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GRAVITY METHOD APPLIED TO BASE METAL EXPLORATION*

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Abstract

During the past decade there have been a number of significant advances in the field of gravity investigations. One important step has been the adoption of a worldwide absolute gravity standard at the 1971 General Assembly of the International Union of Geodesy and Geophysics in Moscow. The reference system, known as the International Gravity Standardization Net 1971, has greatly facilitated the collection and compilation of gravity data on a uniform worldwide basis and hence gravity-based studies of global geological features.

Improvements to gravity instrumentation include the transportable absolute gravity apparatus and the development of the microgravimeter. The absolute apparatus, in particular, has permitted much greater flexibility in establishing and maintaining gravity standards and the possibility of studying secular changes in gravity. The microgravimeter is a highly sensitive version of the standard spring gravimeter capable of measuring changes in gravity of the order of parts in a billion. This improved instrumentation with its attendant increased precision has already proved useful for the detection of chrome nodules in Colombia.

The computer has brought a number of benefits to gravity studies. Perhaps the principal among these stems from its power as a device to store, retrieve and display gravity data. In Canada the ease and convenience with which data can be retrieved has been one of the main factors leading to an increased and more effective use of the gravity method. The process of gravity interpretation has also been greatly facilitated through the use of the computer. As a result it is now possible to derive complex geological models to satisfy any given gravity anomaly by a computer-automated iterative process. This advance has led to the development of statistical and other analytical procedures which place realistic limits on the models.

Gravimetrists are more and more constraining their interpretations within the context of dynamic models, particularly plate tectonic models. Thus modern plate tectonic processes are being used as analogues of paleotectonic developments in the Canadian Shield, which, coupled with geochemical survey data, may result in a better insight into the distribution of minerals within a given structural province. Such studies are becoming increasingly multidisciplinary, an approach that is necessary for the most effective use of gravity data. Thus gravity has played a significant role in the development of statistical methods for base metal exploration by both government and university laboratories. The relationship between gravity anomalies and copper porphyry deposits in British Columbia and sulphide bodies in the Northwest Territories and Yukon Territory, and nickel deposits in Manitoba illustrate some more direct applications of the gravity method to base metal exploration.

Résumé

Il y a eu, au cours des dix dernières années, des progrès importants réalisés dans le domaine des recherches sur la gravité. Une étape majeure a été l'adoption d'une norme mondiale de gravité absolue à l'assemblée générale de 1971 de l'Union de géodésie et de géophysique internationale, tenue à Moscou. Le système de référence, connu sous le nom de Réseau international de normalisation gravimétrique de 1971, a grandement facilité la cueillette et la compilation de données gravimétriques de façon uniforme à l'échelle mondiale, de même que la réalisation d'études gravimétriques de l'ensemble des particularités géologiques.

Les améliorations apportées aux instruments de mesures gravimétriques concernent, notamment le dispositif portatif de gravité absolue et la mise au point du microgravimètre. L'appareil de mesure absolue a permis, en particulier, une plus grande flexibilité dans l'élaboration et le maintien de normes gravimétriques, ainsi que la possibilité d'étudier des variations séculaires de la gravité. Le microgravimètre est une version très sensible du gravimètre classique à ressort qui peut mesurer des variations de la gravité de l'ordre du milliardième. Ce dispositif amélioré, d'une précision accrue, s'est déjà révélé utile dans la détection de nodules de chrome en Colombie.

L'ordinateur a également contribué à améliorer la qualité des études gravimétriques. Son principal avantage, parmi tant d'autres, est peut-être de pouvoir stocker, rechercher et afficher les données gravimétriques. Au Canada, la facilité et la commodité avec lesquelles les données peuvent être obtenues ont été parmi les principaux facteurs qui ont conduit à l'utilisation accrue

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et plus efficace des méthodes gravimétriques. L'analyse des données gravimétriques a aussi été grandement facilitée par l'utilisation de l'ordinateur, avec pour résultat qu'il est aujourd'hui possible de puiser dans des modèles géologiques complexes pour expliquer toute anomalie gravimétrique donnée au moyen d'un procédé interactif automatisé. Ce progrès a conduit à la mise au point de procédés statistiques et analytiques qui délimitent de façon réaliste les modèles.

Les experts en gravimétrie limitent de plus en plus leurs interprétations au contexte des modèles dynamiques, principalement ceux de la tectonique des plaques. Etant donné que les analyses modernes de la technique des plaques sont utilisées comme des facteurs analogue à des formations paléotectoniques dans le Bouclier canadien, alliées à des données provenant de levés géochimiques, il peut en résulter un meilleur aperçu de la distribution des minéraux dans une province structurale donnée. De telles études sont en train de revêtir un caractère des plus multidisciplinaires, ce qui constitue une approche nécessaire à l'utilisation plus efficace des données gravimétriques. C'est ainsi que la gravité a joué un rôle important dans la mise au point, par les laboratoires universitaires et gouvernementaux, de méthodes statistiques pour l'exploration des métaux communs. La relation entre les anomalies gravimétriques et les gisements de cuivre porphyrique en Colombie-Britannique, les inclusions de sulfure dans les Territoires du Nord-Ouest et le Yukon et les gisements de nickel au Manitoba illustrent quelques autres applications plus directes de la méthode gravimétrique à la recherche des métaux communs.

INTRODUCTION

As the government agency responsible for operating the Gravity Service of Canada, the Gravity and Geodynamics Division of the Earth Physics Branch is not directly involved in exploration for base metals. The objectives of the Gravity Service are rather to ensure the availability of data and information describing the gravity field in Canada; to provide a uniform reference standard for gravity measurements in Canada; to provide data and information on the structure and figure of the Canadian landmass from studies of gravity anomalies; to contribute to knowledge of the earth's evolutionary processes for the benefit of the resource development industry, earth scientists, standards laboratories and other government agencies; to participate in international gravity studies; and to provide scientific and technical advice and services to the public and private sectors.

In this paper we first review significant developments in the gravity method that have occurred within the last decade. Major advances have occurred in gravity standards and in instrumentation and the rapid development of computer technology has led to greatly improved methods of data base management, data reduction, and gravity interpretation. We next review progress over the last ten years in mapping the Canadian landmass. We then discuss the role that gravity has played in developing a hypothesis for the formation of the Canadian Shield by plate tectonic processes. According to this hypothesis the Shield is constructed of continental parts of ancient plates joined together at suture lines, the sites of ancient subduction. Such a model may be useful in predicting the occurrence of ordered metalliferous zones analogous to examples found in modern orogens forming above active subduction zones. We describe briefly two other indirect applications of the gravity method to base metal exploration involving a statistical approach. Finally, we briefly describe several recent examples of how the gravity method can contribute in more direct ways to base metal exploration.

RECENT ADVANCES IN GRAVITY INVESTIGATIONS

Gravity Standards

One of the most significant advances in gravity investigations in Canada within the past decade has been the conversion of the reference standard for relative gravity observations to the new world system of absolute gravity values adopted by the International Union of Geodesy and Geophysics (McConnell and Tanner, 1974) which replaces the Potsdam Gravity System. The new system, known as the International Gravity Standardization Net 1971 (IGSN71) consists of 1854 stations around the world (Morelli et al., 1974). The datum for IGSN71 is provided by absolute measurements, the scale is controlled by both absolute and pendulum measurements, and the internal structure is provided by some 24 000 gravimeter observations.

In Canada all gravity measurements made by the Gravity Service are tied to the National Gravity Net (Fig. 8.1), which comprises approximately 3400 control stations having an absolute accuracy of ±0.1 mgal, and a relative accuracy of ±0.05 mgal (McConnell and Tanner, 1974). Most of the control stations have been established with LaCoste and Romberg gravimeters, although a limited number of older connections were made with Worden and North American gravimeters. The network is tied to the 20 stations of IGSN71 that are spread throughout Canada and provide datum and scale for the adjustment of the Canadian net to the new absolute standard. The Geodetic Reference System 1967 has also been adopted in Canada to replace the International Ellipsoid of 1930 as the reference surface for the computation of theoretical gravity.

Not only geophysics but also geodesy and metrology require accurate values of gravity over the earth's surface. The new homogeneous worldwide reference system permits standardization of gravity measurements on land and at sea with obvious benefits to national and international studies. The new system also gives datum and scale with an accuracy compatible with modern instrumental capability (Morelli et al., 1974).

Gravity Instrumentation

Concomitant with the improvement in gravity standards have been major improvements in gravity instrumentation. A decade ago the first generation of absolute gravity equipment was successfully developed in standards laboratories at several locales around the world. These instruments were generally not transportable and were capable of measuring gravity to about ±0.1 mgal. Since that time several types of transportable apparatus have been developed and tested. One of these, the so-called French-Italian apparatus (Sakuma, 1971) is currently operational and a series of measurements is either in progress or planned. Another has been developed in the United States and it is planned to have it operational some time in 1978. In addition to their transportability, the current generation of instruments have an accuracy that is improved by almost an order of magnitude (±0.02 mgal).

Aside from engineering or technical improvements in the design and construction of the components, the principle of operation is standard. An object (usually a corner cube) is either tossed and allowed to travel an up-and-down path or dropped and the time and distance it travels over a particular path are carefully measured. The distance is usually measured by laser interferometer. Any measurement at a location comprises a number of tosses or drops, usually about one hundred, with the time for a complete set of measurements being about 5 days including setting-up and breaking down.

The French-Italian transportable gravity apparatus shown in Figure 8.2 was brought to Canada recently to make a measurement at the national gravity reference site in Ottawa. It is a tossed-object type apparatus designed to provide an absolute gravity measurement according to the formula

$$S = 1/2gt^2$$

where S is the distance between the apex of the trajectory and some reference point and

t is the duration of the trajectory

The distance is measured by a Michelson interferometer in which the interference fringes of a laser beam reflecting upon a corner cube are counted digitally. Time is measured by a high stability digital clock. Both the launching chamber and the interferometer are mounted on damping devices to ensure the corner cube and the laser beam operate as closely as possible in the same reference frame. At unusually noisy sites the apparatus is designed so that the damping units may be controlled by a long period vertical seismometer.

The theory and operation of the various types of absolute apparatus have been well described. For a full discussion of error bounds and corrections the reader is referred to Preston-Thomas et al. (1960), Cook (1965), Faller (1965), and Sakuma (1971).

As dramatic as have been the improvements in absolute gravity measurements, they have not kept pace with developments in gravimeters. Perhaps the single most important development of practical significance to the mining industry is the so-called microgravimeter. This instrument is capable, under ideal conditions, of detecting changes in gravity of ±0.002 mgal. Like most spring-type gravimeters, the performance of the microgravimeter is largely governed by the degree of exposure to external

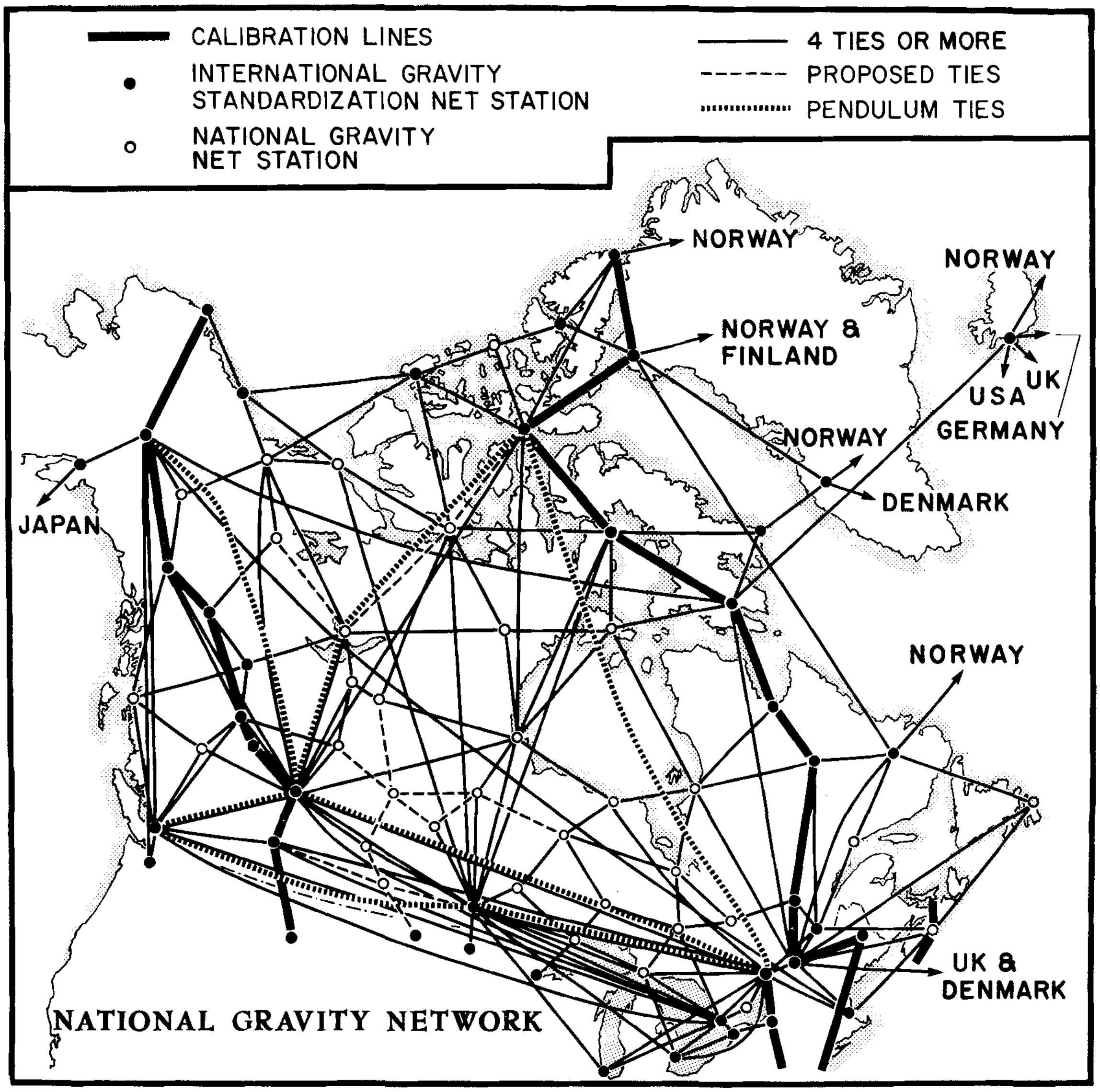

Figure 8.1. The principal control stations of the National Gravity Net, Canada. (After Gibb and Thomas, 1977a; reproduced by permission of Earth Physics Branch.)

sources of vibration during transport. Figure 8.3 shows typical results that might be expected under various transportation modes with the LaCoste and Romberg microgravimeter. Improvements in this performance, in rougher transportation modes, probably can be realized by better designed carrying devices.

Figure 8.4 shows a typical example of the way in which the observations must be carried out if the best results are to be obtained. Theoretically, an ideal network should be established in which every site is connected to every other site, but in practice it is usually sufficient to connect each to three or four other sites. When operating at the limits of accuracy of these instruments it is also usual to observe each leg in the network at least four times. Networks such as that shown in Figure 8.4 are adjusted rigorously by least squares to produce the final gravity values.

Examples of the application of the microgravimeter are comparatively few in the literature. From the standpoint of the mining industry, however, it seems apparent that the microgravimeter would be useful in obtaining accurate estimates of ore tonnages and perhaps in studying the details of the shape of an orebody. The latter application would clearly depend on drillhole information and good density sampling. One example of the use of highly precise gravity measurements in mining has been drawn to our attention by T. Feininger, Escuela Politecnica Nacional, Quito (pers. comm.). In Colombia, chrome nodules occurring in glacial tills have in the past been located by trial and error drilling. Recently, however, the company has adopted the practice of conducting microgravity surveys over the tills and digging for the chrome under the gravity "highs". This method has proved highly successful and consequently has replaced the more cumbersome hit-and-miss approach of drilling.

Another exciting development underway in the field of gravity instrumentation is the airborne vertical gradiometer. Thus far only bench models exist (Heller, 1977; Metzger and Jircitano, 1977; Trageser, 1977) but those engaged in research in this field seem confident that an operational airborne gradiometer accurate to between one and ten Eötvös units is conceivable within the next decade given adequate support. To understand the degree of precision involved, one Eötvös unit, equal to 10^{-9} gal/cm, is equivalent to the pressure exerted by part of the leg of a mosquito on a man's spine, as

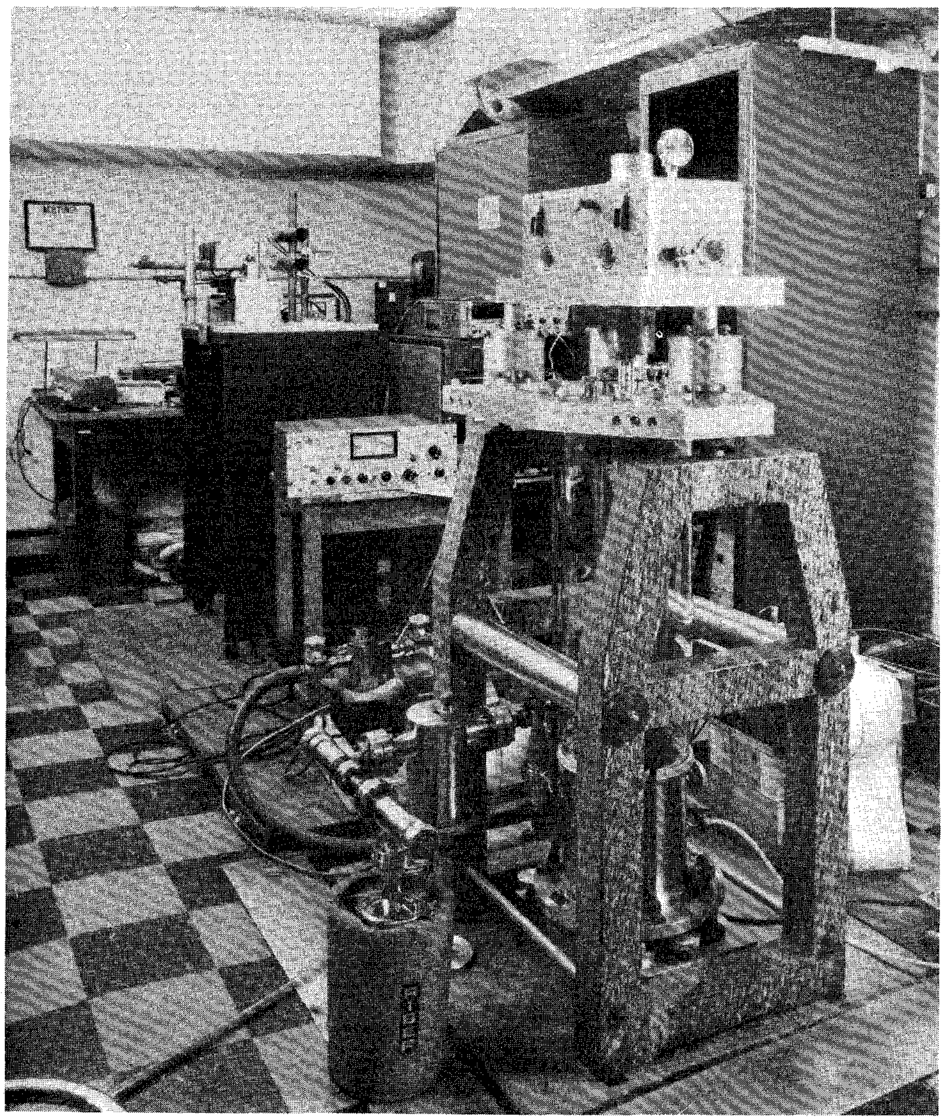

Figure 8.2. *The French-Italian transportable gravity apparatus. (GSC 203492)*

it alights on his shoulder. Any successful development of an airborne gravity gradiometer will have an immediate application to the mining industry because of its potential for rapid, efficient and highly accurate geophysical prospecting surveys.

Computer Technology

Data Base Management

Although employed initially as a data reduction tool in Canada (Tanner and Buck, 1964), the rapid development of the computer soon led to its use for the storage and retrieval of gravity data (Buck and Tanner, 1972; McConnell, 1977). Gravity and related data collected by the Earth Physics Branch are stored in a National Gravity Data Base which presently contains over 300 000 gravity records. Significant contributions to the data base have been made by various government agencies, universities, and mineral and petroleum companies. A notable contribution of 51 000 dynamic gravimeter observations has been made by the Atlantic Geoscience Centre, Dartmouth – a division of the Geological Survey of Canada. The National Gravity Data Base consists of five files (Fig. 8.5), two of which (Instrument Data and Control Station Data) reside on random access devices and are directly accessible by applications software systems (Fig. 8.6) (McConnell, 1977). The two remaining digital files (Anomaly Data and Network Observation Data) due to their large size reside in binary form on magnetic tape. Applications software programs which require data from these files must first search the file sequentially and prepare a subfile upon which subsequent operations are performed. The Control Station Description File is maintained in the form of hard copy reproduced by photo offset or Xerox printing.

Information may be retrieved from the data base in several formats – listings, punched cards, magnetic tapes, and plots depending on the customer's preference. Plots are available at any specified scale and a variety of map projections. Customers who use this service include exploration companies and consultants to the petroleum and mineral industry, provincial and federal agencies responsible for mapping and resource inventories, research geophysicists, geodesists and geologists, and the international scientific community.

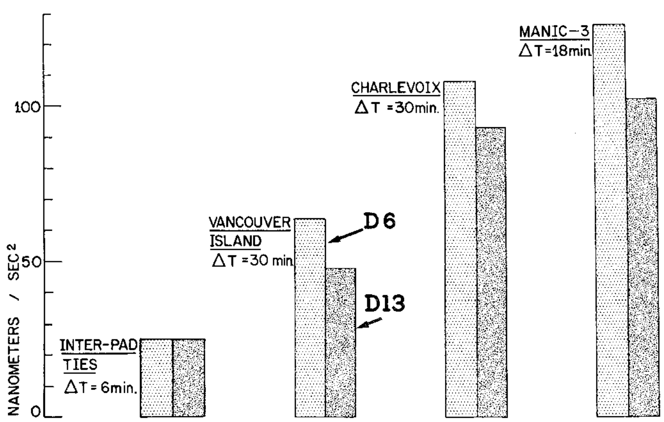

Figure 8.3. *Variability of standard deviation of gravity ties for LaCoste and Romberg microgravimeters D6 and D13 due to different modes of transportation as follows: inter-pad ties, hand carried; Vancouver Island, vehicle on paved roads; Charlevoix, vehicle on paved and unpaved roads; Manic -3, helicopter. The major cause of the variation is exposure to different degrees of vibration. ΔT denotes the average time interval for a gravity tie. (After Lambert et al., 1977; reproduced by permission of Earth Physics Branch.)*

The Gravity Service publishes the results of its surveys in a series of maps, generally at a scale of 1:500 000, known as the Gravity Map Series. These are usually accompanied by a report describing the gravity surveys, the gravity anomalies, and their correlation with geology. Data are also released through the open file system of the Earth Physics Branch.

Data Reduction

Although procedures to observe and reduce gravity data have remained comparatively standard for the most part, the increasingly widespread use of the computer and its greatly enlarged capacity and computing power have led to some significant changes in the reduction of gravity observations in the past ten years. Perhaps the most important change has been the gradual trend away from the simple but rigid concept of a twofold system of gravity surveys (viz. the establishment of a permanent system of control stations from which gravity traverses can be run to provide the more detailed coverage needed for a particular investigation) to a more flexible system better suited to the improved performance of modern gravimeters. The mathematical model for the reduction of observations made in such a fashion is necessarily more complex, often involving a least squares process, but easily within the capacity of present day computers. Side benefits include the capability to process the data in a single pass (if desired) and the availability of much more statistical information from which the results of a survey can be evaluated. Nowhere is this trend more in evidence than for marine gravimetry where the volume of data is enormous, the quality of the individual observations distinctly lower than for land data and port ties few and often far between. Given that properly evaluated data sets are a major goal of any gravity survey, a flexible technique capable of giving reproducible results is needed to provide an unbiased adjustment of the data and at the same time provide reliable

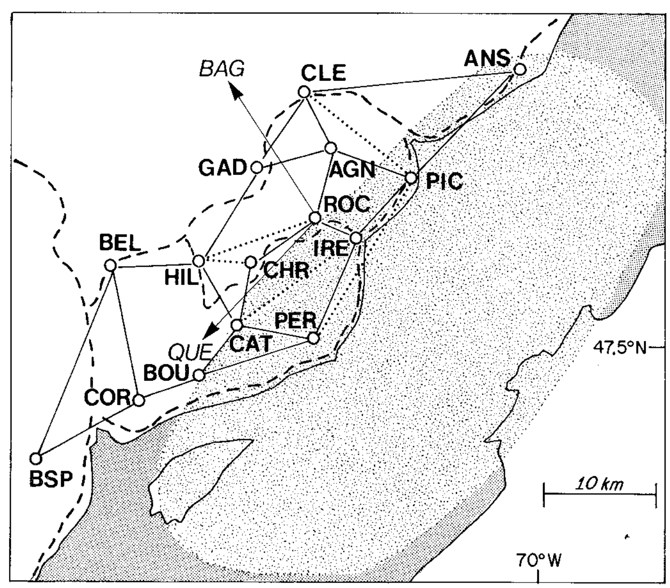

Figure 8.4. *Precise gravity network (solid and dotted lines) and first order levels (dashed lines) at Charlevoix, Quebec. Shading denotes area of seismic activity. Each connection in the gravity network comprises an average of eight to ten gravity ties. Arrows are connections to airport gravity stations at Quebec City and Bagotville. (After Lambert et al., 1977; reproduced by permission of Earth Physics Branch.)*

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estimates of the quality of the observations. An appropriate observational technique in the case of marine gravimetry is the use of frequent crossovers of the cruise lines, ties to at least two different ports preferably at the extremes of the range of gravity and, if possible, the use of a signature line for the calibration of the dynamic gravimeter during the course of the marine survey. The resulting data set can be adjusted by least squares to obtain the most likely values of the crossover points which provide control for the concurrent or subsequent reduction of the intermediate points along the cruise lines. A heavy demand is placed on the software system to edit and compile the data for the least squares adjustment but the results are well worth the effort since the operator gets an immediate overview of the data set from the adjustment, can see immediately where to concentrate his efforts on improving it and gets a feel for the overall quality from the statistics of the adjustment. One example of such a software system is the ASSOB (Adjustment of Sea Surface Observations) system which has been developed at the Earth Physics Branch in Ottawa in response to a clearly indicated need for improved procedures to observe and reduce marine gravity data.

Clearly there is an analogue of the marine case on land where temporarily relocatable stations can be used as repeat points at specified times and locations during a traverse with the result that each traverse is linked to other traverses by an interconnected ad hoc network of repeated sites which plays the same role as crossovers in the case of marine observations. Provided that the data set is tied to primary reference stations for calibration control and an absolute gravity reference (at least in the case of regional surveys), there is no major need to develop an extensive network of control stations in the traditional sense. Modern gravimeters are easily adaptable to this mode of operation without any loss of quality and with the decided advantage that a unified, well understood data set can be produced with a minimum of time and effort on the part of the gravimetrist. If gravity surveys are being carried out to increase the density or upgrade the results of previous surveys more complex reduction models may be the only way of producing a comprehensible data set, other than adopting the somewhat unsatisfactory procedure of adjusting datum and scale arbitrarily to amalgamate the different data sets.

Gravity Interpretation

As with other aspects of the gravity method the computer has brought about many desirable improvements in the procedure of interpreting gravity data in terms of models of earth structure. These improvements stem mainly from the increased power and memory capacity of the computer which permits the use of more flexible, more complex, and more effective interpretation procedures. The end result has been a significant change in the standards for gravity interpretation. No longer is the objective simply to provide a gravity model that is consistent with the geological constraints and other geophysical data, but rather the question must involve a consideration of the tectonic setting and of the possible processes leading to the development of

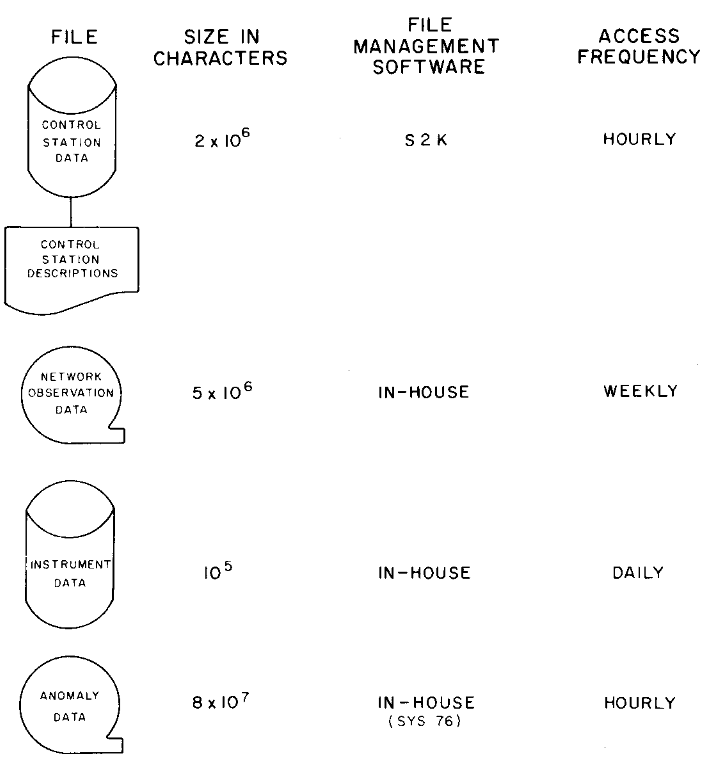

Figure 8.5. *The four digital files and one manuscript file that comprise the National Gravity Data Base. (Modified from McConnell, 1977; reproduced by permission of Earth Physics Branch.)*

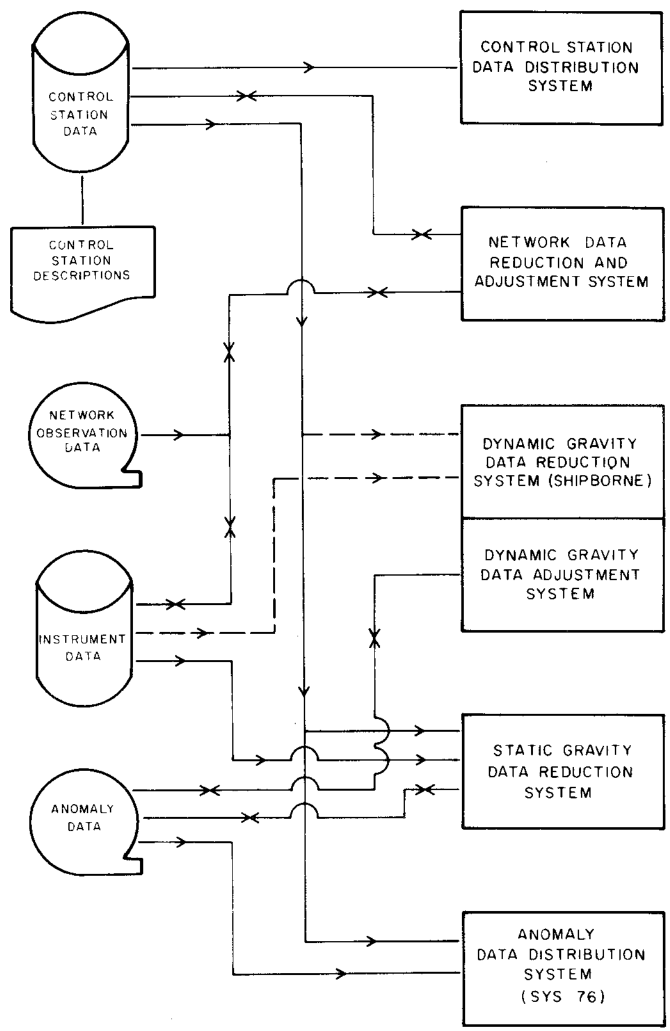

Figure 8.6. *Interaction between the National Gravity Data Base and its associated applications software. (Modified from McConnell, 1977; reproduced by permission of Earth Physics Branch.)*

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the structure, preferably in quantitative terms. It is also likely that statistical or analytical methods of evaluating the reasonableness of the assumptions made during the interpretation will soon become a standard part of gravity interpretations. Some progress in this direction has already been made. Thus Miller (1977) has tried to put statistical limits on the information that can be gained from gravity data and Parker (1977) has attempted to place limits on the possible density distribution that can cause a particular gravity anomaly in special cases. The latter is a particularly important aspect of gravity interpretation that needs pursuing because, while samples can be collected to provide estimates of the densities of various rock types exposed in a given region, the spread of results is all too often so great that an interpreter must make a subjective judgment on the density contrast. Efforts on the part of interpreters to seek improved methods of arriving at density contrasts or determining limits for them should be both encouraged and applauded.

Interpretation procedures themselves have been improved greatly by the computer with the result that a wide variety of methods to deduce models to satisfy a given gravity anomaly have been developed in the last decade. Several authors have recently reviewed the role of the computer in gravity interpretation procedures. The reader is referred to reviews by Grant (1972), Talwani (1973) and Nettleton (1976, chapters 6 to 8). An excellent summary of inverse methods i.e. numerical methods for determining density distributions directly from gravity anomalies has been given by Bott (1973). He has succinctly reviewed linear inverse methods in which the shape of the body is specified and the problem is to determine the density distribution (e.g. Bott, 1967; Kanasewich and Agarwal, 1970) and nonlinear inverse methods in which the density is known and the shape of the body is to be determined (e.g. Tanner, 1967; Cordell and Henderson, 1968; Al-Chalabi, 1970; 1972). Recent papers on inverse methods include those by Parker (1972), Oldenburg (1974) and Lee (1977).

STATUS OF CANADA'S REGIONAL GRAVITY MAPPING PROGRAM

Canada has an area of almost 10 million square kilometres; the adjacent shelf seas cover an additional 3.8 million square kilometres. Within this vast region considerable variations in climate (semiarid to Arctic), in terrain (ancient peneplains to Cordilleran peaks), in vegetation (dense bush to treeless barren lands), and in the means of communication (roads restricted to the southern populated regions), have necessitated a variety of approaches to the gathering of gravity data, both in regard to transportation and to instrumentation. Four main categories of gravity surveys are conducted by the Gravity Service: land surveys; ice-surface surveys; underwater surveys; and sea-surface surveys. The planned coverage by each type of survey is indicated in Figure 8.7. The progress to January, 1977 in surveying these regions is also indicated (the 500 m bathymetric contour is a purely arbitrary limit in Figure 8.7 as many surveys have gone and will continue to go beyond this limit). Approximately 80 per cent of the country has been covered by 183 000 discrete (static gravimeter) stations and 134 000 shipborne (dynamic gravimeter) stations as shown schematically in Figure 8.8.

The first gravity measurement in Canada was made at Winter Harbour, Melville Island in 1820 (Sabine, 1821) during a voyage in search of the Northwest passage. Truly systematic surveys, however, did not commence until 1944 when the gravity meter supplanted the pendulum for routine work. Figure 8.9 is a histogram showing the number of gravity stations established per year from 1945 to 1977 by the Gravity Service. The introduction of helicopters in the early 1960s resulted in a sevenfold increase in annual gravity station production. This increase coincided fortunately with the advent of electronic computers and the Gravity Service rapidly adopted computer methods for gravity data processing (Tanner and Buck, 1964). Perhaps the most significant change in recent years is the increase in systematic sea-surface gravity surveys undertaken by the Gravity Service (Fig. 8.9).

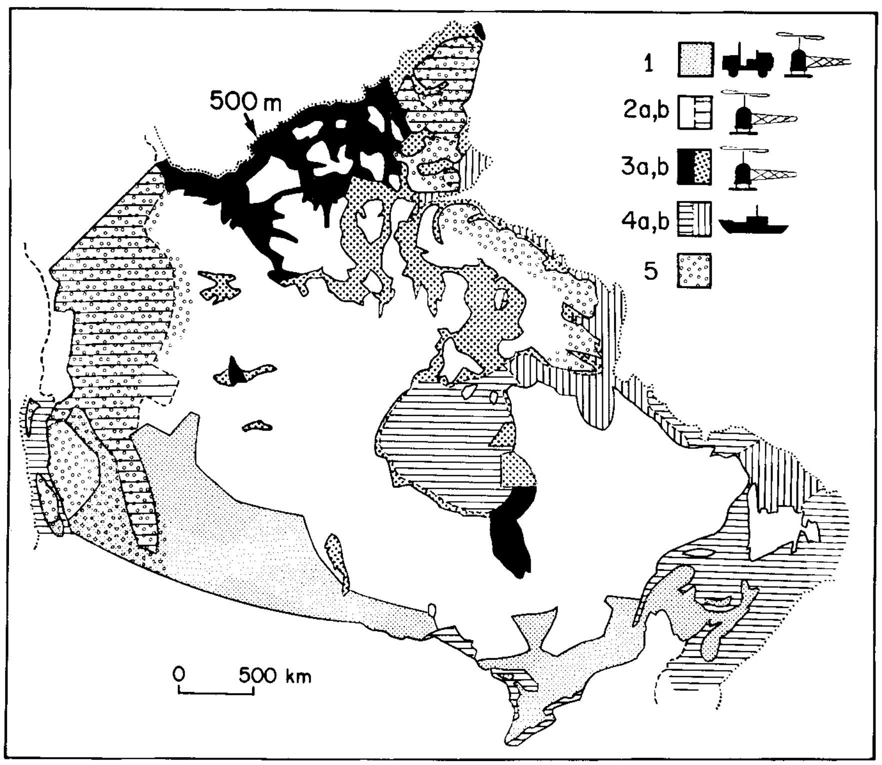

Figure 8.7

Gravity coverage in Canada according to type of survey (to January, 1978). Surveyed and unsurveyed areas beyond the 500 m bathymetric contour are not shown. The distribution of data in oceanic areas is shown in Figure 8.8.

1 - road covered area, 100% surveyed;
2a - hinterland area, 84% surveyed;
2b - unsurveyed area 1 315 000 km^2;
3a - ice-covered area, 35% surveyed;
3b - unsurveyed area 941 000 km^2;
4a - water-covered area, 75% surveyed;
4b - unsurveyed area 526 000 km^2;
5 - mountainous terrain
Total unsurveyed area 2 782 000 km^2.

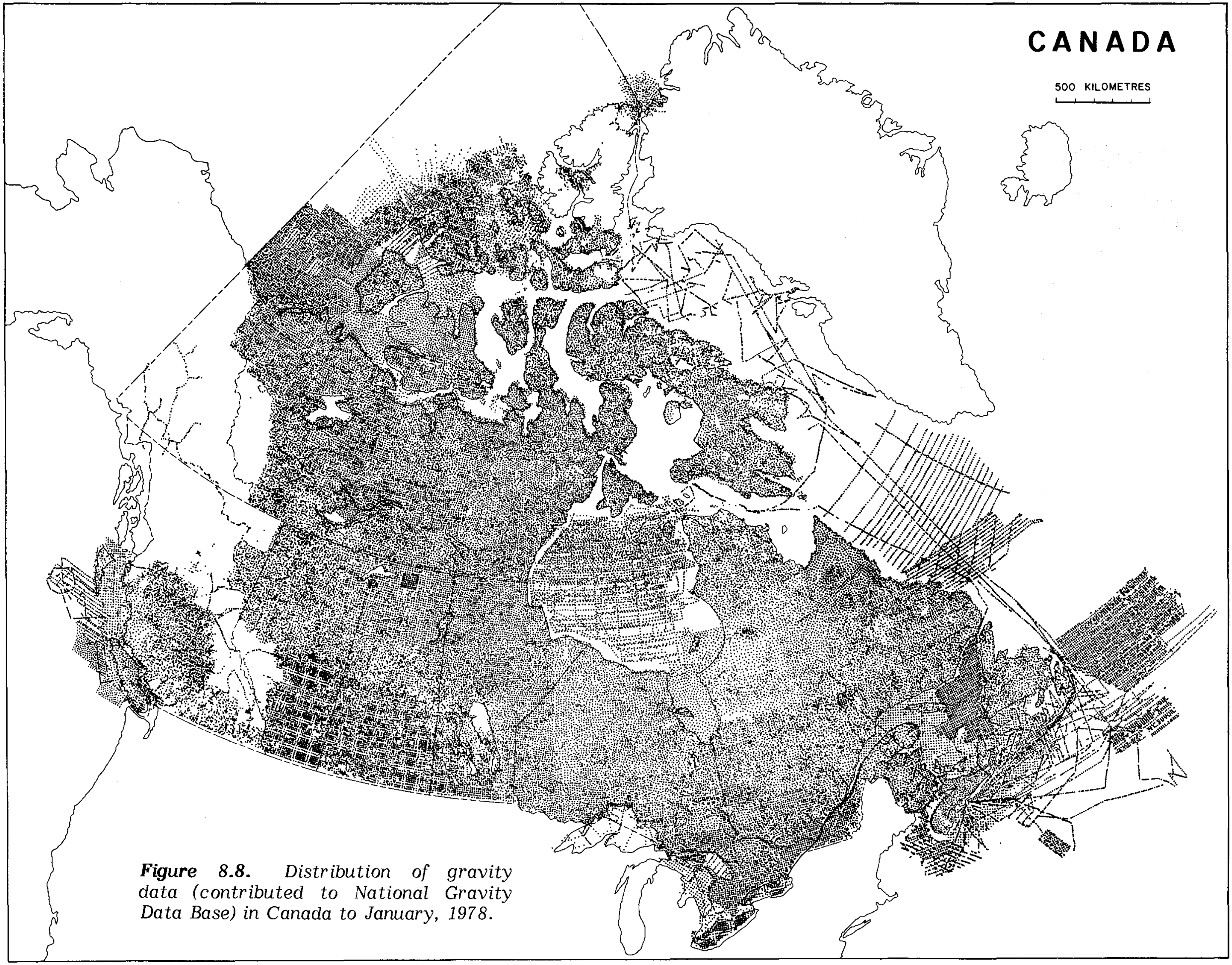

***Figure* 8.8.** *Distribution of gravity data (contributed to National Gravity Data Base) in Canada to January, 1978.*

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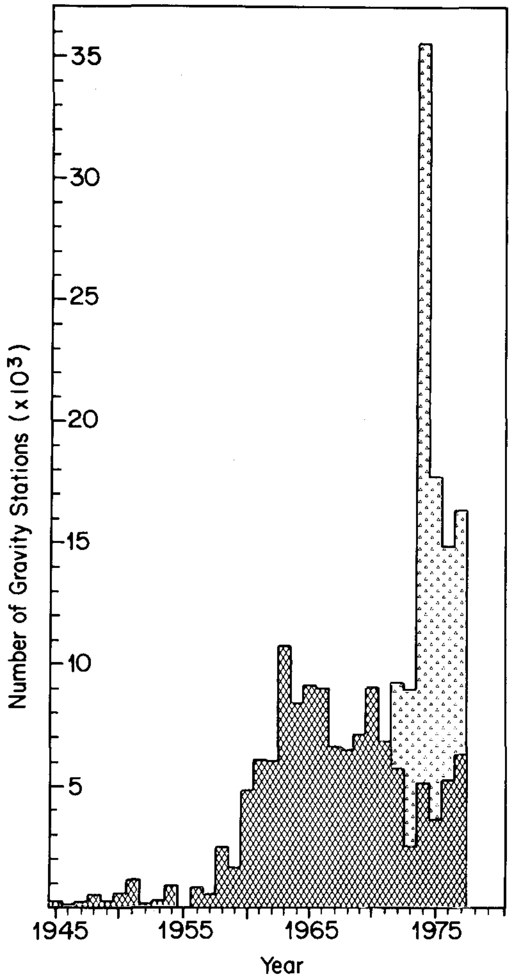


Figure 8.9. *Histogram of number of static (dark shading) and dynamic (light shading) gravity stations per year measured by the Gravity Service, Earth Physics Branch for the period 1945 to 1977.*

This trend is likely to continue for several years. Figure 8.10 shows the cumulative total number of stations obtained by the Service (graph a) and from all sources (graph b) for the same period 1945-1977. The data are graphically illustrated by the most recent edition of the Bouguer Gravity Map of Canada (Plate 2, p. xiii). The methods used to prepare the map have been described by Nagy (1977).

The remaining unsurveyed areas of Canada have a common requirement for nonroutine survey techniques due to difficulties of terrain or other hostile environments. On land the main unsurveyed areas are the western Cordillera of British Columbia and the Yukon, and the mountainous northern Arctic Islands. There progress will depend largely on the availability of monumented stations with known elevations and sufficiently detailed topographic maps. At sea the remaining areas include parts of the Atlantic and Pacific continental shelves, and parts of Hudson Bay, Hudson Strait, Davis Strait and Baffin Bay. Ice-covered regions include the Canadian sector of the Arctic Ocean, the inter-island channels of the Arctic Islands, Foxe Basin, and some of the large inland lakes. The sea and ice surveys are usually undertaken as co-operative efforts with other mapping agencies such as the Canadian Hydrographic Service, the Polar Continental Shelf Project, and the Geological Survey of Canada. The rate of progress will therefore depend not only on the availability of ships and navigation aids but also on the

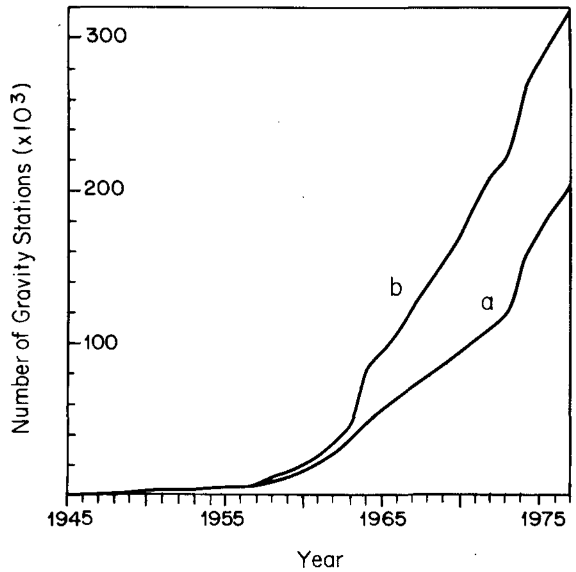


Figure 8.10. *Cumulative total gravity stations contributed to the National Gravity Data Base from all sources for the period of 1945 to 1977 by the Gravity Service (graph a), all sources (graph b).*

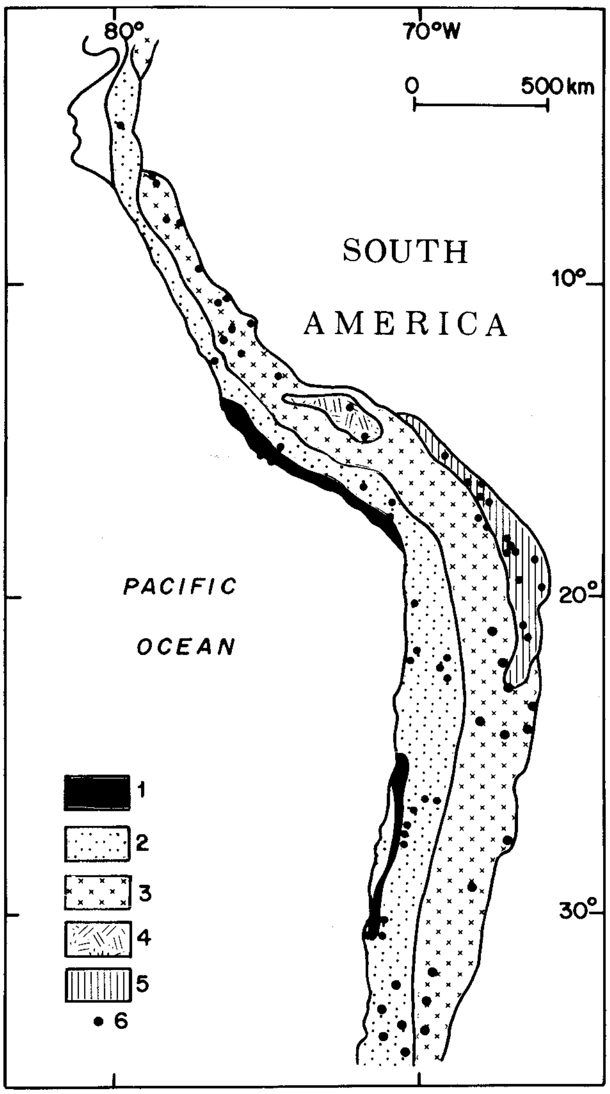
concerns, priorities and continued co-operation of these agencies. At the present rate of coverage the reconnaissance gravity mapping program is likely to continue for 15 to 20 years. In addition to the environmental constraints, the increased cost of navigation and transportation in the remaining areas compared to the rest of Canada will mean that the area mapped each year will decrease if operations are maintained at about the present level. Various aspects of the national gravity mapping program have been described in more detail by Gibb and Thomas (1977a) and McConnell (1977).

SOME APPLICATIONS OF THE GRAVITY METHOD TO BASE METAL EXPLORATION

Although the Gravity Service is not directly involved in exploration for base metals, gravity has played a role in developing a hypothesis for the formation of the Canadian Shield which may provide a regional framework for base metal exploration. We first discuss this hypothesis and other indirect applications of gravity to base metal exploration and we then describe several examples of more direct applications of the method.

Indirect Applications

The theory of plate tectonics has revolutionized concepts of ore genesis. There is growing agreement among economic geologists that there is a fundamental relationship between volcanic processes associated with midocean ridges and zones of subduction and the formation of certain types of ores. Recent studies have confirmed that large deposits of base metal sulphides are formed initially at or near midocean ridges. Such deposits may be recoverable directly from the ocean floors or from obducted sheets of ophiolites preserved (often in orogenic belts) on the continents. Most of these ores, however, appear to have undergone further alteration and concentration in volcanic processes associated with partial melting of oceanic lithosphere subducted beneath island arcs or continental margins. The ore minerals and magmas thus generated rise through the crust and appear to be spatially and temporally related to the subduction zone and its evolution e.g. the type of ore and the composition of magma vary with distance from the trench. Mitchell (1976) has examined the relationship between magma composition and tectonic setting in Cenozoic subduction zones. He showed that characteristic mineral deposits are related to different magmas in different tectonic settings. Such a pattern of mineral occurrences has been described in the Andes (Sillitoe, 1976). From west to east, major longitudinal mineral zones have been identified as follows: Fe, Cu-(Mo-Au), Cu-Pb-Zn-Ag, Cu-Fe and Sn-(W-Ag-Bi) (Fig. 8.11). According to Sillitoe (1976), magmatism and mineralization in the Fe and Cu belts migrated progressively eastwards from early Jurassic to mid-Tertiary time but about 15 Ma ago the Cu-Pb-Zn-Ag belt was formed by a sudden expansion of magmatism to the east.



1. *Fe belt;*
2. *Cu-(Mo-Au) belt;*
3. *Cu-Pb-Zn-Ag belt;*
4. *Cu-Fe belt;*
5. *Sn-(W-Ag-Bi) belt;*
6. *ore deposits.*

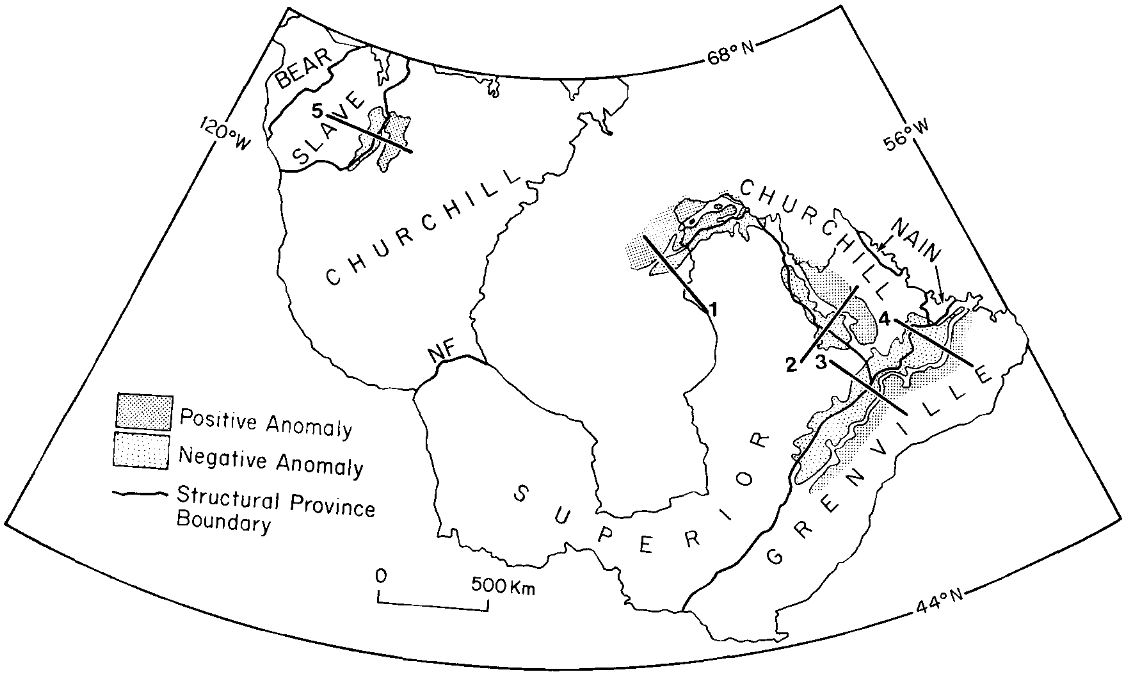
Figure 8.11. *Metallogenic belts of the Central Andes. (Redrawn after Sillitoe, 1976; reproduced by permission of Geological Association of Canada.)*

Mineral zonations related to paleosubduction zones have been recognized in the Mesozoic, Paleozoic, and even the Proterozoic (e.g. Mitchell, 1976). Recent studies by Gibb and Thomas (1976) have suggested that gravity signatures across structural province boundaries in the Canadian Shield may originate from essentially identical structures formed in response to plate tectonic processes operating during Proterozoic time. They have suggested that plate convergence, cratonic collision, and suturing have been instrumental in forming the Shield as we know it today. Three geosutures have so far been proposed, partly on the basis of gravity studies, at or near structural province boundaries. The suture peripheral to the Superior Province is the most easily recognized (Gibb and Walcott, 1971); it is 3200 km in length and extends from the Manitoba Nickel Belt (Nelson front), across the Hudson Bay Lowlands (Gibb, 1975), to eastern Hudson Bay and thence to the Cape Smith foldbelt (Thomas and Gibb, 1977), and Labrador Trough (Kearey, 1976). A second suture has been suggested within the Grenville Province near the Grenville front (Thomas and Tanner, 1975) which separates the Superior and Grenville provinces. This location based on gravity interpretation is but one of several other suggested locations within or bordering the Grenville Province based on paleomagnetic and geological evidence. A third suture has been postulated in the vicinity of the Thelon front, the boundary between the Slave and Churchill provinces in the Northwest Territories (Gibb and Halliday, 1974; Gibb and Thomas, 1977b).

Bouguer anomaly profiles numbered 1 to 5 across five structural province boundaries of the Shield (Fig. 8.12) are shown on a common datum in Figure 8.13a. Apart from short wavelength anomalies attributable to local geological features, all five profiles are very similar. The smoothed gravity signature, called the type anomaly by Gibb and Thomas (1976), was derived by averaging the profiles and is shown in Figure 8.13b within an envelope which varies according to the standard deviation calculated at intervals of 5 km along the profiles. A type crustal model derived from the gravity signature and constrained by seismic results, rock densities and geological information is shown in Figure 8.13c. The correspondence between the computed anomaly and the smoothed gravity signature is shown in Figure 8.13b. The crustal blocks are in approximate isostatic equilibrium.

The model indicates that the younger crustal block is consistently thicker and slightly denser than the older. This consistency is surprising because not only do the structures have a wide geographic distribution but they are also of vastly different ages, suggesting that similar processes have operated throughout much of the Proterozoic time. The density discontinuity of the type model penetrates the whole crust and separates cratons of different density, thickness, age, and internal structure; it was interpreted as a vestigial suture between collided continental blocks. The model with slight modifications to crustal density and thickness applies to all five boundary zones and may apply to other examples in Canada and elsewhere.

Paleosutures have been identified or proposed by several authors at other sites in the Canadian Shield. Talbot (1973), Goodwin and West (1974) and Langford and Morin (1976) among others have suggested that some form of primitive plate tectonic processes played a role in the formation of the Archean crust of the Superior province. Within the Churchill Province possible Proterozoic paleosutures have been recognized in the Fond du Lac area (Walcott and Boyd, 1971; Gibb and Halliday, 1974; Cavanaugh and Seyfert, 1977), in the Wollaston foldbelt (Weber in Donaldson et al., 1976; Camfield and Gough, 1977), in the Flin Flon area (Stauffer, 1974), and in the Foxe foldbelt of Melville Peninsula (Henderson in Donaldson et al., 1976).



1. Superior - Churchill boundary (offshore extension of Cape Smith foldbelt);
2. Superior - Churchill boundary (Labrador Trough);
3. Superior - Grenville boundary (Grenville front);
4. Churchill - Grenville boundary (Grenville front);
5. Slave-Churchill boundary (Thelon front).

Figure 8.12. *Bouguer gravity anomalies at five structural province boundaries in the Canadian Shield. Gravity profiles are shown in Figure 8.13a. NF-Nelson front. (After Gibb and Thomas, 1976; reproduced by permission of Macmillan Press).*

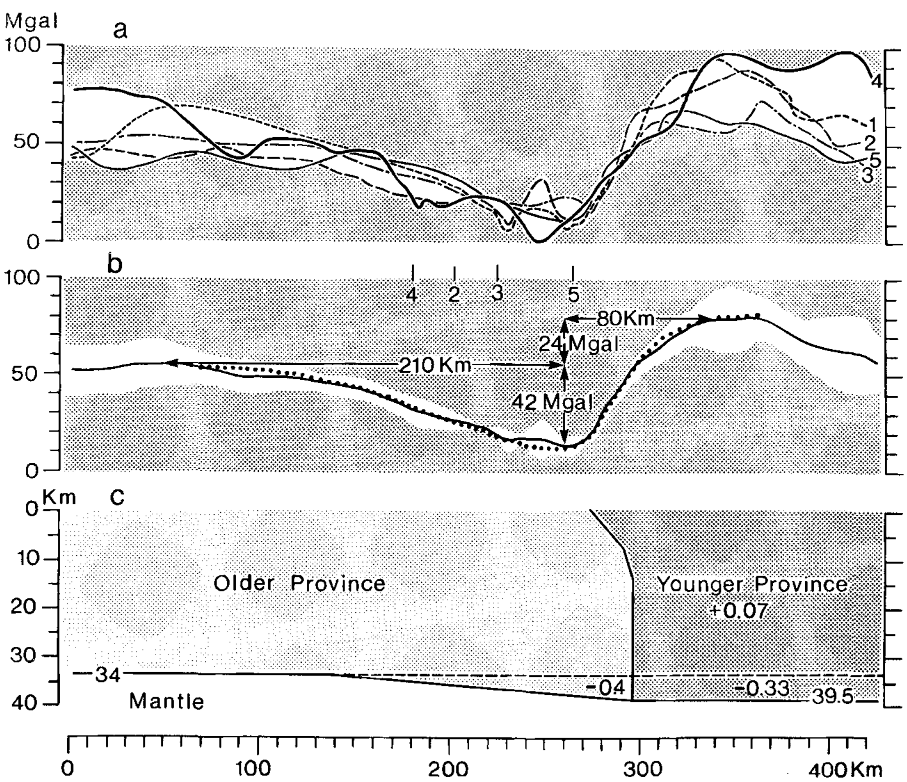
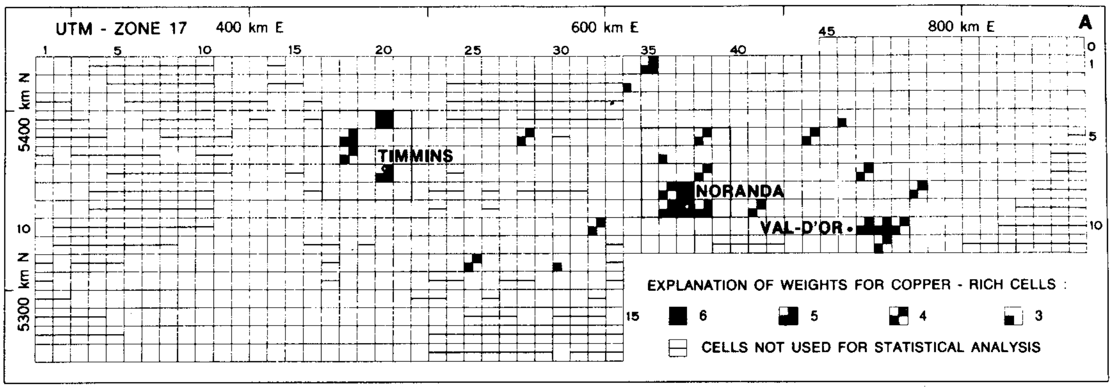


Figure 8.13

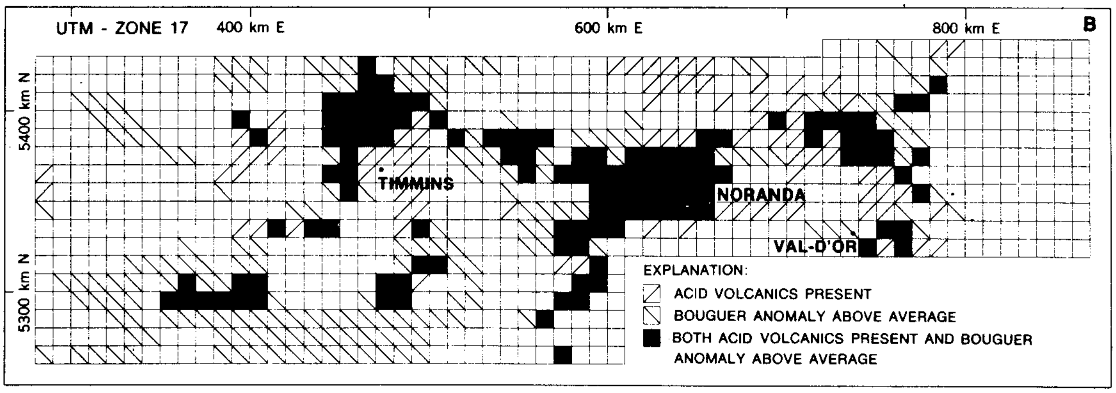
a *Bouguer gravity anomaly signatures along profiles 1 to 5 of Figure 8.12. Vertical lines numbered 2 to 5 show positions of corresponding inter-province boundaries.*

b *Gravity signature (type anomaly) derived by averaging profiles 1 to 5. Unshaded envelope is described by standard deviation calculated at 5 km intervals along profiles. Dotted curve is the gravity effect of type model shown in c.*

c *Type crustal structure derived from type anomaly. Density contrasts in g/cm^3; depths in km. (After Gibb and Thomas, 1976; reproduced by permission of Macmillan Press.)*



a Control cells for copper;



b Presence-absence data for variable 'acid volcanics present' and 'above average Bouguer anomaly' and their combination.

Figure 8.14. *(After Agterberg et al., 1972.)*

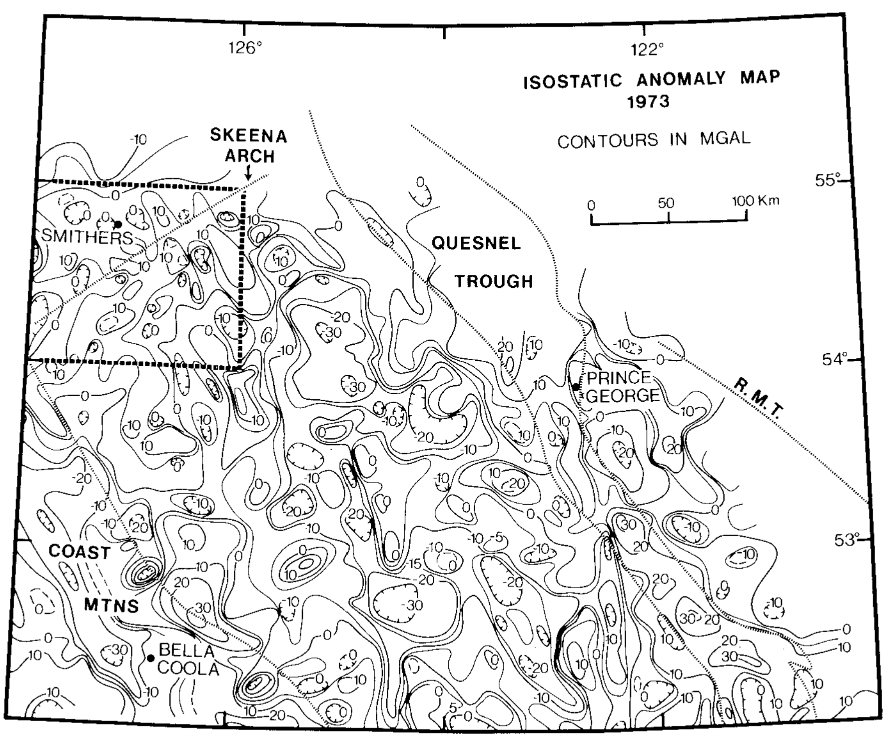


Figure 8.15

Airy-Heiskanen isostatic anomalies for T = 30 km and $\Delta\rho = 0.4\ g/cm^3$ and major geological units of the Parsnip River map sheet (N.T.S. 93). The Smithers-Houston region is outlined in the northwest part of the map. (After Stacey, 1976; reproduced by permission of Geological Association of Canada.)

Hoffman (1973), Sutton and Watson (1974) and Burke et al. (1977) have interpreted the Coronation orogen as a product of Andean-type orogeny or as a product of the Wilson cycle of ocean opening and closing. Van Schmus (1976) has interpreted rocks of the Southern Province involved in the Penokean Orogeny as products of processes similar to modern plate tectonics. Possible suture sites have also been proposed along or near the northern boundary of the Grenville Province (Vine and Hess, 1968; Krogh and Davis, 1971; Irving et al., 1972), along the buried southern boundary (Dewey and Burke, 1973; Baer, 1976) and within the Grenville Province (Chesworth, 1972; Brown et al., 1975). Identification of paleosutures in the Shield and their true polarity may prove to be a useful guide to the distribution of base metals. By analogy with modern examples, equivalent mineral zonations should occur in the hinterland of paleosutures in the Shield. On the assumption that erosion has exposed the deeper levels of large areas of the Shield, we would expect to find minerals formed at levels of the crust deeper than those of modern examples. Evidence that this may indeed be the case is forthcoming from recent geochemical studies in the Shield (Badham, 1976; Allan, 1978).

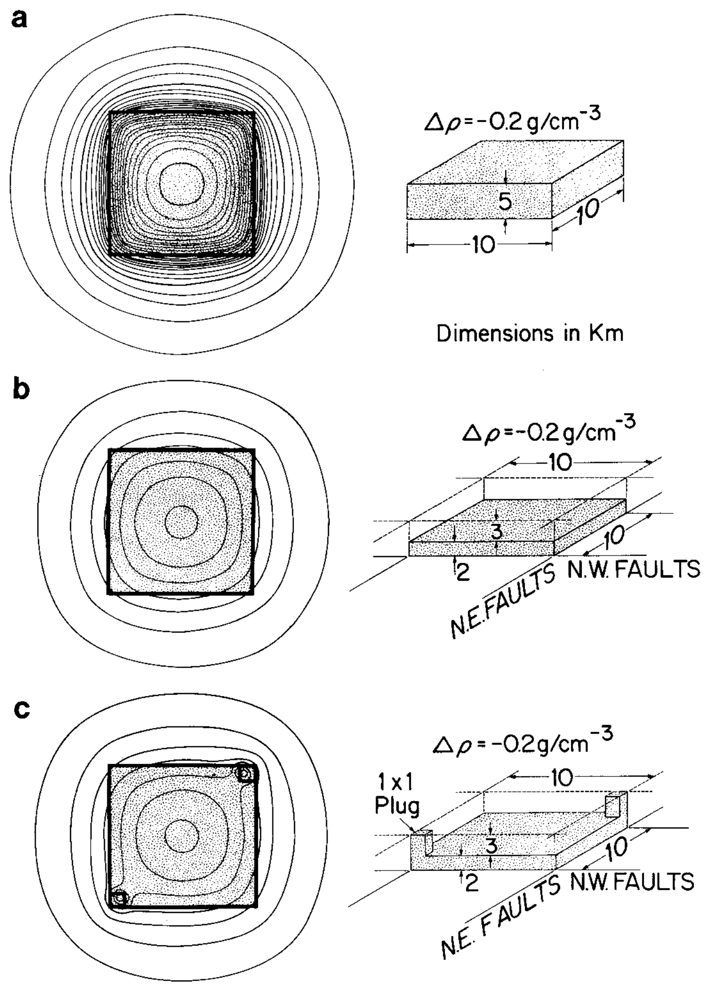
Agterberg et al. (1972) have also employed gravity in an indirect way to assist with the prediction of copper and zinc potential in a test area of the Abitibi belt in the Superior Province. This study provided the first quantitative estimates in terms of statistical probability made by the Geological Survey of Canada of the mineral potential of an area by analysis of certain geological and geophysical parameters. The test area was divided into cells for analysis and the average Bouguer anomaly value per cell was one of ten basic geological and geophysical variables used to express the probability of occurrence of mineral deposits. Bouguer values in each cell were averaged and mean values for cells with no gravity stations were computed by interpolation from surrounding cells. Associations of the basic variables were used to produce 45 new variables. It is of interest to note that for copper in Abitibi, the variable with the largest correlation coefficient was the combination of 'acid volcanic rocks present' and 'above average Bouguer anomaly' (Fig. 8.14). The calculated probability index was also converted to a tonnage of copper or zinc expected from a given region.

In a similar statistical study in the Abitibi area, Favini and Assad (1974) relied exclusively on variables derived from aeromagnetic and gravity maps to predict massive sulphide potential. The parameters used were 'average values' and 'logarithm of the variance', both over a four mile traverse interval, and 'gradient'. Stepwise discriminant analysis was used to derive discriminant functions which could best characterize the geophysical variables in a control area in relation to known sulphide potential. The derived probabilistic sulphide potential profile conformed reasonably well to the known profile emphasizing the usefulness of such methods in the exploration for massive sulphides.

Direct Applications

In British Columbia, Triassic and Cenozoic copper porphyry deposits are associated with granitic plutons ranging in size from large batholiths to small plugs. In the Smithers-Houston area (Fig. 8.15), Stacey (1976) has used the gravity method in a more direct way to formulate a predictive model for copper porphyry exploration. He noted a relationship between local negative gravity anomalies (of about 30 mgal amplitude) and exposed quartz monzonite plutons and suggested that similar but lower amplitude anomalies over the volcanics of the Skeena arch are related to similar but buried plutons. A typical exposed pluton has a diameter of about 10 km and a gravity anomaly of -30 mgal. The anomaly can be explained by a density difference of 0.2 g/cm^3 between quartz monzonite and surrounding quartz diorite and a body 10 km wide extending to a depth of 5 km.

Anomalies associated with the plutons tend to be elongated parallel to faults suggesting that their emplacement was fault-controlled. Figure 8.16a from Stacey (1976) shows the anomaly over a rectangular body similar to that in the Dean River Valley. Figure 8.16b shows the anomaly derived from a body at a depth of 3 km with a thickness of 2 km above a uniform granitic terrain and surrounded by volcanics 0.2 g/cm^3 denser. Figure 8.16c shows small stocks occurring preferentially at the intersection of faults bounding the larger intrusion. Stacey suggested



a quartz monzonite body similar to that exposed in the Dean River valley (amplitude of the gravity anomaly is -25 mgal);
b unexposed quartz monzonite body similar to those believed to lie below the Skeena arch (amplitude of the gravity anomaly is -7 mgal);
c unexposed body similar to the above with small stocks reaching the surface at fault plane intersections (amplitude of the gravity anomaly is -7 mgal).

Figure 8.16. *Computed gravity anomalies contoured at 1 mgal intervals. (After Stacey, 1976; reproduced by permission of Geological Association of Canada.)*

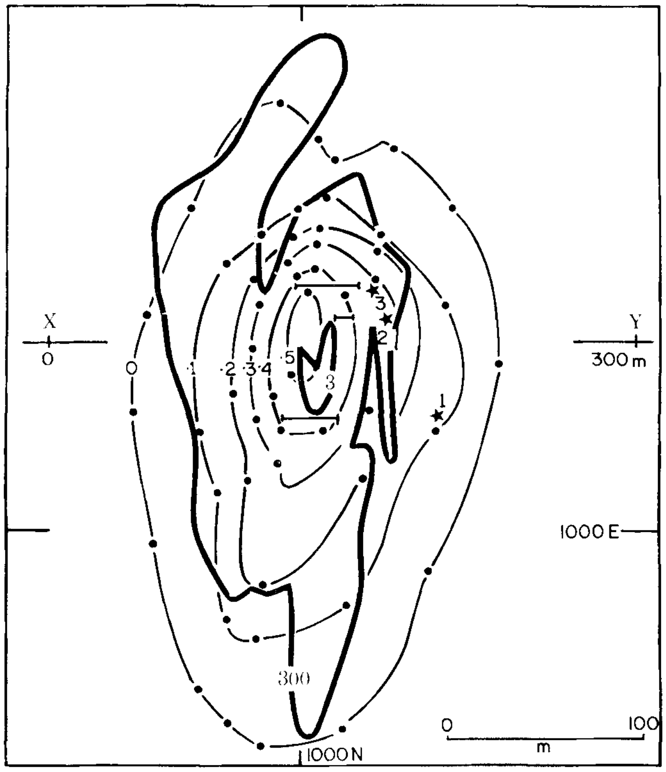


Figure 8.17. Residual gravity anomaly associated with the Agricola Lake geochemical anomaly Northwest Territories. Contour interval 0.1 mgal. Heavy lines represent VLF EM apparent resistivity contours from Scott, 1975. Stars indicate drillhole positions. Solid bars indicate plan views of sulphides as proved by drilling at that time. (After Boyd et al., 1975.)

that Cu mineralization associated with these small stocks came from the surrounding Mesozoic volcanics because the exposed monzonites such as the Dean River Valley example are barren. Using this model, gravity surveys in the vicinity of porphyry stocks can give an estimate of the thickness of overlying Mesozoic volcanics and detailed surveys at the intersection points of regional faults may lead to the discovery of new porphyry stocks in the region.

In a similar application of the gravity method Ager et al. (1973) derived a three-dimensional model of the Guichon Creek batholith from gravity data in British Columbia. They concluded that large low grade copper porphyry deposits of higher than average economic importance are spatially related to the surface projection of the core of the batholith and suggested that precise regional gravity studies could be used to delineate other low grade copper deposits related to batholiths.

In another recent direct application of the gravity method Boyd et al. (1975) mapped the gravity anomaly associated with a massive sulphide body in the Northwest Territories. The target was one of several located by follow-up studies (Cameron and Durham, 1974a,b) of a prominent Cu-Zn geochemical anomaly outlined by a regional lake sediment survey in 1972 (Allan et al., 1972). The body occurs in intermediate to acid volcanics of the Archean Beechey Lake sedimentary-volcanic belt. The target was selected as a test area for multidisciplinary study using a variety of geophysical and geochemical methods.

A Bouguer anomaly map of the area shows anomalies accurate to 0.1 mgal (Boyd et al., 1975) and the residual gravity high separated from the regional field corresponds in

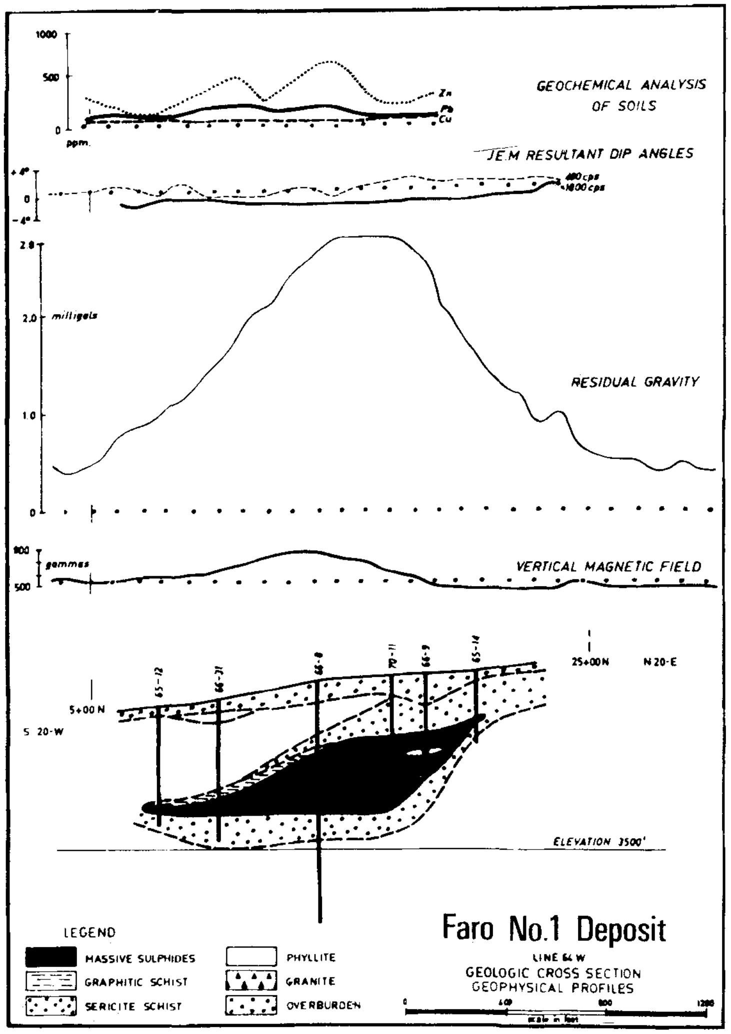


Figure 8.18. Geological cross-section of Faro deposit and geophysical profiles. (After Brock, 1973; reproduced by permission of Canadian Institute of Mining and Metallurgy.)

position with the prominent VLF Radiohm electrical resistivity anomaly over the mineralized zone (Scott, 1975) (Fig. 8.17). The residual anomaly is elliptical in plan and is 320 m by 180 m and has a peak amplitude of 0.5 mgal. The close association between gravity and resistivity anomalies taken together with other geophysical and geochemical survey results strongly suggested the presence of a sulphide body. A massive Zn-Cu-Pb-Ag-Au-bearing sulphide body was confirmed by drilling and further detailed gravity surveys by the YAVA syndicate (Cameron, 1977).

Gravity played an important role in the integrated airborne and ground geophysical exploration program that led to the discovery of the Faro Pb-Zn sulphide deposit of the Yukon Territory (Brock, 1973). Initially gravity was used to further define coincident magnetic and geochemical anomalies. It was later replaced as a primary tool by EM because of relatively high costs, immobility and ambiguity of interpretation. Gravity surveys were finally reserved for follow-up work following discovery of sulphide indications by rotary drilling and proved to be an excellent guide for subsequent diamond drilling programs. The Faro No. 1 deposit was best outlined by a gravity survey (Brock, 1973); a 2.8 mgal anomaly coincides with the thickest section of the

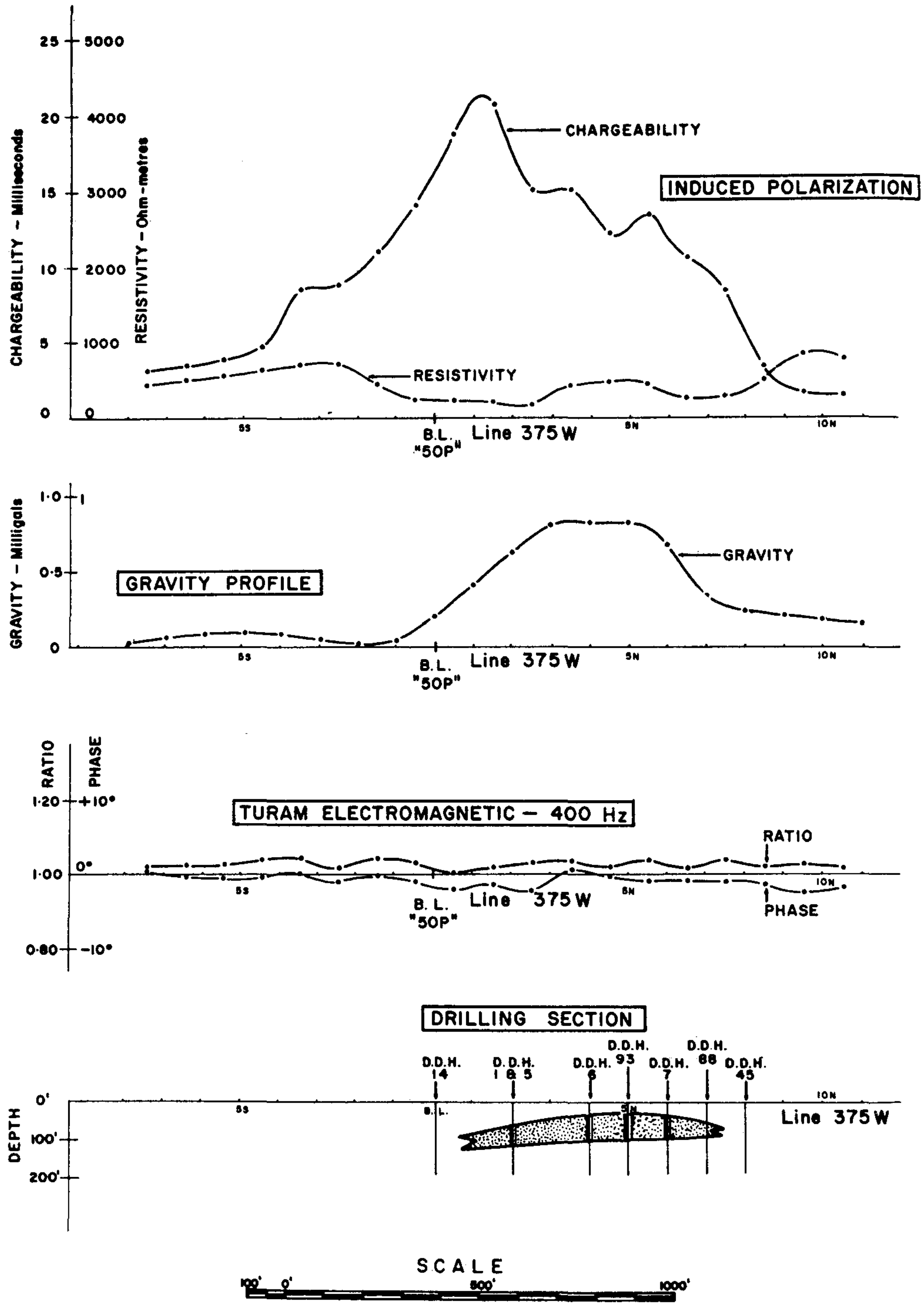


Figure 8.19. *Geological cross-section of Pyramid No. 1 orebody and geophysical profiles. (After Seigel et al., 1968; reproduced by permission of Geophysics.)*

No. 1 zone (Fig. 8.18). Preliminary calculations using the gravity results suggested a mass of 44 million tons. The surface area of the anomaly was later proven to contain about 46 million tons covering the No. 1 zone.

At Pine Point gravity was also used primarily to expedite development drilling after discovery of Pb-Zn orebodies by the induced polarization method (Seigel et al., 1968). The gravity anomalies showed an extremely good correlation with the distribution of Pb-Zn mineralization in the orebodies (Fig. 8.19) and permitted optimal selection of drillhole locations. The gravity results were also used successfully to estimate the total tonnage of the orebodies using the classical method (Hammer, 1945).

In Manitoba, the exposed portion of the Nickel Belt underlies a pronounced gravity minimum and orebodies lie scattered along its axis. This correlation, first noted by Innes (1960) was recently used by Roth (1975) to assist in determining the concealed southerly extension of the Nickel Belt although AFMAG, EM, IP and magnetic methods were the primary tools of investigation. Detailed gravity surveys were also used in this investigation to help outline serpentinite zones discovered by other methods. The correlation between nickel belts and linear regional negative gravity anomalies was also noted by Eckstrand (1976) who compared features of the Manitoba Nickel Belt and the Kotalahti Nickel Belt of Finland.

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