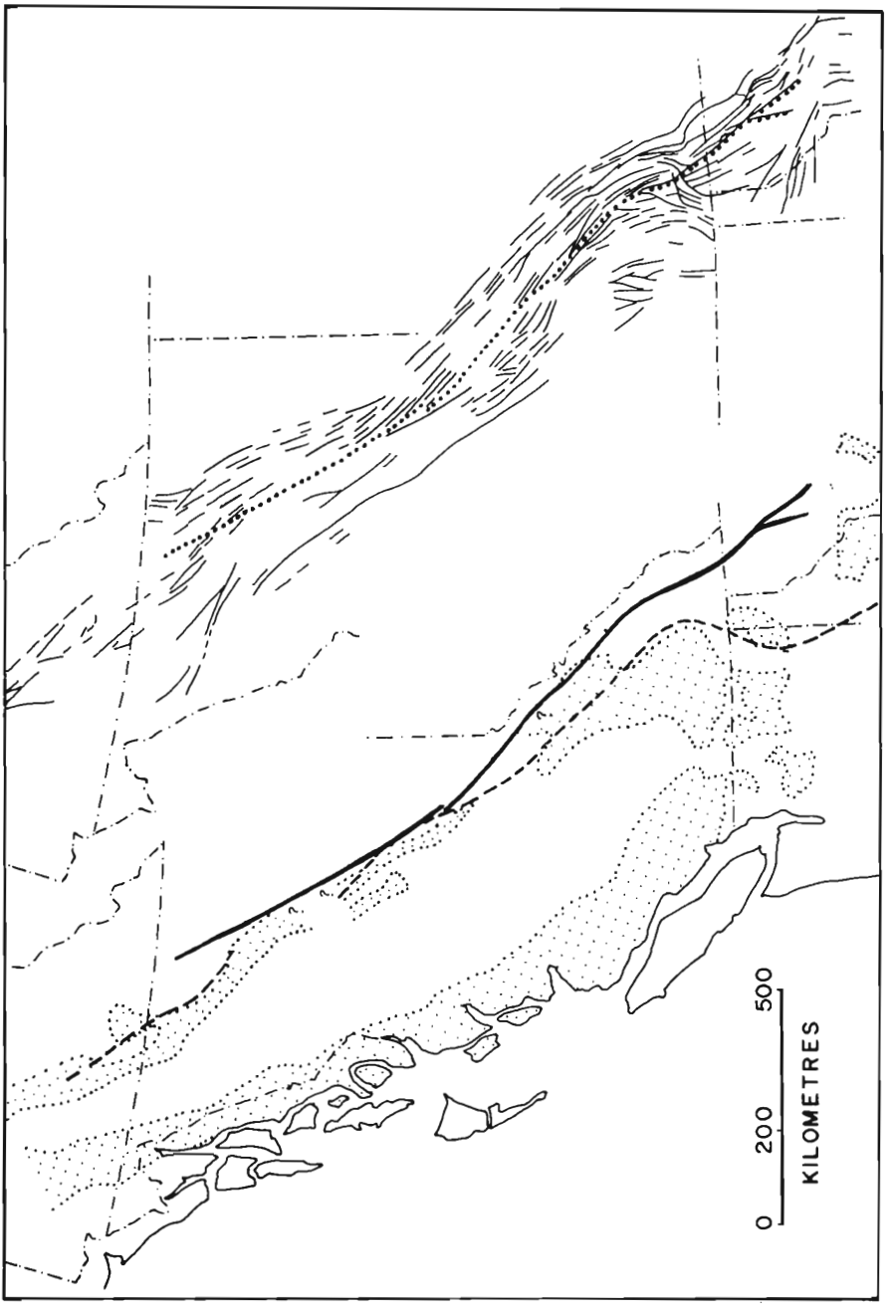


Figure 3. Setting of the Rocky Mountain Trench. On left, its position relative to major areas of granitic and crystalline metamorphic rocks (stippled) and to the approximate eastern limit of eugeosynclinal rocks (dashed line). On right, its position (line of dots) relative to structural trends.

relation of the Trench to a series of thrust faults on the Cassiar side is unknown because the thrust faults are lost from view when they reach the Trench; it is not apparent whether the faults follow the Trench or are truncated in it. The structural obliquity and straightness of this section of the Trench are compatible with strike-slip movement, but stratigraphic evidence apparently is not. Facies lines in rocks ranging in age from Cambrian to mid-Devonian run northwesterly across the Trench without apparent major offset (Gabrielse, informal address, Ottawa, 1962). In particular, outcrops of a distinctive oolitic sandy facies of the Lower Cambrian match each other on strike across the Trench at latitude 58°45'N.

A conglomeratic formation of latest Cretaceous to Paleocene age (the Sifton Formation) occurs in the Trench near latitude 58°N and in a valley that runs northwesterly from that point into the Cassiar Mountains. Similar rocks of Paleocene and latest Cretaceous age are known to occur to the south along the Trench for another 150 kilometres and in a few valleys that diverge from it to the northwest. They are also found in the Trench near latitude 56°N where they are apparently associated with younger Tertiary sediments (as yet unstudied). According to Gabrielse, the Sifton Formation near latitude 58°N was derived from the east, and he infers that, in Paleocene time, a scarp stood at or near the present east wall of the Trench. He believes that the physiographic form of the Trench in the same area is related to downdropping along a normal fault at its eastern edge.

Interpretation of the history of the part of the Trench near 58°N depends greatly on the recognition of the original limits of the Sifton Formation. If it was originally deposited only in the belts in which it is now found, then these physiographic features must have Paleocene ancestry, but if it was once a widespread sheet, its occurrence in the present valleys, while suggesting that they originated by down-faulting, does not prove their antiquity.

The Trench near latitude 55°N

The physiographic continuity of the Trench is interrupted at only one place, at a bend in its general trend between 54°N and 55°N. In this section, the ends of the northern and southern parts are out of alignment by 30 kilometres, and the Trench opens to the west to the Interior Plateau. The region has been investigated on a reconnaissance basis by Muller (1961) and Muller and Tipper (1962). As shown in Figure 4, the northern part of the Trench strikes about 20 degrees more northerly than the southern part, but its south end swings parallel to the southern part so they do not intersect. The bold east wall of the northern part continues southerly as the wall of a diminishing valley within the Rockies. The intervening mountains in turn fade northward into low ridges, although their topographic alignment is somewhat obscured by a pronounced crosswise pattern in the glacial

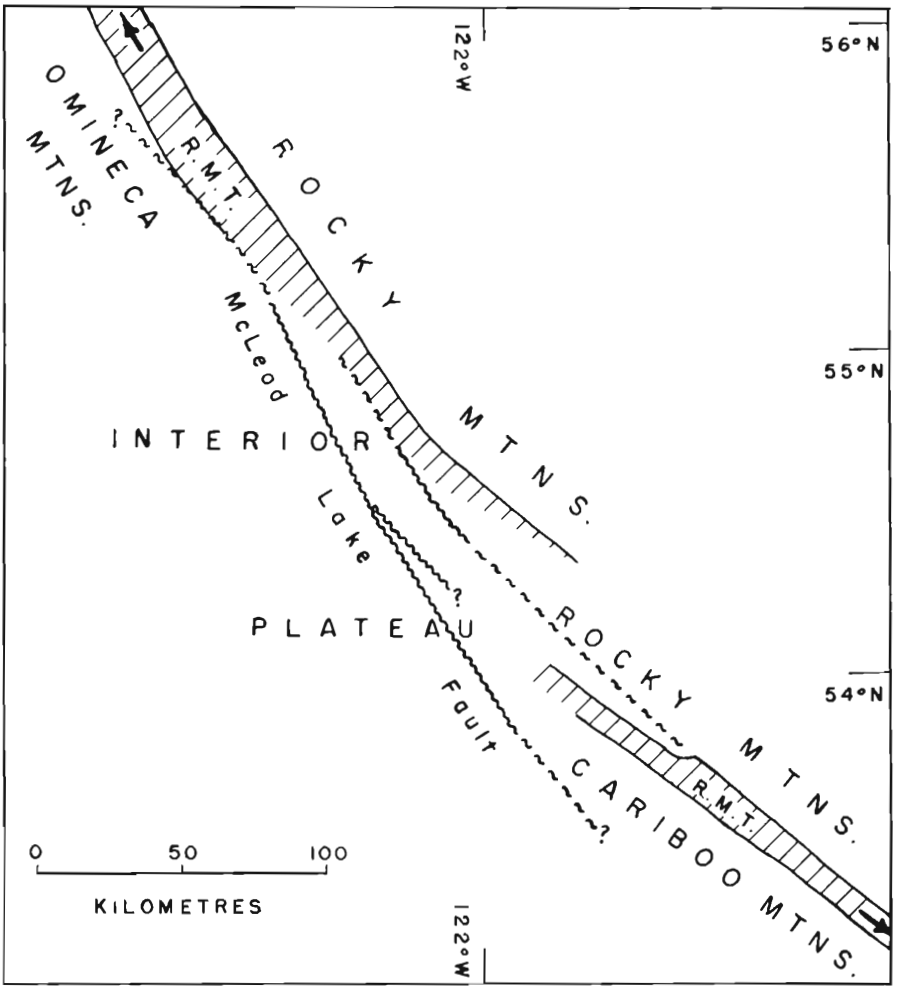


Figure 4. Sketch of region near latitude 55°N, where the Rocky Mountain Trench opens into the Interior Plateau.

topography. In terms of physiography, this region of low ridges is part of the Interior Plateau (Holland, 1964), but its bedrock is probably akin to that underlying the Rocky Mountains. Its formations strike more westerly than the northern segments of the Trench and appear to be cut on the east by a fault aligned with the northern section (Muller and Tipper, 1962). They are obliquely truncated on the west by the McLeod Lake fault (Fig. 4). West of the McLeod Lake fault is the contrasting "western assemblage" containing eugeosynclinal formations and high grade metamorphic rocks.

The McLeod Lake fault, whose course is clearly evident on aeromagnetic maps, runs southward into the Cariboo Mountains. It extends northward to the northern part of the Trench and then appears to swing northwest along it for 50 kilometres. In the latter interval the west side of the Trench is composed of the "western assemblage" whereas its floor is underlain by formations akin to those in the Rockies (Muller, 1961).

The faults in the ends of the two parts of the Trench may have been complementary, displacement being transferred from one group to the other, but if so, the evidence for this has probably been destroyed by the McLeod Lake fault which crosses the projected strike of the southern part of the Trench. On the other hand, a study of aerial photographs of an unmapped part of the area suggests that an important fault to the west of the northern part of the Trench continues southeastward and enters the east side of the broad southern part at an acute angle near latitude 53°45'N.

The Trench near latitude 52°N

The segment of the Rocky Mountain Trench between latitudes 52°45'N and 51°45'N is of interest because it is unusually narrow, especially as compared to the broad segment immediately to the north, and because metamorphic rocks occur along both its sides. The segment is about 7 kilometres wide at its top and 1,500-1,800 metres deep. Its strongly glaciated walls are equally steep, and its bottom is narrow. Its gross course is straight for long distances, and in the two places where the river channel deviates markedly from this course the linearity is maintained by a throughgoing linear drift-filled depression.

The metamorphic grades of the rocks on the east side of the Trench are higher in this segment than is characteristic of the Rocky Mountains. The formations can be traced through several grades to the kyanite schist facies, but details of the timing of metamorphism and tectonic transport are uncertain. The schists are overridden by gneiss of unknown age at a west-dipping fault in the wall of the trench. The metamorphic front is flat arc, convex eastward, and the Trench crosses it as a chord to the arc. Unfortunately, the south end of the arc meets the Trench at too small

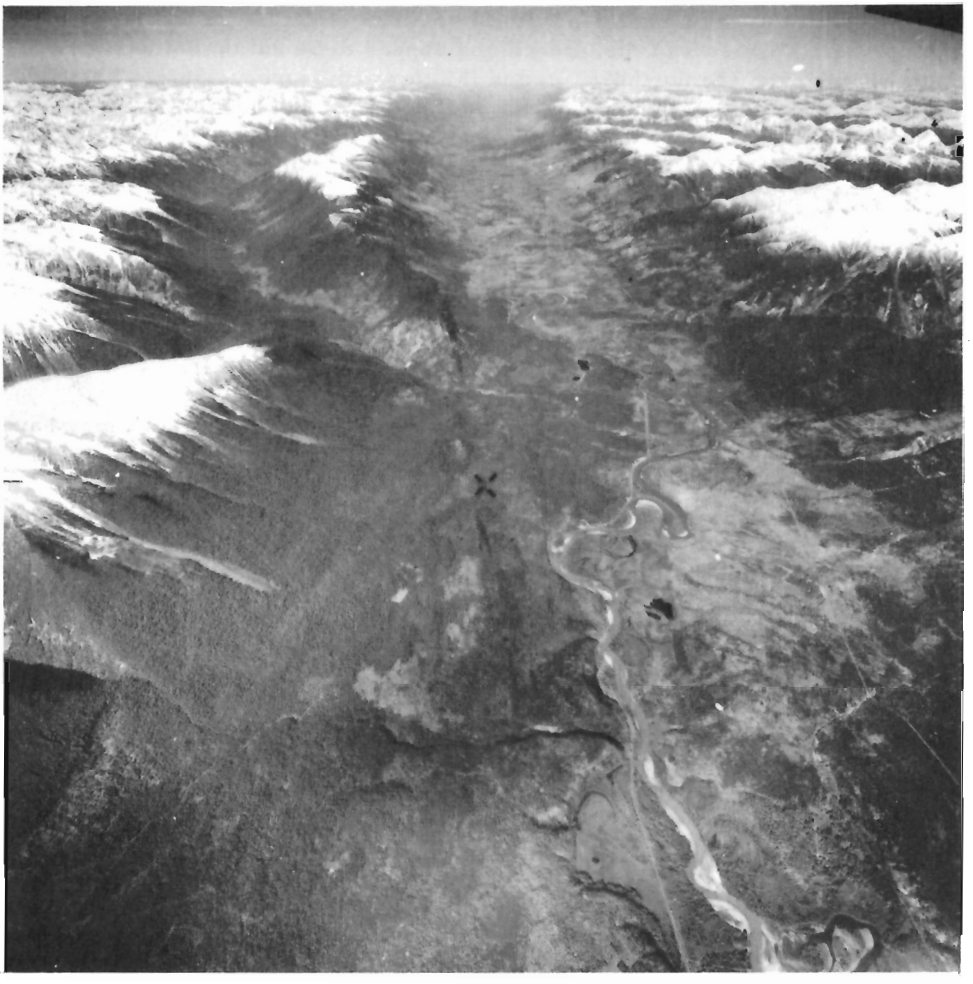


Figure 5. Looking northwest along the Rocky Mountain Trench at latitude 53°N. The Fraser River flows away from the observer. Note the scarp at the west side of the floor. Investigation of this area is planned for 1966. British Columbia Air Photo Library photo B.C. 762:108.

an angle to be useful as an indicator of the amount of displacement along the Trench; and the north end of the arc has not yet been completely delineated.

This segment of the Trench contains a major fault or fault zone which, north of 52°10'N, appears to be a reverse fault dipping steeply to the west (R.B. Campbell, oral communication[1]). It is also a reverse fault farther south (Wheeler, 1963, 1965). North of latitude 52°10'N the fault cuts across the dominant fold trends in both the Rockies and the mountains to the west (the fold trends generally strike more westerly). This suggests the possibility of strike-slip movement along the line of the Trench, with which the emplacement of the above-mentioned gneiss may have been concomitant. The fact that the distinctive gneiss on the Rockies flank faces the south part of a larger mass of similar gneiss on the west flank would seem to preclude later major strike-slip displacement in the line of the Trench itself.

At latitude 52°10'N, where both walls of the Trench are breached at a four-way junction of rivers, the Trench changes strike by 20 degrees and becomes almost parallel to the dominant structures in the rocks along its sides. Here, as farther north, the tightness and complexity of folds in the Rockies increases toward the Trench.

It should be emphasized that the Trench between latitudes 52°45'N and 51°45'N is an erosional valley excavated along a fault zone.

At latitude 51°45', the valley widens and forks, and so, apparently, does the fault zone. The eastern fork, which is the course of the Trench, changes southward into a broad flat-floored valley. The other fork in effect passes into the west wall of the Trench and is believed to follow a major fault (the Dogtooth fault, Wheeler, 1963). This fault is probably a fundamental component of the fault along the Trench to the north, and it (or a related fault) appears to re-enter the Trench south of latitude 51°N. The fault along the east side of the ridge between the valley forks is believed to continue southward in the base of the west flank of the Trench.

The broad valley of the Trench south of the fork is probably the part that is best known to travellers because it is traversed by the Canadian Pacific Railway and the Trans-Canada Highway. It is underlain by thin-bedded argillaceous and calcareous formations that are structurally continuous with the Rockies flank and which appear to be truncated at a small

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[1]R.B. Campbell and R.A. Price of the Geological Survey of Canada are currently studying the geology in this region of the Trench and have kindly provided the information on its metamorphism and structure.

angle at the base of the west flank (Wheeler, 1963). The natural susceptibility of these formations to erosion has been increased by deformation, and as a result, this segment of the Trench is formed by erosion of soft strata adjacent to a throughgoing fault zone. This is in contrast to the narrow section to the north, which is eroded directly into a fault zone. A further contrast is evident in the segment near latitude 49°N to be described next.

The Trench near latitude 49°N

In southern British Columbia, the Rocky Mountain Trench is imposed on an allochthonous terrain. The rocks into which it is carved were thrust relatively eastward during the building of the Canadian Rockies in about Paleocene time. (It may be noted that the building of the Rockies involved more than 150 kilometres of shortening by repetition of strata; Shaw, 1963; Bally and others, 1965.) Part of the Trench occupies the site of a tectonic depression caused by block faulting superimposed on the thrust plates. No major strike-slip movement has occurred along or beside the Trench in southernmost British Columbia since the thrusting.

South of latitude 50°N, the Trench has an asymmetrical profile with a strong east wall and a less pronounced and less regular west side. The east wall rises 1 1/2 kilometres above a gravel floor, and another 1 1/2 kilometres of bedrock relief is hidden beneath the floor. River level in the Trench here is only about 750 metres above sea-level, thus the bedrock relief extends well below sea-level.

The evidence for the hidden bedrock relief comes from the gravity and seismic studies mentioned earlier. With the exception of a few very local areas investigated as potential dam sites and chosen chiefly for their atypical features, this is the only part of the Trench in which geophysical studies indicative of depth to bedrock have been made.

Garland, Kanasewich, and Thompson (1961) interpreted their gravity data to indicate a chain of three deep bedrock depressions in the floor of the Trench between latitudes 49°10'N and 49°40'N. The edge of still another basin is suggested by their northernmost data, but conditions beyond the southern end of their survey are completely unknown and there are no outcrops for 30 kilometres in that direction. Garland and his associates calculated the depth of fill over bedrock to be 425 metres in the northern basin, 700 metres in the central basin, and 900-1,300 metres in the southern basin. Seismic profiles are available for the southern basin, and according to Lamb and Smith (1962), they indicate that the depth to bedrock estimated by Garland, Kanasewich, and Thompson is conservative, the actual depth probably being about 1,500 metres.

The section of the Trench near latitude 49°30'N is of particular interest because bedrock is intermittently exposed right across its floor. Significantly, the belt of outcrops separates two of the deep basins in the bedrock relief. The rocks are Devonian and Mississippian formations that also extend up the west flank of the Trench where they rest unconformably on Proterozoic strata. Thus the floor of the Trench is a structural continuation of its west flank. At the east side of the Trench the Palaeozoic rocks of the floor abut against Proterozoic rocks in the steep east wall, their contact being a well-defined west-dipping fault. The Proterozoic rocks are known to rest on Palaeozoic strata in the stack of folded thrust sheets that form the southern Canadian Rockies. Stratigraphic evidence indicates that the Palaeozoic rocks in the Trench floor are part of a down-dropped upper plate rather than an upthrust lower one.

Similarly at latitude 49°N, the east edge of the Trench is underlain by fault slices that strike along the Trench and which are down-dropped relative to its east flank. Westward from the observed fault slices, the Trench floor is devoid of outcrops for ten kilometres.

The three features mentioned above (major normal faults at the east edge of the Trench; the structural continuity from the floor of the Trench to its west flank; and the great hidden bedrock relief in the floor) seem logically explained as the result of eastward tilting of a structural block that is relatively down-dropped at its eastern boundary and transversely segmented by hinge faults whose throw increases as they approach the eastern boundary fault. The sub-blocks have apparently undergone different amounts of movement, and the resulting transverse steps on the east-tilted major block cause the variations in bedrock relief along the axis of the Trench. This part of the Rocky Mountain Trench is thus a tectonic valley, a block-fault structural depression having influenced its initiation, persistence, and shape.

It is evident that the block-faulting and tilting occurred after the thrust faulting but it was at least early enough to influence the deposition of late Miocene sediments (Leech, 1965). Little is known about the extent and age-range of the Tertiary sediments in this part of the Trench (or elsewhere), but it seems unlikely that the only exposures dated, the late Miocene ones, are the oldest, especially as they are not in the deepest basins in the Trench floor. In the Flathead Valley, 40 kilometres to the east, sediments of latest Eocene or early Oligocene age (Russell, 1964) were deposited in a similar structural depression broken through the thrust sheets of the Rocky Mountains (Price, 1962; Clark, 1964). These sediments provide a younger limit to the age of the thrust faulting and possibly indicate a time of block-faulting in the Trench.

The seismic work done in the Trench at latitude 49°15'N was part of an extensive investigation that traced the top of the crystalline Precambrian "shield type" basement westward from the Canadian Shield and beneath the Plains and Rockies to below the west flank of the Trench (Bally, Gordy and Stewart, 1965). This is the only latitude for which such sub-Trench information is known. The basement surface beneath the southern Canadian Rockies is undisturbed and therefore the great eastward transport that produced the thrust-sheets involved only the sedimentary veneer (Bally, Gordy and Stewart, 1965). The top of the crystalline basement is at a depth of some ten kilometres below the Trench, and according to Bally and his coworkers, the reflection seismic data indicate that the basement surface passes beneath the Trench without appreciable vertical offset. Either it is unbroken or the vertical components of the faults that cut it are too small to have been detected.

Although the Trench near 49°N is underlain by tilted blocks bounded by normal faults, it was not expected that these structures would be clearly evident at the top of the basement at 10 or more kilometres directly below, nor should it be assumed that they would show to the west if the seismic investigation were extended. The dips of the normal faults (both here and farther south) are known only qualitatively because, although their courses are indicated by discontinuities in the stratigraphic successions, their exact traces are rarely definable. Johns and others (1963) interpret the faults near latitude 48°30'N as dipping steeply west to vertically. The faults north of 49°N whose dips can be distinguished are also inclined to the west (the best-measurable one known to the writer dips at only 40 degrees).

The normal faults, or at least those north of 49°N, cut a terrain sliced by low-angle thrust faults. This part of the Trench has a characteristic "half graben" structure whereby blocks are tilted to the east against west-dipping faults, and this structure suggests that these fault planes are curved, flattening with depth. The older thrust faults may have provided paths into which the latter swung, particularly if the block-fault pattern represents extension following the Laramide thrusting, and it is even possible that some normal faults are entirely coincident with pre-existing thrusts. These mechanisms have already been proposed for normal faults east of the Trench.

The Flathead Valley appears to be structurally comparable. It contains east-tilted fault blocks and is bounded on the east by a major normal fault. Near latitude 49°15'N, where outcrop information is augmented by geophysical evidence, the normal fault dips to the west at only about 35 degrees (Oswald, 1964). Oswald interprets the tilting of the segmented down-thrown side to result from rotation on a curved fault plane that flattens with depth, but opinions differ as to the presence of associated antithetic faults (Oswald, 1964; Price, 1962). Dahlstrom, Daniel and Henderson

(1962) proposed that the west-dipping Fording River normal fault[1] merges downward into the plane of an older major low-angle thrust fault, implying that its horizontal component of movement was taken up in the covering strata rather than in the basement. They further suggested that the plane of the normal fault may have originated as a thrust fault subsidiary to the major older thrust. Bally and others (1965) have subsequently confirmed that the major horizontal translations did not involve the basement in this region, thus strengthening the proposal by Dalhstrom and his coworkers as to the shallow nature of the normal faults.

No major strike-slip movement has occurred in or beside the Rocky Mountain Trench in British Columbia south of latitude 49°35'N since the allochthonous terrain was emplaced across it in about Paleocene time. Rocks of Proterozoic, Cambrian, Devonian, and Mississippian ages can be matched across it, within the limits of thrust-sheet geology. Purcell lava, which is Proterozoic in age, occurs on opposing sides of the Trench, and although its northern and southern boundaries have different origins on either side (they are due partly to original depositional pinch-out, partly to truncation by erosion, and partly to cover by younger rocks), the opposing occurrences of this unique formation would seem to preclude major strike-slip displacement along the line of the Trench. Also, the Rockies side of the Trench near latitude 49°30'N contains two regions of contrasting stratigraphy, one north of the other, separated by a fault, and a similar situation occurs on the Purcell side directly across the Trench. In the Rockies, the Proterozoic rocks of the northern region are succeeded by a thick sequence of Lower, Middle, and Upper Cambrian strata, and the Devonian rests on rocks as young as Silurian. In the southern region, the Devonian rests directly on the Proterozoic. In the Purcells too, the Proterozoic of the northern region is succeeded by a thick Lower to Middle Cambrian sequence (limited by the present erosion surface), whereas in the southern region the Devonian rests directly on the Precambrian, as it does directly across the Trench in the Rockies. Furthermore, there is a distinctive fanglomeratic member in the Devonian at the north edge of the Rockies "southern region" and a similar one occurs in the Devonian directly across the Trench, at the north edge of the Purcell "southern region". In addition, Mississippian rocks occur in the floor and in both flanks of the Trench here, yet they do not occur anywhere else along either flank of the south half of the Trench. The conclusion, again, is that no major strike-slip movement occurred in the line of the Trench since the allochthonous terrain was emplaced across it in about Paleocene time.

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[1]The Fording River normal fault is the Erickson fault of Price (1962) and is regarded by Price as the northern extension of the Flathead fault zone.

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SPECULATIONS ON THE SIGNIFICANCE OF THE ROCKY MOUNTAIN TRENCH

The Rocky Mountain Trench is a chain of valleys some of the valleys were, in the author's opinion, initiated directly by tectonic dislocation whereas others were initiated by erosion along fault zones and in adjacent strata that were especially susceptible to erosion. The intriguing problem is, if different parts of the Trench have different origins or different local controlling features, why are they so well aligned and continuous? The diversity of the valley segments cannot deny a throughgoing unity.

Many origins and (or) structural controls have been suggested for the Trench (North and Henderson, 1954, listed more than a dozen, although many of them were even then obsolete). This diversity reflects the local diversities of its character, and authors familiar with only one part have all too often attempted to extrapolate a locally-plausible interpretation to the whole Trench, commonly with results akin to that in the story of "The Three Blind Men and the Elephant". As a rule, the interpretations involve faults, and in this respect, they run the gamut of fault classification. Crickmay's (1964) explanation is a notable exception.

Crickmay admirably expressed the problem of explaining the formation of a valley that is relatively straight and continuous in depth for great distances but which lacks a continuous gradient and a consistent relation between its size and the size of its streams, and whose bedrock structure and land-forms vary from segment to segment. He also stressed the undeniable importance of erosion in forming the Rocky Mountain Trench but, although he (p. 192) regarded the Trench as having "been imposed upon a region inviting to trench-making", he minimized the influence and importance of faults. He followed Schofield's (1921) concept that the Trench developed along a corridor of relative depression between the uplifts responsible for the Rockies and the mountains to the west. However, whereas Schofield (1921, p. 63) regarded "the valleys which unite linearly to form the Rocky Mountain Trench" as being of two types (namely tectonic valleys initiated by normal faults, and purely erosional valleys guided in part by shear zones), Crickmay attributed the Trench entirely to excavation and denied that any part of it was directly initiated by fault displacement of the land surface. In fact, Crickmay suggested (1964, p. 191) that, relative to the adjacent terrain, the Trench is not even a distinctive locus of faults.

That the particular course of the Trench represents more than an erosional channel between belts of uplift is evident when its relation to the mountain belts on either side is considered. The Trench is the western boundary of the Canadian Rocky Mountains and is parallel to their gentle sinuosities (although not their detailed structures), whereas it is oblique to mountains to its west. The Rockies consist chiefly of folded

thrust-sheets stacked on an undeformed basement surface, and their uplift was in part only incidental to the horizontal transport. Although the batholith-bearing terrain to the west was probably also involved in the relative eastward transport, it rose earlier than the Rockies and in a manner that was very different. Moreover the Trench truncates structures on both its sides.

The author favours the idea that the Rocky Mountain Trench marks a deep through-going structure whose (perhaps simple) pattern is diffused and complicated in breaking through the heterogeneous near-surface rocks (Leech, 1964). The position of the Trench suggests the possibility of an ultimate, although possibly indirect, relationship to a cratonic boundary (Henderson, 1959), but this is conjectural because the position of the westward downturn of the basement is unknown and cannot be directly inferred from the present positions of facies boundaries until the amounts of relative eastward transport are established. Also, the south end of the Trench (at least) is well within the craton.

The length of the Trench, the linearity of major segments of it, the presence of major through-going faults to its west (e.g. Pinchi-Ominica Fault), and its orientation relative to Cordilleran structural trends beyond its ends have encouraged speculation that a strike-slip fault is the fundamental controlling structure. It is pertinent in this respect that strike-slip faults are notorious for the diversity of their local structures. However, there is no consistent opinion on the sense of the strike-slip movement. Carey (1958, p. 336) suggested,on the basis of the spatial relationship of the Trench to structural patterns in the western United States,that the Trench should mark a right-lateral strike-slip fault, although in the same paper (p. 211) he argued that the relation of the Trench to structures in Alaska show that it (and/or the Tintina Trench?) marks a left-lateral fault. Roddick (1965) interprets the Tintina Trench as the trace of a right-lateral strike-slip fault of some 250 miles displacement. Contrary to Carey, White (1959, pp. 89 and 85) interpreted bends in the structural trends in British Columbia to indicate counter-clockwise rotation (interior side north relative to the coast), and the strike-slip movements (which he regarded as the least prevalent type) to be left-lateral. Wise (1963, p. 358), in extending Carey's proposal, suggested that much of the inferred right-lateral strike-slip movement in the western United States may have occurred in Palaeozoic or early Mesozoic time. Saint-Amand, Lomhardi, and Shuler (1963, p. 93) postulated, without elaboration, that the Rocky Mountain Trench is a line abandoned by strike-slip faulting, the faulting having shifted to new lines farther west.

Geologists who have studied the Rocky Mountain Trench in the field find proof of strike-slip movement, to say nothing of right-lateral displacement, to be elusive. The trend of much of the Trench is similar to the trends of sedimentary facies boundaries and to the regional tectonic

grain, and much of the tectonic transport has been across its locus. Thus, lithological contrasts that run along the Trench are not necessarily related to it, and transverse features that might have been used to measure strike-slip offset were probably relatively few in the first place and may have been destroyed or masked by tectonic transport. Finally, landscape changes wrought by glaciation and deglaciation may have obscured, and possibly even destroyed, the physiographic evidence of even late fault movements in the Trench. The working hypothesis that the Trench marks a strike-slip fault risks misinterpretation or misuse in that it may be taken to mean that the Trench contains, at the surface, a strike-slip fault zone along its entire length. This it does not.

The presence of block-fault (dip-slip) valleys at the ends of the Trench is not necessarily incompatible with strike-slip movement along its other parts as the block-faulting could be a terminal feature. However, if this is the case, the block-fault valleys should show more evidence of strike-slip movement than has yet been demonstrated. This relationship also seems unlikely if almost the whole of the Trench south of latitude 50°N (i.e. nearly 350 kilometres of it) is a combination of block-fault valleys and consequential erosional links, unless, as Carey (1958) has suggested, the Basin and Range Province (of which these block-fault valleys seem to be northern members) represents extension due to transfer of strike-slip motion from the line of the Trench to another line far to the southwest.

The block-faulting in northwestern Montana and southeastern British Columbia is younger than the "Laramide" deformation that produced the main structures of the Canadian Rockies. Thus if the block-faulting is due to extension related to strike-slip movement, the strike-slip movement must also have been "post-Laramide". The evidence of negligible "post-Laramide" strike-slip displacement along the Trench in both southern and northern British Columbia is cogent.

Neither does strike-slip movement seem to have been concurrent with Laramide deformation. The dominant northwesterly strike of folds and thrust faults in the British Columbia-Alberta section of the Cordillera, and the major (relative) northeastward tectonic transport so clearly evident in the Rockies, indicates such a dominance of forces acting across the strike of the Rockies that concurrent major strike-slip movements along the Trench seem unlikely.

Thus arises the question: If the structural patterns of adjacent segments of the Cordillera really do suggest strike-slip movement along the Trench, was this movement mainly earlier than the major tectonic transport across its line? In such a case, the diversity of the faults along the Trench might be due to older fractures at depth reasserting themselves through the

already fractured and inhomogeneous veneer transported across them by thrusting. It is of interest in conjecturing about older directions of forces and movements that folds of Palaeozoic or younger age having northeasterly axial directions are increasingly being recognized beneath the prevailing imprint of the northwest tectonic grain in the area west of the Trench in southern and central British Columbia (Wheeler 1964).

The hypothesis that any major strike-slip displacements along the line of the Trench were pre-Laramide will be tested when more is known about the faults in its central section. It remains to be established that the series of faults along the Trench between latitudes 50°N and 55°N, and which probably diverges from it at both ends, includes a genetically related throughgoing system. Where the faults have been classified they have generally been called reverse faults, but the possibility of strike-slip movements cannot be eliminated. The faults cut Laramide structures and, in at least a few cases, override them, but it is not known whether they are essentially post-Laramide in age or merely Laramide faults that have been reactivated. In the latter case, they would probably have originated as thrust faults.

The problem of harmonizing local evidence with hypotheses based on grander patterns of continental tectonics is complicated by the question of how much of the Trench traverses terrains that are only shallowly unrooted (as compared to ones that have been involved in deeper mass transport). The southern Canadian part of the Trench traverses rocks underlain by folded, low-angle thrust faults, but farther north, according to Roder (1962), there is also a deeper rotational mass transport of thick incompetent supra-basement rocks. Roder argues that the northern part of the Trench is a graben formed in the final phase of this rotational transport. The units of the unrooted terrain of southern British Columbia continue southward into Montana, and I await with interest a decision as to how much of northwestern Montana is unrooted, particularly in view of the long history and the right-hand displacement postulated for the west end of the Lewis and Clark line (Hobbs and others, 1965). Doubt must remain as to how much of the geology along the Rocky Mountain Trench can be accepted at face value in interpreting its structural history until the amount, the timing, and the character of the tectonic transport across it are better known.

Geophysical studies are sorely needed to define the deep-structural significance of the Trench that is suggested by its length and the straightness of major segments, and by its relation to the structures in the bordering mountains and to the gross Cordilleran structural patterns. The diversities of the various valley segments, and the variations in the surficial and near-surface factors that have influenced their development, do not outweigh these indications of an overall throughgoing deep structural control.

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RIFT VALLEYS

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Abstract

The geological and geophysical properties of the East African, Rhine and mid-ocean rift systems are outlined, and the various hypotheses on the origin of the rift valleys are reviewed. It appears that the tensional hypothesis is most widely accepted. It is suggested that the crust becomes thinner beneath the rifts rather than dropping down into the mantle.

INTRODUCTION

The African-Syrian rift system extends for more than 6,000 km from Turkey to Mozambique, a 52 degree sector of the circumference of the earth. Another well known rift system is that of the Rhine and Rhone valleys in Western Europe, which also has a meridional trend. Rifts within orogenic belts such as the Mid-Andean and the Baikal rifts are not included in this discussion. During the last decades, rift systems have been encountered on the crests of the mid-ocean ridges. The rift valleys are trains of long narrow tectonic troughs bordered by faults. They are regarded as simple tectonic features, because only one deformational element, that of normal faulting, occcurs in them. However, in spite of this simplicity, controversy about their nature is still very active.

CHARACTERISTICS OF RIFT VALLEYS

General Features

The long trains of elongated fault troughs which constitute rift valleys are generally located on the crests of elevated upwarps or swells as in the Arabo-Nubian Shield and the Schwartzwald-Vosges. However, some rifts (mainly those at the end of the trains which commonly diverge into two branches) do not have elevated rims: e.g., the Gulf of Suez, the Gulf of Eilat (Aqaba), and the Roer and Ruhr valleys.

The mid-ocean ridges with their median rifts, as in the Atlantic, Indian and Pacific Oceans, appear to be very similar topographically to the African system. In both cases, the rifts are discontinuous troughs. The African rift system is connected with the mid-Indian rift by the Gulf of Aden.

Dimensions

The widths of most continental and oceanic rifts are about 30-70 km, but narrower rifts (5-20 km, the Dead Sea Rift) and much wider ones (200-400 km, the Red Sea) do occur.

Little is known about the depths of the floors of rifts because they are unfavourable for oil exploration and have not been extensively drilled. The topographic difference between the rims and the valley floor is generally about one kilometre, and at one place between the Afar plain and the high plateau of Ethiopia, it reaches 4 km. Adding the latter value to the depth of the Red Sea gives a difference in elevation of more than five kilometres. In the Dead Sea area, the El-Lisan bore-hole encountered 4 km of Pleistocene rock salt without reaching its bottom. This, combined with the 1.6 km height of the Transjordanian plateau above the Dead Sea, proves that the total relative depression of the Dead Sea Rift is in excess of 5.5 km. The depth of the Rhine Rift near Heidelberg also exceeds 5.5 km (Andres and Schad, 1959), and that of the East African Rifts is supposed to be more than 6 km (Dixey, 1956). The topographic relief of the mid-ocean-rifts is about 2 km.

The dimensions of the elevated swells around the rifts are even more variable and difficult to evaluate: the Schwartzwald-Vosges Shield is 150 km wide; the East African swells are 300-500 km wide; the Arabo-Nubian Shield and the mid-ocean ridges are about 1,500 km wide. The height of the mid-ocean ridges above the ocean floor is about 2-3 km, and the highest point about 5 km. This provides the best estimate for the height of such swells, since those on land have been subjected to much more erosion. In any case, the amount of subsidence along the floors of rifts is generally larger than the rising of the swells around them; e.g., the Red Sea is deeper than the Nile River; the Rhine River is deeper than the Paris basin; and Lake Tanganyika is deeper than Lake Victoria.

Faults

Almost all the faults which border the rifts or occur within them are normal faults. Their dips range from 45° to almost vertical, most commonly being 55°-70°. Reverse faults are very rare. Rifts are not bordered by large single faults, but rather they are outlined by sets of step blocks, and faults that diverge and substitute for one another in an en echelon manner so that they make a zig-zag pattern. It is common for one side of a rift to be much more elevated than the other, and the "main" fault may be missing on one side.

The downfaulted block within the rift is shattered by numerous faults into small horsts and grabens. The minor faults have been termed antithetic and subsidiary (synthetic) by Cloos (1936), and the entire phenomenon has been called "disharmonic faulting" by Picard (1953). The rifts may be asymmetrical, their deepest parts being located along one rim.

Other tensional features are the Gja—vertical dilatation cracks of a few hundred metres length and a few tens of metres width and depth. They occur in the median graben of Iceland, which is regarded as a subaerial outcrop of the Mid Atlantic Rift.

Other Tectonic Features

Strike-slip movements along rifts are known in the Dead Sea Rift (sinistral movement of about 100 km, Quennell, 1959, and Freund, 1965), and in Lake Albert and Lake Edward (dextral (?), Wayland, 1921; or sinistral (?), Johnson and McConnell, 1951; and Sutton and Berg, 1958). Folding in the vicinity of the rifts is uncommon. The raised rims of the rifts are commonly undeformed except in some of the "tails" of the rift faults. Detached elevated blocks are common in the rift zones; most of them (e.g., those of the Sinai Peninsula, the Danakil Mts. in Ethiopia, and Mebya in Tanganayka) are not higher than the rims of the rift. However, Mt. Lebanon (3,060 m) and Mt. Ruwenzori (5,125 m) are much higher than any other feature in their vicinity.

Volcanism

The rift valleys and the mid-ocean ridges are sites of extensive volcanic activity of the Atlantic basalt type, but in spite of this general correlation, there is no detailed correlation between individual features. Volcanic eruptions are widely spread around the East African Gregory Rift, but they are rare in the Western Rift. The volcanic outlets may occur inside the rifts, but they are also commonly outside them. The trends of eruption centres are roughly perpendicular to the rifts (e.g., the Hauran and Kilimanjaro centres and many others). Moreover, the volcanic extrusions frequently occur at the extremeties of the tectonic features: e.g., the Bufumbira between two troughs in the Western Rift, and the Eastern Galilee between the folds of Judea and the faults of the Galilee.

A related feature is the high geothermal gradient recorded in the mid-ocean rifts.

Geophysical Properties

The rifts, both oceanic and continental, are the loci of shallow earthquakes indicating recent tectonic activity. All the narrow rifts have negative gravimetric anomalies of several tens of milligals; but the central parts of the Red Sea and the Gulf of Aden have high (140 mg) positive Bouguer anomalies (Girdler, 1958). The last two regions also yield high magnetic anomalies, arranged in strips (Girdler, 1963).

Age and Development

The sediments inside the African and Rhine rift systems indicate that these structures have been active since the Lower Tertiary, and that this activity began in the Upper Cretaceous. Some authors even believe that it began in the Jurassic or perhaps earlier (Dixey, 1956). Certainly, the tectonic activity of the rifts was contemporaneous with the Alpine orogeny. The two systems, the rifts and the orogens, meet in several places, such as in Northern Syria, and in the northern part of the Jura Mountains.

The trends of the rifts very commonly follow the tectonic structures of basement metamorphic and crystalline rocks (i.e. Precambrian and Hercynian structures such as schistosity, thrusts, mylonites and dykes).

This phenomenon is well expressed in the Western Rift, and also occurs in the Rhine and perhaps in the Eilat rifts.

DISCUSSION OF THE TECTONIC INTERPRETATIONS

In spite of the structural simplicity of the rifts, no tectonic explanation has been generally accepted, and almost all known tectonic agents have been enlisted to explain the structures: e.g., tangential tension and compression; vertical upheaval and downbreak; and magmatic activity. In the following pages, an attempt will be made to review the main lines of thought, their advantages and drawbacks, and a modified explanation will be proposed.

Tension

It was stated above that normal faults govern the rift structures. Normal faults imply extension in a horizontal plane in a direction perpendicular to the strike of the faults. Inasmuch as extension is most simply achieved by lateral tension, the tensional explanation of rift valleys was proposed as early as the middle of the previous century and still commands the widest support. Cloos (1936) experimentally imitated the shape of rifts by stretching a cake of wet clay on two thin boards by moving them away from one another (Fig. 1). The detailed similarity of his results with the structures of the Rhine Rift provided further support for the tensional theory.

It was also suggested in the previous century that the rifted crustal block floats lower in its substratum than the crust adjacent to it as a consequence of its shape. Taber (1927) noted that the centre of gravity of the downfaulted block of the rift is higher than the centre of gravity of any rectilinear section of the adjacent crust because the two normal faults give it the shape of an inverted trapezium. The centres of gravity of the rims are similarly lowered, and the floating crust will therefore sink in the rift and rise at the rims. This model has been adopted by Cloos (1932), and was treated mathematically by Vening Meinesz (1950) (Fig. 2). According to Meinesz, the horizontal tension results in a normal fault along a tilted fault plane which dips at about 63°. By continued separation, one side must bend downward, and the other upward. A second fracture develops where the downward bending causes the maximum curvature—and, therefore, the maximum tensile stresses—at the surface. Meinesz calculated that, in a crust 35 km thick, the second fault plane occurs at a distance of about 65 km from the first one. He also calculated that, in this model, the rift floor subsides 860 m, and the rims rise 640 m. Sediments accumulating in the rift may further depress its floor by 1.1 km. The maximum depth of a 65 km wide rift is therefore 2.6 km. This model adequately explains the negative gravimetric anomaly of the rifts and is still widely accepted by geophysicists (Heiskanen and Meinesz, 1958; Girdler, 1963).

The model of "floating blocks" has, however, many drawbacks. In the first place, it implies that the rifts must be at least 35 km wide for a crust 30 km thick, otherwise the rifted block will not float separately. This leaves narrower rifts unexplained. Secondly, the rifts



Figure 1. A wet-clay model of rift valley showing the subsidiary and antithetic faults. This model was obtained by the moving apart of two solid boards below the wet clay. Note that the principal deformation of the rifted block is its thinning (Cloos, 1936).

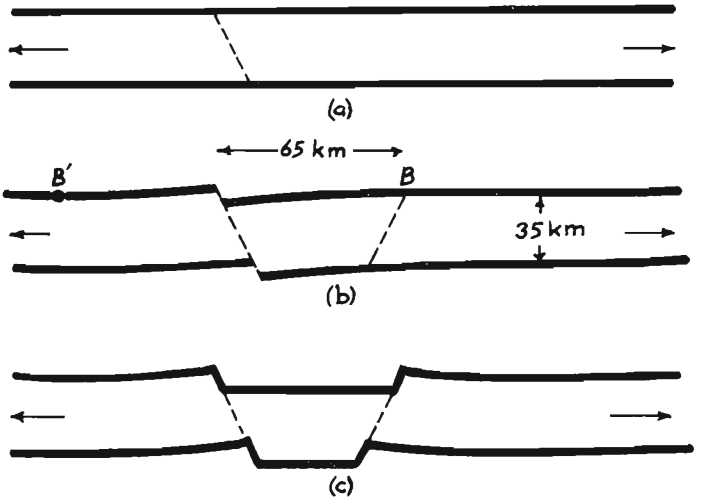


Figure 2. The tensional rift sinks into its substratum as the result of its shape. The second fault develops at B, the point of maximum curvature (Meinesz, 1950).

are much deeper, at least twice as deep as can be achieved by the model. Thirdly, the rifted block in the model remains undeformed, whereas in nature, the rift floors are shattered by numerous faults into horsts and grabens. Fourthly, the model implies that the sides of the rift will be elevated, yet there are several rifts, the sides of which are not uplifted. And lastly, Heiskanen and Meinesz admit that such rifts are "obviously possible only in continental crust", which leaves the mid-ocean rifts unexplained.

It seems, however, that the main objection to the tensional model emerged not from the above problems, but on the basis of another, inexplicitly stated reason. The theory of a contracting globe was generally accepted during the first half of this century, and it is difficult to have tensional stresses in such a globe. The African-Syrian rift system, extending over a sector of 52° of the earth circumference, as noted by Suess (1909), is a tectonic feature of global dimensions. Moreover, the development of the Rhine Rift at the same time as the Alpine orogeny led to the "impossible conclusion..." that "both compression and stretching must be assumed to have occurred in the same place at the same time..." (Beloussov, 1962). Therefore, a model was called for in which tensional stresses are of local character, although the rifts are widely distributed.

It appeared that this demand might be satisfied by another important feature of the rifts—the upheaval of the swells on which many rifts are located. Gregory (1921) proposed that "The first stage... was the formation of a low broad arch... Then the weakening of the supports led to the collapse of the keystones along the top of this arch". Cloos (1939) again provided an experimental and theoretical model. He uparched a wet clay cake by inflating a rubber balloon below it. A rift was formed on the crest of the clay cake by the stretching of its upper part, and since the lower part did not stretch, the faults faded out towards its base (Fig. 3). This means that rifts formed by uparching do not drop into their substratum, and they may therefore be narrower than in Taber's model. Moreover, since the tensional stretching is localized on the arch, global tension is no longer required. This model is still widely accepted, although it has been noted (De Sitter, 1956) that rifts which are not located on swells, such as the Ruhr, Roer, Suez and Dead Sea rifts, remain unexplained.

A further quantitative examination of the latter model shows that it is inadequate. Evans (1925) has noted that "The extension in an anticline would rarely be considerable." This view is verified by the fact that the subsidence in rifts which occur at the crests of anticlines is smaller by one order of magnitude than the height of the anticlines themselves. Evans noted also that the extension is independent of the width of the swell, and depends on the dips on both sides. It will be remembered that the dips of the swells rarely exceed 1°, and that the rift valleys located in their centre subsided more than the swells rose. The erroneous results of Cloos' clay model and mathematical analysis arose because the upper surface of the swell was permitted to extend outward radially. This did not cause any trouble experimentally because the mud cake did not continue beyond the inflated balloon. However, once it happens (cf. Gzovsky, 1954) the uplift is surrounded by tensional cracks at the bottom of the cake and reverse faults at its upper surface (Fig. 4). None of these features occur around the natural swells; and it appears that the area which they occupy does not widen during the upheaval, and therefore, that the extension is due

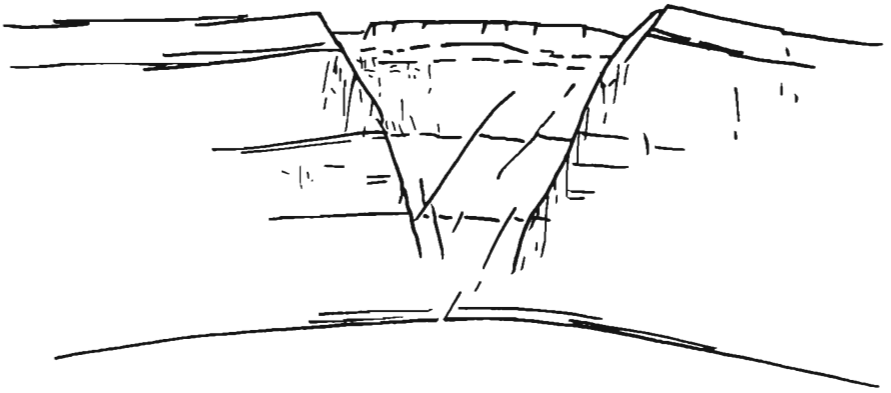


Figure 3. A wet-clay model of rift valley obtained by uparching (Cloos, 1939).

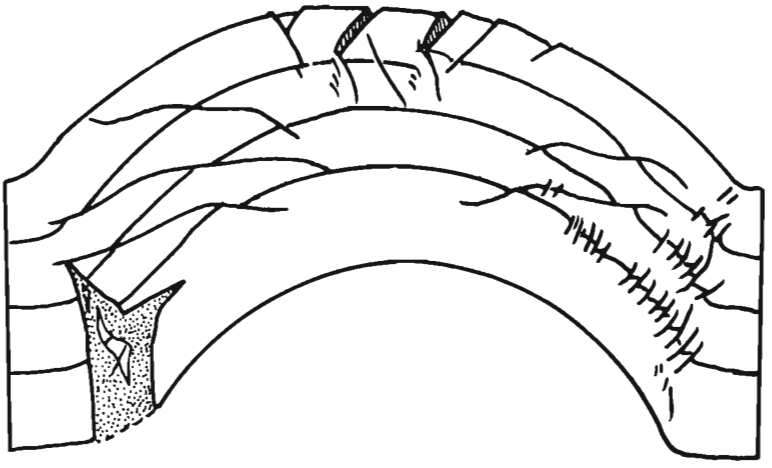


Figure 4. An uparched clay model in which the clay layer extends outside the uplifted part. Note the reverse faults and the dilatation cracks around the uplift (Gzovsky, 1954).

only to the change from a flat surface to a curved one. This extension is negligible in comparison with that calculated by Cloos.

Compression

The alternative theory in which horizontal compressional stresses are the cause of the rifts easily overcomes many of the difficulties of the tensional theory. It too dates from the previous century. Wayland (1921) applied the theory to the Lake Edward and Lake Albert rifts in Uganda, where he could demonstrate a strike slip displacement between the two sides of the rifts which, according to him, implies compressional forces. Furthermore, the high (5, 125 m) Ruwenzori Precambrian block situated between the two rifts can hardly be explained by tensional stresses; nor can the slight folds of the sediments inside the rifts. Wayland did not find any reverse faults in the rifts, and he therefore suggested that two reverse faults build the trough at depth, and that the surficial normal faults are formed by the gravitational breakdown of the overhanging noses of these faults.

The considerable negative gravitational anomaly (more than 50 mg in magnitude) encountered by Bullard (1936) in all the East African rifts, added much support to this theory. Bullard argued that under tensional stresses the lighter segment of the rift would float upwards rather than sink; therefore compressional forces are needed to hold it down. He calculated that a depression bounded by thrusts should be 40-65 km wide in a crust 20-40 km thick, which corresponds to the natural dimensions. It will be recalled that the same phenomena were equally well explained by a tensional model (Meinesz, 1950). An advantage of the compressional model is the unlimited depth of the rift.

Bailey Willis (1928) was impressed by the parallelism between the trends of the Judean anticlines and the Jordan rift, and concluded that they are the result of a single east-west compression. The large amounts of volcanic material which form the Hauran were supposed to be pushed out by the same compression. Willis also assumed that the Dead Sea-Jordan trough is bordered by reverse faults, and he proposed that such a trough should be referred to as a ramp-valley rather than by Gregory's term rift-valley.

Holmes (1944) summarized the evidence in favour of the compressional hypothesis and concluded that this theory overcomes most of the problems that are encountered by the tensional theory. In spite of this, the compressional hypothesis has never gained general acceptance. Geologists have not been able to believe that compressional forces would be expressed on the surface by the normal faults only, and that at least a few reverse faults would not reach the surface. Moreover, if the rifts, as well as the orogens, are due to compression, why are they so different? It has been recognized (Bucher, 1933; Holmes, 1944) that the difference cannot be attributed to the nature of the "basement" rocks, since both the Rhine graben and the Alps are superimposed on similar Hercynian massifs. Finally, Escher (1952) argued that, in a ramp-valley, the negative anomaly should begin well outside the physiographic boundary of the trough, whereas in fact, it is generally coincident with it.

Other Tectonic Approaches

Under these circumstances, many geologists found the theories of regional compression, tension and epeirogeny unsatisfactory.

Dubertret (1947), Tromp (1949) and Henson (1951) were impressed by the close relationship between the Dead Sea rift structures and the folds of Lebanon, Syria and Sinai, and they supposed that vertical block movement rather than tangential stresses played the main role in the tectonic development of this area. Brock (1955), Dixey (1956), and others were impressed by the relation of the East African rifts to elevated swells and to Precambrian tectonic trends. They believed the rifts to be Precambrian structures which lagged behind the rising swells. Jeffreys (1952) suggested that the main contraction of the earth (due to the loss of heat) occurs in an intermediate shell of a few hundred kilometres thickness. He postulated that the outer shell does not contract because it has already lost its heat, and that the innermost sphere is not able to contract until the intermediate shell has contracted. The contraction in the intermediate shell leaves gaps into which parts of the outer shell are dropped as rifts.

It is difficult to discuss the above theories because they ignore structural details.

Magmatic Theories

Hills (1948) and Bishopp (1959) suggest that magmatic activity is a possible cause of the formation of the rifts. Hills proposes that radiogenetic heat is concentrated in the mountain roots. This fuses the rocks and forms intrusions and extrusions which, after the chilling, build the swells and rifts according to the differences in the densities of the products. Bishopp says that, after the volcanic material has been extruded, the top of the swell drops into the vacant place left behind.

Certainly, the importance of thermal energy in the development of rift structures cannot be over-emphasized; it is evident in the extensive volcanic activity and the high heat flow along the rift valleys. But the crucial problem in relation to thermal energy is not its occurrence or its source in the earth, but the way it is concentrated in the restricted regions of the rifts. Bishopp does not refer to this problem at all, and Hills' explanation of concentration of radioactive material in mountain-chain roots is not in accordance with the fact that the African rifts transect several Precambrian orogenies of different ages, which in any case are much too ancient to be heat concentrations in the Tertiary.

A MODIFIED TENSIONAL HYPOTHESIS

The Problems

Having reviewed the main approaches to an explanation of the rift valleys—tensional, compressional, vertical and magmatic—it may be stated that in spite of its problems, the tensional theory has gained the widest support.

The problems are the following:

a) What is the mechanism which made the rifts much deeper than calculated from the models of Cloos and Taber?
b) How can one rift be as narrow as 4 km and another one as wide as 400 km?
c) Why are most rifts located on swells, and yet some not?
d) How have the high Lebanon and Ruwenzori Mountains been erected in a tensional stress-field?
e) What is the explanation for the negative gravitational anomalies along narrow rifts? How do they relate to the positive anomaly in the Red Sea?
f) What is the relation between the rifts and the volcanism?
g) What are the areal and temporal relations between the rifts and the orogenies?

"Necking" Hypothesis

A stretched rod of metal commonly "necks" before it is torn. The tear usually has a "cone-in-cone" shape, which resembles the shear planes of normal faults. This phenomenon has been applied by Bucher (1933) to the problem of the origin of the rift valleys. He stated that the strain of tension is thinning whereas the strain of compression is thickening. Observing critically the models of Cloos (and many others, Figs. 1, 3), it is evident that the main strain achieved is not the dropping downward of the rifted block, but its deformation from a narrow thick block to a wide thin one. The whole system of faults is only the agent of this "necking". In Cloos' experiments the base of the clay cake remained flat, because it was supported by the solid bottom boards, but in experiments carried out by the writer, where the cake floated on a liquid (e.g., iron sand on mercury, semola on water glass), the base of the rift is raised by the fluid while its top dropped (Fig. 5). The crust below the rifts is therefore believed to be thinner than elsewhere, and the mantle protrudes upwards as an "antiroot". When the extension continues, the crust becomes thinner and thinner until it is torn and exposes the mantle. This apparently happened in the Red Sea, and in a more advanced form, this process may result in the formation of ocean basins.

There are therefore no limitations as to the maximum width of the rifts in this tensional mechanism. The minimum width depends on various factors, but mainly on the extent of stretching and thinning of the crust prior to the faulting. A rift floor may reach the depth of the ocean bottom (about 4 km), and the sediments accumulating in it may depress it farther.

The Gravity Anomalies

We have already learned that the negative gravity anomalies found satisfactory solutions in the compressional (Bullard) as well as in the tensional (Meinesz) hypotheses. We must, however, be aware of the conjectural nature of the values of the density contrasts between the rift sediments, the crust and the mantle used in these calculations. This makes the gravimetric calculations very tentative. Nonetheless, it appears that, since the thickness of the sediments in the rifts is much larger than that proposed

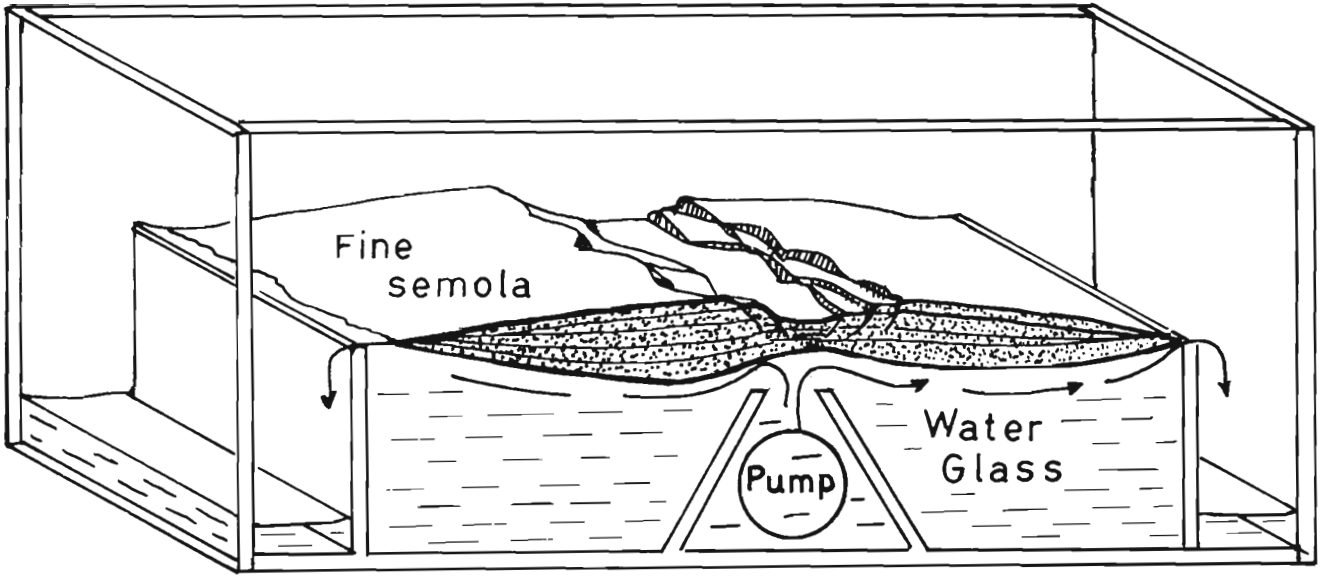


Figure 5. A dry sand (semola) model of rift valley floating on a heavy fluid substratum (water glass). The fluid substratum rises below the rift, and the rifted crust becomes thin (necks). The dilatation was achieved by an outflowing convection current rising in the fluid substratum below the rift.

for the above mentioned gravimetric calculations, the negative anomaly should be larger. This mass deficiency is compensated, according to the "necking" hypothesis, by the rise of the heavy mantle below the rift (Goguel, 1957). Futhermore, although the rift is isostatically compensated, the light sedimentary mass affects the measurements more strongly because it is much closer to the gravimeter than the heavy mantle mass. Lastly, only the "necking" hypothesis provides a single explanation for the negative anomalies in narrow rifts and on both sides of the Red Sea Rift, and for the positive Bouguer anomaly in the middle of the Red Sea where no thick sediments cover the exposed mantle.

The Raised Rims

Bucher is consistent in his theory when he discusses the problem of the raised rims. Just as tension results in thinning expressed on the surface as rifts, the rims are expressions of thickening which is due to compression. This is in accordance with his geotectonic concept of alternation of compression and tension with time over the whole globe. In Carey's (1958) tectonic model, there is no room for compression, since only tension is possible at the surface of an expanding earth. According to his theory, the raised rims are due to isostatic compensation of the deficiency of crustal material in the rift. He supposes that the isostatic adjustments in the solid crust cannot act on small blocks, and therefore the whole area of the rift and its surrounding is raised, thus forming the marginal swells. Moreover, Carey suggests that small detached blocks within the rift, such as the Ruwenzori, are not able to compensate isostatically over short periods, but may be raised passively with the whole region to a very high elevation.

It should be mentioned that Bucher and Carey did not endeavour to explain the rifts that are not surrounded by swells. And, the alternation concept of Bucher and the expanding earth theory of Carey raise many other problems which cannot be discussed here.

The theory of thermal convection currents in the mantle has been applied by several writers (e.g., Heiskanen and Meinesz, 1958) to many of the problems raised above. The rising warm current lifts the swell above it; the supply of heat is responsible for the high geothermal gradient and for the widespread volcanism. The outward flow of the current drags the crust outward from the centre of the swell and thus creates the rifts. Where the current bends back downward, it sucks down the geosynclines and compresses them into the orogens. All these tectonic events are the results of one fundamental cause and are therefore simultaneous.

Further advantages of this theory are that the rifts located outside the swells, and the high blocks of the Ruwenzori and Lebanon may also be explained. The tear between the two blocks drifting apart from the crest of the swell does not terminate abruptly but extends outwards. In these places the rifts usually diverge (e.g., Suez-Eilat, Ruhr-Roer) in order to disperse the dilatation over a wide terrain, and they are not surrounded by a swell. Several faults may be oblique to the movement of the current, and strike-slip movement becomes the most pertinent event along them (e.g., Dead Sea, Lake Albert). Under these circumstances every slight change in the trend of the faults forms an obstacle to the movement and might be rotated and compressed considerably. The sinistral strike slip movement

along the Dead Sea fault has a slight E-W dilatational component along its southern part where the rift is formed, and a strong SE-NW compressional component along the Lebanon Mountains, which elevated them to their present height (Freund, 1965). It appears that a similar explanation may be adopted for Mt. Ruwenzori.

Nevertheless, it should be admitted that under closer inspection the convection current theory raises many new problems. Three currents are supposed to rise in the Mid-Atlantic, East Africa and Mid-India (Girdler, 1963), but there is no indication of the two descending currents which should occur between them. Conversely, the Indonesian and Japanese island arcs may indicate the descending limbs of two convection cells, but there is no indication of an uprising current between them. It seems that, if convection currents exist at all, they are one-sided rather than symmetrical, their shape is influenced by the distribution of the continents and oceans (Bullard, 1964), and they flow outwards obliquely rather than perpendicularly from the rising current (Wilson, 1963). Moreover, the explanation of every rift system by a particular (and in the case of systems such as the Rhine Rift by a rather small) rising current is merely transferring the problem into a deeper level, without achieving any progress towards its solution.

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PATTERNS OF MAGNETIC ANOMALIES OVER THE MID-OCEANIC RIDGE

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SUMMARY[1]

Recent studies have revealed several important properties of magnetic anomalies over the Mid-Ocean Ridge Rise system. These anomalies may be conveniently divided into "axial anomalies" over the axial zone of the ridges and "flank anomalies" which exist over the ridge flanks. The axial zone of the ridges is characterized either by a single large anomaly or by a very striking pattern consisting of several anomalies of nearly constant wavelength, the amplitude being maximum at the crest and decreasing symmetrically on either side. The anomalies over the ridge flanks have longer wavelengths than the axial anomalies, show no diminution in amplitude away from the crest (in some cases there is actually an increase) and, generally, are not as regular in shape as the axial anomalies. The longer wavelength (or perhaps more properly, spacing) of the flank anomalies is associated with a wider spacing of the causative bodies and cannot be explained merely by a larger depth to these bodies. The flank anomalies are not axial anomalies at greater water depths.

The large amplitudes, the extreme symmetry and regularity of the axial magnetic anomalies and their linearity in a direction parallel to the strike are revealed by a closely spaced aeromagnetic survey over the Reykjanes Ridge SW of Iceland. There is some evidence for the linearity of the flank anomalies over the Reykjanes Ridge and also over other segments of the Ridge-Rise system.

North of the Mendocino fracture zone in the Pacific, the magnetic anomalies near 130°W are identified as axial magnetic anomalies. Further west are the longer wavelength anomalies associated with the flank of the East Pacific Rise. However, south of the Mendocino fracture zone, the anomalies near 130°W have longer wavelengths corresponding to flank anomalies. The wavelengths of the magnetic anomalies as well as other recent geophysical results appear to confirm the deduction made by Menard that the East Pacific Rise extends to the North East Pacific.

The magnetic anomaly patterns in the North East Pacific have been used by Vacquier and others to deduce large scale strike slip motions along the fracture zones.

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[1] For the complete paper, see:
Talwani, M., Le Pichon, X., and Heirtzler, J.R. 1965. East Pacific Rise. The magnetic pattern and the fracture zones. Science 150, 1109-1115.

The establishment of the association of the magnetic pattern with the East Pacific Rise makes it possible to give a different explanation for the matches of the anomaly patterns across the fracture zones—an explanation that does not involve large scale motions. It is suggested that (i) the different segments of the crest of the East Pacific Rise developed at their present locations, (ii) the matches in magnetic pattern are due to similarities in the pattern at equal distances from the rise crest, and (iii) differential uplift due to the formation of the rise is responsible for depth differences across fracture zones.

We are not sure of the ultimate origin of the ridge magnetic anomalies. However we do believe that the symmetry of the magnetic pattern and its parallelism to the strike of the ridge requires that the magnetic anomalies owe their existence to the formation of the ridge, which in turn is caused by a change of density in the upper mantle. The spreading ocean floor theory of Hess (1962) and Dietz (1962) with reversals of the magnetic field has been used by Vine and Matthews (1963) to explain the axial anomalies over the ridge crest. However we feel that the variation in amplitude of the axial anomalies as well as the completely different character of the flank anomalies argues against the Vine and Matthews hypothesis.

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DISCUSSION

Dr. V.V. Beloussov (USSR)

The displacement along the Mendocino Fault is not very convincing because I think there is a very striking difference in the anomalies to the north and to the south of the fault. To the south you have a very large wavelength, whereas to the north, there is a more complicated structure. Perhaps they are quite different blocks of the earth's crust, in which case, it would be very difficult to say anything about the displacement.

Dr. Talwani

Perhaps you misunderstood me. I did not say they were displacements. What I said was that the magnetic patterns across the eastern part of the Mendocino fracture zone are different. The pattern

south of the fracture zone is similar to the pattern north of the fracture zone but much farther to the west. We have tried to show that the anomaly patterns are related to the distance from the ridge-crest. Thus the difference in magnetic patterns across the Mendocino fracture zone is the effect of different distances from the crest rather than that of active movement.

Dr. B.D. Loncarevic (Can.)

I would first like to comment on a question asked yesterday by Professor Hess with regard to our paper on the Mid-Atlantic rift zone, and then I will offer a suggestion for the difference in the period of anomalies across the ridge. I think Hess's objections to the suggestion that dykes cause the magnetic anomalies along the Mid-Atlantic ridge were probably based on the assumption of a very long single dyke, which was not what we had in mind. We tried to emphasize that a width of one mile might be a unit size for the intrusion. You will recall that the central valley has a number of blocks, and that these blocks are normally magnetized in one section and reversely magnetized on either side. Now the distance between the normal and reversed areas is about 30 km. The last reversal of the field is a million years which gives you 3 cm per year for the growth of the ocean, which is the right sort of figure. If you go out to, say, 200 km from the centre of the rift, the wavelength of the magnetic anomalies is, as Dr. Talwani has just said, about 70 km. The possible explanation is that, 6 to 10 million years ago, there was much more dyke production along the ridge, and therefore the floor of the ocean was spreading faster and the anomalies therefore developed with a longer wavelength. In other words, the average rate of intrusion would have been much faster than it is at present. An alternative possibility is that the reversals of the earth's magnetic field took longer 10 million years ago — on a cycle of two million rather than one million years.

Dr. Talwani

I agree — that explanation can, of course, be made. I would like to point out one more problem with this theory. In a paper in press, Ewing, Le Pichon and Ewing discuss the age of sediments found on the Mid-Atlantic ridge. They find Miocene fossils in several cores less than 90 km from the crest. Dr. Saito recently examined a dredge taken 18 years ago by Ewing very close to the rift valley and examined once by Shand in which he finds — I believe — baked middle Miocene fossils covered by volcanic glass. Also, the cores taken in some abyssal hill areas just off the ridge flanks run into Pliocene material 5 m below the bottom. The total thickness of sediment is probably not more than 25 m. I do not know how unequivocal the evidence is, but one might make the case from the sedimentary record that there is no evidence that the ridge is younger towards its centre.

Dr. B. Heezen (U.S.A.)

This pattern is very interesting. If you look at the map of the South Atlantic Ocean, you can see the same pattern repeated over and over again across each of the fracture zones — that is, a rift valley and its offsets. The offsets are variable — some of them are only a few miles; others are 120 miles or more. The fracture zones, however, are hundreds of miles long, so it is clear that, at the moment, if you can judge by seismicity, the active zone is at the crest of the ridge and along the part of the fault between the offset parts of the crest. Therefore we can tell today, I think, that movement is going on along the centre of the fault but not at its ends. Thus the simple idea that it was just a strike slip fault which translated everything an equal distance is not correct. And if one uses this as a guide, one can easily see similar magnetic anomalies in the Pacific and conclude that each anomaly that you see was not one continuous line at the time that the magnetic body was formed. This does not mean however that there has been no movement. If the magnetic bands represent intrusions — and it may represent them in extension — the two sides of the intrusion could have moved apart as the dyke filled the centre. Then the zone could have fractured and filled again. So I don't think that the argument that these zones represent only distances from the axis is entirely convincing. The other thing that we noticed is that the ridge is not always the same width: at some places, it is a hundred miles wide; at other places, it is two thousand miles wide. And at the cross-fracture zones, the ridge seems to show a rather restricted growth, implying some differential movement. In other words, in a part of the zone that is a thousand miles wide, you might encounter the same numer of bands as you do where it is only 500 miles wide. This is easily seen in the equatorial Atlantic where the whole ridge width is much restricted in the area from about the equator to 15° north. It is wider to the north and much wider south of about 2°. I would predict that when the ridge is studied in detail, you will find that there are the same number of magnetic zones south of 2° as to the north, but they will be much farther apart. This is a similar explanation to that just given but I think that the two are significantly different.

Mr. P.H. Serson (Can.)

In about 10 days, the Dominion Observatory is taking off on a three component airborne magnetic survey which will cover Greenland, the Greenland Sea, Norway, Sweden, Finland, Denmark, and Iceland. I've had correspondence with Dr. Heirtzler, and he's shown us some of his results, and we've put it in our planned survey to fill in the gap between the Lamont survey and our survey of Iceland. Our flight lanes will be about 20 miles apart. There won't be nearly the detail that you've shown, but we hope to fill in that gap and find out what happens in between the area you surveyed.

REVIEW OF HEAT FLOW MEASUREMENTS ALONG THE MID-OCEANIC RIDGE SYSTEM[1]

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Palisades, New York

Abstract

More than 350 measurements of heat flow have been made in the vicinity of the mid-oceanic rift system. The results show great variability on a local as well as a regional scale. The local variation is believed to be principally due to local environmental disturbances. Three sections of the ridge system have sufficient data to study the variation of heat flow in relation to the ridge axis. They are the Mid-Atlantic Ridge between 30°N and 40°S, the Mid-Indian Ocean Ridge between 10°N and 40°S, and the East Pacific Rise. In each of these areas, the crestal zone of the ridge shows heat flow higher than the world average 1.5 μcal/cm^{2}sec. The average value of heat flow of the crestal zones of the East Pacific Rise and the Mid-Atlantic Ridge is 3.3 μcal/cm^{2}sec. In the Mid-Indian Ocean Ridge it is 1.89 μcal/cm^{2}sec. The flanks of the Mid-Atlantic Ridge have a mean value of 1.35 μcal/cm^{2}sec, whereas those of the Mid-Indian Ocean Ridge have predominantly low values, the average value being about 1.0 μcal/cm^{2}sec. The flanks of the East Pacific Rise have a mean heat flow of 1.57 μcal/cm^2·sec.

Using these rough averages, the total heat flow through the Mid-Atlantic Ridge and the Mid-Indian Ocean Ridge is found to be near the world average, whereas in the East Pacific Rise the total heat flow is greater than the surface flow for the earth as a whole.

INTRODUCTION

The Mid-Oceanic Ridge system referred to in the title is the world-encircling, seismically active oceanic ridge system defined by Ewing and Heezen (1960). Some of the first heat flow measurements by Sir Edward Bullard showed that the axial zones of the mid-oceanic ridges have high heat flow. To date, more than 350 measurements of heat flow have been made in the vicinity of the mid-oceanic ridges, including data from several detailed surveys with station spacings as close as 30-50km as well as isolated single measurements.

One characteristic of the values determined in the vicinity of the oceanic ridges is their great variability on a local and regional scale.

[1]Lamont Geological Observatory Contribution No. 924.

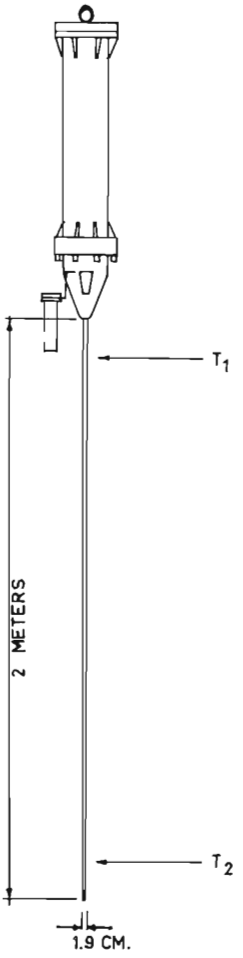


Figure 1

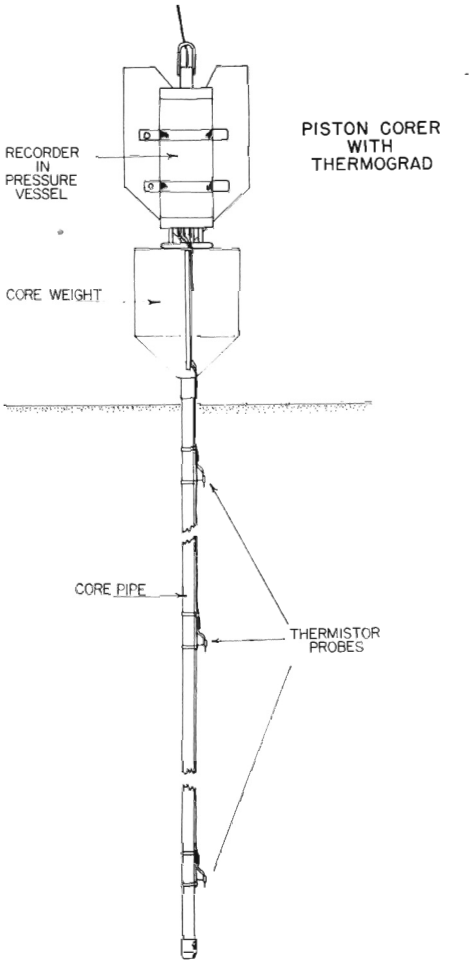


Figure 2

Figure 1. A temperature gradient probe of the type designed by Bullard. T_1 and T_2 indicate positions of thermal elements in hollow probe. An in situ recorder is housed in the pressure vessel on top.

Figure 2. A temperature gradient probe of the type designed by Ewing.

They range from 0 to 10 $\mu cal/cm^2 sec$. A second characteristic is that high values are commonly found in the zone near the crest whereas low values are more common on the flanks.

Interpretation of the ridge heat flow values is difficult because of their great scatter. Lee and Uyeda (1965) have calculated a standard deviation of 1.56 $\mu cal/cm^2 sec$ for all ridge determinations, only slightly less than the overall mean of 1.82 $\mu cal/cm^2 sec$. Factors that contribute to the observed scatter of the data may be classed as experimental or local environmental disturbances.

MEASUREMENT OF HEAT FLOW FROM THE OCEAN FLOOR

Two types of temperature gradient probes are being used to measure heat flow from the ocean floor. One is a solid cylindrical probe with two temperature sensors enclosed at the ends of a hollow steel rod (generally 2 metres or more in length). It measures the temperature difference after the probe has penetrated the sediment on the ocean floor (Fig. 1) (Bullard, 1954). The second type of probe is shown in Figure 2. It has thermal sensors outrigged from a standard piston coring device This apparatus measures the temperature at three or more points after it has penetrated sediment. Typical results from a station made with the outrigged instrument are shown in Figure 3. The temperature differences measured by the three probes (solid dots) are shown as a function of depth below the surface, and conductivity determinations made on the core sample returned to ship are shown as open circles. The use of the three probes permits heat flow to be measured over two intervals, thus providing a check on both the constancy of heat flow with depth and the validity of the measurements.

RESULTS OF MID-OCEANIC RIDGE HEAT FLOW MEASUREMENTS

Variability of Heat Flow Data

The measurement of heat flow along the mid-oceanic ridges by either of the above techniques is difficult because much of the ridge floor is exposed rock, and at many stations, only partial penetration is achieved. As a result, the quality of data that have been published varies considerably, and this undoubtedly contributes to their scatter. However, there is a sufficient number of reliable stations along the ridge system to show that the variation is not entirely caused by instrumentation and that the main regional trends published to date are supported.

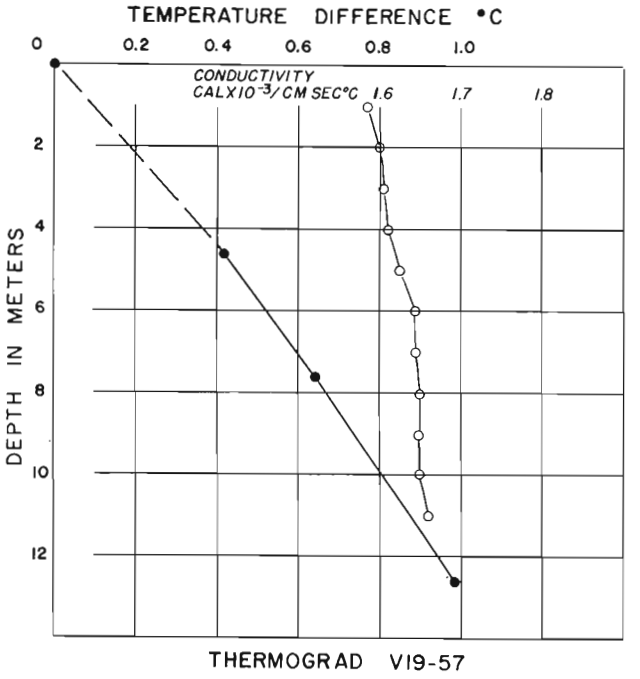


Figure 3. Temperature and conductivity data from a typical station using the Ewing-type probe.

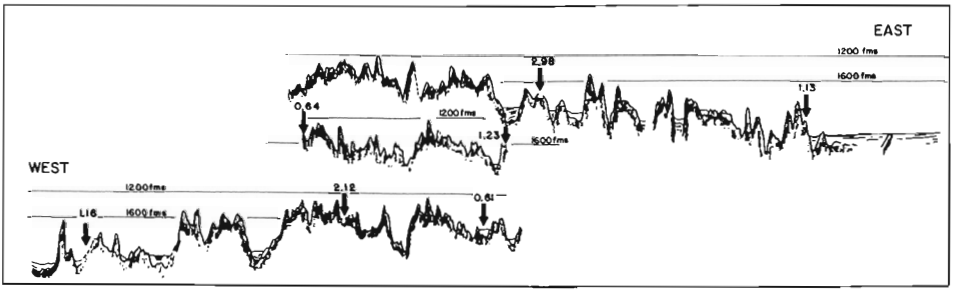


Figure 4. A profile of the topography and sediment structure of the Carlsberg Ridge in the Indian Ocean at about 6°N. The central axis was crossed three times with tracks spaced roughly 15 km apart.

A second factor contributing to the observed variability in the data is the high probability of environmental disturbances that principally result from the rough topography of the ridges.

In Figure 4, a profile over the Carlsberg Ridge is shown which is based on seismic reflection results (1961). Heat flow values are indicated along the profile. The vertical exaggeration is about 20:1, and the topography is drawn more bluntly than it is in reality because many small-scale features cannot be resolved by the reflection technique.

Heat flow that is regionally uniform at depth may be distorted near the surface by topography. Isotherms must spread out beneath peaks and concentrate below depressions to match the nearly constant temperature of the water at the ocean floor. Also the sediment over the mid-oceanic ridge is not uniformly distributed, and bottom sediments generally have lower conductivity than the bedrock causing the rough topography. Thick pockets of sediment therefore tend to inhibit heat flow, and the edge effects near the boundaries between bedrock and sediment cause large local disturbances (as wide as a few kilometres) in the regional field (Lachenbruch, 1966). Transient disturbances may result from recent erosion or deposition of sediment since these processes may uncover or bury isotherms. The seismic profile in Figure 4 shows layering in the sediment pockets that results from sediment flowing from peaks into depressions.

Distribution of Values Along the Ridges

Considering the variability on the data, if one is to determine the average heat flow for an area, one must either (a) use a large number of measurements randomly distributed, trusting that the disturbances are not systematic in one sense; or (b) try to correct each measurement for local disturbances using topography or sediment distribution from concurrent geophysical surveys. It is not possible at present to accurately locate stations with respect to the topography, thus only course (a) is open to us.

Three areas of the world-wide ridge system have a sufficient density of measurements to merit study. These are:

1. the Mid-Atlantic Ridge between 30°N and 40°S;
2. the Mid-Indian Ocean Ridge between 10°N and 40°S; and
3. the East Pacific Rise between 50°N and 40°S.

Mid-Atlantic Ridge

The stations in the vicinity of the Mid-Atlantic Ridge are shown in Figure 5. Open circles show published data, solid circles represent new data (Langseth, Le Pichon, and Ewing, in press). The axis

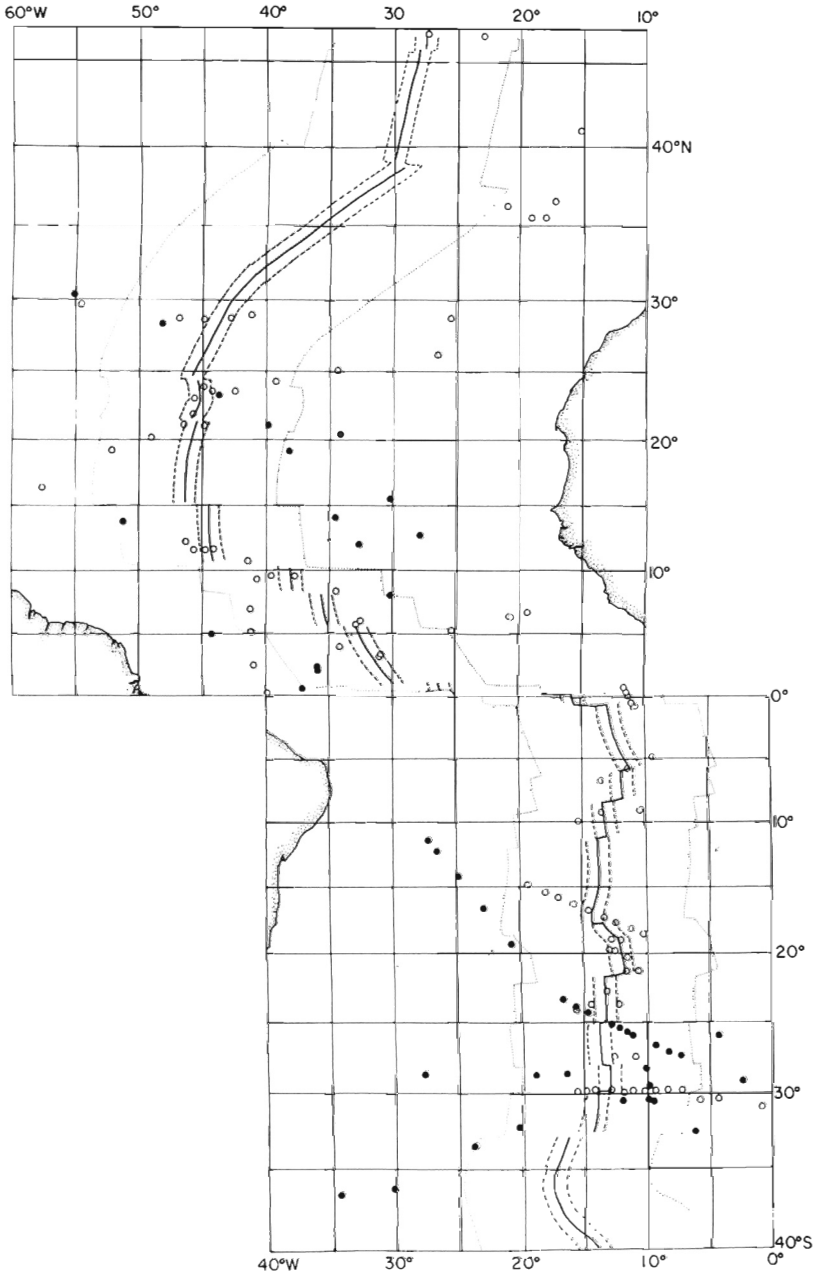


Figure 5. The location of heat flow measurements in the vicinity of the Mid-Atlantic Ridge. The solid dots represent unpublished values by the Lamont Geological Observatory used in the histograms (Fig. 6).

of the ridge is indicated by a solid line drawn to best fit the broad topographic ridge crest (the crest generally has a median rift valley), the large magnetic anomalies that are characteristic of the ridge, and the zone of earthquake epicentres. A crest zone is defined by the dashed lines on either side of the axis, and the outer limits of the ridge are shown by dotted lines 800 km to either side of the axis. The 1600 km width for the ridge has been chosen on the basis of topography and magnetics, following ideas outlined by Heirtzler and Le Pichon (1965). The reason for defining two zones in the ridge is that nearly all of the high heat flow measurements are confined to the 200 km zone near the axis. About 50 per cent of all measurements in the crest zone are greater than 2 μcal/cm^2 sec.

A histogram of values in the Mid-Atlantic Ridge crest is presented in Figure 6A. A wide spread of values is immediately obvious. Some of the low values may result from poor definition of the ridge axis while others must certainly result from local disturbances. The mean of 29 measurements along the crest is 2.92 μcal/cm^2 sec.

A histogram of values for the flanks is presented in Figure 6B; more numbers are available than over the crest, and the variation is less because of the absence of very high values. The mean of 1.35 μcal/cm^2 sec is not significantly different (considering the scatter) from the mean of all Atlantic values of 1.29 μcal/cm^2 sec.

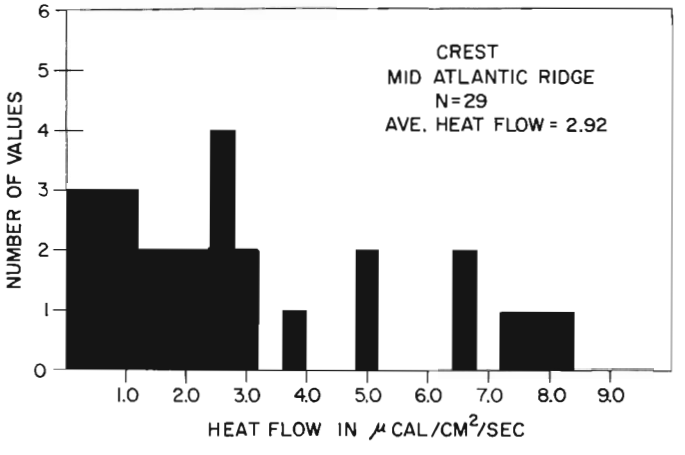
Mid-Indian Ocean Ridge

The locations of Indian Ocean Ridge values are shown in Figure 7. This ridge is relatively narrow topographically; its crest zone is about 100 km wide, and its outer limits are defined at 500 km to either side of the axis. (The southeast branch of the Mid-Indian Ocean Ridge is not shown on the figure.) The crest values are presented in the histogram in Figure 8A. They also show a great scatter, but despite the large number of low values, the average of 1.89 μcal/cm^2 sec is higher than the world average. Preliminary data from recent Lamont measurements not shown here would add several more high values in the crest zone.

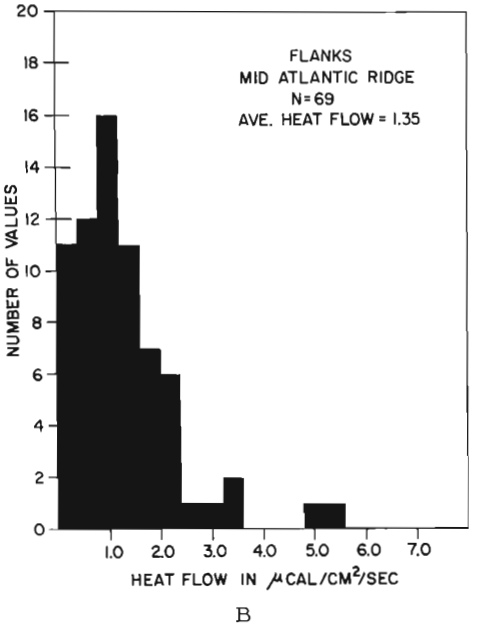
Flank measurements (Fig. 8B) show a strong predominance of low values, averaging 1.11 μcal/cm^2 sec.

East Pacific Rise

By far the largest number of measurements has been made in the East Pacific Rise (Fig. 9). The greater number of successful stations results to some degree from the smoother topography and a more even distribution of sediment. The crest zone is defined as extending to 250 km



A



B

Figure 6 (A and B). Histograms of heat-flow values in the Mid-Atlantic Ridge. An interval of 0.4 μcal/cm^2 sec is used.

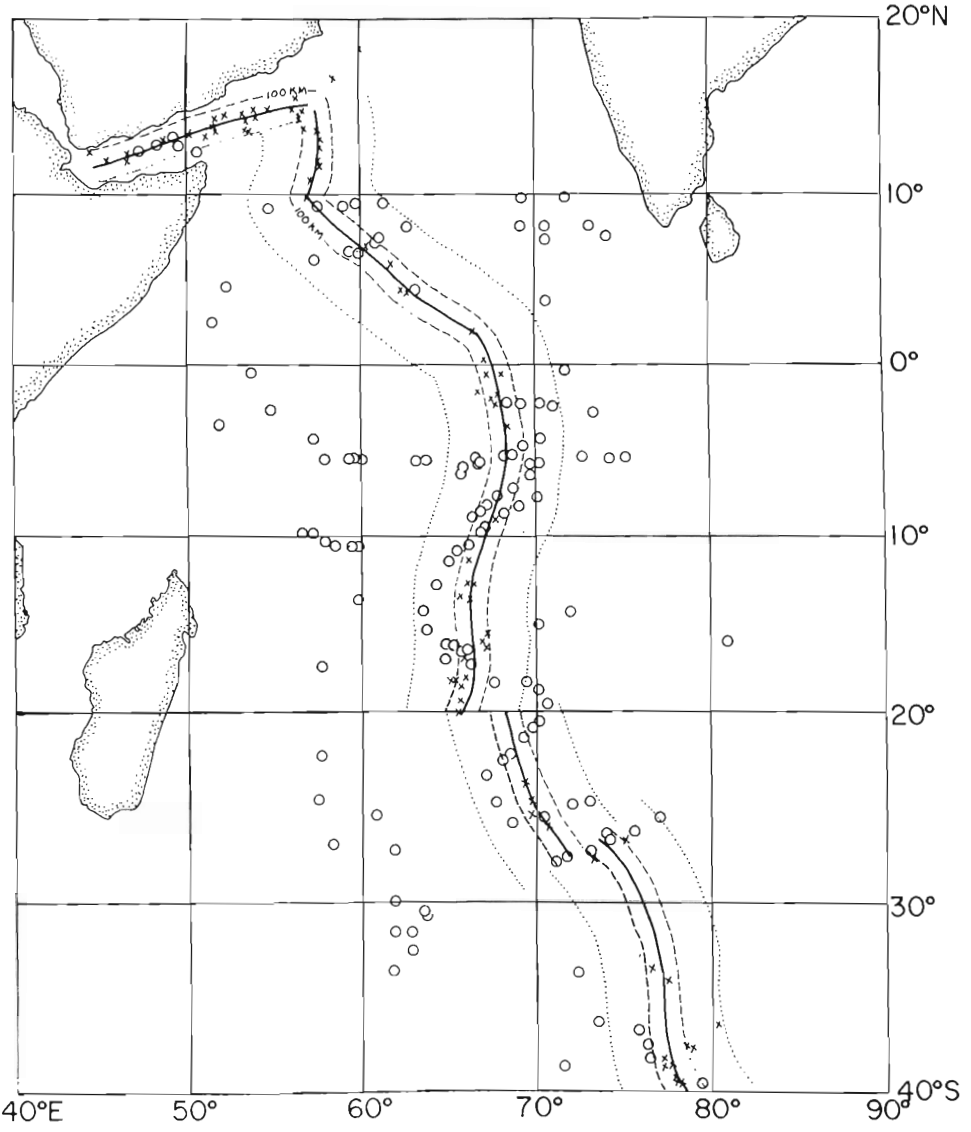
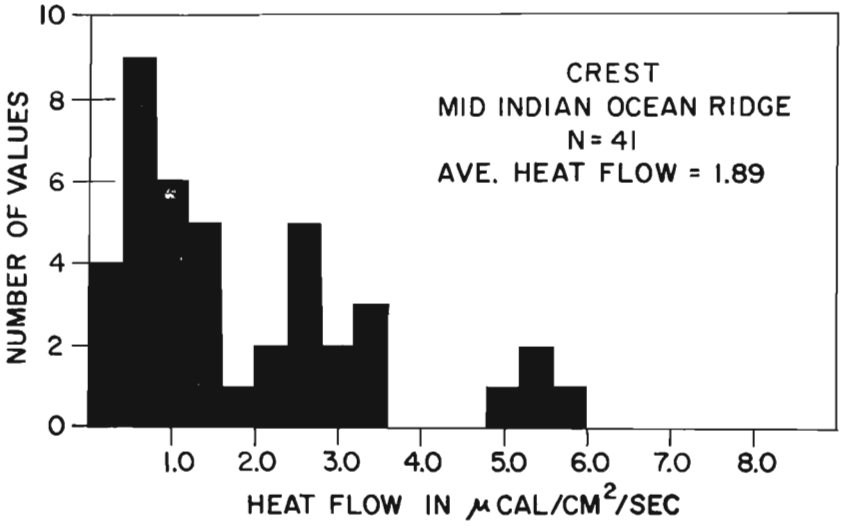
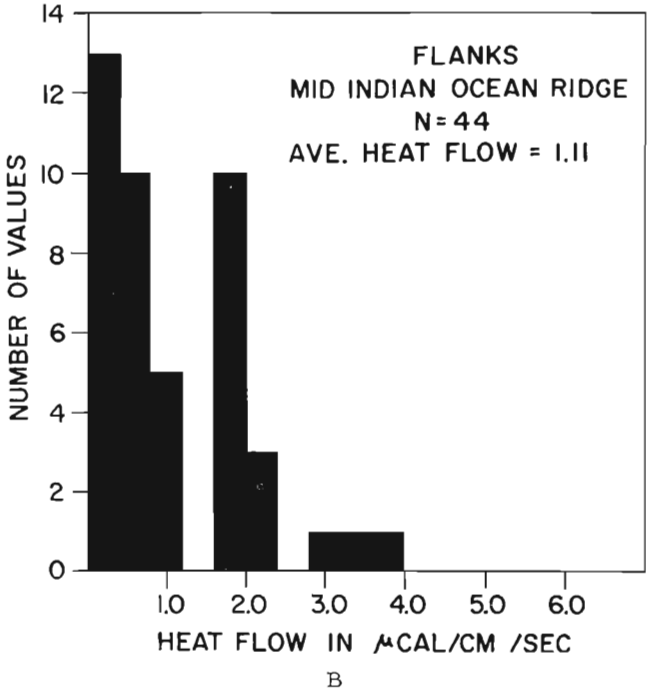


Figure 7. The location of heat-flow measurements in the vicinity of the Mid-Indian Ocean Ridge. This figure includes many unpublished values by Vacquier and Von Herzen.



A



B

Figure 8 (A and B). Histograms of heat-flow values in the Mid-Indian Ocean Ridge.

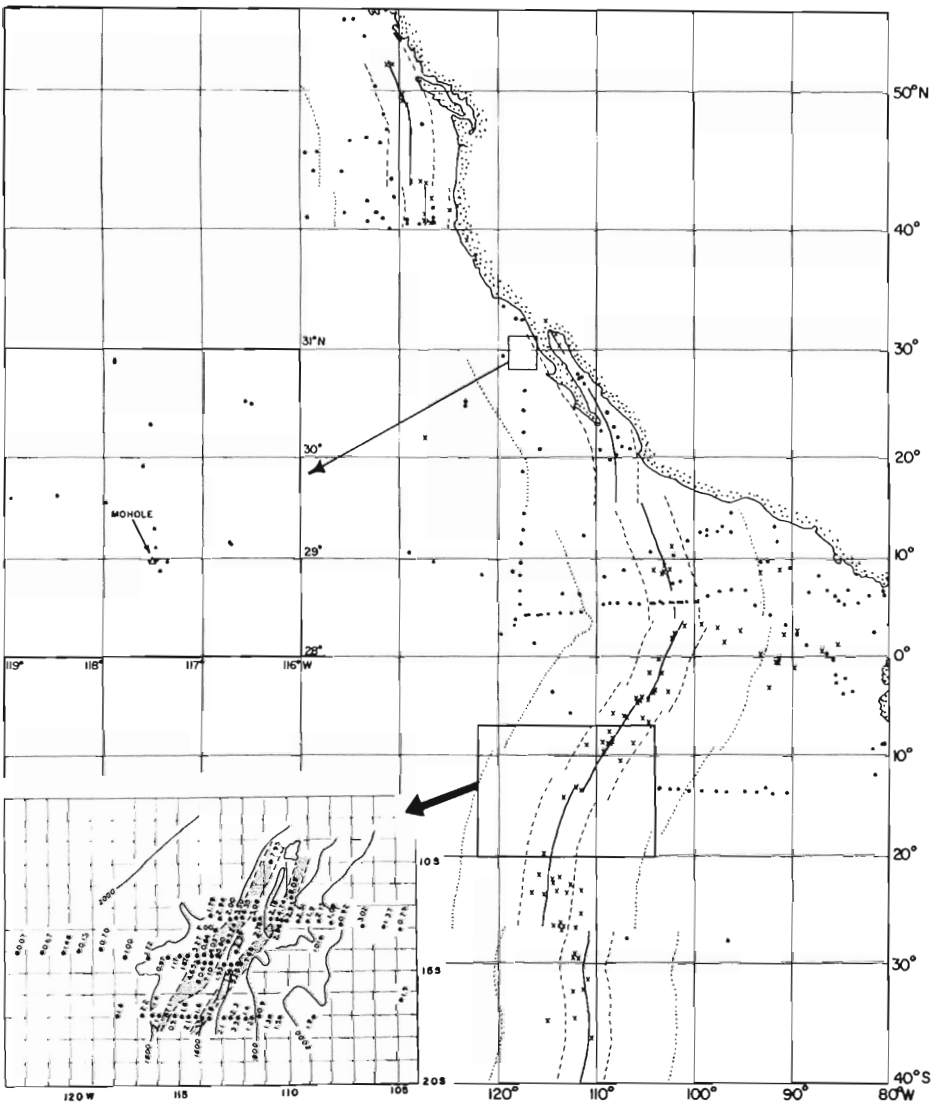


Figure 9. A map of the eastern Pacific showing the location of heat-flow measurements near the East Pacific Rise. Inset maps show two areas where the station spacing is too close to be shown at the figure scale.

on either side of the ridge axis, and the ridge limits are drawn at 1000 km to either side of the axis. There is no clear boundary to the rise, thus the 2000 km width is rather arbitrary.

The crest values presented in a histogram in Figure 10A comprise 87 measurements. The variation is large, but numbers greater than 2 μcal/cm^2 sec are more common than lower values. The average is 3.12 μcal/cm^2 sec.

In Figure 10B, the flank measurements from the East Pacific Rise show a distribution similar to that for all oceanic values (see for example, Lee and Uyeda, 1965). They have a mode and an average of about 1.7 μcal/cm^2 sec, close to that of all heat flow values. If we were to slightly extend the boundaries of the ridges, this average would decrease because large areas of low heat flow lie adjacent to the East Pacific Rise (Von Herzen and Uyeda, 1963).

CONCLUSIONS

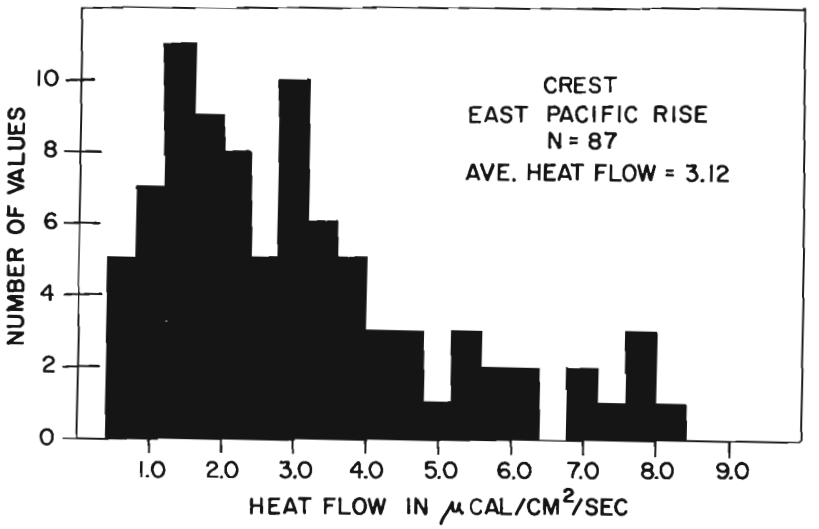
In summary, the available data indicate that the crests of the mid-oceanic ridges are characterized by higher than normal heat flow. In the sections of the Mid-Atlantic Ridge and the Mid-Indian Ocean Ridge studied, the flanks show heat flow somewhat below the mean of all values. It is interesting that the overall average for both of these ridges is very near the world mean value, 1.5 μcal/cm^2 sec. If this average has any significance it could suggest that the excess of heat escaping in the crestal zone is tapped from the flanks, and mechanisms such as refraction of the heat flow at depth or mass transport of heat by fluid lava from the flanks to the ridges could explain the existing anomalies. However, the overall average of heat flow along the East Pacific Rise is well above the mean; this implies either that abnormal amounts of heat are being produced under this rise, or that the upward transport of heat beneath the rise is more efficient than in the adjacent basins.

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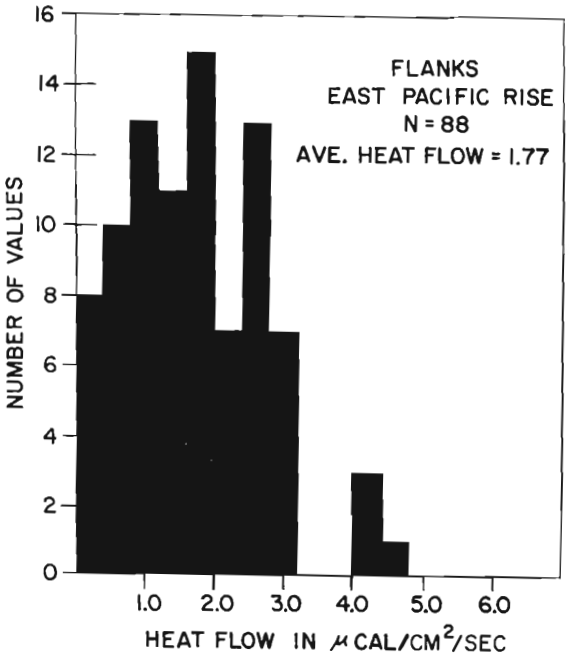
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A



B

Figure 10 (A and B). Histograms of heat-flow values in the East Pacific Rise.

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DISCUSSION

H. Kuno (Japan)

I am very pleased to know that such a large number of heat flow measurements have been made. I personally believe the determination of heat flow to be one of the observations most fundamental to the understanding of various phenomena of the earth.

D.C. Krause (U.S.A.)

I have heard other people use world averages lower than your figure of 1.5 μcal/cm^2 sec – figures more like 1.2. Have you any comment?

Dr. Langseth

The large variation in the data makes it very difficult to decide what value to choose as reference, and certainly, as has been pointed out, oceanic heat flow measurements are prejudiced by being concentrated along the mid-oceanic ridges. Many people prefer the mode of the histogram at about 1.1 μcal/cm^2 sec to the average value that I have used, and I think if a fair distribution were obtained it would probably be lower than 1.5. However, I used the average value because it was taken in the same way as the local averages that I have calculated.

S.K. Runcorn (U.K.)

Don't you think that a more sophisticated statistical model might be tried. The average will almost certainly be high since high values are given the same weight as low ones.

Dr. Langseth

Yes, but more sophisticated approaches are not yet warranted. The relatively small quantity of data still forces us to give somewhat suspect values the same weight as very good ones.

E. Irving (Canada)

The remanent magnetic intensities and susceptibilities of rocks have log-normal distributions and, when analysied on this basis, give meaningful averages. Your heat flow values appear to have a similar distribution, and until geometrical averages are taken, it is difficult to say whether the differences referred to are real or not. A systematic depression of your averages is to be expected.

SATELLITE GRAVITY OBSERVATIONS AND CONVECTION IN THE MANTLE

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School of Physics, University of Newcastle upon Tyne

The determination of the harmonics of low degree of the Earth's gravitational potential from observations of satellite orbits is providing key data concerning the physical processes in the mantle. That there exist non-hydrostatic low degree harmonics was first suggested by Jeffreys, who fitted a spherical harmonic series up to and including terms of the third degree to about a thousand values of gravity obtained by pendulum measurements on land and sea. Due to the non-random distribution of observation points over the globe, and the smallness (one part in 10^5) of the deviations of g, smoothed in this way, from the international gravity formula, Jeffreys' discovery was not widely accepted. In fact Heiskanen and Vening Meinesz took as their fundamental axiom of geodesy that such deviations from hydrostatic equilibrium did not exist, for the wavelengths of the supposed undulations of the geoid were over an order of magnitude greater than the depth at which isostatic compensation of the variations of mass in the crust was thought to be complete. Behind the conflicting views lay different geophysical philosophies. Vening Meinesz from his discovery of belts of negative anomalies near Java – evidence of deformation of oceanic crust – and from a broader analysis of the distributions of oceans and continents, had been led to postulate the existence of convection currents in the Earth's mantle. Jeffreys, on the other hand, from studies of the Earth's mechanical behaviour, became convinced that the mantle of the Earth possessed finite strength. The fluid behaviour of the mantle which Vening Meinesz required seemed to him to require the Earth to have a hydrostatic shape, disturbed only to a negligible amount by the convection currents. Jeffreys regarded the existence of the low degree harmonics of gravity, which require stress differences in the mantle of up to 50 bars, as support for his view of its finite strength.

It appears that the main features of Jeffreys' geoid have been remarkably supported by the data from satellite orbits. The low degree harmonics exist and the presence of regions of low gravity south of India, high in Europe and low near the Caribbean, have been confirmed. But I believe that his interpretation of the physical cause of these anomalies is incorrect and that, in fact, the observations support the hypothesis of convection currents in the mantle.

There are two objections to Jeffreys' view that the mantle has finite strength. Solid state physics, on the one hand, shows that at high temperatures all solids should flow by diffusion across crystal boundaries

however small a stress difference may be applied. The creep rates are minute but due to the exceptionally long time scale encountered in Earth physics, creep rates millions of times less than the smallest investigated in the laboratory (10^{-9} sec^{-1}) can have large geophysical effects, removing for example any stresses built into the Earth's mantle in its early development. Though Jeffreys does not speculate about the cause of the density differences in the mantle responsible for the low degree harmonics, his rigid Earth must have acquired them in its earliest history. One could conceive that on certain geochemical theories of the origin of the continents that appreciable density inequalities might be left in the mantle during the upward movement of sialic material. Or they might be supposed to have arisen during the Earth's formation. O'Keefe has described them as the scars resulting from the supposed parting of the Moon and Earth visualised by G H. Darwin, a theory recently revived. All these views however come up against the difficulty of how these stress differences have maintained themselves for the order of 10^9 years.

The other objection arises from geology and geophysics. Flow structures in rocks are common, and it is always supposed that they have been caused by the tendency of flow to occur at high temperatures and pressures some tens of kilometres in the crust. The isostatic adjustments of the varying loading of the crust must imply vertical and horizontal flow of material below the level of compensation. Continental drift cannot occur without large scale flow patterns in the Earth's mantle.

No flow can be driven without density differences, and these are then a possible cause of the gravity anomalies. It may easily be established that this is quantitatively a satisfactory explanation in order of magnitude (Runcorn, 1964).

An exact discussion of the problem is possible. The geopotential U outside the Earth at point (r, θ, ϕ) is usually expressed as

$$U = \frac{GM}{r} \left\{ 1 + \sum_{n=3}^{\infty} \left(\frac{a}{r}\right)^n \sum_{m=0}^{n} \left[C_{nm} \cos m\phi + S_{nm} \sin m\phi\right] P_n^m(\theta) \right\}$$

when M is the Earth's mass, and the associated Legendre functions are defined by

$$P_n^m(x) = (1 - x^2)^{m/2} \frac{d^m P_n(x)}{dx^m} .$$

C_{nm} and S_{nm} are the coefficients determined by the satellite observations.

The notation $D_n S_n(\theta, \phi) = \sum_{m=0}^{n} [C_{nm} \cos m\phi + S_{nm} \sin m\phi] P_n^m(\theta)$

for a general surface harmonic of degree n is convenient. The gravitational field $\underline{g} = \nabla U$, and for positive M, C_{nm} and S_{nm} the radial component of g is directed towards the origin.

Runcorn (1964) showed that the inertia, acceleration and Coriolis forces may be ignored in discussions of the hydrodynamics of the mantle.

If the curl of Navier Stokes equation is taken, we obtain

$$-\mu \nabla^2 (\nabla \wedge \underline{v}) = -\nabla \wedge \nabla p + \nabla \wedge \underline{F}$$

where F is the external force per unit volume of fluid in the direction of increasing coordinates. Thus $\underline{F} = +\underline{g}\rho = -\frac{\underline{r}}{r} g \rho$.

$$\mu \nabla^2 (\nabla \wedge \underline{v}) = -\underline{r} \wedge \frac{g}{r} \nabla \rho .$$

Putting $\underline{v} = \nabla \wedge \nabla \wedge \underline{r} W$

$$-\mu \nabla^2 (\underline{r} \wedge \nabla \nabla^2 W) = -\frac{g}{r} \underline{r} \wedge \nabla \rho .$$

$$\mu \underline{r} \wedge \nabla \nabla^4 W = +\frac{g}{r} \underline{r} \wedge \nabla \rho .$$

Hence $\rho = +(\mu r/g) \nabla^4 W$.

The arbitrary function of radius which should be added to the solution is omitted as it plays no part in the convection problem.

Now $\nabla^2 U = -4\pi G \rho$.

Putting $k = (4\pi G \mu r/g)$, and assuming k is a constant corresponding to a uniform earth in which $g \propto r$,

$$\nabla^2 U = -k \nabla^4 W .$$

Runcorn (1965) gives the solution of this equation as

$$U = -k \nabla^2 W + V$$

where $\nabla^2 V = 0$.

He argues that the harmonic V depends on the boundary conditions but, as these were not then clear, omitted V altogether and recognized the solution

to be incomplete (Runcorn 1964, 1965). We can now obtain the complete solution with reasonable confidence of its applicability to the earth.

We proceed as follows letting

$$W = \sum_{n=0}^{\infty} W_n(r)\, S_n(\theta, \phi).$$

In the convecting part of the mantle bounded by spheres r=a, r=b

$$U_M = -k \sum \left(\frac{d^2 W_n}{d r^2} + \frac{2}{r} \frac{dW_n}{dr} - \frac{n(n+1)}{r^2} W_n \right) S_n(\theta, \phi)$$

$$+ \sum \left[A_n \left(\frac{a}{r}\right)^{n+1} + B_n \left(\frac{r}{a}\right)^{n} \right] S_n(\theta, \phi).$$

Below the lower boundary of the convecting part of the mantle

$$U = \sum C_n \left(\frac{r}{b}\right)^{n} S_n(\theta, \phi).$$

At both upper and lower boundaries the potentials are continuous and the radial components of the potential gradient are discontinuous due to the distortion of the boundaries by the convection currents. Runcorn (1966) has shown this distortion is equivalent to a surface distribution of matter which, for rigid boundaries, is proportional to the pressure, p. Thus at the upper boundary, r = a.

$$D_n \frac{GM}{a} [1] = -k \left(\frac{d^2 W_n}{dr^2} + \frac{2}{a} \frac{dW_n}{dr} - \frac{n(n+1)}{a^2} W_n \right) \Bigg|_{r=a} + A_n + B_n .$$

$$D_n \frac{GM}{a} (n+1) - k \left(\frac{a d^3 W_n}{dr^3} + 2 \frac{d^2 W_n}{dr^2} - \frac{2+n(n+1)}{a} \frac{dW_n}{dr} + \frac{2n(n+1)}{a^2} W_n \right) \Bigg|_{r=a}$$

$$- (n+1) A_n + n B_n = \frac{4 \pi G \rho a}{g S_n(\theta, \phi)}$$

$$= -k \left(a \frac{d^3 W_n}{dr^3} + 3 \frac{d^2 W_n}{dr^2} - \frac{n^2+n}{a} \frac{dW_n}{dr} + \frac{n^2+n}{a^2} W_n \right) \Bigg|_{r=a} .$$

At the lower boundary of the convecting region, r = b.

$$-k\left(\frac{d^2W_n}{dr^2} + \frac{2}{b}\frac{dW_n}{dr} - \frac{n(n+1)}{b^2}W_n\right)\Bigg|_{r=b} + A_n\left(\frac{a}{b}\right)^{n+1} + B_n\left(\frac{b}{a}\right)^{n} = C_n.$$

$$-k\left(b\frac{d^3W_n}{dr^3} + 2\frac{d^2W_n}{dr^2} - \frac{2+n(n+1)}{b}\frac{dW_n}{dr} + \frac{2n(n+1)}{b^2}W_n\right)\Bigg|_{r=b}$$

$$-(n+1)A_n\left(\frac{a}{b}\right)^{n+1} + nB_n\left(\frac{b}{a}\right)^{n} = nC_n - k\left(b\frac{d^3W_n}{dr^3} + 3\frac{d^2W_n}{dr^2} - \frac{n^2+n}{b}\frac{dW}{dr} + \frac{n^2+n}{b^2}W\right).$$

For the boundaries we take $W_n = \frac{dW_n}{dr} = 0$.

Thus $$D_n\frac{GM}{a}(n+1) + k\frac{d^2W_n}{dr^2}\Bigg|_{r=a} - (n+1)A_n + nB_n = 0.$$

$$D_n\frac{GM}{a} + k\frac{d^2W_n}{dr^2}\Bigg|_{r=a} - A_n - B_n = 0.$$

$$-k\frac{d^2W_n}{dr^2}\Bigg|_{r=b} + A_n\left(\frac{a}{b}\right)^{n+1} + B_n\left(\frac{b}{a}\right)^{n} - C_n = 0.$$

$$-k\frac{d^2W_n}{dr^2}\Bigg|_{r=b} + (n+1)A_n\left(\frac{a}{b}\right)^{n+1} - nB_n\left(\frac{b}{a}\right)^{n} + nC_n = 0.$$

$$\therefore D_n\frac{GM}{a}(2n+1) + k(1+n)\frac{dW_n}{dr^2}\Bigg|_{r=a} - (2n+1)A_n = 0$$

and $$-k(n+1)\frac{d^2W_n}{dr^2}\Bigg|_{r=b} + (2n+1)A_n\left(\frac{a}{b}\right)^{n+1} = 0.$$

Thus

$$\left.\frac{d^2W}{dr^2}\right|_{r=a} = \sum_{n=3}^{\infty} - \frac{2n+1}{n+1} \frac{GM}{ka} D_n S_n(\theta,\phi) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

if the term containing $(\frac{b}{a})^{n+1}$ can be neglected. The justification for neglecting the contribution of the lower boundary is strong if the convecting layer is deep because of the reasonably high values of n. Taking μ and K constant is a poor approximation for the Earth and a more realistic model could change the sign in equation (1) but would involve a particular theory of convection for its solution. Equation (1) relates the low harmonics of the geoid to a quantity at the outer boundary of the convecting region that is the vertical gradient of the horizontal velocities and, consequently, the fluid traction applied to the crust.

Figure 4 of Runcorn (1965) shows an earlier and very recent geoid from which the tractions can be found. If the explanation of the low harmonics of the geoid in terms of convection is substantially true, then these tractions should show a marked correlation with the zones of compression and tension in the crust. The correlation is by no means perfect; this would hardly be expected in view of the uncertainties in the determination of the coefficients of the harmonics of the geoid and the inhomogeneities of the crust. However, it will be seen that, along the Andes and the Rockies, there is strong convergence of the tractions, as also along the Japan trench, the Tonga trench and the Java trench, compressional features in the ocean floor. Divergence of the tractions causing extension of the crust occur in the East Pacific; in the North and South Atlantic just west of the ocean ridges; and in the Indian Ocean near the Carlsberg ridge, along a zone extending from near Lake Baikal in Asia to south of Australia. The associations with the East Pacific rise, the mid-Atlantic ridge, the Carlsberg ridge and the circum-Antarctic ridge, are reasonably good. The line of tension in the Atlantic is definitely west of the mid-Atlantic ridge but shows a similar displacement to the east south of the equator. The supposed line of rift valleys through Asia-Lake Baikal and the East African rift valleys are also clearly associated with diverging tractions.

It is concluded that the hypothesis of convection shows every indication of providing an explanation of the lower degree harmonics of the Earth's geoid. One may therefore look to the increasing development of accurate knowledge of these harmonics, through satellite observations, as a means of investigating the dynamics of the earth's mantle, and of understanding the origin of tectonic activity.

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DISCUSSION

L. Knopoff (U.S.A.)

I should like to make three comments. First, the negative gravity anomaly in the Indian Ocean seems to be closing the Red Sea Rift rather than opening it; the rising currents under the negative gravity anomaly would push Arabia to the west. Second, recent work by Takiuchi (Tokyo) and Anderson (Pasadena) seems to show that the viscosity in the mantle is not uniform with radius, and that the value that came from the Fennoscandian uplift applies to the upper mantle only, perhaps to depths as great as the low velocity layer. Perhaps one should apply to the lower mantle the values derived by MacDonald from the rates necessary to maintain the non-hydrostatic figure of the earth. MacDonald's value is about 10^{26} poise. This would require an increase in temperature to 100,000° to drive the convection. Third, if one assumes a homogeneous earth then the values of the Rayleigh number with the viscosities of the order you choose is so high that it is doubtful that the mantle could be in laminar convection, but must rather be in turbulent convection.

Dr. Runcorn

With regard to Dr. Knopoff's first point, I think the contrary is the case. The negative gravity anomaly in the Indian Ocean would in my hypothesis be a place where the current is rising, and therefore horizontal flow radiates from its centre outward. Thus Arabia will be pushed to the northwest, and East Africa to the southwest, thereby opening the Red Sea. However, the satellite observations have only been computed up to the eighth degree, and one cannot suppose that every tectonic detail is reflected in the geoid. An eighth degree harmonic has 16 zeros in 360 degrees, thus phenomena having a wavelength less than about 3,000 km will not be seen. Further, the calculation of these harmonics of the gravity anomalies is still very difficult and doubtless the accuracy is not high.

With regard to the second point concerning the variation of viscosity through the mantle, we really know very little, theoretically or observationally, about the variation of viscosity with radius, and I believe therefore it is scientific to take the simplest hypothesis of uniform viscosity until this evidently conflicts with what is known. Specialists in solid state physics tend to say that the geophysicist is completely naive in talking about a viscosity in connection with creep in the mantle. However the processes of creep studied in the laboratory have mechanisms that are certainly different from the exceedingly slow creep responsible for convection in the mantle. It is interesting to find that specialists in creep still find it convenient to suppose the mantle has a viscosity. It is arguable that the mechanism of creep in the mantle is a diffusion mechanism, in which case, it is quite theoretically correct to use a viscosity. The question then is whether the viscosity varies with radius. At this point speculation depends not only on the mechanism of creep but on the temperature distribution and the presence or absence of phase change in the mantle, and it is not very fruitful at the moment. I agree with Dr. Knopoff that the main objection to the interpretation I have been giving today is the discrepancy between the J_2 term determined from satellite gravity and the hydrostatic value calculated from the Darwin-Radau theory. This discrepancy, although a small one, between a flattening of 1/298 and 1/299 can hardly be interpreted except by a rigid mantle or a viscosity, 10^{26} poise, too high for convection hypothesis, although because it conflicts with that obtained from the rise of Fennoscandia, may refer to the lower mantle. I wonder if the approximate hydrostatic theory in which the flattening can be calculated from the moment of inertia factor is adequate for the earth. The inner body is possibly very dense (18 gm/cc). It contributes negligibly to the earth's gravity (because it has a small radius) but appreciably to the gravitational field in the core, which divided into the centrifugal force determines the ellipticities of the equipotential surfaces, the variations of which with radius enters into the Darwin-Radau equation. Dr. G.J.F. MacDonald, in supposing that this gravity anomaly arises from the lower mantle restricts convection rapid enough for continental drift to the upper part of the mantle. One therefore supposes that the density variations associated with these currents explain the harmonics of gravity above the second degree or that these also arise from the lower mantle, but their origin is then a mystery unless the lower mantle is entirely rigid so that the explanation of the discrepancy in the ellipticity proposed by MacDonald is wrong. Recently W.J. Eckert has reviewed very carefully the motion of the moon and, in particular, the precession of its nodes. He shows that there is a discrepancy of 10" of arc per century. He concludes that the moon must have a moment of inertia factor (i.e. the moment of inertia divided by its mass times its radius squared) of about 1. If one accepts these data, of course, the moon is completely hollow! It is rather interesting that this discrepancy which he finds is also linked to the value of flattening of the earth. The differences in the polar and equatorial moments of inertia of the earth and the moon come in from the theory of the moon's motion. It is the

flattening given from satellite gravity observations that is used in the calculation of Dr. Eckert in which the hollow moon results. If the flattening could be reduced by about 1/3 per cent, bringing it into agreement with the hydrostatic value of flattening then the necessity for having a hollow moon could be removed. So this discrepancy between the hydrostatic values of the earth's flattening and the one which is obtained from satellite gravity is also linked to the problem of the motion of the moon's nodes. Because of the absurd result of this line of reasoning there is clearly something wrong. Thus I think that Dr. MacDonald's solution of the problem of the flattening of the earth by supposing that a large part of the mantle is rigid is probably not the answer to this problem.

Regarding the high Rayleigh number of the mantle convection, I think experiments show that the fact that this number appears to work out to about 10^3, that of the critical Rayleigh number in which marginally stable flow begins, does not mean that the number of cells present in the mantle must be very much greater than that predicted by the marginal condition. The experiments suggest that the cell size remains the same as the Rayleigh number increases but the flow restricts itself into narrow jet streams.

B. Loncaravic (Canada)

You suggest that the discrepancy in the Red Sea area arises because it is too small to be detected by your present analysis. There is another one that is on the scale of 8,000 miles which appears on all the satellite traces. Specifically, the surface ship gravity observations obtained in the Indian Ocean area give an average negative gravity anomaly corresponding very nicely to the geological picture; but in the Atlantic, it is different. In the Atlantic the anomaly is positive; it is positive in gradient increasing to the north, and it's certainly not the east-west gradient that you show – i.e. from about 20 mgal positive near the west, to 20 mgal negative on the east coast of the Atlantic.

Shipborne sea gravimeter measurements over most of the regions show a positive average value over the Atlantic, of the order of 20-30 mgals at 30° north, and 40-50 mgals at 45° north.

Dr. Runcorn

Yes, but as you know, Uotila's geoid map is based mostly on submarine measurements, not satellite measurements, and yet it gives the negative in the Atlantic very close to the satellite one. This suggests that a depression in the geoid is present – and a rising convection current.

THE EVOLUTION OF MEGA-UNDATIONS A MECHANICAL MODEL FOR LARGE-SCALE GEODYNAMIC PHENOMENA

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Abstract

Mega-undations are the largest deformations of the earth's crust, having diameters of thousands of kilometres. They result from deep-seated mass circuits, probably in the inner mantle. Their potential amplitudes are about 100 km, but their actual heights are not more than a few dozen metres because the arching which they involve is partly compensated by gravity spreading of the earth's upper layers.

Where mega-undations occur in continental regions (as in Gondwana and Laurasia), new oceanic basins are opened, and mid-oceanic ridges form at the crest of the mega-undations. Relatively deep parts of the outer mantle rise to the ocean floor, and the overlying structural layers glide laterally, much like the spreading of a tilted stack of books. The uppermost layer (the crust) moves farthest, but the next deeper layers (the asthenosphere and sclerosphere) are also affected. The displaced continental shield has distinctive geotectonic features: frontal geosynclinal subsidence (followed by orogenesis); extension phenomena at its rear; and right- and left-lateral faults on its "starboard" and "port" sides, respectively. The crest of mega-undations may shift with time, and different stages in their evolution can be distinguished at different places on the earth.

These features are illustrated by the Atlantic mega-undation and the associated drift of the North American continent; and by the geotectonic evolution of the Indian Ocean and its adjoining continental masses.

HISTORICAL REVIEW

After the 1920's, the "mobilistic" concept of continental drift was not widely accepted by geologists because of the verdict reached by geophysicists against the mechanisms of continental drift suggested by Alfred Wegener; and because of the influence of the "non-drift" concepts of the evolution of the earth's surface advanced by Charles Schuchert, Hans Stille, Erich Haarmann and others. The field investigations of the author of volcano-tectonic structures and mountain building in Indonesia caused him

also to favour a non-drift concept for the structural evolution of the earth, as was developed in his "Undation Theory". This concept deals with the origin of upwarps of various dimensions in the earth's surface (primary tectogenesis), which are volumetrically compensated by the subsidence of the adjacent areas. These differential vertical deformations have the appearance of waves or "undations". The potential energy accumulated by the undations can be reduced or wiped out either by erosion and sedimentation, or by spreading under gravity (secondary tectogenesis). This is the main thesis of the Undation theory (Van Bemmelen, 1929-1965).

After the Second World War our knowledge about the physical properties of the deeper levels of the earth greatly increased, as well as our knowledge about the high-pressure phases of matter. Moreover, the development of our knowledge through research in oceanography and palaeomagnetism, and by means of artificial satellites and other new methods has given a great wealth of data about the geotectonic design of the earth's surface and its dynamic evolution.

These data on a supra-regional scale appear to be definitely in favour of continental drift. There are no submerged "borderlands" or "isthmian links" as was supposed by the "fixistic" concepts, but rather a marked contrast in structure and composition down to a depth of hundreds of kilometres between the continental and oceanic areas (Cook, 1962). Moreover, there is a remarkably good fit between the coast lines of the disrupted cratonic shields (Carey, 1958, Wilson, 1962, Bullard and others, 1965). These newer data are all in favour of continental drift, whatever its mechanism might be.

Thus, the elaboration of the Undation theory (by means of the scientific method of "prognosis" testing; Van Bemmelen, 1961) led the author to postulate mega-circuits of matter in the mantle (Van Bemmelen, 1958), having differential vertical and horizontal movements in the different structural spheres of the earth ("stockwerk tectonics", Van Bemmelen, 1962).

This newer development of the undation theory is still "fixistic" for the mechanisms of structural evolution occurring inside the framework of local and regional processes (i.e. within the realm of the observations of the field geologist), but it is "mobilistic" for those geodynamic processes that move matter beyond the limits of this framework. On a super-regional geotectonic scale, the mobilistic principles come to the fore. As the effects of the local, regional, and super-regional geodynamic processes are superimposed on each other, we might speak of a "relativistic" approach to the description and explanation of the structural evolution (Van Bemmelen, 1962; 1964a,d).

FUNDAMENTAL PRINCIPLES OF THE UNDATION THEORY

The development of the Undation theory is based entirely on its fundamental principles, which will now be summarized. The earth strives for internal equilibrium with a minimum of free potential energy. There are factors that disturb this equilibrium (equilibrio-turbal factors), giving rise to processes that tend to restore it (equilibrio-petal processes). However, the internal equilibrium must be established at two essentially different levels, and this complicates its restoration. It must be established at: (a) a submicroscopic level where electromagnetic forces are predominant. This is the realm of physical chemistry and includes chemical reactions, phase-transitions, and radio-active decay; and (b) a megascopic level, where mass forces are dominant (e.g. the force of gravity). At this level, the earth strives for hydrostatic and rotative equilibrium in its planetary and cosmic setting.

When, for some reason, gravitational equilibrium is not realized, stress fields develop having plus and minus deviations from an equilibrium distribution of potential energy. These deviations then give rise to mass displacements that tend to re-establish gravitational equilibrium.

Mass-displacements that occur in a more or less coherent, non-dispersed state, are called "geodynamic processes" (Van Bemmelen, 1964 a). Gravity is their leading force, and is the motor of the free potential energy. All mechanical explanations of the geodynamic processes are ultimately based on gravity, whether they are based on the contraction theory of the earth, the theory of convection currents, or the modern versions of an expanding earth hypothesis. The author's concept of generalized gravity tectonics attempts to explain all geodynamic processes from this unified point of view.

The geological evolution of the earth is the effect of a huge and complicated chain reaction. Physicochemical reactions striving to establish equilibrium in submicroscopic realms disturb the gravitational equilibrium in the megascopic realm. Flow of matter under gravity is the equilibrio-petal response in the megascopic realm, but by changing the pressure and temperature conditions of the matter concerned, this process again disturbs the physicochemical equilibrium. Various conjectures can be made about the character of the physicochemical energy at depth – that is, whether it is radioactivity, phase transitions between the boundary of the core and mantle, or the differentiation of the lower mantle into matter of higher and lower density. In any case, it is highly probable that any endogenic production of free energy at depth will trigger chain reactions, during which the free energy is changed from one type into another, until it ultimately is radiated into space as low-level heat radiation. An attempt to outline this terrestrial

chain reaction and the interdependence of primary and secondary tectonics at various scales is given in Table IV of the author's paper on the present state of the undation theory (Van Bemmelen, 1964 d).

MAGNITUDE OF UNDATIONS

Five categories of undations can be distinguished according to their diameter at the earth's surface.

(1) The smallest type is caused by diapiric phenomena in the sedimentary skin or "epiderm". It is represented by superficial laccoliths and salt domes.

(2) Minor undations are caused by diapirism of magmatic matter in the basement complex or "meso-derm". Some examples are: mantled gneiss-domes; batholithic intrusions; volcano-tectonic domes of the size of the Askja dome in Iceland (Van Bemmelen and Rutten, 1955), the Toba-Batak dome in Sumatra (Van Bemmelen, 1929), and the Sunda dome on Java (Van Bemmelen, 1934).

(3) Meso-undations are represented by the upwarp of mountain ranges and the development of their side-deeps. The causative mass-displacements of geanticlinal upwarps reach down to the lower part of the crust or "bathyderm". The mass displacements of mountain building occur for the greater part in the outer 100 km of the geoid, called the "tectonosphere" (Van Bemmelen, 1962).

(4) Geo-undations are represented by geosynclinal downwarps, such as the former Tethys and the present Gulf of Mexico, and by continental or marine upwarps such as the Rocky Mountains, the Bermuda Rise (Van Bemmelen, 1964 c), and the mid-ocean Rises. The mass displacements in depth accompanying geo-undations reach down into the upper part of the upper mantle, which is characterized by somewhat reduced seismic velocities (Gutenberg's "low velocity channel" or the "asthenosphere").

(5) Finally, there are mega-undations, which have diameters of many thousands of kilometres. These can be studied by "geonomic methods", such as determinations from artificial satellites (Kaula, 1963). The plus and minus deviations from normal gravity amount to some dozens of milligals, and the gradients of the gravitational field are very low, indicating that their cause is very deep-seated, probably in the lower mantle. Mega-undations are thought to be the cause of continental drift as will be discussed in the following paragraphs.

GEOMECHANICAL MODELS

Data obtained by means of artificial satellites have confirmed Jeffrey's opinion that the earth is not a perfect ellipsoid of rotation with an isostatic distribution of matter. It appears that the earth has extensive fields of gravity anomalies, having diameters of thousands of kilometres (Kaula, 1963). The anomalies are coupled with internal stresses of the order of 100 bars (Kaula, in Knopoff, 1964 p. 113), and these stresses are of the same magnitude as the stress released by creep fractures during deep earthquakes (Orowan, 1964, 1965).

Most probably the stress fields associated with the gravity anomalies cannot be supported permanently by the mantle. Thus, these mega-fields of isostatic anomalies at the earth's surface are only a transient phase in a geodynamic process having the dimensions of the mega-undations. Orowan (1964, 1965) draws attention to the common misconception that flow movements in the mantle take place under conditions of Newtonian viscosity or ideal plasticity. The crust and the outer mantle, down to depths of many hundreds of kilometres, are probably composed of matter in a crystalline state, and their deformation is probably characterized by creep or hot-creep, called "Andradean viscosity" by Orowan (1965, p. 1008).

In this process, competent lamellae in the upper mantle and the lower crust that are more or less undisturbed internally are mutually separated by zones of strong differential movement (high strain rates); this is typical of the gliding movements ("Gleitbretter") defined by Walter Schmidt (1932). Such an Andradean viscosity occurs to depths of at least 700 km, the maximum depth of earthquake foci. This is near the base of Bullen's seismic C-sphere, called "Sclerosphere" (Lustich, 1962). Knopoff (1964) has concluded that the sclerosphere is strong enough to prevent convection currents. There may be mass-circuits in the asthenosphere (the B-sphere), and even magma chambers in the tectonosphere and crust, but these would be of only restricted extent, and they would not be able to cause geodynamic phenomena of such an amazing uniformity and great extent as continental drift, mid-ocean rises, major transcurrent faulting of the Mendocino type and the aseismic lateral ridges or nemataths like the Ninety-East Ridge.

Wilson (1963 a,b) has tried to escape the above mentioned difficulty by suggesting that the sclerosphere is pierced by upward and downward branches of mega-convection currents generated in the lower mantle. The horizontal upper parts of these mass-circuits would pass as undercurrents beneath the tectonosphere, and their drag would cause phenomena such as continental drift, aseismic lateral ridges, and major transcurrent faulting.

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Apart from the objections to this model pointed out by Knopoff on the basis of Rayleigh numbers, it is difficult to accept its geochemical consequences. Specifically, matter from the lower mantle would have to rise almost to the surface and return down again without having been subjected to any chemical reactions such as differentiation or contamination. It seems probable that the mean chemical density of at least a considerable fraction of the material would have to be altered to such an extent, that the fundamental condition of thermal convection currents – that of chemical homogeneity – would no longer be fulfilled.

Bernal (1961) has suggested that the convective cell is entirely restricted to the lower mantle. Such deep seated convection currents would cause a drag force at the base or the upper mantle, and this could cause a state of tension in the seismic A, B and C spheres above the ascending branch, and a state of compression above the descending one. The zone of tension might produce the world-encircling rift belts, the zones of compression, and normal, intermediate and deep foci of earthquakes. Bernal's geomechanical model attractively explains many geodynamic phenomena, but there are some objections from mechanical and seismological points of view.

In the first place, it is difficult to imagine that drag forces can be transmitted upward through the A, B and C spheres for many hundreds of kilometres to cause the important geotectonic processes observed near the surface. Secondly, the mechanical concept of drag implies that the speed of the "undercurrent" is greater than the movements of deformation in the higher strata. In fact, the rate of the deformation at the surface appears to be so high (centimetres per year) that the speed of the drag flow in depth would have to be incredibly high. Moreover, recent seismological studies are not in agreement with this prediction (prognosis) of the model of deep seated drag. Koning (1952, 1953a,b) and, more recently, Harrington (1963) have shown that normal, intermediate and deep focus earthquakes are not distributed along zones dipping from the oceans beneath the continents. Rather, their distribution is in more or less horizontal zones, which shift in an "en echelon" manner toward the continents with depth. Harrington (1963, p. 71) comes to the following conclusion: "The overall picture would be that of a composite substrata current, consisting of several superimposed layers flowing at different rates, the shallower layers moving faster than the deeper sheets". This is the mechanism of glide lamellae, moving laterally under the force of gravity in response to their own potential energy. The lamellae can move autonomously much like the units of a tilted stack of books.

It is not necessary – in fact, it seems improbable – that drift movements of the crust are the result of dragging by undercurrents. The crust can undergo lateral movement either (a) passively on the back of

sideward-moving deeper layers, or (b) independently from its base by gravity flow if it is separated from its base by a layer of lubricant. In the latter case, the higher units move faster and farther forward than the deeper ones, which is a characteristic feature of gravity tectonics by gliding.

Ritsema (1964) has recently published a number of reliable fault plane solutions that are of importance to this geomechanical problem. The hearth mechanisms of the thrust, or block, type (as defined by Ritsema, ibid. p. 71) indicate that in regions such as Japan, South America, and Fiji, the upper block is generally thrust farther forward towards the Pacific than the lower block. However, the deeper focus earthquakes in the area of Japan and South America, indicate an opposite direction of the thrust movements, namely the underlying unit moves oceanward with respect to the upper block. In Indonesia and Fiji, the relative oceanward movement of the upper block persists even for the hearth mechanism of the deep foci.

These observations can be interpreted in the following way. The oceanward movement of the crust and the uppermost part of the mantle is consistent with the hypothesis that they are glide lamellae moving autonomously, in response to their own free potential energy, toward the Pacific Ocean as was suggested by Harrington (1963) and the author (1964b, 1964c). In Indonesia and Fiji, this mechanism persists even to the base of the sclerosphere. This might indicate that there are mega-undatory upwarps of the upper mantle in the rear of these areas, which have a considerable potential amplitude, but which cannot reach appreciable height because of spreading by gravity.

As is indicated in Figure 1, the causative mass displacements of mega-undations are probably situated in the lower mantle. The viscosity of the upswelling part of the lower mantle is probably lower than the viscosity of the upper mantle. It is to be expected that the spreading of this upswelling might produce a kind of undercurrent at the base of the upper mantle, as was already suggested by Bernal (1961) (See Figs. 7, 8, 9). This undercurrent would be at a depth of many hundreds of kilometres, in the zone of deep earthquakes and perhaps deeper. Thus we would have to deal with autonomous and independent gravitational "flow movements" in the A, B and C spheres. Only locally, as in Japan and South America, does an undercurrent in the lower mantle cause drag phenomena at the base of the C-sphere.

This concept differs from the common idea that shallow undercurrents at the base of the crust cause drag phenomena. In the higher structural levels, above the deep earthquakes (and, in Indonesia and Fiji, even inclusive of that level), the reliable fault plane solutions published by Ritsema (1964) are in favour of a mechanical picture of glide-lamellae comparable with the spreading of a tilted stack of books.

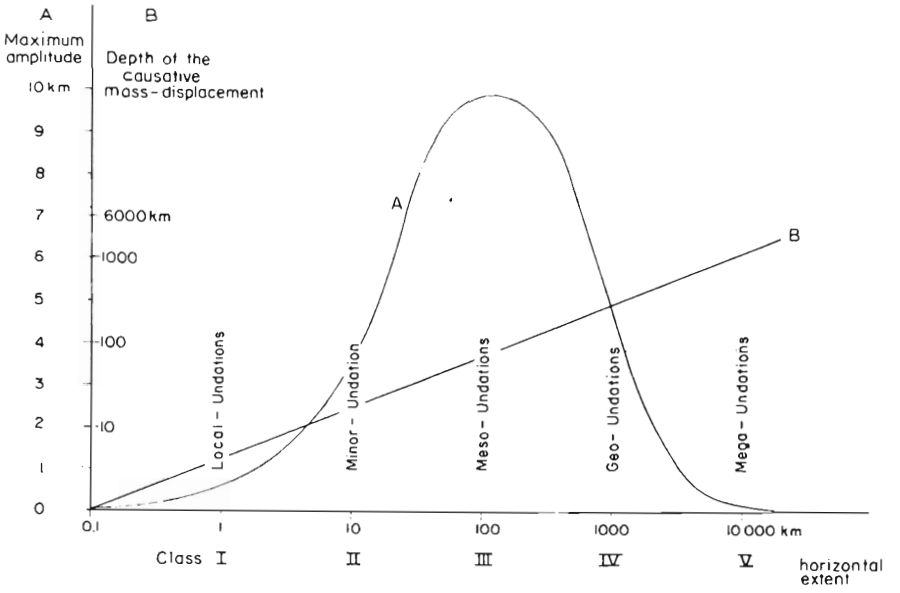


Figure 1. Relation between the diameter of the earth's undations and the depth of the causative mass displacements. After Van Bemmelen (1964 Fig. 2).

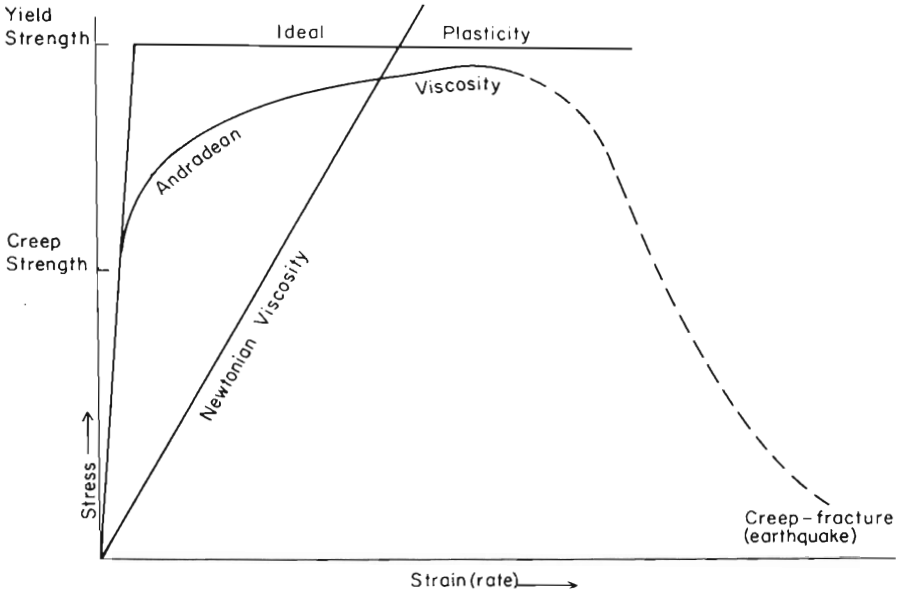


Figure 2. Possible stress-strain relations in the earth's mantle. After Orowan (1964, Figs. 1 and 5).

A general decollement of the crust or tectonosphere (A-sphere) over the lubricating asthenosphere (B-sphere) will occur away from the crest of a mega-upwarp. Thus the lateral displacement of the frontal part of a drifting continental shield might be the cumulative effect of two types of movement:

(a) gliding movements of lamellae in the outer sphere down to depths of 300 or 400 kilometres,
(b) passive transport or active drag by an undercurrent, occurring between 600-700 (or between 500 and 1000) kilometres depth.

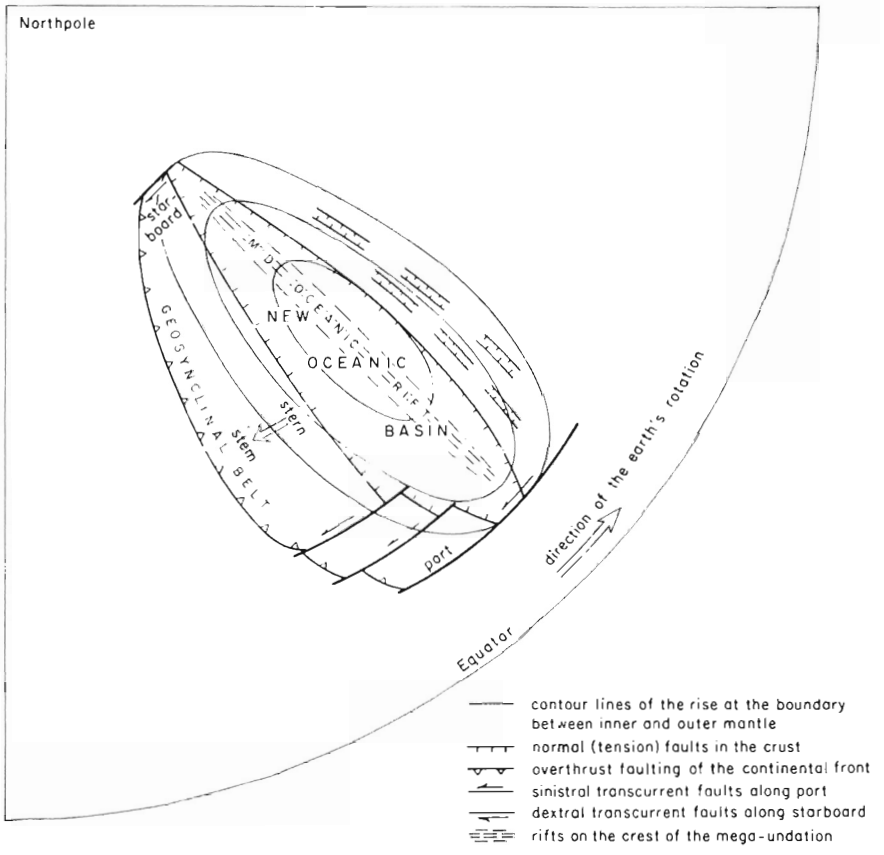
Between them is a gap in seismicity.

The lateral spreading of the top part of a mega-undation will tend to open up a new oceanic basin, which structurally is a window in which upper mantle is exposed. Isostatic balance is preserved, save for small negative gravity anomalies above the top part of the mega-undation and positive ones above its flank, because of the replacement of the outer spheres at the top by an ocean basin and because of the replacement of upper mantle at its base by material of higher density from the lower mantle. The amplitude of the mega-upwarp in the transitional zone between upper and lower mantle might be of the order of a hundred kilometres, whereas at the surface, the gravitational spreading of the upwarp may even result in a reduction of the actual height of the solid earth due to the formation of a new ocean basin.

The confining pressure in the rising part of the upper mantle is greatly reduced by the decollement of the overlying spheres so that an eutectic fraction of basalt magma will be segregated (Reay and Harris, 1964). This primary basalt magma of upper mantle origin, which probably has a tholeiitic composition in its contaminated state (Engel, Engel and Havens, 1965), has a lower specific density. It will rise through potential tension fissures forming dyke-swarms in the uppermost part of the mantle and in the crust. Finally, "flood basalts" will reach the surface.

These expectations are consistent with recent information on the buoyant bodies having low seismic velocity, underlying mid-ocean ridges (Talwani, Pichon and Ewing, 1965; Bott, 1965). These bodies are called "oceanic asthenoliths" by the author.

The mechanical model of gravity tectonics on a grand scale in the upper mantle (caused by buoyant matter in the lower mantle) will first result in tensional rifting of the overlying crust, which process may be accompanied by intrusion and extrusion of basaltic magma. When the upwarp continues it will cause a lateral spreading under gravity, affecting successively deeper levels, such as the crust or tectonosphere, the asthenosphere, and the upper levels of the sclerosphere.



Scheme of the relations between a mega-undation (primary tectogenesis) and the continental disruptions and drift (secondary tectogenesis, or gravity tectonics) North Atlantic type.

R.W. van Bemmelen (1965)

Figure 3. Scheme of the geodynamic relation between a rising mega-undation (primary tectogenesis) and the continental disruptions and drift of the overlying crust (secondary tectogenesis or gravity tectonics on a geotectonic scale) (North Atlantic type). After Van Bemmelen (1965, Fig. 5).

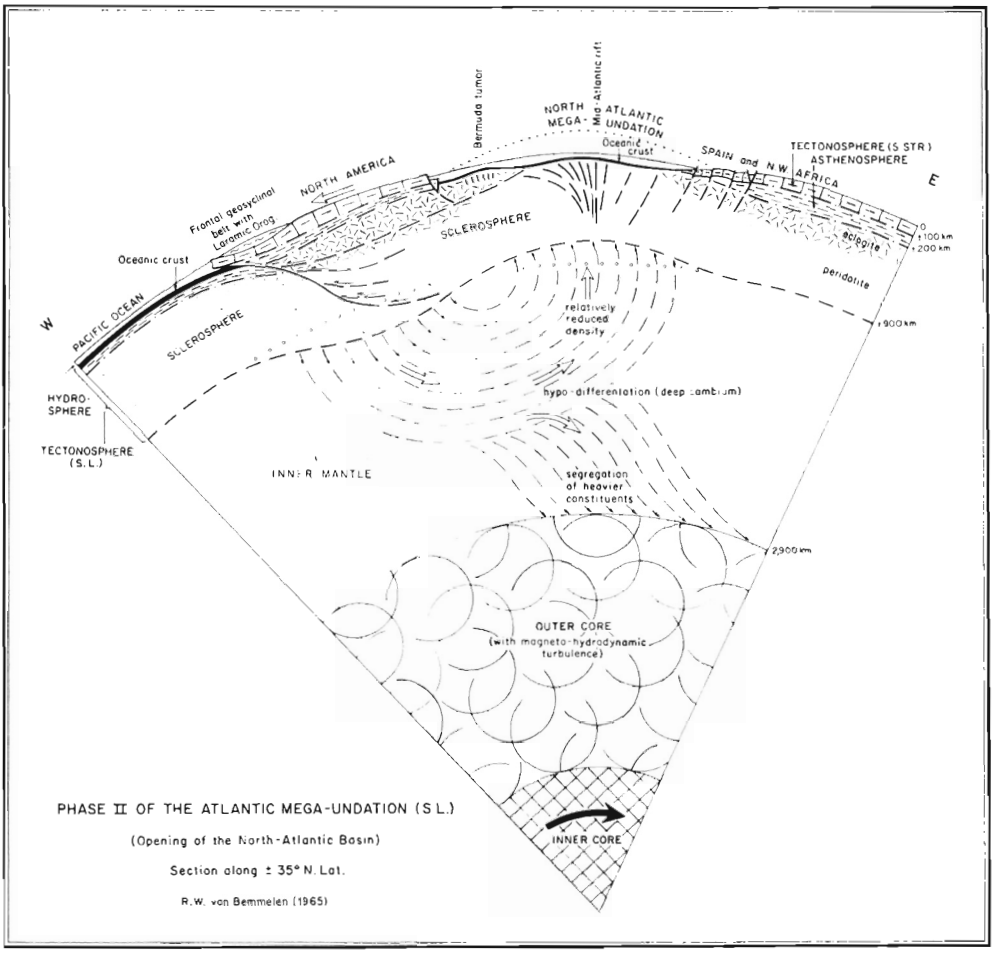


Figure 4. Scheme of the mass circuit accompanying a mega-undatory upwarp of the earth's surface (Atlantic type). The section is taken along latitude 35 °N. After Van Bemmelen (1964c, Fig. 4).

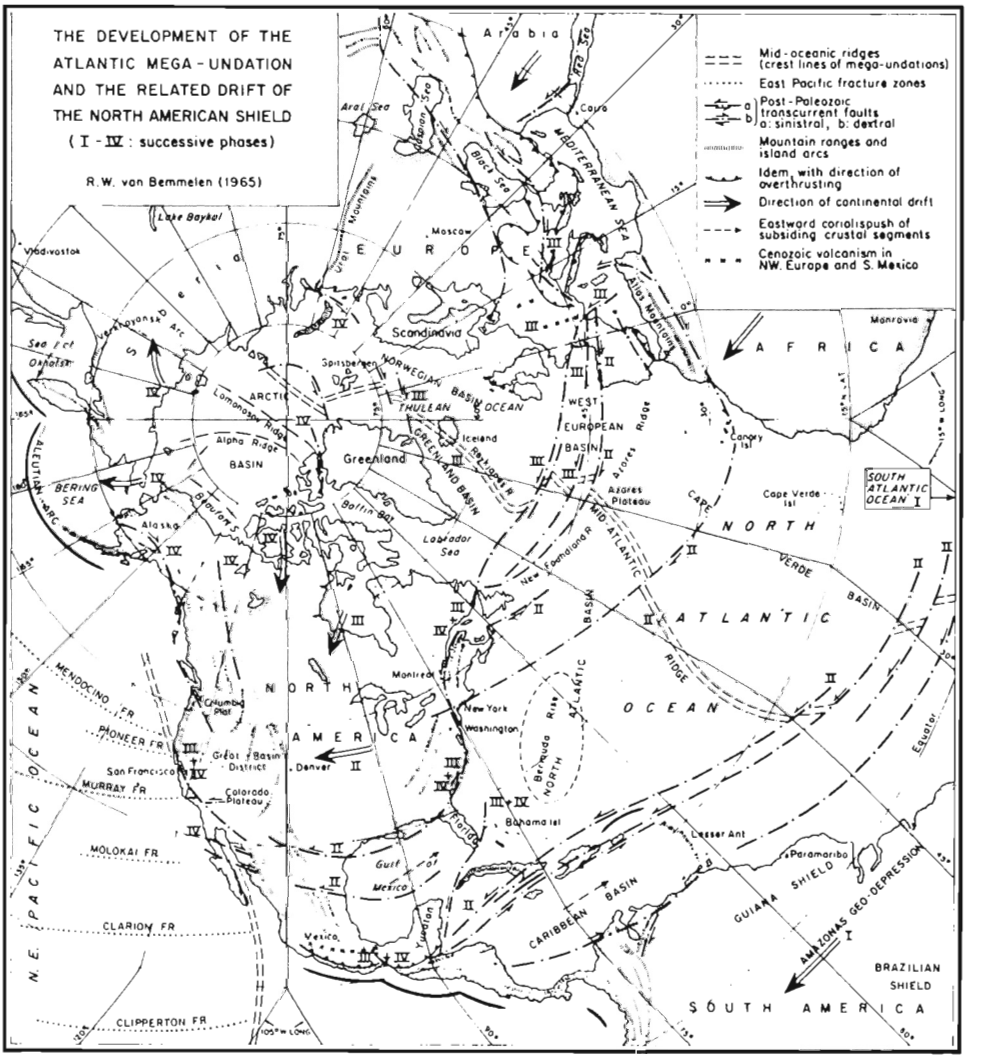


Figure 5. Geotectonic features of the northern part of the Atlantic mega-undation. After Van Bemmelen (1964c, Fig. 5).

At the frontal side (the stem) of the forward-sliding crustal shield, the floor of the ocean will be pushed down and overridden. This process will cause a deserpentinization of the oceanic layer. Because this is an endothermic process, terrestrial heatflow will be considerably reduced at that place. This prediction is conform with observations along the transition between Hondo and the Japan trench (Horai, Uyeda and Rikitake, 1964). The water vapours liberated by such a deserpentinization might produce ascending hydrothermal solutions, and they might cause the high explosivity-index of the circum-Pacific volcanism.

In the rear of the moving block of crustal shield, decollement of the crust might expose deeper strata of higher temperature. Thus at the east side of Japan this mechanism of flow, as suggested in Figure 8, would cause regional metamorphism of high pressure and low temperature. This expectation (prognosis) of the geomechanical model is confirmed by the recent study of Takeuchi and Uyeda (1965).

At the other places, the reduction of pressure by the decollement of the higher structural levels promotes the transition of high density to low density phases. The formation of the Bermuda tumour and the Argentine (Bromly) tumour might be explained in this way (Van Bemmelen, 1964b; see also Figs. 4, 5).

As mega-undations are probably caused by upwelling of matter in the lower mantle, their crests will occur completely independent from the structural configurations at the surface. They may occur entirely inside the boundaries of a primeval ocean (the Darwin Rise, recognized and described by Menard, 1964) or inside the boundaries of primeval continents (Gondwana and Laurasia). It is also possible that their crests are situated partly in the realm of a primeval ocean and partly in a continental realm, as is the case with the crest of East Pacific Rise between 28° and 40° N latitude.

The independence of the crest lines of the mega-undations from the surface structures is also indicated by the haphazard manner in which the rifting of the overlying crust occurred with respect to its older geotectonic trendlines.

It is to be expected that drifting movements of the cratonic shields are finally hampered and brought to a halt by other mega-upwarps of the geological surface. The northward drift of India is stopped by the Tibet-Mongolian mega-undation, the northeastward drift of Australia by the Darwin Rise, and the westward drift of North America by the East Pacific Rise (see Figs. 5, 6).

The crest of mega-undation is neither necessarily of uniform age nor in a fixed position. The crest lines of various mega-undations may

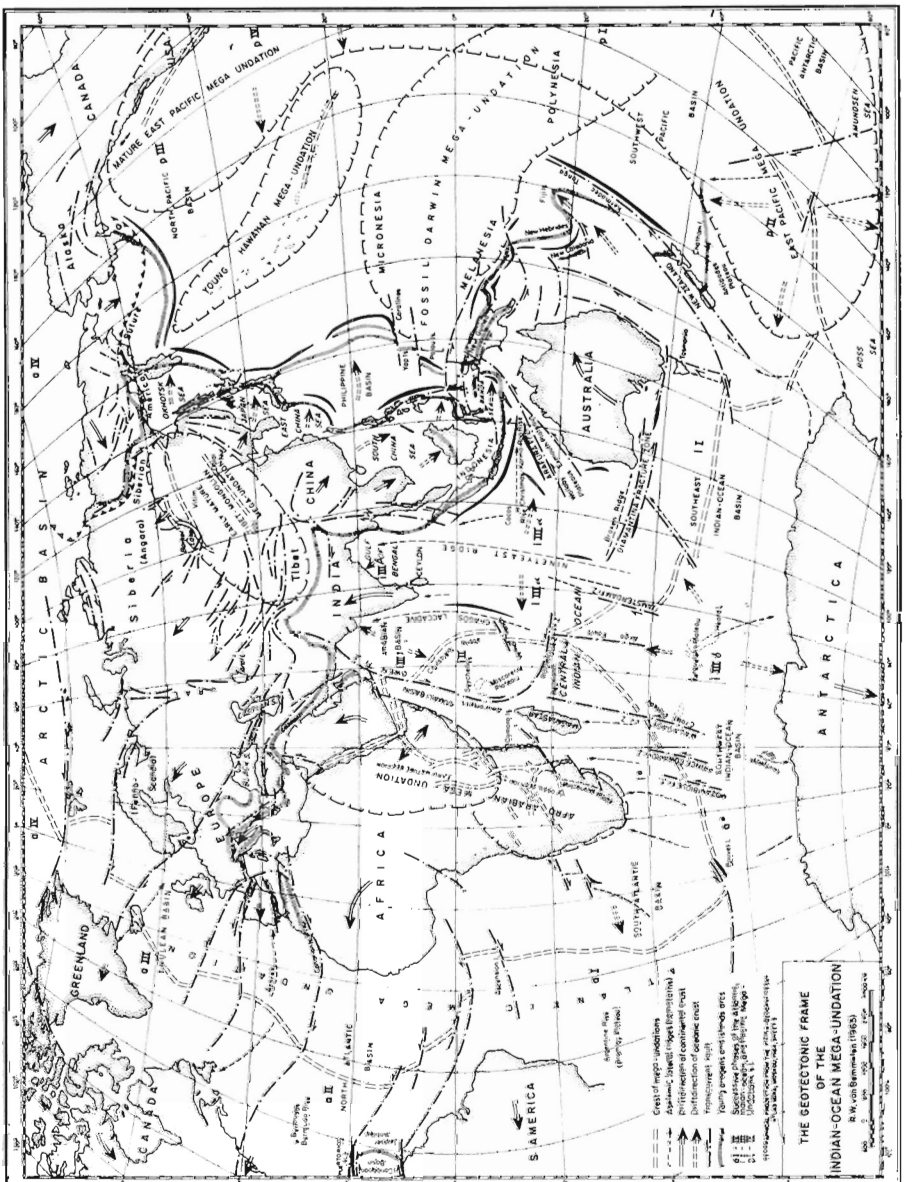


Figure 6. Geotectonic features of the Indian Ocean and the adjoining continents. After Van Bemmelen (1965, Fig. 6).

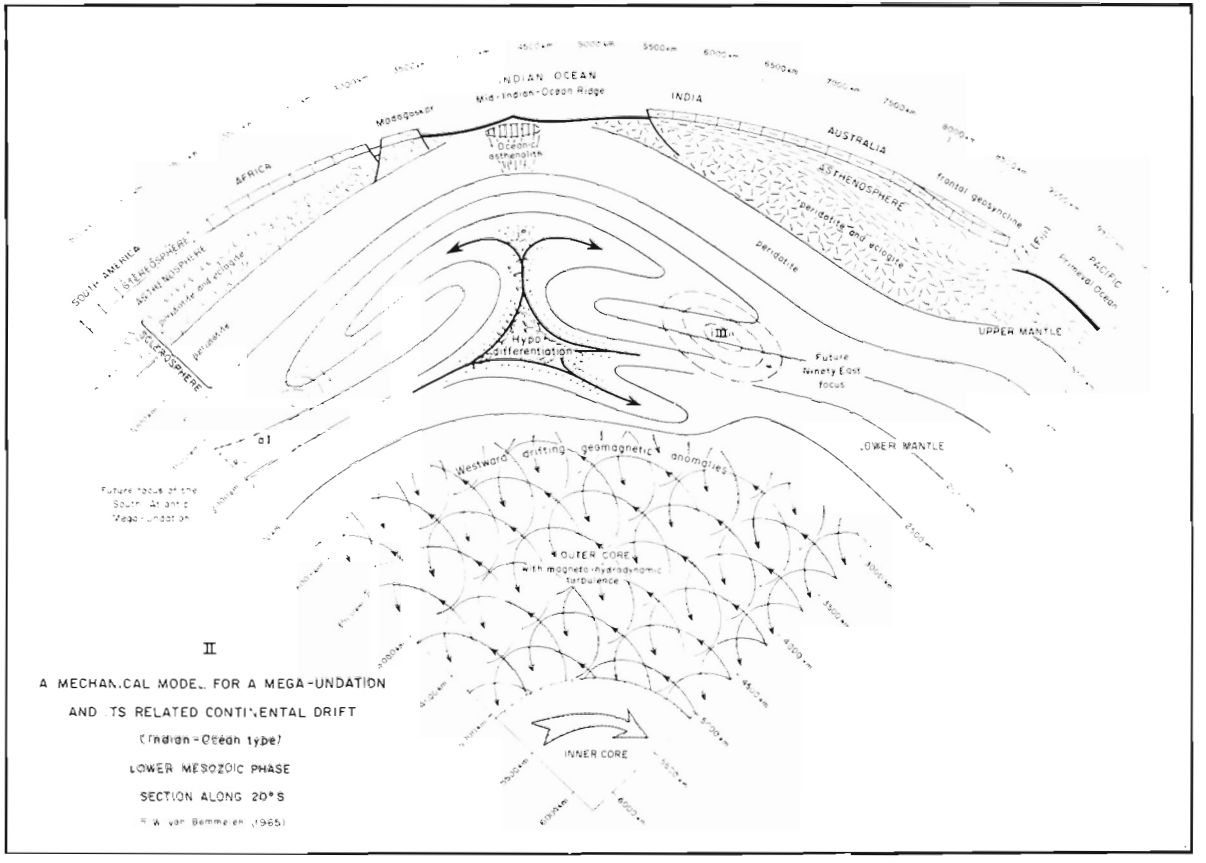


Figure 7. Section across the Indian Ocean mega-undation during its early-Mesozoic phase of evolution. After Van Bemmelen (1965, Fig. 3).

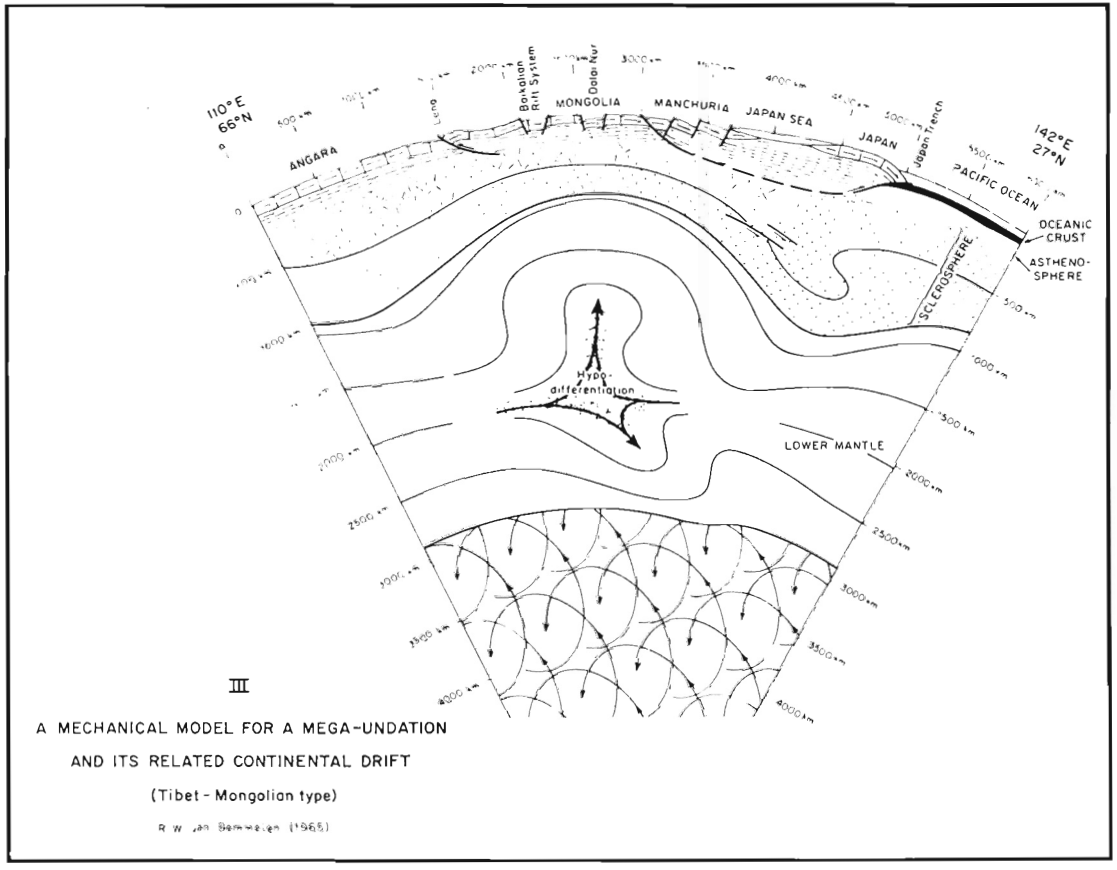


Figure 8. Section across the Tibet-Mongolian mega-undation at its present stage of evolution. After Van Bemmelen (1965, Fig. 4).

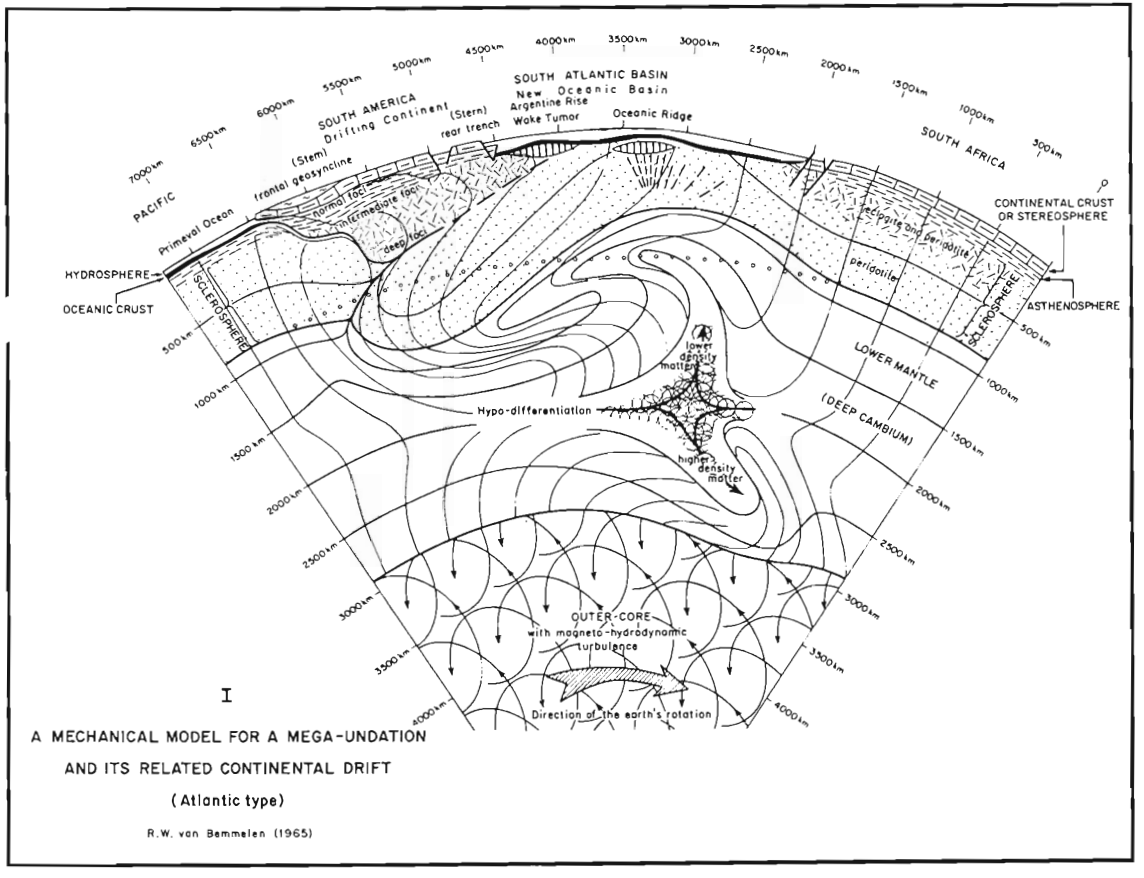


Figure 9. Section across the Atlantic mega-undation at its present stage of evolution. After Van Bemmelen (1965, Fig. 2).

coalesce into a group, such as the Atlantic Group, the Indian Ocean Group and the East Pacific Group (see Table II in Van Bemmelen, 1964d, p. 392).

Moreover, the summit of the crest may shift both along its length and sideways in the course of time (see Van Bemmelen, 1965). For instance the site of active volcanism shifted from east to west along the crest of the Young Hawaii mega-undation over a distance of 3000 km in the course of about 100 million years.

If the crest of the mega-uplift shifts sideways, the mid-oceanic rise (which has an oceanic asthenolith underneath and a rift-belt on top) will be subjected to younger shear faults. This later transcurrent shear, is characteristic of the rift belts in late maturity as in the East Pacific, Atlantic and Indian Oceans. The youthful Hawaii Rise is still free of them, as are the mega-undatory upwarps of early maturity in Afro-Arabia and northeast Asia.

The shifts of the crest lines can occur both gradually and in a jerky manner. If the shifting is gradual, a kind of wave motion with rolling hinges wanders over the earth's surface. This might cause a kind of "surf-riding" of crustal shields gliding on the advancing top part of the mega-undation. It is possible that the spectacular drift of the Indian Shield is an example of such a continental surf-riding. Palaeomagnetic, geotectonic and oceanographic data indicate that India moved in the Cenozoic from the southern to the northern hemisphere over a distance of more than 6000 km. The average speed was more than 10 cm per year (Van Hilten, 1962, p. 423). It left the straight "nematath" of the Ninety East Ridge for 6000 km long in its wake.

GEOTECTONIC EXPECTATIONS OF THE MODEL

In summary, it can be said that the geomechanical model for the development of mega-undations on the basis of gravity tectonics leads to many expectations (prognoses) that can be tested by geological observations (diagnostic facts).

The main prognoses are:

(1) Above the crest of a mega-undation occurring beneath a continental shield, the following successive stages of evolution are to be expected:

(a) rifting and the formation of tension grabens,
(b) extrusion of plateau basalts,
(c) opening of a new ocean basin,

(d) formation of a mid-oceanic rise at the top of an oceanic asthenolith with a rift structure at its crest.

(2) The continental crust, flowing or gliding laterally from the crest of the rising mega-undation in response to gravitational force, will be characterized by the following geotectonic features:

(a) compression and geosynclinal subsidence along its front (stem),
(b) extension phenomena at its rear (stern),
(c) dextral shear-movements along its "starboard" side,
(d) sinistral shear movements along "port" side.

(3) The shifting of crest lines in either longitudinal or lateral directions will be either gradual or jerky, and will give rise to complications and further developments of the structural patterns.

The successive development of the geological features, accompanying the growth and decline of mega-undations, permit the distinction of the four stages of evolution summarized in Table I.

TEST CASES

The expectations of the geomechanical model outlined above can be compared with the observations on the actual geotectonic features of the earth's surface and the geological study of their evolution in time. This has been done by the author for the evolution of the Atlantic and Indian Ocean Mega-Undations (Van Bemmelen, 1964c, 1965), and there appears to be good agreement in both cases. The result of this testing implies that the proposed geomechanical model probably conforms with the actual geodynamic evolution, and that this working hypothesis deserves further testing and elaboration on a quantitative basis.

A clear example of the opening of a new ocean basin is the Thulean Section of the Atlantic between Greenland and Northwest Europe. Westoll (1965) describes the first stages of rifting across the Laurasian Continent during the younger Palaeozoic (since Old Red time). When these geotectonic movements came to a halt during the Lower Mesozoic, a narrow sea basin comparable with the Red Sea had developed between Greenland and Northwest Europe, and great transcurrent faults had formed (e.g. the Great Glen Fault in Scotland, and the Cabot Fault in North America). During the lower Mesozoic, the Atlantic Ocean was probably still narrow. However, it was again subjected to rifting and widening, this time in relation to the development of the Atlantic mega-undation sensu lato from south to north (Van Bemmelen, 1964a; and Fig. 5). During its third phase, the Atlantic mega-undation invaded the area between Greenland and Northwest Europe.

Table I

Stages of Evolution of Mega-Undations

Stages of Diagnostic Evolution Geological Features	Youth	Early Maturity	Late Maturity	Fossil
Juvenile volcanism (Tholeiitic basalts)	Active	Declining	Almost extinct	- -
If occurring in continental realms	Beginning of extension phenomena	Well developed rifts and grabens. Narrow new oceanic engulfments	Wide new ocean basins	- -
		Strike-slip faults of the San Andreas type		
If occurring in oceanic realms	- -	Strike-slip faults of the Mendocino type		
Formation of geo-undatory mid-ocean rises	- -	Active	Declining	- -
Transcurrent faults across the mid-oceanic rift-zones	- -	- -	Active	- -
Transcurrent faults across the outer margins of the mega-undation. (Due to adjoining mega-undations.)	- -	- -	- -	Active
Type examples	Hawaiian Mega-undation	Afro-Arabian and Tibet-Mongolian Mega-undations	Atlantic Mega-undation	Darwin Mega-undation

Its NE-SW crestline cuts across the NNE-trending western boundary of the Caledonian System at a sharp angle, and during the subsequent widening of the Thulean Basin, the southern part of this boundary (situated to the east of the crestline) moved relatively eastward, giving the Moine thrust in Scotland, whereas the northern part moved relatively westward to the East coast of Greenland (see Wager and Hamilton, 1964). These parts are about 1800 km apart.

The northern end of the Moine section links onto the southern end of the Greenland section by seismic lateral ridges (nemataths) that unite with the median rift-belt in Iceland (Fig. 5).

Walker (1965) has estimated the dilation of Iceland in two ways. (1) The visible dilation in the active volcanic zones crossing Iceland, as evidenced by gaping cracks (gjár) and volcanic fissure eruptions, amounts to about 30 m in the last 5,000 to 10,000 years, or about 1/2 cm per year on the average. (2) The dilation caused by the emplacement of dykes of fluid basalt amounts to 200-400 km for a prism of lava 10 km thick with the present width of Iceland (500 km). This also would represent a dilation of about 1/2 cm per year on the average. The author's geomechanical model for the spreading of a mega-undation predicts that higher structural spheres will move faster than the lower ones. In the case of Iceland, the diagnostic facts seem to confirm the prognosis. The rate of movement of the continental crust (Greenland with respect to Scotland) amounts to 3 cm/yr on the average; whereas the spreading of Iceland, situated on the mid-ocean ridge where the upper mantle is probably rising to the surface, amounts to about 1/2 cm/year.

Northwest Europe, being situated at the eastern side of the Thulean section of the Atlantic mega-undation, was subjected to extension phenomena in an W-E to WNW-ESE direction since the Upper Mesozoic. The iron ores of Salzgitter, southeast of Hanover, are deposited in N-S trending Y-shaped extension of Upper Jurassic age (Post Dogger, Pre-Neocomian). The Gifhorn Graben and the East-Holstein Graben in Northern Germany also began to subside in late Mesozoic time. The Albian transgression of Great Britain and Northern Germany seems to be related to subsidence phenomena accompanying extension of the basement complex. Volcanic activity had already begun in Eocene time (e.g. the Schonen basalts of Sweden), and it was followed in Oligocene time by the development of the Thulean province of plateau basalts, extending from Eastern Greenland to the northwest coastal belt of Europe. In a later stage, volcanic activity was concentrated in the N-S row of igneous complexes in Scotland and in the zone of extension grabens extending from the Mediterranean along the Rhône Graben and the Central Massif of France to the Rhine graben in Germany and the Oslo Graben in Norway. The latter zone, which is known as the Mediterranean-Mjösen belt of faulting and rifting, has a N-S to NNE-SSW direction,

commonly referred to as the "Rhinean direction" by German geologists. It is conjugated with fault lines more or less at right angles to it (WNW-ESE) in what is called the "Hercynian direction". The Rhinean fault system is clearly a feature of crustal extension, and the Hercynian fault system, although also accompanied by differential vertical movements in the basement complex, is predominantly a system of transcurrent faulting. The diapiric rise of NNE-SSW trending "walls" of Zechstein Salt in northwest Germany was probably triggered off by tensional drifting in that direction of the basement complex and the base of the overlying sedimentary column. These walls are offset by sinistral transcurrent faults. The north-south Holstein Graben is offset in a left lateral direction with respect to the Gifhorn Graben. The latter is dislocated near Celle by dextral transcurrent movements in the basement along the Aller-lineament, which caused sigmoidal deformation in the structural trend lines of the overlying sedimentary cover. Even the NW-SE trending Peelhorst beneath the southern part of the Netherlands may be bounded by dextral transcurrent faults of Pliocene age (Ridder and Lensen, 1960).

The strike-slip faults in the Hercynian direction occurred more or less contemporaneously with the extension phenomena in Rhinean direction. The extension had different magnitudes in different sections, so that the crustal slices at right angles to the Rhinean direction were separated by both dextral and sinistral shear faults.

Still farther to the southeast, in the wake of extension phenomena in the Hercynian direction (i.e. in the Alpine System of Europe), are important northwest trending strike-slip faults formed during lower Cenozoic time (see e.g. Van Bemmelen and Meulenkamp, 1964; Van Bemmelen, 1964c, p. 414-415).

The Thulean Basin is bordered on the south by a great sinistral strike-slip fault system, which extends from Southern France to Labrador, and it is bordered to the north by a great dextral system of transcurrent faults which extends along Jan Mayen from the northern border of Scandinavia to Greenland (see Fig. 5). The Basin formed at the crest of a mega-undation that constitutes the third section of the Atlantic Mega-Undation sensu lato. It was developed since Upper Mesozoic time and is already in a stage of late maturity (see Table I).

The foregoing paragraphs contain a discussion of phenomena that have occurred at the top and in the wake of the Thulean Mega-Undation. A few words will now be said about the movements at its front. The present author (1964c) suggested that the drift direction of the North American Shield was counter-clockwise (first east to west, then from northeast to southwest, and finally even from north to south) due to its progressive encircling by the phases II, III and IV of the Atlantic mega-undation sensu

lato. The E-W drift was pre-Laramide in age, and was related to the spreading of the North Atlantic section (II). The NE-SW drift of the Laurentian shield was post-Laramide, and was related with the spreading of the Thulean section (III). According to this geomechanical model, we might expect at the southwest side of the Laurentian shield to show a conjugated pattern of shear faults, sinistral E-W offsets and dextral N-S offsets. Diagnostic observations seems to confirm this prognosis. In a recent analysis of the transcurrent faulting in the northern Rocky Mountains, Smith (1965) concluded that the post-Laramide WNW-ESE trending Lewis and Clark lineaments in western Montana and northern Idaho show important sinistral shear movements. On the other hand, the NNW-SSE Rocky Mountain lineaments show dextral transcurrent movements (St. Amand, 1957, Carey, 1958). The E-W trending Osburn system of dextral transcurrent faults in the Coeur d' Alene district of western Idaho, described by Wallace and others (1960), seems to be mechanically contradictory to the Lewis and Clark lineaments. However, Smith (1965) proposes that the Osburn fault originally had a more northerly direction, parallel to the Rocky Mountain lineaments (like the NNW-SSE Hope fault with its dextral shear), but because of progressive left-lateral transcurrent movements along the Lewis and Clark lineaments, rotated counter-clockwise and came in line with the system of left-lateral mega-shears.

The principle of chronological succession has been stressed by the present author in his explanation of the geotectonic features of the Atlantic Mega-Undation sensu lato (Van Bemmelen, 1964c). Only in this way can the geotectonic evolution of the Thulean Mega-Undation be understood mechanically.

CONCLUSION

The model of the structural evolution of the earth's crust and the ocean basins, as outlined in this paper, is based on the concept of generalized gravity tectonics. The geodynamic model of mega-undations explains many geotectonical and geophysical data from a unified point of view. The correspondence between the deductions from this model (such as the expectations about continental drift and the accompanying geotectonic phenomena, and the opening up of new ocean basins) and geonomic observations, shows that this working hypothesis is a valid base for further research in the field of large scale geodynamic processes.

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EQUATORIAL SHEAR ZONE

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Abstract

The hypothesis is presented that a shear zone encircles the earth at the equator. This shear zone is considered to be generated by the westward drift of South America relative to Africa, and by the westward movement of northern Australasia by 2800 km relative to southern Australasia. The shear zone is bounded by two great circles oriented 12 degrees apart. One of the great circles is the equator; the other intersects the equator at 150°W long. and 30° E long., and is most distant from it at the Australasian and Caribbean island arcs.

In Africa, the shear zone is shown by east-west trends consisting of coastal faults, gravity anomalies, changes in lithology, earthquakes, volcanoes, faults, and discontinuous shear zones developed in Precambrian and Cretaceous (or later) rocks. Three possible paths for the shear zone exist in eastern Africa. In the equatorial Atlantic, the shear zones are manifest in east-west fracture zones between 0° and 13° N lat. In South and Central America, they are evidenced by sedimentary basins along the east coast, and by subsurface features in the Amazon basin, an equatorial break in the Andes Mountains, a Cretaceous basin in the Guiana Precambrian shield, wrench faults in northern Venezuela, and the lineament marked by the Puerto Rico Trench and Cayman Trough. Several fracture zones delineate the equatorial shear zone in the eastern Pacific. In the western Pacific, a left-lateral shear zone trends from the Vitiaz Trench, through the Solomon Islands, and through New Guinea to Celebes. The equatorial shear zone is almost nonexistent in the Indian Ocean.

No other great circle band presents such a large percentage of consistent linear shear zones and structural trends.

The simplest model (Model I) for explaining the equatorial shear zone is a 2800 km left-lateral displacement of the northern hemisphere relative to the southern hemisphere. However, this is rejected because of contradictory geologic, geometric, time and dynamic relationships. The accepted model (Model II) requires continental drift, relative hemispheric displacement, and a mechanism such as mantle convection currents to maintain oceanic rises in the centres of the ocean basins. Model II is further

used to explain the development of the Indian Ocean, the Caribbean region, and the oceanic rises, including the Darwin Rise.

On the basis of geological evidence, the shear zone is considered to have developed during Cretaceous (perhaps Late Cretaceous) time. The shear zone inclined at 12 degrees to the equator may be a former equator. If so, it places north axial pole during the Cretaceous at 78°N lat., 120°E long., a position compatible with palaeomagnetic data.

INTRODUCTION

Although the geology of the equatorial regions of the earth is complex and land field work in tropical regions is extremely difficult, parts of the tropics have become geologically well known. In recent years, oceanographic surveys of the sea floor have been widely extended, and when these surveys are compared to the land geology, a zone of deformation encircling the earth at the equator is revealed which displays continuity in regard to time, structural trends, and overall tectonics. This paper presents the evidence for such an equatorial shear zone (Fig. 1), discusses geologic models for its origin, and relates the zone to polar movement. The reader may prefer to read the discussion first and then judge the models in light of the listed evidence.

The hypothesis was initially formulated during the analysis of a survey made by the cable ship RECORDER (Cable and Wireless Ltd., London) in connection with submarine telephone cables in the Western Pacific. It has since been tested on surveys with the research vessel TRIDENT of the University of Rhode Island. The study was largely supported at the University of Rhode Island through the Office of Naval Research, Contract Nonr 396(08). Reproduction of the material contained in this report in whole or in part is permitted for any purpose of the United States Government. Constructive criticism of this paper has been given by H.W. Menard and M.E. Stern.

ASSUMPTIONS

Two assumptions are generally made in the interpretation of oceanographic data.

Assumption 1: Bathymetric features on the sea floor are geological structures that can be identified on the basis of their topographic forms. The justification for this assumption is that it has been confirmed in many instances by geophysical investigations and geologic sampling of the sea floor (e.g. Menard, 1964; Hill, 1963).

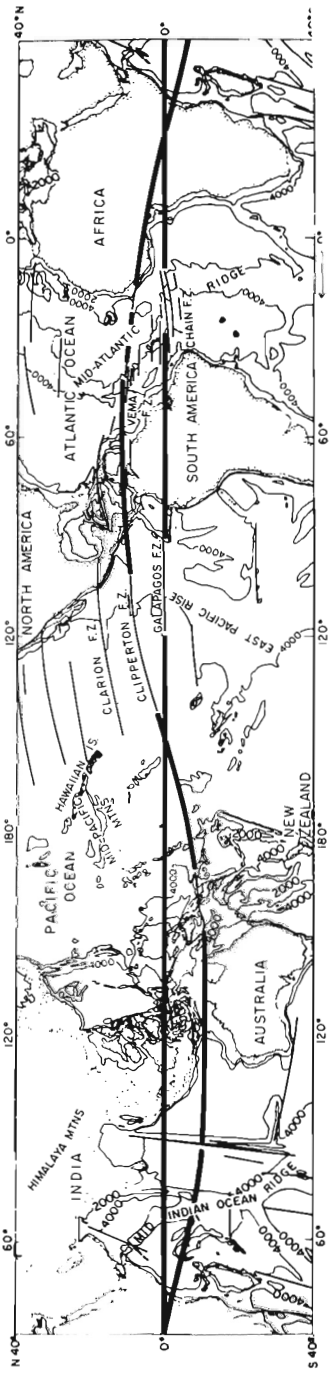


Figure 1. Equatorial shear zone. The limits of the equatorial shear zone are shown as well as fracture zones and major faults, some of which are related to the shear zone.

Assumption 2: Once formed, bathymetric features persist. Although land features are, in terms of geologic time, rapidly modified or removed by erosion, the erosive agents affecting the sea floor are minor, and topographic features are only removed through tectonic destruction or burial by sediment or lava. Even buried features may be found through geophysical means (e.g. Ewing, Ewing and Talwani, 1964; Talwani, LePichon and Ewing, 1966). Hamilton's (1956) discovery of Cretaceous corals on the Mid-Pacific Mountains is an example of the validity of the assumption.

EVIDENCE FOR AN EQUATORIAL SHEAR ZONE

Atlantic Ocean

The Mid-Atlantic Ridge near the equator appears to be displaced en echelon by a number of east-west trending, left-lateral fracture zones (Heezen and Tharp, 1961; Heezen, Tharp and Gerard, 1961; Heezen, Gerard and Tharp, 1964; Heezen, Bunce, Hershey and Tharp, 1964; Krause, 1964). The central rift is seemingly displaced by the same amounts as the topography, and the estimated total offset, which is largely confined between the equator and 13°-14° N lat., is about 2800 km (Fig. 2).

Krause (1964) has shown that a related fracture, the left-lateral Guinea fracture zone, intersects the coast of West Africa, and the Barracuda fault zone off Guadeloupe in the Antilles (Hess, 1955a; Krause, 1964) is a long straight fault that is possibly of the same type.

Beginning at the Guinea fault zone, the coast of Africa takes a long bend to the east until it resumes its southward trend at the Cameroons. This long bend has the same length as the apparent separation of the Mid-Atlantic Ridge (i.e. 2800 km).

The Bend of West Africa

The Guinea fracture zone is marked by a sharp, 230 km bend in the topographic trend of the West African shelf and slope (Krause, 1964). The northernmost effect of the zone may be the volcanic Cape Verde Islands, but no identifiable east-west trending structure has been observed there. The geology of Sierra Leone along the landward extrapolation of the Guinea fracture zone shows that the zone does not continue directly eastward. (This accords with the absence of displacement along the landward extensions of other oceanic fracture zones.) The only significant east-west structures in Sierra Leone are minor offsets or shears, mostly with right-lateral displacement, in a north-south zone of Precambrian serpentine (Wilson and Marmo, 1958; Anonymous, 1960; Marmo, 1962).

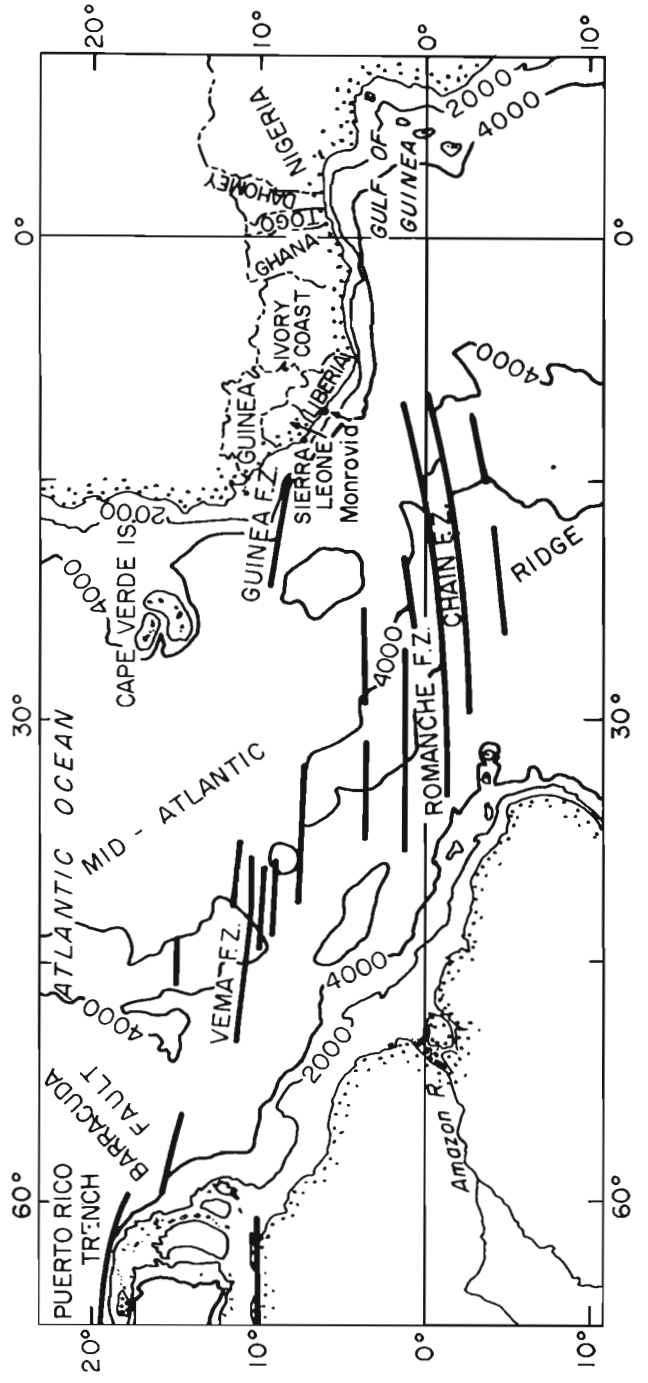


Figure 2. Locations and fracture zones in and around the equatorial Atlantic Ocean.

It is improbable that more than a small branch of the fracture zone swings north through Guinea. The terrain there is poorly mapped, but the only northeast structures are a shallow Palaeozoic depression (Furon, 1963) and a Palaeozoic fold belt (Sougy, 1962).

The main segment of the fracture zone seems to swing to the southeast, parallel to the shore, thus bypassing the serpentine bodies. A magnetic anomaly trending N 36° W from Lake Mape near the Liberian border on the southern coast of Sierra Leone can be interpreted as a fault with downthrow to the southeast (Pollett, 1960), although oil well drilling does not show this downthrow to be large (Pollett, 1964).

Pollett (1960, p. 9) points out that the "straightness of the Liberian coast from Sino to Monrovia and the comparative closeness of deep water to the shore might be ascribed to a fault striking at about 130° [S50°E]. Such coastal faults, though with quite different strikes, are known to exist in Ghana and the Ivory Coast. Intrusions of gabbro and diabase or dolerite older than the Cenozoic sediments and forming conspicuous hills at Robertsport and Monrovia and possibly causing the Krim-Kpaka anomaly [an anomaly striking S 42° E in southeastern Sierra Leone near the Lake Mape anomaly] are not inconsistent with a tectonic origin for the Sino-Monrovia coastline especially as a production of its direction northwest of the Liberian frontier passes near the assumed centre of the Colony gabbroid complex. Faulted coastlines in Eritrea, the Yemen and Madagascar are associated with large expanses of effusives which must have intrusive roots in depth" (present author's words in brackets). He considers that the gabbroid complex may result from an intersection of the postulated Sino-Monrovia fault and a fault zone trending S 20° E. Krause (1963), on the other hand, suggested that the complex was derived from an asteroid impact.

In the Precambrian metamorphic Kasila series, three trends occur: a gneiss strike at S 10° E; a joint strike at N 70° E; and dolerite dyke strike at S 60° E (Pollett, 1959). The dykes which are narrow, are post-metamorphic and correlate in direction with the equatorial shear.

Dolerite dykes also occur in eastern central Sierra Leone (11° N, 8°40'W). Their trends there are generally about S 75° E, although at least one local zone trends almost north-south (Grantham and Allen, 1960, Pollett, 1962). Kimberlite dykes, probably of Cretaceous age, trend N 60° E; they cut the dolerite dykes and are therefore younger.

The geology of much of western equatorial Africa is very poorly known. An exception is a strip extending from the coast to the north-east corner of Liberia that was mapped by the LAMCO Corporation for the Government of Liberia (J. Offerberg and J. Tremaine, 1961, unpublished ms., Liberian Government, Monrovia). The survey revealed a prevasive

shear pattern in the Precambrian rocks parallel to, and near, the coast. Offerberg and Tremaine (p. 22) say, "The Precambrian rocks of Liberia, for the most part, conform to a system of West African Strikes trending northeast-southwest as opposed to a counter northwest-southeast system, which prevails in Sierra Leone and parts of Guinea. . . Nearer the coast, where the Liberian trend becomes more westerly, it appears to blend slightly with that of Sierra Leone." Crushed zones (of unknown age) are common, and east-west diabase dykes abound. The coast line is a fault line.

The above features indicate a wide zone of shear extending inland from the coast.

The countries bordering the Gulf of Guinea (Ivory Coast, Ghana, Togo, Dahomey, and Nigeria) show a similar geologic history – in fact, it is a history more or less typical of Africa. The following summary is from Furon (1963). The Precambrian was overlain in some places by thin Palaeozoic sediments, and after a long hiatus, the "continental intercalaire" was deposited during a period ranging from Late or post-Jurassic to Cenomanian (Cretaceous). The great Cretaceous marine transgression of Africa began during the Albian, and this is the basis for Furon's (p. 49) statement, "The modern Atlantic Ocean and the west coast of Africa were formed in the Cretaceous." Thick Cretaceous deposits were laid down in several coast basins along the Gulf of Guinea, and in the Ivory Coast, according to Furon,there was a major collapse parallel to the coast along which the basement was depressed to 3 km. Movement on the latter structure continued into the Quaternary. The structure extends eastward along the Ghanan coast, and Furon (p. 233) says that a ". . . study of earthquakes confirms that a fault borders the coast and explains the unforeseen thickness [1.3 km] of the Mesozoic and Tertiary sediments". Thick Cretaceous and Eocene sediments (up to 1.8 km) form the coasts of Togo and Dahomey, where seismic prospecting has revealed a very sharp flexure of the margins of the Precambrian basement. These deposits also extend along the coast of Nigeria, and Cretaceous sediments overlie the Precambrian basement along the coast of Cameroon and Rio Muni. Toward the end of the Cretaceous, there was a period of diastrophism marked by faulting, uplifts and depressions. The Cameroon trough extends northeasterly from the Gulf of Guinea towards Chad and is bordered by large faults whose throw reaches one kilometre. Several large volcanoes are associated with the trough, the volcanic activity continuing from Upper Cretaceous to modern times. The trough extends inland for at least 280 km. Furon questionably attributes the Tibesti volcanics to the same trend although they are 2000 km to the north-northeast. On the other hand, the volcanic islands of the Gulf of Guinea (Fernando Pó to Annobon) are certainly of the same group; they trend southwest for 700 km. The boundaries of the West African Precambrian bodies show no simple relationship to the coast line, suggesting that they have been broken off at the coast (Furon, 1958, 1963).

Central Africa

The Congo basin represents an enigma in the present hypothesis. The stratigraphy of the basin, again according to Furon (1963), is as follows. A Precambrian basement is overlain by "Terminal Precambrian" deposits. South of the equator, these are overlain by Karroo sediments (Upper Carboniferous-Permian), which have in turn been covered by Jurassic, Cretaceous and Cenozoic deposits. The Precambrian is buried in the centre of the Congo basin by as much as 3500 m of younger sediment.

At first glance, the Congo basin shows little evidence for the existence of an equatorial shear zone (cf. ASGA-UNESCO, 1963). However, a closer look leaves room for some possibility. Furon (p. 282) says "It is very difficult to correlate the Precambrian rocks of Katanga with those of the western Congo and to follow the described formations on the ground as one travels around the Congo basin." On the other hand, he notes (though apparently with some question in his mind) that Cahen and Lepersonne (1956) were able to establish satisfactory correlations.

The oldest Mesozoic beds dated in the Congo basin are Upper Jurassic (Kimmeridgen). Haughton (1963) points out that the eastern Congo basin is rimmed by lower Lukaga (younger Karroo) series between 2° N and 10° S lat.

The Karroo (Permo-Carboniferous) changes in character in a north-south direction, but an argument for continuity exists between 1° S and 5° S lat. (ASGA-UNESCO, 1963). However the older beds (Walikale beds) are more or less confined to a small part of Kivu (Furon, 1963) and hence may represent deposition unrelated to the younger Karroo (Lukaga) beds. The Karroo sediments are cut off on the south by a northwest trending structure (ASGA-UNESCO, 1963).

The presence of Upper Precambrian sediments on the east side of the western Rift Valleys constitutes strong evidence against a wide shear zone of large horizontal displacement between 1° S-6° S lat. The Upper Precambrian was very extensive at one time and almost flat lying. At 1° S lat., east of the Congo basin, the Precambrian basement changes in type and age in an irregular way (ASGA-UNESCO, 1963). New evidence for east-west shear in Africa (Krause, 1964; de Swardt, Garrard and Simpson, 1965) complicates the older hypothesis of north-south trending, or northwest- and northeast-trending structures.

Three alternative routes for the equatorial shear zone exist through Central Africa (Fig. 3): (1) the simplest one, along the equator, (2) one to the south, and (3) one to the north. The following is the evidence for the equatorial path:

1. The only east-west band of earthquakes in Central Africa occurs near the equator (1°S-2 1/2°S lat.) west of the West Rift Valley at Lake Kivu and extends 450 kilometres west to the Congo River (De Bremaecker, 1959).

2. The only east-west trending belt of African volcanoes, the Kivu volcanoes, lies along the same earthquake belt to some distance west of Lake Kivu.

3. The high volcanic cones of Mt. Kenya and Mt. Kilimanjaro lie on the north and south boundary, respectively, of the proposed shear zone. Note that all three of these features are of Pliocene to Recent in age. Nonvolcanic Mt. Ruwenzori, and Lake Victoria lie within the equatorial shear zone.

4. An east-west trending, narrow band of infaulted Karroo occurs at the equator in northern Lake Victoria at Entebbe (Anonymous, 1962). Precambrian structures also trend east-west.

5. The geologic structure underlying northwestern Lake Victoria (at 0°20'S lat.) trends east-west.

6. Various geologic maps of Central Africa show many discontinuous east-west structural trends.

7. The southern limit of late Tertiary-Recent mafic volcanoes that extend from Ethiopia to Tanzania ends sharply at Mt. Kilimanjaro.

The possible southern path for the equatorial shear zone extends approximately from Camaroon on the Atlantic Coast to the north end of Lake Nyasa. There is the following evidence of its existence:

1. A shear zone of large magnitude trends southeasterly between Lake Tanganyika and Lake Nyasa (Sutton and Watson, 1959, and other geological maps). Sutton and Watson attribute this to Precambrian deformation, but mainly because the rocks are of Precambrian age (they belong to the Ubendian system). The shear must have occurred before the emplacement of the Songwe scarp carbonatite (Brown, 1964), which is approximately 100 million years of age. This body is situated just northwest of Lake Nyasa. The maps show that this trend continues east of Lake Nyasa. In central Tanzania near 7°40'S, 35°45'E, Whittingham (1961, p. 35) points out "There is a broad belt of cataclastic rocks (mica-schists and granulites, sometimes ferruginous) running due east from

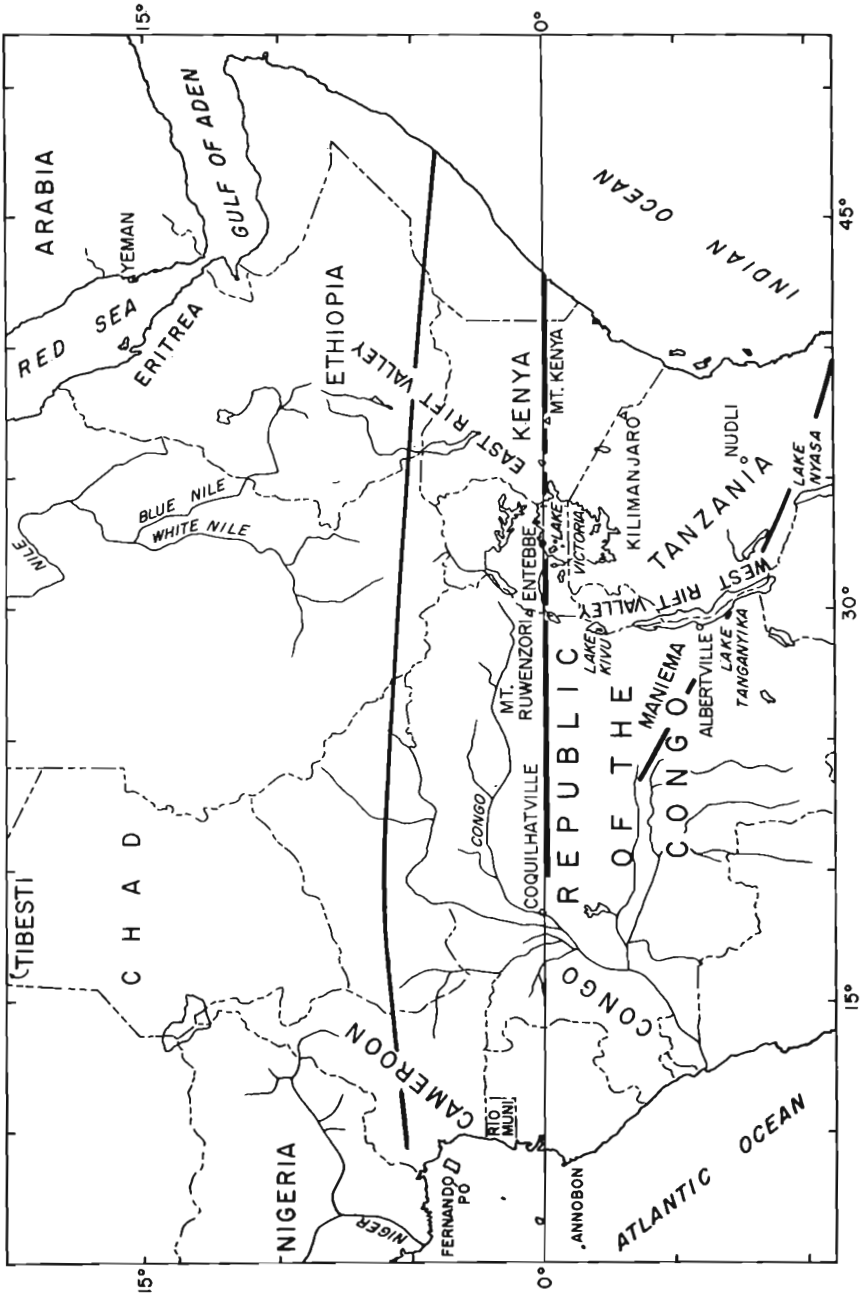


Figure 3. Diagram of Central Africa showing possible (northern, equatorial proper, and southern) paths of the equatorial shear zone. The actual zone would be much wider than the widths of the lines indicating the paths.

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Nduli." He believes the zone originated in late Precambrian time and underwent renewed movement in Neogene time. On the west side of Lake Tanganyika, the Ubendian system is called the Ruzizi group, and the structures bend to the west in Maniema (eastern Congo) (Haughton, 1963).

2. A very pronounced left-lateral, east-west shear zone occurs at 15°S, just south of Lake Nyasa. De Swardt and others (1965) attribute the zone to Precambrian deformation, but also describe later movements.

3. A gravity high occurs within the Congo basin between Coquilhatville, western Congo (0° lat., 18° E), and trends southeasterly to 3°S, 23° E along the Ubengian-Ruzizi trend (Anonymous, 1959b). Other east-west trends also exist.

4. At 6°S, 35 1/2° E in Tanzania, the Precambrian rocks display a west-northwesterly trend, the Dodoman trend (Haughton, 1963).

5. Southwest of Albertville, the Precambrian Muhila Formation has an east-west trend (Haughton, 1963).

There is no evidence that these shear zones and trends correspond in age to the equatorial shear zone, but the evidence that the main movements were Precambrian in age is not compelling either. Much evidence exists that Precambrian structures have guided later movements (Furon, 1963, Brown, 1964) so that any one shear zone may have movements of many ages.

An examination of the geologic maps of Central Africa (maps available in the library of the Yale Geology Department) revealed many more east-west and northwest trends. These trends are sufficiently common to be important but sufficiently discontinuous to be enigmatic.

The following is the evidence for the northern route (this path passes aprroximately along 5°N lat.):

1. It marks the northern limit of African carbonatites (cf. ASGA-UNESCO, 1963).

2. If the equatorial shear zone is of Bajocian-Bathonian age (i.e. Mid-Jurassic) or earlier, the shear zone is entirely developed in Precambrian rocks. The geologic map of Africa (ASGA-UNESCO, 1963) and the tectonic map of Africa (Furon, 1958)

show enough structure in this region to suggest considerable structural complexity.

3. Wilson's (1963) reconstruction of Gondwanaland requires that the equator pass approximately through this northern zone sometime after the breakup of the hypothetical pre-Mesozoic proto-continent.

A strip of Karroo and Jurassic beds in tectonic troughs along the Indian Ocean coast of Kenya and Tanzania limits any horizontal displacement along the equatorial shear zone in that region to a point either 2 1/2° S lat. or much further south.

Certainly the existence of a through-going shear zone is not obvious, but secondary movements may have confused the structure (e.g. movements along such features as the rift valleys of Central Africa and the northeast-trending structures of southwestern Africa).

South and Central America

The equatorial shear zone is at one of its two widest parts where it cuts through the Americas (Fig. 1). In this region, it can be divided into two belts (Fig. 4): 0°-12° N lat. and 12°-25° N lat. The former belt, which is the equatorial shear zone proper, is confined to South America. The latter comprises the Caribbean Sea and Central America, and although it is related to the equatorial zone, it also has more or less independent history of its own.

I. The Zone from 0°-12° N lat. The southern boundary of the equatorial zone lies beneath the Amazon basin, a few degrees south of the equator (3-4° S), but can be identified across the entire breadth of South America. It is evidenced by these features:

(a) The structural depression of the Amazon River between the Guianan Precambrian shield and the Brazilian Precambrian shield. The depression is rimmed by outcropping Palaeozoic rocks (Stose, 1950), but the structure under the river seems to be different.

(b) An apparent offset in the eastern continental slope as revealed by east-west topographic trends. These trends appear to mark the extension of the Chain and Romanche fracture zones (Heezen, Bunce, Hershey, and Tharp, 1964).

(c) The São Luís and Barreirinhas sedimentary basins (Mesner and Wooldridge, 1964), which lie east of the Amazon River

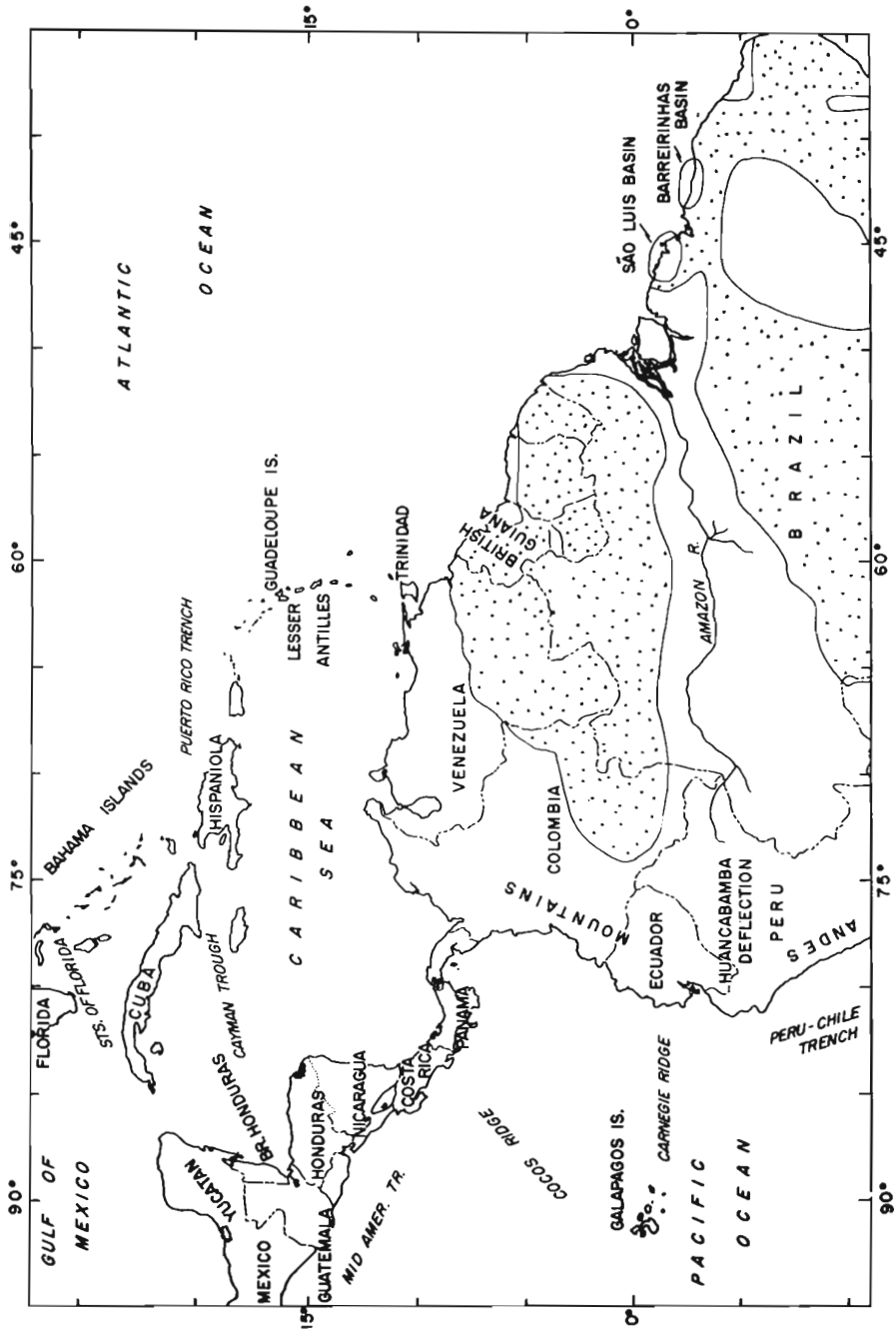


Figure 4. Locations of the equatorial shear zone in South America and the Caribbean region. Precambrian shields are stippled.

mouth at the Brazilian coast. These basins trend east-west, and are faulted and separated from the ocean basin by a ridge buried under the continental shelf. They were initiated by faulting and sedimentation in the Lower Cretaceous.

(d) East-west trending diabase intrusions in the upper and middle Amazon basin (Mesner and Wooldridge, 1964). Mesner and Wooldridge give palaeogeographic maps showing that the Amazon basin was already in existence, and therefore a zone of weakness, as early as Middle Devonian time. However, the stratigraphic sections reported by these authors show that the pre-Triassic sediments of the Amazon resemble those of other Brazilian basins, while the post-Jurassic sediments show considerable change.

(e) Major east-west fault trends in northwest Peru (Ham and Herrera 1963, p. 50). These are parallel to the axis of the Huancabamba deflection which is the major break in the Andean system at 6° S lat. The Huancabamba deflection existed as a marine strait in early Cretaceous time. Permian deposits are not known north of the deflection in Ecuador. A major change in trend of the Subandean fault zone along the east side of the Andes occurs at the Huancabamba deflection, and the continuity of the fault zone through the deflection has not been proved (Ham and Herrera, 1963).

(f) The east-west trending Carnegie ridge (Shumway, 1954), which lies off the west coast of Ecuador just north of the westward projection of the Huancabamba deflection. The ridge causes a constriction in the Peru-Chile trench, marking the northern end of the trench. If the Peru-Chile trench is associated with right lateral faulting as has been suggested (St. Amand and Allen, 1960; Benioff, 1962), then the Carnegie ridge is a continuation of the Huancabamba deflection. The southern boundary of the equatorial shear zone would be the southern edge of the Carnegie ridge. The Galapagos Islands are situated on the western end of the ridge.

(g) The east-west trending Galapagos fracture zone (Menard, 1964). This is situated west of the Galapagos Islands directly at the equator.

The existence of an equatorial shear zone within the Guianan shield (about 4° N lat.) has been demonstrated in British Guiana by McConnell, Williams, Cannon and Snelling (1964), who say (p. 115), the "northern and southern provinces are separated just north of latitude 4° N by

an east-west rift valley about 100 miles long and 30 miles wide which magnetometer observations suggest may contain up to 20,000 feet of (?) Cretaceous-Tertiary sediments." The continental slope east of the shield also trends east-west.

The east-west faults, ridges and basins in northern Venezuela have been extensively studied (e.g. Rod, 1956). Large, east-west trending wrench faults are present and generally have right-lateral displacement.

II. The Zone from 12°-25° N lat. The Caribbean structure is developed at approximately the widest portion of the shear zone. The projection of the Guinea fracture zone-Vema fracture zone-Barracuda fault into the northern Antilles, indicates that the Antillean structure and the equatorial structure are tectonically related. The author would project the northern limit of the Atlantic faulting into the Puerto Rico Trench and into the Cayman Trough. Hess and Maxwell (1953) have proposed large left-lateral displacements for these faults.

The east-west trending Cayman Trough (the major northern shear zone of the island arc) is represented on land in Guatemala by the Motagua fault (McBirney, 1963). This feature affords a test of the hypothesis of the present paper. McBirney points out that fault zone is ancient (since late Palaeozoic) and very highly sheared, and that it is a primary structural feature of the Caribbean region. McBirney states (p. 213), "I find no proof of large-scale lateral displacements. Unfortunately, rocks on opposite sides of the fault zone include nothing that serves as a reliable marker for horizontal offset, although the Tertiary basaltic rocks mentioned above ... suggest a left offset of at least 20 km". However, it is noted that the shear zone separates rock types of different character and structure, and that repeated uplift of greater than 7 kilometres and perhaps much more has been demonstrated. Horizontal displacements may have been very great. In its western part, the fault zone seems to swing toward the northwest. McBirney (1963) and Williams, McBirney and Dengo (1964) emphasize a later (Tertiary and Quaternary) north-south or northwest-southeast trend, which the latter authors interpret as a zone of right-lateral shear paralleling the Middle America Trench. This is consistent with interpretations that have been made of structures to the north off Baja California (Krause, 1965b), in the Gulf of California (Rusnak, Fisher, and Shepard, 1964), and in the Middle America Trench (Benioff, 1962; Fisher, 1961). In effect, the western part of the east-west zone would be bent northerly, and the western extension would then be found to the north.

The actual northern limit of the zone is placed north of Cuba at 25° N lat. and is extended through the Florida Straits and the Bahama Islands. This limit is approximately in line with the Clipperton fracture zone to the west.

Pacific Ocean

I. The Eastern Pacific. At the equator in the eastern Pacific, the Carnegie Ridge (Shumway, 1954) trends westward toward the Galapagos Islands, and the east-west trending Galapagos fracture zone (Menard, 1964) can be traced westward to 0° lat., 120° W long.

The Clipperton fracture zone is traced from Clipperton Island (Menard and Fisher, 1958) on a great circle to 3 1/2° N lat., 148° W long. (Heath and Moore, 1965). The zone is on the projection of the Cayman Trough lineament, and marks the approximate northern boundary of the inclined great circle of the equatorial shear zone (not including the Caribbean blister). Menard and Fisher (1958) consider the displacement along the Clipperton fracture zone to be right lateral on the basis of vague, but suggestive data. This point is discussed below.

The approximately east-west trending Clarion fracture zone (Menard, 1955) marks the approximate northern limit of the shear zone in the Caribbean region. This fracture zone converges toward the equator along a great circle and has been mapped to 15° N lat., 150° W long.

The intersection of the two great circles of the hypothesized equatorial shear zone is at 0° lat., 150° W long., near Christmas Island. Very little is known about this region although a zone of disturbed topography seems to pass through Christmas Island, Jarvis Island, the Phoenix Islands, Ellice Islands and thence to the Solomon Islands (Menard, 1964; Udintsev and others, 1963).

II. The Western Pacific. Krause (in press a) has demonstrated the existence of a left-lateral shear zone between the Papuan Peninsula of eastern New Guinea and Guadalcanal Island of the Solomon Islands (Fig. 5). Visser and Hermes (1962) have shown that a left-lateral fault zone extends from western New Guinea to Celebes, an observation that is supported by Krause (1965a). Carey (1958) suggested that a left-lateral shear zone probably transects the length of northern New Guinea.

Allen (1962), following Menard and Fisher (1958), pointed out a close proximity of large wrench faults and trenches in each of the Philippine Trench, the Hikurangi Trench and the Peru-Chile Trench. Scheidegger (1963) pointed out that according to fault plane solutions of seismic data, almost all of the faulting associated with trenches is wrench faulting. I have already suggested wrench faulting in the case for the Puerto Rico Trench and Bartlett Deep in accordance with the observations of Hess and Maxwell (1953). This relationship will be assumed to hold for a number of trenches of the Australasia, as will now be discussed.

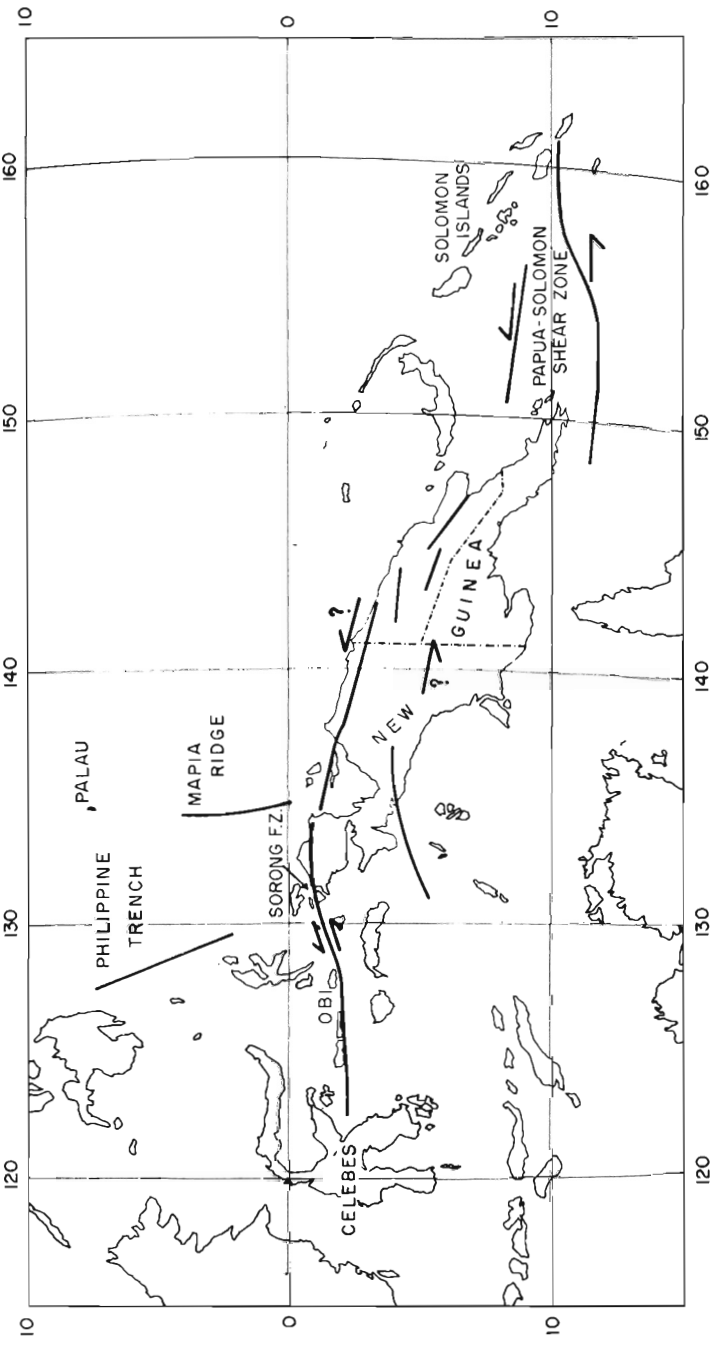


Figure 5. Simple tectonics in the New Guinea region (from Krause, 1965a).

The New Britain Trench leads into Huon Gulf. Unpublished data shows that its physiographic continuation leads up a steep submarine valley to the delta of the Markham River. Faulting is reported (Visser and Hermes, 1962) along the Markham Valley, but no one seems to have cited detailed evidence for active faulting.

The Santa Rosa basin north of Central New Guinea is a north northwest trending flat-floored basin that is 500 fathoms deeper than the neighbouring sea floor to the north. If allowance is made for the sediment fill, it can be inferred that the basement floor of the basin probably has a trench-like profile. The analogue of the basin to the east is the Melanesian Trench (Krause, 1965a). These features lie at the equator, and I consider them to represent the northern edge of the shear zone. West of Geelvink Bay and Mapia Ridge another east-west trough exists at the margin of the continent (Krause, 1965a), but soundings are few (unpublished chart by the Netherlands Hydrographic Department). The Melanesian Trench, which was first recognized and named by Udintsev (1960), marks the northern edge of the subcontinental region occupied by the Bismarck Archipelago (Fig. 6). The Vityaz profiles show that an east-west lineament exists to the north of the trench that probably represents the edge of the shear zone at exactly the equator (Fig. 6) (Anonymous, 1958a, 1958b).

Krause (in press a) discussed the en echelon character of the Solomon Islands and the field evidence to support the hypothesis that faulting has caused that character. Considering this to be so, a reconstruction of the Solomons suggests 900 km of left-lateral shear.

The Papua-Solomon shear zone (Krause, in press a) passes east beyond Guadalcanal into the Vitiaz Trench to the north of the Santa Cruz Islands. Its eastward continuation is obscure because of lack of soundings, but as was noted above, a zone of disturbed sea floor seems to continue to Christmas Island.

Menard (1964) described the Darwin Rise in the central Pacific. This would be cut by the shear zone, but present evidence on the nature of the Rise neither confirms nor denies the existence of the zone.

The Java Trench in the Indian Ocean runs east-west at what is considered to be the southern edge of the shear zone. The northern edge of the equatorial shear zone runs through Waigeo, the northern arm of Celebes and along a basement ridge in Borneo. The Sumatra-Java curve is considered to be the result of a general shearing of the archipelago.

Thus several of the major island arc systems of the world are confined to the equatorial shear zone: viz. (1) the Indonesian arcs, (2) the Bismark-New Britain arc, and (3) the Caribbean arcs. The relationship is

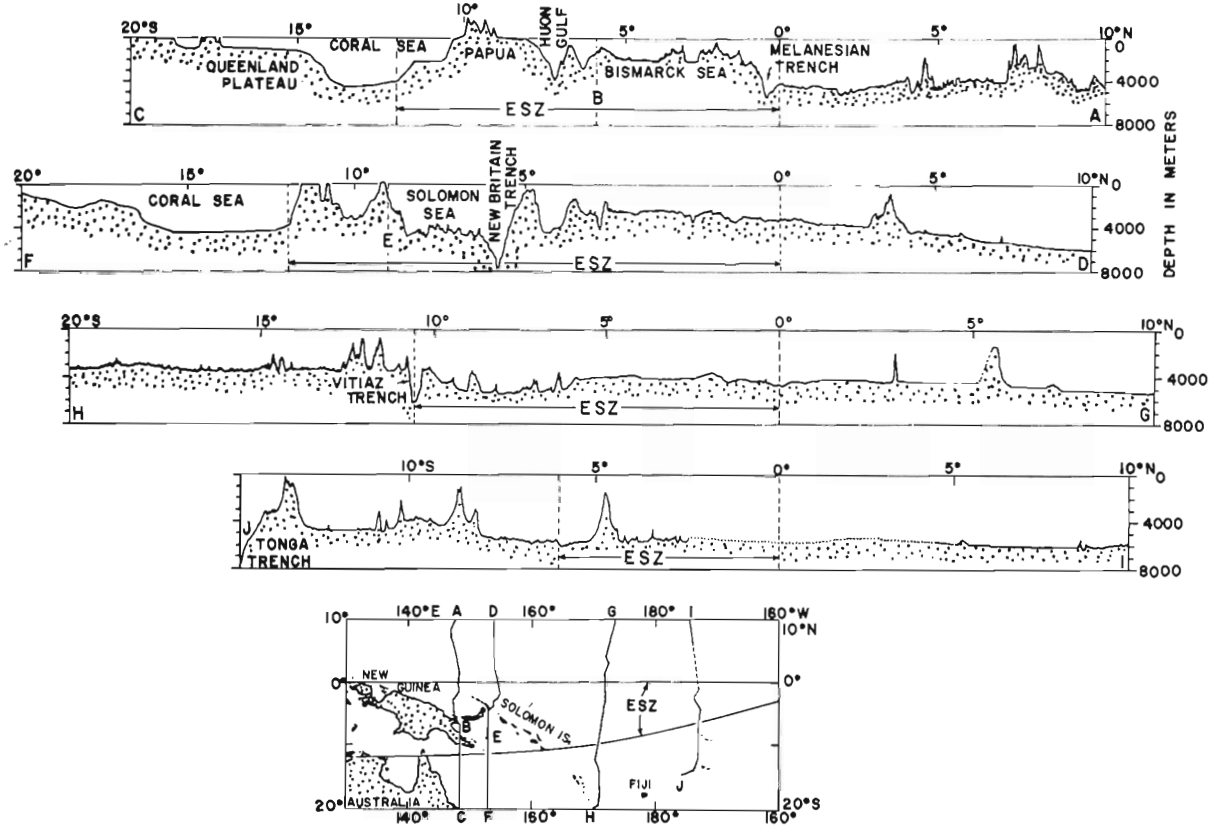


Figure 6. Profiles across the equatorial shear zone in the western Pacific. Profiles AB and DE were made on the 25th voyage of the VITYAZ (Anonymous, 1958b). Profiles BC and EF are based on data from Krause (in press a) and other sources. Notice that the depth scales of profiles AC-CF and GH-IJ differ slightly.

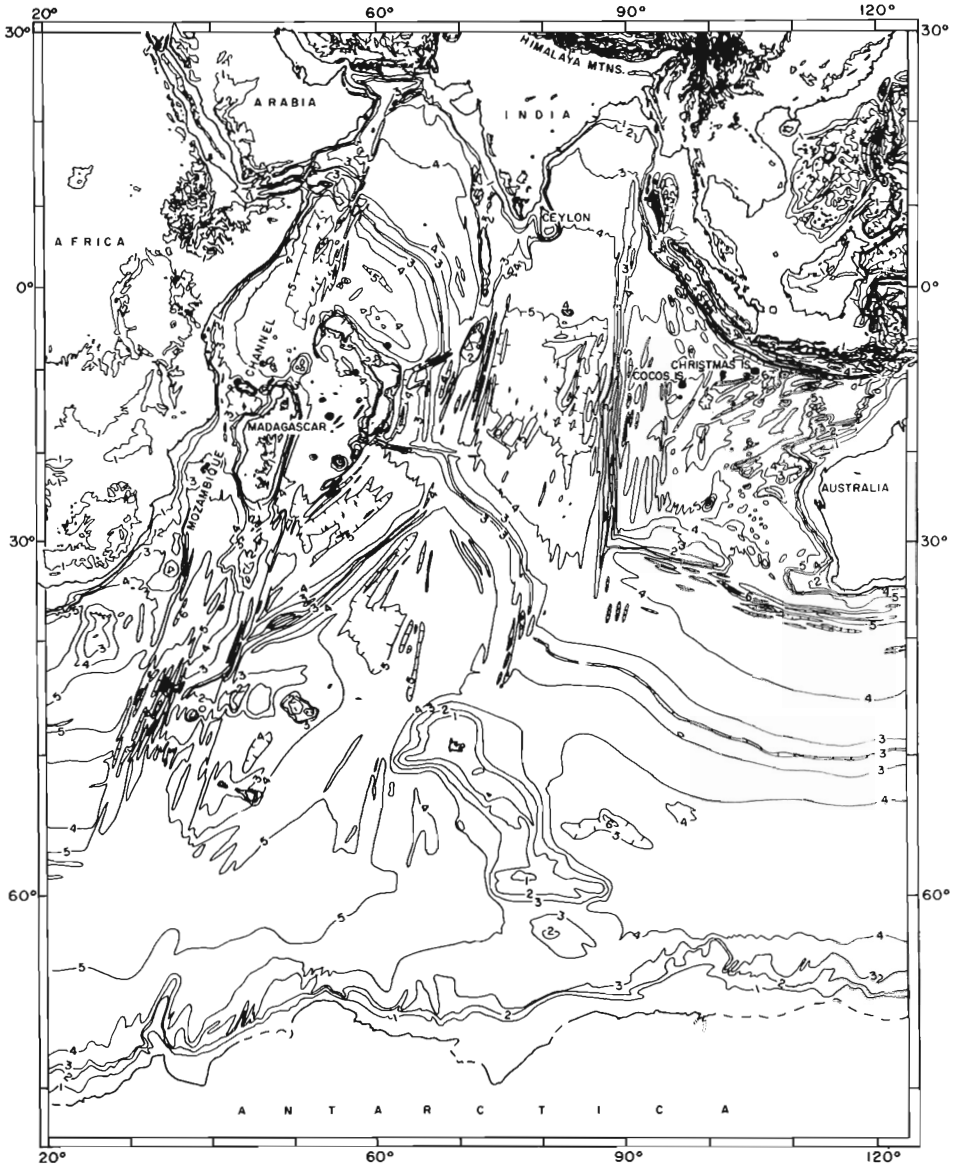


Figure 7. Bathymetry of the Indian Ocean (simplified from Heezen and Tharp, 1965). Contours in kilometres.

considered genetic in that the arcs developed concurrently with the equatorial shear zone.

A trend to the west in the Indian Ocean at 11°S lat. continues through Christmas Island (this is not the Christmas Island of the Pacific) and Cocos Island (Heezen and Tharp, 1965).

Indian Ocean

The Indian Ocean shows no evidence for east-west shear near the equator (Fig. 7) (Heezen and Tharp, 1965) except south of Java, and along a range of hills south of Ceylon. In the region of concern, the trends are all north-south. Although this would seem at first to refute the hypothesis of an equatorial shear zone, it does quite the opposite. It gives a sequence of events not otherwise decipherable. This is discussed in more detail below.

Summary of Character of the Equatorial Shear Zone

The equatorial shear zone is bounded by two great circles oriented 12 degrees apart, one of which is the equator. The other great circle intersects the equator at about 150°W long. and 30°E long., with a possible ambiguity amounting to a shift of these positions by 15 degrees to the east. The shear zone is best displayed in the Atlantic Ocean and the western Pacific Ocean. The Caribbean island arc and the Indonesian, Bismarck, and Solomon island arcs are developed at the greatest separations of the 12 degree great circle and the equator.

The hypothesis of an equatorial shear zone requires that the displacement be distributed in some way through the zone approximately defined by the two great circles. This automatically deforms the inclined great circle by displacing or warping the part in the northern hemisphere relative to the part in the southern hemisphere. The point of intersection between the equator and the other great circle is no longer a point but a region. Interestingly, the uncertainty in positions noted above is sufficient to include the expected displacements required by the hypothesis.

DISCUSSION

Probability of the Shear Zone's Existence

One measure of the probability of the existence of the hypothesized equatorial shear zone is to compare the length of identifiable features along its length to other possible great circle zones. For the equatorial shear zone, only those features were used that have been tested or fall within the assumptions of the hypothesis. For other great circle

zones, any structural feature was used that was near to and approximately parallel to the great circle.

The equatorial shear zone can be directly identified at the equator by geologic structures for 180 degrees of its path. In addition a 45 degree segment for the Indian Ocean must be removed from the total because the hypothesis requires that that segment be destroyed by the drift of India. Therefore the shear zone can be identified for 59 per cent of its length. The other parts lie in the mid-Pacific, in Africa and in south America, the section in the mid-Pacific being largely unknown because of a lack of detailed information. By the same approach, the great circle inclined at 12 degrees to the equator can be traced for 56 per cent of its length.

Eight other great circle zones were tested which contain the major shear zones and tectonic zones of the world. Only two approached the possibilities of the equatorial shear zone. A great circle parallel to the San Andreas fault was accompanied by parallel features for 49 per cent of its length, and a great circle parallel to the Darwin Rise (i.e., trending northwesterly in the mid-Pacific) was accompanied by parallel features for 51 per cent of its path. In both cases, the geologic features are of such diverse nature, and the remaining parts of the paths presented such great obstacles to the concept, that the circles were rejected as possible shear zones.

Available Hypotheses of Origin

The hypothesis being presented must be considered to be a working hypothesis, one among several alternatives, selected because it best explains the available facts. Possible explanations of the observed geologic features are:

(1) an equatorial shear zone of constant displacement,
(2) continental drift,
(3) shear zones inclined to the equator,
(4) secondary effects of convection currents in a basin with stable outlines, and
(5) the features are unrelated.

These will be discussed in turn.

1. An equatorial shear zone of constant displacement. The observations are explained by a shear zone determined by the equator and a breat circle inclined to it by 12 degrees. The shear zone is assumed to be caused by a 2800 km left-lateral displacement wherein the northern hemisphere has moved westward relative to the southern hemisphere. This displacement is evident in changes in trend in the Indonesian arcs, Central America, the Mid-Atlantic Ridge and the west coast of equatorial Africa.

2. Continental drift. For the Atlantic, assume that the Mid-Atlantic Rift maintains its position in the centre of the ocean basin. Assuming for the sake of a reference point that Africa has not moved, and that South America moves west, the rifts move one half as far to the west as does South America. Because of the bend of Africa and South America, the mid-line of the North Atlantic basin lies west of the mid-line of the South Atlantic basin (diagrammatically shown in Fig. 8 II). Because of the geometric offset, the east-west points of contact between the basin and the east side of South America have differential movement of right lateral sense. This is preserved as a disturbed zone (a fracture zone) across the entire basin. This relative movement gives a dynamic right-lateral movement along the western end of the fracture zone (and the eastern end as well, if we assume both continents are actively drifting). Yet the displacement as measured by the mid-lines of the basins (i.e., the rift zone) displays left-lateral separation due to the bend of the continents.

For the Pacific, most of the elements of the Australasian tectonic structure can be elaborately explained through the hypothetical breakup of Gondwanaland (Du Toit, 1937) and the subsequent northeasterly drift of India and the easterly and then northerly drift of Australia.

3. Shear zones inclined to the continent. Carey (1958) has discussed various zones of this type. His concepts are close to those of the equatorial shear zone but enough different to imply different tectonics. One divergent concept of his is that of the Tethyan shear system (his Fig. 57) which trends east-northeast through the Caribbean region.

4. Secondary effects of convection currents in a basin with stable outlines. Assume that a basin with a stable outline exists for the Atlantic Ocean and that convection currents exist whose plane of rotation is in the east-west direction and whose narrow upwelling axis is in the centre line of the ocean (Fig. 9). Assume further that the ocean floor is carried along by the currents (Dietz, 1962; Hess, 1962). A tensional rift is thus formed at the centre line of the basin. In this discussion, pay close attention to the difference between the actual movement of the rock masses as the movement is occurring and the relative movements as determined from the geometry. The equatorial bend of the ocean basin will cause a discontinuity in the axial trend of the convection current and a definite discontinuity of movement between the North and South Atlantic basins. East of the basin mid-lines, the sea floor moves easterly toward the continent, and similarly west of the mid-lines, the sea floor moves west. Between the mid-lines along the discontinuity, opposite horizontal movement of the crustal blocks occurs along the discontinuity in a right-lateral sense. Beyond the mid-lines, two situations can exist:

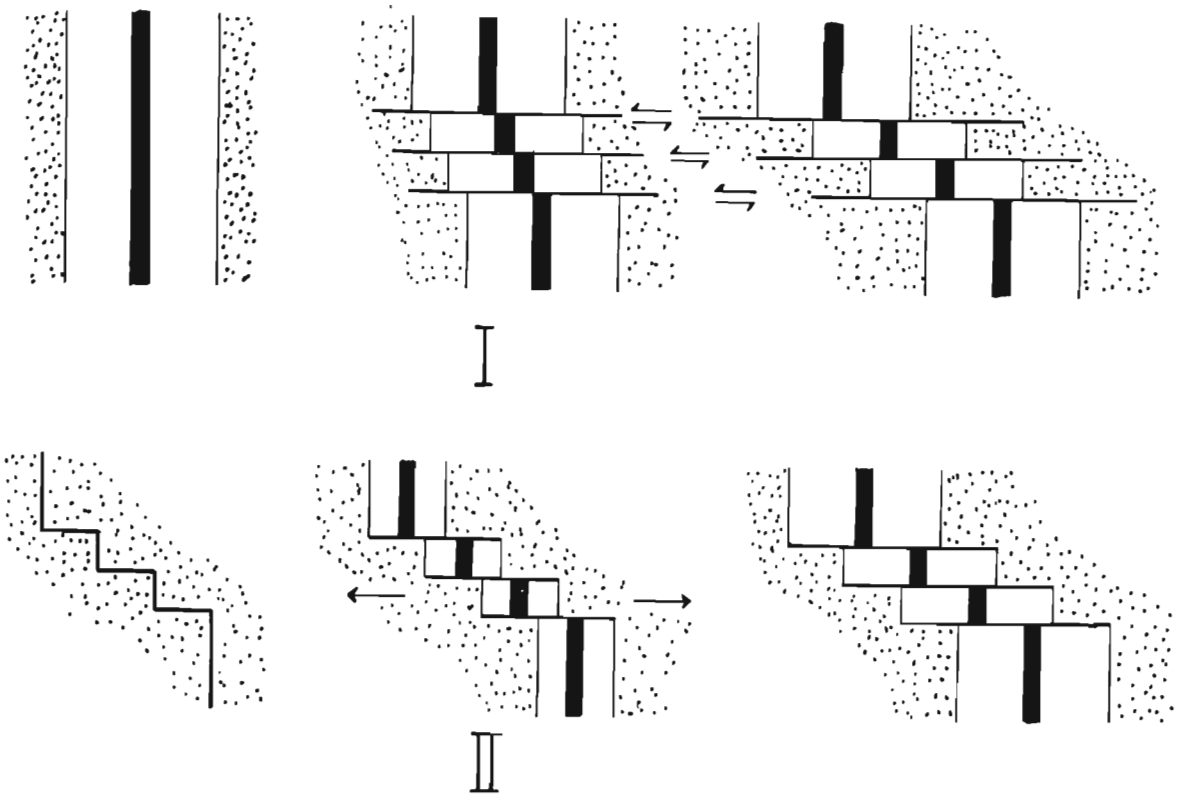


Figure 8. Simple hypotheses of the development of the equatorial Atlantic basin. (I) Basin showing left-lateral displacements along faults. (II) Expanding basin with a central feature always maintained. Notice the similarity of the end product where only the existence of landward faults shows the difference.

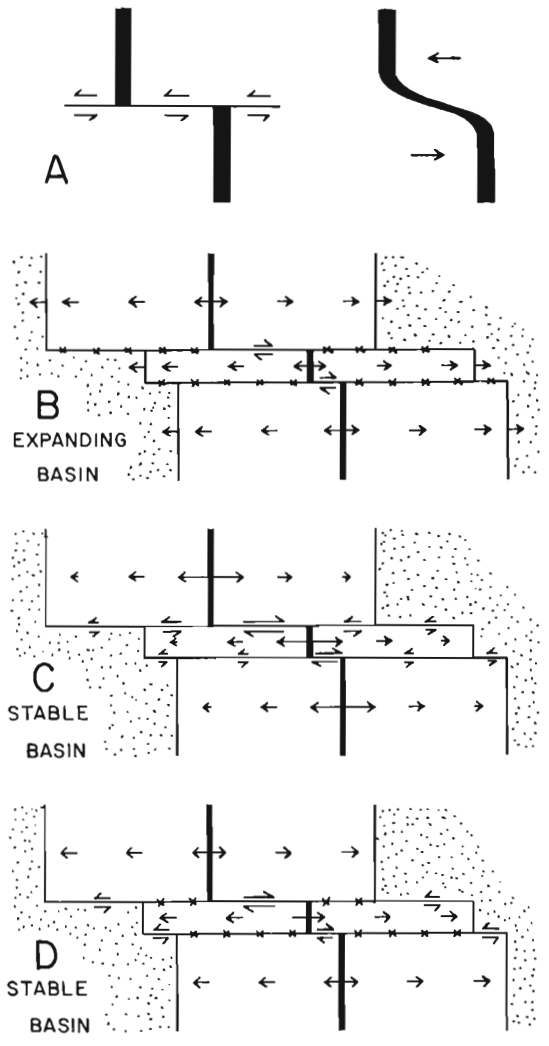


Figure 9. Models showing equatorial shear zones. (A) Model shows a shear zone of constant displacement with a fault in one location equivalent to a broad band of shear elsewhere. A mantle convection current is assumed in Models B, C, and D which upwells in the centre of the ocean basin and which then spreads and carries the ocean floor outward. The ocean floor therefore increases in age outward from the centre. The arrows show the assumed movement of the sea floor (and continents in Model B); the barbed lines show relative movements of blocks on opposite sides of a fault; the crosses show that no movement occurs on that section of the fault. Note that the true motion need not correspond in direction to the relative motion. (B) Continents drifting at the same rate as the sea floor moves. (C) The ocean basin has a stable outline, and the movement of the sea floor decreases toward shore. (D) The ocean basin has a stable outline, and the movement of the sea floor is constant toward shore.

(a) Assume that the velocity of displacement of the sea floor decreases in the direction of the continent due to the wide breadth of the descending limb of the convection current in that the vertical velocity component of the convection current grows at the expense of the horizontal component as the edge of the basin is approached. Beyond the mid-lines at the discontinuity (i.e., west of the North Atlantic mid-line and east of the South Atlantic mid-line), relative movement exists across the discontinuity in a left-lateral sense because, although both blocks are moving in the same direction, they are moving with different velocities. For example, in the eastern Atlantic, the sea floor east of the South Atlantic mid-line is moving faster than the sea floor north of the discontinuity because the northern sea floor is near the continent. Relative left-lateral displacement is occurring but on a system that is moving easterly in its entirety.

Note that the central displacement is right lateral but that the marginal displacements are left lateral. Paradoxically, the offset of the mid-lines (rifts) appears to be left lateral despite the fact that they are stable in position.

(b) Assume that the velocity of the sea floor is constant from the mid-lines to the continents. The central portion of the discontinuity would display right-lateral movement as explained above. Beyond the mid-lines, no relative movement along the discontinuity would occur, but the discontinuity would exist physically, and it would be carried passively toward the continents. Further assume that similar structures were formed on the sea floor at both the North and South Atlantic mid-lines at the same time and assume that these same structures were identifiable at some later time after they have moved away from the mid-lines equally in both hemispheres. The structures would be superficially misleading in that they would suggest a left-lateral displacement across the discontinuity equal to the separation of the mid-lines at the discontinuity. This same feature applies to case (a)[1].

5. The last hypothesis available is that the available facts have been totally misinterpreted and that the fracture zones are unrelated. The evidence presented above is considered to refute this possibility.

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[1] J. T. Wilson (1965) has independently developed the concept of the "transform" fault which is similar to that presented in hypotheses (2) and (4) above and in Figures 8 (II) and 9. Our analytical descriptions differ somewhat, but they deal with the same phenomena and are complementary.

At the Upper Mantle Symposia (this volume), J. T. Wilson, M. Talwani and this writer (this paper) each discussed such transform faults and presented evidence for their existence.

Working Models

The equatorial shear zone can be explained by two models. In Model I, the northern hemisphere is rotated (relatively) to the west (left-lateral shear) by 2800 km (25° long.). Most of the pre-shear geologic elements of the earth have north-south trends (Fig. 10). Model II assumes that there has been 2800 km of left-lateral shear in the Pacific, while in the Atlantic, continental drift caused the development of structures with the appearance of left-lateral shears (Fig. 11). Both models have advantages and disadvantages, but Model II is favoured on the basis of present evidence. The reasons are as follows:

1. An equatorial shear zone has not been proven in Africa or South America although ample evidence of discontinuous east-west shear does exist. Furthermore, the possible geological correlations within the two continents prior to the proposed displacement are interesting but not convincing. A reconstruction of the African continent was attempted by redrawing the geologic map of Africa (ASGA-UNESCO, 1963), but no correlations were possible, partly because of the reconnaissance character of most of the geologic mapping of the African Precambrian rocks. Correlations for various divisions of the Precambrian rocks of West Africa with those of Central Africa is not yet possible because the information does not yet exist. Correlations that do seem to exist cannot yet be trusted.

2. The geology of the Congo basin and of the Ethiopian plateau do not permit the shear of Model I to be later than mid-Jurassic while the 12 degree polar shift of the model (see the section on Polar Wander) suggests mid-Cretaceous movement.

3. Bullard, Everett and Smith (1965) have strengthened the concept of continental drift by producing, with the aid of a computer, an excellent least squares fit of the continents on either side of the South Atlantic, and a good least squares fit of the continents on either side of the North Atlantic. The latter fit is improved by Schoeffler's (1965) finding that the great thickness of sediments in the Cape Breton embayment (north of the Pyrenees Mountains) is post-Jurassic and, therefore, deposited after continental drift began. Bullard's geometry is so good as to take precedence over the superficially simpler north-south geometry of Model I.

4. Laughton's (1966) rift model for the Gulf of Aden is so suggestive of the equatorial Atlantic that a similar mechanism must be considered for the development of the Atlantic features. Laughton considers the Gulf to form through northward movement of Arabia relative to Africa.

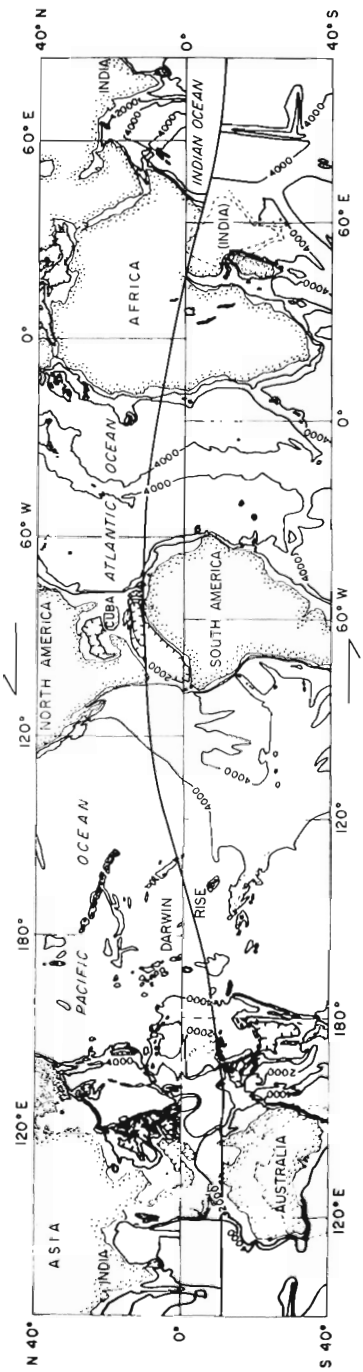


Figure 10. Model I. The geography of the world is reconstructed assuming 2800 km of left-lateral shear along the equatorial shear zone. As an aid to the reader in orienting himself, the map (and Figs. 11, 12) has been reconstructed without deleting geography which has developed in Cretaceous and later time as in much of Indonesia, the Philippine Islands, New Guinea, and the Caribbean island arcs. Former positions of Australia and India are indicated.

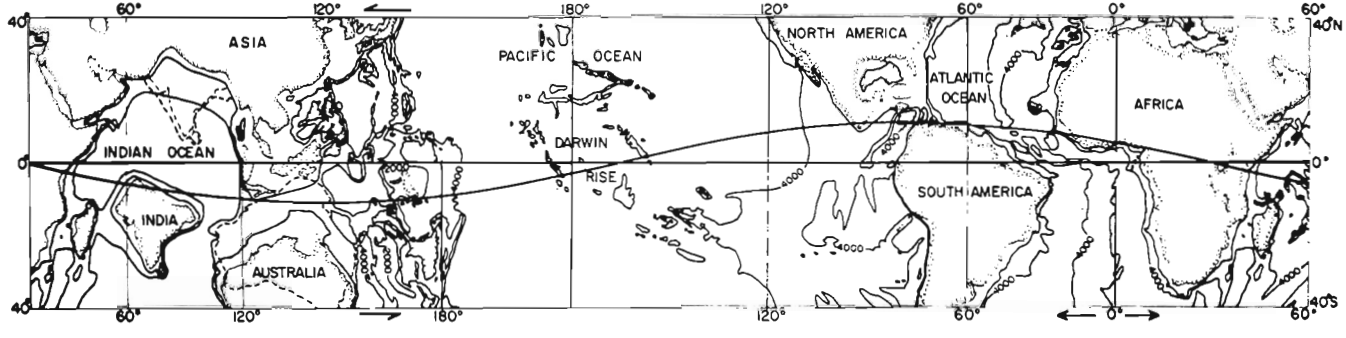


Figure 11. Model II. The geography of the world is reconstructed assuming 2800 km of left-lateral shear along the shear zone in the western pacific and assuming mainly continental drift in the Atlantic with 550 km of left-lateral shear between North and South America. The world is assumed to be constant in size and therefore the Pacific basin depicted larger with a centred Darwin Rise. Geography formed in Cretaceous or later time has not been deleted as an aid to orientation. The present geography of the Indian Ocean is shown on the right, a hypothetical former geography on the left.

Model II arises out of Model I, but is further supported by the continental drift as inferred from a 12 degree shift in the axis of the earth's rotation (see section on Polar Wander and Palaeomagnetism). It is the same as Model I for the western Pacific in that it requires a 2800 km left-lateral shift. The following north-south trens are therefore correlated: (1) Tonga Ridge, Norfolk Ridge, and Lord Howe Ridge-Solomon Islands-Euripik Swell-Marianas Ridge; (2) A rounder shape to the Darwin Rise (Menard, 1964); (3) Marshall Islands-Society Islands; and (4) Marquesas Islands-Line Islands (?). As in Model I, it is required that Australia drift to the north and east in harmony with geological evidence and palaeomagnetic evidence (Runcorn, 1962).

In the Atlantic, Model II requires the specialized conditions outlined earlier in the hypotheses where the continents passively drift apart. The shear zone develops an artificial left-lateral appearance because of the geometry of the basin, and because of the restriction that the centre of the basin always remain at the centre (either through convection currents or through uniform expansion of the sea floor).

The situation in northern South America, the Caribbean, and the eastern Pacific probably reflects the processes occurring in both the Atlantic and the western Pacific. Shearing within the continental block was probably minor, but in the Caribbean, the evidence of shear is considerable.

Model II therefore combines the first and second hypothesis given in the section on Available Hypotheses of Origin. The fourth hypothesis is tenable in the equatorial Atlantic for a later period in the development of the Atlantic basin but is not necessary to the thesis of this paper. The third hypothesis would apply to conditions prior to the formation of the equatorial shear zone. One of the purposes of this paper has been to eliminate the fifth hypothesis.

Carey's (1958) hypotheses of continental drift included important elements of the hypothesis of the equatorial shear zone, and Tanner (1963) concluded that an equatorial "maximum deformation" belt existed. However, beyond our agreement that some such zone exists and our support of Hess and Maxwell's (1953) hypothesis for the deformation of the Caribbean basin, our conclusions on the displacements and origin of the zone are incompatible, and I do not accept Tanner's model. R.W. Fairbridge (1965, personal communication) also has concluded that an equatorial deformation belt exists in some form.

Age of the Equatorial Shear Zone

The age of the equatorial shear zone can be obtained in part from the dating of land geological features. Its early history is not clear but

can be defined within certain limits. The events of Model II are much more in line with the palaeomagnetic evidence than those of Model I.

The deformation in the western Pacific occurred during the Cretaceous, perhaps in Late Cretaceous time (Krause, 1965a; in press a, in press b). The geological history of northern New Guinea begins with a large thickness of Late Cretaceous mafic volcanic rock and radiolarites resting on an ultramafic basement which is thought to be mobilized mantle rock (Visser and Hermes, 1962). The volcanism continued through Eocene time but was almost absent during Oligocene time. A major fault zone, the Sorong fault zone was established prior to Pliocene time, and had large movements between Miocene and Pliocene time (Visser and Hermes, 1962). Major east-west trending structures were formed in Pliocene and Quaternary time (Visser and Hermes, 1962; Krause, 1965a).

Southern New Guinea is part of the Australian continent and has a history beginning in Cambrian time that continues up to Miocene time without striking change. The crust becomes increasingly mobile from Miocene to Recent time.

Papuan (southeastern New Guinea) geology began in Jurassic time with deep troughs. Cretaceous time marked extensive crustal mobility. Miocene and Quaternary time mark orogenies. The geology of the Solomon Islands begins in Miocene time with shallow water limestone and sandstone deposits on a weathered and eroded basement of mainly mafic volcanic rocks.

The geologic history of North Borneo begins with very thick Upper Cretaceous or Eocene spilites, pillow basalts and radiolarian cherts with associated ultramafic rocks (Wilson, 1961). The northern Indonesian and Philippine region shows a generalized geologic history of extensive Cretaceous volcanism, an intense late Miocene orogeny and a Quaternary orogeny (Krause, in press, b), a history more or less shared by the rest of Indonesia (Kuenen, 1950; Anonymous, 1959a) which however has some elements of other ages.

The structures in the Caribbean were initiated mainly in Middle Cretaceous time and have continued to evolve to the present time (Ewing and others, 1957; Hess, 1960).

Arkell (1956) considers that the Atlantic began to develop in Jurassic time. However most evidence indicates that the main evolution of the Atlantic basin and Caribbean basin occurred in Cretaceous time. The evidence is in the form of Cretaceous sediments on basement (see for example, Furon, 1963; Haughton, 1963; Hess, 1960; Stose, 1950; Cohee, 1962).

The drift of Australia seems to have coincided in time with the development of the equatorial shear zone.

The rather strange juxtaposition of the undisturbed and non-volcanic Cretaceous sediments in Southern New Guinea and the volcanic Cretaceous sediments in Northern New Guinea can be explained by northward thrusting or movement of Australia over the sea floor. Furthermore, the immediate lack of the shear zone between New Guinea and Australia is due to northward movement of Australia. The island arcs of eastern Indonesia fit well the concept of the northward moving block of Australia. Krause (in press, a) has pointed out suggestive evidence on the floor of the Tasman Sea in the form of volcanoes, for the northward drift of Australia.

The age and origin of the equatorial shear zone in Model II are compatible with Hess' (1955b) serpentine zones.

Since all structures in the shear zone seem to date from Cretaceous time, I conclude that the equatorial shear zone developed at that time. Secondary movements occurred in Miocene and Quaternary time.

The Problem of the Equatorial Shear Zone in the Indian Ocean

Explicit in Wegener's (1924) theory of continental drift was the hypothesis that the subcontinent of India has drifted northward and is thrusting against Asia thus producing the Himalayas. Many eminent men have argued against this hypothesis but as work has advanced, evidence has accumulated in its favour. The evidence is both geologic (see Arkell, 1956) and geomagnetic (Bhimasankaram, 1965). The ships of the Indian Ocean Expedition recently tested the hypothesis in a survey of the Indian Ocean. Heezen and Tharp (1965) have compiled this information on a physiographic diagram and bathymetric chart (Fig. 7), and it very strongly supports the hypothesis.

The events are also fairly well placed in time. The Mozambique Channel was already in existence in mid-Permian (Haughton, 1963) while the coast of the Indian Ocean became more clearly defined during the Jurassic (Arkell, 1956). India, however, remained connected to Madagascar until Campanian time (Upper Cretaceous). Most of India's movement occurred during the middle and late Tertiary (Arkell, 1956). Its northward movement apparently affected most of the Indian Ocean basin because Heezen and Tharp's map shows northerly trends as far south as 40°S lat. Thus any evidence of an equatorial shear zone would have been completely obliterated with the possible exception of a minor, late Cenozoic development south of Ceylon.

This northward drift of India fits well with the hypothesis of Model II for the equatorial shear zone, although another much less probable explanation for the origin and evolution of India's drift can be developed from the Model I. A reconstruction of the geology places India a large distance to the south prior to the equatorial shearing, and reconstruction of Africa leaves a big gap in its eastern side (south of the equator) into which India can be fitted (Fig. 10).

Central America and the Caribbean Region

A relative movement between North America and South America of 10° longitude (1100 kilometres) is suggested by:

(1) the physiography and geology of the Caribbean region and
(2) a 10 degree gap between southeastern United States and Africa when the Atlantic basin is closed by bringing the bordering continents together.

The movement is not predicted by Model II but may develop from complications derived from the model. Relative rotation of the continents is required by the hypothesis of continental drift, and this can give the described movement. Superimposed on this relative movement are movements within the Caribbean region which have given rise to the Caribbean Island arc system.

Several models for the reconstruction of the Caribbean region can be formulated. The complication here concerns the Caribbean Island arc system and its adjacent, east-west trending shear zones (Hess and Maxwell, 1953) through the Cayman Trough and through northern Venezuela (Rod, 1956). I accept the model of these authors for the eastward thrust of the Caribbean Sea and island arc. Combining this with the hypothesis of an equatorial shear zone, I have derived in Figure 12 the simplest reconstruction consistent with the facts. A large number of alternatives are available, but they require more special conditions than the present one. Inasmuch as the actual palaeogeography would probably be more complex, the reconstruction is considered to be only a first order approximation.

Figure 12 shows the present configuration and a mid-Cretaceous reconstruction. Note that the Caribbean Island arc is shown to have been part of the Andean chain. The faults and island arc are zones of weakness involved with the equatorial shear zone. The shear zone occupying northern Venezuela and the Cayman Trough each have 8 1/2° (longitude) displacement. In addition, a deformational zone exists to the north to approximately 25° N lat. with a displacement of 6 1/2° (longitude) uniformly distributed through the zone. The Andean system therefore included the

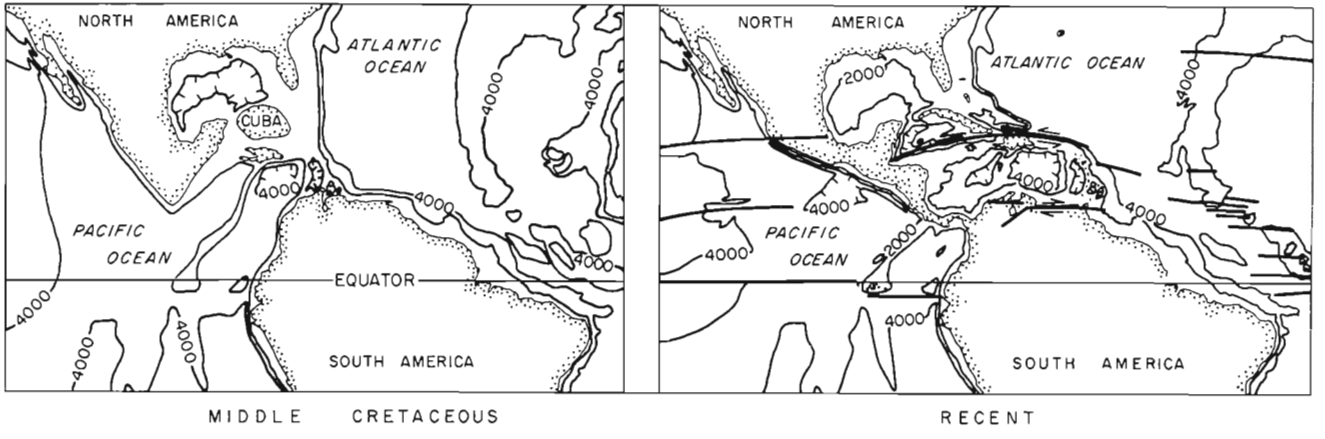


Figure 12. Hypothetical development of the Caribbean region. Caribbean geography is reconstructed assuming 550 km of left-lateral shear between North and South America and an 1100 km eastward thrust of the Caribbean basin. Geography formed in Cretaceous or later time has not been deleted as an aid to orientation.

Caribbean island arc, the greater Antilles, Cuba and the Bahamas. Related trends, which have been referred to as the Oachita system, exist in western Florida (Drake, Heirtzler and Hirshman, 1963).

Jurassic sediments do not exist in eastern Venezuela but occur in distantly spaced Trinidad and western Venezuela (Arkell, 1956). The latter two areas are adjacent in the reconstructed position of the Caribbean for Mid-Cretaceous time. Also, the Jurassic sediments of western Venezuela and Colombia resemble those of Cuba (Arkell, 1956). Jurassic rocks may also be present on Haiti (Arkell, 1956).

Note in the reconstruction in Figure 12 that the Honduran-Nicaraguan Peninsula is united with the Yucatan-Guatemala Peninsula. Also, Yucatan and the former Cuba occupy a considerable portion of the Gulf of Mexico. The conclusion is almost inescapable that the Gulf of Mexico formed through the separation of Yucatan Peninsula, and that the Cuban platform separated from continental North America. Arkell (1956) points out that an ancestral Gulf of Mexico existed in Jurassic time but differed greatly in outline.

The faults to the south of the Caribbean do not have as much displacement as the faults to the north so that there is a net left-lateral displacement across the Caribbean even though the faults on either side are of opposite sense.

The displacement across the Cayman Trough-Puerto Rico Trench alignment can be obtained by joining Cuba with Hispaniola, and the Bahama Islands with the Antilles. The displacement is 780 km at the Antilles. The Cayman Trough intersects Central America at Guatemala. The horizontal separation of the north-south trending 100-fathom line off British Honduras (north of the lineament) and the north-south trending 100-fathom line off Nicaragua (south of the lineament) is also 780 km.

The northern limit of the shear zone (25° N lat.) reorients the Bahama Islands and Cuba. The deformation here seems to be a plastic one rather than faulting, although local faulting probably gives us the structure of the Bahama Islands. I further conclude that the deformation of Central America has been one of shear combined with development of major faults.

The Cocos Ridge and the Beata Ridge (ridge south of Hispaniola) may be related and may have been separated by the eastward thrust of the Caribbean basin. The ridge then would be analogous to a mid-ocean rise before Mid-Cretaceous time. Figure 12 shows the western hemisphere in pre-Mid-Cretaceous time before the development of the equatorial shear zone. This model yields modern geography by a 5 degree

(longitude) left-lateral displacement of North and South America and by a 10 degree eastward thrust of the Caribbean region (Fig. 12).

Notice that in the reconstruction (Fig. 12), the northern configuration of South America is a mirror image of the features in the northern Caribbean, suggesting that they were once together. The time of drifting apart is uncertain if it exists, but may have been initiated by the equatorial shear zone or else accentuated by the zone. This drift partly explains the fact that the southern fracture of the equatorial shear zone is south of the equator in Brazil.

Oceanic Rises and Ridges

Menard (1958) pointed out that the rises and ridges occupied the centre lines of the ocean basins. The process by which the rises and ridges form was apparently the same in pre-Cretaceous time (as represented by the Mid-Atlantic Ridge) as at present (as represented by the Mid-Indian Ocean Ridge). The Mid-Atlantic Ridge has occupied the centre of the Atlantic Basin since its formation and has continued to develop as an entity, as has the Mid-Indian Ocean Ridge.

The East Pacific Rise shows no displacement although certain fracture zones follow major boundaries of the equatorial shear zone. The major development of the rise post-dates the major development of the shear zone but has been affected along older lines of weakness. H.W. Menard (1966) has found confirming evidence on the East Pacific rise.

If Menard's (1958) conclusions that rises develop in middle of ocean basins also hold for the Darwin Rise, then the western margin of the Cretaceous Pacific Ocean must have been farther to the southwest; that is, Australia must have been much farther west and south. The outline of the Pacific Ocean would have been much simpler at that time (i.e., oval). The northward and eastward drift of Australia (and New Zealand?) changed the geometry of the Pacific basin so that the position of the Darwin Rise was no longer stable. The Darwin Rise broke up, and the East Pacific Rise developed in its stead. The Darwin Rise was probably contemporaneous with the equatorial shear zone. Tentatively, the geological events concerning the shear zone lead to the breakup of the Darwin Rise and to the formation of the East Pacific Rise.

By these reasonings, the Mid-Atlantic Ridge was well developed before Cretaceous time, the East Pacific Rise began in Cretaceous or early Tertiary time. The Darwin Rise was well developed in Cretaceous time. The Mid-Indian Ocean Ridge began perhaps in Jurassic time but mostly developed in post-Miocene time.

The two boundaries of the equatorial shear zone are great circles, one along the equator and the other inclined at 12 degrees. This association suggests that the inclined great circle may be a former equator, and that the shear zone formed during a 12 degree migration of the earth's pole of rotation to its present site. Under this hypothesis, the former pole would have moved northward from a position near 78° N, 120° E during Cretaceous time. The path is essentially along the Lomonosov Ridge.

Whether the migration occurred instantaneously, or over a million years, or over 10 or 100 million years can only be guessed at, but weak evidence favouring the longer times is available from palaeomagnetic investigations and from land geology. This evidence will be discussed in future publications.

The hypothesis of Model II is compatible with the data from palaeomagnetic investigations indicating a pole near 78° N lat., 120° E long. during Cretaceous time (Runcorn, 1962, 1964), and it is also compatible with palaeomagnetic evidence regarding the movements of the various continents, especially Australia and India. On the other hand, the uncertainties of the palaeomagnetic evidence do not allow for more detailed tests of Model II.

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GENERAL SESSION: RESOLUTIONS AND RECOMMENDATIONS

Chairman: T. Sorgenfrei (Denmark)

Dr. Sorgenfrei: I would call upon Dr. Heezen to give the introductory remarks to this general session on resolutions and recommendations relating to investigation of the World Rift System.

B.C. Heezen (U.S.A.): In the last two days we have taken a tour around part of the World Rift System. Starting with the Levant, we went through the Red Sea and the Indian Ocean; we heard about a piece of the North Atlantic and the Central Zone of Iceland. We did not hear much about the Arctic due to the unfortunate absence of our authorities on the Arctic Basin, but we have heard a little about the Baikal Rift. We then went on to discuss the Pacific Ocean and the Western United States. These various rifts are all parts of one essentially continuous system, all lying on a continuous belt of shallow seismicity. That the gradual discovery of this world-wide rift system occurred only during the last 15 years is due to the fact that only in this period have we been able to study the ocean and its physiography in any detail. However, the land parts have all been known for a century or more; and the essential characteristics of the rifts of Europe and of East Africa have been known for over 50 years. It was only with the aid of continuous echo soundings and seismicity that we recognized the continuity of this rift system. Dr. Udintsev pointed out that the whole width of the Mid-Indian Ocean has a structure similar to the crest.

We are dealing with a large part of the earth's crust. The belt is about 1,000 miles wide, on the average, and some 30,000 miles long. In the ocean, we have been able to determine the physiography and measure a few specific geophysical parameters such as magnetic anomalies, gravity anomalies, and heat flow anomalies. However, on the continents it has been possible to study the geology of the rifts in more detail – as was demonstrated by the discussions of Iceland and the Western United States, and as could also be demonstrated in East Africa. The continental parts of the rift system, particularly the East Africa part, are rather short on geophysical studies; and the oceanic parts are short on geological studies.

The mid-oceanic ridge-rift system represents one of the three basic types of the earth's crust: viz. the continents, the ocean basins, and the mid-oceanic ridge. If we are correct in thinking that it is a system with rather uniform characteristics, the explanation of its origin is fundamental to the explanation of any orogenic belt, or any earth deformation process, since so much of the earth is involved. It is important, therefore, that we study certain parts of it in more detail. A beginning has been made, but detailed investigations are still extremely rare.

We have heard a little bit about recent geological mapping, in the form of dredging, along the rift valleys of the Indian Ocean. A little dredging has also been done in the Atlantic. But we need to collect more rocks; we need to do more old-fashioned geology. I believe that submarine geologists and oceanographers got off on a wrong foot because they thought, originally, that the bottom of the ocean would be completely covered with sediment. However, we now know that large areas of the ridge system are almost devoid of sediment, and that rock outcrops are common.

We have also heard a bit today about big displacements of the Mid-Oceanic Ridge, which have been claimed on the basis of broken magnetic anomaly patterns. Part of the uncertainty with regard to the meaning of the displaced magnetic anomalies stems from the fact that no one really knows what causes them. This again might be solved by a little detailed work, and detailed sampling of the bottom to see whether the stripes that you see in the magnetics might be correlated with rock types or alternately reversed and normal remnant magnetism.

The whole idea of a continuous rift system, as I stated earlier, is only a few years old. At first it was quite controversial. Judging from papers given today, I think we can assume that the majority of speakers here believe that there is some sort of a system; although many doubts have been expressed about whether we are using the right term for it, or whether it has indeed a uniform pattern of characteristics throughout its length. Nevertheless, the feature seems to be established as one of the three basic types of the earth's crust.

The fact that this symposium was held under the auspices of the Upper Mantle Committee indicates that something was expected that would relate to the upper mantle. One justification is, of course, that any feature which covers so large a percentage of the earth's surface may have some unique foundation in the upper mantle; therefore one can study continents, ocean basins, and continental margins in their upper mantle relationships. But perhaps one of the more intriguing thoughts is that the mid-oceanic ridge may represent the upper mantle itself – very little altered and perhaps nearly exposed at the surface. The occurrence of ultrabasic rocks in the deeper parts of the rift valley, as reported by Dr. Udintsev, hints that these valleys are cutting deeply into the crust or even into the mantle. It will be interesting, when the Mohole is drilled, to find out how closely the samples obtained compare with those dredged from the mid-oceanic rift valley.

It is obvious that – although the rift valleys seen in Africa have a great topographic similarity to those in the ocean – there are also rather radical differences; and these differences may tell us something more about the origin of the whole feature. For example, the rift valleys are represented in some areas by positive gravity anomalies, and in other areas by negative

anomalies; but in most areas they show no anomaly at all. Similarly, magnetic anomalies may be positive or negative, or – at places – absent. This might seem discouraging at first, but perhaps it is our greatest hope of understanding the complex processes that have built the rift system; in other words, these contrasts may eventually be interpreted in terms of a mechanism or mechanisms, and history or stages of development. Thus we had the idea that the Red Sea is opening up a small active rift valley in the middle of the larger cleft, and that it may be compared to a more advanced stage in the Gulf of Aden which is a bit wider and looks a bit more like an ocean. Perhaps the Gulf of Aden may in turn be compared to the Norwegian Sea which is a little wider still (200-300 miles wide) – and this again might be compared to the still wider Atlantic. The idea that the Red Sea, the Gulf of Aden, and the Atlantic represent various stages in the development of an ocean is indeed intriguing.

Dr. Sorgenfrei: Thank you Dr. Heezen. Now that we have had a summary of the program over the past two days, I would invite discussion and proposals relating to recommendations to be submitted to the Upper Mantle Committee.

Dr. M. Maldonado-Koerdell (Mexico): I hope that I was able to impress you this morning with the importance of the Central American Isthmus in the study of world tectonics. You will recall that there are two main structural areas in the Central American Isthmus, nuclear Central America to the north, and the Costa Rica-Panama Spur to the south. Between these is a graben or rift-like structure which deserves attention in the study of the world rift system, and I would emphasize that this is a convenient and inexpensive area for such an investigation. It has a system of fractures on its south and north sides separated by a lowland of very sparse relief, opening on one side to the Gulf of Fonseca, and on the other, to the Caribbean Sea. The northern boundary is a canyon-like depression where it enters into the Caribbean Sea. Moreover, we have three sets of phenomena going on at the same time: (1) continuous volcanic activity. More than 40 volcanoes have been in eruption during the last 5 or 6 centuries; (2) continuous earthquakes; and (3) structural displacements in both horizontal and vertical directions. Thus we have an area having major structural and dynamic importance to the Upper Mantle Project, and I would therefore submit the following recommendation.

Studies of the Central American Isthmus by the Pan American Institute of Geography and History and collaborating agencies should be assisted in the following ways:

1) Precise levelling and triangulation networks should be established to detect vertical and horizontal displacements along the Nicaragua Depression.

2) Explosion seismological investigations should be conducted in Lake Nicaragua, and seismological profiles should be made across the Gulf of Fonesca.

3) Measurement of earth tides should be made in the Climandega Plain. (This is located between the Gulf of Fonesca and the Nicaragua Depression and is occupied by Lakes Managua and Nicaragua.)

4) Petrological studies should be carried out in both areas in conjunction with geochronological determinations and other geophysical studies.

5) A volcanological observatory should be established as a central agency for such studies, and for the training of scientists for the Central American countries.

Dr. Sorgenfrei: Thank you Dr. Maldonado-Koerdell. Are there more recommendations?

Dr. F.K. North (Canada): These are comments rather than recommendations, and would have been made during the session proper had it not been behind schedule.

In trying to synthesize results from quantitative measurements at sea with those from factual observations on land, we may fall into one of two errors.

First, we may try to fit the continental grabens in a scheme which fails to account adequately for all their observed features. Though most of these are well known, one which is never mentioned is that the known continental grabens are dominated by trends approximately meridional. There are no known latitudinal equivalents of the African rifts or the rifts of Europe and the Americas. The big east-west continental downwarps are not tensionally faulted. This needs explanation.

Second, closely-known continental grabens are nearly all one-sided or half grabens. One feasible reason for this is that the master fault in each case may antidate the graben as such. There is abundant evidence for this in the African rifts. If it is true, the grabens now exhibit some features which are typical of the faults as they were originally (they may have been strike-slip faults), and not typical of grabens. We should avoid trying to fit such features into an overall explanation of graben origin.

Dr. Sorgenfrei: As Dr. North has indicated his remarks are not recommendations but, rather, comments. However, they do contain the recommendation

that, in studying the world rift system, we should not concentrate wholly on the oceans, we must also take more heed of the continental areas. Are there other recommendations?

Dr. D.H. Matthews (U.K.): I should like to make two recommendations, both I am afraid mainly concerned with the oceans. The first, I know from discussion with several people, has some support; the second one is a purely private kite and I am quite prepared to see it shot down.

(1) An investigation of the ends of ridges. The places where the mid-ocean ridges meet the land are especially significant in investigations of their origin. It is desirable to study the differences in response of the continental and oceanic crusts to underlying disturbances in the upper mantle by mapping the gravity anomaly pattern and the magnetic anomaly pattern across the transitional zone between the rift valleys and their associated structures on land and the median structure of the mid-ocean ridge. It is recognized that such work may involve airborne magnetometer surveys and helicopter support of ground parties, but it is believed that the dating of the beginning of the present sequence of volcanic and tectonic activity on land is of the greatest importance in establishing the age and origin of the mid-ocean ridge system.

(2) An investigation of major lineations in the structure of the ocean floor. We should attempt to identify, map and, if possible, date the lineaments of topography and magnetic anomaly on the deep ocean floor. This can best be accomplished by detailed surveys but may also be attempted by correlating adjacent profiles.

Dr. Sorgenfrei: Thank you Dr. Matthews. Dr. Whitham?

Dr. K. Whitham (Canada): I have been surprised in the last few days that no one has mentioned the potential of electromagnetic induction methods for the study of temperature distribution under rifts. These could be fairly easily applied in East Africa, Iceland and possibly in the Azores. The point I would like to make is that there should be a major experiment carried out on the East African rifts to study the electromagnetic induction situation. When one does this type of experiment, one hopes to measure the temperature at the present time, and at depth. This can be very interesting because most people forget about the dynamics of rifts. If you assume a rift system is in equilibrium, the present heat flow as measured by a gradient quite near to the earth's surface can be assumed to tell you something about conditions at great depths inside the earth. In a non-equilibrium case, the assumption is incorrect. The electromagnetic induction method on the other hand, although it has many failings, may tell you the conditions at depth at the present time, and if you find that there is a discrepancy between these and extrapolations from present heat flow measurements, you then have an extra

piece of knowledge. In effect, you have a dimension in time, and you have the knowledge of whether a rift system is growing, decaying, or in equilibrium. This is something that I think is missed by all other methods such as the gravity field and the D.C. magnetic anomalies associated with polarization patterns, and remanent magnetization. Now I cannot claim very much success for our efforts, but I can claim that we in Canada have tried this sort of approach in certain areas.

Dr. Sorgenfrei: Thank you Dr. Whitham. Dr. Thorarinsson has a comment.

Dr. S. Thorarinsson: I would like to recommend that more effort be made to obtain more absolute geological ages by the K-Ar and other methods for the rocks of the different rift systems. This should improve our knowledge of the ages of the different rift systems, and permit us to calculate more exactly the rate of the tectonic movements involved in their formation. My impression from listening to the papers given at this symposium is that we are badly in need of absolute dates. Now many of the rift systems are accompanied by extrusion of basaltic and other rocks, and there are so many possibilities of materials to date that I think that this should be emphasized. This will serve to underline the part of Dr. Matthews' recommendation relating to the historical development of the rift system. In a more general vein, I would recommend as close a cooperation as possible between geologists and geophysicists in the study of problems pertaining to the World Rift System.

Dr. Sorgenfrei: Thank you, Dr. Thorarinsson.

Dr. R.W. Girdler (U.K.): I would endorse the first proposal by Dr. Matthews concerning the need for work where the oceanic rift system meets the continents, and I would like to emphasize the importance of aeromagnetic work in regions where the oceanic rifts intersect the continents. Some of the critical areas, such as the junction of the Red Sea and Gulf of Aden are difficult of access, and it is such areas where aeromagnetic studies are most needed. These are also the areas that would benefit most from international support. At the Upper Mantle meeting in Nairobi we had a specific proposal to ask for a U.S. Mapping mission to do aeromagnetic work over the junction area of the Red Sea and the Gulf of Aden. It seems to me that it is very important that we investigate this area in detail and try to correlate the magnetic data with those available for the Gulf of Aden and the southern part of the Red Sea. Aeromagnetic work seems to be the obvious way to link the geophysical techniques used at sea and on land.

Dr. Sorgenfrei: Thank you, Dr. Girdler.

Dr. J.B. Hersey (U.S.A.): I would further endorse the recommendations of Dr. Matthews and Dr. Girdler with this proposal.

The value of detailed surveys of the properties of the mid-ocean ridge-rift system has been demonstrated by the work of several groups. However, these studies have been concentrated near the crest of the ridge. It is most important that detailed surveys be carried out to the flanks of the ridge and beyond.

It is proposed, therefore, that detailed surveys be made in selected areas across the entire system and, where possible, that these be connected to the continental strip surveys proposed as a part of the Upper Mantle Project.

Dr. Sorgenfrei: Thank you, Dr. Hersey. I believe Dr. Heezen has a proposal.

Dr. Heezen: In Nairobi there was a suggestion that the existing information on East Africa be compiled. The East African group made an excellent compilation before the meeting, and more work was planned along the same line. I think that we should follow this lead in other areas and endeavour to compile what is already known.

The general encouragement of studies of continental rifts where they meet with the oceanic rift system has been mentioned by several speakers. I think this should be extended to cover the continental rifts in general.

There is need of a liaison between different groups that are working on rifts and rift problems, so that data can be exchanged and can also be more readily comparable when it is collected. It has been suggested that the Upper Mantle Committee might consider the formation of a working group in their organization on the study of rifts – to provide such a liaison between different groups, and to be a centre for transmission of information and plans.

It has also been suggested that – if the work on rifts is accelerated, which it seems destined to be – there should be another meeting on the subject in the next few years to communicate ideas to a larger group than is represented at this small, selected symposium. The meeting might be part of the next general assembly of the International Union of Geodesy and Geophysics.

Dr. Sorgenfrei: Thank you, Dr. Heezen. Are there any comments to these proposals?

Dr. T.F. Gaskell (U.K.): As I understand it, one of Dr. Heezen's recommendations is that everybody should look to their own territory, their own country and see what they have got in the way of grabens or rift valleys. As

an amateur in this, I thought the only rift valleys were in East Africa. I was most impressed with the report on East Africa, and I think that everyone else who has got rift valleys in their backyard should report to a working group such as Dr. Heezen is suggesting so that we will know a bit more about the world as a whole.

Dr. Sorgenfrei: Thank you, Dr. Gaskell. And Dr. Laubscher?

Dr. Laubscher (Switzerland): There is already a working group on tectonics, and it has distributed questionnaires on exactly this question. Every country was supposed to submit reports on the rifts in its backyard by August 1 (1965).

Dr. Sorgenfrei: Thank you Dr. Laubscher. Your remark demonstrates how important it is to have liaison amongst working groups. I think Dr. Harrison would now like to take the floor.

Dr. J.M. Harrison (Canada): Mr. Chairman, this question of another working group bothers me a trifle. We have ten working groups now, and although we may have a different situation facing us with respect to the World Rift System, the working groups were specifically selected to cover the major international projects to be undertaken or supported by the International Upper Mantle Committee. I would therefore like to modify Dr. Heezen's suggestion to the extent that, if another group is to be organized, it be given some other name, perhaps "project group". I would assume that perhaps whoever was in a coordinating role in this group might call on the appropriate specialists from other working groups to provide appropriate information on a particular discipline. The working groups by themselves cannot carry out projects, they were set up as disciplinary groups. I therefore suggest the following recommendation:

It is recommended that a "project group" on the World Rift System be established to provide liaison between various groups concerned with the study of rifts, to coordinate proposals, and to promote research on these structures so fundamental to our knowledge of earth processes.

Dr. Sorgenfrei: Thank you, Dr. Harrison. This was a proposal to alter a proposal. What does Dr. Heezen remark to this?

Dr. Heezen: The suggestion by Dr. Harrison sounds perfect to me. I think that it is a very good suggestion on how to resolve an administrative problem.

Dr. Sorgenfrei: Thank you, Dr. Heezen. If Dr. Heezen agrees, I think nobody will differ with him. Are there any other proposals? Dr. Runcorn?

Dr. S.K. Runcorn: I would like to make an appeal for work to be done on the examination of seismic travel times. I was interested in a paper published a few years ago in Germany in which it was stated that the times of travel of seismic waves to the core boundary and back varied in different parts of the earth. Now I think that in view of the discussions in the last two days it would be worth looking to see whether there is any relationship between the seismic travel times and the major features of the earth's surface – such as the rift system. I have in mind, of course, the possibility that the anisotrophy of crystals produced by the convection in the mantle might produce say, 5 per cent differences in seismic velocities, which would be detectable provided one took sufficient care.

As a second proposal, I would draw attention to a remarkable positive gravity anomaly over the Indian Ocean slightly to the southeast of the tripartite join of the Carlsberg Ridge and the Circum-Antarctic Ridge. I think it is true to say that this is the only gravity anomaly, high or low, which does not appear to be related at all to the features that we have been talking about in this symposium. In view of this, I think we might recommend that someone take a good look at the anomaly and its possible causes.

Dr. Sorgenfrei: Thank you, Dr. Runcorn. Dr. Beloussov?

Dr. V.V. Beloussov (U.S.S.R.): It would be very unreasonable for me to make any proposals to this audience because as the chairman of the Upper Mantle Committee I must adopt your proposals. It would be impolite for me to attempt to impose something upon you. However as the chairman of a future meeting of the Upper Mantle Committee, I would like to clarify the situation a little for myself, and I ask you to correct me if I have misunderstood your proposals.

First, we – not only I, but I think all the Bureau and all the Upper Mantle Committee – would like to have your support in proposing that the problem of world-wide rift system is a very important one in earth science. With this support, then we can continue to select more specific problems to recommend for study.

Now let us consider some of the details of our would-be resolution. For example, with regard to the oceanic parts of the rift system, I understand from the proposals that have been made during this meeting that you would like detailed studies in selected regions in order to know more about the deep structure and external shape of the rift zone. These detailed studies should cover not only the grabens themselves, but all parts of the mid-oceanic ridge. Particular attention was drawn to two or three regions where these suboceanic ridges meet the continents, and it is to be considered that these regions are especially critical.

Then we must consider the continental part of the rift system, and I understand from your point of view – and I am speaking always from your point of view – that it would be desirable to prepare a synopsis of all the data available on grabens situated on the continent. Some of these continental rifts are very well known, as for example the Rhine graben, and such synopsis would be very useful.

Next we should think about the future presentation of the results of our studies, and in this regard it was recommended that we hold a symposium on the rift system during the next general assembly of the Union of Geodesy and Geophysics. I would like to suggest that this symposium be based upon invited papers. It would be very good to have a broad and exact review of the situation in this field.

Finally, it was recommended that a group be organized to coordinate and, in some respects, supervise all future work on the rift system. I think this is a very sound proposal because so far, the structure of our Upper Mantle Committee is vertical. We are divided into groups according to specialities or disciplines, but now we should attempt to combine disciplines within the framework of our projects. I think it would be completely reasonable to have such a group, and its proposed title, "Project Group", would seem quite acceptable. This is essentially what I wanted to say, and it is basically a question: Have I understood your suggestions correctly?

Dr. Sorgenfrei: Thank you, Dr. Beloussov. I think that you have summarized the situation very well, and I think that you understand it very well. Now that we have had a summary, and if there are no other proposals, I think we may convene the meeting, and close for tonight.

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APPENDIX I

PROGRAM

SYMPOSIUM ON THE WORLD RIFT SYSTEM
OTTAWA, CANADA, 1965

4 September A.M.

DEAD SEA, RED SEA AND AFRICA

Chairman: V.V. BELOUSSOV Reporter: T.N. IRVINE

V.V. BELOUSSOV (USSR): Opening Remarks.
R. FREUND (Israel): The Dead Sea Rift.
L. KNOPOFF (USA): Gravity Profiles Across the Dead Sea Rift.
T.D. ALLAN (UK), and M. PISANI (Italy): Gravity and Magnetic Measurements in the Red Sea.
S.T. KNOTT (USA): Red Sea Seismic Reflection Studies.
A.S. LAUGHTON (UK): The Gulf of Aden in Relation to the Red Sea and Afar Depression of Ethiopia.
R. GIRDLER (UK): The Relationship of the Red Sea, Gulf of Aden and Ethiopian Rifts to a Possible Region of Uprising Mantle Convection Beneath the Arabian Sea.
A.S. ROGERS (Ethiopia): Some Comments on the Rift in Ethiopia.
B.B. BROCK (South Africa): The Rift Valley Craton.

4 September P.M.

THE INDIAN, ATLANTIC AND ARCTIC OCEANS AND SIBERIA

Chairman: E.F. ROOTS Reporter: A. LAROCHELLE

E.F. ROOTS (Canada): Opening Remarks.
L. PICARD (Israel): Thoughts on the Graben System in the Levant.
D. MATTHEWS (UK): The Northern End of the Carlsbad Ridge.
R.L. FISHER (USA): Indian Ocean Rifts and Fracture Zones.
E. BEDERKE (Germany): The Development of European Rifts.
B.D. LONCAREVIC, C.S. MASON (Canada), and D.H. MATTHEWS (UK): Mid-Atlantic Ridge Between 45°N and 46°N.
S. THORARINSSON (Iceland): The Median Zone of Iceland.
N.A. FLORENSOV (USSR): The Baikal Rift Zone (read by V.V. BELOUSSOV).
C.R. TWIDALE (Australia): Fault Blocks and Rifts in Southern Australia (by title).

5 September A.M.

THE PACIFIC OCEAN AND WESTERN NORTH AMERICA

Chairman: S. THORARINSSON Reporter: E.F. ROOTS

G.B. UDINTSEV (USSR): Results of Upper Mantle Project Activities in the Indian Ocean on the Research Vessel VITYAZ.
M. MALDONADO-KOERDELL (Mexico): Geological and Geophysical Work in the Gulf of Fonseca-Nicaraguan Depression Area, Central America, by the Pan American Institute of Geography and History and Associated Agencies.
M. HILL (USA): The San Andreas Fault System, California and Mexico.
W. HAMILTON and W.B. MYERS (USA): Cenozoic Strike-Slip Faulting and Related Deformation in the Western United States.
G.A. THOMPSON (USA): Rift System of Western United States.
K.L. COOK (USA): Rift System in the Basin and Range Province.
G.B. LEECH (Canada): The Rocky Mountain Trench: Not a True Rift.

5 September P.M.

PETROLOGY AND GEOPHYSICS OF RIFTS

Chairman: H. KUNO Reporter: T.N. IRVINE

H. KUNO (Japan): Opening Remarks.
M. TALWANI (USA): Patterns of Magnetic Anomalies over the Mid-Oceanic Ridge.
R.W. VAN BEMMELEN (Netherlands): Evolution of Mega-undulations in the Atlantic and Indian Oceans (Presented by F.P. AGTERBERG).
D. KRAUSE (USA): Equatorial Shear Zone.
M. LANGSETH (USA): Review of Heat Flow Measurements in the Mid-Oceanic Ridge.
S.K. RUNCORN (UK): Satellite Gravity Observations and World-Wide Tectonics.

DISCUSSION OF RECOMMENDATIONS

Chairman: T. SORGENFREI Reporters: T.N. IRVINE
A. LAROCHELLE
E.F. ROOTS
W.H. POOLE

Recommendations were submitted and read by:

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F.K. NORTH (Canada)
D.H. MATTHEWS (UK)
K. WHITHAM (Canada)
J.B. HERSEY (USA)
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APPENDIX II

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