National geophysical facilities

Geophysics in United Nations projects

J.M. Brown

United Nations
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Abstract. The United Nations is engaged in conducting large exploration programs in the developing countries throughout the world. The cost of these programs can vary from, say, $700,000 to perhaps $3,000,000 depending upon the scale of the operation and the objectives to be obtained. Extensive use is made of applied geophysics. The objectives vary, but the larger programs are designed to prepare the way for investment by the Government or private sector according to national policy.

The geophysical element of these programs usually includes aerial survey followed by ground geophysics together with geological and geochemical surveys. From analysis of the data so obtained further geophysical surveys may be undertaken in order to select drilling targets.

Operations include investigations for porphyry copper mineralization, iron ores, potassium deposits and so on. Others are in the field of geothermal energy and in groundwater.

A considerable portion of the work is contracted, proposals being sought on an international sis. Geophysics also features in the establishment of training institutes a.u in the provision of fellowships.

Of the larger programs being undertaken by the United Nations a few are in the final stages and from the analysis of these, sound contributions to economic development can be expected.

Résumé. Les Nations Unies ont entrepris de vastes programmes de reconnaissance dans les pays en voie de développement à travers le monde. Dans la poursuite de ces programmes d'étude, la géophysique appliquée est largement mise à contribution. Le coût de ces programmes peut varier considérablement selon l'envergure des opérations et les buts à atteindre, disons de $700,000 à $3,000,000 environ. Les objectifs varient, mais les programmes les plus importants ont pour but de préparer la voie aux investissements qui seront publics ou privés, selon la ligne de conduite de l'Etat.

La partie de ces programmes qui concerne la géophysique comprend généralement des levés aériens suivis d'études géophysiques au sol ainsi que des relevés géologiques et géochimiques. L'analyse des données ainsi obtenues permet d'entreprendre des relevés géologiques plus détaillés et de déterminer des emplacements précis pour le forage.

Le travail comprend également des recherches en vue de mettre à jour des minéralisations de porphyre cuprifère, des gisements de fer, de potasse, etc. D'autres études portent sur les sources d'énergie géothermiques et sur les eaux de fond.

Une bonne partie du travail est exécutée par des entrepreneurs; l'appel de soumissions se fait à l'échelle internationale. La géophysique a aussi une place de choix dans le programme d'études des instituts de formation et dans l'octroi des bourses d'études post-doctorales.

Certains des plus importants programmes entrepris par les Nations Unies en sont au stade final et leur analyse permettra, espère-t-on, d'élaborer des programmes économiques opportuns et judicieux.

For several years now the United Nations has been assisting governments of developing countries to carry out investigations of their mineral resources. In these programs – sponsored by the United Nations Development Programme – applied geophysics plays an important role. These programs vary from the provision of a single expert in geophysics for a period of a few months to the providing of a team of experts and exploration equipment for a period of several years.

At present some 35 major operations are in progress and are directed towards the search for exploitable minerals and the training of national counterpart personnel in the various associated disciplines and methods of exploration. The accompanying map and table show the locations and statistics of these projects.

Geophysical exploration techniques are employed in accordance with the requirements of the program. The personnel may be recruited directly by the United Nations or an operation may be contracted in whole or in part. The objectives vary, but the larger programs are designed to prepare the way for investment from the governmental or private sector according to national policy. The emphasis is on the early economic development of mineral resources and to this end investigations employing all applicable modern geophysical techniques are undertaken.

The scale of operations in any given area is often difficult to decide. One school of thought has propounded the view that a saturation program is the only really satisfactory method of determining the mineral potential of an area. This type of survey involves a detailed systematic examination of the area employing geochemical, geophysical and geological techniques, drilling and massive laboratory support. This is a high-cost survey but has the merit that nothing of significance should be missed. Another school considers that the existing geological data are the basis for planning exploration programs. This type of operation progresses from a broadly based survey to detail in successive stages. Areas are eliminated at each stage until drilling targets are selected. This is a lower-cost type of operation but it does require that judgments be made at each stage as to which portions should be dropped from the exploration program. There is always a risk that an orebody could be missed.

The larger United Nations programs are based on evidence of potential mineralization. This evidence is obtained from studies of existing literature and maps. Field studies of the areas which are considered to have potential are made and the economic and technical basis for large operations established. Thus the effort is concentrated on evaluating this potential and the field program is designed accordingly.

After a study of all available data of a given area, a program is prepared, the geophysical techniques being integrated into an over-all investigation plan. It is often constituted as follows:

Photogeological interpretation;
Reconnaissance geochemical prospecting;
Aerial magnetic and radiometric surveys of selected areas;
Ground follow-up by geological, geochemical and geophysical surveys;
Aerial electromagnetic surveys, if applicable;
Further detailed ground surveys;
Drilling, pitting and trenching;
Evaluation of results.

There are many variations on this theme of mineral exploration and a continuous review of the results is made at each stage.

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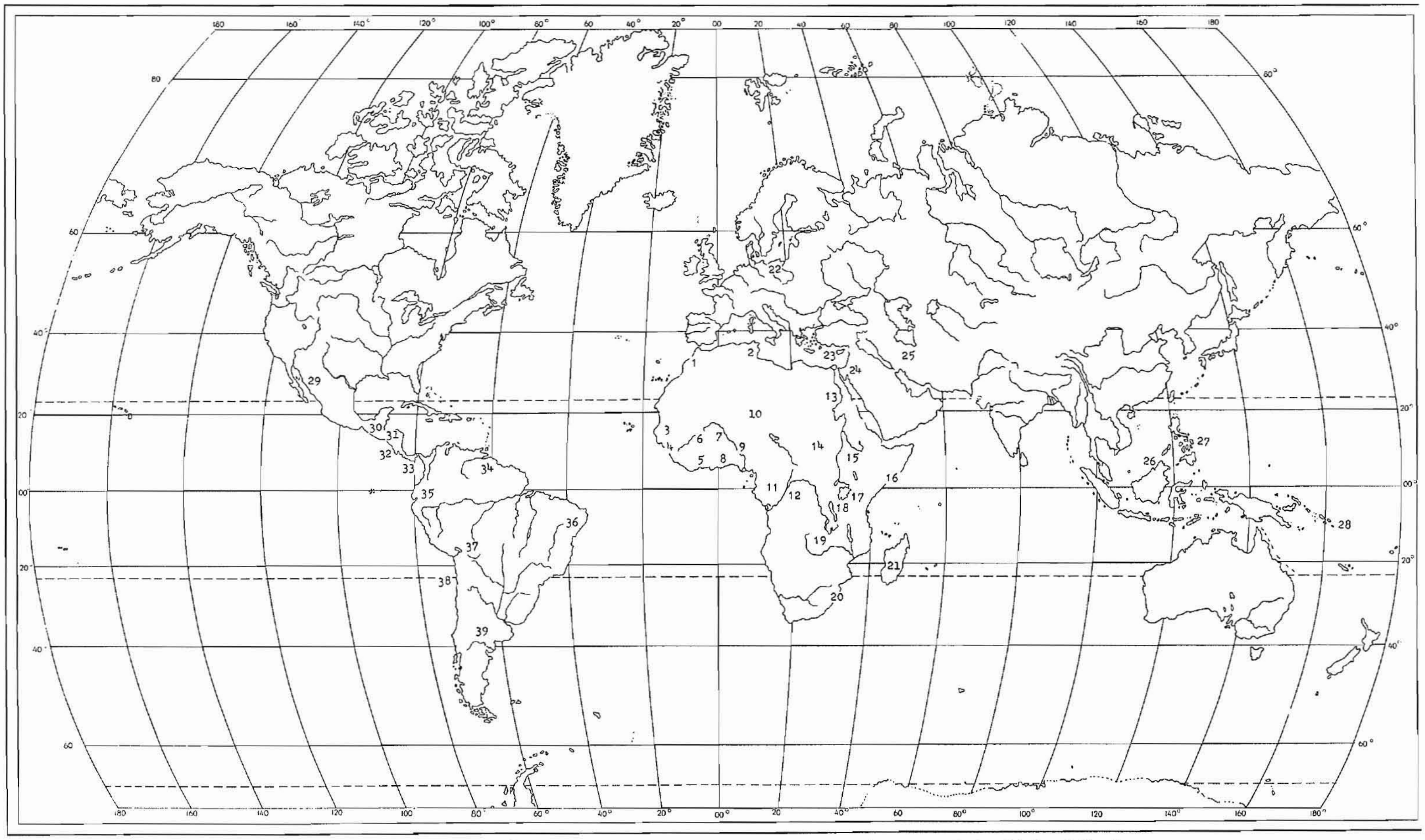


Major mineral exploration programs conducted with the assistance of the United Nations.

Country (see map)	Size of Area (in km^2)	Methods Employed	Duration (in years)	Professional Staff		Costs in U.S. Dollars		
				UN	Government	UNDP	Government	Total
1. Morocco	500	A,Q,R,S		4-5 and subcontract	3-5	870,500	553,300	1,423,800
2. Tunisia	10,000	A,B,F,G,H,I,Q,S,T	3	4 and subcontract	3	870,500	553,049	1,423,549
3. Senegal (1)	25,000	A,B,F,G,H,I,K,N	3 1/4	5-6 and subcontract	5-7	721,800	552,978	1,274,778
4. (2)	25,000	A,B,F,G,I,L,Q,S	2	7 and subcontract	4	437,700	348,724	786,424
5. Ivory Coast	35,500	A,B,C,D,F,G,H,I,K,L,P,Q,S	3	5 and contract	4	979,300	918,600	1,897,900
6. Upper Volta (1)	10,000	A,F,G,H,I,K,L,P,Q,S	3	5-6 and contract	5	964,600	508,500	1,473,100
7. (2)	–	A,H,I,Q,R,S,Y	1	3 and contract	5-7	431,400	101,100	532,500
8. Togo	20,000-30,000	A,B,C,D,F,G,H,K,L, P,Q,U,S,X	3-4	6-8 and contract	3-4	1,136,750	610,000	1,746,750
9. Nigeria	55,000	A,B,C,D,E,F,G,H,I, K,L,P,Q,S	3 1/4 (terminated)	4 and contract	18-22	520,000	536,499	1,056,499
10. Niger	21,000	A,B,F,G,H,K,L,P,Q,S	3 1/2	6-8	1	896,200	575,500	1,471,700
11. Congo (B)	10,000	A,B,F,G,I,L,P,Q,S	3	7	2	704,800	619,100	1,323,900
12. Congo (K)	7,000	A,B,L,P,Q,X,S	3			793,500	673,660	1,467,160
13. U.A.R.	50,000	A,B,C,D,E,F,G,H,I, K,L,P,Q,S	4 3/4	9 and contract	12-16	1,673,600	2,113,506	3,787,106
14. Sudan	123,000	A,B,C,D,E,F,G,H,I, K,P,Q,S	3 3/4	7 and contract	14	1,171,200	836,585	2,007,785
15. Ethiopia	82,000	A,B,C,D,E,F,G,H,I, K,L,O,P,Q,S	4	7 and contract	22	1,248,900	934,307	2,183,207

16. Somalia	25,000	A,B,C,D,F,G,H,L,P,Q,X,S	4	5 and contract	–	566,300	354,622	920,922
17. Kenya	25,000	A,B,F,G,H,K,L,Q,S	2 1/2	5	9	496,700	408,600	905,300
18. Tanzania	3,500	A,B,C,D,E,F,G,H,K,L,Q,S	3	4 and contract	14	576,000	441,500	1,017,500
19. Zambia	45,000	A,B,C,D,E,F,G,H,I, K,L,P,Q,S	3 1/2	4-5	8 and contract	676,400	816,600	1,495,000
20. Swaziland	20,000	A,B,C,D,E,F,G,H,I, J,K,L,P,Q,S	4	3 and contract	5	427,500	505,016	932,516
21. Madagascar	70,000	A,B,C,D,F,G,H,L,N,P,Q,S	2 3/4	8 and contract	7	927,200	658,088	1,585,288
22. Poland	13,500	A,M,Q,X,S	2	3 and contract	8+ seismic and drilling services	921,600	1,464,311	2,385,911
23. Cyprus	4,500	A,B,C,D,E,F,G,H,J, K,L,N,Q,S	5	11-12 and contract	13	1,121,300	1,842,250	2,963,550
24. Jordan	–	A,B,F,G,H,I,J,K,L, N,P,Q,S,V	3 1/2	4	12	486,200	484,840	971,040
25. Iran	–	A,B,F,G,H,K,L,P,Q,S,V	5	15	18-25	1,425,300	2,220,000	3,645,300
26. Malaysia	1,200	*,A,B,F,G,H,K,O,Q,S	3	2	–	(450,000 estimated)	(100,000 estimated)	(450,000 estimated)
27. Philippines	–	A,B,F,G,H,I,K,L,Q,S,V	4	6	10-14	719,900	653,340	1,373,240
28. BSIP	(25,000)	A,B,C,D,E,F,G,H,J, K,L,P,Q,S	3 1/2	4 and contract	8	893,100	771,962	1,665,062
29. Mexico	59,000	A,B,C,D,F,G,H,I,J, K,O,P,Q,S	3 (completed)	7 and subcontract	10-20 as required	788,500	1,908,300	2,696,800
30. Guatemala	20,000	A,B,F,G,H,K,L,P,Q,S	4	10	6	789,900	541,300	1,331,200
31. El Salvador	6,500	A,B,F,G,H,K,L,P,Q,S	3	7-9	4	673,600	407,560	881,160
32. Nicaragua	25,000	A,B,C,D,F,G,H,K,L, O,P,Q,S	2 1/2	6-7 and subcontract	3-6	693,000	446,300	1,139,300
33. Panama	17,000	A,B,C,D,F,G,H,K,L, P,Q,S	4	10 and subcontract	7	971,500	613,423	1,584,923
34. Guyana Phase I	33,000	A,B,C,D,E,F,G,H,J, K,L,O,P,Q,S	3	2-4 and subcontract	8	627,700	592,010	1,219,710
Phase II	(20,000)	A,B,C,D,E,F,G,H,I, J,K,L,P,Q,S	3	8-10 and subcontract	11	929,000	1,077,000	2,006,000
35. Ecuador	20,000	A,B,C,D,F,G,H,I,K, L,P,Q,S	3	5-7 and subcontract	7-9	819,600	387,420	1,207,020
36. Brazil	1,000	A,M,Q,W	2 1/2	3-4 and subcontract	4	569,850	410,750	980,600
37. Bolivia (1)	30,000	A,B,C,D,E,F,G,H,K, L,P,Q,S	3 1/2	6 and subcontract	12	866,300	836,120	1,702,420
(2)	–	R,S,U,V	5	5-6	35-40	733,400	1,685,065	2,418,465
(3)	500	A,B,N,P,Q,R,S,T	4	4-5	9	729,800	530,630	1,260,430
38. Chile (1)	30,000	A,B,C,D,F,G,H,I,K, P,Q,S	2 1/2	4-8 and subcontract	6	946,000	740,000	1,686,000
(2)	4,500	A,B,C,D,F,G,H,K,P,Q,S	1 1/2	7-9	4-6	463,150	392,000	855,150
(3)	1,300	A,F,G,H,I,N,Q,R,S,T	2 1/2	5-7	11	1,084,400	924,508	2,008,908
39. Argentina (1)	128,000	A,B,F,G,H,I,K,P,Q,S	3 1/2	10	18-30	1,068,100	1,669,400	2,737,500
(2)	(400)	A,B,F,G,H,I,K,Q,S	1 1/2	6-9 and subcontract	14	1,102,900	1,056,280	2,159,180

The table comprises a list (not complete) of major mineral exploration programs that have been conducted or are in progress by governments assisted by the United Nations.

The figures contained in the table are to be understood as those obtaining at the time operations started. The final figures will vary to some extent from those quoted.

The table does not include projects in which the main emphasis is in groundwater investigation or in geothermal investigation. There are several such projects, all of which employ geophysical techniques to some degree.

Symbols

* Mineral operations form part of larger comprehensive resources development project
A. Geological mapping
B. Geochemical sampling
C. Aerial magnetometer survey
D. Aerial radiometric survey
E. Aerial electromagnetometer survey
F. Ground magnetometer survey
G. Resistivity surveys
H. Electromagnetometer surveys
I. Induced polarization surveys
J. Gravity surveys
K. Self potential surveys
L. Radiometric surveys
M. Reflection seismic surveys
N. Refraction seismic surveys
O. Aerial photography
P. Photogeological surveys
Q. Drilling
R. Ore dressing and beneficiation
S. Assaying and chemical analyses
T. Limited entry underground or stripping
U. Pyro- and hydrometallurgy
V. Establishment of institution (including bureaux of mines and geological surveys)
W. Pilot plant and feasibility studies
X. Well logging
Y. Transport studies

Staffing of operations

Depending upon the objectives of the programs the United Nations may recruit its geophysicists directly and purchase or rent equipment. This procedure is adopted where the training of nationals represents a major part of the operation. The field operations are directed and undertaken by United Nations personnel in close association with national geophysicists or geologists. This is essential if the exploration programs are to continue after the departure of the international personnel. The United Nations personnel are recruited through the Office of Personnel and the criteria for selection are mainly technical competence and appropriate experience in the particular aspects of the exploratory work to be undertaken.

Training

Strong emphasis is placed on the training of national geophysicists during the course of operations. In addition to working closely with United Nations geophysicists, national geophysicists may be awarded fellowships by means of which they receive training in geophysics. These fellowships may be in specific aspects of applied geophysics, e.g., techniques in the analysis of seismic data, or in applied geophysics in general. The recipient must have the necessary qualifications for the course he intends to pursue and must be associated with the United Nations Development Programme that is in operation in his country.

Fellows have undertaken studies in many of the industrial countries. The place of study is not necessarily a university or technical institute. Practical training is often achieved by arranging that the fellow be attached to a geophysical contracting company: he is thus exposed to the field procedures and methods of analysis applied by a company. Other organizations to which he may be attached include geological surveys or bureaus of mines in the industrial countries.

Equipment

The equipment for operations is purchased through the Purchase and Transportation Section of the United Nations. Technical specifications are prepared and suppliers are then invited to submit bids on the basis of these specifications. A particular make of equipment *may* be required: this is agreed upon when special circumstances obtain, such as local availability of spares.

The title to equipment purchased by the United Nations remains with the United Nations throughout the project unless special circumstances obtain or agreement to turn over the equipment during the life of the project has been reached. On completion of operations, the equipment is usually turned over to the government: part of the project is usually the training of nationals in the use of the geophysical equipment.

Reports

During the course of the project, staff members are encouraged to publish technical papers on matters of interest. Government staff must obtain the clearance of their government to publish, and the UN staff that of UN Headquarters. This is simply to ensure that if the paper touches on non-technical, matters, these reflect accurately the UN's position.

Contracted reports, e.g., aerial geophysical, are usually made available by the government to interested parties. The UN retains copies of all contracted reports and these are available for study provided prior authority to make them available has been given by the government concerned.

The final reports of the projects are published and are circulated to member governments. These reports contain a summary of all matters relating to the project, the major findings and recommendations for future activity. These final reports are just beginning to come along.

Those which have been published include:

Bolivia: Pilot Mineral Survey of the Cordillera and Altiplano

Chile: Mineral Resources Survey in the Province of Coquimbo

Uganda: Airborne Geophysical Survey of Three Regions in Uganda.

The responsibility for producing the version to be published is that of the United Nations: the contents must be approved by the government concerned before publication.

Seminars

Interregional seminars are an important means by which technical information is disseminated. These are organized by the United Nations in conjunction with a host country. A recent example will illustrate this.

In July 1967 such a seminar was held in Moscow. It was entitled 'Interregional United Nations Seminar on New Methods of Mineral Exploration with Emphasis on Geophysical Techniques'. Developing countries were invited to send a suitably qualified fellow to the seminar. During the course of the seminar (which was attended by 40 participants from the developing countries) 24 papers were read and discussed. These papers were delivered by specialists invited to attend the seminar by the United Nations and by the host country. By this means the participants were made aware of current developments in mineral prospecting and had the opportunity to discuss with the speakers problems specific to their own countries. The papers, many of which dealt with the most recent advances in geophysical instrumentation and techniques, will be published shortly by the United Nations.

Operations

An example of a typical UNDP operation is one at present under way in western Argentina. An area of about 140,000 square kilometres was selected as having the potential of porphyry copper mineralization. The area was chosen by the government after an analysis of data which had been accumulated over a period of years and discussions with consultants in the field of mineral exploration. The preliminary phase involved the preparation of a work plan including estimations of personnel required, types of equipment needed and, of course, the costing of the operation.

After a thorough literature search a photogeological study of the area was undertaken and from this, together with field checks and a geochemical reconnaissance program, the area was reduced to about 80,000 square kilometres. Within this area more detailed geochemical, geophysical and geological surveys were undertaken. This geological work included magnetometer, electromagnetometer, resistivity and test induced polarization surveys. From an analysis of the results obtained it was decided that the combination of geochemical and induced polarization/resistivity techniques would be the most fruitful. Induced polarization surveys were contracted and these, together with geological data, enabled the selecting of sites for test drilling to be made.

To date the drilling has shown the presence of copper-bearing porphyries. The present programs of both induced polarization surveys and drilling operations are intended to determine the economic potential of the porphyries and to locate additional deposits.

Another example is the program undertaken in Guyana. Again areas were selected for investigation following upon the work of the Geological Survey of Guyana. An aerial magnetometer survey of the areas of interest was obtained, using a Gulf Mark III instrument, and the Geological Survey of Guyana with United Nations assistance undertook ground follow-up surveys, using total force and vertical component magnetometers, resistivity and electromagnetic instrumentation. After analysis of the results, limited aerial electromagnetic surveys were mounted and detailed ground follow-up work instituted. The results of these operations have led to a further follow-up program which includes additional aerial electromagnetic operations, ground surveys and an intensive drilling program.

Some 25,000 line kilometres were flown in southern and western Ivory Coast. The line separation was 1 kilometre and the terrain clearance 150 metres except over rugged terrain where a clearance of 300 metres was adopted. This work is now being followed up by the government and by United Nations staff. In addition, a contract geophysical team employing a variety of instruments is in the field. A large low-grade iron deposit has been located and consideration is being given to making a detailed gravity survey of the deposit.

In Uganda approximately 36,000 line kilometres of aerial magnetic and scintillation counter survey were flown together with some 14,000 line kilometres of combined electromagnetic, magnetic and scintillation counter survey. The combined survey was flown over an area which is believed to contain base metal sulphides. From geological, geochemical and ground geophysical work, a rock series – the Kilembe series – had been identified. Within this series but separated from the project area by a rift valley, a major copper mine was in operation.

The aerial work led to an intensive ground follow-up program using magnetometer, resistivity, AFMAG and electromagnetic techniques. These were supported by detailed geochemical work. This follow-up work has been in progress for five years and the major effort, at present, is being made by a large mining company. Their follow-up technique is basically intensive geochemical work with detailed geophysical surveys in limited areas. These, in turn, are supported by test drilling.

In Bolivia the presence of steeply dipping tabular exposed bodies which usually contain conductive sulphides led to a decision to use an electrical method of prospecting. Although it was realized that the topography was very rugged it was hoped that sufficient information could be obtained from electromagnetic flying to justify intensive ground operations.

From the study of the results approximately 40% of the recorded electromagnetic anomalies were rejected as being due to sharp variations in ground clearance or because they could be attributed to surface conductivity.

The ground follow-up was initially based on magnetic and electromagnetic surveys together with geochemical traverses. Electromagnetic instrumentation includes simple horizontal loop (vertical dipole) and Turam units. The rugged terrain made effective use of the Turam units very difficult and the emphasis was placed on the use of more portable horizontal loop (vertical dipole) equipment. This resulted in a loss of 'penetration' but the oxidation was relatively shallow and the horizontal loop equipment was much simpler to operate in these conditions.

Self-potential methods were tried but strong and erratic background gradients on the steep surface slopes made it all but impossible to recognize anomalous values that might be attributable to sulphide bodies.

The combination of electromagnetic and geochemical work together with, of course, geological studies, led to the selection of targets worthy of drilling. Bismuth/tin intersections of economic grade were made by drilling. These are still being investigated but there is no doubt that the intersected mineralization is of economic significance.

A survey to study the mineral resources of the Atacama region in northern Chile was undertaken by the United Nations and the Chilean Government. This survey comprised photogeological mapping, regional and local geological mapping, aerial and ground geophysical surveys, geochemical surveys and diamond drilling. The main effort was directed towards the findings and appraising of copper and iron deposits.

Airborne magnetometer surveys resulted in the discovery of several magnetic anomalies. The more important were investigated by ground magnetic and electromagnetic surveys supported by drilling which led to the discovery of a large orebody of magnetite. The Corporación de Fomento Producción is now undertaking a very extensive drilling program to determine the size and grade of this orebody. Preliminary studies show the ore to be high grade.

The operations also included detailed investigations for copper, gold, silver, and manganese. Induced polarization, Turam, magnetic and gravimetric surveys were used in these investigations together with detailed geochemical studies.

The results of these operations were such that the government decided to extend the investigations to the south of the Atacama region into Coquimba. By 1966 geophysical work, including induced polarization surveys, together with diamond drilling, proved the existence of a large porphyry copper deposit. Intensive diamond drilling programs will be required to determine the size and value of the reserves and, of course, the economic significance of the deposit.

Aerial magnetic surveys were contracted to determine the extent of iron ore deposits. The results of these surveys are now being followed up.

The United Nations as an agency, does not generally undertake petroleum exploration programs unless these form part of an over-all exploration program. There are a few exceptions to this statement but usually any such activity would be of a preliminary nature: for example, offshore work in Burmese and Korean waters where a pneumatic energy source was employed. Some support has been given to the development of a capability in seismic geophysics in a number of countries: this has comprised the provision of suitably qualified personnel and some modern seismic equipment. In this field of seismic geophysics the United Nations will shortly start operations in Poland. Modern seismic field equipment and a playback centre will be provided. The objective is to locate fairly deeply buried potash deposits by means of seismic reflection techniques. These in turn will lead to the planning of a deep drilling program. Offshore seismic operations are planned for Trinidad: this will be the follow-up operation after an offshore aerial magnetic survey.

Geophysical techniques have also been applied in geothermal exploration, e.g., seismic studies in Turkey and electrical studies in El Salvador. Attention is also being focussed on the use of infrared imagery applications to geothermal studies and to groundwater problems.

Future operations

Planning for future operations in several developing countries is in hand. Shortly, for example, operations will start in Madras, India directed towards the location of base metals. This will include the obtaining of a photographic cover of the project area, photogeological studies, aerial geophysics and a ground follow-up program. In Sudan and Ethiopia similar types of operations are being developed. Under consideration are requests for assistance, for example, from the governments of Kenya, Somalia, Venezuela, Zambia. . . . .

In all of these, applied geophysics figures prominently. In planning the field operations for such requests a close study of the efficacy of applied geophysics is made. The particular instrumentation and techniques to be adopted is argued out. Well tried methods may be used or these may be supplemented by more recently developed techniques. The advances in instrumentation for magnetotelluric investigations are being considered at present. Magnetotellurics would appear to be a potent tool in prospecting for conductors occurring underneath a sedimentary overburden.

The use of transients in electrical prospecting is being examined. This would appear to have a useful application in prospecting for conductive orebodies. The aerial system is well known but so far, to the best of my knowledge no commercial ground systems have been available for use. Such a system was recently described in Moscow and its practical field application discussed.

In aerial instrumentation the United Nations has been employing the gamma-ray spectrometer and has also been examining the use of vapour magnetometers for structural mapping purposes.

Contract work

The United Nations draws heavily on the geophysical industry for execution of operations, – with one exception all aerial work in the last seven years has been contracted. (The total distance flown under contract to the United Nations exceeds 500,000 line kilometres.) For contract work a list of suitably experienced contractors is prepared and invitations are sent to the selected contractors to submit proposals to undertake the operation in accordance with the technical specifications. By obtaining proposals through international competition the interests of governments are secured. The award of contract is based on the technical content of the proposals, the calibre of the personnel proposed and, of course, the cost. Cost is important but more important is the technical competence of the contractor, the operational plan he puts forward in his proposal and his abilities in the interpretation of geophysical data. The United Nations point of view is that the interpretation which includes, in addition to the analysis of the geophysical measurements, a careful appraisal of existing geological data, whatever the source, and which results in enabling the planning of detailed geological or geochemical surveys or further geophysical surveys and leads ultimately to a decision to drill or not to drill, is the most acceptable.

The United Nations had been criticized by contractors in some countries for requesting too detailed an interpretation of data, and by other contractors for not insisting on a more elaborate interpretation. But the United Nations has to rely heavily on the professional experience of its contractors: precautions are taken to ensure that an acceptable standard of performance is achieved and though this at times leads to arguments it is in the public interest that standards be maintained and that quality control is exercised. It is also appreciated that the receipt of a report on a geophysical operation does not mean that the interpretation has been done once and for all but that as new data become available the geophysical analysis has to be re-examined and refined.

At all times the objectives of the geophysical operations are kept in sight. Applied geophysics *per se* is not the objective but the analysis of the data in geological terms.

Experience has shown that where aerial geophysics is concerned contract operations are much more economical and efficient. The assembling of an internationally recruited team and the purchase of complex equipment is much too expensive. The support necessary to run a large geophysical operation is such that its cost is prohibitive for locally organized teams. This also applies to ground operations where a large variety of equipment is required for short periods.

Difficulties in recruiting suitably qualified and experienced personnel for ground operations can be another reason for the United Nations to use contractors.

Positioning

Most of the United Nations geophysical programs are conducted in areas which are poorly mapped. Aerial photography of varying quality may be available. This helps, but in aerial operations recourse often has to be made to microwave systems of navigation. The need for accurate positioning cannot be over emphasized. Ground crews can waste a great deal of time trying to locate an area revealed to be of interest by analysis of, say, aerial electromagnetic measurements only to find that they are unable to relate ground measurements to aerial. In United Nations programs in addition to using whatever maps or photographic cover that is available, limited additional aerial photography may be contracted to enable the precise locating of targets. If an aerial program using an electronic navigation aid has been conducted, a plot of the navigation data may be used to assist in positioning ground teams.

Cost of operations

The larger programs usually involve expenditures varying from about $700,000 to perhaps $3,000,000. These costs cover operations extending over a period of 2 to 4 years and are comprised of contributions from the government concerned and the UNDP.

The government contribution usually takes the form of making available technical and field personnel, buildings, laboratory facilities, fuel and perhaps vehicles. Sometimes a cash contribution is also made. The UNDP finances the cost of international experts, equipment and contracts for specialized operations.

A typical operation might comprise the supply of a project manager, geophysicist, geochemist and, say, two economic geologists, together with geophysical, geochemical and drilling equipment. In addition, an aerial geophysical program may be financed by the UNDP.

Institutes

Applied geophysics also figures prominently in the United Nations programs to develop institutes. In establishing institutes for geology or geophysics the United Nations intends, with the governments' support, to build up a capability in the undertaking of geological mapping programs and the assessment of the mineral resources of the country. An example is the Geological Institute in Iran where the government, with United Nations assistance, has established an infrastructure around which is being built a sound geological survey and the capacity to undertake geophysical exploration programs.

The above observations have been devoted to the larger geophysical operations, but, in addition to these, geophysicists and geophysical equipment have been made available to governments for smaller but important programs, e.g., in the U.A.R., an experienced geophysicist was made available to assist in developing suitable ground exploration techniques for base metals. A seismic geophysicist advised the geophysical staff of the Israeli Government on modern playback equipment and on techniques of analysis of seismic data. Consulting geophysicists are employed to supervise field operations, advise governments on preparation of technical specifications and to make critical analyses of the methods being adopted by the United Nations personnel or United Nations contractors in the field of exploration geophysics.

It is the practice of the United Nations to employ geophysicists to ensure that contract operations are conducted in accordance with the technical specifications, e.g., when an aerial geophysical survey has been contracted a supervising geophysicist will be on site with the contractor to make acceptances of the contractor's work, to vary the flying program as required and to formally certify that the work has been conducted satisfactorily.

Application of geophysical techniques

Throughout, I have referred to the use by the United Nations of a variety of geophysical techniques in mineral exploration: these are being used to assist in obtaining an understanding of the geology of the area being investigated. The United Nations is aware that the use of these techniques does not mean that the discovery of a mineral deposit is guaranteed, but that geophysical techniques properly applied can be used to eliminate barren ground thereby permitting concentration of effort on more promising ground.

The above outline of United Nations activity in geophysics applies only to programs in the mineral exploration field. Other agencies of the United Nations also employ geophysicists on their own programs and, in addition, undertake fundamental studies in the earth sciences, but the United Nations in its capacity as an executing agency leans heavily towards economic development of nonagricultural resources and thus is involved much more in the application of geophysical techniques than in basic research studies.

Of the larger programs being undertaken by the United Nations only a few are in the final stages of operation. It is too early to give details of results, but from the data which has been accumulated so far, encouraging results are to be expected. Spectacular achievements are not anticipated, but from analysis of some projects nearing completion sound contributions to economic development can be expected.

Applied geophysics in the Natural Environment Research Council in Great Britain

K.C. Dunham

Institute of Geological Sciences
London, England

Abstract. A short historical review summarizes past activity by United Kingdom organizations in geophysical exploration as applied to economic geology and groundwater both in and around Britain and in programs overseas. The principal methods used are discussed briefly and illustrated by a few more-detailed examples. Organizational changes following the formation in 1965 of the Natural Environment Research Council are described, with special reference to integration of the former Geological Survey of Great Britain and Overseas Geological Surveys within the new Institute of Geological Sciences. A forward glance is directed towards identifying projects suitable for future research by governmental organizations, possibly in collaboration with university and industrial groups.

Résumé. Une brève revue historique résume les activités des organismes du Royaume-Uni engagés dans l'exploration géophysique appliquée à la géologie économique et aux eaux souterraines au Royaume-Uni et outre-mer. L'auteur présente les principales méthodes utilisées et les illustre à l'aide de quelques exemples détaillés. Il décrit les modifications qui ont suivi la création en 1965 du Natural Environment Research Council et accorde une attention spéciale à l'intégration de l'ancienne Geological Survey of Great Britain et de l'Overseas Geological Surveys en un nouvel Institute of Geological Sciences. L'auteur jette ensuite un coup d'oeil vers l'avenir et tente de définir des projets de recherches qui pourraient être entreprises par les organismes gouvernementaux probablement en collaboration avec les universités et l'industrie.

The Natural Environment Research Council was established by Royal Charter in 1965 to assume responsibility for the earth sciences, oceanography, nature conservation, fisheries and other aspects of research in applied biology. The Geological Survey of Great Britain (founded 1835, only a few years before Sir William Logan began geological work in Canada) with its associated Museum of Practical Geology was transferred to it from the former Department of Scientific and Industrial Research. The Overseas Geological Surveys was transferred from the Overseas Development Ministry, and the geological organisations were incorporated in 1966 under the title of the Institute of Geological Sciences.

Almost the whole of the geophysical activity within NERC lies within the IGS, the only exception being certain marine geophysical work undertaken by the National Institute of Oceanography.

The Department of Geophysics of the Institute (Chief Geophysicist, Dr. W. Bullerwell) includes not only sections working on applied geophysics in the United Kingdom, the U.K. Continental Shelf but also overseas. In addition the department is responsible for the Global Seismology Group under Dr. P.L. Willmore at Edinburgh, and the Geomagnetism Group under Mr. B.R. Leaton at the Royal Greenwich Observatory, Herstmonceux, Sussex. Special investigations into radioactive and rare minerals are conducted by a unit within the Department of Geochemistry of the Institute (Chief Geochemist, Mr. S.H.U. Bowie) but much of the equipment used is, of course, physical rather than chemical. The Department of Hydrogeology (under Mr. D.A. Gray) also employs physical apparatus and geophysical techniques in its work.

The concentration of resources into a single Institute is expected to strengthen greatly the potential for undertaking applied geophysics at all levels. If some of the newer developments, such as global seismology, appear academic at first sight, the part their rigorous disciplines can impose in testing speculative hypotheses in economic geology should not be underestimated. The benefit of assimilating the sophisticated instrumentation and computer processing available in the best modern observatory practice is obvious.

The present survey of the development and scope of the geophysical activities of the Institute was largely prepared by the three departmental heads mentioned above. I am glad to acknowledge with thanks their contributions.

Geophysics applied to regional, prospecting and mining problems

Historical. The first reference to applied geophysics in England is probably that given in the historian Froude's account of the siege of Exeter in 1549 (Weaver, 1942). He describes how an adroit engineer detected the presence of assailants mining underground by the vibrations of a pan of water, thus enabling steps to be taken to blow them up or drown them in their holes. The description might be regarded as the first reference to the application of the seismic method to mining or perhaps more strictly, counter-mining. Other early applications include those of R.W. Fox who, in 1830, observed potential differences between different parts of an overbody in Cornwall, thus anticipating the self-potential (S.P.) method; Lloyd, who developed a sensitive magnetometer in 1843, and Threlfall and Pollock who constructed a quartz gravity-balance in 1899. British Government interest, however, only began to materialise after the vigorous application of geophysical methods to oil prospecting along the Gulf coast in the 1920s, and after trials had been made at the Hodbarrow hematite mine in Cumberland in 1925. Early in 1927 the Committee of Civil Research appointed a subcommittee on geophysical surveying which reported in November of the same year* recommending a full-scale trial of geophysical methods over known mineral deposits in Australia. The field tests were made during 1929 and 1930 by the Imperial Geophysical Experimental

**Geophysical Surveying.* Report of a sub-committee of the Committee of Civil Research. HMSO, London, 1927.

Survey which was financed equally by the British and Australian governments and the full results were published in the well known text by Broughton Edge and Laby (1931). Many aspects of the four methods described, electrical, gravitational, magnetic and seismic, remain fundamentally unchanged in spite of some radical changes in instrument design, notably to produce great improvements inportability.

Meanwhile, in Britain, during the period 1927-31, the Geological Survey undertook a series of tests in which the capabilities of torsion balance and magnetometer methods applied in the examination of local geological problems were examined, with encouraging results. The first of these tests comprised detailed traverses across the line of the Swynnerton Dyke (McLintock and Phemister, 1928; Hallimond, 1930a). Next a more extensive survey was made to assess a magnetic anomaly known to exist near Melton Mowbray (Hallimond, 1930b; McLintock and Phemister, 1931a). Later, traverses were made across the line of the Pentland fault near Edinburgh, where Carboniferous rocks lie in contact with the lavas of Arthur's Seat (McLintock and Phemister, 1929; Hallimond, 1931). Finally, some magnetometer traverses were surveyed across the line of the Lornty Dyke, near Blairgowrie (McLintock and Phemister, 1931b).

Though all the tests produced significant results, the final one perhaps is most interesting in relation to recent developments in geophysics. The Lornty Dyke is a tholeiite of Brunton type and the associated magnetic anomaly could not be explained on the basis of simple induction. To study this, oriented samples were collected from field exposures and the permanent magnetisation tested in the laboratory. The permanent magnetisation was weak but definite and did not coincide either in direction or intensity with that expected by cooling in the Earth's present field; approximate calculations showed that it could account for the shape of the observed field profiles (Hallimond and Herroun, 1933). The investigation is thus of interest in being one of the earliest palaeomagnetic studies linking evidence from field surveys with that obtained in the laboratory.

The interest aroused by these trials, further stimulated by the conspicuous success of the IGES program and the clarity and completeness of the subsequent report, makes it surprising that more geophysical work was not commenced in Britain during the years immediately following and, in particular, that no regional geophysical survey was commenced.

Most of the surveys undertaken in Britain during the period 1930-39 were local though some interesting studies relating to the fundamentals of the electrical resistivity method (Tagg, 1930; 1935; Lancaster-Jones, 1930), and its application in prospecting for coal (Whetton, 1934; Cox, 1935), water supplies (Bruckshaw and Dixey, 1934) and to measurements in boreholes (Shaw, 1937) were made by commercial and university groups. During the same period, however, the British Petroleum Company commenced some seismic work in the East Midlands (Lees and Cox, 1937) and in 1939, shortly before the outbreak of war, the Anglo-American Oil Company commenced a regional gravity meter survey in northern England.

Geological survey geophysical unit. In 1946, the Geological Survey decided to set up a geophysical section which commenced its field program in 1947 with a small team on gravitational investigations and had by 1962 built up to a complement of 11 scientific staff with a wide range of modern prospecting instruments covering all standard techniques. Throughout its operations the department has maintained a balance between basic and applied research. Its activities include:

1. Obtaining gravity, magnetic, electrical, seismic and other geophysical data on a regional basis to assist appraisal of broad geological structure;
2. Studying the physical properties of rock formations through surface measurements, investigations in boreholes and laboratory tests on samples;
3. Detailed geophysical applications for economic purposes or to assist field geologists in mapping concealed boundaries or in siting boreholes;
4. Trials of new geophysical instruments and techniques;
5. Reduction and analysis of geophysical data and critical assessment of data-handling and interpretation methods;
6. Advising government departments, industry and other research institutions and joining in co-operative researches with university teams and industrial groups; and
7. Disseminating geophysical information by publishing maps and reports, and by affording training facilities.

During World War II, geophysical prospecting for minerals was co-ordinated by the Home Ore Control department, Ministry of Supply, the main applications being in the search for hematite and manganese ore resources (Groves, 1952). Officers of the Geological Survey took an active part in this work, conducting magnetic surveys to locate hematite deposits in Cumberland and Furness (Hellimond and Whetton, 1939; Hallimond and Butler, 1940; Dunham and Rose, 1941). In other surveys in the Northern Pennines, magnetic observations were applied to trace faults which might control nonmagnetic vein deposits, mainly barytes, by detailing the anomalies resulting from displacements in an extensive dolerite sill (Hallimond and Butler, 1949; Hallimond and Eyles, 1949).

The war years also saw a marked increase in the use of geophysical methods in the search for oil, taking the form of extensive regional surveys by gravity meter and magnetometer, followed up by detailed seismic work in selected areas. As the results of these investigations were progressively released after the war, together with some of the results of subsequent drilling (Lees and Taitt, 1946; White, 1949; Falcon and Tarrant, 1951), related benefits became apparent from the advance in geological knowledge pertinent to the search for other economic deposits, and possibly coal reserves in particular, and this recognition did much to foster an increased interest in exploration geophysics.

Regional surveys and follow-up. Two major undertakings have been the continuation of the gravity and aeromagnetic maps of Great Britain. Since 1950, the department has been responsible for collating all gravity data obtained in Great Britain, for which the gravity survey is now about 75 per cent complete, the Geological Survey being responsible for about half the present coverage, the other half being divided about equally between university groups and oil companies. In relation to possible mineral provinces perhaps the most interesting gravity survey in Britain in recent years was one undertaken by a Durham - Cambridge University research team over the Northern Pennines (Bott and Masson-Smith, 1957) which suggested that the North Pennine orefield might be underlain by a large intrusive granitic body; such an intrusion, the Weardale granite, was later proved and examined by means of a government-grant financed borehole drilled for Durham University (Dunham, *et al.*, 1965).

Shortly after the war some airborne trials of a wartime antisubmarine magnetometer as further developed by the Ministry of Supply during 1948, indicated potential application to geological studies in southern Britain. Extensive surveys with this instrument were planned by the Geological Survey to commence in 1949 but had to be postponed because of the country's serious financial difficulties at that time. Suggestions for reviving the program in the years immediately following were unsuccessful – possibly because though the method had proved useful in remote and poorly mapped areas, few examples were available for areas with the detailed geological information in Britain. During 1955, the Nuffield Foundation financed a pilot aeromagnetic survey in central England, to be supervised by the Geological Survey. The area was chosen carefully to include both flat and hilly terrain and a good range of geological problems. Detailed geological mapping had been completed over the whole area, which had also been surveyed by gravity meter and much of it by ground magnetometer. Mining information was also available in several places.

The results of this trial were entirely convincing. In several parts of the area the aeromagnetic data cast a new light on structural problems which had previously been recognised and in other places where the subsurface structure was less well established they suggested localities for future drilling. Other examples demonstrated the supplementary character of gravity and magnetic information and indicated the potential value of exploration combining these techniques. Following detailed appraisal of the results of this pilot survey, aeromagnetic surveys by contract were continued progressively each year until the end of 1965, by which time the whole land area of the United Kingdom, together with parts of the adjacent continental shelf, had been surveyed aeromagnetically.

During 1955-57 the main aeromagnetic surveys were conducted over Mesozoic-covered areas which gave relatively low prospect of metalliferous deposits at shallow depth. Anticipating, however, that the surveys would shortly be extended on to the Palaeozoic areas and even to known mineral provinces it was decided in 1957 to carry out a pilot survey to assess the feasibility of conducting electromagnetic measurements simultaneously with the aeromagnetic observations during the regional surveys over such areas. The trial was made over an area in southwest Cornwall long known as a metalliferous mining region, using a dual frequency out-of-phase system, flown at a height of 500 feet, together with a Photographic Survey Corporation magnetometer and radiometric equipment. Results of the tests were not encouraging, mainly because the electromagnetic arrangement showed a marked response to surface conductors and a good deal of artificial interference was encountered. It was felt that the flying height was too high for best electromagnetic results but possibly too low for the magnetometer which was occasionally disturbed by the effect of railway lines and other ground installations. A combined survey using magnetometer and radiometric equipments only was flown in an adjacent area during 1958, but no combined surveys have been flown since then.

Since 1955 much of the detailed ground geophysical work undertaken in application to geological mapping or to mineral exploration has been designed as direct follow-up to the aeromagnetic or airborne electromagnetic work. Generally speaking surveys undertaken for geological mapping or structural investigation have proved more successful than those made for mineral exploration. As an example, three deep boreholes drilled in Northern Ireland following an aeromagnetic survey and two years of ground survey over the whole of the country have resulted in the proving of deep sedimentary basins and the discovery of substantial stratified salt deposits (Bullerwell, 1964). On the other hand ground magnetometer follow-up in an area near Okehampton, Devon, revealed systematic anomalies of narrow width and unexpectedly large amplitude. Additional study showed these to be associated with significant SP, resistivity, electromagnetic and Induced Polarization (IP) effects which drilling indicates to have arisen from disseminated pyrrhotite at shallow depth.

Overseas geophysical operations. Parallel with the development of programs within the U.K. has been a development of activities overseas. Before 1939 geological investigation in each British colonial territory was the responsibility of a government geologist with one or two assistants. After the war, Geological Surveys were set up in these territories on a more or less autonomous basis to undertake geological mapping, water supply development and mineral resources assessment. Normally these sections had neither geophysical staff nor geophysical instruments and a geophysical section was therefore set up at the Directorate of Colonial Geological Surveys (later Overseas Geological Surveys – OGS) to supply geophysical assistance as necessary. The aim was to establish a team of experienced geophysicists, versatile in all techniques and with a comprehensive range of equipment. Demand for the services of this section fluctuates considerably but the present complement of 8 scientific staff has proved generally adequate.

In about 12 years of continuous operation, geophysical applications have been 47 per cent to mineral prospecting, 32 per cent to water supply and 21 per cent to general geology. Field surveys usually involve one or two geophysicists for three to six months. Labour, transport and camp facilities are provided locally and the geophysicists are often accompanied and assisted by local geologists. Much of the work undertaken has been to establish whether particular problems would be amenable to geophysical investigation rather than to undertake production surveys to prove the extent of deposits. This has led to an experimental approach and perhaps the use of more than the minimum equipments necessary in establishing which might be inapplicable and which satisfactory.

The kind of target varies considerably. In less developed countries, communications are often too poor to allow development of the less valuable deposits unless near the coast. Thus gold, diamonds, tin and sulphides have been investigated inland, and iron, coal and bauxite in coastal areas or inland areas with better communications. Special problems have also arisen in that many geophysical instruments appear inadequately designed to withstand corrosion under the humidity common in tropical coastal and jungle areas. Deep tropical weathering and the occurrences of laterites, silcretes and calcretes can give disturbed surface conditions which raise problems in interpretation.

The section is also called upon to advise in connexion with the placing of commercial contracts and in particular whether the problems are suitable for geophysical investigation and as to the conditions which should be imposed on any contractor. In advising on one such request the OGS section was able to take part in an interesting comparison experiment in the Geita and Migori areas of East Africa, where surveys over the same area were flown by three aerial geophysical survey contractors using different electromagnetic instrumentation and techniques – the rotary field method, the Rio-Mullard method and the AFMAG method (Makowiecki, *et al.*, 1965).

Geophysical investigations overseas have frequently been undertaken in conjunction with parallel geological, geochemical or other scientific investigations. As an example operations in Thailand during 1965-66 formed part of an integrated geological, geochemical and geophysical scheme of exploration aiming at location of lead-zinc bodies. Even within its subsidiary discipline the geophysical work was quite diversified, including gravity, magnetic, SP, EM-gun, Turam, AFMAG and IP measurements.

Commercial geophysics. Little has been said about the development of contracting companies in the U.K. During the past few years these have increased in number mainly in the provision of services in engineering geophysics. It is possible to make an interesting brief comparison of some of the larger groups with the development of the IGS in that while diversifying their activities, yet the central role of geology appears to have gained more prominence. Thus one firm (Huntings') active in the fields of aerial photography, airborne, ground and marine geophysics and natural resources surveys has now taken the designation 'Geology and Geophysics'.

In another direction little has been said of the liaison between the governmental geological organisations, the nationalized undertakings and the universities. This remains very close, in spite of the setting up of geological and geophysical groups within other organisations, such as the National Coal Board and the Gas Council, responsible for the control of specialized programs undertaken mainly by contract. The National Coal Board group has played a pioneer role in economic development of offshore resources, commissioning sparker surveys and undertaking an extensive drilling program off the coasts of Northumberland and Durham between 1958 and 1965, reported by Clarke, *et al.*, (1961), and has commissioned gravity and seismic work on land to study areas of possible development from existing mines. Geophysical collaboration with university groups which commenced with exchanges of gravity data is now extensive in all branches of geophysics and seems likely to continue to expand with increased specialisation of equipment and common use of research vessels.

The future. The Institute of Geological Sciences continues to fulfil the function formerly exercised by the Geological Survey in the collection and compilation of commercial geological and geophysical information on a confidential basis; in fact these functions have expanded to include data obtained from licensed exploration on the continental shelf. This in turn is promoting stronger contacts with exploration groups and commercial contractors undertaking marine investigations. The Institute has also itself commissioned two marine surveys by commercial contract, one, during 1966, in the Moray Firth and the other, during 1967, in the northeastern part of the Irish Sea. In other areas the Institute's staff are commencing their own marine operations.

Thus the new organisation is seen as meeting the challenge of the problems of the solid earth including its physical properties and its mining resources by establishing a closer integration between geology and all branches of geophysics. It recognises that the aim of geophysical methods of prospecting is to provide the geologist with information additional to that obtainable from surface exposures and from borings, to supplement, but not replace, normal geological methods, by guiding investigations to the most crucial and advantageous sites for detailed investigation or drilling. Recent investigations, especially overseas, have demonstrated the advantages of broadly based integrated exploration schemes combining photogeological and airborne geophysical reconnaissance with ground parties combining geological, geophysical and geochemical techniques. Future activity may expand efforts of this kind. In other cases the phasing of individual operations may be altered to introduce geophysical controls at an earlier stage. Because of the long history of geological mapping in the U.K. it has been inevitable that in many cases geophysical methods have been introduced at a late stage of exploration. However, for the few land areas not yet geologically mapped in detail this sequence will now be altered since some geophysical information, aeromagnetic information in the least case, is available for all land areas. Phasing will be similarly revised in operations at sea, since the greater speed of under-way geophysical profiling as compared with stationary operation of corers and samplers makes it uneconomic to commence geological sampling in advance of geophysical scanning. Increasing use of automatic processing methods may well prove the most rapid field of advancement, and the clear benefits likely to accrue appear to justify an intense effort to develop data banks and cross-referencing procedures in a single form applicable to all disciplines within the field of geological science.

Geophysics in prospecting for atomic energy minerals

Historical. Since its formation in 1944, the Atomic Energy Division has been concerned with the search for and appraisal of atomic energy mineral deposits in the United Kingdom and overseas territories. The development and testing of geophysical equipment and techniques particularly suited to the study of natural radioactivity was a major responsibility of the Division during the years of intensive uranium search from 1945-59, and the recent resurgence of activities in the uranium exploration field is again bringing this type of development research into prominence. The wide range of successful instruments developed during the earlier phase of work resulted from effective collaboration between Division geologists and officers of the Atomic Energy Research Establishment, Harwell. This combined effort ensured the application of the most up-to-date electronics engineering developments to the problems being encountered by the operational geologists in the field and laboratory at the time, and further ensured that design features affecting weight, shape, handling and performance of the instruments met the stringent demands of field operations in a variety of climatic conditions. Advances in electronics engineering were reflected in the progressive reduction in size of survey instruments and the development of highly sensitive, stable scintillation counters which by 1959 had largely replaced the bulkier, less efficient Geiger Mueller (G – M) instruments for many survey applications.

During the 1945-59 period, Atomic Energy Division officers were deployed, in prospecting or advisory capacities, in many overseas territories where the techniques and instruments developed in the U.K. were applied to economic geological problems. Car-mounted radiometric surveys were conducted over more than 10,000 miles of road and track in west Africa and over the accessible parts of Bechuanaland and Swaziland. Aeroradiometric surveys were carried out over part of the Zambian Copper Belt, and the Lomagundi and Sinoia districts of Rhodesia. Portable ratemeters were used by Division staff for assessment work in Australia, New Zealand, west and central Africa and Portugal. Other aids to the exploration and development of uranium deposits (borehole gamma-logging equipment, shielded detectors for ore sorting) were also employed in assessing discoveries in some of these countries.

During the same period, the AED undertook a limited amount of radiometric surveying and mineral assessment in the United Kingdom. The most important geophysical operations were participation in a combined aeromagnetic, EM, aeroradiometric survey covering 1120 square miles over the SW England mining province (Bowie, Miller, Pickup and Williams, 1958) and an aeromagnetic, aeroradiometric survey over the adjoining eastern part of the SW England peninsula (3395 square miles). These surveys were contracted to Hunting Aerosurveys Ltd. but the AED provided the aeroradiometric equipment and technical supervision of data reduction and plotting. A smaller aerosurvey (422 miles), employing only scintillation equipment was flown by Fairey Air Surveys Ltd. in 1959, over an area in Argyllshire where the greater topographical relief proved to be less critical to maintaining constant ground clearance than had been expected.

Since 1960, the AED has given technical guidance in aeroradiometric surveys in Pakistan and Turkey and has loaned the specially developed equipment to several geophysical contracting firms who have carried out aeroradiometric surveys in several overseas countries.

Finally, the possibility of an increased demand for beryllium for the atomic energy industry about the beginning of the present decade led to the development of geophysical equipment for detecting and assaying beryllium ores employing the (γ, n) reaction. The portable beryllium detector was employed extensively in central and west Africa for the assessment of resources. In Rhodesia, the instrument led to a substantial increase in knowledge of the geochemistry of beryllium pegmatites and established the existence of major reserves of beryl in fine-grained form which had hitherto been overlooked.

Aeroradiometric surveys. The first equipment developed by the AED and AERE employed a single 4.7-diameter sodium iodide crystal as detector. Operational experience in Africa indicated the need for greater sensitivity, and development led to the production of the successful AERE Type 1531 B equipment, which is still in use. This is a total gamma detector employing three 4.7-diameter crystals, output being presented both as a deflection on a microammeter and as a trace on a Texas Instruments recorder. For the type of survey carried out to date under AED direction or specification, 100 per cent coverage (with the 'half-signal' as cut-off) has been aimed at. This meant maintaining a flying height of about 500 feet with a line spacing of 440 yards. Satisfactory detection of low-amplitude, small-area anomalies has been achieved at this altitude, except in unusual topographical circumstances which prevent the gamma flux from reaching the aircraft.

The main problem presently facing the uranium exploration geologist is the role which gamma energy discrimination can play in the identification of radioactive anomalies from the air. The electronics industry can produce equipment capable of analysing a spectrum at aerosurvey flying speeds (in fact at least one commercial equipment is on the market at present) but it has not yet been satisfactorily shown that discrimination can be achieved at the practicable or economic flying heights necessary for large-area surveys. Apart from this problem of the resolution of degraded energies with increasing ground clearance, there is the doubt whether the geologist can safely eliminate from ground follow-up an anomaly which exhibits only a thorium component. Obviously, the more information that is available at the reconnaissance stage the better, but the economics of obtaining the information must be studied and its significance assessed. Research aimed at resolving these problems is at present being undertaken by the Atomic Energy Division.

Gamma spectrometry. The analysis of gamma spectra on the ground is possible with existing British equipment of both portable and transportable (car-mounted) types.

Under favourable conditions of geometry and count rate, both types of instruments are able to differentiate between the gamma spectra emitted by natural concentrations of uranium, thorium and potassium in the field, with the radioactive material *in situ*. The design of instruments more specifically suited to geological investigations requires more extensive studies and these are currently being conducted by the Atomic Energy Division, in collaboration with the Electronics Group at Harwell. The existing instruments available employ thallium-activated sodium iodide detectors but research is in hand at AERE into the possibility of using lithium-drifted germanium detectors for greater resolution.

Borehole logging. Gamma-logging equipment has been used for many years by the Atomic Energy Division, first in the exploration for uranium deposits but with the advent of scintillation detectors of high sensitivity and resolution the equipment is also used extensively for stratigraphical logging. Standard equipment is portable and has a depth capacity of 1000-1200 feet, while a vehicle-mounted, power-operated equipment has a capacity of 6000 feet and is thus specially suitable for the study of deep stratigraphical boreholes put down by the IGS, National Coal Board and commercial organisations. The role of gamma logs for correlative stratigraphical studies in support of groundwater, coalfield and other economic geological investigations is well known. However, the Atomic Energy Division has a responsibility for the long-term study of the radioactivity of British rocks and the gamma logs have already indicated the whereabouts of some interesting concentrations of uranium. An example is the presence of uraniferous shales in the Lower Namurian which have been detected in boreholes at widely separated localities from northern England to SW England.

The AED also has facilities for obtaining gamma-gamma logs from which bulk rock density can be deduced. It is hoped shortly to put this type of measurement on a quantitative basis and, by employing a double detector spacing, to eliminate drilling mud and cavity effects and to make it possible to determine bulk density in a radioactive environment.

Other developments currently under study include down-the-hole measurements by X-ray fluorescence analysis and gamma-ray spectrometry.

Radon monitoring. The Atomic Energy Division was among the first to pioneer radon measurement in ground air as a means of detecting hidden uranium ore deposits. Following the recently revived interest in long-term uranium supplies, this technique has assumed a new importance and current investigations are aimed at obtaining results that are quantitatively significant. This entails studies not only of overburden type and thickness, but of atmospheric conditions during the period of survey. Results to date show considerable promise in regions where the cover is composed of glacial till, but it seems likely that the method will be no less applicable where the overburden material is composed of any relatively unconsolidated material.

Portable radioisotope X-ray fluorescence analyser. In collaboration with the Wantage Research Laboratory (AERE) and British electronic companies, the Atomic Energy Division has introduced two portable analysers based on the use of a radioisotope and balanced filters (Bowie, Darnley and Rhodes, 1965). The radioisotope, in the form of a button source about 1 cm across, replaces the conventional X-ray tube with its associated power supply and the balanced filters are used to select the secondary fluorescent radiation instead of the customary crystal spectrometer. The first instrument introduced in 1965 was of ratemeter type, particularly suitable for the early stages of mineral exploration and assessment. However, because of the relatively short time constant and the need to estimate the two filtered readings by ratemeter, this instrument was inadequate where a low limit of detection of high accuracy was required. To remedy this the second instrument has a scaler with an automatic subtracting device which enables the count rate between the two filtered readings to be displayed as a net count. In addition the instrument is of variable single-channel design with a combined automatic-manual timing device that enables the counts to be integrated over a longer period of time than was possible with the ratemeter instrument. All this adds up to an instrument with a lower limit of detection and a greater degree of accuracy than its predecessor.

Since March 1965, a series of experiments have been carried out on elements other than tin, and, to date, suitable sources and filters have been introduced to give reliable results on copper, lead, zinc, titanium, iron and molybdenum. In addition to these elements, work is being conducted on chromium, manganese, nickel, barium, platinum, tungsten and zirconium.

The limit of detection and accuracy of these instruments is of the order of 0.01 to 1 per cent depending on the element, so that they are regarded as being suitable for mineral exploration and assessment rather than tools for geochemical investigations. However, for elements such as tin, molybdenum and titanium for which the limit of detection is 0.01 to 0.03 per cent they could be of value in basic geochemical investigations.

Geophysics in groundwater exploration

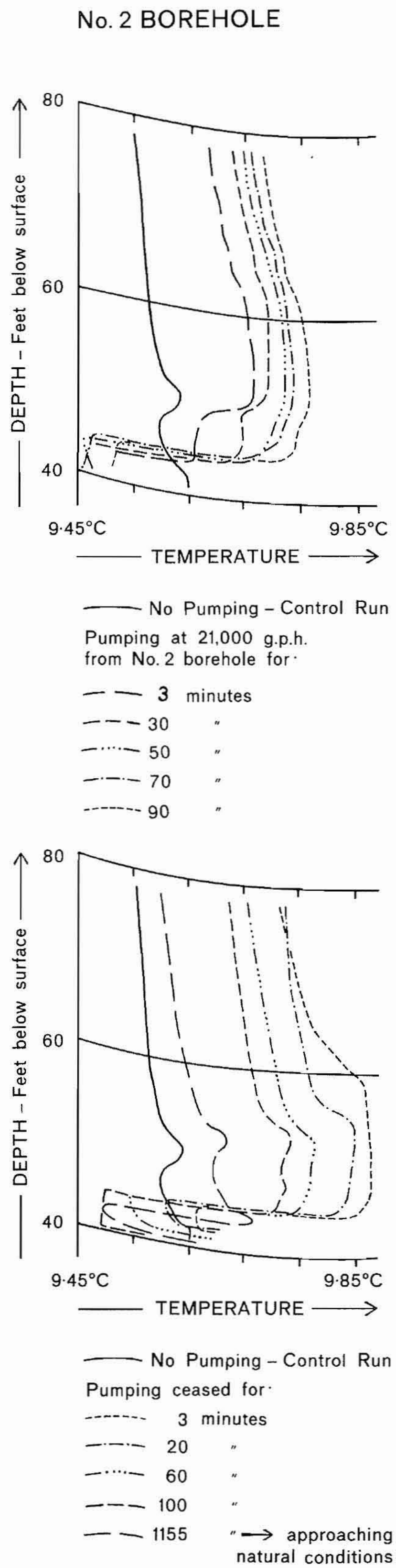
U.K. practice. The average annual rainfall in the U.K. varies from more than 170 inches in the west to less than 22 inches in the south and east. This uneven distribution is a reflection of the geological structure to the extent that the high-rainfall areas are composed of impermeable Lower Palaeozoic strata which young towards the lower rainfall districts of the south and east, where Mesozoic and Tertiary strata crop out. As a result, surface-water supplies are dominant in the west and north whereas groundwater supplies are concentrated in the south and east. Water-bearing deposits have been developed as sources of supply from the time of the earliest settlements, and since the middle of the last century new sources of groundwater supply have been brought into use at an increasing rate. Since 1948 the average rate of abstraction of groundwater has increased by about 2 1/4 per cent per year although locally it has exceeded 10 per cent, and abstraction in 1964 amounted to 1224 million gallons per day (excluding water abstracted by the National Coal Board).

This development of the groundwater resources has been greatly facilitated by the 1 inch/mile maps of the Geological Survey. Many of the maps dealing with the groundwater provinces belong to the Old Series which were surveyed before the turn of the century at the 1-inch scale and, by present-day standards, leave much to be desired. Nevertheless they defined the boundaries of the outcrops of the known aquifers and permitted exploration to proceed on a relatively firm basis over their outcrops and concealed extensions. Prior to 1945 the Geological Survey collected well records provided on a voluntary basis but since then, when national control of groundwater abstraction was first introduced, it has acquired them by statutory right. By 1963 this national collection of well records provided a density of between 3 and 4 records per square mile in the major groundwater provinces (Gray, 1964).

This has led to a position in which, for most sites in the principal groundwater provinces, estimates can commonly be made prior to drilling or other exploration, of the relevant groundwater parameters such as occurrence of groundwater, the depth to water-table, thickness of aquifer, and the chemical quality of the groundwater, within the limits of accuracy normally available from current geophysical methods. Clearly there are exceptions to this but, in the main, the advice sought from the geophysicist is changed in degree and emphasis by comparison with that required in a less well-known environment, although the methods available to him are not significantly different. In these circumstances geophysical exploration for groundwater has not been extensively employed in the U.K.

There are two main exceptions to this general condition. Some 40 per cent of the groundwater used in England and Wales is derived from fissure flow in the Cretaceous chalk, and qualitative surface surveys have been made using electrical resistivity methods to define 'iso-resistivity' contours. These frequently show closed areas of low resistivity which have been drilled with success. No satisfactory explanation has been offered, however, of the flow conditions in a fissured aquifer which would lead to a meaningful distribution of the lows which are commonly identified in this type of survey, nor is it established that the drilling successes are statistically significant. Valuable contributions have also been made in the estimation of thicknesses of glacial and postglacial superficial deposits, particularly in the identification and quantitative definition of buried channels (Ineson, 1960). Shallow, sledge-hammer seismic prospecting is also employed locally for the identification of buried channels and there is scope for further work using this method in the development of supplies from superficial deposits, particularly in the hard rock country of the north and west. Neither gravity nor magnetic methods have been used exclusively for hydrogeological purposes within the U.K.

In the field of subsurface methods, however, geophysics has made a greater impact. Most groundwater is derived from consolidated fissured strata, and the Water Department of the Institute of Geological Sciences has worked for some years in this field and is undertaking a research program into three-dimensional flow systems in various aquifers. Some of the earlier work



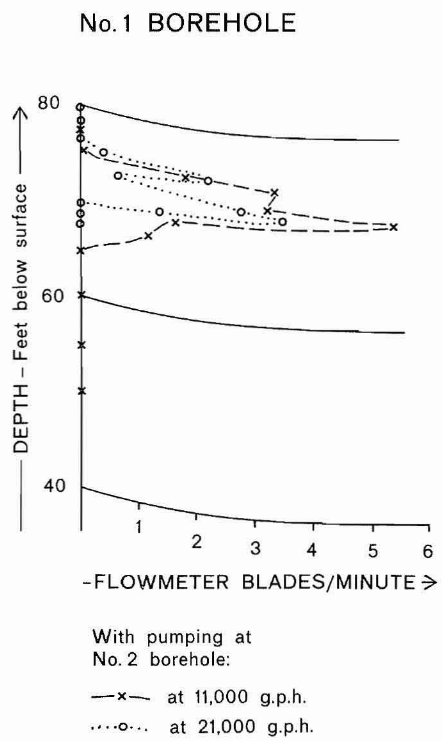


Figure 1. Temperature and flowmeter measurements in No. 1 and No. 2 boreholes at Charterhouse, Somerset, England.

in this field has been described elsewhere (Ineson and Gray, 1963). Standard electrical logging methods are employed together with a temperature logging system, both absolute and differential being used (Gray, 1964), and a low-velocity, light-operated flowmeter (Anon., 1966), electrical conductivity probes and, from July 1967, a borehole television camera.

An example can be cited of the use of the temperature-logging equipment and the low-velocity flowmeter in observation and production boreholes drilled into a limestone/shale sequence of Lower Carboniferous age at Charterhouse in the Mendip Hills of Somerset. The wells were logged before, during and after pumping from a production borehole 200 feet northwest of the observation well, and the quantitative responses of the temperature equipment and of the flowmeter to changes in rate of fissure flow, consequent upon the changes in head in the boreholes, are illustrated in Figure 1. The flowmeter observations are unusual in that No. 1 borehole is down the hydraulic gradient from No. 2, and the observed velocities in No. 1 reduce as the rate of pumping from No. 2 increases and the natural discharge through the fissures is reduced.

It is intended that these equipments will be used to locate levels of fissure flow and to relate quantitative changes to natural and artificially induced changes in head. The television camera will be used as a supplement to observe the size, distribution, shape, orientation and geological relationships of the fissures through which flow takes place. It will also be used for stratigraphical purposes in uncased, pre-existing boreholes for which drillers' logs are not available or inadequate.

Overseas practice. The position of geophysical methods in groundwater problems in a number of overseas territories, in some of which U.K.-based organizations or personnel have been involved, was reviewed recently by Shaw (1963).

Organization. Groundwater exploration by geophysical methods has been organized in the past by the Overseas Geological Survey and the Geological Survey of Great Britain as well as by well-sinking contractors and consultants. The British universities have concerned themselves mainly with research into geophysical methods rather than with groundwater exploration as such. Abroad, the Overseas Geological Surveys provided most of the trained personnel engaged in this work in the territories under their direct jurisdiction as well as those acting in independent territories formerly under their guidance. Within the U.K. most exploration is currently undertaken by direct contract between statutory water undertakings or river authorities and well sinkers who themselves supply geophysical services or who work in association with one of the geophysical consultant companies. In general, such exploration in the principal aquifers is limited to electrical resistivity surveys covering a few acres of outcrop. Such contrasts are normally arranged only where medium- to large-scale development is proposed – say schemes involving abstraction of more than 500,000 gallons (Imp.) per day. It must be remembered in this context that yields of 1, 2 and 3 million gallons per day are common in the principal British aquifers. Outside the research organizations, subsurface methods are generally limited at present to electrical resistivity and self-potential.

This over-all position may now change following the implementation of the Water Resources Act 1963. The responsibility for the conservation and management of groundwater resources is placed with twenty-nine River Authorities. The Act has only been in operation since 1965, however, and it remains to be seen to what extent geophysical exploration will be expanded.

Current research. Programs of numerous organizations concerned with water-supply problems lean heavily upon geophysical methods in the broader sense of the term. For example, electrical resistance analogue models of groundwater flow are being developed at several centres. A new development at the Institute of Geological Sciences is the investigation of infiltration into the unsaturated zones of sandstones. Neutron-scattering, rock moisture probes are employed to observe at weekly intervals the change in moisture at research sites where access tubes have been installed to a depth of 12 metres. This has been achieved by the use of an emplacement rig designed in the Department and operated from the power take-off of a Land Rover (Anon., 1967). Soil moisture suction values are also determined with tensiometers to assist in the interpretation of flow phenomena and, to complete the water balance for the sites, relevant meteorological factors will be measured to permit the computation of potential and actual evaporation and fluctuations in water level will be recorded in observation boreholes.

Gas and water permeameters, as well as a Boyle's Law porosimeter and standard saturation techniques, are now being employed in a study of regional and local variations of the hydrogeological characteristics of consolidated granular aquifers.

On as crowded an island as the U.K., the use of radioactive tracers in groundwater problems is necessarily restricted for safety reasons. However, work is now proceeding in collaboration with the Atomic Energy Research Laboratories on the testing of a point dilution probe which will employ a radioisotope as the indicator of fluid flow through gravels. The dating of groundwater by tritium determinations is also undertaken and investigations into tritium-layering have been started.

Future activities. Changes in the pattern of geophysical exploration for groundwater may follow the implementation of the Water Resources Act 1963 but they are likely to be minor as far as surface exploration in the U.K. is concerned. In borehole logging, however, the position differs and increased usage can be foreseen.

The scale of future overseas activities will be governed to a large extent by national and international policies. The need is clearly recognised for joint investigation by geophysicists and hydrogeologists, backed by appropriate geological mapping and ancillary facilities. Many programs could with advantage be associated with the activities of international organisations such as UNESCO and FAO. Subject to availability of staff and equipment, the Institute wishes to offer its hydrogeological services to the developing countries and is planning to set aside men for this purpose, in the belief that this is one of the most valuable forms of scientific aid it can offer.

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Geophysics in prospecting and exploration for mineral deposits in the U.S.S.R.

V.V. Fedynsky
V.V. Brodovoi
V.A. Gelamkov

Ministry of Geology, U.S.S.R.

Abstract. Geophysical methods are widely used in the Soviet Union in the exploration and prospecting of deposits of metallic and nonmetallic minerals and rare earths as well as groundwater. The organization of geophysical exploration is based on the principle of the interrelation of geological and geophysical data.

The main stages of geophysical investigations are the regional study of potential ore areas, and the exploration of mineral deposits and the subsequent prospecting of these deposits. At each stage geophysical exploration precedes geological investigations and prospecting-reconnaissance work.

Results of geophysical surveys are widely used for the compilation of metallogenetic, tectonic and geological maps. Geophysical methods are used not only in the direct search for orebodies but also in the indirect search, structural-tectonic and lithological features indicating favourable areas for further study. Emphasis is being placed at present on the extension of the methods for direct search; the further extension of combined geophysical and geochemical techniques; the extension of the application of induced polarization methods and large-scale gravimetric surveys for deep deposits; the application of seismic surveys for structural studies; and the wider application of large-scale aerogeophysical surveys including magnetic, electrical and radiometric methods.

Borehole geophysics is receiving increasing attention, especially X-ray fluorescence, various electrical methods, three-component magnetometry and geochemistry.

Various geophysical logging techniques are used in the prospecting of metallic and rare-earth deposits. These include resistivity, natural electric fields, sliding contacts, electrode potentials, and magnetic and radiometric methods. The purpose is to establish lithological sequences, ore intervals and rough estimations of grade.

Résumé. L'emploi des méthodes géophysiques est très répandu en Union soviétique où elles sont appliquées à l'exploration et à la recherche de minéraux métalliques et non métalliques, de terres rares et d'eaux souterraines. L'organisation de l'exploration géophysique est fondée sur le principe de l'interrelation des données géologiques et géophysiques.

Les principales étapes des recherches géophysiques sont l'étude des régions potentiellement riches en minerai, et l'exploration des gisements minéraux et la prospection subséquente de ces gisements. A chaque étape, l'exploration géophysique précède les études géologiques et les travaux de prospection et de reconnaissance.

Les résultats des études géophysiques sont utilisés couramment pour la compilation de cartes métallogéniques, tectoniques et géologiques. Les méthodes géophysiques servent non seulement à la recherche directe de venues de minerai mais aussi à la recherche indirecte, car alors les caractéristiques structuro-tectoniques et lithologiques indiquent les régions qui justifient des études plus poussées. On insiste présentement sur l'extension de ces méthodes à la recherche directe; sur l'extension des techniques géophysiques et géochimiques combinées; sur l'application accrue des méthodes de polarisation provoquée et des levés gravimétriques à grande échelle dans le traçage de gisements profonds; sur l'usage des levés séismiques dans les études structurales, et sur l'application plus répandue des levés aérogéophysiques à grande échelle, à l'aide notamment des méthodes magnétiques, électriques et radiométriques.

Les forages géophysiques reçoivent une attention croissante, s'appuyant surtout sur la géochimie, la fluorescence aux rayons X, diverses méthodes électriques et l'usage du magnétomètre à trois composantes.

Diverses techniques de diagraphie géophysique sont utilisées dans la prospection des gîtes de métaux et de terres rares, entre autres les mesures de résistivité, des champs électriques naturels, des contacts glissants, des potentiels des électrodes, et les méthodes magnétiques et radiométriques. On cherche ainsi à établir les séries lithologiques, la répartition des couches de minerai et à en évaluer approximativement la qualité.

The first geophysical surveys for mineral deposits in Russia were carried out at the end of the 19th century and in the early part of the 20th century, by Professors D.M. Mendeleyev and V.V. Bauman, among others, but systematic geophysical investigation was started only after the Revolution. The decree for the organization of a special commission for exploration in the region of the Kursk magnetic anomalies (OKKMA) was signed by V.I. Lenin in 1919. This commission conducted systematic magnetic and gravimetric surveys in areas of widespread occurrences of ferruginous quartzites.* Since then all geological and geophysical investigations have been planned and executed by state institutions.

During the last 48 years mining geophysics in the U.S.S.R. has undergone great changes. There are many skilled geophysicists in the U.S.S.R. at present with a firm technical background, and there are a network of research institutes, special geological departments accomplishing routine field work in different regions, high schools and universities. This is a reliable guarantee of the development of mining geophysics and its further progress.

The development of exploration geophysics in the U.S.S.R. may be divided into five periods:

1919-1933. A period of experimental application of geophysical methods, or trial of their capabilities. Research institutions dealing with exploration geophysics were founded and the first theoretical and experimental investigations were made, which provided the basis for the principles of a new phase of geological science.

1934-1941. Beginning of routine field application of geophysical methods in the U.S.S.R. Organization for training geophysicists in high schools, colleges and universities. Production of the earliest types of geophysical instruments.

*The term ferruginous quartzite or iron quartzite is equivalent to siliceous iron formation in North America.

1941-1945. Geophysical exploration was concentrated on the solution of the urgent problem of providing the country with strategic mineral resources.

1946-1959. A period of rapid development of research and routine field activity in exploration geophysics as well as of geophysical instrumentation. Developments in the theory, technique and equipment of exploration geophysics were directed toward enlarging the field of application of geophysical methods in prospecting and exploration of such raw materials as iron, manganese, titanium, chromium, nickel, copper, lead, zinc, tin, aluminium, cobalt, tungsten, molybdenum, mercury, antimony, gold, beryllium, tantalum, niobium, uranium and thorium. In addition to ore deposits, geophysical methods began to be used in prospecting for nonmetallics: diamonds, mica, pegmatite, corundum, quartz, rock salt, potash, sulphur, phosphate and underground water (Fedynsky, 1961).

Since 1960 the emphasis has been on obtaining improved geological and geophysical data. Another problem has been the development of techniques for locating deep-seated orebodies which could not be discovered by other means. Great attention is paid to the methods of mapping structural ore guides in mineral districts (airborne geophysics, seismic methods, gravimetry, etc.), to the methods of direct prospecting with deeper penetration (high-accuracy surveys with a gravimeter, methods of induced polarization and transients, etc.) and especially to the methods of borehole geophysics for the investigation of rock masses adjacent to and between holes as well as to geophysical investigations in mines.

Another feature of mining geophysics for the last decade has been the rapid development of nuclear geophysics and its application in the exploration and exploitation of ore deposits. Substitution of geophysical sampling for chemical analysis is of great economic value. In addition, computer processing of geophysical data is now being used.

At present geophysical exploration in mining areas of the U.S.S.R. is an integral part of a broad system of geological exploration. It is employed for geological mapping on a regional scale for prospecting, exploration and sampling of various ore deposits, as well as in hydrogeology and civil engineering. Particularly important are geophysical surveys in areas covered by unconsolidated deposits which cannot easily be investigated by conventional geological techniques, and also in prospecting for buried and deep-seated orebodies.

The number of geophysical investigations used in prospecting and exploration for ore deposits is explained by the great economic benefit derived. Expenditures for mining geophysics in separate orebearing regions account for 8 to 20 per cent of the total cost of geological reconnaissance. Total expenditures for mining geophysics (including geophysical methods of geological surveying and hydrogeological investigations) account for 35 to 38 per cent of the cost of all geophysical exploration in the U.S.S.R.

The table shows the relative distribution of the amounts spent for geophysical surveys in orebearing areas. The use of gravimetry and borehole geophysics is more widespread in the U.S.S.R. than in other countries. High-accuracy surveys with gravimeter and borehole geophysics (as mentioned before) are important in prospecting for deep-seated ore deposits.

Organization of geophysical investigations in the U.S.S.R.

The organization of all geological surveys by state institutions according to the general plan which permits them to carry out geophysical investigations, provides for:

1. Systematic study of an area progressing from reconnaissance surveying to detailed search for all types of minerals.
2. Use of all available data of previous geological, geophysical and geochemical surveys in areas under investigation and in the adjacent areas with similar geology.
3. The maximum correlation of geological, geophysical and geochemical surveys during the exploration of an area.

The system of training contributes to the close co-operation of geologists and geophysicists. The students in geophysics in high schools and universities have programs in physical, mathematical, geophysical and geological sciences, and students in geology have compulsory geophysical lectures.

Most routine geophysical surveys in the U.S.S.R. are accomplished by territorial geological departments (more than 50 departments conduct combination surveys in mining areas) which include specialized geophysical expeditions and field crews.

About fifteen institutes of the Ministry of Geology, institutes of the Academy of Sciences and of its branches, the Academies of Sciences of Soviet Republics, and geophysical departments in high schools and universities, conduct research work in mining geophysics. These scientific institutions are mainly engaged in complex, geological and geophysical studies.

The system of training specialists and the organization of geological-geophysical surveys in the U.S.S.R. provide mutual

Relative distribution of expenditures for geophysical surveys in U.S.S.R. and other countries.

	U.S.S.R.* (per cent)	Other Countries** Except Socialist Countries (per cent)
1	2	3
Total expenditures for geophysics	100	100
Petroleum and natural gas	56.6	94.2
Regional reconnaissance	10.3	not picked out
Minerals	33.1	4.4
Airborne geophysics	taken into account in 'regional reconnaissance'	1.4
Ground methods for minerals	100*	100**
Magnetic	12.4	6.5
Electrical prospecting	29.2	31.6
Gravimetry	23.2	3.8
Seismic	8.7	44.1
Borehole geophysics	19.2	5.1
Geochemical prospecting	5.7	6.1
Radioactive methods	1.6	1.0
Geothermal survey	not picked out	0.3
Other methods	—"—	1.5

*Only the activity of the ministry of Geology of the U.S.S.R. **Smith, Neal I. Geophysical activity in 1965, *Geophysics,* 30 (6), 1966.

enrichment of geophysical and geological investigations and general improvement of their results.

Organization of geophysical exploration in mining areas at the present time is based upon two main principles: close co-operation and interrelation of geological and geophysical investigations, and specialization of most of geophysical exploration.

Geophysical activity has been concentrated in specialized organizations (expeditions, trusts) because of the great variety of geophysical modifications employed for the solution of complex prospecting problems. Effective and flexible use of these modifications is possible only in the hands of highly experienced operators employing proper technical means. Specialized organizations are capable of successfully mastering and handling new equipment which has become very complicated due to electronics. On the other hand, there is increasing integration of geological and geophysical parties and expeditions which make wide use of well tested and approved geophysical techniques. But excessive division of geophysical organizations into small separate detachments and brigades within geological expeditions infringes upon the specialization of geophysical survey, inhibits the use and control of new methods by skilled geophysicists and, as a result, lowers the quality of these investigations. For these reasons such a division is not widely used.

Modern geophysical surveys in mining areas are conducted in combination. In addition to proper geophysical methods, exploration complexes also include geochemical investigations, particularly in prospecting for nonferrous metals and rare earths. Pedogeochemical surveys are used mainly for studying secondary dispersion haloes in eluvial formations. Directly connected with geophysical exploration are some types of geological activity—geological investigations of anomalous zones, test drilling, pit sampling, etc. Their principal purpose is to identify the geological nature of physical fields and promising anomalies in areas previously located by geophysical methods. Such a combination of geological and geophysical techniques arranged in suitable priority makes it possible to locate and recommend for further evaluation the most promising ore occurrences and in some cases to predict ore reserves.

The combination of geophysical and geological methods that is in current use in geophysical expeditions although not formal, is organized. It is founded on the use of principal physical and physical-chemical properties to permit more profound geological interpretation of geophysical parameters and further improvements in technique and instrumentation of field and laboratory work.

The many chemical analyses (about six to seven million assays a year) completed during the geophysical surveys became possible with the development of special laboratories for routine emission spectrographic surveys of geochemical samples (400,000 to 500,000 samples in a laboratory). The daily production of such a laboratory is 3000 to 4000 analyses for 25 to 30 elements.

Pedogeochemical surveying is the leading method for geochemical prospecting and is carried out by a specialized detachment of a geophysical field crew.

All geophysical surveys made for geological mapping as well as for prospecting for metallic and nonmetallic minerals are conducted according to special plans. Before 1950, surveys were made mainly in scattered, isolated areas, frequently at the margins of known deposits, but during the last 10 or 15 years they have systematically covered large areas in the search for mineral deposits. The results have greatly increased the geological effectiveness of the surveys. As a rule, areal geophysical surveys are made on a systematic grid basis according to the international sheet numbering, which facilitates their connection and adjustment and eliminates unnecessary repetition and overlapping. In such surveys searches are conducted for all of the economic minerals to be expected within the area.

Exploration of mining areas, including geophysical investigations, is accomplished according to a certain sequence. The most effective sequence is a transition from regional investigations to prospecting and then to exploration of the deposits. At each stage a geophysical survey should be made before the geological survey, prospecting and exploration. By this means the geologist-surveyor, before starting his work, has at his disposal the geophysical base of the sheet and a preliminary geological sketch made from geophysical data, with indications of the most promising targets, while the geologist-explorer gets recommendations for proper location of the drill sites as well as information concerning drilling technology, such as depth of bore holes and inferred cross-section. Analysis of the available geophysical information facilitates the future survey and helps direct the prospecting and exploration toward the most promising areas, with less drilling and development work needed.

The purposes of geophysical investigations

At present geophysical investigations are made in mining areas of the U.S.S.R. for the following purposes:

1. Division of the territory into tectonic zones, investigation of deep structures as well as of relationships associated with the distribution of ore deposits and fields, and location of areas promising for prospecting.

2. Regional studies of structural and tectonic conditions of mining regions and location of areas favourable for the occurrence of ore deposits. The results of these two stages are used for making small-scale geological, metallogenic and forecast maps.

3. Geological mapping of mining areas on large scales (1:50,000 to 25,000)* and, in particular, selection of prospective areas with favourable lithological, magmatic, structural and other ore-controlling factors.

4. Direct search for ore deposits by distinguishing the anomalies produced by orebodies, or mapping the zones of metamorphism adjacent to the ore (indirect search).

5. Exploration of ore-bearing fields and deposits, including detailed search for new orebodies and tracing known ones by detailed ground surveys and investigation of rock masses near and between bore holes.

6. Core-logging of exploratory holes, locating and sampling ore intervals, as well as the control for technical conditions of the holes.

7. Hunting for orebodies which were missed previously and additional study in mines which are at the exploration stage.

8. Sampling of rocks and ores *in situ* in mine workings and subsurface holes, in outcrops and roadcuts and on the highways.

*The scale of geophysical surveys and maps in the U.S.S.R. is defined by the intervals between traverses. This interval for magnetic and metallogenic surveys is, as a rule, 1 scale measure of a report map; for gravimetry and electrical survey it is 2 scale measures. An interval between stations along the traverse is equal to or less than the interval between traverses.

9. Hydrogeological surveys and searches for aquifers, and engineering geology problems.

These problems are solved at three successive stages of geophysical exploration: regional investigation of mining areas; prospecting and location of mineral deposits; and exploration of the deposits.

Geological conditions for the application of geophysical methods in mineral explorations are naturally different at different phases of explorations, for each type of mineral, and for different deposits. Nevertheless, it seems possible to make some general remarks on this point.

Large blocks of the earth's crust have different densities, elastic, magnetic and electrical properties and these differences are manifest in physical fields at the earth's surface. Regional anomalies constitute a significant part of the total fields of various parameters and it is not hard to separate them from the general background.

In prospecting for minerals the situation is much more complicated. Geophysical anomalies produced by orebodies at the earth's surface are difficult to distinguish against a background of varied interference and are still more difficult to interpret. Therefore direct searches for orebodies are possible only in a particularly favourable geological situation. One has to resort to indirect methods of prospecting for orebodies, by distinguishing various metamorphosed zones adjacent to the ore that are indicated by physical fields and primary dispersion haloes. The problem of indirect search for orebodies is solved by studying ore-guides. Orebodies are generally confined to contacts between different rocks, to definite horizons, to plutonic plugs, faults and other structural, lithological and facial features of the area under investigation. In indirect searches for ore deposits, special importance is attached to checking geological interpretation by drilling test holes or digging mine workings.

In the detailed exploration of discovered deposits geophysics should be considered primarily as a means of reducing the number of drilling and mine working jobs necessary because they can be properly pinpointed by geophysics. This reduces the cost and speeds the exploration. In particular, geophysics is responsible for locating new orebodies missed in the course of exploration and also extensions of known deposits.

During all stages of geophysical investigation the physical properties of rocks and ores are studied at special laboratories of large expeditions and trusts. In the field, geological detachments equipped with portable apparatus study the magnetic properties, density, electroconductivity, etc., of the rocks.

Geophysical surveys in regional investigations in mining areas

Regional geophysical investigations in folded areas consist of aeromagnetic and gravity surveys on a scale of 1:200,000 as well as of electrical and seismic surveys conducted mainly along traverses.

Information pertaining to deep crustal structures down to the lower boundary of the Mohorovicic discontinuity is generally obtained from deep seismic soundings (DSS). The purpose of DSS is the tracing of the main crustal boundaries, location of deep faults, investigation of the relationship between deep and shallow structures, etc. DSS profiles generally extend for hundreds of kilometers, crossing different tectonic regions. DDS are generally made according to a technique of continuous profiling with medium-frequency refraction and reflection surveys, gravity and magnetic surveys.

In recent years (1963-1966) deep crustal investigations have been accomplished by means of seismological observations using energy of close and remote earthquakes and recording arriving seismic waves with the high-resolution Zemlia recording units.

Regional seismic refraction investigations are used for studying the relief and composition of the crustal basement, which is surrounded by mountain regions covered with unconsolidated deposits hundreds of metres thick, such as in the Urals, Tien-Shan, Baltic and Ukranian Shields. Seismic refraction and reflection prospecting surveys are conducted to investigate consolidated, weakly faulted, Palaeozoic sedimentary formations containing bauxite areas, copper-bearing sandstones and placer gold deposits. Recently seismic refraction investigations have been used in studying the internal structure of the basement at depths of from 1 to 10 or 12 km, as in the Kola peninsula, Urals, Altai, Ukrainian Shield and other mining areas.

Electrical prospecting is used in regional investigations as a supplementary tool. In folded areas with unconsolidated cover of 200 to 300 metres, electrical prospecting on a scale of 1:200,000 to 1:100,000 is usually conducted by vertical electrical sounding (VES). The structural elements of the Palaeozoic basement are investigated by dipole electrical sounding (DES) and transient techniques.

Nearly all the folded areas of the U.S.S.R. have been covered by aeromagnetic surveys on a scale of 1:200,000. The interval between the lines is 2 km, locations being determined by either aerovisual or photographic means.

The results of regional geophysical investigations are plotted on various types of maps, including geotectonic, magmatic provinces and forecast metallogenic.

Contouring of the Moho discontinuity as well as other crustal interfaces is made with allowance for statistical and analytical relationships of the gravity field. The depths of the Moho discontinuity and of the basalt layer usually vary along fault zones (or tectonic sutures arising from attenuation of movements along faults). It enables one to locate crustal blocks which differ in structure and geological history. For example, the results of geophysical investigations conducted in areas of folded rocks in Kazakhstan showed that a comparatively high elevation of the Moho discontinuity and thickening of the basalt layer corresponded to the area of Caledonian folding whereas a greater thickness of the crust (due to significant thickening of the granite layer) corresponded to the area of Hercynian folding.

The results of deep seismic soundings along the Sverdlovsk profile, crossing the central part of the Urals, are shown in Figure 1 (Khalevin, *et al.*, 1966). The profile extends from 450 km; at the west it reaches the Russian platform and at the east the area of the folded Urals. Palaeozoic and the older dislocated formations are apparent at the surface and in the middle of the DSS profile. The Precambrian basement is beneath more than 3000 metres of sediments in the pre-Urals depression and on the Russian platform. At the east slope of the Urals the thickness of continental sediments increases gradually to 1000 metres near t. Tyumen. The earth's crust in the Urals is characterized by subhorizontal bedding and structures in the form of blocks. Seismic data clearly traces the Moho discontinuity at depths of 33 to 47 km, and a gneissic granite complex at depths of 2 to 8

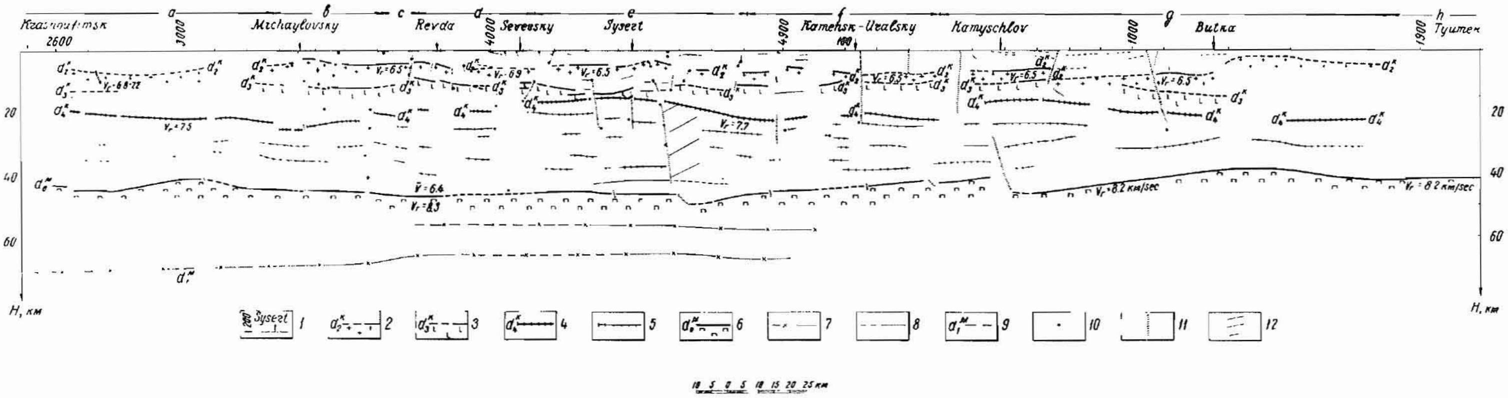

Figure 1. Profile of deep seismic sounding (DSS) across the Urals (by Halevin, *et al.*, 1966). 1. Observation positions with projection of nearby positions; 2. Surface of Precambrian basement (granite-gneiss complex); 3. Surface of basalt layer; 4. Boundaries of inner-basalt layer; 5. Reflection boundaries; 6. Mohorovicic discontinuity; 7. Boundaries determined from elastic waves resulting from earthquake in upper mantle; 8. Seismic boundaries in upper part of crust; 9. Reflection boundary inside mantle (DSS data); 10. Points of wave diffraction from different wave data; 11. Inferred deep faults and zones of disturbed condition of seismic boundaries; 12. Zone of complete absence of sub-horizontal bedding. (a)–(g) principal structural elements (according to tectonic map of the Urals, edited by I.D. Sobolev): (a) Pre-Urals downwarp; (b) West-Urals zone of folding; (c) Central-Urals uplift; (d) Tagil-Magnitogorsk depression; (e) East-Urals uplift; (f) East-Urals depression; (g) Zautals uplift.

km. The Moho discontinuity determines the formation of the geosynclinal 'roots' of the Urals which have an amplitude of 3 to 7 km.

The western boundary of the Urals geosyncline is determined by Michailovskiye's series of deep faults, which transect the earth's crust as well as the upper mantle. Inside of the Urals geosyncline, according to the character of the seismic waves which are influenced by features of the deep structure and evidence from magnetic and gravitational fields, one can distinguish large tectonic features including structural depressions and structural highs which are delimited by deep faults in the crust. Their boundaries are defined more exactly by geophysical methods in some places. The earth's crust in the Urals in general, and in the Tagil-Magnitogorsk geosyncline in particular, is characterized by more rapid velocity of the seismic waves and higher rock densities, corresponding to an increase in basic minerals in the earth's crust. The most useful part of the investigation has been the conclusion concerning the similarity of the structure and composition of the crust in the Tagil-Magnitogorsk geosyncline to the western part of the East-Urals structural high, and therefore the promise of finding economic deposits there such as are found in the Tagil-Magnitogorsk depression.

Investigation of the earth's crust by geophysical means confirms the principle of density heterogeneity of the underlying upper mantle. The main petrographical provinces which are distinguished in this way are well correlated with the data obtained for the depth and thickness of the crustal layers. For example, areas with a thick basalt layer are characterized by a great development of basaltic magma (the Urals, north Kazakhstan); the thick granite layer corresponds to a granite province (central Kazakhstan).

Crustal investigations which consist of studying the behaviour of the principal interfaces, the distribution of granite intrusions, and the location of deep faults when related to geological concepts make it possible to locate the principal geotectonic regions. These regions are characterized by a similar geological history, a series of specific formations, areas of intrusions identical in composition and age, and finally, by a certain thickness and structure of deep crustal horizons typical for each area and each block.

An example of the result of such investigations is the structural-geophysical map of Kazakhstan (1:1,500,000), which shows the areas of intrusive and extrusive rocks, the structural-tectonic characteristics of regions, the depth of the crystalline basement, etc. Deep faults are marked in folded areas by extensive, frequently linear, zones of high gravity gradients and also by a variation in the nature of the gravity and magnetic fields. Major faults attenuating in the granite layer are recognized from diverse and peculiar pattern combinations of gravity and magnetic anomalies.

Physical fields at the surface typically mark protrusions of the ancient basement rocks, rigid lumps, major geoanticlinorium uplifts and tectonic highs of great orders of magnitude. As a result, uplifts of the basement are shown by high gravity and magnetic values. However, a few synclinal structures in the Urals and north Kazakhstan, which are composed of thick Lower Palaeozoic volcano-sedimentary formations, show high gravity and magnetic values.

Most of the lows – tectonic depressions, synclines and graben synclines – are generally marked by low gravity and magnetic fields. Magmatic units are also distinctly recognizable by their physical fields. Every type of intrusion – ultrabasics, gabbro-diorite, granite, syenite and alkaline formations – are characterized by typical gravity and magnetic fields. Belts of ultrabasic intrusions are marked in the Urals by chains of local high gravity anomalies and intensive magnetic anomalies. Smaller masses are indicated only by local magnetic anomalies. Intrusions of gabbro-diorite are clearly recognized by their magnetic fields which cause intensive positive anomalies. In a gravity field they are distinguished differently, the field varying from neutral to high. Acid masses are distinctly marked by intense gravity lows.

Contents

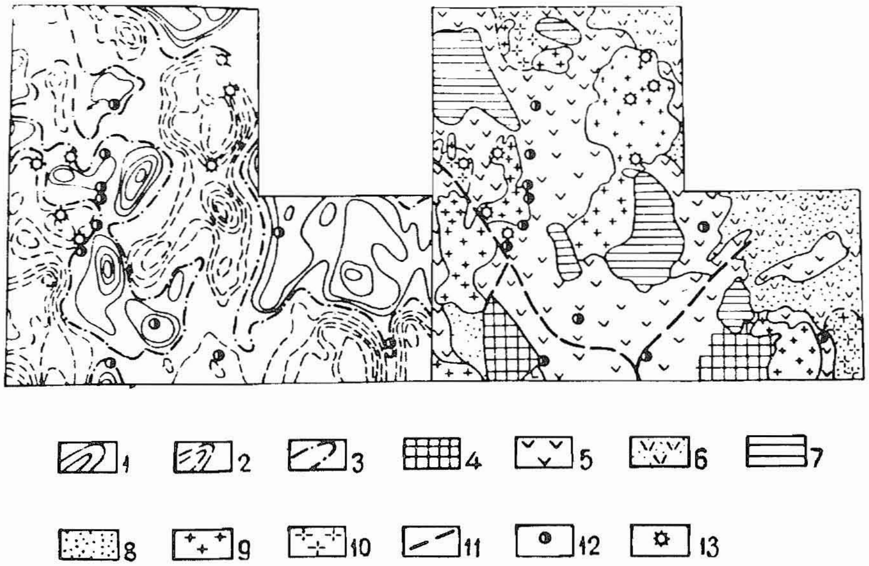

Figure 2. Use of gravimetric survey for metallogenetic forecast (reported by Anoshin, and Ivanov, 1966). 1. Isoanomalies of higher mean gravitational field Δg; 2. Isoanomalies of lower mean gravitational field Δg; 3. Isoanomalies of intermediate mean gravitational field Δg; 4. Precambrian metamorphic formations; 5. Basic and intermediate Cambrian and Ordovician effusive rocks; 6. Zones of basic and intermediate effusive rocks inferred from gravimetry; 7. Troughs, filled with Devonian-Carboniferous sediments; 8. Mesozoic-Cenozoic deposits; 9. Granitoids; 10. Regions of deep-seated granitoid intrusion inferred from gravimetry data; 11. Tectonic dislocations; 12. Areas of sulphide (mainly pyrite) mineralization; 13. Areas of rare-metal mineralization.

Effusive magmatism is less clearly reflected in physical fields. Areas of development of thick basic effusives are marked by high gravity values and by a mosaic pattern of inverse magnetic anomalies. Acid effusives show low gravity values.

The example of Kazakhstan shows that 50 or 60 per cent of intrusions, and in some areas more, are covered by unconsolidated sediments and cannot be investigated by conventional geological methods. They can be studied only by geophysical techniques and drilling. The results of geophysical surveys are used in preparing contour maps of the basement and in determining the thickness of sediments, information which is essential in prospecting for minerals of a sedimentary origin and for underground water.

Large-scale regional geophysical surveys are used for geological mapping of mining regions (scale 1:200,000). The results of these surveys constitute lithologic–tectonic sketches, which are very important for preparing geological maps. Geophysical materials and results of their geological interpretation are widely used in the preparation of forecasts–metallogenetic maps and location of areas which seem promising for mineral prospecting. Application of geophysical and geochemical data in forecasts are highly reliable since a thorough allowance is made for geological-geochemical situations which control the distribution of ore occurrences and deposits. There is still much to be done in the field of geological prediction from geophysical and geochemical data though even now one can outline some interesting relationships. For example, there is an undoubted relation between large zones of commercial copper-nickel mineralization and areas of thicker and shallower masses of basic and ultrabasic rocks, i.e., basalt (or, more exactly, second basalt) layer of the earth's crust in the Kola peninsula, the Urals, Taimir and other regions.

Ore fields appear to cluster along faults of high orders of magnitude which are recognized in the upper crustal layers, particularly along the so-called feathering fault system.

Obviously there is a relation between endogenic ore deposits such as rare earths, polymetallic and primary gold, and granite belts. Such deposits most frequently occur within granite belts where they are confined to areas near intrusives.

Geophysical methods used to investigate ore-controlling factors

Regional geophysical surveys are used for tectonic investigation of large structures within the crust and for more precise definition of structures and areas of metallogenetic belts and provinces, while medium-scale (1:200,000) and large-scale (1:50,000 and more) surveys are used for smaller structural, lithological, magmatic and other geological factors controlling ore distribution.

Geophysical methods are used in the U.S.S.R. more and more for metallogenetic mapping on medium and large scales, and for preparation of metallogenetic maps. The result of these complex geologo-geophysical surveys is used to locate areas promising for the search of certain types of deposits and to arrange them in a proper priority list.

For example, the search for pyrite deposits in the Urals is recommended in areas composed of volcanic-sedimentary formations with a high proportion of volcanic rocks including those of acid composition; such areas have high gravitational fields and characteristic low magnetic fields. Areas favourable for finding chromite are those of ultrabasic massifs which are easily identified from gravity and magnetic surveys. These massifs are confined to zones of regional deep faults and form thick and extensive ultrabasic belts. Chromite deposits are generally located in areas of feeder (incurrent) channels, which are easily distinguished by local gravity highs and are most frequently associated with deeper horizons of the massifs.

Areas of ultrabasic rocks are also interesting with respect to the search for nickel-cobalt sulphide and silicate deposits as well as those of asbestos, talc and magnesite.

Skarn copper, iron and other deposits are usually confined to exocontacts of granite intrusions or to fault zones not far from them. Parent granitoid massifs are usually distinguished by higher magnetic values and are surrounded by intensive anomalies in the zone of active exocontact. Gravitational fields above them may be either higher or lower. The search for rare-earth deposits in areas of granite massifs is planned on the basis of radioactive anomalies as well as on geochemical data concerning the presence of stray fluxes and dispersion haloes of tungsten, molybdenum, bismuth, beryllium, niobium and tantalum. Granite intrusions are outlined by local gravity lows, which are particularly important in areas covered by Meso-Cenozoic sediments.

Figure 2 illustrates the possibility of gravitational field use for metallogenetic forecast in one of the half-closed Kazakhstan regions (Anashin and Ivanov, 1966). Copper-pyrite deposits are situated at the flank of the higher gravitational field anomalies and are associated with effusive rocks; rare-metal deposits are associated with local low gravitational fields near acid intrusions.

Gold mineralization in primary rocks can be associated with diorite intrusions and ore-controlling tectonic movements which can be traced from gravity and magnetic anomalies. Prospecting for gold deposits may also be guided by geochemical data from indications of the presence of dispersion haloes of elements using indicators such as arsenic, lead and copper. Prospecting for gold may also be conducted in zones of sulphide mineralization which are characterized by high conductivity and chargeability.

By now, certain ore-controlling factors have been determined for most types of solid mineral deposits. Often they are reflected in the associated physical fields. The investigation of structural-tectonic, lithological, magmatic and other elements of geological structure controlling the localization of ore deposits, as well as the participation in drawing up large-scale forecast-metallogenetic maps, are both important trends in the development of mining geophysics. The determination of which anomalies are orebodies is the purpose of geological investigation in its next stage. In some instances, the large-scale metallogenetic forecast forms the basis for prospecting indirectly for new deposits, particularly for deep-seated units.

The principal geological method for drawing up forecast metallogenetic maps is based on the results of geological surveys. Similarly, among geophysical methods, areal magnetic and gravity surveys play the leading role in metallogenetic investigations. The study of structure and tectonics in mining areas and their ore-controlling role require systematic surveys of large regions, covering the whole mining area. Therefore complex airborne geophysical prospecting, particularly airborne electromagnetic, acquires fresh significance.

Another significant trend in geophysics for metallogenetic investigations of composite mining fields is the introduction of seismic methods for internal structural investigations at great depths (Karayev and Trostnikov, 1966). Taking advantage of the experience gained from petroleum investigations, seismic prospecting is used for mapping the crystalline basement covered by unconsolidated deposits, to locate ore-controlling structures in ore-bearing complex rocks, as in Rudnii Altai, the Urals, Turgai and northern Caucasus, and for investigating tectonics inherent to the Palaeozoic and to the older crystalline basement. The purpose is to determine any systematic regularity near the sites of deposits such as occur in the Almalyksky region, Baltic shield, Rudnii Altai and Chinghiz. The principal seismic information is obtained from great depths (as a rule more than 1000 to 1500 metres) and this hinders the subsequent development and use of seismic surveys. Hence, one of the primary trends of research activity in this sphere is the development of methods for getting geological information from shallower depths, comparable to deep prospecting.

A developing trend in seismic surveys of ore deposits is the study of the morphology of ore-bearing intrusions and associated deep-seated units. Among the purposes of this kind of work are: defining the position of the upper surface of the intrusions and the thickness of the overlying formations; studying the contacts; differentiating intrusions according to their petrography; and determining the depths of their layering and the morphology of the under surfaces. A knowledge of the structural features and the composition of intrusions will contribute to a more effective way of prospecting for deposits of chromite and rare metals as well as contact-metasomatic, stockwork and other types of deposits, the formation and position of which are closely connected with intrusive activity.

A most important trend in mining seismic surveys is tectonic investigations such as discovering and mapping deep and feathering faults, and ascertaining the connection between mineralization and intrusive position.

Geophysical investigations in ore prospecting

The principal purpose of mining geophysics is the prospecting for ore deposits by distinguishing anomalies caused by orebodies (direct search) or by zones adjacent to orebodies (indirect search).

In the U.S.S.R., a wide combination of geophysical methods is used for prospecting for various useful minerals and types of ore deposits; these methods are based on the differences in the properties of rocks and ores, such as magnetic susceptibility, density, electric conductivity, electrochemical activity, polarization, velocity of elastic waves and radioactivity, as well as their physical states, such as magnetization and electrochemical processes.

Following is a review of the most typical combinations of geophysical methods used in the U.S.S.R. for prospecting for the principal groups of useful minerals.

Ferrous metals. Geophysical methods are widely used in prospecting for iron ore and chromite; these methods are also used on a small scale in prospecting for manganese and titanium deposits.

The iron ores in the U.S.S.R. are principally magnetite, ferruginous quartzite and siderite. Most geophysical prospecting consists of magnetic and gravity surveys. Areas promising for iron ores are covered by aeromagnetic surveys on a scale of 1:25,000 to 1:50,000 with photo- or radio-navigation control. Successful aeromagnetic surveys on a 1:10,000 scale have recently been made with an aircraft flying in the field of radar navigation stations (control accuracy ±20 to 25 metres). Aerogeophysical surveys are conducted over large areas, with a periodic reflying over promising or commercial areas, if necessary, as new and more sensitive equipment is developed.

To facilitate the ground exploration of promising anomalies, aeromagnetic surveys are accompanied by detailed ground surveys. New types of ground magnetometers and a vehicle-borne proton magnetometer which has an accuracy of ±2 to 3 gammas have been successfully tested. Gravity surveys conducted in promising areas on scales of 1:50,000 to 1:25,000 help to distinguish areas of weakly magnetic rocks (martite, hematite) and permit deeper geophysical exploration.

Gravity and magnetic anomalies not only define areas promising for iron prospecting but provide information on the dip and strike of orebodies and contribute to preliminary estimation of the size of an ore target.

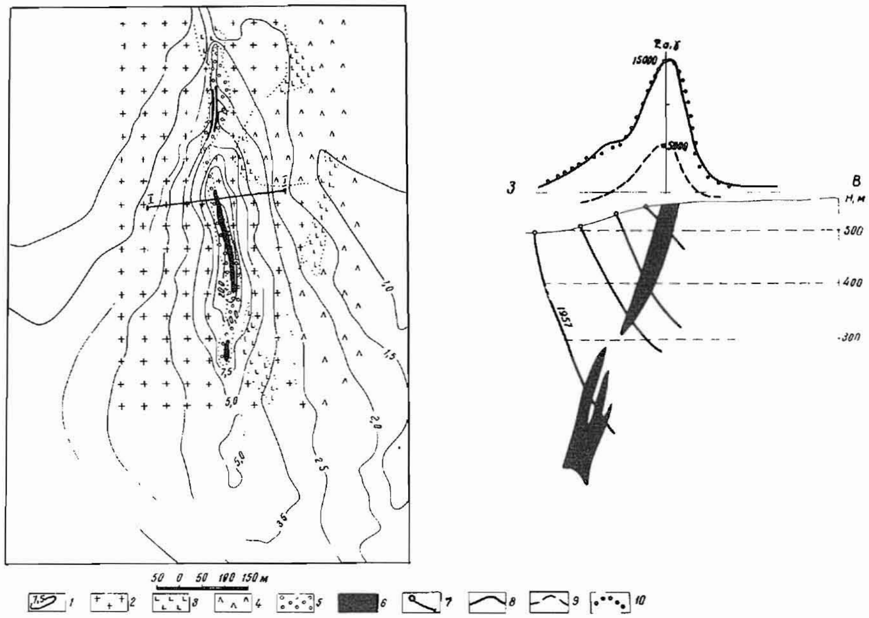

Figure 3. Results of magnetic survey over the Odinochnoye deposit in east Sayani (by B.I. Terehob). 1. Isogams ΔZ (thousand); 2. Granodiorite, quartz-diorite, diorite; 3. Hornfels; 4. Porphyrite; 5. Skarn; 6. Ore; 7. Holes; 8. ΔZ observed curve; 9. Theoretical ΔZ curve of orebody, revealed by earlier drilling; 10. Theoretical ΔZ curve, derived by selection, based on depth of the orebody.

The principal purpose of geophysics in industrial regions not far from operating mining enterprises is the development of methods of prospecting for deep-seated magnetite deposits.

Besides careful interpretation of magnetic and gravity fields and the study of structural-tectonic elements and their ore-controlling effect, other special methods of determining vertical gradients and variations of the magnetic field are used for this purpose, together with bore hole magnetics.

Figure 3 shows the anomaly over a deep-seated magnetite body beneath a well known orebody in eastern Sayani. This discovery was based on the results of the interpretation of intricate ground magnetic patterns (Krutikhovskaya, Schmidt, 1961).

Seismic prospecting was successfully used in ferruginous quartzite deposits of the Voronezh and Ukrainian crystalline shields (Kursk magnetic anomaly, Krivoi Rog) to locate and follow ore horizons covered by unconsolidated sediments up to 500 metres thick and to detect large deposits of secondary redeposited ores within these horizons. In Krivoi Rog basin, seismic prospecting was also used for investigating the deep structure of iron ore formations of the Belozerskaya syncline.

Siderite does not differ magnetically from the associated rocks. However, geophysical methods were successfully used in prospecting the Bakal siderite deposits in the southern Urals. The location of deposits within the ore field is controlled by diabase dykes, which create lineal magnetic anomalies. The high density of siderite (3.3 to 3.5 g/cm^3) allows us to use gravity surveys. With the help of this kind of survey a new siderite bed more than 100 metres thick at a depth of 400 metres was found below a known and mined deposit in Mount Irkustan.

Geophysical investigations have been effective in prospecting for iron ore. No less than 90 per cent of the iron ore deposits of the U.S.S.R. have been discovered and explored by a broad application of geophysical methods.

Geophysical methods are also effective for the prospecting of chromite deposits. Magnetic and gravimetric surveys at a scale of 1:200,000 to 1:50,000 are used to study ultrabasic massifs with which chromites are associated and, in particular, the roots of dunite differentiates of ultrabasic masses which are the most favourable for mineralization (Bekzhanov, *et al.*, 1965). The most attractive areas are investigated by detailed surveys at a scale of 1:10,000 with gravimeters and gravitational gradiometers* to indicate mineralization. These surveys are supplemented by control drilling. Such methods permit prospecting to a depth of 500 metres.

Geophysical discoveries of new commercial chromite deposits in Kazakhstan have practically solved the problem of shortages of this mineral in the U.S.S.R.

Geophysical methods have also been used in titanium prospecting though less frequently and less efficiently. The same methods are used in prospecting for titaniferous magnetite as are used for magnetite. Location of titanium deposits by geophysics is a more complicated problem. It is solved by electrical surveys which are conducted for studying the morphology of buried relief and locating buried shelf zones, ancient river beds, etc. If such places contain magnetite they are easily mapped by magnetics (Figure 4).

Aluminum raw materials. Bauxite. Geophysical methods are used in the U.S.S.R. to locate stony and clayey varieties of bauxite, associated with a Mesozoic weathering zone. The search begins during an examination of areas which are promising for bauxite, for the purpose of studying their structural conditions, mapping carbonate and aluminum-bearing rocks, studying unconsolidated formations, and making contour maps of the buried basement (Igoshin, *et al.*, 1965). By this means the areas and structures promising for bauxites are determined. In addition to other methods a significant role is played by seismic refraction surveys. They are generally run along a grid (6 to 8 km) enabling one to

*The highspeed gravitational gradiometer GRB-2M has been produced in the U.S.S.R. since 1959. The apparatus measures horizontal gradients of gravity with a sensitivity of ± 6 Eotvös units, the time for observation is 12 minutes.

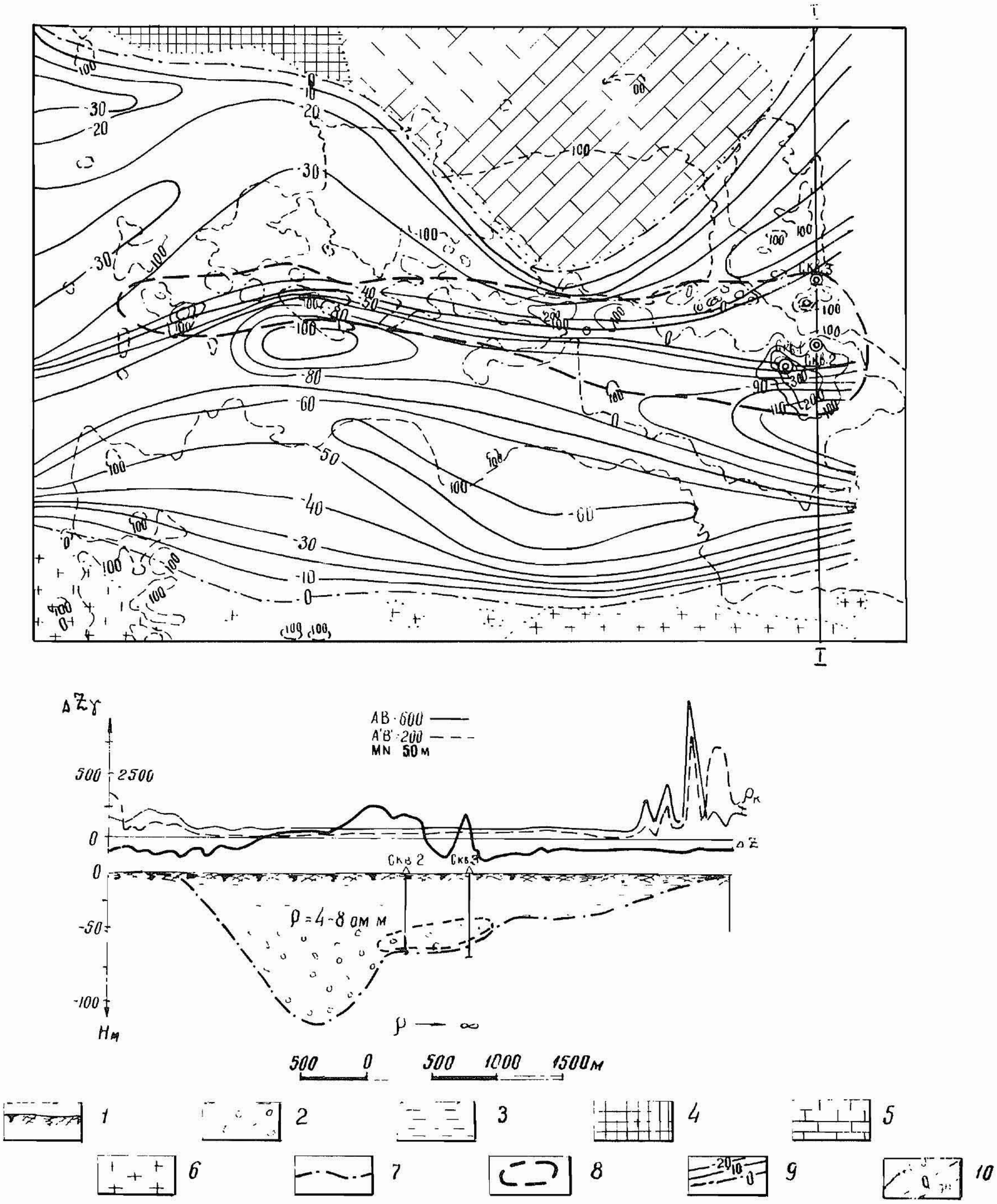

Figure 4. Geophysical investigations for study of buried placers in central Kazakhstan (by B.P. Yumanov, and V.A. Klichnikov). 1. Surface; 2. Shingle; 3. Clay; 4. Quartzite; 5. Granite; 6. Bedrock relief; 7. Areas of wolframite and magnetite placers; 8. Zones of placers, from geophysical data; 9. ΔZ curve; 10. Contour lines on VES data.

follow extensive limestone areas, depressions and karst zones in which bauxite deposits are confined.

During the main phase of prospecting, large-scale (1:25,000 to 1:50,000) geophysical surveys are conducted, primarily by magnetic and electrical (VES and electric profiling) methods. Making VES measurements along a grid of 200 × 500 metres, one makes a detailed study of the hypsometry of the bedrock surface, locating any large depressions and karst zones in carbonate areas which may be favourable for bauxite accumulation. The VES technique is effective only if a recent cover is more than 30 or 40 metres thick. Areas covered by a thinner layer of loose sediments (less than 15 or 20 metres) are better mapped by symmetrical electrical profiling with two different electrode separations AB.

Magnetic surveys (1:25,000 to 1:10,000) in conjunction with electrical prospecting allows us to locate bauxite deposits with high magnetic susceptibility in depressions. As a rule, anomalies

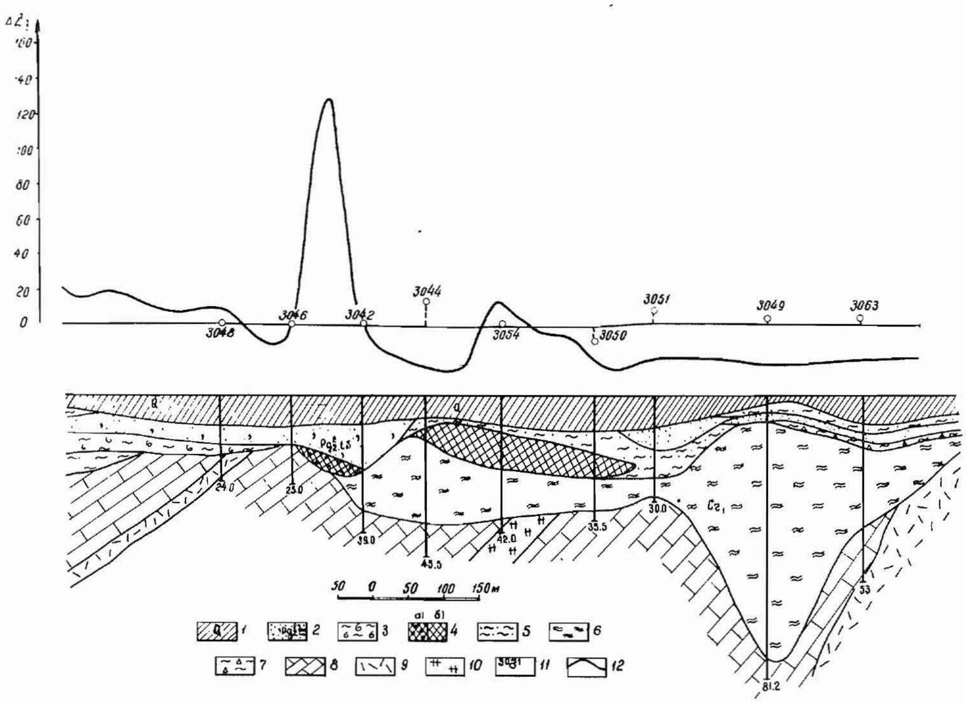

Figure 5. Magnetic anomaly over stony bauxite deposits in Turgai (by V. Safin). 1. Soil, loam, sandy loam; 2. Glauconitic quartz sand; 3. Grey clay with organic remains; 4. Bauxite (a) stony, (b) clayey, mainly unconsolidated; 5. Bauxite clay; 6. Mothley clay; 7. Proluvium-deluvium clay; 8. Limestone; 9. Tuff, tuff breccia; 10. Diorite; 11. Holes, drilled by Temirskaya GEP before geophysical surveys; 12. ΔZ curve.

above them have small intensities (70 to 150 gammas) and limited sizes (a few hundreds of metres).

Primary objectives for prospecting for bauxites are depressions in limestone, accompanied by local anomalies in the magnetic field. If geophysical recommendations are confirmed by control drilling, depressions and magnetic anomalies are distinguished, and detailed surveys (1:10,000 to 1:5,000) are conducted on these to outline the bauxite deposits and evaluate the whole region. The results of magnetic prospecting above such deposits are shown in Figure 5.

The geophysical surveys of the second and third stages must be made in conjunction with control drilling of the order of 5000 to 7000 linear metres.

In the case of an unfavourable geoelectrical section, as for example in the Turgai depression, the mapping of depressions with bauxite-bearing rocks may be made with the help of gravity surveys on a scale of 1:50,000 to 1:10,000 (contour interval 0.5 to 0.2 milligal) rather than with the help of electrical prospecting.

Application of geophysical methods facilitated the discovery of new bauxite-bearing areas on the Siberian platform and commercial deposits in Angara region and Chadobets uplift.

Copper ores. The principal types of copper ores in the U.S.S.R. are pyrite, copper porphyry and copper sandstone. Prospecting for pyrite ores has until recently been based upon electrical dc techniques; it also included lithogeochemical surveys (1:10,000 to 1:50,000). Geochemical surveys played the principal role in the search for deposits in Kazakhstan.

A great contribution to the increase in effectiveness of copper prospecting has been the introduction of induced polarization surveys (1:10,000 to 1:25,000). This technique is extremely reliable in locating disseminated mineralization and therefore permits us to indirectly find deep-seated orebodies by locating any adjacent zones of disseminated mineralization (Komarov, 1965).

High-conductivity ores are also discovered by transient surveys, using type MNNO-1 equipment. The method is characterized by its great depth of penetration (down to 150 metres) and speed. Besides induced polarization and transient methods, in the last few years highly accurate gravity surveys (scale 1:10,000) have been successfully introduced in prospecting for copper sulphide deposits. Geophysicists in the Urals, (Yarosh and Polyakov, 1963), when prospecting for large orebodies, can determine depths up to several hundreds of metres from gravimeter surveys.

Figure 6 shows the geologic and geodensity sections and the gravity results at a copper sulphide deposit in the central Urals. The geodensity section is derived from determinations of rock and ore densities which were measured on drill cores. The orebody, with a density of 4.50 g/cm^3 is surrounded by haloes of altered rocks with an average density of 3.20 and 2.82 g/cm^3. Quantitative calculations indicate the anomalous effect of the orebody is only 0.3 milligal; the combined effect of the orebody and zone adjacent to it increases to 0.6 milligal. Thus, this relatively shallow body and another deep-seated orebody is confidently determined by gravity surveys. Even minute bedrock relief must be considered when making high-accuracy surveys with gravimeters.

Increasing numbers of gravimeter surveys on a scale of 1:50,000 (contour interval of 0.5 milligal) are being used for locating and mapping ore-controlling structural elements in such copper areas as Mugodzhari, Rudnii Altai and the Urals.

Deep geochemical surveys have recently been made in areas covered by thick unconsolidated formations (up to 30 or 50 metres). Geochemical samples are taken from bore holes. About 10 are drilled per square kilometre. The deep geochemical survey helps to locate in the ancient weathered zone the buried remnant dispersion haloes of copper, lead, zinc, molybdenum, arsenic and

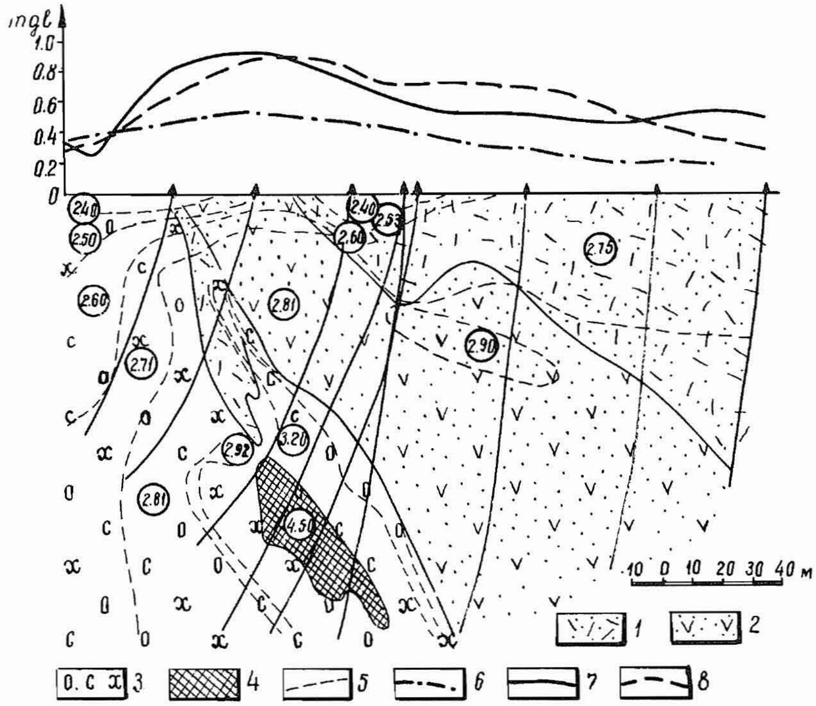

Figure 6. Results of a gravity survey over a blind sulphide vein in a deposit in the Urals (N.S. Shmeliov). 1. Albitophyre and its tuff; 2. Porphyrite and its tuff; 3. Quartz-chloritic-sericitic rocks; 4. Massive sulphides; 5. Areas of rocks with inferred indentical density, g/cm^3; 6. Calculated Δg curve over orebody; 7. Measured Δg curve with regional background; 8. Measured summary Δg curve of orebody with calculation of all density boundaries; 9. Bore holes.

silver. Vertical geochemical sections give an idea of the morphology of hidden dispersion haloes and also reflect the direction of migration of the elements.

Geological studies, such as traverses and checking and evaluating the physical properties of mine and drill core samples, are made to acquire the best geological interpretation of the geophysical data, in order to verify the preliminary estimation of the discovered targets.

Prospecting for copper-bearing sandstones is a more complicated problem for geophysicists. Geophysical surveys are not yet able to locate such mineralization directly. They can only solve such structural problems as determination of depth of ore-bearing sandstones and location of areas in which they are the most shallow, detection of anticlinal folds and faults favourable for mineral accumulation, etc.

Copper-bearing sandstones were prospected in Kazakhstan by reflection and refraction seismics, electrical (VES) surveys (1:200,000) and gravity surveys (1:50,000). Lithogeochemical, IP and direct current surveys, as well as magnetics are used selectively, mainly on the sides of depressions, where producing formations are exposed or are hidden beneath alluvium (Al'mukhanbetov, *et al.*, 1963).

In the U.S.S.R. porphyry copper deposits in Middle Asia (Almalyk), central Kazakhstan (Kounrad, etc.) and some other regions, geophysical methods were unsuccessful in the direct search for porphyry copper deposits for a long time. Disseminated ores could not be distinguished by their electrical resistance, nor did their magnetic susceptibility, density and other physical properties help to distinguish them from the enclosing rocks. However the effectiveness of geophysical surveys has greatly increased with the study of ore-controlling structures and the introduction of induced polarization.

The porphyry coppers of the Almalyk region (Wolfson, *et al.*, 1964) occur in syenite-diorites which can be distinguished from the associated rocks by their higher magnetic and gravity values. The copper deposits are mainly confined to the intersections of westerly and northwesterly tectonically weak and hydrothermally altered zones which have significantly lower magnetic and gravity values (Figure 7). The high sulphide concentrations can be readily detected by IP measurements.

The usefulness of classifying fault intersections according to the chances of finding porphyry copper deposits can be enhanced by including results of metallogenetic surveys and analyses of primary dispersion haloes in bore holes drilled for mapping or prospecting. Several new commercial deposits have been discovered in this region with the help of geophysics.

Nickel. Geophysical methods are employed in prospecting for deposits of both copper-nickel sulphide and nickel silicates.

Copper-nickel sulphide mineralization of the Norilsky region in the northwestern part of the Siberian platform is spatially and genetically related to differentiated intrusions along ancient faults and is generally concentrated at their bottoms (Volkov, *et al.*, 1963; Feigin, 1967). Intrusions are mapped (1:50,000) with the help of magnetic and gravity surveys in combination with electrical prospecting by direct current methods (Figure 8) and in some cases with seismic prospecting. Detection of ore-bearing intrusions within promising areas is accomplished by an IP survey. The chargeability of such intrusions is essentially higher than that of barren traps and sedimentary rocks. Ore-bearing portions of the aforementioned intrusions which are covered by alluvium are traced by a combination of self potential, gravity and IP measurements. Accessible areas are covered by a lithogeochemical survey. Natural groundwater sources are used for hydrochemical investigations.

A large new copper-nickel deposit in the north of Siberia has recently been discovered by a combination of geophysical techniques.

Magnetic and gravity surveys on a scale of 1:50,000 to 1:25,000 are used for locating nickel silicate deposits by mapping ultrabasic intrusions which extend linearly along deep faults.

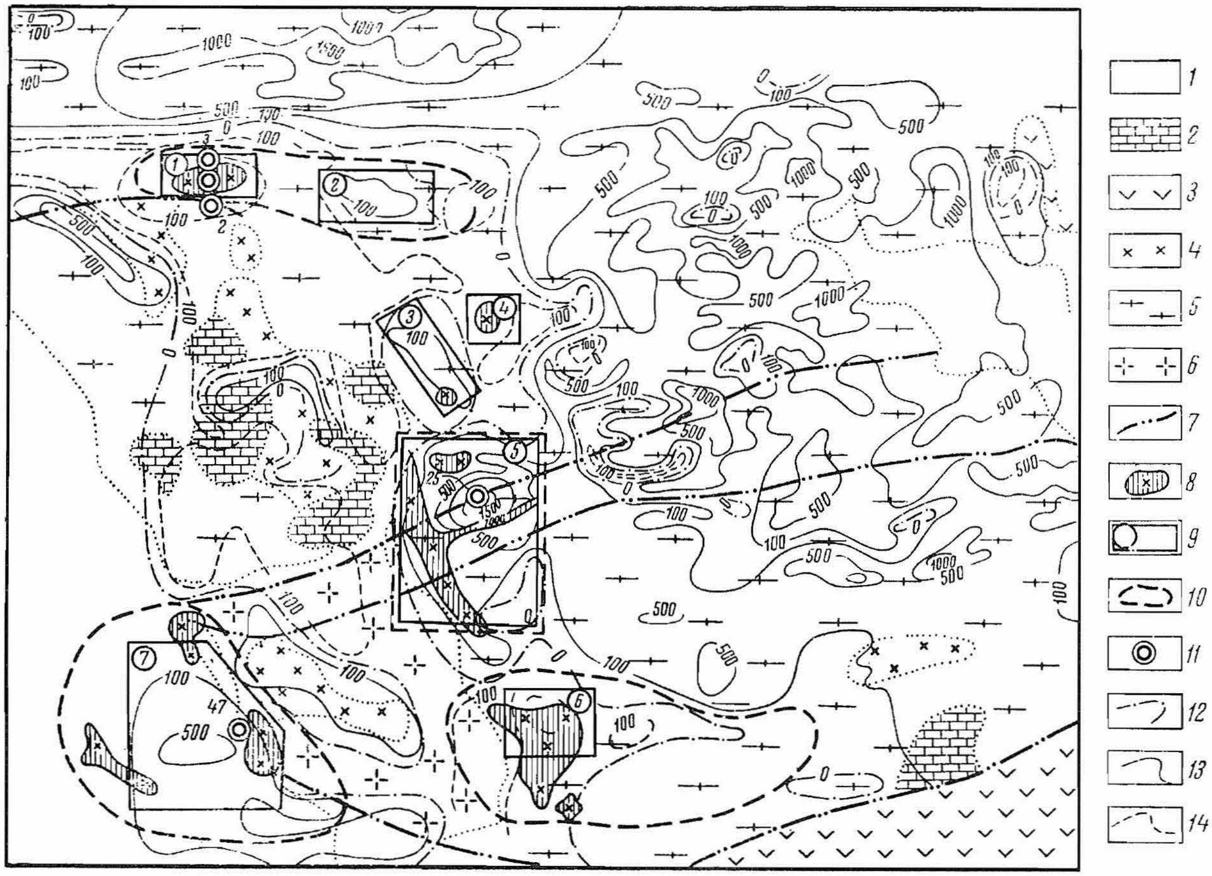

Figure 7. Magnetic survey for mapping factors controlling location of porphyry copper deposits, Almalikskoye ore field (Volfson, *et al.*). 1. Recent sediments; 2. Limestone; 3. Effusive rocks; 4. Granodiorite-porphyry; 5. Syenite; 6. Quartz porphyry; 7. Faults; 8. Revealed stock of granodiorite-porphyry; 9. Contours and numbers of areas recommended for copper prospecting; 10. Contours of areas with inferred development of granodiorite-porphyry stocks; 11. Controlling holes; 12. Zero contour line; 13. Positive contour line; 14. Negative contour line.

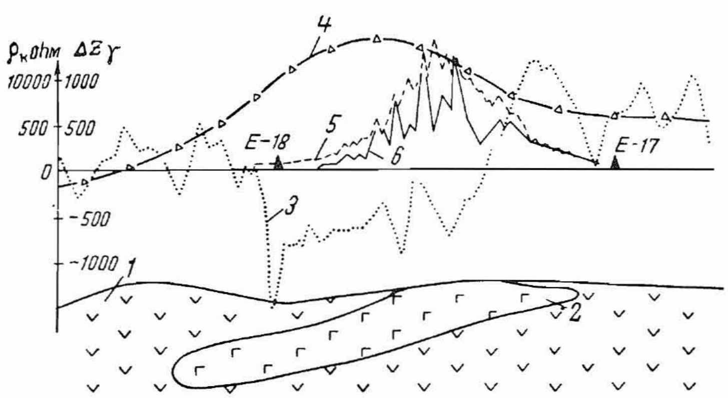

Figure 8. Geophysical profiles over typical gabbro-dolerite intrusion in the Norilskyi region (Volkov, *et al.*). 1. Effusive rocks; 2. Gabbro-dolerite intrusion; 3. ΔZ curve; 4. Δg curve; 5. $AB = 60$ m, $AB = 180$ m, ρ_p curve.

Some intrusions may be differentiated according to their petrographical composition by electrical prospecting, using VES or electrical profiling techniques. The survey (1:10,000 to 1:25,000) is conducted to determine the thickness of alluvium and, if possible, to distinguish the ultrabasics in the zone of weathering. In case of a thin cover of recent sediments, the combination of prospecting techniques also includes a lithogeochemical survey, which helps to locate areas of shallow weathering.

Gravity surveys (Vagshal, 1965) were successfully used in the middle Urals to prospect for nickel silicate deposits; all the known deposits of fissure and karst type were clearly identified by local gravity lows (Figure 9).

Polymetallic complex ores. Geophysical methods used for locating complex ore deposits are similar to those frequently used for pyrite deposits (Revyakin, *et al.*, 1966), namely magnetic and lithogeochemical surveys and IP and SP electrical surveys (1:25,000 to 1:50,000). In such areas, surveys on a scale of 1:50,000 are used to delineate structures.

The first phase of 1:50,000 prospecting results in the selection of areas in which to conduct detailed surveys (1:10,000 to 1:5,000) to locate zones of primary mineralization. The combination of methods remains the same but with a greater use of various direct current electrical techniques (combined, dipole, symmetrical profiling and electrical methods) as well as gravity surveys (1:10,000). The maximum depth of penetration of ground geophysical methods is 80 to 100 metres. In prospecting

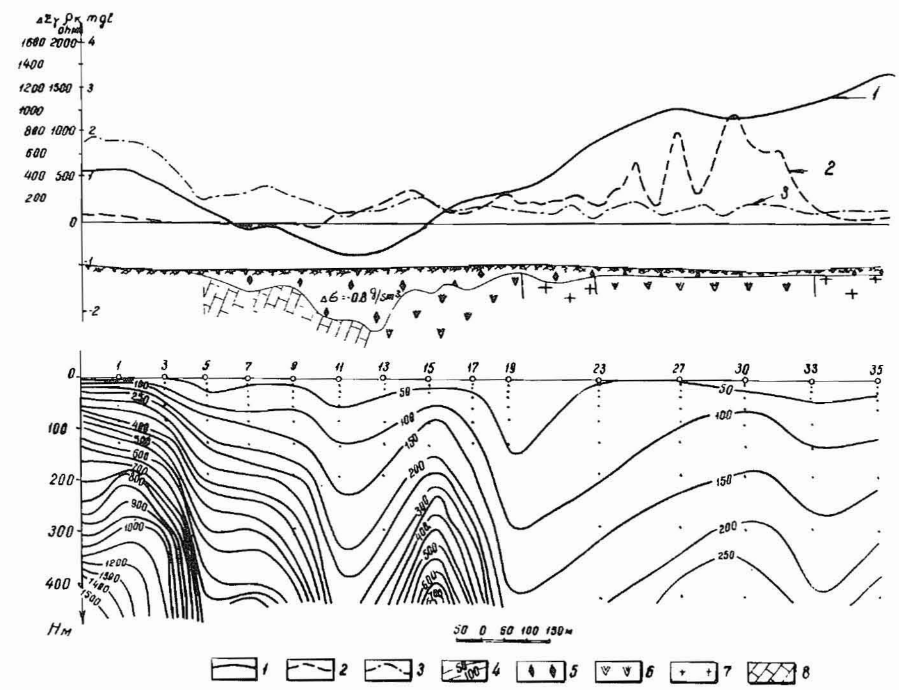

Figure 9. Results of geophysical surveys over a nickel silicate deposit (by D.S. Vagshal). 1. Δg curve; 2. ΔZ curve; 3. ρ_p curve; 4. Vertical section of electrical resistance; 5. Zone of weathering; 6. Serpentinite; 7. Granite; 8. Marble.

for large orebodies by a transient process method, or gravimeters, the depth of penetration increases (up to 200 metres, or more). Surveys at Rezanovskoie polymetallic occurrence (Figure 10) are an example of the greater depth of penetration of the transient method. Primary ores are oxidized to a depth of 150 metres and cannot be distinguished by other geophysical methods.

Every year a greater number of new discoveries are made with the help of geophysical and geochemical methods. These include the discovery and evaluation of the central Kazakhstan polymetallic province as well as the discovery of new complex ore deposits in east Zabaikalye, Buriatia, Krasnoyarsk district, Karatau and Azerbaidzhan. A great polymetallic deposit, Ozernoie, was found with the help of geophysical methods in Eravninsky district, Buryatsckaya, A.S.S.R. in 1962 (Matukhin and Krupski, 1966). This deposit is confined to the crest of an anticline which is composed of effusive rocks of medium acid composition, and is controlled by a series of northeast-trending faults. The ores which outcrop contain siderite and magnetite in addition to the lead and zinc sulphides. Ore-controlling faults show up clearly as zones of higher conductivity and as chains of local narrow magnetic anomalies which are caused by the presence of magnetite in the fault. The deposit itself is characterized by local gravity anomalies (intensity is 4.0 milligals and 300 E), by anomalies of induced polarization (10 to 17 per cent) and self potential (up to 450 mv), and by low electrical resistance (100 or 200 ohm) compared with average of the wallrock resistance of thousands of ohms (Figure 11), as well as by geochemical dispersion haloes of zinc and lead up to 1 per cent.

Tin ores. One example of using geophysical methods in tin prospecting is the geological exploration program conducted by the Northeastern Geological Survey. The mineralization is associated with quartz-tourmaline-sulphide veins in a contact zone of a granite massif. Most veins are accompanied by zones of altered

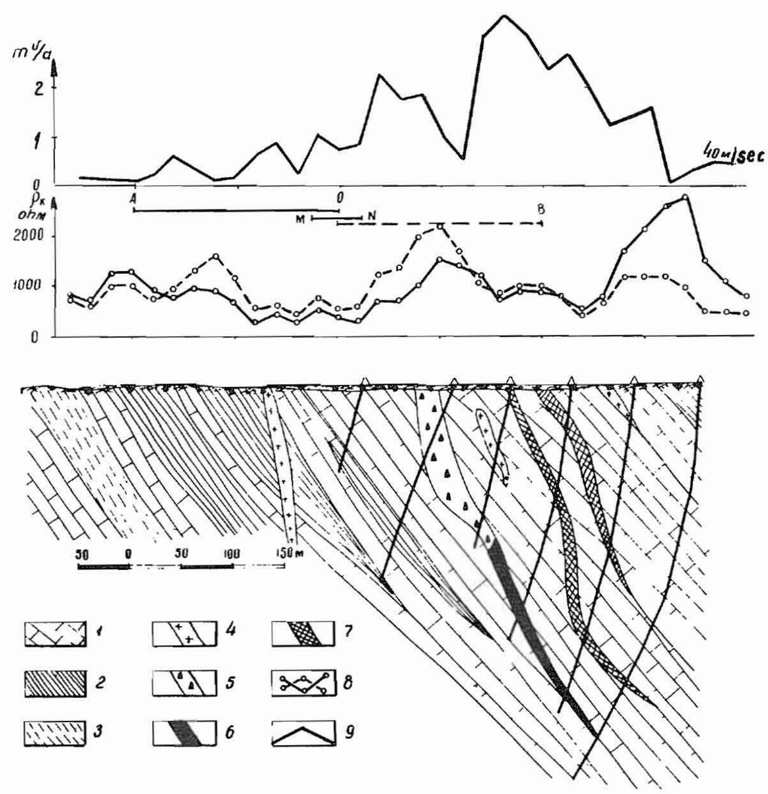

Figure 10. Transient curves over Rezanovskoie deposit, east Zabaikalie (by M.P. Sedov). 1. Dolomitic limestone; 2. Carbonaceous and graphitic schist; 3. Clayey shale; 4. Granodiorite dyke; 5. Oxidized lead-zinc ore; 6. Massive lead-zinc ore; 7. Areas of impregnated mineralization; 8. ρ_p curve; 9. IP curve.

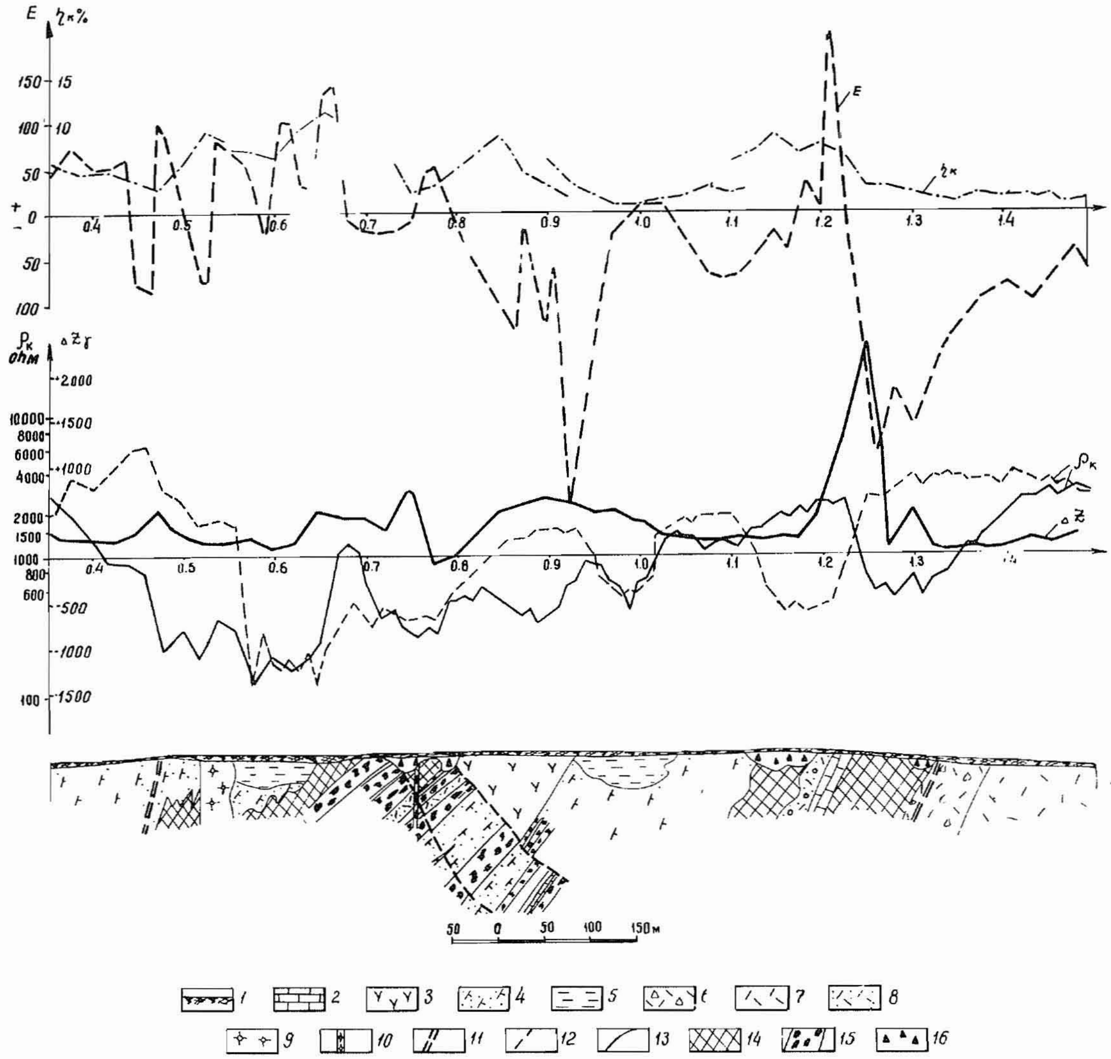

Figure 11. Results of complex geophysical surveys over a polymetallic deposit, Ozernoye, Buriatskaya ASSR (by N.I. Emelianenko, *et al.*). 1. Alluvium; 2. Limestone; 3. Effusive rocks of intermediate composition; 4. Tuff; 5. Clay; 6. Felsitic lavo-breccia; 7. Quartz-porphyry; 8. Felsite-porphyry; 9. Syenite-porphyry; 10. Quartz-porphyry dyke; 11. Boundaries of mineralized zone inferred from geophysical data; 12. Tectonic dislocation, inferred; 13. Sideritic ore; 14. Impregnated pyrite ore; 15. Zone of oxidation over the siderite; 16. Agglomerate volcanic breccia.

granite such as sulphides, chlorite and limonite. Under these conditions orebodies are located by ac electrical techniques, and the structure of the deposits is determined in detail by dc techniques. Electrical prospecting is usually combined with exploratory tunnelling and inclined drilling.

Geophysical techniques similar to those used for complex ores are used for tin prospecting on the Pacific coast, and in other areas where tin mineralization is confined to hydrothermal sulphide veins. Figure 12 shows the results of magnetic and self potential surveys of a skarn sulphide-cassiterite veins at one of the tin deposits of the Pacific coast, recently discovered with the help of geophysical data. The sulphide vein, which contains pyrrhotite, is distinguished by a magnetic anomaly with an intensity of more than 300 gammas. Several commercial tin deposits have been discovered in the U.S.S.R. with the help of geophysics.

Rare metals and gold. Rare metals (tungsten, molybdenum) are located by magnetic, radiometric and lithogeochemical surveys (1:50,000 to 1:25,000) in combination with geological exploration. The surveys result in the location of intrusive masses which offer promise of stockwork type of deposits. The stockworks are generally marked by local magnetic and radiometric anomalies (Benevolensky, 1962) and also by the presence of dispersion haloes of rare metals. The investigation of the form of the intrusions and of the ore-bearing overlying formations is made with the help of a gravimeter survey (1:20,000 to 1:50,000) and SP measurements whose anomalies are due to a great amount of pyrite in the ores. In the case of tantalum-niobium and beryllium prospecting, orebodies are detected by geochemical surveys with the help of radiometry and lithogeochemical methods.

Geophysical techniques for gold prospecting vary depending upon the type of deposit. Areas promising for gold discoveries are

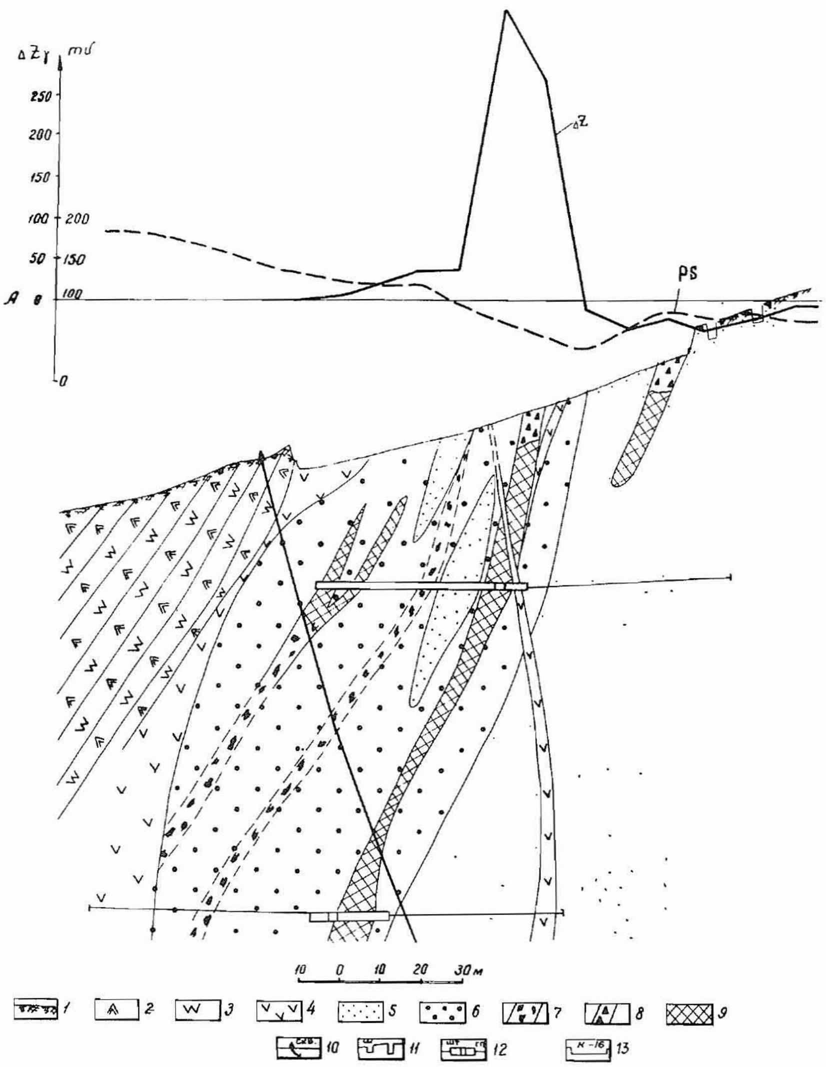

Figure 12. Geophysical results at a sulphide-cassiterite deposit at Primorye (by N.A. Kukushkin). 1. Alluvium; 2. Siliceous rocks; 3. Quartzite; 4. Porphyrite; 5. Sandstone; 6. Hornfels; 7. Streaky impregnated scheelite-sulphide ore; 8. Oxidized ore; 9. Massive scheelite-sulphide ore; 10. Diamond drill hole; 11. Exploration shaft; 12. Adit and subsurface drill hole; 13. Main trench.

located by regional geophysical surveys. Magnetic and lithogeochemical surveys, accompanied in promising areas by electrical and gravity surveys (1:25,000 to 1:50,000) facilitate mapping of small diorite intrusions and faults which control quartz bodies (Abramovich, 1965). A lithogeochemical survey locates dispersion haloes of accessory element-indicators (arsenic, copper, lead). Promising areas are surveyed in detail (1:5,000 to 1:10,000) by the aforementioned techniques. The most promising anomalies are tested by drilling.

Geophysical surveys are also widely used in an indirect search for gold placers. Symmetry profiling and VES electrical methods indicate the contours of ancient buried valleys. Seismic refraction investigations are used successfully, too, and gravimeter surveys are becoming standard. The same combination of geophysical methods is also used for prospecting for placer deposits of other useful minerals, such as diamonds, cassiterite and platinum.

The discovery of many new gold deposits in the U.S.S.R. attests to the effectiveness of geophysical techniques.

Diamonds. Geophysical methods are also widely used in the U.S.S.R. for nonmetallic mineral prospecting but in this paper we shall describe the role of geophysics only in diamond prospecting.

An extensive region with diamond occurrences in Yakutiya was discovered and is being successfully explored with the help of geophysics. An aeromagnetic survey gave marked local ΔT anomalies having an intensity of 100 to 700 gammas over kimberlite pipes (Figure 13). Anomalies are also found above basic dykes; in contrast to anomalies caused by kimberlite pipes which are round, these are elongated (Men'shikov, 1962). In some areas outliers can create round magnetic anomalies, too, and distinguishing them from the pipes is possible only with gravimetry. Decreased gravitational fields occur above the pipes whereas increased fields occur above trap outliers.

There are three types of pipes in Yakutiya that are equally marked by a magnetic field: basaltic kimberlites, micaceous kimberlites and carbonatites, but only basaltic kimberlite pipes are diamond-bearing. Classification of the magnetic anomalies is done successfully by airborne spectrometer surveys in sufficiently exposed areas. Diamond-bearing kimberlites are distinguished by a low percentage of phlogopite (up to 1 per cent) and therefore with a minimum quantity of potassium (Figure 13), whereas micaceous kimberlites contain up to 12 per cent of phlogopite, and give distinct anomalies with a higher content of potassium.

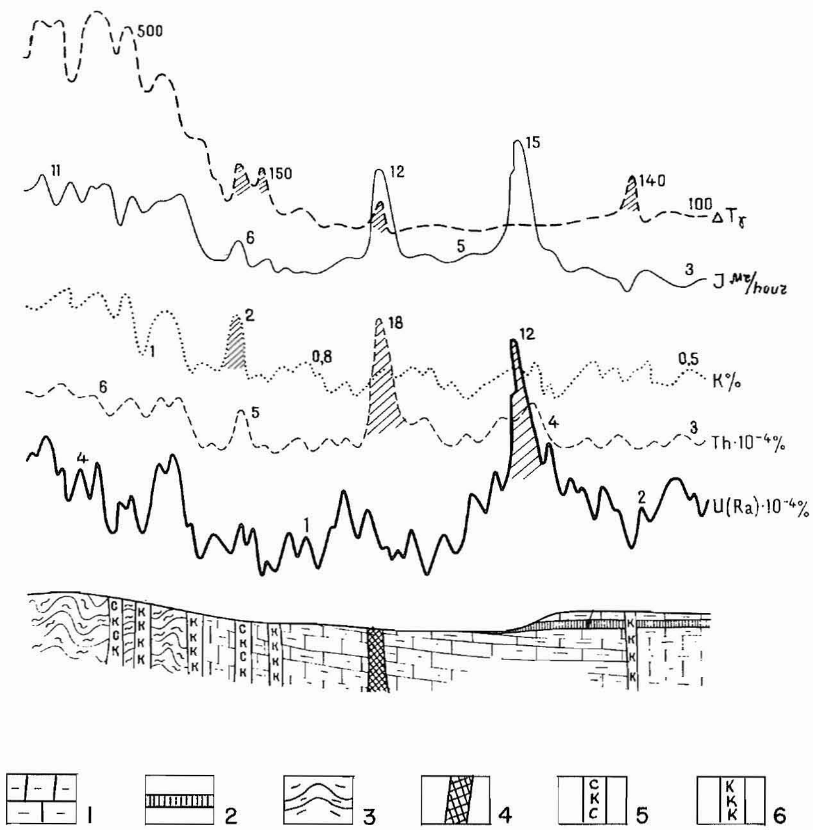

Figure 13. Complex airborne survey over kimberlite pipes of Yakutiya (from data of Yakutskoye Geological Office). 1. Marly limestone; 2. Bituminous limestone; 3. Amphibolite, gneiss; 4. Carbonatite; 5. Micaceous kimberlite; 6. Diamond kimberlite.

Carbonatite pipes contain, as a rule, zircon, pyrochlore, and columbite and are distinguished by anomalously higher gamma-radiation and uranium and thorium content (Smirnov, *et al.*, 1967).

Geophysical investigations at the exploration stage

Geophysical investigations at this stage are made by well logging and so-called bore hole geophysics and have two main functions: investigation of bore hole logs in the course of drilling; and location of orebodies near and between bore holes and pits.

The geological problems solved by the logging methods can be divided into four groups:

a) subdivision of a geological section in a well column;

b) detection of ore intervals, estimation of thickness and location of orebodies;

c) investigations of water conditions of ore deposits; and

d) control of technical conditions of a bore hole.

The most significant in the complex of logging methods for exploration of ferrous, nonferrous and rare-earth deposits are electrical logs – resistivity, SP, the sliding contact log and its modification – current log. To locate minerals possessing a high electronic conductivity, an electrode potential technique is used.

In addition, bore hole sections in mining areas are surveyed by other types of geophysical measurements – magnetic, and particularly radioactive. Magnetic logs include measuring magnetic susceptibility down the bore hole for locating rocks containing ferromagnetic minerals. It is used at the deposits of magnetic iron ores, complex ores containing pyrrhotite and magnetite and is also used for differentiation of igneous and some metamorphic rocks. At iron ore deposits a magnetic log is also used for estimating iron content in magnetite ores. In the last few years new instruments and a method of logging the magnetic susceptibility of weakly magnetic units have been worked out for bauxite, siderite, manganese and other deposits.

Radioactive logs serve not only to locate intersections with a low content of ore minerals but to make a quantitative estimation of this content. Neutron logs provide information on lithology and porosity of rocks and help to detect manganese, lithium, cadmium, boron and other minerals. The neutron-gamma log is used to differentiate the section and to detect potash salts. Induced radioactivity logs are used to estimate fluorite, manganese, copper and aluminum content in bore holes. Photo-neutron logs are used at beryllium deposits to locate ore intervals and to make quantitative estimates. The composition of rocks and of lead, tungsten, molybdenum, tin, antimony, mercury and arsenic ores is investigated by selective gamma-gamma logs in combination with density gamma-gamma logs.

Ore intersections in bore holes are located and investigated with the help of optimum combinations of logging techniques, the choice based upon the type of section and mineralization. In addition, logging data are used in the correlation of bore holes to delineate configurations of orebodies and plot structural maps.

Figure 14 is an example of an application of well logging for determining the bore hole section and shows the results of an electric log made by resistance, self potential and electrode potential methods at one of the copper-sulphide deposits in the Urals. In this particular case the complex electric log method indicates the geological section of the bore hole, and the thickness and position of ore intersections.

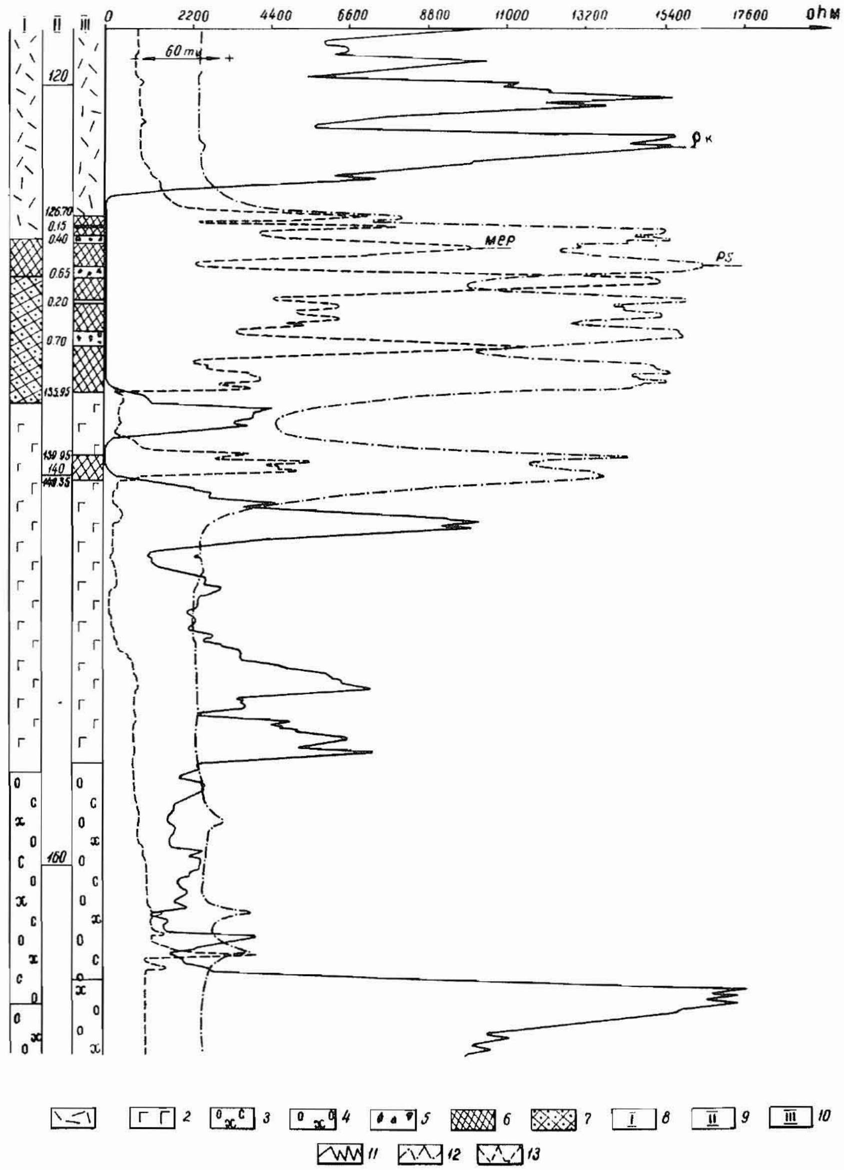

Figure 14. Results of electrical logging at pyrite deposit (V.E. Babenkov). 1. quartz-porphyry; 2. Diabase; 3. Chlorite-sericite-quartz rocks; 4. Quartz-chlorite rocks; 5. Lean impregnated ores; 6. Copper-pyrite; 7. Copper-zinc pyrite; 8. Geological column; 9. Depth column; 10. Logging column; 11. ρ_P curve; 12. *SD* curve; 13. MEP curve.

Another type of geophysical investigation in exploration of ore deposits is so-called bore hole or subsurface geophysics. In contrast to well logging which differentiates directly only the section cut by the hole, bore hole geophysics can penetrate rocks away from the hole. These methods have recently developed into an independent branch of mining geophysics and are now finding an ever-growing application. Placing current or potential (often both) devices in a bore hole in the vicinity of orebodies provides a depth of investigation which is practically the same as the depth of a dimaond drill hole. Moreover, downhole measurements help to eliminate certain disturbing factors related to shallow heterogeneities in the upper part of the section.

Bore hole geophysics is applied in the U.S.S.R. not only in the exploration stage of known mineralized areas, but also in detailed prospecting at the flanks of deposits. Bore hole geophysics plays an especially important role in prospecting deep-seated ore deposits.

The combination of various subsurface geophysical techniques includes the mise-a-la-masse method (Rodionov, 1959) and variations of this method (electrical correlation), SP, IP, radio-wave surveying and three-component magnetic logging.

Subsurface investigation between bore holes is usually made by radio wave surveys (Petrovskiy, 1964). The range of the survey depends upon the frequency and conductivity of the enclosing rocks. In high-resistivity rocks a reliable signal may be obtained from more than 600 metres. By using this method extensively one can locate orebodies that were missed by drilling, make an accurate delineation of orebodies that were intersected by bore holes, and even reduce the number of exploratory holes needed. With the development of the CP-6 instrument by the All-Union Institute of Exploration Technique, this method was applied more broadly.

In the mise-a-la-masse method (variation of electrical correlation) a current electrode is placed in one of the bore holes and potential and gradient measurements are made in the remaining holes. Dry batteries serve as the power supply, and measurements are made in the bore holes every 5 or 10 metres by such

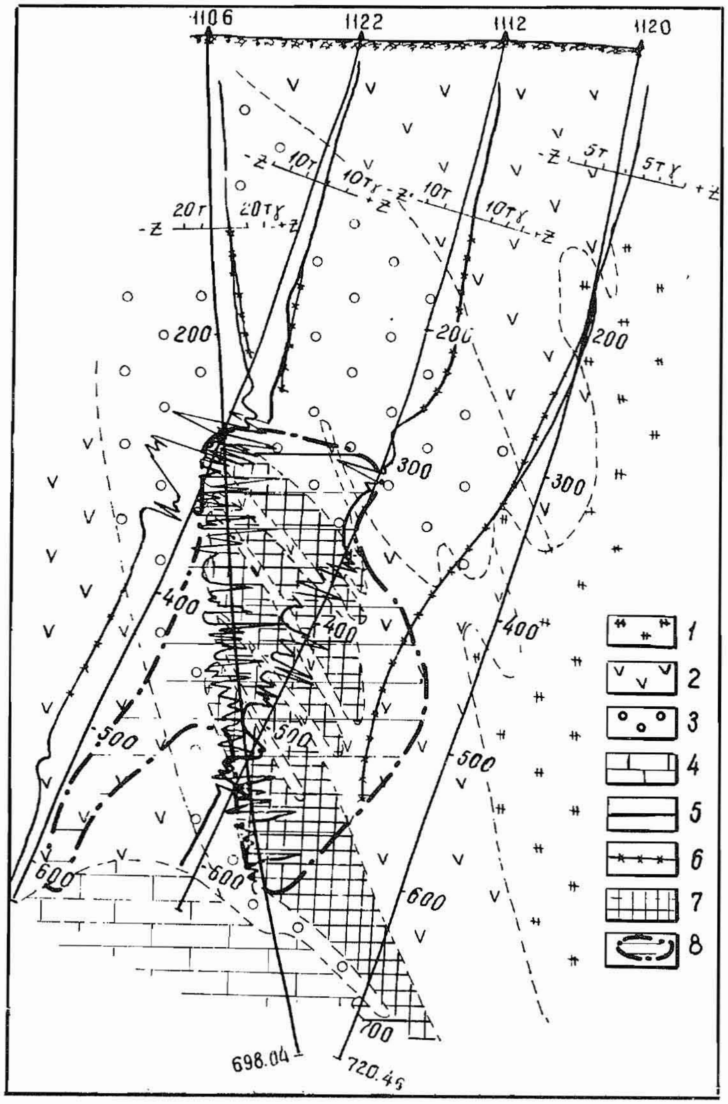

Figure 15. Results of bore hole magnetic survey at Severo-Peschanskoye magnetite deposit (O.N. Molchanov). 1. Diorite; 2. Porphyrite; 3. Skarn; 4. Limestone; 5. ΔZ curve; 6. Calculated curve; 7. Shape of orebody, from geological data; 8. Shape of orebody, from bore hole geophysics.

conventional electrical equipment as potentiometer and electronic compensator (Kozyrin, *et al.*, 1964).

The same type of measurements, using nonpolarizing electrodes if there is no power supply, makes the study of spontaneous potential in bore holes possible (Semenov and Kalashnikov, 1967).

Subsurface induced polarization measurements differ from conventional ones in that polarizing potential is applied to electrodes which are grounded in a bore hole or pit, not on the surface.

Subsurface magnetic fields are measured by a serial TCM-3 bore hole magnetometer which has three perpendicular fluxgate detectors. The readings of these detectors, enable vectors of the geomagnetic field in the borehole to be plotted and these are indicative of the location of a nearby magnetic body (Ponomarov and Avdonin, 1966).

Subsurface magnetic measurements are used both at the exploration stage and at the prospecting stage, particularly for checking anomalies revealed by ground and airborne surveys. At a north Peschanskoye magnetite deposit in the north Urals a bore hole which was drilled within a magnetic anomaly of about 3000 gammas located in a complex magnetic field at the west contact of the Auerbakhov granite mass, penetrated to a planned depth of 180 metres through slightly magnetic porphyrites and skarns which created the anomaly. However, bore hole magnetic measurements showed a gradual increase in the magnetic field intensity toward the bottom of the hole and at the insistence of the geophysicists the drilling of the test hole was continued, at 230 metres a large orebody with a commercial iron content was intersected. The further exploration of the deposit by three-component magnetics allowed the geophysicist to delineate the actual shape of the orebody (Figure 15), which differed considerably from the original concept. This interpretation and, in particular, the existence of the southwestern branch were confirmed by further geological surveys.

These methods are used primarily in iron ore and sulphide (copper and complex) deposits. They help to investigate the earth around the bore holes and between them, to locate orebodies missed by drilling, to make a reliable correlation of ore intervals in the section and to determine the morphology, dip and strike of orebodies.

The interpretation of complex methods of bore hole geophysics is so reliable that some orebodies can be delineated and calculations of reserves can be made with the help of the geophysical data.

These surveys are most widely used in the Urals and Rudnii Altai where they help in the investigation of areas within a radius of about 100 or 300 metres around bore holes and in correlating orebodies at distances of up to a few hundred metres.

Geophysical methods used in preparation for mining

Since the 1950s geophysical methods have been widely used for detailed exploration of known orebodies and for locating those which had been missed in geological reconnaissance. Integrated exploration methods used for iron deposits of the Urals, Gornaya Shoriya and Krivoi Rog, as well as for copper and polymetallic deposits of the Urals and Rudnii Altai include gravity measurements (effected with gravimeters and gradiometers), radio-frequency bore hole measurements, magnetic susceptibility measurements in the walls of underground workings, magnetic and electrical logging of underground bore holes and electrical correlation. At the Norilsk copper-nickel deposits dipole horizontal electromagnetic profiling is successfully used in underground exploration while at the Armenian pyrite deposits the induced polarization method is used to advantage.

Several new methods are being developed and tested on an experimental scale, including a method based on the registration of penetrating cosmic radiation, a method employing the seismo-electrical effect and thermometric method.

New orebodies of ferruginous quartzite, magnetite, copper pyrite, pyrite, and copper-nickel have been discovered by geophysical methods. The discovery of new polymetallic veins at the Akhtalskoye deposit by the induced polarization method can serve as an example (Figure 16) (Badalyan, *et al.*, 1966).

Another, and no less important trend in geophysical exploration effected during the exploitation of a deposit is geophysical

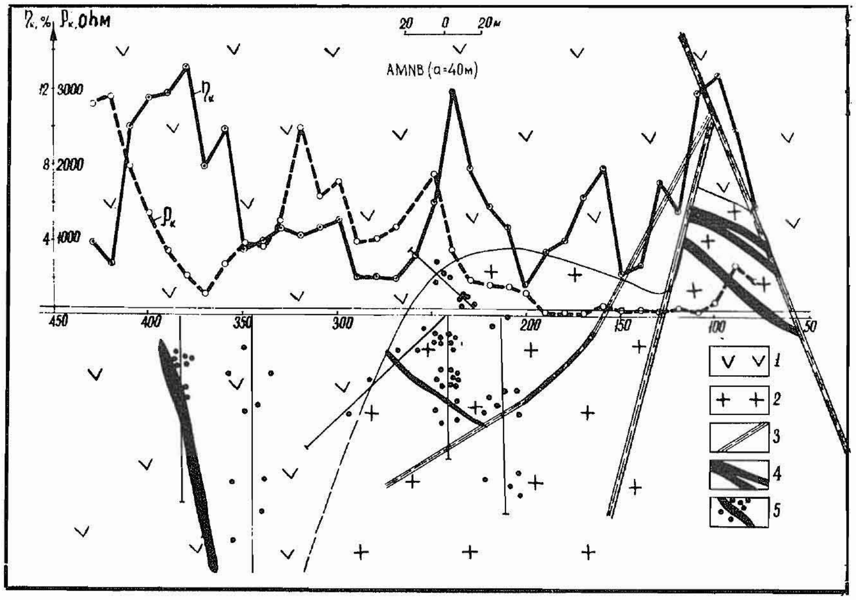

Figure 16. Mining version of induced polarization method at Akhtalskoye polymetallic deposit (S.V. Badalyan). 1. Porphyrite; 2. Quartz porphyry; 3. Tectonic dislocation; 4. Previously known polymetallic orebody; 5. Polymetallic orebodies with sulphide mineralization revealed by geophysical methods.

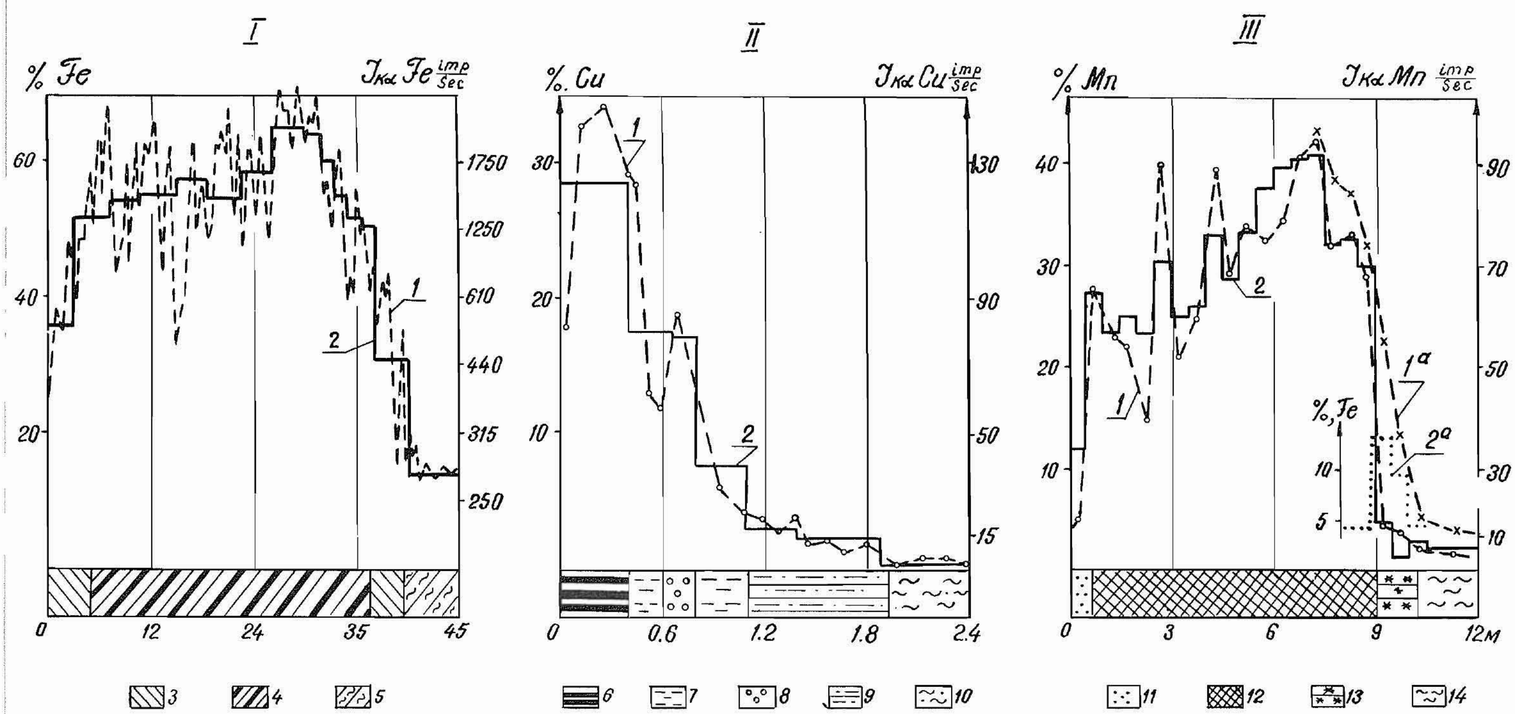

Figure 17. Comparison of results of channel and radiometric sampling at mine workings. I,II,III – Deposits of iron, copper and manganese, respectively. 1. Radiometric sampling, ((1a) The same with use of filter); 2. Channel sampling, (2a) Results of chemical analysis on iron; 3. Quartzite; 4. Martite ore; 5. Shale; 6. Chalcosite ore; 7. Sandstone ore, medium-grained; 8. Conglomerate ore; 9. Red-grey sandstone; 10. Siltstone; 11. Quartz sand; 12. Oxidized manganese ore; 13. Rock with iron; 14. Clay.

sampling by X-ray fluorescence. The high efficiency of this method of geophysical sampling, the possibility of *in situ* determination of useful ores in natural occurrences without selection and treatment of samples, the high sensitivity of the method, equalling or even exceeding the sensitivity of chemical analyses – all these features ensure a wide application of geophysical methods at mine workings.

In underground mine workings more than ten different methods have already been tested. They are based on the use of radioisotope sources of nuclear radiations, mainly on the interaction of gamma rays with various substances.

The selective gamma-gamma method (SGGM) is practised on the largest scale. It helps to estimate heavy metal content such as iron, manganese, antimony and lead in samples or *in situ*. The sensitivity of this method is 0.1 per cent for ores with complicated composition.

An X-ray fluorescence analysis method has been introduced which is based on the excitation and measurement of the characteristic X-radiation of the element under observation (Ochkur, *et al.*, 1965). The sensitivity of this method is 0.01 per cent for sample treatment and 0.1 per cent *in situ*.

Figure 17 demonstrates the results of a comparison between trenching and X-ray fluorescence sampling. Every element had its own source of excitative radiation. The agreement of the methods was quite satisfactory.

In the last few years a new method of nuclear resonance fluorescence, based on Mössbauer effect has been developed in the U.S.S.R. The method has a highly selective capacity and is applied in determining tin. Its sensitive limit is 0.01 per cent. The exactness of this method for tin sampling is equal to chemical analysis.

The further development of nuclear geophysical methods is extremely interesting and promising.

Conclusion

The combination and mutual co-ordination of geological, geophysical and geochemical methods at different stages in the geological study of ore areas ensures the effectiveness of geological prospecting in the U.S.S.R. The ever growing demands and the increasing requirements of the geological service face geophysicists with new and still more complicated tasks in the exploration of new ore areas and prospecting for mineral deposits. Consequently, the importance of geophysics increases yearly. Many factors contribute to this importance: a systematic and steady increase in the scale of geophysical activity in the country; a highly developed system of industrial and research organizations engaged in developing and introducing new mining geophysical methods; an effective educational system; and a stable technical basis which allows the instant use of various up-to-date achievements, both in science and technique.

In the U.S.S.R. within the last decade the emphasis in the development of mining geophysics has been on increasing the depth and economic efficiency of geophysical investigations.

Increasing the depth of penetration in prospecting for deposits will include the large-scale forecast metallogenetic method and, in particular, the further development of airborne surveys, gravimeter and seismic surveys; wider use of deeper ground geophysical methods including high-accuracy detailed gravimeter surveys; electrical prospectings with induced polarization and transient methods; the rapid development of bore hole geophysics; and the introduction of statistical and computerized methods of treatment for separating the feeble anomalies caused by deep-seated deposits from various backgrounds.

As a rule, by applying geophysical methods in geological mapping and prospecting for ore deposits we can reduce the volume of diamond drilling and thus economize. The intensive development of mining geophysics and geophysical sampling at mining enterprises also brings great economic benefit within a short time and without requiring large capital investments. These trends in mining geophysics are bound to continue in the next few years.

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Mining geophysics in India and the role of government in this field

L.N. Kailasam

Geological Survey of India

Abstract. Geophysical techniques are being widely used in India in prospecting for minerals. Most of the work in mining geophysics is being done under government auspices, almost entirely by the Geological Survey of India. This division has at present a staff of more than 200 and has carried out to date about 300 field investigations. Reconnaissance airborne magnetic, electromagnetic and scintillometric surveys for base metals and radioactive minerals will be made in three major belts to be followed by detailed geological and geophysical surveys and exploratory drilling. The field activities of the Geophysics Division are supported by a Research and Development Unit.

In 1966 the total work done in mining geophysics included 980 man-months of field work by 32 geophysical crews involving an expenditure of $400,000 and 200 man-months of research and development work costing roughly $41,000.

Résumé: L'emploi des techniques géophysiques se pratique à grande échelle, en Inde, pour la prospection des minéraux. La plupart de ces travaux géophysiques sont effectués sous les auspices du gouvernement, soit, dans leur presque totalité, par la Commission géologique de l'Inde. Cette division qui emploie plus de 200 personnes a réalisé, jusqu'à maintenant, environ 300 missions. Il est prévu d'entreprendre, dans trois régions importantes, des études de reconnaissance aérienne par méthodes magnétique, électromagnétique, et scintillométrique destinées à la prospection de métaux communs et de minéraux radioactifs, et d'y procéder par la suite à des études géologiques et géophysiques détaillées, ainsi qu'à des forages d'exploration. Les activités extérieures de la Division de la géophysique reçoivent l'appui technique d'un Centre de recherche et de développement.

L'ensemble des travaux de géophysique minière entrepris en 1966 représente 980 mois-hommes de mission, réalisés par 32 équipes géophysiques et ayant coûté la somme de $400,000, ainsi que 200 mois-hommes de recherche et mise au point ayant coûté environ $41,000.

Geophysical prospecting methods are an important and integral part of modern techniques of mineral exploration. Recent years have witnessed considerable advances and development in this field in instrumentation and field techniques as well as interpretation methods. The development in the field of airborne geophysical techniques in mining geophysics for ore deposits and groundwater has been particularly striking, as also in the field of borehole and underground geophysical exploration.

In India, the application of geophysical methods in the exploration for metallic ores, groundwater and nonmetallic minerals other than petroleum, i.e., mining geophysics, came into vogue on a regular and systematic basis only with the establishment of a Geophysics Division in the Geological Survey in 1945. Prior to its inception, foreign oil companies had conducted some geophysical exploration for oil, especially by seismic methods in the sedimentary basins of northeastern and northwestern India, but in the field of mining geophysics there had been only very limited and sporadic activities.

Since its inception, the Geophysics Division in the Geological Survey has been undergoing steady expansion and development in its size and activities. The rate of this growth and development can be gauged from the fact that, whereas in 1950 the geophysical staff consisted of seven professional and 15 nonprofessional workers, including workshop personnel, the strength rose to nearly 60 by 1956 with 13 professional and 47 nonprofessionals and by the close of the Third Five Year Plan period in 1966, the strength of the division had increased to more than 200 with some 100 professionals and an equal number of nonprofessionals. By the end of the Fourth Five Year Plan period, the Geophysics Division in the Geological Survey is expected to have a total strength of more than 400 field, workshop and research personnel.

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About 50 geophysical field investigations had been carried out by the end of the First Five Year Plan period in 1956 and these included 26 for ore deposits, three for nonmetallic minerals, four for petroleum and 18 for groundwater and civil engineering projects. Some 65 additional investigations were conducted during the Second Five Year Plan period between 1956 and 1961 including 28 for ore deposits, five for petroleum, eight for other nonmetallic minerals and 11 for groundwater and civil engineering projects.

By 1966, at the end of the Third Five Year Plan period, the total number of geophysical field investigations conducted was more than 300, roughly half of which have been for metallic ores (mostly for base metals) and the rest for nonmetallic minerals such as coal, graphite, lignite, diamond, etc., and groundwater and civil engineering projects. The number of geophysical crews in the field has also been steadily increasing from four or five in the early stages after the establishment of the division to more than 30 at present.

The Geological Survey of India under the Ministry of Mines and Metals of the Government of India at present carries on almost all the work in the field of mining geophysics in this country. However, the Central Water and Power Research Station under the Ministry of Irrigation and Power, which has a small geophysical unit, carries on geophysical investigations for the study of foundation conditions at dam sites, etc., connected with the various hydroelectrical projects in this country and the associated problems of groundwater at these sites. In this field of civil engineering it shares its work with the Geological Survey of India.

All the major methods of surface geophysical exploration, viz., electrical, gravity, magnetic and seismic as well as surface electromagnetic (inductive), electrical well-logging and radioactive

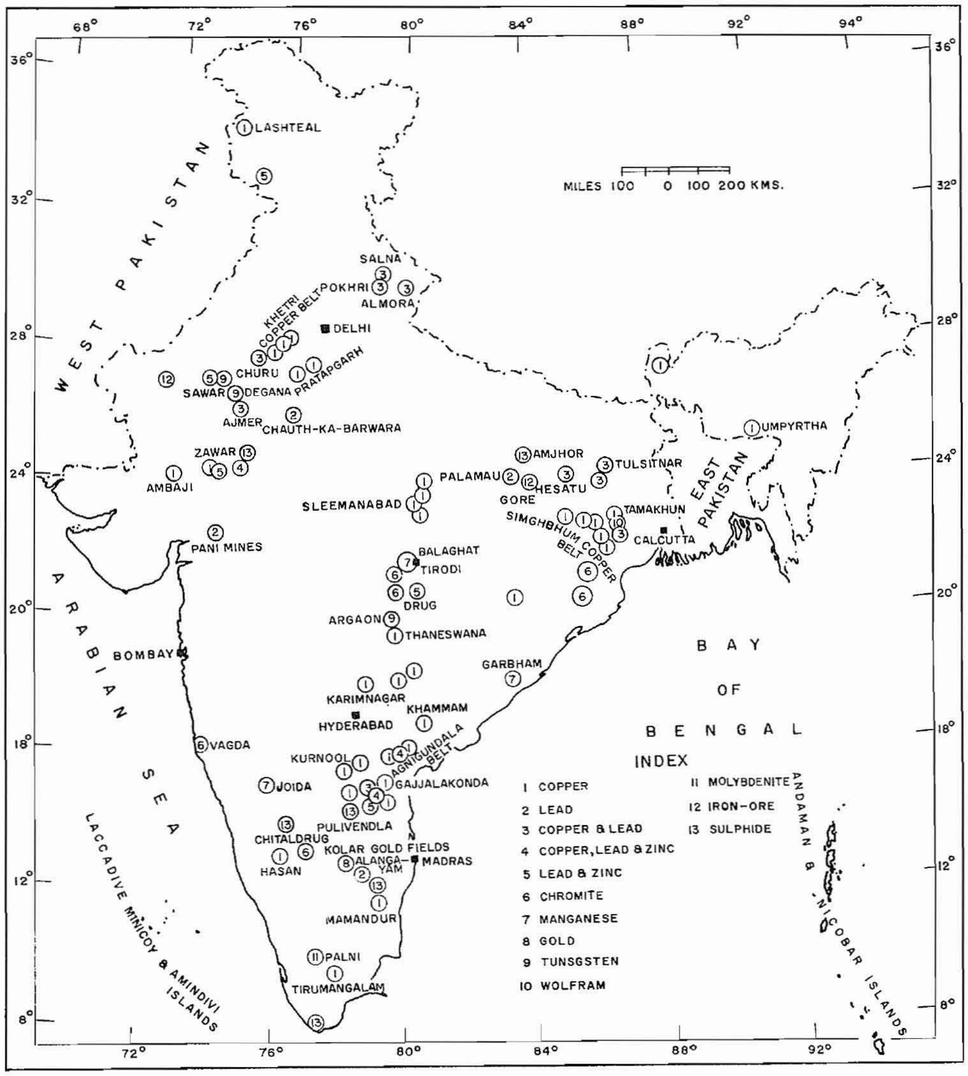

Figure 1. Geophysical investigations for metallic ores carried out by the Geological Survey of India.

methods are employed for the geophysical investigations. The induced polarisation methods which, as is well known, are particularly well suited for the exploration of disseminated conductive orebodies, are to be introduced shortly and the construction of IP equipment in the Geophysical Laboratory is now well under way. The Geophysical Division has a large and well equipped workshop and a laboratory for research and development where a number of research projects are in progress. These include electromagnetic and seismic model studies, determination of magnetic properties, electrical resistivity, seismic velocity and elastic coefficients of various Indian rock formations and mathematical methods of interpretation of geophysical data. Many of the latest types of geophysical field instruments have been designed and constructed in the Geophysical Laboratory and these meet more than half the requirements of the department's geophysical field parties which at present number roughly 32 annually.

The distribution of geophysical investigations conducted so far by the Geological Survey for metallic ores, nonmetallic minerals (other than petroleum), groundwater and civil engineering projects are shown in Figures 1 to 4. The significant results of some of the important investigations may be recounted briefly.

Base metals

India is particularly short of base metals. The annual production of copper ore, lead concentrates and zinc concentrates in 1965 stood at roughly 468,000, 5,500 and 9,600 tons, respectively. Efforts to locate economic deposits of these minerals have been greatly intensified and at present about half of the geophysical crews are engaged in base metal exploration. The areas investigated are shown in Figure 1. Particular mention may be made of the three important and major belts, viz., the Khetri copper belt in Rajasthan in western India, the well known Singhbhum copper belt in Bihar in eastern India and the recently developed Agnigundala mineralised belt in Andhra Pradesh in southern India where major deposits of copper, lead and some zinc have been located.

The Khetri copper belt in Rajasthan is situated about 160 km (100 miles) to the southwest of Delhi (Figure 1) and the total extent of this belt, as delineated on the basis of geological and geophysical studies, is over 80 km in a northeast to southwest direction. The important rock formations in this area are quartzites and phyllites of the Delhi system of Archaean age with metamorphosed basic intrusive rocks such as amphibolites and epidiorites. Impure marbles and dolomites are associated with the

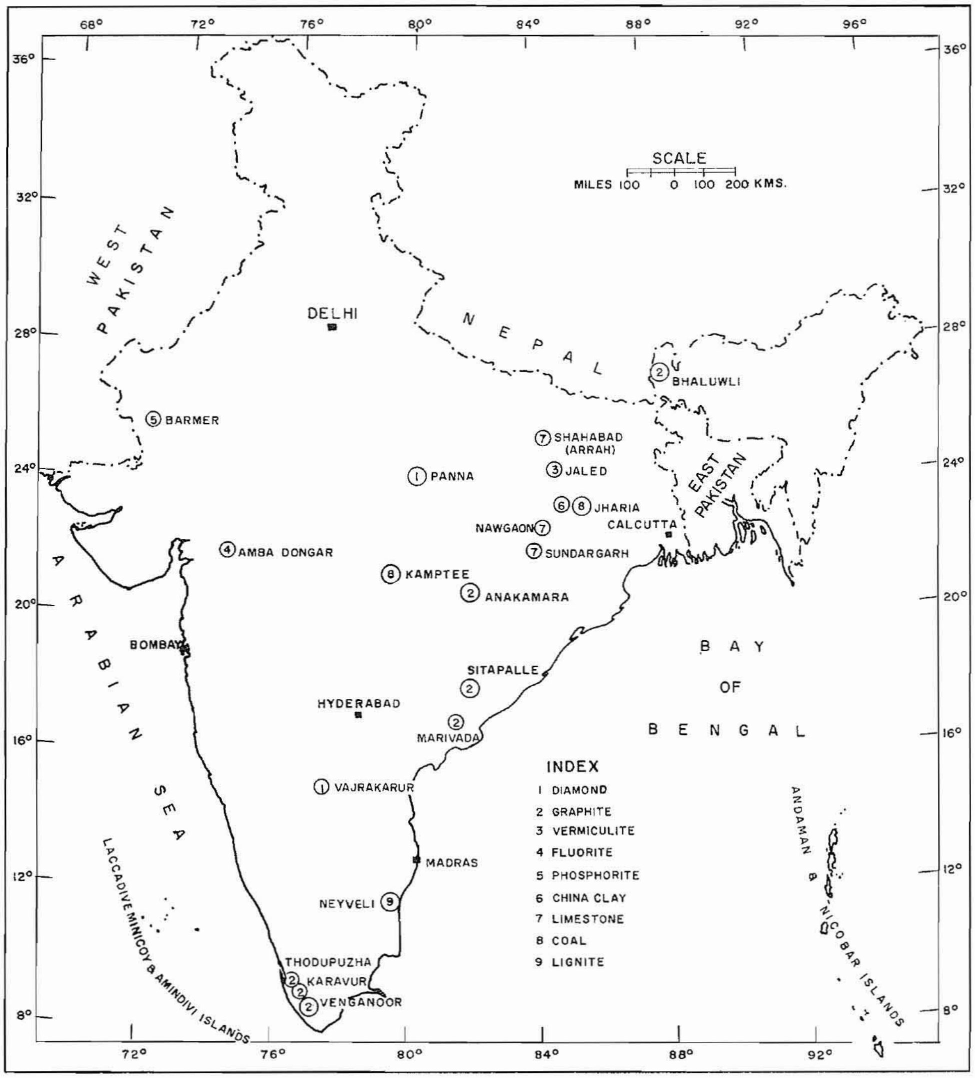

Figure 2. Geophysical investigations for nonmetallic minerals carried out by the Geological Survey of India.

quartzites. Parts of this belt are covered by blown sand. Structurally this belt is characterised by two major plunging anticlines in the Singhana area in the northern part of the belt and in the Kishorepura and Raghunathgarh area in the south. Shear zones have been developed along the limbs of the fold and in many places have been subjected to faulting. Mineralisation has taken place along major strike faults in the Kishorepura-Satkui, Girwari-Dhanota and the Saladipura-Kotri areas (shown in Figure 5(a)) where geophysical anomalies have been indicated. Intensive and systematic surveys employing self potential, electrical resistivity, magnetic and electromagnetic (dipole profiling) methods supplemented by borehole EM measurements have been conducted for more than 10 years in this belt and these have rendered valuable aid to the extensive exploratory drilling that has been carried out so far. A number of pronounced anomalies have been delineated which are shown in Figure 5(a), many of which have been confirmed by test drilling for mineralisation. Magnetic anomalies have been indicated over the amphibolites, epidiorites and also in the mineralised zones, because of the presence of associated magnetite. Strong SP, electromagnetic and resistivity (conductive) anomalies have been observed in the mineralised zones containing chalcopyrite and pyrite (Chakraborty, 1960; Datta, N.P., 1961; Paul, P.C., 1961; and Joshi, 1962).

In the Saladipura area in the southern part of this belt, the geophysical surveys have yielded highly successful results. This part of the belt is characterised by rich massive sulphide deposits consisting mainly of pyrite and pyrrhotite as proved by intensive exploratory drilling recently carried out in this area. Typical electromagnetic, self-potential and magnetic anomaly profiles obtained over these deposits are presented in Figure 5(b) (Joshi, 1965). In one of the test boreholes drilled in this anomaly zone, a massive sulphide body 13 m thick was encountered at approximately the geophysically estimated depth of 30 m, consisting mainly of pyrite (75 to 80%) and pyrrhotite. The estimated sulphide reserves in the Saladipura area on the basis of the exploratory work carried out so far are around 6 million tons. The total reserves of copper ore in the Khetri Copper Belt, as estimated at present are roughly 140 million tons of 0.8% grade copper and 10 million tons of 2.0% copper.

Detailed ground geophysical surveys employing mostly self-potential, electrical, resistivity and magnetic methods with electromagnetic coverage in some parts, have been conducted in the

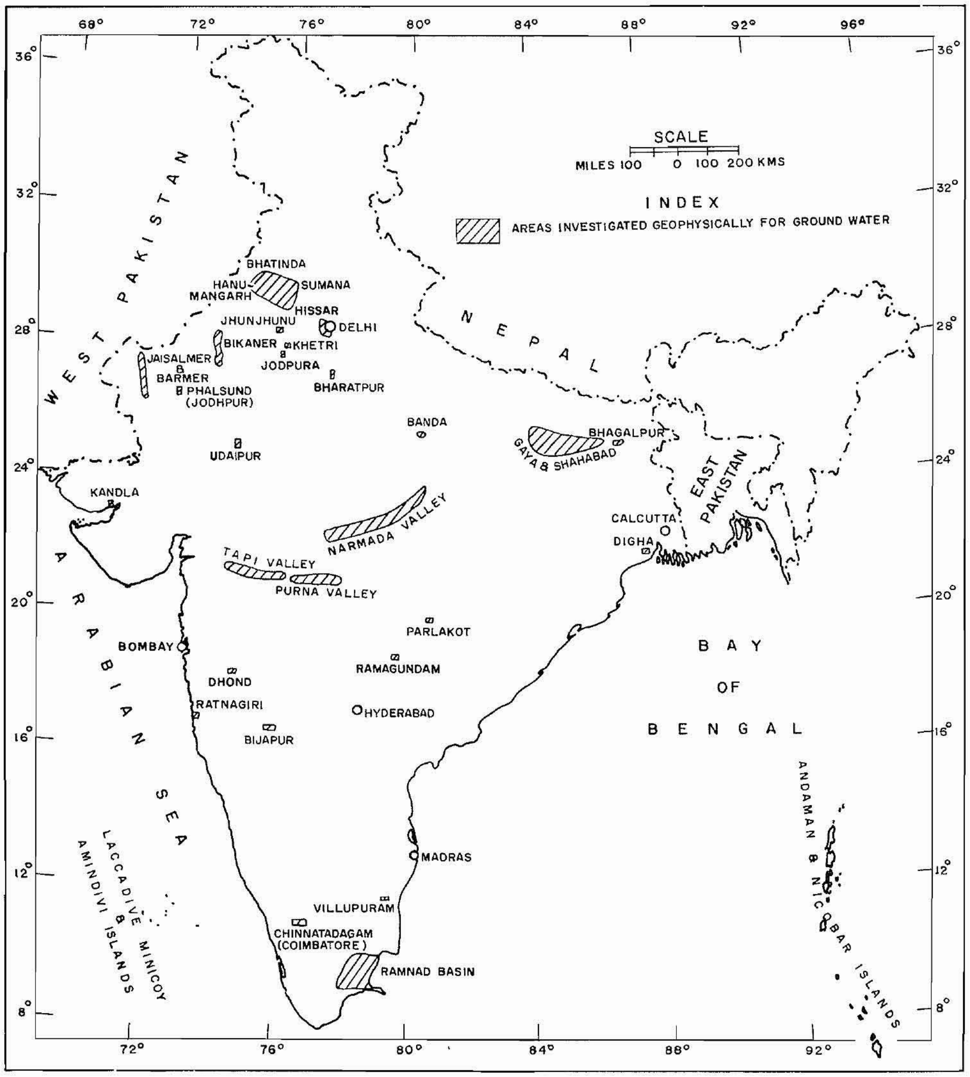

Figure 3. Geophysical investigations for groundwater carried out by the Geological Survey of India.

well known Singhbhum copper belt of Bihar. This belt extends northwest-southeast along the strike for more than 100 km. The copper mineralisation in this area (mainly chalcopyrite) is associated with a major thrust zone traversing the entire belt. Almost the entire production of copper ore in India at present is from the Mosabani, Dhobani and Badia regions of this belt. The major rock formations of this region are quartzites, phyllites, talc and mica schists and chlorite schists of the iron ore series (Archaean age) and lava flows with intrusives of epidiorite and sodagranite. The intrusive sodagranite which occurs quite extensively in this belt along the thrust zone is presumed to be connected with the mineralisation. Some strong geophysical anomalies have been outlined in this belt, especially in the Andherikal, Barachaki, Khejurdari and Tama Pahar areas (Figure 6(a)), and in the last mentioned area exploratory drilling has yielded encouraging results (Paul, P.C., 1954; Subrahmanyam, 1962; and Bose and Chatterjee, 1963). Some typical self-potential, electromagnetic and magnetic anomaly profiles pertaining to the Khadandungri area of this belt are shown in Figure 6(b). The total reserves of copper ore in the Singhbhum belt on the basis of exploratory drilling conducted so far are about 72 million tons, the average grade of copper being 1.5%.

The Agnigundala mineralised belt in Andhra Pradesh is now being explored intensively for base metals (mostly copper and lead with some zinc) and the potentialities of this belt appear to be quite promising. The ore deposits of this region are located in the eastern margin of the Cuddapah basin. The rock types include argillites, slates, phyllites, interbedded quartzite, limestone, dolomite and granite-gneiss of Precambrian age. The mineralisation consists mostly of chalcopyrite, pyrite and galena with some sphalerite at places, and occurs generally in the quartzites and dolomites, as veins and also in disseminated form. The rock formations in this region are considerably folded and faulted. Detailed self-potential, electrical resistivity, electromagnetic (inductive) and magnetic surveys have been conducted in parts of this belt and are still in progress (Simha, 1954; Bhanumurthy, *et al.*, 1966). Feeble self-potential anomalies and EM anomalies varying from 2 to 10% in the in-phase and out-of-phase components have generally been indicated. Some of the typical anomaly profiles are presented in Figure 7. In areas where the mineralisation is practically restricted to galena, no significant anomalies have been indicated and induced polarisation and bore-hole techniques will have to be used. Reserves of some 12 million tons of medium-grade copper-lead ore with average grade of 1.5%

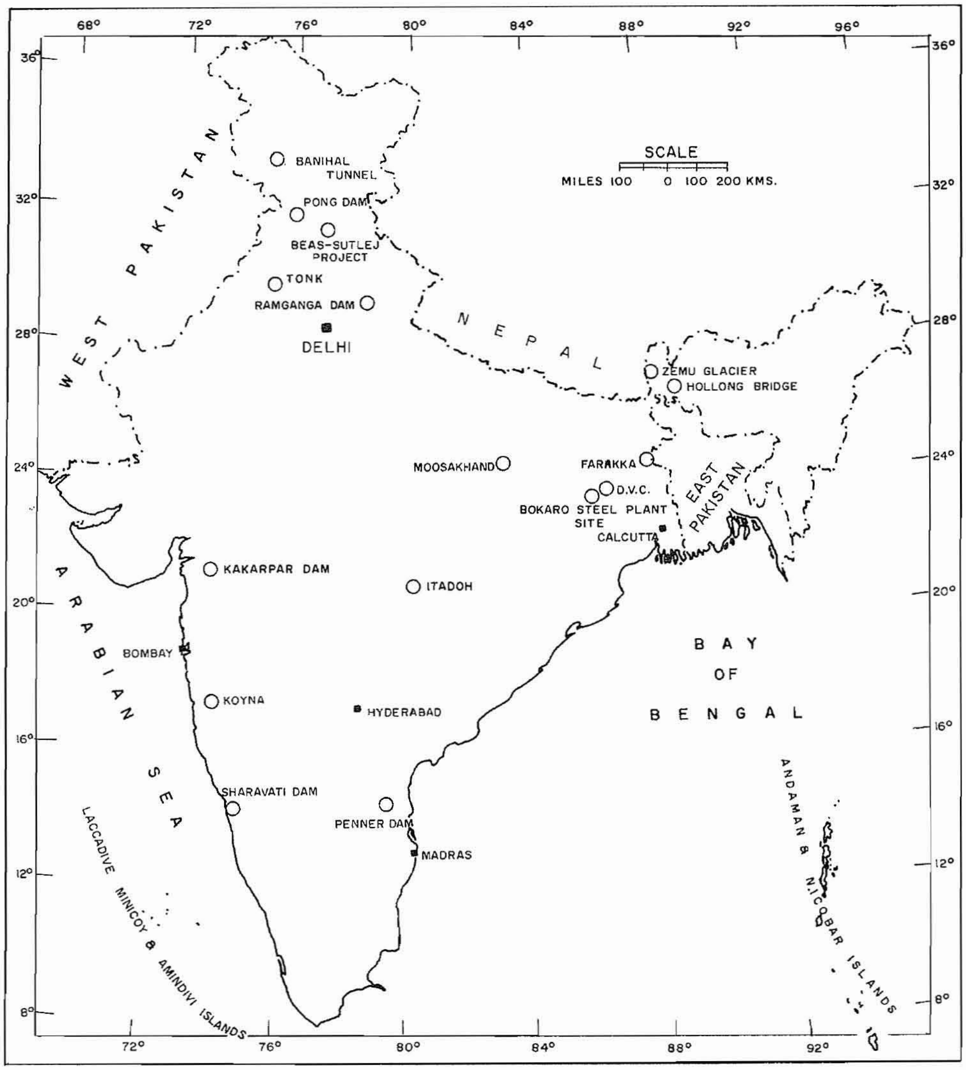

Figure 4. Geophysical investigations for civil engineering projects by the Geological Survey of India.

copper and 5.8% lead have so far been tentatively estimated in this belt.

Electrical, magnetic and electromagnetic surveys have also been conducted in the Zawar lead-zinc belt near Udaipur in Rajasthan, which is at present the chief producing area for lead and zinc ores in India. The mineralisation is mostly confined to fracture zones in dolomites and phyllites, the other formations being quartzites, slates and conglomerates, all forming part of the Aravalli system of middle Precambrian age. The deposits occur over a series of steep ridges. Some prominent EM anomalies were outlined, mostly in the in-phase component, of the order of 5 to 20% (Sastry, 1962).

Some other smaller occurrences of copper, lead and zinc ore in various parts of the country have been investigated geophysically, including some areas in the Himalayan region. All these areas are indicated in Figure 1.

Iron ore

Since India is endowed with large reserves of high-grade iron ore, the proved reserves being around 20,000 million tons, which occur at very shallow depths and are readily workable, large scale geophysical investigations for iron ore have not been undertaken till now. In the Mahendargarh area of Punjab where the country rocks consist of phyllite, calc-schists, quartz-biotite schists, felspathic quartzites, siliceous limestone, with intrusive pegmatites and quartz veins, the magnetic surveys carried out recently have yielded prominent anomalies and test drilling has proved large number of iron ore bodies (magnetite). Intensive exploratory drilling is now in progress in this area.

Sulphide ores

Extensive and systematic geophysical investigations for pyrite in the Chituldrug belt, Mysore State, yielded a large number of significant and important anomalies (self-potential and resistivity). The main rock formations in this belt are chlorite schists, ancient volcanic rocks comprising traps, agglomerates and tuffaceous rocks, the mineralisation being associated with the trap rocks. Most of the geophysical anomalies have been confirmed by exploratory drilling as being due to orebodies and reserves of 3 million tons of pyrite have been proved. The ore has a low sulpher content of about 20% and will therefore need beneficiation.

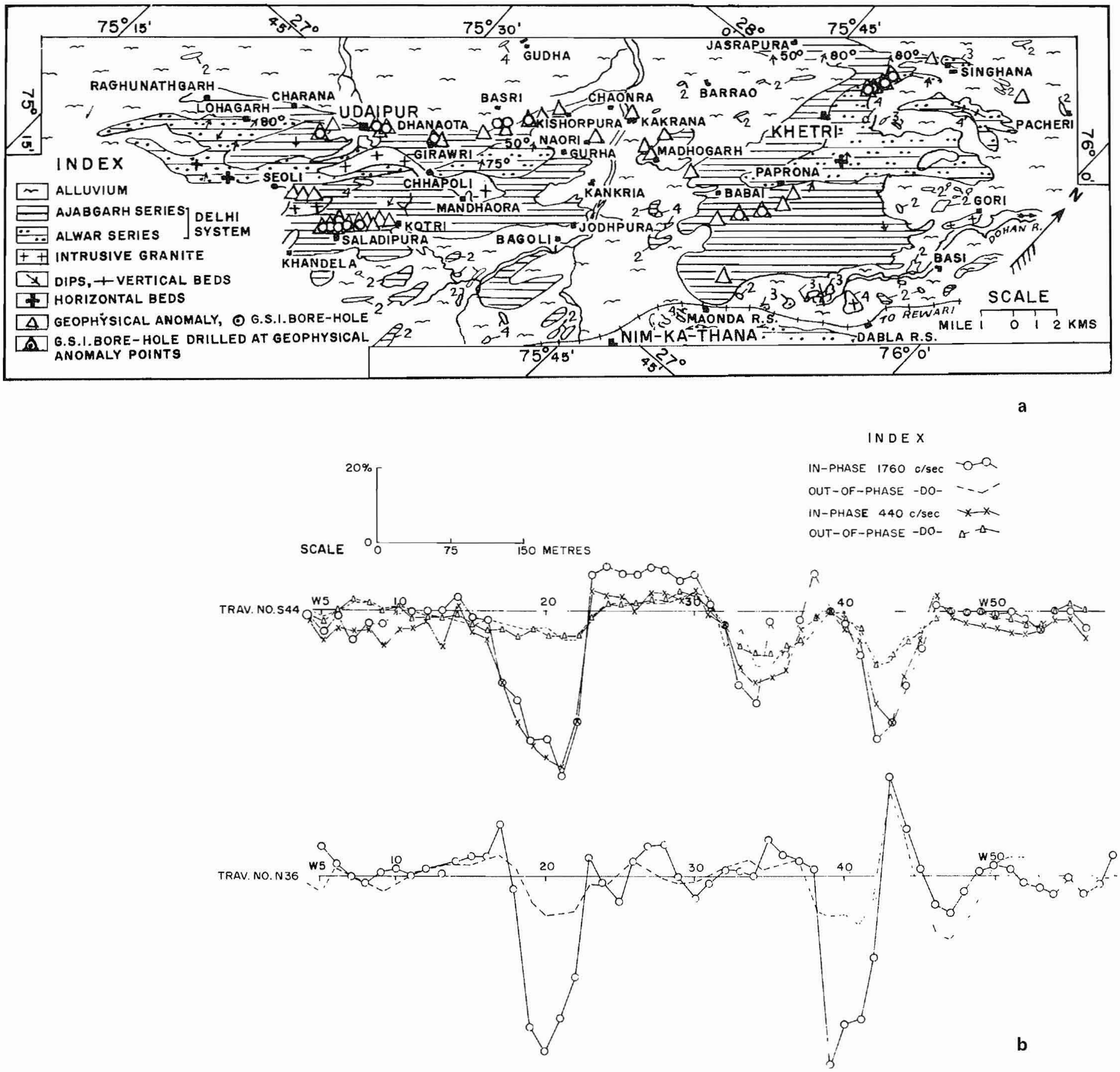

Figure 5. (a) Geologic map of Khetri copper belt, Rajasthan, showing geophysical anomalies and boreholes. (b) Typical electromagnetic profiles, Saladipura area, Sikar district, Rajasthan.

Other areas investigated for sulphides include the Thaniar area in North Arcot district of Madras State, the Amjhor pyrite belt in Bihar State and the Ramallakotta-Veldurti area of Kurnool district in Andhra Pradesh.

Chromite

Detailed and extensive gravity-cum-magnetic surveys for chromite are being conducted in the Cuttack-Dhenkanal-Keonjhar belt of Orissa. The chromite in this belt occurs as lenses and veins in laterites derived from ultrabasic rocks of Archaean age.

A number of clear and significant gravity anomalies ranging in magnitude from 0.1 to 0.5 mg were obtained in this belt, some of which have been verified by test drilling. Figure 8(a) shows the geologic map of the Surabil-Gurjang-Ostia area of this belt where gravity surveys have yielded highly successful results. The results of test drilling over one of the prominent anomalies, which

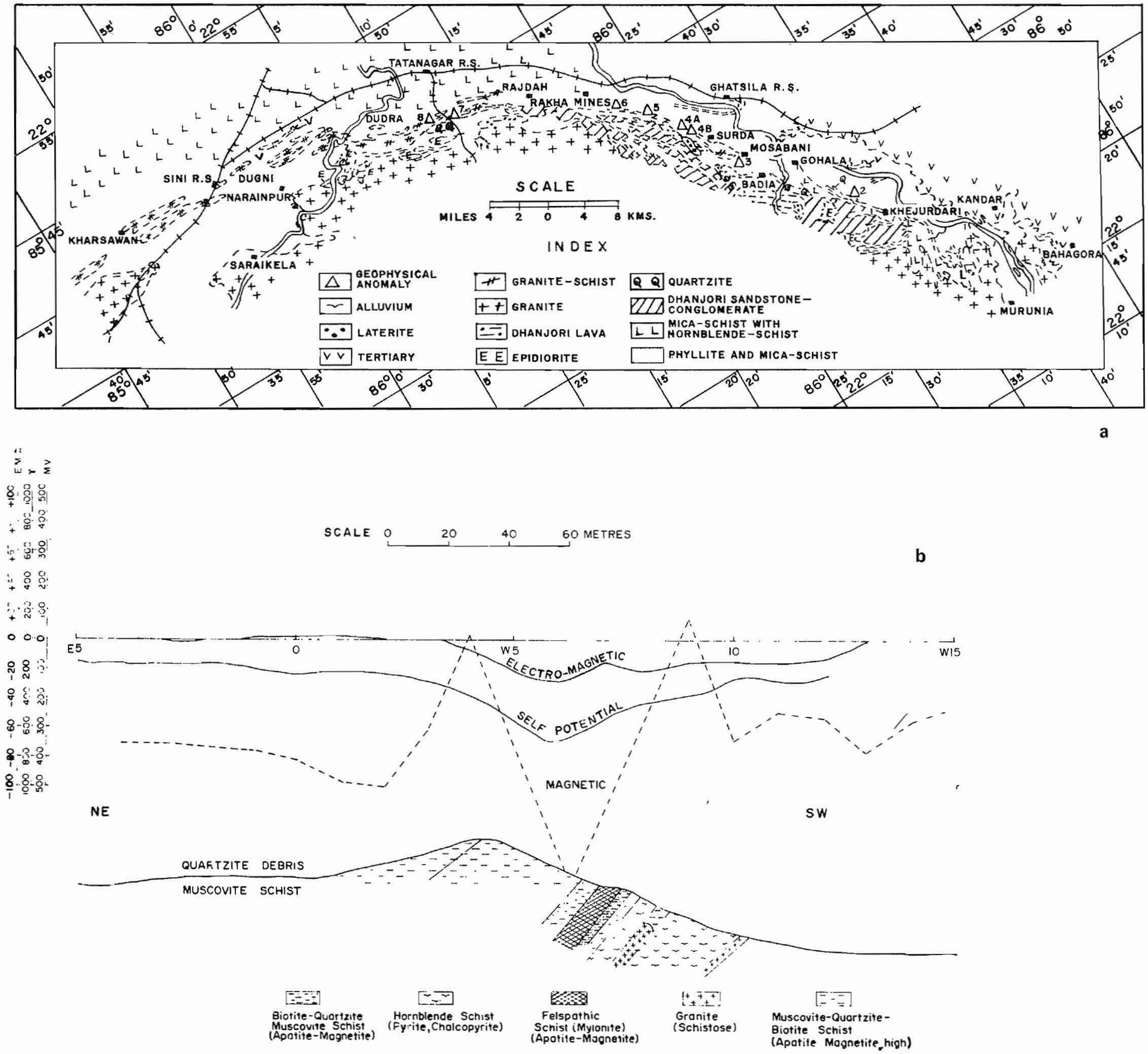

Figure 6. (a) Geologic map of Singhbhum copper belt, Bihar, showing geophysical anomalies. (b) Self-potential, magnetic and electromagnetic profiles and geologic section in Khadandungri area, Singhbhum, Bihar.

proved a thick lense of chromite, are shown in Figure 8(b). The chromite ore in this area is only feebly magnetic compared to the intrusive pyroxenite and dunite. The investigation is still in progress and the entire belt is to be covered by systematic gravity and magnetic surveys (Banerjee, *et al.*, 1964).

In the Vagda and Kankauli areas of Maharashtra where chromite occurs in the form of veins and lenses in basic and ultrabasic rocks (dunites and serpentinites with laterite), the country rocks being Precambrian biotite gneiss, detailed gravity-cum-magnetic surveys enabled the delineation of the extension of the known chromite bodies.

In the Pauni area of Maharashtra, where chromite occurs as veins associated with dunite and serpentinite enclosed by Archaean gneissic rocks, the gravity surveys did not yield useful results because of the small size of the orebodies. The magnetic method, however, was useful in delineating in unexposed areas, the serpentinite bands carrying the chromite veins.

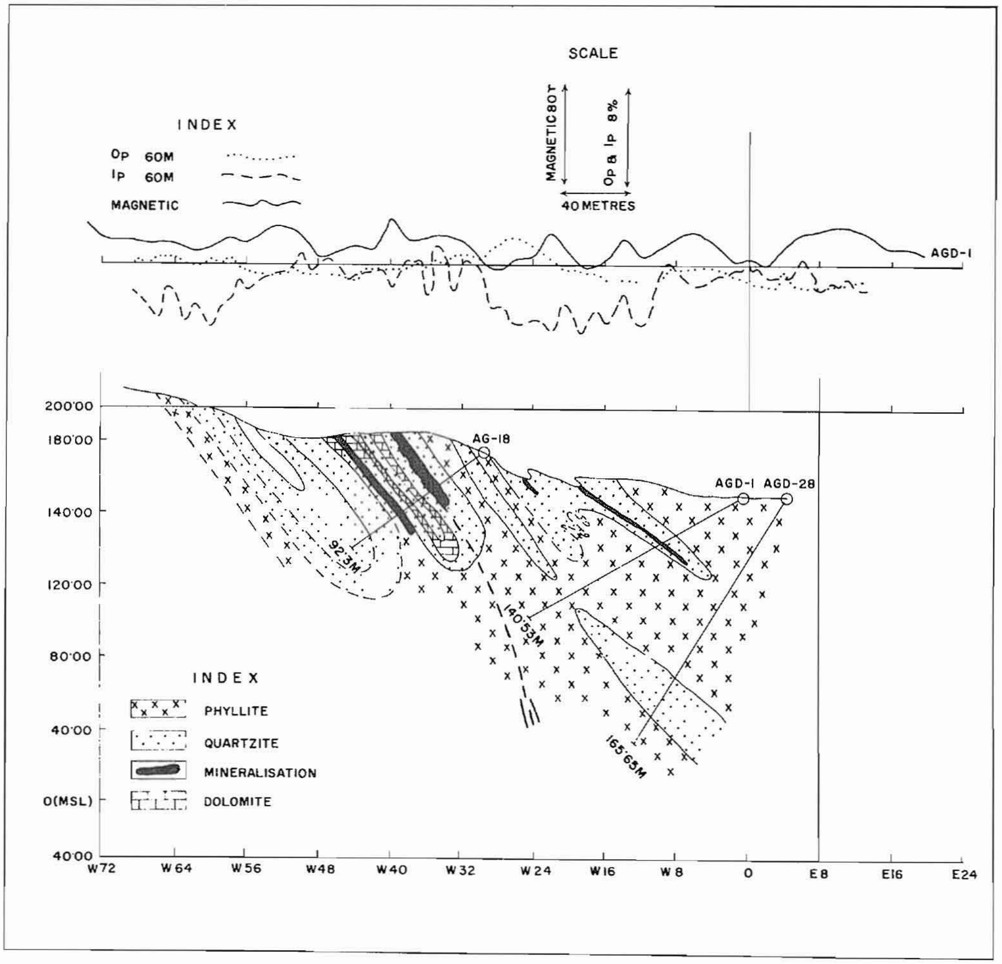

Figure 7. Magnetic and electromagnetic profiles in the Agnigundala mineralised belt, Andhra Pradesh.

In the Bairapur and adjacent areas of Hassan district of Mysore State, chromite occurs in serpentinite associated with amphibolite and dunite in a schist belt surrounded by Archaean gneisses. The magnetic method was not useful in the location of chromite bodies because of overlapping magnetic susceptibility of the pyroxenite and serpentinite, but a few well defined gravity anomalies are to be verified by test drilling.

The annual production of chromite ore at present in India is roughly 60,000 tons.

Manganese

India is one of the leading producers of manganese ore. The annual production is around 1,600,000 tons, most of it coming from the central parts of the country in the States of Madhya Pradesh and Maharashtra.

Magnetic surveys conducted in the Tirodi, Pawnia, Ramtek and neighbouring areas in the manganese belt proved highly successful in locating massive pocket-type deposits. The ores are associated with a series of metamorphic rocks of Archaean age presumed to have been formed by the metamorphism of manganese-bearing sediments deposited with sands, clays and limestone. The ores are associated with mica schist, gneisses and calc granulite. The ore minerals include pyrolusite, manganite, jacobsite and other manganese silicates. The magnetic anomalies (vertical force) vary from a few hundred to a few thousand gammas. They are of both the localised type with limited lateral extent due to pocket-type deposits and the elongated type due to bands of iron mineralisation.

In the Kodur, Baguvalasa and Ramabadrapuram areas in the Srikakulam district of Andhra Pradesh, manganese ore consisting of mangen-magnetite, vredenbergite, psilomelane and pyrolusite occurs in garnet-granulites and garnetiferous quartzite associated with a Precambrian khondalite suite of rocks consisting of quartzites, calc granulites, crystalline limestone, garnet-sillimanite-gneiss, etc. Here the magnetic response was found to be very erratic because of the highly variable nature of the magnetic susceptibility of the manganese ore minerals, some of which are weakly magnetic. The gravity surveys were more useful and yielded better results (Jagannadham, 1961).

Gold

The main gold-producing areas in India at present are the Kolar gold fields and Hutti Gold Mines of Mysore State in South India.

In this area metamorphosed Precambrian rocks occur in a schist belt consisting chiefly of schistose and fissile amphibolite and a few bands of ferruginous quartzite. Archaean gneisses occur along the margins of the schist belt. Dolerite dykes traverse the belt in all directions. The auriferous lodes occur within the schistose and fissile amphibolites at the contact of massive granular amphibolites. As some of the known lodes are sulphide bearing, the self-potential method was tried to locate possible

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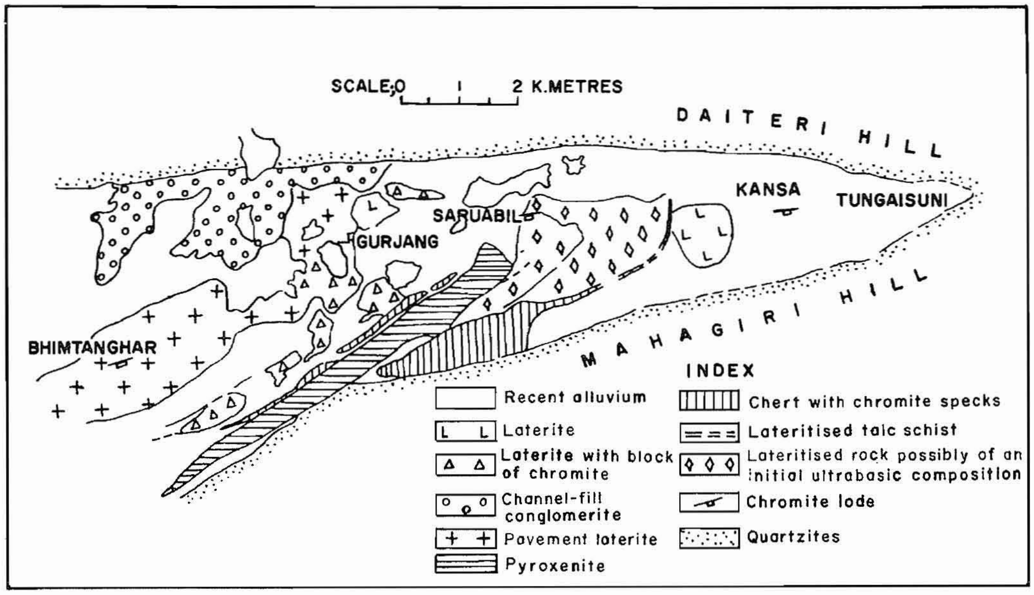

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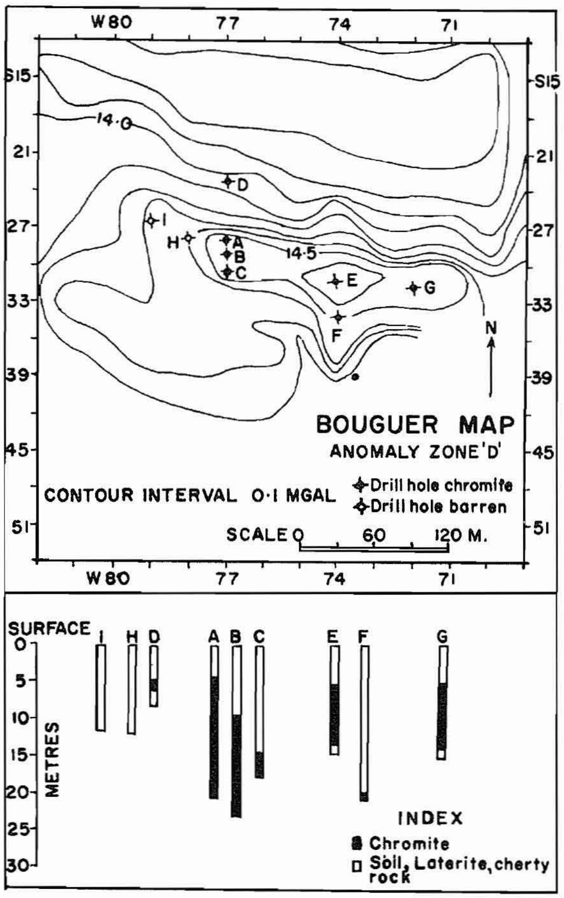


Figure 8. (a) Geologic map of Kansa-Saruabil-Ostia Gurjang area Cuttack-Dhenkanal chromite belt, Orissa. (b) Gravity anomaly map of area to the south of Gurjang, Orissa, showing drilling results.

additional sulphide-bearing suriferous lodes outside the mining area. The surveys did not yield any significant indications, barring a few SP anomalies due to graphitic lenses occurring within the area. Some test resistivity measurements were also made, but did not yield any significant result (Ramachandran and Vaidyanathan, 1959). The present production of gold in India is about 4000 kg per year.

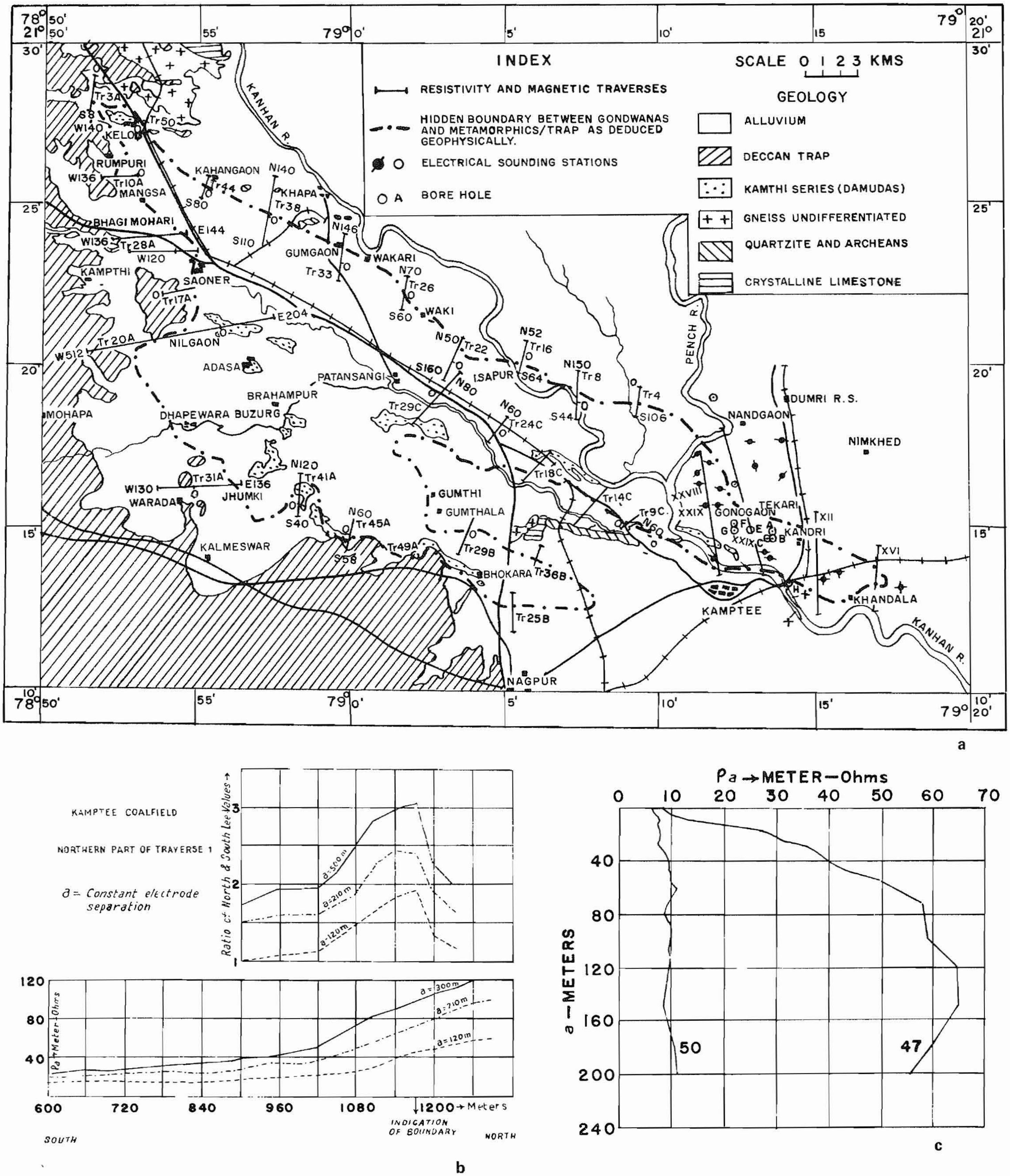
In addition to the investigations for ores described in the foregoing sections, limited geophysical surveys were carried out for molybdenite in Maduri district, Madras State, and for tungsten ore in the Nagpur district of Maharashtra, employing magnetic, EM and resistivity methods.

Coal

India has substantial reserves of coal. The annual production of coal at present is roughly 70 million tons. The main producing fields are the Jharia and Raniganj coal fields of Bihar and West Bengal. The other important fields are Wardha and Pench-Kanhan valley coal fields in Maharashtra, the Singareni coal field in Andhra Pradesh, and the Korba and Koranpura coal field in Madhya Pradesh.

One of the major geophysical surveys conducted for coal was in the Kamptee coal field of Maharashtra, which is now being actively developed. Coal occurs in this area in the Barakar formation of Lower Gondwana (Permian) age, consisting of sandstones and shales preserved in a faulted trough within the Archaean granites and gneisses. The Barakars are overlain by the Lower Gondwana, Kamptee sandstones which are barren of coal. The problem for geophysical investigation was mainly the delineation of the concealed boundary between the sedimentary rocks and the Archaean gneisses and basaltic lavas of the Deccan Trap.

Systematic electrical resistivity and magnetic surveys were carried out in the area. The boundary between the two formations was successfully delineated by resistivity and magnetic traverses taking advantage of the appreciable resistivity and magnetic susceptibility contrasts between the sandstones and the crystalline rocks. Over the western part of the coal field,



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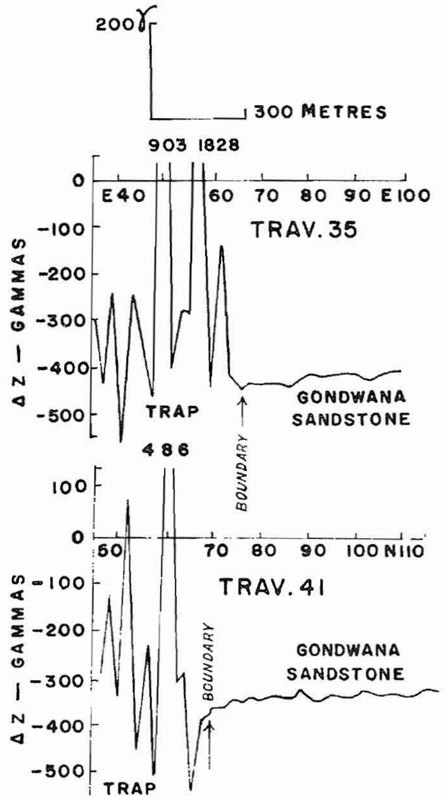


Figure 9. (a) Electrical resistivity and magnetic investigations of the Kamptee coal field, Maharashtra. (b) Apparent resistivity traverses across gneiss-sandstone Gondwana boundary. (c) Resistivity depth probe curves over coal seam and barren Barakar sandstones. (d) Magnetic profiles across sandstone-trap boundary.

however, where the Deccan Trap rocks are in contact with the sandstones, the resistivity method was not suitable for the delineation of the boundary because of the low order of resistivity of the Deccan Traps. The magnetic method, however, was very effective for the delineation of the boundary in this part of the coal field because of the characteristically high magnetic susceptibility of the Deccan Trap in relation to the Gondwana sandstones (Kailasam, 1952; Aravanudhan, 1960; Mitra, 1962; Ray, 1964).

The typical results of this investigation are presented in Figure 9(a), (b), (c) and (d) indicating the hidden boundary of the coal field as mapped geophysically and the resistivity and magnetic traverses across the crystalline-sandstone and trap-sandstone contacts, respectively.

The resistivity data further indicate a high resistivity, of around 400 to 500 ohm-metres, for the coal beds in contrast to a low resistivity (of the order of 40 to 60 ohm-metres) for the Gondwana sandstones. This enabled the study of the distribution and disposition of the major concealed coal beds within the sandstones, aiding considerably the exploratory drilling that has been conducted in this area. The apparent resistivity curves for two depth probes, one over a major coal seam in the Barakar sandstones and the other over Barakars free from coal (shown in Figure 9(c)), clearly bring out the high resistivity of the coal seam.

Useful electrical resistivity and magnetic surveys were conducted at Korba in Madhya Pradesh for the study of the extension of coal fields and for structural studies. Reflection and refraction seismic methods were successfully employed to map the Archaean basement of the Lower Gondwana basin in the Jharia coal field in Bihar and thereby to determine the thickness of the sediments.

Lignite

Extensive and detailed gravity investigations were conducted in the major lignite belt of Neyveli and in the neighbouring areas of South Arcot district of Madras State. The lignite in the South Arcot sedimentary basin occurs as thick lenses and seams within the Miocene Cuddalore sandstones and clays at depths of 50 to 150 m. The depth to the crystalline basement in this area, as determined by reflection seismic surveys, is around 2000 m, and the maximum depth of the Tertiary sediments enclosing the Cuddalore formations is about 600 m. The maximum thickness of the lignite bed encountered in this area is roughly 16 m at a depth of 50 m from the surface. Clear and distinct gravity anomalies of around 0.1 to 0.7 mg (in the residual gravity map) were obtained over the major lignite bed which is now worked and which supports a large thermal and briquetting project and other ancillary industries. Gravity anomalies have been obtained farther to the south of this known lignite field. These anomalies have also proved the occurrence of lignite, indicating the existence of large reserves of lignite in this basin (Kailasam, 1958a; Reddi, 1964).

Graphite

Geophysical investigations for graphite employing mainly self-potential methods, have been conducted in the Trivandrum, Punalur and Ernakulam districts of Kerala State and these are still in progress. Graphite occurs in this area in the form of lenticular bands and veins within the laterite, associated with garnetiferous biotite-gneiss, biotite-granite and pegmatites. The graphite generally occurs at shallow depths but deeper occurrences are also expected within the laterites and gneisses.

The results of the self-potential surveys are highly encouraging. Several large SP anomalies of around several hundred millivolts have been obtained; many of them were proved to be shallow, large, high-grade graphite bodies by subsequent trenching, pitting and drilling operation. A typical anomaly of this kind, obtained in the Chenga-Venganoor area of Trivandrum district, is presented in Figure 10 (Simha, 1960; Rao, 1961).

Self-potential surveys for graphite have also been carried out in the Marivada, Goparam and Sitapalle areas in the Godavari districts; in the Racha Konda area of Khammam district in Andhra Pradesh; in the Dahigaon area of Sambalpur district and the Athmallik area of Dhenkanal district of Orissa. Several significant anomalies have been delineated in all these regions. Exploratory drilling will probably be carried out shortly in some of these areas.

Diamond

Magnetic and electrical resistivity surveys were conducted in the Panna diamond belt to locate possible additional buried volcanic

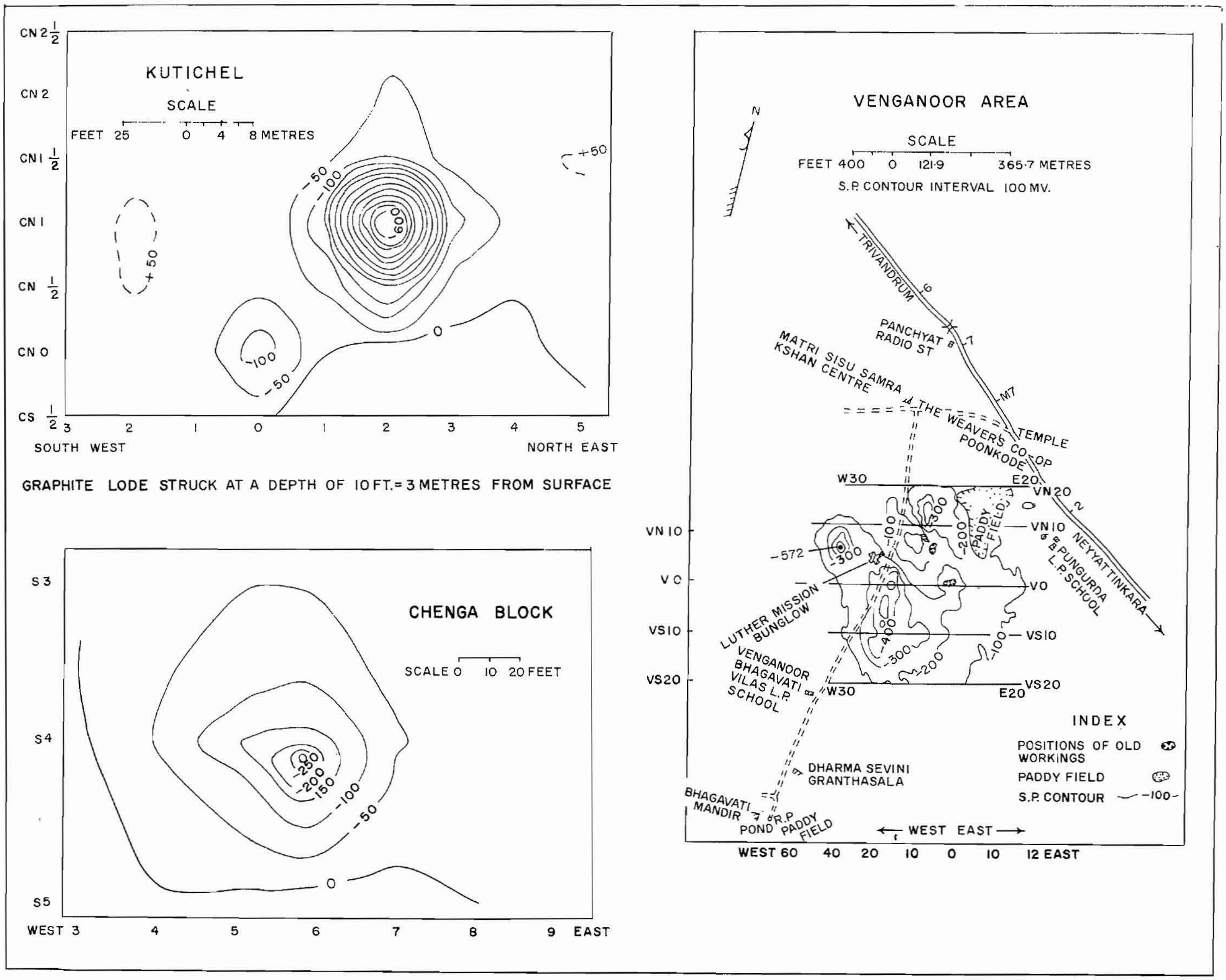


Figure 10. Self-potential surveys for graphite in Trivandrum district, Kerala State.

pipes similar to the well known diamond producing Majhgawan pipe. The country rock in this area consists of Kaimur sandstones of Vindhyan (Precambrian) age which are more or less horizontal, underlain by the rocks of the Lower Vindhyan system. The Bundelkhand granite constitutes the basement rock. Test magnetic and resistivity observations conducted over the known diamond-producing volcanic pipe at Majhgawan having yielded appreciable magnetic and resistivity (conductive) anomalies and the surveys were extended to the adjoining areas to attempt to locate additional volcanic pipes. As a result of these surveys, another major volcanic pipe, about 180 m in diameter with a roughly circular outline, buried under an alluvial cover of 5 metres, was located some 2.5 km to the north-northwest of the known Majhgawan pipe. As the top portions of the tuffaceous rocks in the pipe are highly weathered and conductive, the resistivity traverses across the pipe gave a marked conductive anomaly, enabling an accurate delineation of the periphery of the buried pipe. This new pipe which is now being worked is also reported to be diamondiferous. The magnetic and resistivity anomalies over this buried pipe are presented in Figure 11(a) and (b) (Sarma and Nandi, 1959).

Electrical resistivity and magnetic surveys were also conducted in the Wajrakarur and adjoining areas in Anantapur district. Andhra Pradesh for the location and delineation of buried diamondiferous volcanic rocks. The area consists mainly of granitic rocks including granite-gneiss, graphitic gneiss, pegmatite and quartz veins with basic intrusive volcanic rocks resembling somewhat the Kimberlite rocks of South Africa. There are also some old workings in the area.

The magnetic method was not useful in this region as the values are considerably influenced by large anomalies due to deep seated effects. The resistivity method, however, was quite

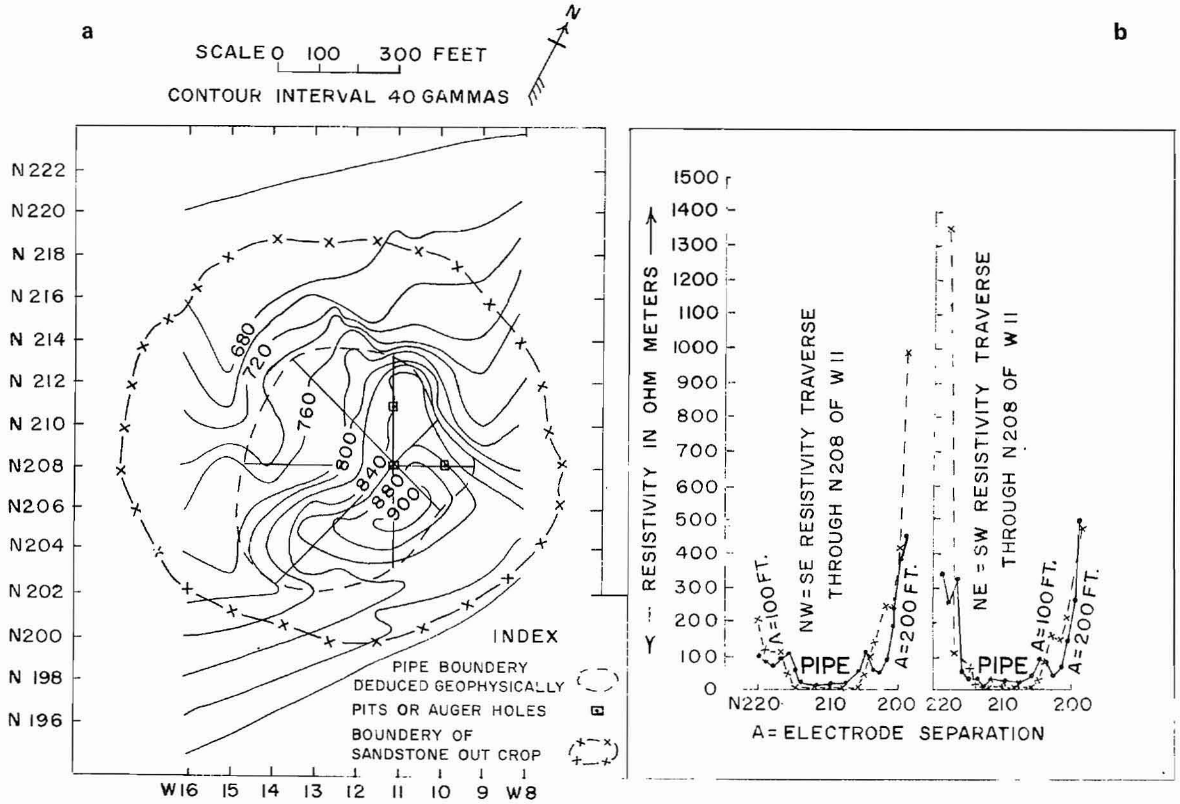


Figure 11. (a) Magnetic anomaly map over buried volcanic pipe, Panna diamond belt, Madhya Pradesh. (b) Resistivity traverses across buried pipe.

effective in mapping the buried lateral extension of the volcanic formations over a considerable distance. The potentialities for diamonds in this belt have yet to be tested by large-scale pitting, trenching and screening operations.

Other geophysical investigations for nonmetallic minerals include surveys for fluorite, vermiculite, china clay and flux-grade limestone. Seismic and electrical surveys for flux-grade limestone have led to the location of large reserves in the Shahabad area of Bihar and in the Sundargarh area of Orissa.

Groundwater

The application of geophysical methods to groundwater exploration is of special importance in India, as large parts of the country suffer from an acute shortage of water for both domestic and irrigation purposes. The recent drought in parts of Bihar, Uttar Pradesh and Madhya Pradesh has accentuated the problem and has brought it into sharper focus.

For purposes of geophysical exploration for groundwater in India, the areas may broadly be divided into four categories, viz.: (a) the arid and semiarid regions of northwestern India, including the desert areas of Rajasthan where the problem is mainly one of locating groundwater in unconsolidated overburden and consolidated sedimentary formations, in addition to the investigation of salinity conditions which are widely prevalent in these parts; (b) the semiarid areas of the Deccan trap in Central and Western India; (c) the hard-rock areas of the peninsular shield; and (d) the inland river valleys or basins, embayments and coastal sedimentary basins which offer possibilities of large supplies of water for irrigation purposes.

More than 30 geophysical investigations for groundwater in various parts of the country, falling under the categories mentioned above, have been conducted in the past few years. These are indicated in the sketch map shown in Figure 3. Electrical resistivity and shallow refraction seismic are the principal methods used. In the deeper sedimentary basins, reflection seismic methods have also been used for basement mapping and for the study of stratigraphic and structural disposition of overlying consolidated sediments. Electrical well logging has been conducted in most of the tube wells for the study of porosity and permeability characteristics of acquifers and for the stratigraphic correlation of formations including producing strata.

In Rajasthan, electrical resistivity and shallow refraction seismic investigations have been conducted in various parts of the desert region. In the Shergarh, Chaba and Phalsund areas in Jodhpur district, where the annual rainfall varies from 10 to 20 inches, where the surface sands are underlain by Vindhyan sandstones and Malani rhyolites (Precambrian), and the depth to water-table varies generally from 6 to 40 metres, resistivity surveys enabled the demarcation of zones of fairly potable water from zones of brackish water. In the Lunkaransar, Bikaner and adjoining areas which are covered by a thick blanket of blown sands overlying Eocene beds of shales, clays, lignite and sandstones which in turn are underlain by Vindhyan (Precambrian)

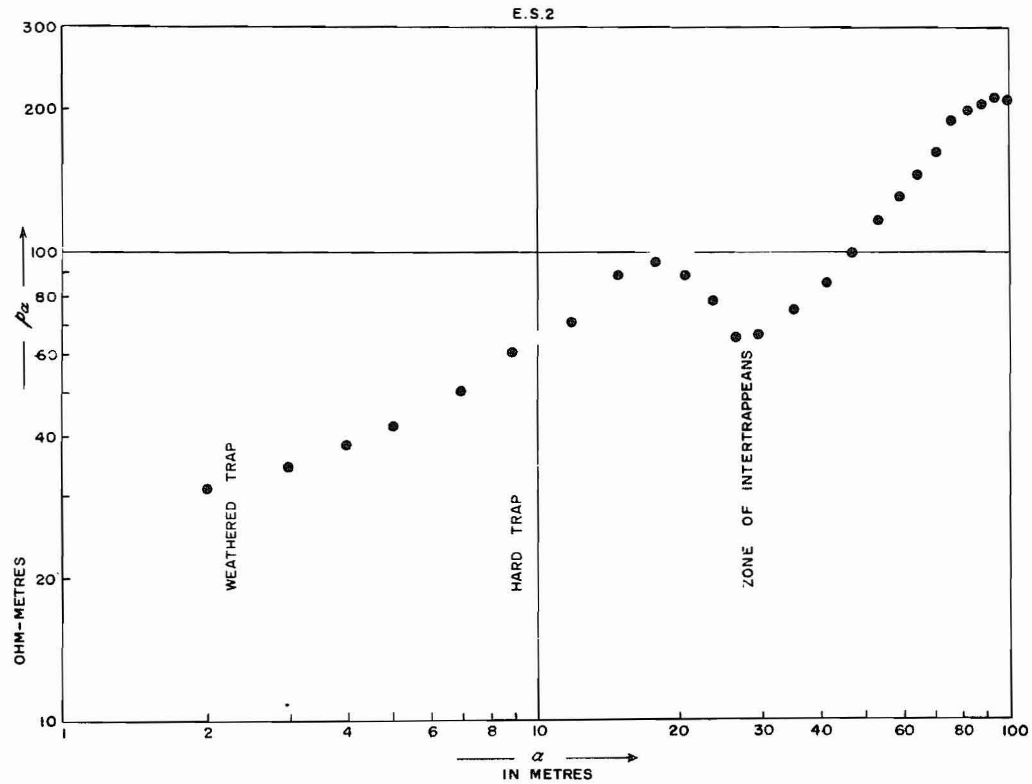
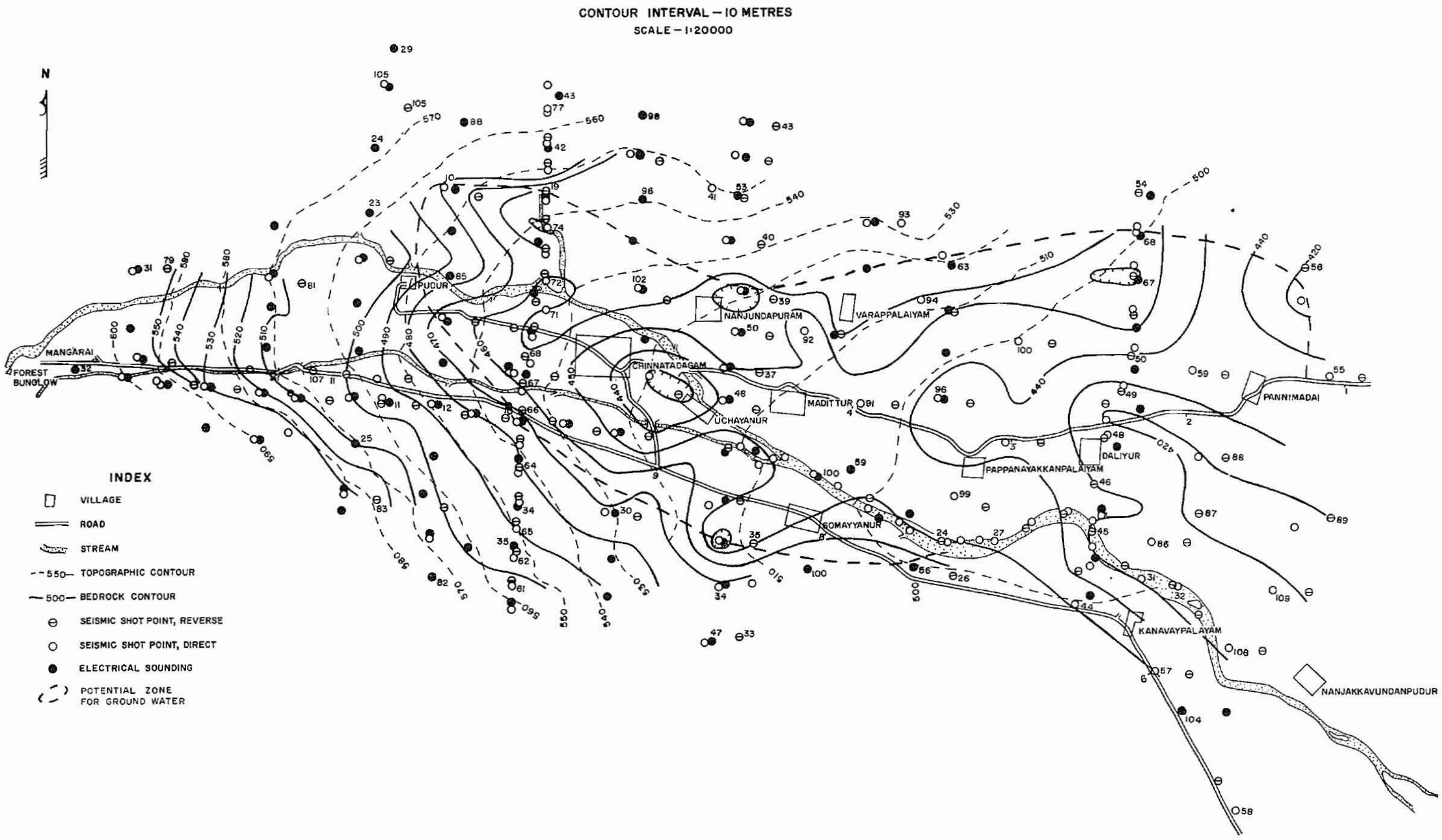
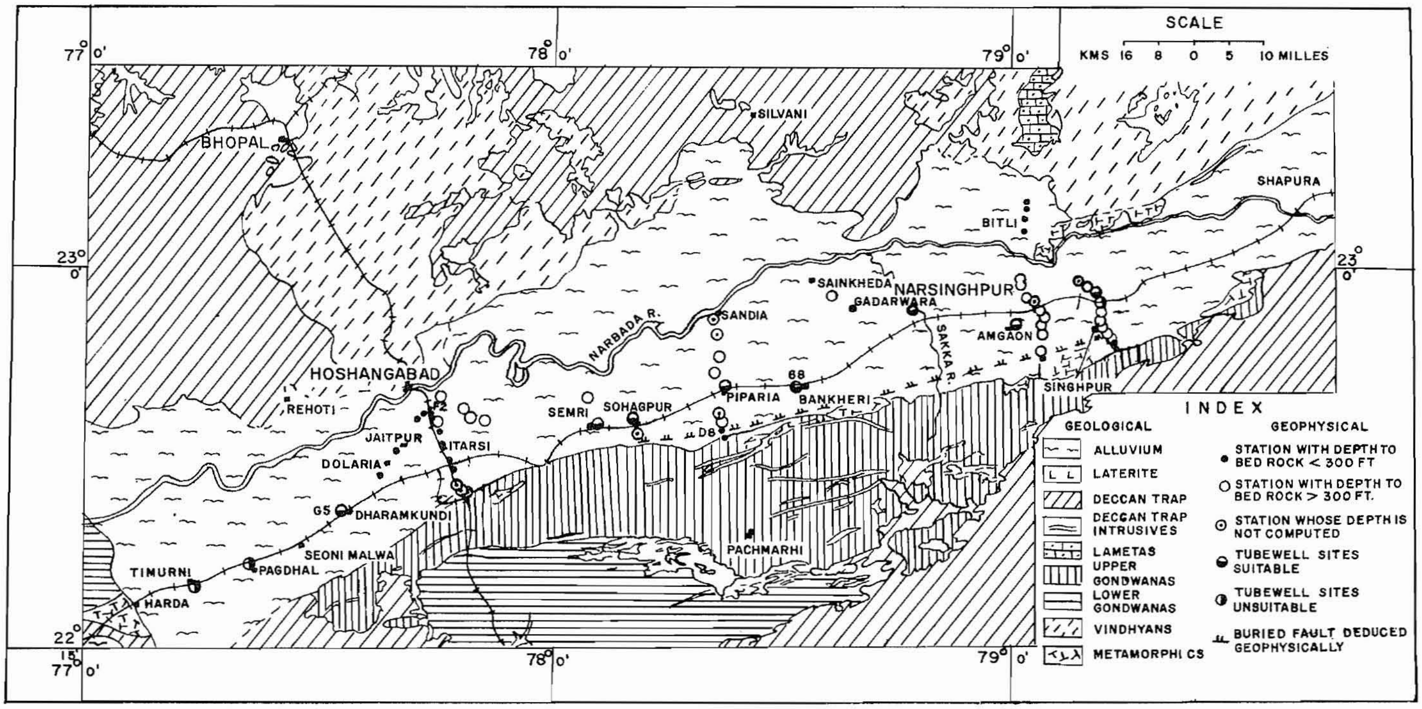


Figure 12. Typical electrical depth probe curve over Deccan Trap, Bombay State.

Figure 13. Subsurface topography of bedrock as deduced from geophysical survey, Chinnatadagam area, Coimbatore district, Madras State.





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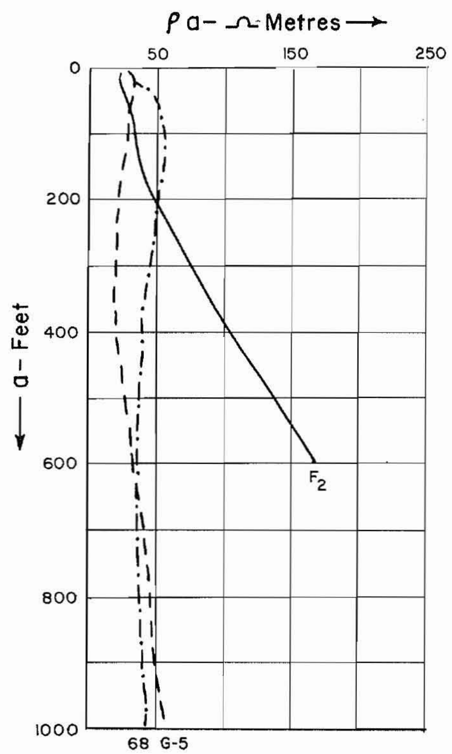

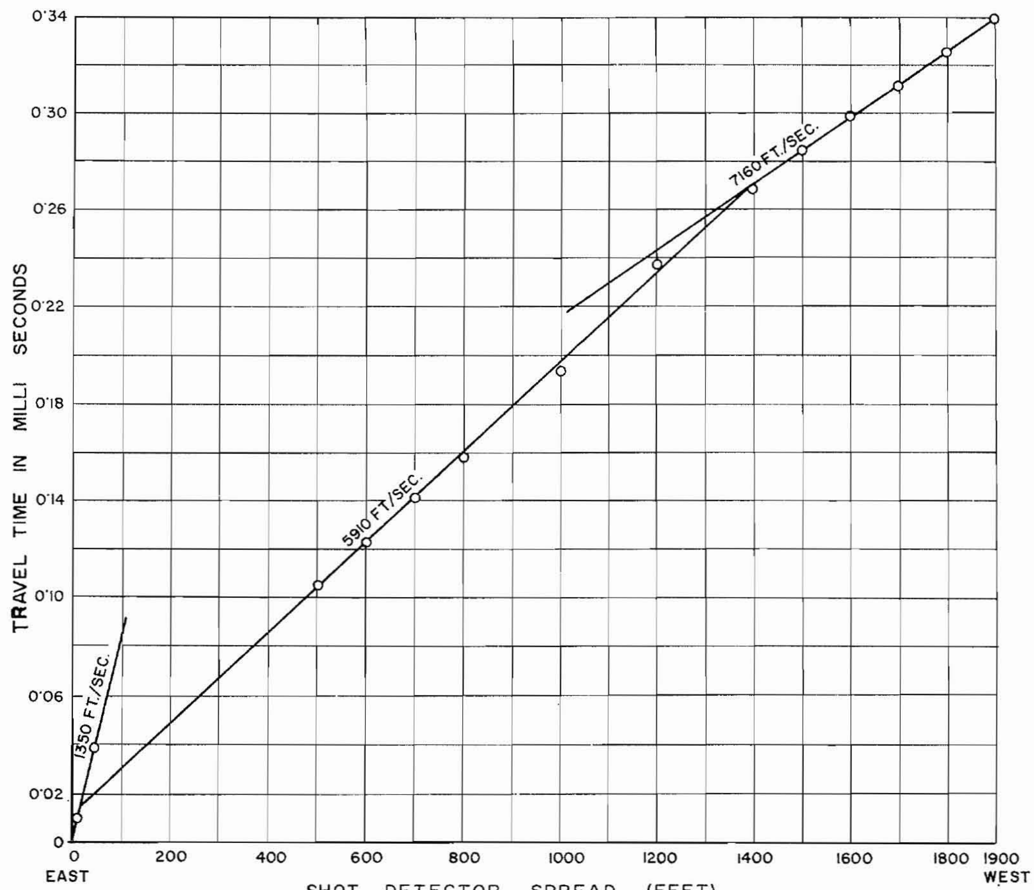

c

Figure 14. (a) Geologic map of Narmada valley indicating geophysical results. (b) Apparent resistivity curves over buried Deccan Trap (G5), Gondwana sandstone (68) and Vindhyan sandstone (F2). (c) Typical seismic refraction travel-time curves over Gondwana sandstone.

sandstones, electrical resistivity and refraction seismic surveys are currently in progress. The friable and conglomeratic sandstones of Eocene-Cretaceous age are the main water-bearing formations and the geophysical problem is largely one of subsurface mapping of these beds and investigating their thicknesses. The conditions of very low rainfall, and strong evaporation have resulted in the concentration of salts in the overburden, rendering the resistivity method unsuitable, and therefore seismic methods are most commonly employed. Electrical methods, however, have been of some use in the delineation of the less brackish zones (Roy, 1966). Similar investigations are also in progress in the Jaisalmer district of western Rajasthan where Tertiary and Jurassic sandstones constitute the main water-bearing formations. The refraction methods have been useful in determining the depths and subsurface extents of these formations and electrical surveys have been useful in delineating the less brackish zones (Chakraborty, 1966).

The groundwater conditions in the Deccan trap areas of central and western India pose some difficulties and problems. The basaltic rocks of the trap are fine grained and compact and the location of water is restricted to the vesicular portions of the trap, the decomposed zones and intertrappean sedimentary beds. These intertrappean beds generally consist of friable sandstones, ash beds, etc., and under favourable conditions constitute good aquifers. The Deccan trap lavas have a low to moderate resistivity varying from 40 to 300 ohm-m, which often makes it difficult to distinguish thin intertrappean beds at depth from the compact lava flows. The decomposed zones and topographic features over the trap formation under unconsolidated overburden, can, however, be investigated by resistivity as well as seismic methods. Figure 12 shows a typical resistivity depth probe curve over the Deccan trap formations in the Borivli area near Bombay (Nair, 1964). An intertrappean formation is clearly indicated at an estimated depth of 20 m. Refraction seismic surveys in this area have enabled the mapping of the subsurface topography of the hard fresh trap, bringing out features such as buried channels and depressions in the trap.

Electrical resistivity and refraction seismic surveys have also been conducted in the hard rock areas of peninsular India in Madras State. Figure 13 presents the subsurface topography of the bedrock as deduced from resistivity and refraction seismic surveys in the Chinnatadagam area near Coimbatore in Madras State. Composite gneisses form the main rock formation in this area. Depths of 60 to 80 m have been indicated in the deeper parts of the valley as a major feature in the form of a longitudinal channel. The results thus indicate favourable potentialities for water in this valley (Nair, *et al.,* 1965).

In the alluvial areas of the Narmada valley in Madhya Pradesh (Figure 14(a)), electrical and refraction seismic surveys conducted to aid the selection of sites for deep irrigation tube wells, yielded highly successful results. The valley is drained by the Narmada River and the alluvium of the valley conceals complex geology with a diversity of rock types such as Deccan traps, Vindhyan and Gondwana sandstones, limestones and Archaean gneisses. The geophysical investigations indicated depths to bedrock of from 30 to more than 200 metres and this was verified by subsequent drilling. In many places the nature of the bedrock was also correctly predicted on the basis of the resistivity and velocity characteristics as deduced from the resistivity and seismic profiles. Figure 14(b) shows three apparent resistivity depth probe curves G_5, 68 and F_2 over the alluvium of the valley with indicated depths to bedrock of 125 m (Deccan trap), 180 m (soft Gondwana sandstones) and 30 m (hard Vindhyan sandstones), respectively. The travel-time curves shown in Figure 14(c) indicate Gondwana sandstones at an estimated depth of 100 m (Kailasam, 1958b). Many of the tube wells drilled at the sites selected on the basis of the geophysical results are now producing wells.

In the Ramnad Basin of Madras State in the southeastern extremity of the country, large parts of which are semiarid and arid, refraction, reflection and electrical resistivity surveys have enabled the determination of the thickness of sediments and the basement topography. The depth to the Precambrian crystalline basement near the sea coast in the eastern parts of this basin is more than 2000 m as indicated by the seismic data. It has been possible to distinguish between zones of brackish and potable water on the basis of resistivity survey results (Mathew, 1962; Jagannadham, *et al.*, 1964; Kailasam, 1966).

Geophysical investigations for groundwater have also been conducted in other areas in the country which are shown in Figure 3.

Civil engineering projects

Geophysical investigations have been conducted to assist most of the major civil engineering projects in the country, for foundation and structural studies. These are indicated in Figure 4 and include the Maithan and Panchet Dam sites of Damodar Valley Corporation in West Bengal and Bihar, the Sharavati Hydroelectric Project in Mysore, the Beas-Sutlej Link Project and Punjab and Himachal Pradesh, the Farakka Project in West Bengal and the Ramagundam Project in Andhra Pradesh. The most recent of these is the intensive and detailed survey of the foundation conditions at the Bokaro Steel Plant site in Bihar, conducted at the request of the project authorities.

Refraction seismic, electrical resistivity and magnetic methods were used for the Beas-Sutlej Link project area in Punjab and Himachal Pradesh in northwestern India. This is the largest river valley project in the country and has for its objectives the diversion of Beas River through a system of lakes and tunnels, enabling the ultimate discharge of the diverted supplies into the Sutlej river at Bhakra lake near Dehar. In the process of diversion, the net height differential of about 1000 feet would be utilised for power generation. The project includes two dams at Pondoh and Pong across the Beas River, a major diversion tunnel from Pondoh to Sundernagar, a hydroelectric power station and finally a canal system for providing water for irrigation in the semiarid areas of Rajasthan.

The project area comprises rock types ranging from sedimentary rocks like sandstone, siltstone, claystone and limestone to igneous rocks such as granites, diorites and traps, and metamorphic rocks including slates, phyllites, schists and quartzites. Seismic data yielded useful information regarding bedrock depths. The resistivity method was not particularly effective in this area but was, however, useful in delineating zones of less compact rocks along the major Pondoh-Sundernagar tunnel alignment. The magnetic data gave supporting evidence regarding faults in the vicinity of the Sundernagar-Pondoh tunnel.

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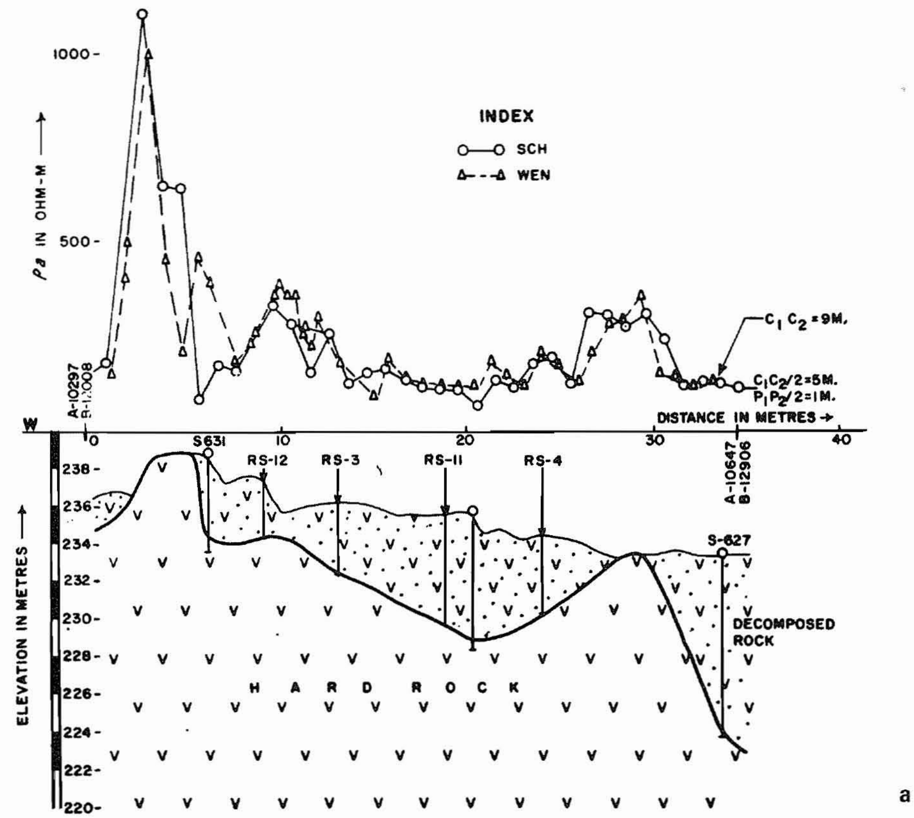

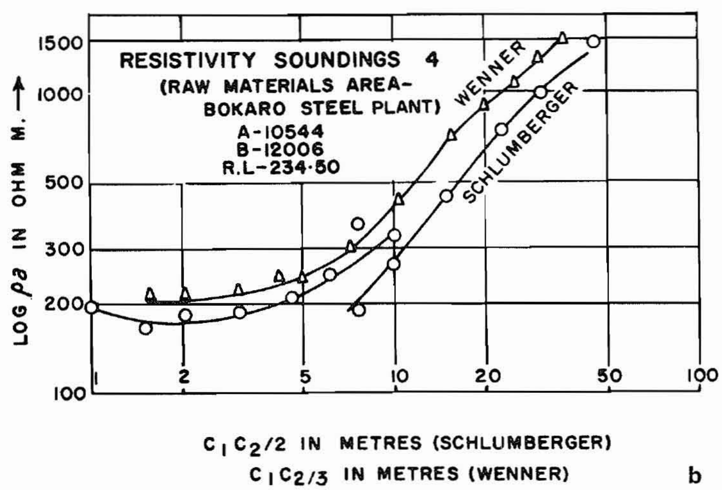

Figure 15. (a) Resistivity traverse and bedrock section, Bokaro Steel Plant site, Bihar with borehole data. (b) Apparent resistivity depth probe curve, Bokaro Steel Plant site.

At the Bokaro Steel Project site, Hazaribagh district, Bihar, extensive electrical resistivity depth probes and traverses supplemented by refraction seismic soundings were conducted to determine the bedrock configuration. Granite gneiss of Archaean age constitutes the bedrock which outcrops at places. The maximum depth to bedrock is about 30 m. The gneissic rocks in this area have been subjected to strong differential weathering giving rise to a very irregular bedrock surface and varying thicknesses of weathered rock necessitating resistivity measurements at very close intervals to delineate the hard bedrock surface. A typical bedrock section as deduced from the resistivity traverses together with the drilling data are presented in Figure 15(a). Typical resistivity sounding curves are shown in Figure 15(b) (Subrahmanyam, *et al.*, 1966).

Well logging

The Geological Survey of India possesses many well logging units with capacities ranging from 1000 to 5000 feet. These include single electrode resistance, multielectrode resistivity, gamma-ray and temperature logging units.

Electrical, radioactive and thermal logging of boreholes is conducted extensively for groundwater, coal and base metals. So far 2500 boreholes have been logged in different parts of the country, the deepest hole logged being in the Raniganj coal field to a depth of 4650 feet. Such logging operations have been employed (1) to determine the true resistivity of strata in boreholes (2) for computing the relationship between true resistivity on the one hand and lithological, physical and chemical characteristics of the strata on the other, (3) and for estimating thermal gradients in sedimentary, metamorphic and igneous formations to aid in regional correlation of subsurface data.

Research and development

The Research and Development Unit of the Geophysics Division has on hand a number of research projects bearing on field exploration techniques, mathematical methods of interpretation of geophysical data and geophysical instrumentation.

The elastic properties and seismic wave velocities of Indian rock formations under varying conditions of pressure and also the magnetic and electrical properties of Indian rocks have been systematically studied in the laboratory by equipment and instruments specially designed and constructed in the Geophysical Workshop. The results of some of these investigations have been published (Datta and Simha, 1967).

The electromagnetic response of conducting half-planes to vertical-vertical dipole profiling has been studied by means of model experiments. A method of quantitative interpretation of the ratio of resistivity to thickness, depth, dip and the position vertically above the conductor has been developed from the in-phase and quadrature response curves. Response diagrams and curves have been compiled for the solution of the unknown parameters related to good conductors at various depths and dipping at various angles (Nair and Biswas, 1966).

Model studies of seismic prospecting and induced polarisation methods are in progress.

A number of geophysical prospecting instruments have been designed and constructed in the Geophysical Workshop and Laboratory. These include DC resistivity and spontaneous polarisation potentiometers, surface electromagnetic (inductive) prospecting instruments, proton precession magnetometer, magnetic susceptibility meter for *in situ* field measurements, magnetic field compensator, and geothermal probe. (Gupta Sarma and Biswas, 1965, 1966a, 1966b; Datta, S., 1965a, 1965b; Datta, S., and Gupta Sarma, 1964.)

In the Mathematics Branch, studies have been conducted on the interpretation of self-potential, gravity and magnetic data, and many master curves for DC resistivity prospecting, both for symmetrical and asymmetrical electrode configurations have been computed and prepared (Paul, M.K., 1961, 1965; Paul, M.K., *et al.*, 1965, 1966).

In connection with field technique research, borehole methods of low-frequency electromagnetic prospecting are being developed and an instrument has been designed and constructed for field exploration.

General statistical data

Since geophysical field exploration is being conducted by using a complex of geophysical methods, the field crews are also composite in nature. The composition of geophysical crews for 6 to 8 months of field work per year, and annual expenditures for various types of investigations are listed in the accompanying table.

Type of Investigation	Expenditure in U.S. Dollars	Composition of Party
Reflection seismic	37,500	4 geophysicists 2 surveyors & 2 drillers 2 mechanics and helpers
Refraction seismic and Resistivity	17,500	4 geophysicists 3 surveyors & 1 driller 2 mechanics and helpers
Magnetic and Gravity	13,500	4 geophysicists 2 surveyors and helpers
Combined SF, Resistivity, Magnetic and EM	11,000	4 geophysicists 2 surveyors and helpers
(All for ground surveys only)		
Logging	650	1 geophysicist and one helper

Expenditure covers computation, interpretation and preparation of reports.

In 1966 the total work done in mining geophysics by the Geological Survey included 980 man-months of field work by 32 geophysical parties involving an expenditure of $400,000, and 40 man-months of research and development work at a cost of roughly $41,000.

Conclusions

The foregoing review of the activities in mining geophysics in India will provide an idea of the scope and magnitude of the operations in this field. As almost the entire work in mining geophysics in the country is being conducted under government auspices, the role of government in the further intensive and accelerated exploration for the rapid development of India's mineral resources need hardly be stressed. In mining geophysics the accent in the next few years will continue to be on nonferrous metals and groundwater. Under the Fourth Five Year Plan of the Geological Survey, the geophysical activities of the department are to be expanded considerably for the exploration of base metals, various nonmetallic minerals and groundwater, in addition to some investigations connected with engineering geology problems. Airborne magnetic, electromagnetic and scintillometer surveys for base metals and radioactive minerals, are to be undertaken on a systematic basis for the rapid coverage of large areas which seem promising. Such surveys have already been initiated by the Ministry of Mines and Metals with foreign collaboration in three specific areas, viz., eastern Cuddapah region of Andhra Pradesh where airborne surveys are now in progress, the Aravalli region of Rajasthan in western India and the Mica belt and Ranchi Plateau of Bihar in eastern India. Other areas have also been tentatively selected by the Geological Survey for combined airborne surveys for base metals and other minerals, which may be done in part under foreign aid programs and eventually, on a systematic basis, by the Geological Survey, which is actively considering the setting up of an airborne geophysical unit within the Survey. This will naturally involve a further considerable increase in the staff of the Geophysics Division. Commensurate with the field activities, experimental and instrumentation research will also be strengthened and expanded further.

Acknowledgments

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