Ferrous, radioactive and other minerals

Contents

Geophysical methods of prospecting and prognostic valuation of iron deposits in the U.S.S.R.

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Abstract. Combinations of geophysical methods or techniques are used in exploration and evaluation of different types of deposits and in the description of geological and tectonic features related to iron deposits. These include aeromagnetic, gravimetric, electrical and seismic surveys.

Magnetic surveys are the principal methods used for prospecting for magnetite deposits in basic and ultrabasic rocks, gravity studies on these rocks are of a subsidiary character and electrical prospecting methods are mostly experimental in character. Combinations of magnetic and gravity surveys have proven to be most effective for exploring occurrences of ferruginous quartzite and for locating enriched ore bodies of hematite, martite and hydrohematite within beds of ferruginous quartzite. Prospecting with magnetic methods in combination with other techniques led to the discovery and evaluation of some of the largest iron ore areas in the U.S.S.R. such as Kursk Magnetic Anomaly and to new discoveries in a number of the established iron mining areas.

Electrical logging, vectorial magnetometry, magnetic susceptibility, radio wave sounding, radioactivity logging, gamma-gamma density, spectral relations, and neutron methods are used for logging boreholes.

Résumé. L'exploration et l'évaluation des différents types de gisements, ainsi que la description des caractéristiques géologiques et tectoniques propres aux gisements de fer, sont faites à l'aide des renseignements fournis par la combinaison des méthodes ou techniques géophysiques, à savoir, aéromagnétiques, gravimétriques, électriques et sismiques.

Les études magnétiques sont celles qui se pratiquent généralement dans la recherche des gisements de magnétite au sein des roches basiques et ultrabasiques, tandis que les études gravimétriques de ces roches ne présentent qu'un caractère auxiliaire et que les études électriques ne sont pratiquement qu'expérimentales. La combinaison des méthodes magnétiques et gravimétriques s'est avérée des plus efficaces pour la prospection des venues de quartzite ferrugineux et pour le traçage des dépôts enrichis d'hématite, de martite et d'hydrohématite dans les couches de quartzite ferrugineux. La prospection effectuée au moyen des méthodes magnétiques en combinaison avec d'autres techniques a permis de découvrir et d'évaluer quelques-unes des plus importantes zones ferrugineuses de l'U.R.S.S., comme l'anomalie magnétique de Kursk, et de nouveaux gisements dans un grand nombre de régions ferrifères bien connues déjà en exploitation.

Les techniques du carottage électrique, de la magnétométrie vectorielle, de la susceptibilité magnétique, du sondage par ondes radioélectriques, du carottage radioactif, de la densité gamma-gamma, des relations spectrales et de l'activation des neutrons sont mises en application pour l'étude diagraphique des forages.

All known genetic types of iron ores are found in the Soviet Union. The most important of them industrially are the following:

1. Deposits of metamosphosed Precambrian ferruginous quartzites and the high-quality, rich ore deposits of complex genesis related to them. Examples of this type are the deposits of the Saksagansky ore field in Krivoy Rog in the Ukraine; Mikhailovskoe, Yakovlevskoe and Lebedinka, in the Kursk magnetic anomaly area; Olenegorsk in the Kola Peninsula; and Karsakpai in central Kazakhstan.

Similar deposits in Canada are the jaspillites of the Nastapoka Islands, tectonites in the vicinity of headwaters of the Albany River Matonipiy Lake, and the hematite deposits in Labrador and New Quebec.

2. Most of the skarn-magnetite ore deposits are Paleozoic. These are found in the Urals: the Magnitogorsk, Goroblagodatsk, Pestchansk deposits; in Kazakhstan: Sokolovsk, Karabayevsk, Karadzhal; in highland Shoriya: Shalym, Sheregesh, Tashtagol; and in the Amur area, the Garin deposit.

In Canada similar deposits are encountered in southeast Ontario and in the adjacent regions of Quebec.

3. Sedimentary deposits of both marine and continental origin are of Carboniferous, Mesozoic and Cenozoic ages. These are represented by the Kerch deposits in the south of the European part of the U.S.S.R.; Ayatsk deposits in the Urals; Lisakovsk deposits in the Kustanai region; and Berezovsk deposits in the Chita region.

In Canada the Wabana deposit in Newfoundland may be referred to this type, but its genesis is a point of controversy.

Hydrothermal deposits are of less interest for the industry. The most important of them are those genetically related to trap formations such as the Korshunovsk, Rudnogorsk deposits of the Angara-Ilym group in the Irkutsk area.

Magmatogenic deposits are in Kapan, Kusinsk and Kachkanar in the Urals; and the Afrikanda, Eno-Kovdor, Pudozhgorsk deposits in Karelia and Kola Peninsula. In Canada, the eastern Ontario titaniferous magnetite deposits are similar to those in the U.S.S.R. Hydrothermal deposits of siderite of the Bakalsk type in the Urals, infiltration types like Alapayevsk in the Urals, and residual deposits of the ferruginous laterite such as Elisavetinsk in the Urals are of secondary importance.

Diversity in the genesis of iron ore deposits is the cause of great variation in the composition, morphology and in mode of occurrence of orebodies. They differ in their physical properties as well. All these variables in the characteristics of deposits require different research techniques and possible uses of geophysics in exploration for deposits of different types.

The employment of geophysical methods in prospecting for rich magnetite ores is of first rate importance, since magnetite ores which can be concentrated easily are of special interest for the industry.

In the course of exploration for iron deposits, geophysical methods are employed both for discovering the anomalies that may be related directly to the deposits that is direct prospecting, and for indirect prospecting when the principal task is to discover and to study the factors controlling ore deposition and locations.

These factors differ for different types of ores, but still they always involve a combination of lithological, magmatic and tectonic factors, which can be studied in many cases by geophysical methods.

At present geophysical prospecting for iron ore deposits are carried out in the Soviet Union by using a combination of methods to furnish a maximum of information under specific conditions.

The choice of methods is established for each specific case on the basis of the analysis of information available on the regional geology, the patterns of distribution of deposits, the nature of the geophysical fields and physical properties of rocks and ores, and also by way of special experimental and methodological studies.

Basically the following three types of geophysical surveys are used for definite stages of geological study: (1) prospecting survey, 1:100,000 to 1:200,000; (2) detailed prospecting survey, 1:25,000 to 1:50,000; and (3) reconnaissance prospecting, 1:10,000 and larger.

The first two types of survey are generally applied to provide for discovery of other commercial minerals simultaneously.

Prospecting surveys are conducted primarily with airborne magnetometers, generally on a scale of 1:200,000 or more, seldom 1:100,000.

Aeromagnetic surveys confined to anomalies that are most interesting for exploration are accompanied by ground surveys aimed to delineate the anomalies and to obtain more adequate and precise information about their nature for making preliminary interpretations. Magnetic and gravimeter observations are undertaken along special interpretation profiles over anomalies which are favorable and over probable ore-bearing ground. During the ground phase of work, geological surveys are carried out on outcrops or areas with shallow overburden and are accompanied by mining work and rock sampling for petrographic and mineralogical analyses and studies of physical properties of the rocks. Gravimeter surveys on a scale of 1:200,000 are also carried out at this stage of the exploration. The results of aeromagnetic and gravimeter surveys are used for determining ore prospect areas, and for geological mapping and tectonic studies.

Areal electrical prospecting surveys are carried out in order to obtain more precise information on the structure of the marginal zones of synclines and graben, to elucidate the topography of the crystalline basement, and to study tectonics of the sedimentary cover in the areas investigated by aeromagnetic and gravimeter observations on a scale of 1:200,000. For this purpose methods of telluric currents TC, MTC, electric sounding VES and in some cases profiling are used; less often seismic profile shooting is used.

Geophysical prospecting surveys on a scale of 1:200,000 - 1:100,000 generally precede geological survey work of the same scale and are conducted by specialized organizations such as geophysical trusts and geophysical teams from the geological offices.

Detailed prospecting surveys on a scale of 1:50,000 to 1:25,000 are performed in the areas considered to be promising on the basis of previous observations. The object of these surveys is to obtain more precise information on the structure of ore zones and ore fields, to distinguish individual deposits and to estimate their extensions and mode of occurrence. Geophysical work is done in areas where ore-bearing zones are overlain by unconsolidated deposits, to determine the thickness of the latter.

Prospecting for rich magnetic ores is performed principally through aeromagnetic surveys on a scale of 1:50,000 to 1:25,000, accompanied by areal magnetic prospecting work along individual profiles for interpretation and measuring the Z_a and H_a magnetic-field components; aeromagnetic surveys and gravimeter surveys are carried out by high-precision gravimeters and gradiometers. Geological observations and rock sampling for petrochemical and physical studies are performed on the areas of exposed rock along the interpretation profiles.

Areal gravimeter surveys on a scale of 1:50,000 to 1:25,000, 0,5 - 0,2 mgl are carried out in the ore-bearing regions where quantitative interpretation is highly complicated. Ground magnetic prospecting work, on a scale 1:50,000 to 1:25,000 is performed in individual areas where large orebodies can be overlooked because of a complex structure of the magnetic field or weak anomaly effect.

During this period, as well as during the subsequent period of more detailed prospecting work, much stress is laid on studying the effect of the upper portion of the rock and ore section on the character of the anomalous magnetic field. Maps prognosticating ore areas and fields with indications of promise of deposits, ore manifestations and anomalies warranting more subsequent detailed study are drawn on the basis of results from the detailed prospecting surveys. Reconnaissance surveys on a scale of 1:10,000 and larger are carried out for prospecting these anomalies. Geophysical work of this scale is usually performed only in connection with prospecting for rich magnetite ores that are relatively shallow, and generally are carried out by ground magnetic surveys. Areal gravimeter observations with gravimeters, gradiometers and torsion balances are performed less often.

Experience gained in the U.S.S.R. has made it possible to classify iron deposits prospected by geophysical techniques in three groups in terms of parameters defined by geophysics. The boundaries between these groups are not well defined. In fact, there are intermediate forms among the deposits that may belong to one or another of the groups.

The first group includes the deposits with orebodies that are slightly different in their physical properties from the enclosing rocks. This group includes mainly the hydroxide and silicate iron ores, occurring in continental, lagoonal and coastal deposits. The intensity of magnetic anomalies over deposits of this type varies from tens to one hundred gammas.

The magnetic field is characterized by irregularities due to the variability of the magnetic properties of the ore field. Usually a slight difference is observed between weak magnetic anomalies over the orebodies and anomalies induced by the enclosing rocks. Other physical properties of the ore fields and enclosing rocks do not differ significantly either. Therefore, the geophysical research is principally carried out within scales of 1:200,000 to 1:100,000 and 1:50,000 to 1:25,000 with the purpose of solving structural-tectonic problems, mapping depression margins and syncline-

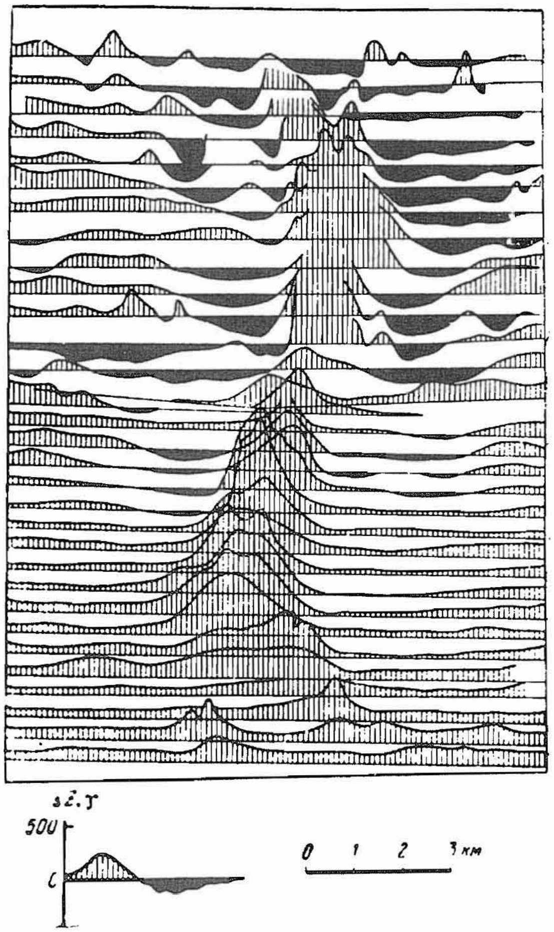

Figure 1. Magnetic field over Belozerka iron deposit, which was discovered by aeromagnetic survey (after V.V. Suslennikov).

troughs and of studying the topography of the upper surface of the rocks which underlie the ore-bearing horizons, etc.

The second group includes deposits with orebodies that are considerably different from the enclosing rocks in their physical properties, primarily in their magnetism and density. This type includes mainly magmatogene and residual deposits: (1) apatite-magnetite and titanomagnetite deposits related to the ultrabasic alkaline intrusions and gabbroid intrusions, (2) rich iron ores genetically and spatially related to the Precambrian siliceous iron formations, the Kursk Magnetic Anomaly, and Krivoy Rog, and (3) residual deposits of ores derived from decomposed ultrabasic rocks.

The third group includes deposits with orebodies that differ considerably from the enclosing rocks in their physical properties. This group includes primarily ferruginous quartzites, skarn-magnetite and hydrothermal iron deposits.

We shall consider the first and second types since they are of greatest importance.

Most basic and ultrabasic rock masses with related ore-bearing formation or zones are characterized by a high or excess magnetism and density compared to that in the enclosing granites, gneisses, schists and carbon-bearing rocks. These masses of basic and ultrabasic rocks are distributed along large fractures which have developed at the junction of structures that differ in age and character. Therefore, in the provinces and areas where the deposits under study are located, more or less extended belts with local chains of moderately intensive anomalies are clearly distinguished from the anomalous magnetic and gravity fields in the background.

Only general outlines of intrusions are delineated in aeromagnetic surveys, the magnetic field within the outlines of these anomalies being only poorly differentiated. In the case of the detailed ground surveys and shallow bedded masses, sharply alternating fields with large gradients are observed as a rule, resulting from the wide range of variation of the magnetic properties of rocks.

Mineralized gabbro and ultrabasic rocks have the highest values of magnetic susceptibility because of their high magnetite content.

The ores are also characterized by elevated density values varying from 3.0 to 4.9 g/cm^3. Densely impregnated and rich massive ores possess the highest densities.

Orebodies are also distinguishable by high electrical polarization, and solid ones by electrical conductivity as well. Observations from the inductive method or the method of induced polarization show in some cases that electrical axes of conductivity correspond to the orebodies. Their coincidence with local Z_a maximums may serve as a criterion for discovering orebodies.

Under all conditions magnetic surveys remain the principal method in prospecting for iron ores of the apatite-magnetite and titanomagnetite type.

The study of gravity fields over basic and ultrabasic rock masses, as a means of prospecting for iron deposits, are of secondary importance, while the electrical prospecting is mostly experimental.

The main difficulty arising in prospecting for magnetite, titanomagnetite and other varieties of this type of magnetite ore is the difficulty in distinguishing ore anomalies from the background magnetic field of the source rocks which also possess high magnetism and great irregularity in the magnetic fields related to them.

Magnetic prospecting is the most reliable for locating deposits where mineralization is presented in vein-type bodies (the Kusinsk group of gabbro-amphibolities in the Urals), or in sheet-like and dyke-like deposits (Pudozhgorsk and Koykar deposits in Karelian gabbro-diabases).

Logging of magnetic properties is a great help in prospecting drilling, for defining more accurately the ore contacts, furnishing data about the environment close to the boreholes, and estimating the magnetic iron content in the borehole section.

All the rich ores of the weathered parts of the magnetite and hematite-magnetite ferruginous quartzites are classified in two types: (1) sheet-like, nest-like and linear fractured deposits of the martite, martite-hematite and hydrohematite ores found in KMA and Krivoy Rog (Figure 1); and (2) rich iron ores of complex genesis, column-like and joint deposits of martite and hydromartite ores found in the Saksagansky belt of the Krivoy Rog Basin.

The rich iron ores listed above are genetically and spatially related to ferruginous quartzites.

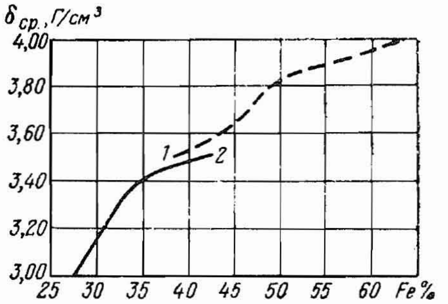

Figure 2. Composite graph showing the relationship between average density and iron content of (1) ore, (2) ferruginous quartzites (KMA region).

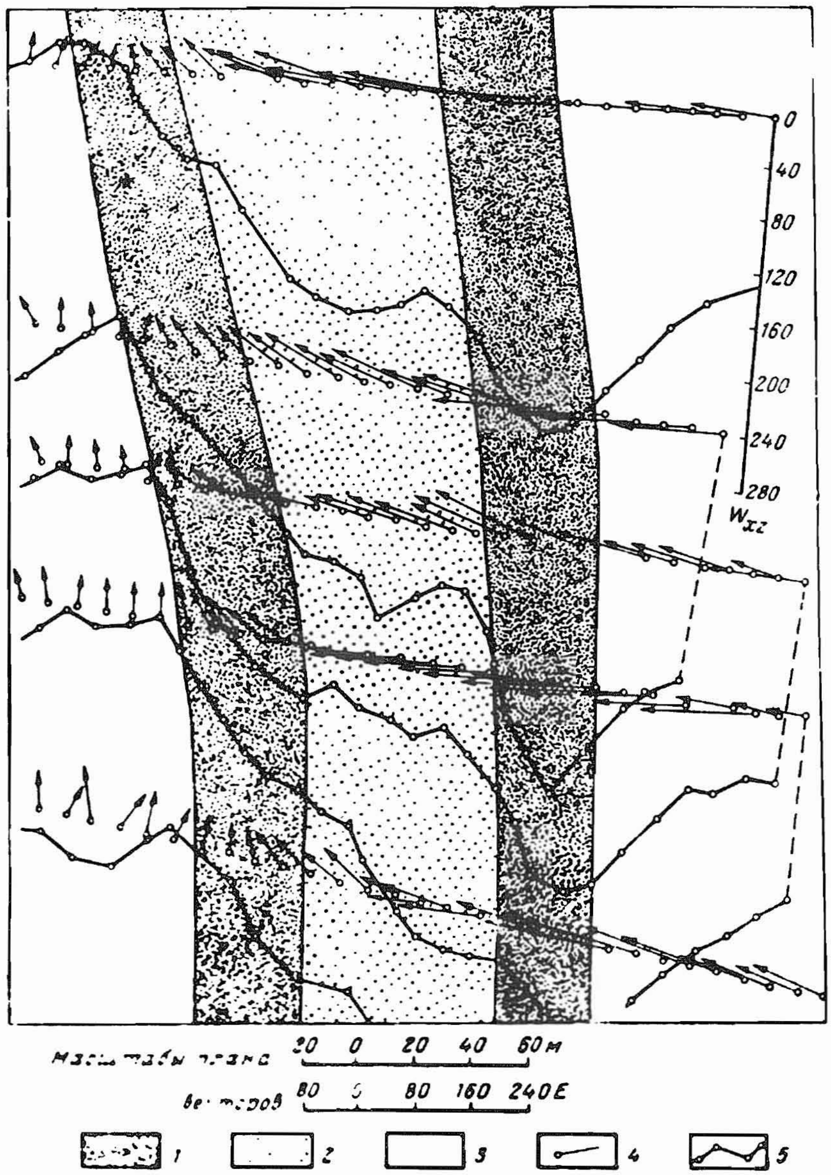

Figure 3. Example of subdividing ferruginous quartzites on the basis of iron content (southern part of Krementchug anomaly). 1. Jaspillite. 2. Iron hornfels. 3. Schist. 4. Horizontal vector of gravity force. 5. Horizontal gradient of gravity, W_{xz} eötvos units.

Rich ores do not differ from ferruginous quartzites in density, d = 3.3 - 3.7, but their magnetism is several hundred and even a thousand times as weak as that of magnetite and hematite-magnetite ferruginous quartzites. Therefore, in such cases when an oxidized zone in ferruginous quartzite has great vertical thickness a decrease in intensity of the local magnetic field is observed. However, some other factors may be responsible for the decrease in intensity such as a decrease in the thickness of the bed of ferruginous quartzites, changes in the composition of sedimentary facies, or subsidence. Under favorable conditions the mapping of the rich mineralized zones, such as sheet-like deposits of great vertical thickness, may be carried out as part of the combined methods used for magnetic and gravity prospecting. If the gravity data show that the thicknesses of rock layers and their excess densities are essentially the same and the magnetism has sharply decreased then these facts will be an indication of the presence of a thick weathered part or orebody. Even less ambiguous results may be obtained by seismic prospecting, since rich iron ores represent a leached zone in the ferruginous quartzites which is characterized by a decrease of boundary velocities from Vr 5000 m/sec to Vr 3000 m/sec and by high seismic energy absorption.

The main criteria for prospecting for high-grade iron ores in the weathered crust and for ores of complex genesis are the following: (1) lithological, i.e., their relation to the ferruginous quartzite beds which may be mapped successfully by geophysical methods (Figure 1); and (2) structural-tectonic, i.e., relation of large deposits to tectonically weakened zones.

Examples of such tectonically weak zones with ore deposits of the weathered crust type are fractures and zones of block faulting or displacement. The thick weathered crust type of deposit in the Kursk magnetic anomaly (KMA) area related to the edge of the Dnieper-Don Basin formed syngenetically with the rich ore deposits in the Belgorod region of the KMA. Other deposits formed in folded areas, synclinal folds, flexure fold areas and at the intersections of structurally weak zones of different directions, including the column-like and articulated deposits of Krivoy Rog.

Hence, in the prospecting for rich iron ores indirect methods are essential and important for delineating ferruginous quartzites and for tectonic studies of the ore-bearing zones and the basement.

Therefore, in iron-ore exploration pertaining to group (2) 'direct' prospecting is carried out only in individual favorable cases, but geophysical methods, generally magnetic prospecting and gravimetry, make it possible to solve principal problems connected with indirect prospecting. These problems are as follows: (1) location and delineation of mother rocks to which iron ore deposits of this group are related genetically and spatially; and (2) studying the condition of the occurrence and the structure of the mother rocks and distinguishing highly promising areas for prospecting drilling.

Ferruginous quartzites may be subdivided into the following two large groups which greatly differ as to their magnetic properties: magnetite group, and hematite-martite group. Ferruginous quartzites rich in magnetite have magnetic susceptibility values from 0.04 to 0.2 CGSM. At the same time ferruginous quartzites rich in hematite have values of from 0.003 for pure martite varieties to 0.03.

Rocks enclosing ferruginous quartzites, such as various slates and gneisses are either nonmagnetic or slightly magnetic. Their density ranges from 3.3 to 3.7 g/cm^3 whereas for the enclosing rocks it usually does not exceed 2.8 g/cm^3. The density of ferruginous quartzite is a function of ore mineral content (Figure 2).

Thus, the magnetite varieties of the ferruginous quartzites have magnetic intensities hundreds and thousands of times greater than the crystalline rocks enclosing them and very high densities compared to the rocks enclosing them. The difference in densities is 0.5 to 1.1. This points to the possible effectiveness of the magnetic and gravity mapping for prospecting, especially the former.

Extensive high-intensity linear anomalies are characteristic of magnetic fields in regions with well developed siliceous iron formations (Figures 1 and 3).

Within the Russian platform these anomalies are found in the vast territory extending from the Black and Azov Seas (the Odessa and Zhdanov anomalies) to the Kola Peninsula (the Olenegorsk and Kirovogorsk anomalies). These anomalies extend from several kilometers to over ten kilometers, the Krivoy Rog - Krementchug zone, zones in the northeast and southwest of KMA, and the Olenegorsk anomalies. Their intensity amounts to tens of thousands of gammas and in several to over tens of mgl.

The fractures common to both physical and geological structures of these iron ore deposits are further defined by coinciding geophysical data. Extensive linear magnetic anomalies are also found over the ferruginous quartzites in Karsakpai in Kazakhstan, Khingan in the Far East, in Tuva and in other regions.

Apart from the intensive magnetic and gravity anomalies of high intensity, other anomalies with relatively low intensities are encountered in the iron ore basins of this type. These anomalies are associated with the beds of ferruginous quartzites rich in hematite, especially in the areas with deeply developed oxidized zones, martite and hydrohematite varieties, and likewise in areas where thin ferruginous quartzite remnants are preserved in the roots of synclinal folds under a thick series of Mesozoic sediments.

During geological work in the iron ore areas of this type the first and second stage magnetic surveys conducted are aeromagnetic and are accompanied by some ground work aimed at determining the location and character of the anomalies or anomalous zones. Ground surveys are also accompanied by gravity studies. An aeromagnetic survey makes it possible to investigate the general extent of the iron ore formation present and to get some idea of the structure or form of the iron occurrence.

During the 1:50,000 - 1:25,000 scale work some of the peculiarities about the distribution and mode of occurrence of the ferruginous quartzites within individual ore areas and fields are elucidated. The principal purpose of the magnetic prospecting at this stage is to discover the most promising areas for organizing more detailed prospecting work. The most promising areas are considered to be those where anomalies suggest the presence of extensive fields of ferruginous quartzites or thick contiguous seams underlying sedimentary rocks and occurring at depths which permit direct mining work.

In large-scale surveys some of the structural details of individual ore deposits are displayed in the pattern of the gravity and magnetic fields, such as contorted beds, flexures, shears and points of wedge out, all of which are essential for orienting drilling.

For steeply dipping uniform beds of ferruginous quartzites good results are obtained by combined quantitative interpretation of the magnetic and gravity anomalies which permit determination of their thickness, angle of dip, excess density and depth of occurrence.

Investigation of the thickness of the sedimentary cover involves the use of electrical and seismic prospecting methods (Figure 4).

Magnetite and skarn-magnetite ore deposits are located among carbonate and silicate rock complexes, effusives, tuffs and shales in the contact zones near highly basic or alkaline granitoids.

The deposits consist of massive and impregnated ore beds which vary in form, size and range from persistent sheet-like bodies (the deposits of Sarbai, Kachar in North Kzakhstan and Magnitogorsk in the Urals) to the deposits of very complex morphology represented by groups of discrete bodies of variable forms such as the Kondoma, Telbess, Tashelgin, Irba and other groups of the Altai-Sayany iron ore province.

Magnetic properties of the ores of these deposits give high values, and they vary within wide limits mainly because of the variability of the magnetite content. At the same time the rocks contiguous to orebodies, ore-free skarns, effusives, sedimentary rocks and a great number of igneous rocks, especially those of the acid series, are practically nonmagnetic or weakly magnetic. Density values of these rocks are below 2.9 g/cm^3.

It is the high excess magnetic properties and ore densities that create characteristic features in the physical fields of this type of iron ore area. Notably these are the presence of high-intensity local magnetic and gravity anomalies, from one thousand to over ten thousand gammas; several to over ten thousand gammas mgl. which can be distinguished from the background of the fields over the enclosing sedimentary-volcanogenic masses (Figure 5).

The character of the anomalous fields in the ore areas, determined in the course of small-scale surveys, aeromagnetic and

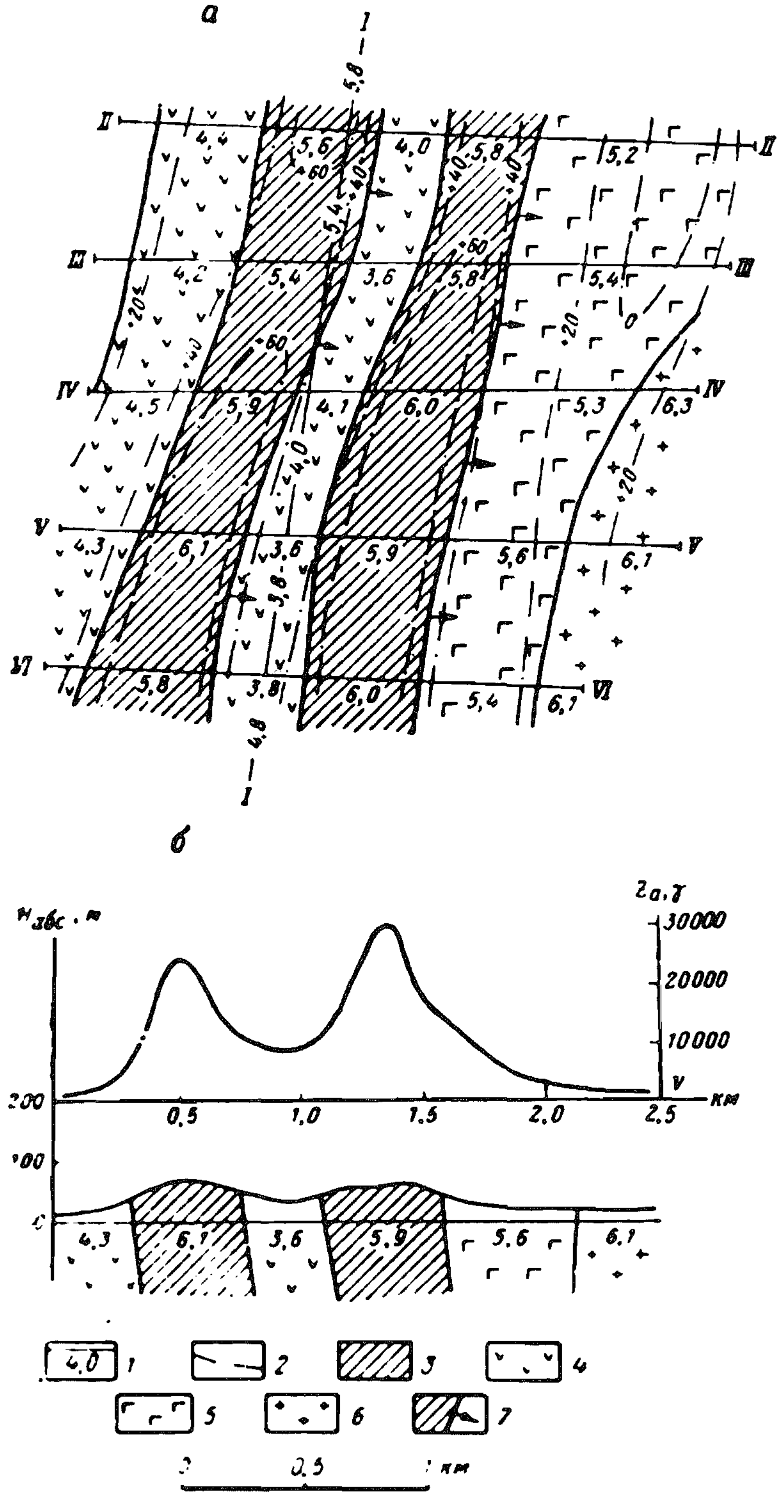

Figure 4. (a) Geophysical and geological plan of the crystalline basement of an area in the KMA region. (b) Geological and geophysical section and Z_a curve along survey line. 1. Surveyed line and values of limit velocity V_g km/sec. 2. Top of the Precambrian basement. 3. Ferruginous quartzites. 4. Schists: $V_g <$ 5 km/sec; $x < 10.06^{-6}$ CGSM. 5. Gneiss: $5.0 < V_g < 6.0$ km/sec; $\rho < 2.7$ g/cm^3. 6. Granite. 7. Dip of iron quartzite beds indicated by gravimetric survey.

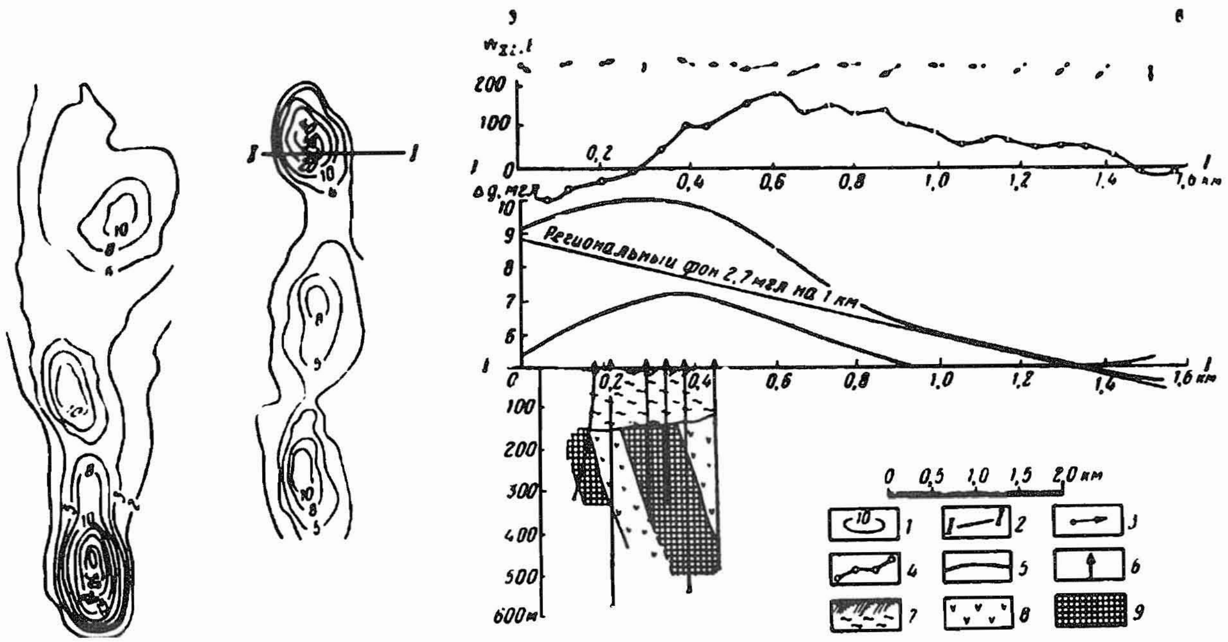

Figure 5. Results of gravity survey of a magnetite deposit (after Lyubimov and Poddubny). 1. Isodyne Z_a. 2. Location of gravity profile. 3. Vectors of the gravity force gradient. 4. Curve of the gravity force gradient W_{xz}. 5. Gravity force curves Δg. 6. Boreholes. 7. Sedimentary formations. 8. Diorite. 9. Magnetite ore and scarn.

ground, is formed not by individual deposits, except for the large ones, but by such elements as ore units, ore zones, and tectonic structures controlling the distribution of individual ore units.

Apart from the magnetic ores, the main highly magnetic rocks in the areas with skarn-magnetite deposits are intrusives of high basicity and effusive rocks.

The nature of anomalies over shallow magnetite deposits, their intensity, gradients and geometry differ considerably from anomalies over intrusives which are larger and less intensive and whose structure is often intricate because of the inhomogeneity of the petrographic composition of rocks. The anomalies associated with the effusive rocks are characterized by frequent changes of the anomaly sign and by general irregularities of the fields.

The peculiarities of the anomalies related to skarn-magnetite ores diminish rapidly with the depth of the orebodies, and it becomes impossible to identify the ore anomalies from the anomalies caused by the intrusives or some other magnetic rocks.

To cut the volume of work and give proper direction to exploration drilling it is necessary to determine, first of all, whether the anomaly observed is related to metalliferous or to nonmetalliferous bodies.

In the areas where the behaviour of the attenuation gradient of the T-curves over metalliferous and nonmetalliferous magnetic bodies has been investigated, the character of the attenuation makes it possible, to some extent, to judge the nature of the anomalies. For this purpose electric prospecting was conducted in some areas with magnetite ore deposits, the induced polarization method, the combined profiling method and the VES, resulting in the construction of vertical iso-ohm field sections. Positive results have been obtained for shallow-seated bodies.

In the interpretation of anomalies related to deposits of the type under study it is necessary to carry out quantitative calculations for determining the parameters of orebody occurrences and their magnetic masses. The depth of the occurrence and the magnetic mass are determined both from aeromagnetic surveys and from the results of ground observations. These data classified according to their degree of reliability, taking into account geological position of the bodies causing the anomalies, serve as the material for prognosticating the value of the areas under investigation.

From the experience gained in studying various magnetite ore deposits in the U.S.S.R. it has been established that the surveys within a scale as small as 1:200,000 to 1:100,000 make it possible to discover the main ore units and large deposits in iron ore areas. The surveys within larger scales provide for discovery of the bulk of the large and medium deposits that are not too deeply seated and for a considerable number of small deposits near-surface. It was magnetic prospecting in combination with some other techniques that led to the discovery and evaluation of some of the largest ore areas in the U.S.S.R. such as KMA, Turgai, Middle Azov area, etc.; and prospects in quite a number of the old ore areas, such as the Krivoy Rog, Urals, and Shoria Mountain deposits which were also explored by magnetic prospecting. As a result of geophysics and primarily magnetic prospecting, such large deposits as the Mikhailovsk and Lebedinka in the KMA, Kremenchug and Belozerka in the Ukraine, Pestchansk in the Urals, Sokolov and Sarbai in North Kazakhstan, Tagarsk, Beryambinsk in the Middle Angara area, Garinsk in the Far East, etc., were discovered. In many cases magnetic prospecting, particularly when used in combination with gravity prospecting, makes it possible to evaluate the occurrence of orebodies, parameters of the deposits and of promising reserves with an accuracy sufficient for practical purposes. Full advantage is being taken of these opportunities, the main problem being to subject them to interpretation that is as reliable and unambiguous as possible. For this purpose in carrying out magnetic prospecting various supplementary investigations are conducted, other than combination with other methods, such as: aeromagnetic surveys, observations of the magnetic field variation, that is comparison of intensities within the anomalies and in a normal field, studies of the magnetic susceptibility of rocks by the superimposed magnetization method, magnetic logging of the boreholes. All sorts of transformations of the magnetic field observed are also carried out.

Geophysical methods of borehole investigation are used in the Soviet Union at all stages of geological exploration where drilling is available.

In the course of iron ore prospecting borehole investigations are generally conducted for solving the following problems: (1) more precise definition of ore intervals within borehole sections; (2) discovery of orebodies in the near-aperture space; (3) correlation of ore subsections in various boreholes; (4) determination of Fe-total and Fe-magnetic; (5) lithological subdivision of the section; and (6) estimation of the nature of ground magnetic anomalies.

Alongside the electrical logging use is made of the borehole magnetometry of vectors, whereby T, Z and H components are studied along a borehole, and magnetic susceptibility logging is performed.

The borehole vectorial magnetometry together with the electrical correlation method and radio wave sounding serves both for prospecting for orebodies and for studying the ore field structures.

The nuclear methods generally employed are the natural radioactivity logging and also gamma-gamma density and selective logging.

The borehole vectorial magnetometry and magnetic susceptibility logging are of primary importance for the deposits of rich magnetite ores both in the period of prospecting ascertaining the stripped ore intervals, examination of the near-aperture space, estimation of the nature of surface anomalies, and in the period of exploration consisting of determination of the magnetic iron content.

In areas with deposits of complex compositions, characterized by the presence of hematite, hydrohematite and martite ores, use is made of the radioactive logging methods, natural radioactivity logging (gamma-logging), density logging (gamma-gamma logging of the density). The method of spectral relations and neutron methods are being introduced now for quantitative determinations of iron content in the deposits of complex composition.

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Iron ore exploration in North and South America

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Abstract. The application of geophysics to iron ore exploration may be direct or indirect. Both modes of application depend upon the existence of a measurable physical property contrast directly or indirectly associated with the iron ore.

Because magnetite is almost unique among ore minerals in its property of magnetic polarization, magnetic surveying is the geophysical method most widely applied in iron ore exploration. Theoretical curves and field examples illustrate the variation in magnetic response as a function of latitude in North and South America.

Résumé. L'application de la géophysique à l'exploration du minerai de fer peut être directe ou indirecte. Les deux modes d'utilization dépendent de l'existence d'une propriété physique mesurable et directement ou indirectement associée au minerai de fer.

Parce que la magnétite est presque le seul des minerais à présenter une polarization magnétique, les relevés magnétiques constituent la méthode géophysique la plus souvent utilisée dans la recherche du minerai de fer. Des courbes théoriques et des exemples sur le terrain illustrent la variation de la réponse magnétique en fonction de la latitude en Amérique du Nord et en Amérique du Sud.

The successful application of geophysical methods to iron ore exploration, as with any other ore, depends upon the existence of a measurable physical property contrast associated directly or indirectly with the sought after commodity. Geophysical instruments and techniques have been developed which record variations in gravity and magnetic fields, electrical fields, electromagnetic fields and also variations in the distribution of various radioactive decay products. Anomalies in these fields, however, cannot be uniquely interpreted in terms of the geometry and physical properties of the source; and herein lie many of the real problems and apparent failures of geophysics. Our geophysical instruments are nothing more than auxiliary eyes, temporarily substituted for our conventional method of observing the earth. But, no matter how the observations are made, the picture must form a self-consistent framework defining our concept of geological reality. Geophysics then must be regarded as an observational tool whose products both complement and supplement and sometimes alter the inferences of visual observation.

Magnetic method

Because the magnetic polarization properties of the ore mineral magnetite is almost unique among rock constituents, magnetic surveying is the method most widely applied in iron ore exploration. Geophysical literature and private company files abound with examples of magnetic surveys directed to iron discovery. Ores with a high magnetite-to-hematite ratio such as those associated with igneous rocks may be detected directly by magnetic methods. In the search for enriched hematite ores derived from banded iron formation, the magnetic method has been used as an indirect guide to ore. The hematite orebodies are nonmagnetic but may be related genetically, structurally, or stratigraphically to lithologic units which are magnetic. Magnetic surveying then can serve to localize the areas of interest in which other exploration methods may be applied.

Polarization of magnetite

The total magnetic polarization I_t is the sum of the induced or susceptibility polarization I_i and the permanent or hard polarization I_p:

$$I_t = I_i + I_p$$

where $I_i = kH$ and k is termed the magnetic susceptibility.

Werner (1945) has made a comprehensive study of the magnetic susceptibility of ores and rocks from 27 different iron mines or mining districts. He concluded that:

1. Susceptibility values show considerable scatter even for the same magnetite content.
2. The increase of susceptibility with magnetite content is greater than a linear one.
3. The variation of susceptibility values for very high-grade ores suggests considerable variation in the susceptibility of pure magnetite.
4. Certain ore districts displayed a regular variation of susceptibility with magnetite content. This suggests a uniform susceptibility for pure magnetite throughout the district.

For magnetite ores the bulk susceptibility k is given by

$$k = \frac{Kv}{1 + CKv} \qquad 1$$

For hematite ores, skarns, basic and acid igneous rocks, limestones, and dolomites the susceptibility is given by

$$k = \frac{Kv}{1 + CKv} + 120(S - S_1) \cdot 10^{-6} \qquad 2$$

In the above expressions K represents the susceptibility of magnetite and v the volume fraction of magnetite in the ores or rocks; S represents the specific gravity of the hematite-plus-gangue portion of the ores or rocks and S_1 is the specific gravity of the gangue material consisting of quartz, feldspar, limestone or dolomite. The factor C may be considered an internal demagnetization factor.

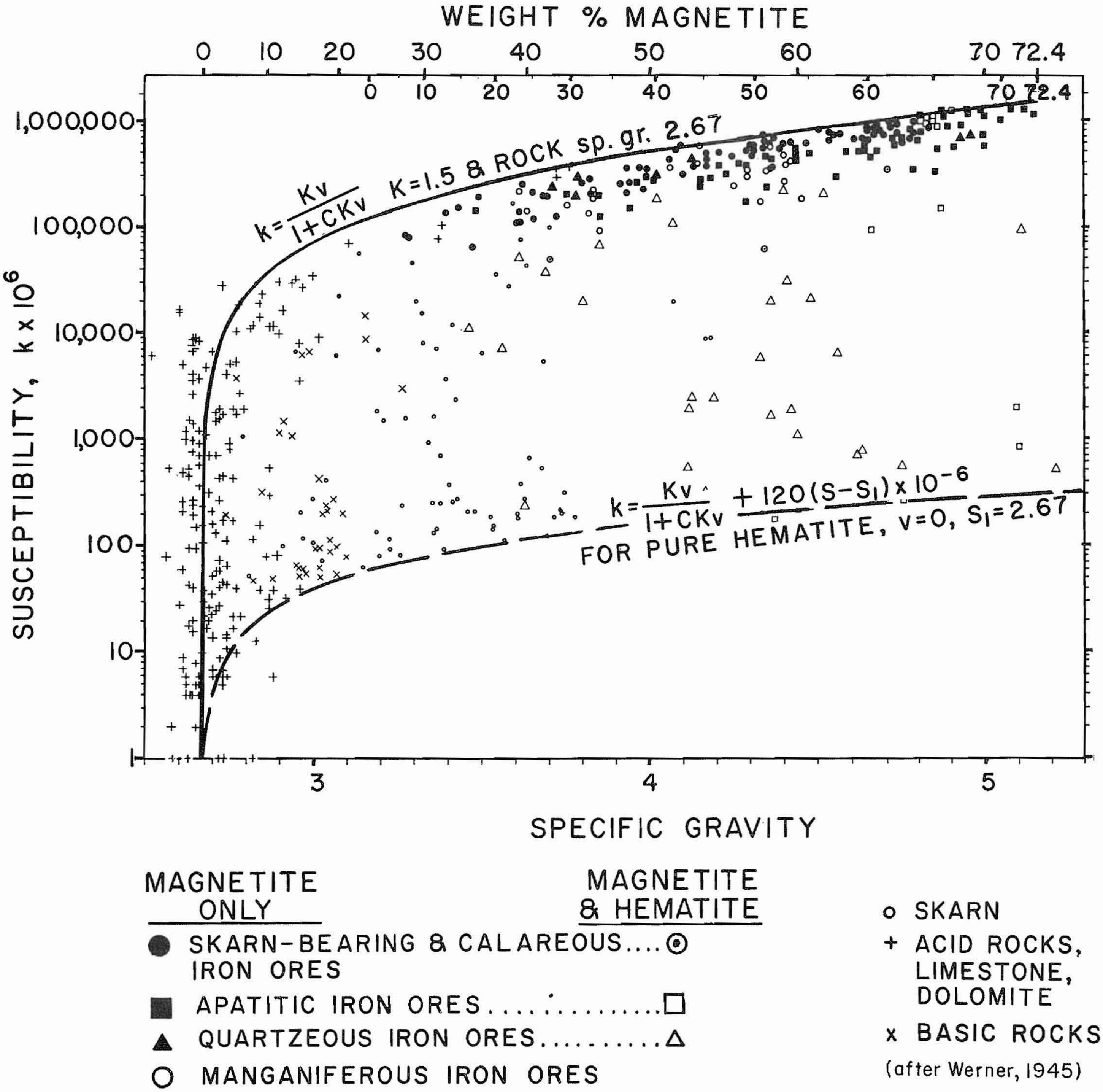


Figure 1. Summary of susceptibility measurements. The specific gravity is set up in a linear scale, k in logarithmic. The two upper scales, indicating weight percent F_e, refer to samples containing magnetite and rock material of specific gravity 2.67 and 3.17 respectively.

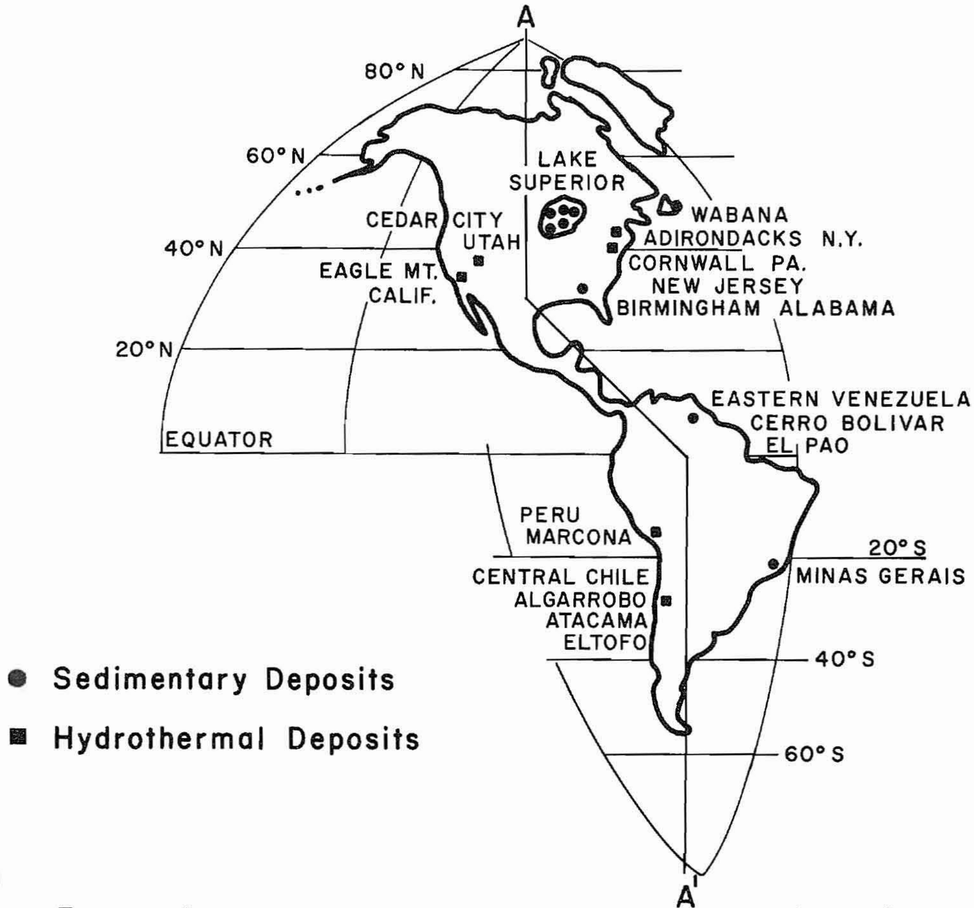


Figure 2. Principal iron ore districts in North and South America.

For magnetite ores

$$C = \frac{4\pi}{3} \cdot \frac{1 - \nu^{1/6}}{\nu}$$

For rocks of lower magnetite content (hematite ores, skarns, igneous and sedimentary rocks) the following expression for C should be used:

$$C = \frac{4\pi}{3} \cdot 1 - \nu \frac{2 - \nu^{1/6}}{6}$$

The results of Werner's study are shown in Figure 1. The solid line represents Equation 1 for ores composed of gangue material with specific gravity 2.67 and magnetite with susceptibility K=1.5. This curve forms an approximate upper limit for the susceptibility determinations of all specimens except the acid igneous rocks lowest in magnetite. The dashed curve represents Equation 2 for low magnetite rocks. It can be seen that this curve forms the approximate lower limit of the hematite-bearing ores as well as for skarns and basic rock.

Table I compiled from Werner's data indicates the K values obtained for various types of ores. The quartzitic iron ores (sedimentary ores of the silica-iron oxide type) are represented by too few determinations to consider the K value reliable. However, the susceptibility of skarn-bearing and calcareous ores may be considered approximately known if only the magnetite content is known. For apatitic or manganiferous iron ores the K values are spread too widely to make susceptibility estimates on the basis of magnetite content.

Table I. K values for various types of ores.

Ore Type	For 30 to 100% by Vol. Fe_3O_4 Range of K	Mean K	Number of Determinations	No. of Mines
Quartzeous iron ores	0.79–1.08	0.89 ± 0.12	4	3
Skarn-bearing and calcareous iron ores	0.77–2.73	1.43 ± 0.13	68	10
Manganiferous iron ores	0.65–2.60	1.20 ± 0.37	17	4
Apatitic iron ores	0.65–1.98	1.03 ± 0.26	53	7
For all specimens		1.27 ± 0.29	142	–
For all mining fields		1.21 ± 0.29	–	24

Interpretations of magnetic data often neglect the existence of remanent magnetization, that part of the polarization which does not require the existence of an applied field. However, the remanent magnetization need not be in the same direction as the earth's field and often is stronger than the induced magnetic polarization. Nagata (1953) finds that the ratio of remanent to induced magnetization for rocks is often in the range of 2 to 10 and for some basaltic volcanic rocks the ratio may exceed 100. We have no such body of data concerning the remanent polarization of magnetite iron ores.

In studying iron deposits over a wide range of latitude it is important to recognize the latitude dependence of magnetic response. Figure 2 shows the location of the major iron ore

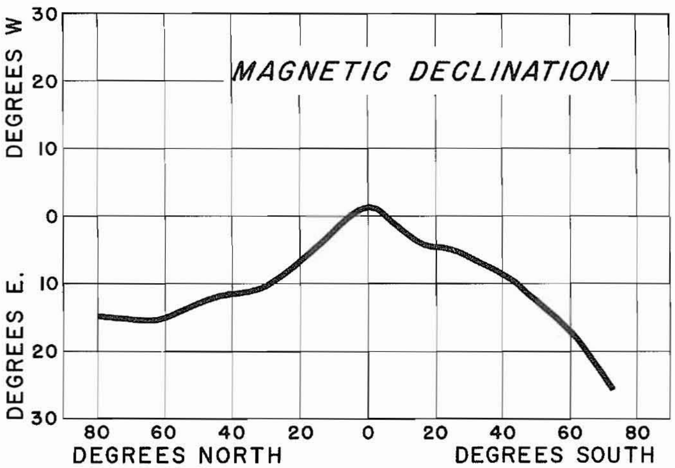


Figure 3. ,Magnetic declination as a function of latitude along line *A–A′* (Figure 2)

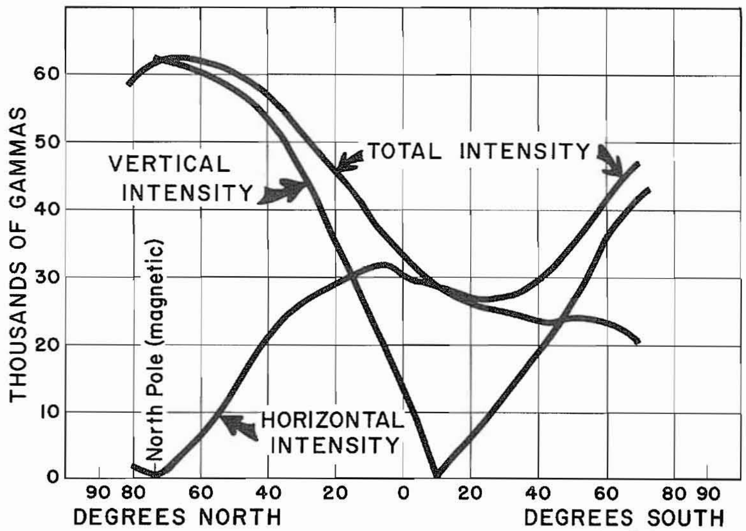


Figure 5. Intensity components of the earth s magnetic field as a function of latitude along line *A–A*

districts in North and South America. Figures 3, 4 and 5 illustrate the variation in the elements of the earth's main magnetic field along line *A A*,′ through North and South America. Figure 6 (Reford, 1964) illustrates the variation in total intensity response of a thin vertical dike magnetized by induction as a function of magnetic latitude and strike of the dike. At low magnetic latitudes the shape of the response curve is strongly dependent upon strike, while at high magnetic latitudes there is very little strike dependence.

Bath (1967) has reported interesting experiments on the viscous magnetization of iron formation of northern Minnesota. All iron formations in that area exhibit positive magnetic anomalies. This is somewhat surprising because magnetic property data from this area almost always indicate that remanent magnetization is greater than induced magnetization. Therefore, in steeply folded or overturned iron formation one might expect negative anomalies on one flank and positive on the other. The fact that only positive anomalies are found suggests that there is a strong component of viscous magnetization and that iron formation remaining in its present attitude for a long time will acquire a strong remanence in the direction of the present earth's field.

Figures 7 and 8 show the results of two experiments on Minnesota iron formation. The samples first were demagnetized and then subject to a field of 1 oersted for time intervals up to about 12 hours. It is noteworthy that the increase in remanent magnetization along the banding is more than 100 percent of that across the layers. The values are sufficiently high to provide a satisfactory explanation for the positive character of anomalies over most Minnesota iron formation. It would seem that the

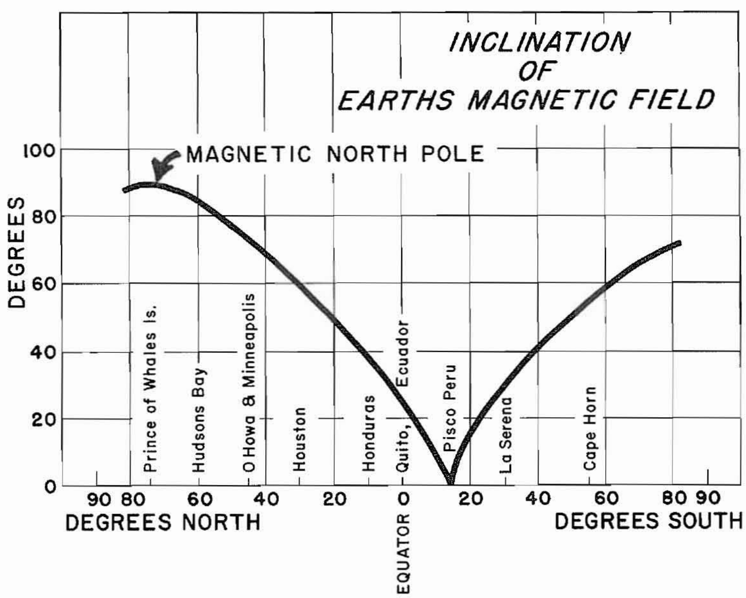


Figure 4. Inclination of the earth's magnetic field as a function of latitude along line *A–A′* (Figure 2).

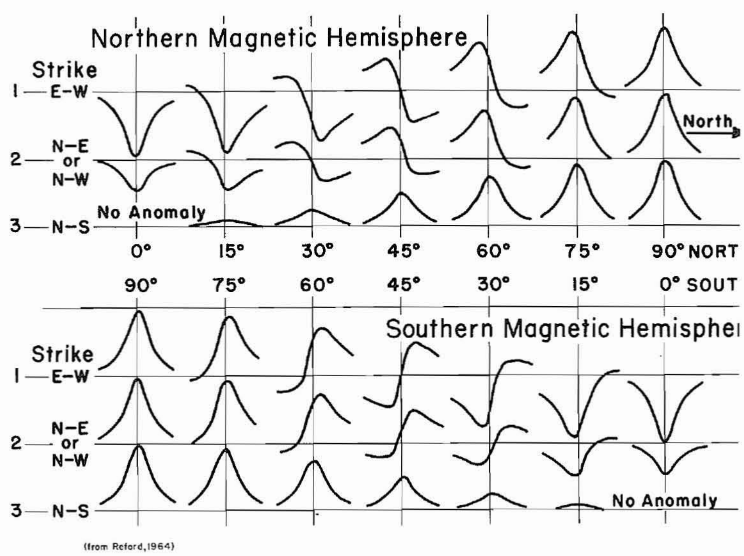
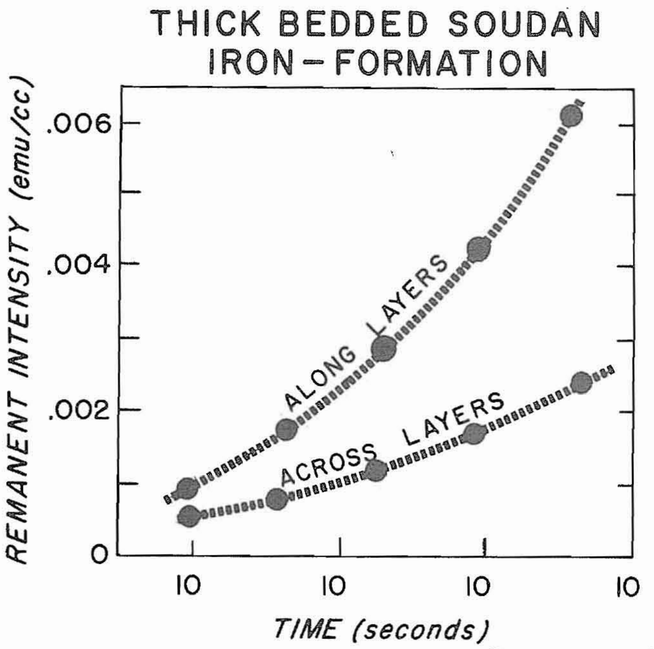
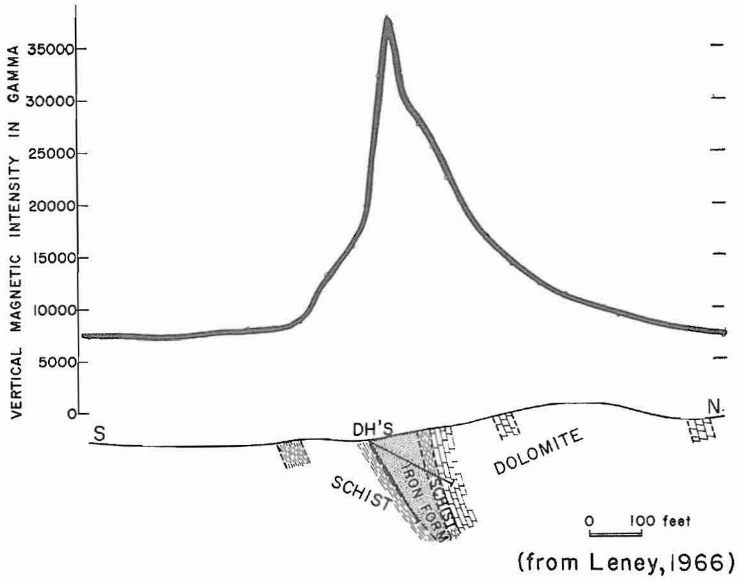


Figure 6. Total intensity anomalies over a thin vertical semi-infinite sheet magnetized by induction as a function of magnetic field inclination.



(from Bath, 1967)

Figure 7. Increase of remanent intensity as a logarithmic function of time for specimens of thick-bedded Soudan iron formation.



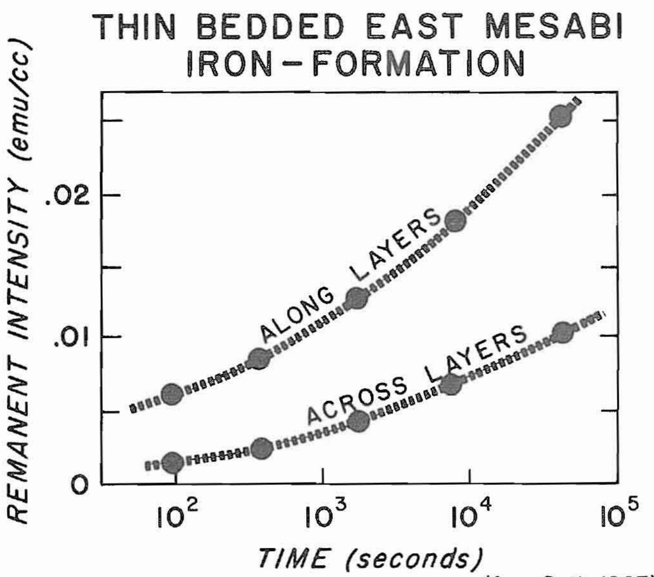
(from Leney, 1966)

Figure 9. Magnetic anomaly over a north-dipping iron formation.

viscous magnetization of iron ores would be a fruitful area for further study.

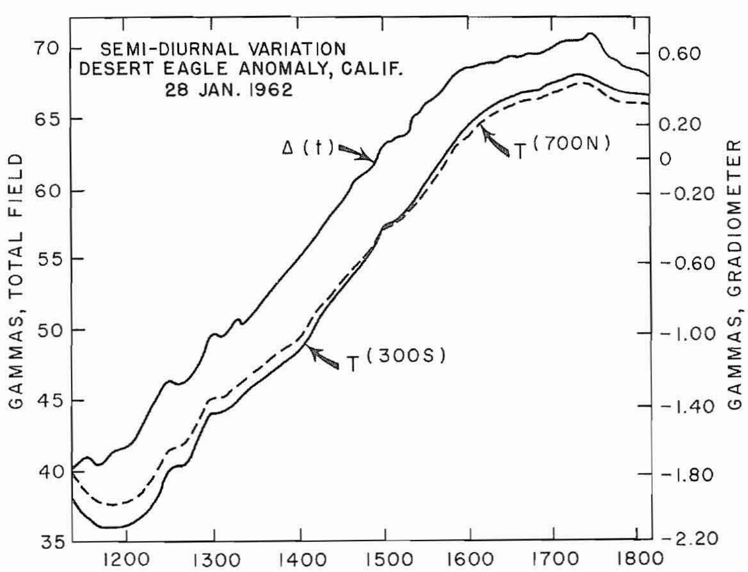
Figure 9 (from Leney, 1966) is an example of the type of magnetic response obtained over iron formation in the Lake Superior region.

An interesting extension of the magnetic method has recently been reported by Goldstein (1964). He described experiments to distinguish between induced and remanent magnetization of near-surface sources. Two rubidium vapor magnetometers capable of resolving the field to 0.01 gamma were used. Simultaneous observations were made at stations approximately 1000 feet apart. Observations were made of magnetic field micropulsations with periods from 5 to 150 seconds, and of the longer-period diurnal variations. The basic assumption of the technique was that a source of remanent magnetization would have a response independent of the strength of the external field. On the other hand, the response of a source having only induced magnetization should be directly proportional to the external field. Therefore, a measure of the intensity of the induced magnetization can be



(from Bath, 1967)

Figure 8. Increase of remanent intensity as a logarithmic function of time for thin-bedded east Mesabi iron formation.



(after Goldstein, 1964)

Figure 10. Long period geomagnetic variations observed January 28, 1962 at Desert Eagle anomaly stations 700N and 300S.

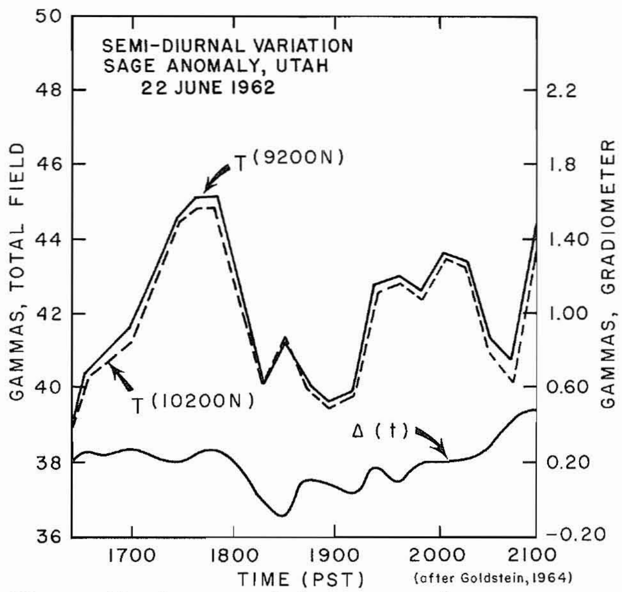


Figure 11. Long period geomagnetic variations observed June 22, 1962 at Sage anomaly, stations 9,200N and 10,200N.

obtained from the amplitude of the time variations observed simultaneously at two sites, one the static field anomaly and the other removed from it. The spatial variation of the induced alternating field can be used to estimate the susceptibility contrast if the direction of the inducing field and the geometry of the orebody are known.

Figure 10 shows the long periodic variation in the total field on and near an anomaly due to induced magnetization. Note that the difference curve, the gradiometer, follows the diurnal fluctuation in the total (intensity) field. Figure 11 shows the same type of information for a remanent magnetization source. Here the gradiometer curve does not follow the total intensity variations.

Figure 12 (after Gay, 1963) shows a NS air magnetic profile across a magnetite deposit in the Marcona district of Peru. The district is near the geomagnetic equator, the field inclination being about −4 degrees. The ore zone coincides with the steep gradient between the high and low intensity peaks. In the region of profile *A* it strikes about N70E. Figure 13 is a profile across the north end of the same ore zone where the strike is approximately N20E. Gay found that in general the ore was indicated by a high-low combination with the ore in between the two. At times the ore zone was displaced toward the high or toward the low part of the curve depending upon the local dip and strike.

Figures 14 and 15 show the magnetic field about the Dayton iron deposit which is located about 64 degrees north, geomagnetic latitude. The data were taken at 250, 500, 750, 1000, 2000 and 3000 feet terrain clearance as well as on the ground. Figure 14 is an east-west section view showing the shape of the earth's magnetic field, with contours in hundreds of gammas. The field is approximately symmetrical about a north-south axis. Figure 15 is a north-south section through the same ore zone. Note that the field is distorted to the south by the inclination of the earth's magnetic field.

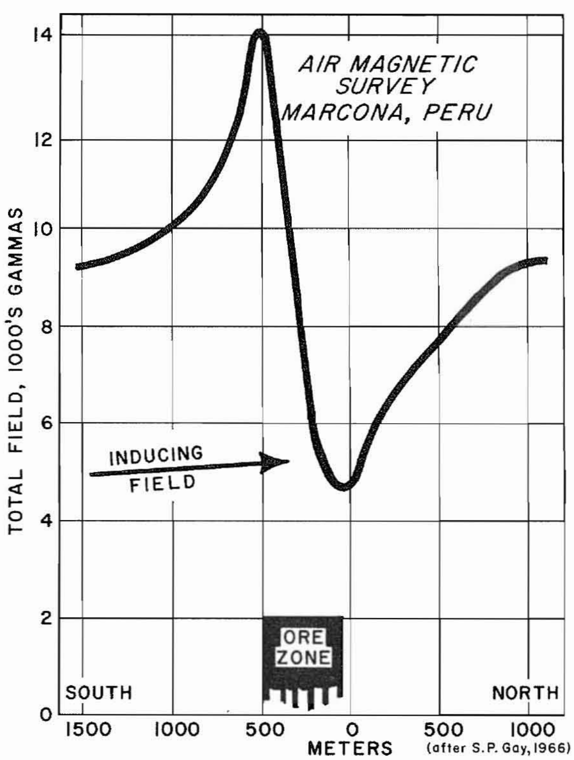


Figure 12. Interpolated air magnetic profile, Marcona district, Peru.

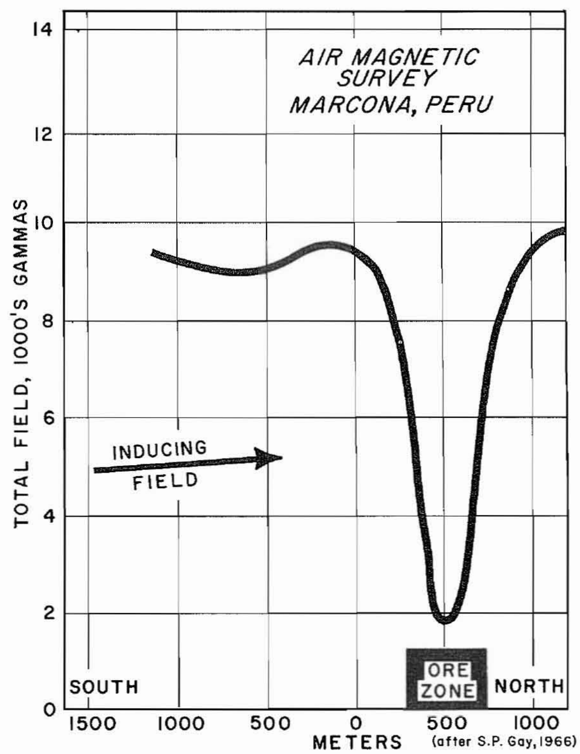


Figure 13. Interpolated air magnetic profile, Marcona district, Peru.

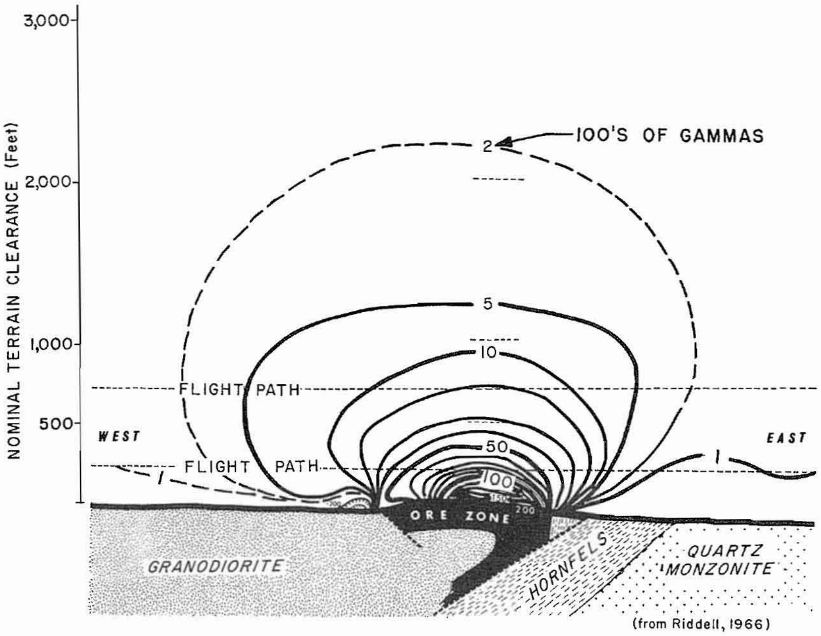


Figure 14. East-west section through the anomaly field of the Dayton orebody, Nevada.

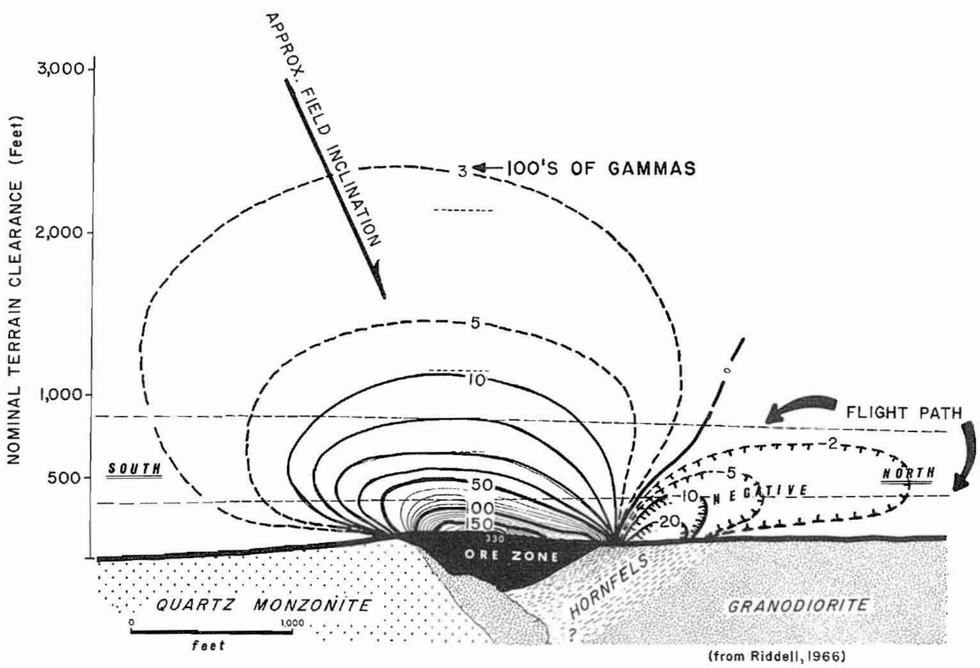


Figure 15. North-south section through the anomaly field of the Dayton orebody, Nevada.

Gravity method

Gravity surveying is finding increased application in the search for and evaluation of iron deposits. Positive gravity anomalies are most often found in association with iron ores. The most common ore minerals, hematite and magnetite have a specific gravity of about 5.1. The normal density range for environmental rocks is 2.6 to about 3.1. However, the density contrasts observed in the field seldom are as great as suggested by the figures for minerals and rocks. The density of ores is reduced by their content of lower-density dilutent minerals such as quartz and calcite. The increase in porosity of ores because of secondary leaching or local brecciation leads to further decrease in bulk density. The density of the environmental rocks is frequently increased by the development of abundant high-density minerals such as garnet and grunerite. Figures 16 and 17 (Hinze, 1966) illustrate the effect of ore composition and porosity upon the density of iron ores. Referring to Figure 16, we see that, for example, a quartz magnetite rock having 20% soluble iron would have a density of about 3.1. Referring to 17, we see that a quartz-hematite orebody having 50% iron could have a bulk density greater than, the same or less than 3.1, depending upon the moisture content of the ore.

In some cases negative anomalies have been found associated with direct shipping ores. Brant (1948) has reported such an association in the Labrador trough area. Apparently the process of natural leaching of silica from the iron-rich protore resulted in

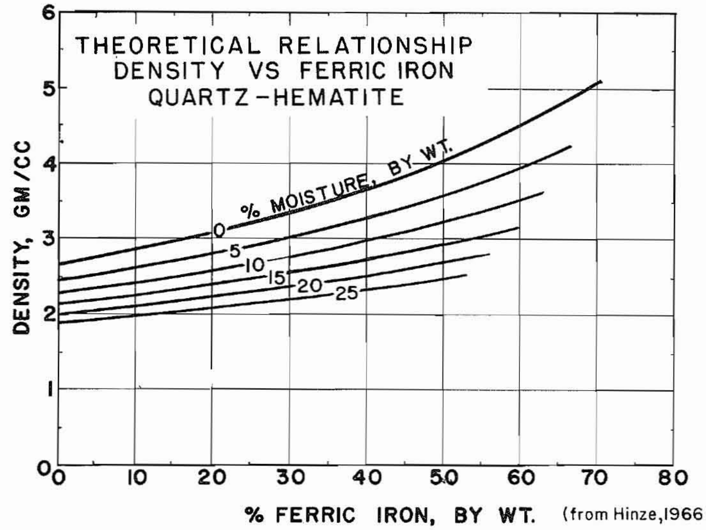


Figure 16. Relationship between density and percentage soluble iron for theoretical and observed iron ores.

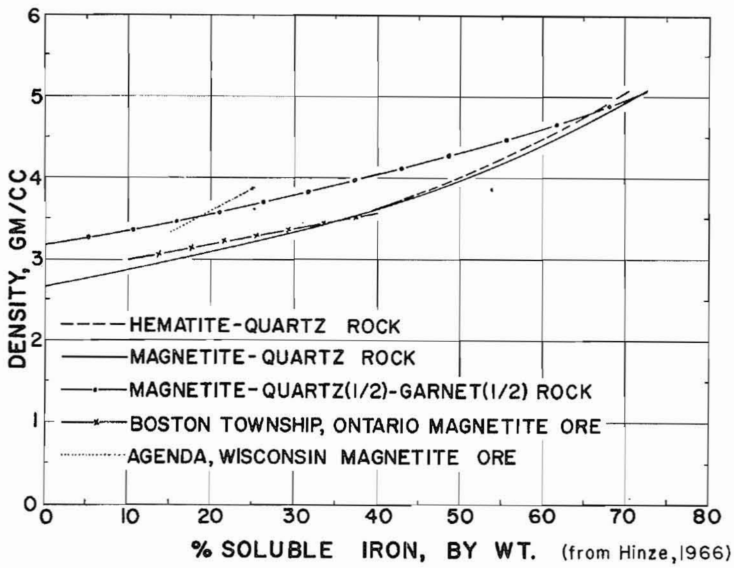


Figure 17. Theoretical relationship between density and percentage of ferric iron in a hematite-quartz rock with varying degrees of porosity.

an increase in porosity and hence a decrease in bulk density. Hinze (1966) reports that in the Vermillion iron range of Minnesota the iron formation produces both positive and negative anomalies. The country rock, the Ely greenstone, has a mean density of 2.95. The iron-rich portions of the Soudan iron formation have a density of about 3.20. The iron-poor areas of the Soudan have a density of 2.80. Thus negative anomalies associated with the leaner portions of the formation may be used as an aid in mapping the course of the zone of interest.

Figure 18 is an example of a gravity profile over an iron orebody. Note that the peak gravity value lies over the horizontal ore zone and the same zone is not clearly indicated by the magnetic data.

Electrical methods

The application of electrical methods in iron exploration has been primarily on an experimental basis. The results of numerous field experiments demonstrate that many electrical methods can provide useful information under favorable conditions. As examples, Ward (1961) has demonstrated in field experiments that a magnetite body having high conductivity and high permeability responds to electromagnetic induction either as a permeable mass or as an eddy current conductor, depending upon the frequency applied. Frischknecht (1961) has conducted experimental electromagnetic surveys over the oxidized iron formations in the Mesabi and Cuyuna Ranges and over the magnetic taconites in the eastern Mesabi and western Gogebic ranges. Zablocki (1962) has studied the electrical and magnetic properties of a replacement-type magnetite deposit by means of drill hole logging. He noted that approximately 20 percent magnetite by volume was necessary to render the rock conductive. In a similar study in the Gogebic iron range, Zablocki and Keller (1957) showed that solid conduction occurred in cases where the magnetite content was as little as 6 percent by volume. The difference in magnetite content necessary to significantly influence the conductivity is considered due to differences in the mode of occurrence of the magnetite grains of the deposit. In the replacement deposit the magnetite occurs as disseminated crystals; the Gogebic range magnetite is concentrated in thin beds and anastomosing bands which provide good electrical continuity over large volumes of rock.

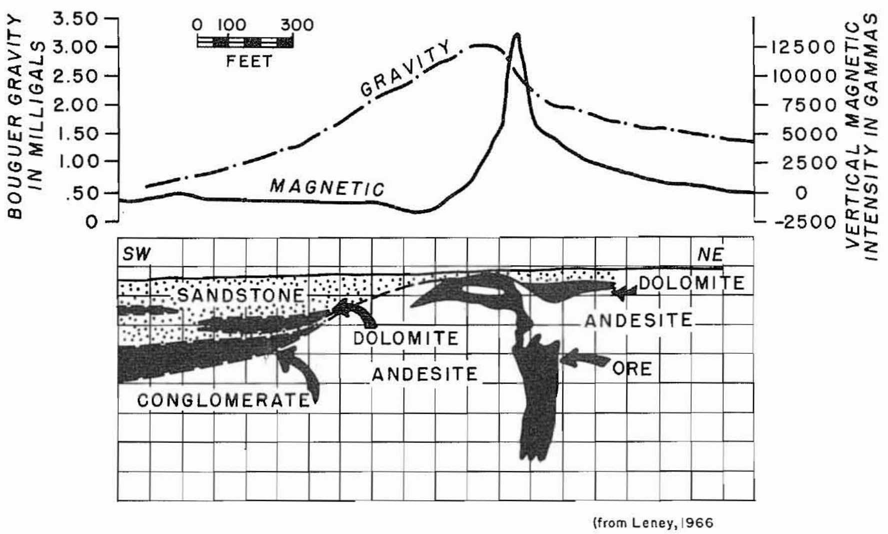


Figure 18. The Northwest orebody at Iron Mountain Missouri. The horizontal lobe of the body is indicated best by the gravity data.

Contents

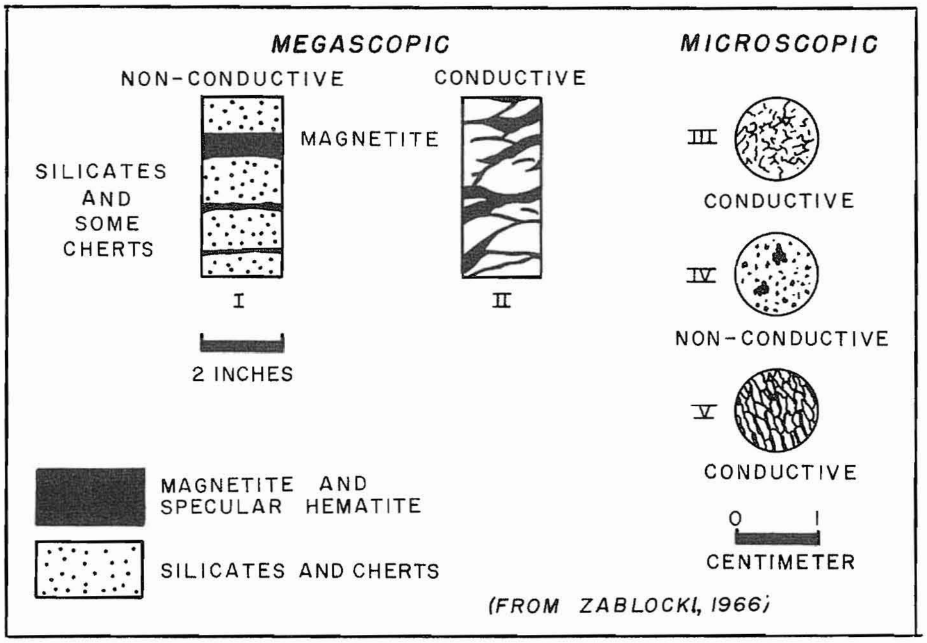


Figure 19. Features influencing electrical conduction through iron-bearing rocks, western Gogebic iron range, Wisconsin. Dark areas shown in thin sections are magnetite and specular hematite, light areas are silicates and chert.

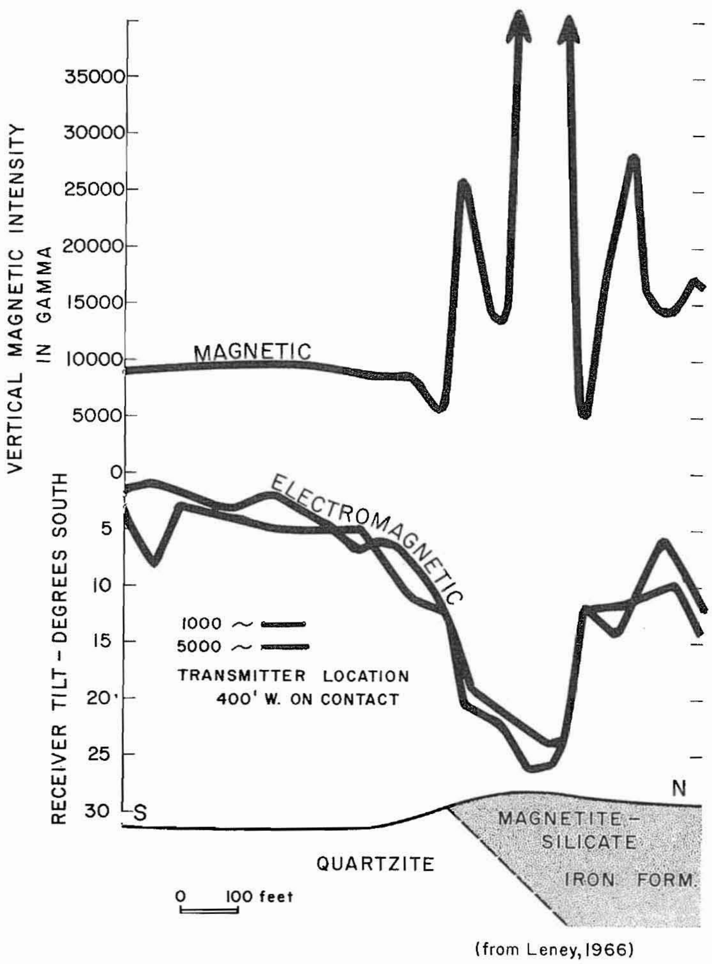


Figure 20. Vertical loop electromagnetic and magnetometer profiles over a contact between quartzite and iron formation.

Figure 19 illustrates geometric arrangements of magnetite giving rise to conductive and nonconductive iron ores. An example of a pronounced electromagnetic response obtained with a tilt-angle EM system over conductive iron formation is shown in Figure 20. Zablocki (1962) has investigated the electrical properties of iron formation by logging techniques and has found that in some areas the resistivity and self-potential curves (Figure 21) were of diagnostic value in some areas while in other areas the same types of data were not of significant value. Table II tabulates the resistivity values of iron formation and country rock at several localities in the Lake Superior region (from Zablocki, 1962). Except for rocks containing electronically conducting minerals, the resistivity is primarily a function of porosity. The porosity of iron formation was found to vary directly with the degree of oxidation. Resistivity measurements then can provide an indication of the degree of oxidation and leaching of the iron formation.

Geoelectrical measurements in iron ore prospecting have been too rare to permit firm conclusions regarding the general usefulness of these techniques. In the electromagnetic measurements over magnetic bodies the magnetic permeability as well as the electrical conductivity may affect the response and make the results difficult to interpret. The usefulness of electrical measurements is probably directly related to the amount of geological and geophysical control data available.

Conclusion

At present, there is an abundant worldwide supply of iron ores. The high level of exploration activity we have witnessed after the second World War has largely ceased. The present supply picture is the result of two factors – first, since the war there have been significant iron ore discoveries in many parts of the world, notably in Western Australia, on the west coast of South America as well as in the U.S. and Canada. However, the major contributor to the present world supply was a technological revolution that was initiated when the first pellet went to market in 1956. Production of pellets has made possible the use of low-grade

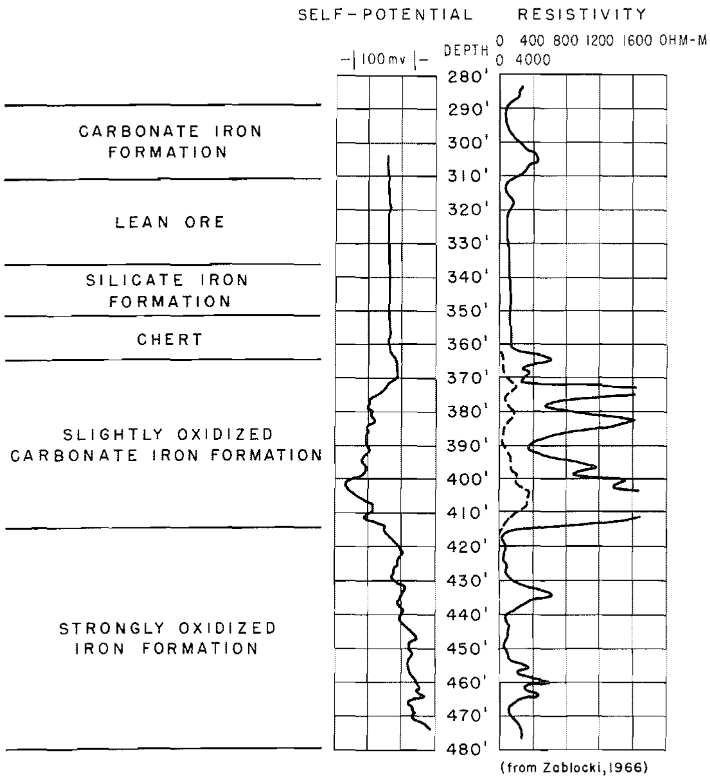


Figure 21. Self-potential and resistivity logs of oxidized iron formation Cuyuna iron range, Minnesota.

Table II. Resistivities of rocks in the Lake Superior region.

Rock Type	Resistivity (in ohm-meters)
Cuyuna iron range	
Glacial till	500–1,000
Lacustrine sediments	30
Slate	1,000–5,000
Slate with graphite	1– 1
Unoxidized iron formation	400–1,800
Hard iron ores (low porosity)	200– 700
Oxidized iron formation (depending on degree of oxidation)	100– 500
Soft iron ore (high porosity)	35– 80
Quartzite	5,000
Western Mesabi iron range	
Iron ore (high porosity)	50– 80
Western Gogebic iron range	
Slate	1,000–5,000
Slate with graphite	1
Slaty iron formation	5,000
Iron silicates and carbonate	1,000–5,000
Magnetite with silicates	1,000–5,000
Specularite and magnetite-bearing cherts	1– 30
Quartzite	5,000
Iron River district	
Unoxidized graywacke	1,500
Oxidized graywacke	100– 500
Unoxidized iron formation	400– 800
Oxidized iron formation	80– 400
Iron ore (soft hematite)	20– 60
Iron ore (hard goethite)	120– 200
Pyritic-graphitic slate	1– 1

taconite ores and also the use of replacement type ores having a high content of sulfur, copper or other deleterious constituents.

It may be some years before we again see a repetition of the exploration activity that we witnessed during the 1950s. But when the time does come, improved magnetic measuring and interpretation techniques as well as a number of auxiliary geophysical methods will be available to aid in the search.

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Iron ore prospecting in Scandinavia and Finland

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Geological Survey of Sweden

Abstract. Three centuries of a systematic and successful geomagnetic search for iron ores has left today's Scandinavian prospector with the challenge of exploration in remote or virgin ore provinces and interpretation of vague anomalies caused by deep-seated or abnormal orebodies. Modern geophysical iron ore prospecting in Finland, Norway and Sweden relies on many up-to-date techniques. Annual expenditures are over the $1 million level.

Based on available geological evidence aeromagnetic reconnaissance surveys are made, with detailed closeup where necessary. Interpretation of the following ground magnetic surveys is facilitated by use of advanced data processing. During the last decade additional geophysical methods have been increasingly used, particularly gravity measurements to support the magnetic results and to extend the search to nonmagnetic ores. Rock property measurements facilitate interpretation efforts. Magnetic drill hole logging has proven an effective tool for localization of deep ore. Many local problems have encouraged flexibility in instrumentation, technique and organization of the surveys.

Some special exploration cases in Finland and Norway are reviewed. The Geological Survey of Sweden's 1963-1972 inventory survey of iron ore resources in the Lapland district is examined.

Résumé. Après trois siècles de prospection géomagnétique relative au minerai de fer en Scandinavie, il reste maintenant au prospecteur à explorer des provinces éloignées ou vierges et à interpréter des anomalies vagues ou insolites causées par des massifs de minerai profonds ou anormaux. La prospection géophysique moderne du minerai de fer en Finlande, en Norvège et en Suède repose sur une grande variété de méthodes récentes. On affecte annuellement plus de $1 million à ces travaux.

Les travaux de reconnaissance aéromagnétique accompagnés de relevés plus détaillés lorsque c'est désirable et possible, sont suivis, de relevés magnétiques ordinaires au sol et l'interprétation est poussée aussi loin que le traitement des données peut le permettre. Au cours des dix dernières années, il y a eu une notable augmentation dans l'utilisation d'autres méthodes géophysiques, et surtout des méthodes gravimétriques, afin de confirmer les résultats obtenus par les méthodes magnétiques et pour donner plus d'ampleur aux recherches de minerais non magnétiques. Les mesures des propriétés de roches facilitent les travaux d'interprétation. La diagraphie magnétique des sondages est un instrument très important pour localiser les minerais en profondeur. Différents problèmes locaux ont amené une certaine flexibilité dans l'utilisation des instruments, des techniques et dans l'organisation des travaux.

L'exploration des minerais en profondeur en Finlande et en Norvège est examinée. On présente aussi de façon assez détaillée une entreprise de la Commission géologique de la Suède qui consiste en un inventaire des ressources en minerai de fer du district Kiruna commencé en 1963 et qui doit se poursuivre jusqu'en 1972.

Even within such a relatively small unit as Scandinavia, prospecting activities depend on a complex combination of many background conditions. Obvious local prerequisites are promising geological environment and encouraging legislation. In established mining districts both economic and social traditions may determine measures to provide satisfactory ore reserves and to meet changing tendencies of the market.

All the mineable iron ores in Sweden (Geijer and Magnusson, 1952) belong to one of two iron ore provinces, both situated within the Fennoscandian Precambrian shield (see Figure 1). In the old mining district of Bergslagen (Magnusson, 1960) quartz-banded ores with an average Fe-content of 33% are the most prevalent, followed by apatite ores (57% Fe) and skarn- or limestone ores (33% Fe). In the iron ore province of Lapland (Grip, *et al.*, 1960) apatite ores of the Kiruna type (60% Fe) are predominant but many sizeable skarn-ores (40% Fe) and a few sedimentary ores (34% Fe) are known, but they are not mined at present. In both provinces the ores always occur in leptites, i.e., acid supracrustal volcanic rocks, usually referred to the Svecofennian cycle.

For centuries iron ore mining and manufacture in Bergslagen formed the backbone of Swedish economy. Today approximately 75% of the total production and 85% of the export come from the Lapland mines of LKAB (Luossavaara-Kirunavaara AB), in which the state has held a 95% share since 1957. About 40 privately owned mines account for the remainder. Sweden's present annual production of close to 30 million metric tons supplies about 5% of the world's iron ore consumption. An excellent review of the Swedish mining industry, with a historical introduction, has been given by Chris Mamen (1967). The need for a broad knowledge of quantities and qualities of reserves is a major concern of the mining industry and a strong incentive to maintain vigorous exploration programs for iron ores.

Norway and Finland are less favoured by iron ore deposits, and iron mining has never reached the same importance as in Sweden. However in recent years both countries have made determined efforts to develop their mining industry. As a result of both state and private prospecting and research enterprises, mining has started on some new iron ore finds. During the last decade iron ore production has been rapidly increasing and is now approaching 3 million metric tons per year in Norway and 1 million tons in Finland. The sites of working mines are shown in Figure 1. Deposits marked T depend for competetiveness on their content of ilmenite or vanadium.

In a report by Poulsen (1953) the Norwegian iron ore reserves are estimated to be more than above 1 billion tons. Finland has reported reserves of 200 million tons of Fe- and Ti-ores. Prospecting activities to widen the ore base, particularly the quality, continue in both countries.

Geologically set in a young sedimentary basin, mainland Denmark has only negligible deposits of bog ore. Even on the Danish dependency Greenland, geologically closely related to Canada, no iron ores of any importance have so far been discovered.

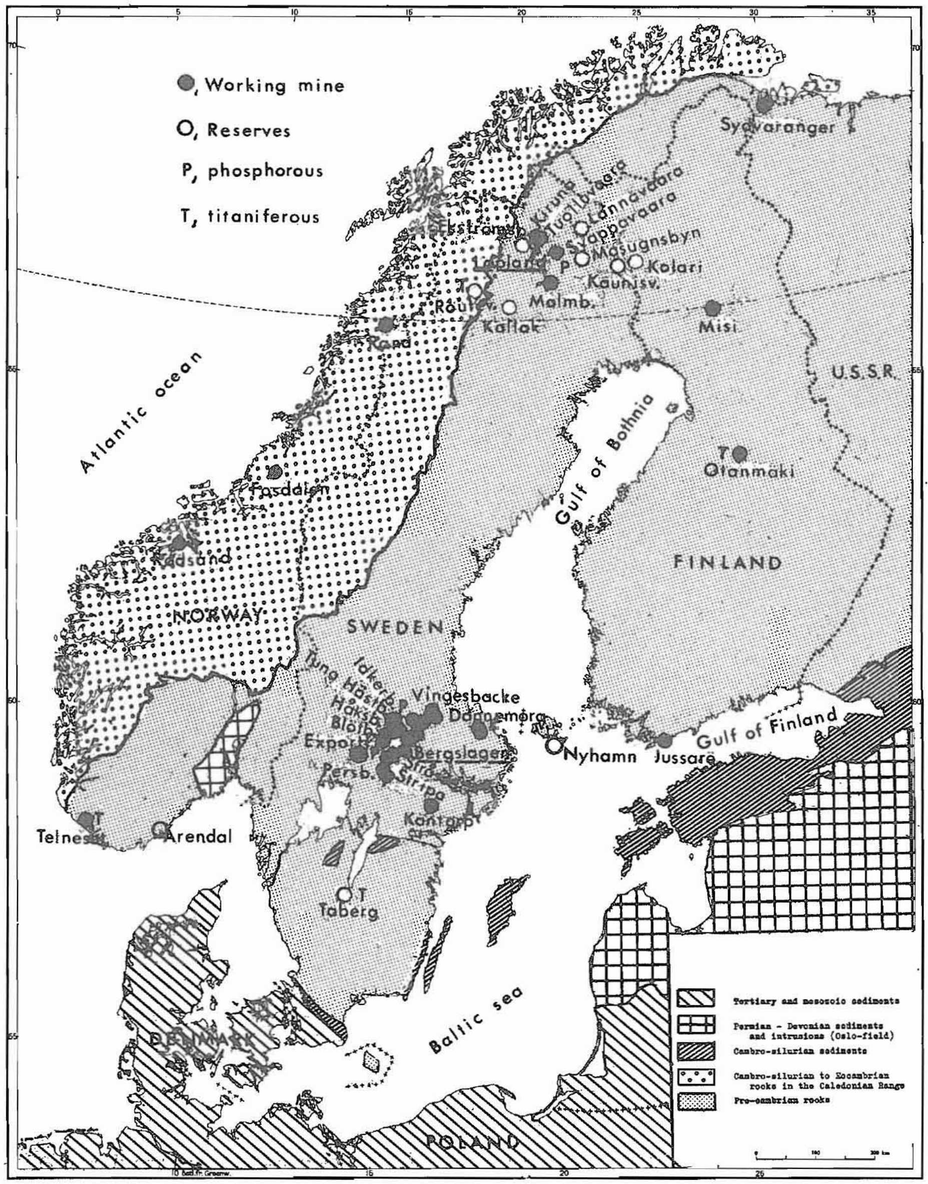

Figure 1. Geological sketch map of Scandinavia with most important iron ore mines and known major reserves.

Iron ore prospecting

History. Outside the Caledonian mountain range the Precambrian bedrock is covered to more than 95% by glacial drift. Thus the Scandinavian environment is conducive to the introduction of any prospecting method superior to classical trenching.

Systematic prospecting measurements of local anomalies in the Earth's magnetic field are reported in Sweden as early as 1640 (Carlborg, 1963). The first recorded case of a true geophysical find dates from 1667. Further records are scarce, but the finding of ample reserves of iron ore by the end of the 17th century after a marked shortage some years earlier attests to the success of the new prospecting tool.

Ever since then magnetic prospecting for iron ore has been practised determinedly and with continuously improved instrumentation. The first instrument was probably a modified mariner's compass. It was superseded in 1770 by the Swedish Mine-compass (see Figure 2), probably the oldest instrument invented solely for prospecting purposes. In the Mine-compass a balanced magnet, turnable horizontally around a needle and pivoted so as to be able to swing even in a vertical plane, allows observations of sudden changes in both declination and vertical intensity when carried along terrain lines. The Thalén-Tiberg magnetometer, was developed in 1870. It is a simple and efficient instrument, capable of measuring D, H and Z with an accuracy of about 100 gammas. In surface exploration it has now been replaced by modern magnetometers, but still finds some application in underground reconnaissance and check up.

Present prospecting activity. Exact figures for expenditures for mining exploration are not published. However, information for the years 1963 or 1964 collected by the Mining associations of Norway (A. Eriksen, 1967) and Sweden (president A. Boman, private communication) may be combined with other available data on the estimates of costs spent on surface prospecting for all kinds of ores and are given in the table. Exploration enterprises by state-owned mines are listed among companies, and so are

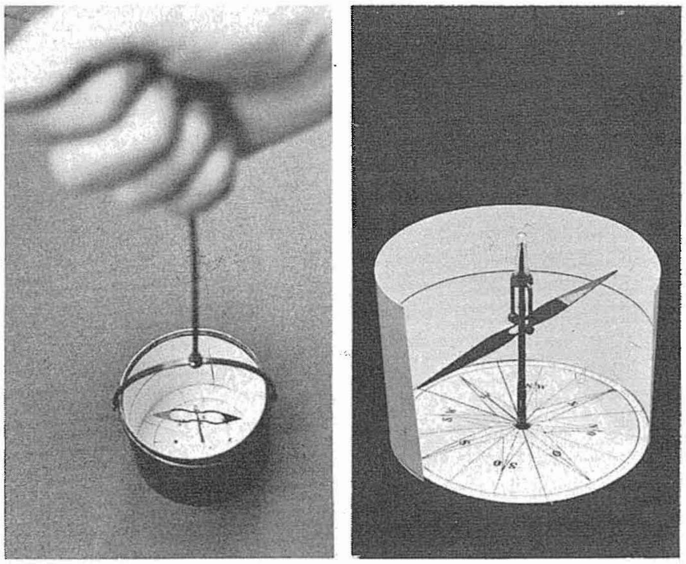

Figure 2. Swedish Mine-compass. Left: On search traverses the compass was carried in bow or triple-string. Rotating and dipping movements of the magnet were observed. Right: Close-up on another compass, demonstrating the suspension of the needle, the length of which was generally 1 to 2 inches.

investigations made by the Geological Survey of Norway on commission for Norwegian companies.

Of the Norwegian total expenditures in 1963 about 70% are reported to go to iron ore prospecting. For Sweden the corresponding figure may be taken to be about 55%, while the Finnish percentage is probably much lower, maybe somewhat below 40%. By these admittedly rather uncertain estimates, we come out with present annual expenses for iron ore prospecting proper of about 15 million S.Kr., of which 5 million S.Kr. (ab. $1 million) are spent on geophysics. It is particularly noteworthy that governmental institutions, in the form of the geological surveys in all three countries, are taking an active part in prospecting as well as conducting normal routine geological mapping operations.

As the surveys' own costs included in the table comprise only current expenses, their share of the total enterprise is actually higher than the 35% listed. More than half of the geological and geophysical work is on their behalf. New discoveries made by the surveys are concessioned to state-owned companies or leased to existing private companies in the district.

The more important mining companies have their own prospecting organizations. Naturally these prospecting groups vary in size and resources with the economic strength and ore reserve problems of the companies in question. Small companies as a rule rely on private contractors or technical support from their government and so do even the larger companies when special equipment is required.

Prospecting techniques

Introduction. Centuries of efficient iron ore prospecting have disclosed most of the 'easy finds'. Clever and successful predecessors have left today's Scandinavian prospector with the challenge of exploration in virgin and often inaccessible ore districts, or the interpretation of vague or complicated anomalies from deep-seated or unusual bodies in the classical mining provinces. The trend to cope with this situation may be discerned in all three countries.

Airborne magnetic surveys. In old mining districts as well as in virgin areas the first approach is generally an aeromagnetic reconnaissance survey based on available geological evidence. Several contractors, Scandinavian and foreign, have been entrusted with orders from private companies. In Finland, Norway and Swedish Lapland, however, the systematic surveys made by government institutions form the most important contributions.

The Geological Survey of Finland (Geologinen Tutkimuslaitos (GTL) in Helsinki) developed in 1954 a combined magnetic and electromagnetic airborne system. Since that time about 75% of the total area of Finland has been covered methodically with this equipment with lines at 400 m intervals and a flight elevation of 150 m. Numerous contemporary detailed surveys have been conducted, often at the request – and partial payment – of private mining companies. Magnetic and electromagnetic maps are published regularly.

The Geological Survey of Norway (Norges Geologiske Undersøkelse (NGU) in Trondheim) initiated a similar system in 1959. Since the topography in most of Norway is extremely rugged, local conditions influence line spacing and height, and much time must be spent on exactly locating the flight lines and altitude from camera strips. One third of the country has been already flown and the coverage increases at 5% per year. Many local surveys have been performed, among these several on contract for private companies.

The Geological Survey of Sweden (Sveriges geologiska undersökning (SGU) in Stockholm) started in 1959, but only with magnetic equipment. A detailed systematic survey has been

Prospecting expenditures in Scandinavia – all ores, 1963 (Finland and Norway) or 1964 (Sweden).

a) Total expenses in million S.Kr. (1.00 S.Kr. = $0.20)

	State Instit.	Companies	Total	% of Prod. Value
Finland	3,2	7,3	10,5	(?)
Norway	0,8	4,6	5,4	2,2
Sweden	6,2	7,2	13,4	0,8
Total	10,2	19,1	29,3	
% of Total	35	65		

b) Proportion on activities by percent

	Finland			Norway			Sweden		
	State	Priv.	Total	State	Priv.	Total	State	Priv.	Total
Geology	23			5	17	15	26	15	20
Geoph. ground	12	not		30	14	16	25	17	21
" air	30	avail-		38	33	34	9	1	5
Geochemistry	4	able	–	22	–	3	2	–	1
Drilling	31			5	36	32	36	43	40
Research	–			–	–	–	2	24	13
	100			100	100	100	100	100	100

run every summer in the iron ore district of Lapland (Werner, 1963). Forty thousand km^2 have been flown with a 200 m line spacing at 30 m altitude. The results are published in the form of aeromagnetic maps at a scale of 1:50,000 after any areas of potential economic interest have been secured. Besides the Survey effort more than half the area of Sweden has been covered by private airborne measurements, but the results are not commonly available and are of greatly differing density and quality.

The magnetometers used by the three geological surveys are of the total intensity fluxgate type. Much development work has been done on instrumentation and on elaborate print-out systems, the latter as preparation for automatic data processing.

To improve the quality of the interpretation, considerable effort is made to determine susceptibility and remanence of both the ores and the prevailing rock types. In the Kiruna district for instance, Werner (1945, 1967) reports the remanent magnetization of most rocks and ores to be isothermal with Q-values ranging from 0.2 to 1, with a noted concentration towards the lower value, which has lead to a set of simplified rules for interpretation.

Ground magnetic surveys. In a few cases aeromagnetic anomalies may be drilled directly. Normally, however, they are followed up by geological large-scale mapping combined with conventional detailed ground magnetic measurements on promising local anomalies.

In view of the latitudes in question, measurements of the vertical intensity are standard, but D and H measurements are frequently used where the interpretation of the results is particularly ambiguous. Total intensity measurements are rare. Over shallow ores the accuracy is less important, but when the magnetic bodies are deeply buried and advanced interpretation techniques are required, the flank characteristics of the anomalies must often be known within 10 gammas or even better. This puts a premium on precision instruments.

In many companies established procedures for two-dimensional interpretation by means of nomograms and master curves for common geometrical shapes are currently being replaced by 'indirect-approach' model-programs for computers. Much development work is probably conducted these days on expanding this technique to three dimensions.

Again, measurements of magnetic properties of ore and host rock are desirable for a reasonably safe interpretation. As most new finds are in virgin settings or not outcropping, it is often necessary to drill a few holes to get core samples for examination. Such holes are often logged with drill hole magnetometers to further help the evaluation of the anomalies and guide subsequent drilling.

Additional ground geophysics. The above sampling procedure may prove too costly in cases where the interpretation of the surface magnetometer survey indicates deposits of questionable economic value. As well, transportation and service problems in barely accessible places may increase the cost of drilling. In such cases the application of additional geophysical methods, particularly gravimeter measurements, may prove to be more efficient. The possibility of discovering non-magnetic hematites is another strong motive to use gravimeter measurements in an early stage of a survey. In fact, the results obtained by combined magnetic and gravimetric ground surveys have so often rendered superior information, that a general trend during the last decade has been to introduce gravimeter measurements as a standard procedure in iron ore prospecting.

Interpretation techniques have been developed to fully utilize the combined magnetic and gravimetric results. Based on the calculation of total excess mass, or, for ore close to the surface, of tonnage for each meter in depth, and even density-contrasts in the upper part of the ore, it has been possible to put more definite limits to the true magnetization of the ore (Werner, 1965). This in turn provides new possibilities for the use of magnetic results to check the gravimetric quantitative interpretation, and obtain a more accurate and detailed delineation of the deposit. A further development of the interpretation technique for combined results, using direct methods based on computer procedures, is in progress (Vogel, 1964). Some informative case histories have been reported at Nordic geophysical meetings, but none have so far been published in languages of international usage.

The usefulness of other geophysical methods has also been examined. Seismic methods have been tried to establish the position of contacts between dipping ore sheets and the host rock in an effort to determine the depth extension of the sheets. However, with the small velocity contrast involved it appears that transformation and crush zones around the contacts render the results in most cases unreliable or of very little value.

Investigations have been made to determine whether electromagnetic measurements, particularly the Slingram method would be able to locate shallow hematite bodies. However, pure hematites appear to have conductivities which are too low to allow detection with EM methods (Werner, 1961). This was confirmed by results obtained with the INPUT method, which failed to indicate hematite deposits during test flights in Lapland in 1965.

Special techniques. Because much exploration work is carried out in remote and inaccessible areas, flexibility in organization and choice of methods is essential. The growing interest in deep-seated ores has also been an incentive to develop special techniques and instrumentation. Several drill hole magnetometers have been developed which are capable of measuring three magnetic components with an accuracy of 50 to 100 gammas. Recently this has been achieved with probes of diameters down to 36 mm, able to work to a depth exceeding 100 m. Up to now only meter-reading instruments have been in use, but development of a continuously recording apparatus is under consideration.

Of particular interest are cases where magnetometer logging has 'saved' a dry hole, for instance by indicating the distance from the hole to ore, or by explaining unexpected ore displacements (Figure 3). Just as obvious is the advantage of using drill hole results to delineate the position of the lower magnetic pole of the body to estimate the depth extension of an orebody. Drill hole magnetic measurements may be used as a standard to enhance the interpretation of ground magnetic results and to guide drilling programs thereby often helping to keep drilling costs down.

An interesting case of extensive use of magnetic drill hole logging has been reported from the Otanmäki mine in Finland. A drill hole magnetometer (Levanto, 1959) was used in all rotary drilled holes, even underground, to aid the exact mapping of the

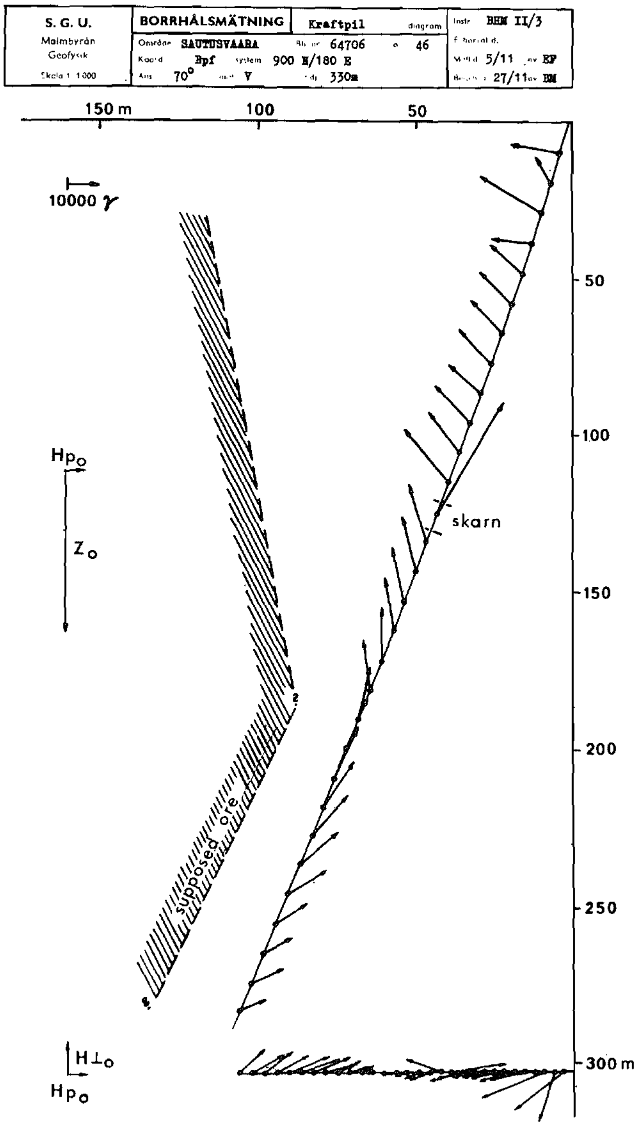

Figure 3. Magnetic drill log from a 'dry' hole, where the orebody has unexpectedly been cut by an oblique fault. The anomaly vectors indicate that below 200 m the ore boundary lies almost parallel to the ore.

thin, irregular, steeply dipping ore sheets of the mine. Even caving and blasting operations are directed with the assistance of magnetic measurements. Magnetic check-ups across cave roofs and measurements with a company-built permeameter in pneumatic-drilled test- or shotholes are matched with the mining operations. The results are compiled in ore-quality diagrams, which are used to guide the actual shooting. A description of the mapping and interpretation procedures for magnetic drill hole logging as used at Otanmäki is given by Levanto (1963).

From the Fosdalen mine in Norway a complete case history has been published by Logn (1964). Airborne and ground magnetic measurements had indicated, after careful smoothing, that the ore mined at that time probably continued in the strike direction after a downfault of 600 m. Starting from the lowest level, an exploratory adit was driven over the supposed ore. As demonstrated in Figure 4, magnetic H and Z measurements in crosscuts to the adit indicated the existence and probable position of the ore sheet. By a clever drilling method, where carefully guided deflection and wedging saved expensive tunnelling, the ore sheet was finally established to lie between 700 and 1200 m below the surface.

Another example of an unorthodox approach has been presented for the Raajärvi mine in Finland by Paarma and Levanto (1960). What was requested at Raajärvi was an exact delineation of the irregular outcropping part of the ore before removal of 30 m of overburden. Among other methods, measurements were tried with a conventional Z-magnetometer at two different levels (about 60 cm apart) at each station. On the vertical derivative maps constructed from these measurements, the strongest horizontal gradient proved to give the best fit with the actual ore boundary. The authors strongly recommend direct measurements of the vertical gradient of the magnetic Z-component as a most efficient tool for mapping of near-surface structures.

State inventory survey in Swedish Lapland. The state interests in exploration in the Scandinavian countries are mostly motivated by long-term control of supplies for vital industries or distribution of man-power. The major systematic survey now in progress in Swedish Lapland may serve as an example of state-managed prospecting and at the same time of a typical Scandinavian approach to iron ore exploration.

Facing, during the last decades, an accelerated depopulation of already sparsely inhabited Lapland, the Swedish authorities initiated a general survey of the social and economic problems and possibilities of the province of Norrbotten (comprising the actual part of Lapland), where the state has vast interests in land and mines. Within the scope of this survey it was found to be particularly important to acquire sound and up-to-date knowledge of quantity, quality and geographical distribution of all iron ore resources in this province. Accordingly a 1963 parliamentary resolution authorized SGU over a 10-year period, with an annual appropriation of 4 million S.Kr. (about $800,000), to carry out a detailed inventory of iron ore reserves in Lapland. A temporary claim stop for private interests, with the possible exception of companies already established in exploration, was intended to prevent dispersal of mining rights.

A special group has been set up within SGU to perform the ordered inventory survey. The geophysical department contributes with airborne magnetic measurements, as previously described, while the ore department takes care of the ground follow-up, with parallel geological, geophysical and drilling teams.

Geology. Earlier geological outline maps had been published on a scale of 1:400,000. The aeromagnetic maps now form the basis of detailed remapping to be published on a scale of 1:50,000. Much structural information is supplied for the geological maps from rough magnetic interpretation prior to the geological field work, followed by more detailed interpretation during the compilation of the geological results. Two examples of the delineation of interesting structures are given by Cornwell (1964). Collection of orientated samples of all important rock types and subsequent determination of induced and remanent magnetization aid the geophysical interpretation. An attempt to correlate prevailing rock types with statistically classified types of magnetic anomalies is still at an experimental stage.

Contents

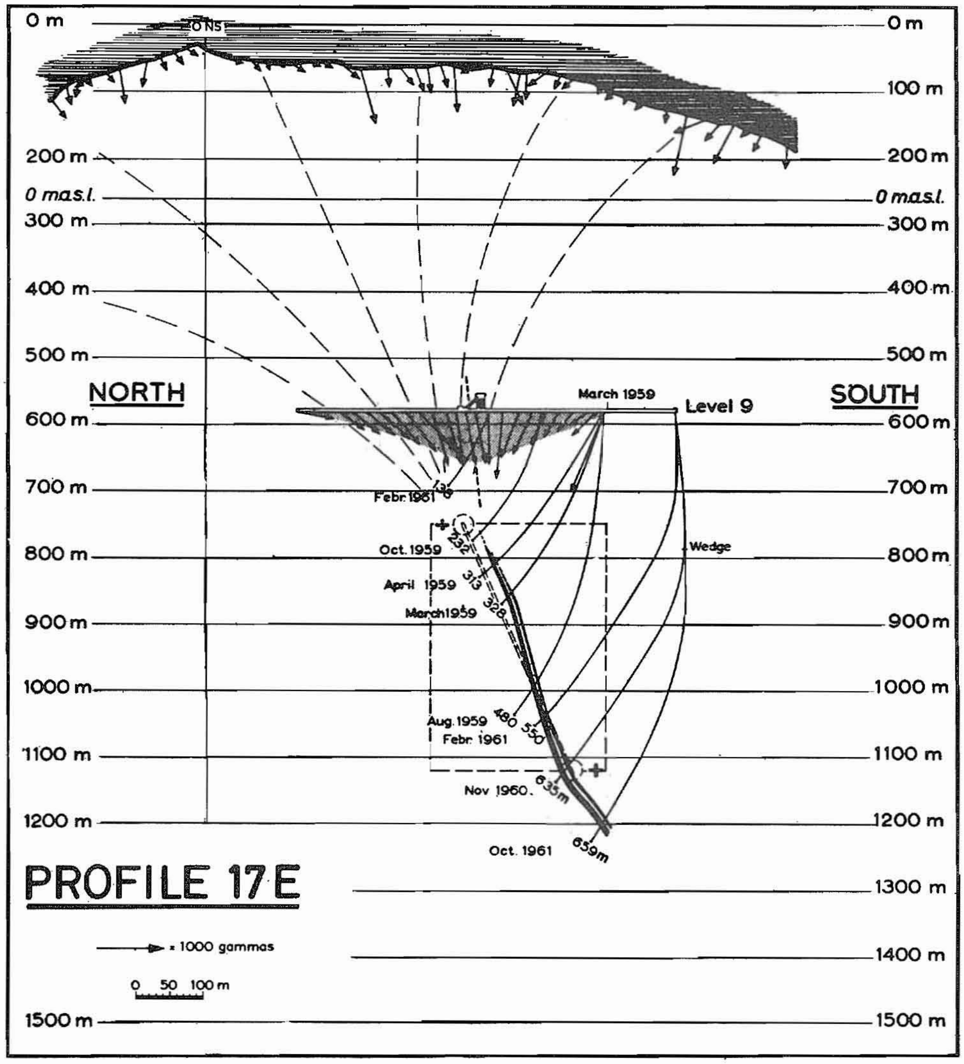

Figure 4. Profile from Norwegian Fosdalen mine. Total magnetic anomaly observed at surface and in crosscut at a depth of 500 m. Magnetics and guided drilling delineated 'eastern' ore (courtesy of Ø Logn).

Concurrently with the geological mapping, all 'suspicious' aeromagnetic anomalies are visited and, if possible, geologically classified from outcrop or boulder observations. Every anomaly which cannot be attributed to nonmetalliferous rocks on geological grounds is checked with ground magnetometry and gravity methods.

Geophysics. On the basis of the aeromagnetic map a reconnaissance survey is made with a standard line and point spacing of 80 × 20 m for magnetic and 320 or 160 × 40 m for gravimetric measurements. Denser measurements are planned and carried out as required from the reconnaissance results.

The results are presented in anomaly maps on a scale of 1:5000 for reconnaissance and 1:2000 for detailed measurements. With a computer printout system and photographic reduction it is possible in these scales to have all anomaly figures easily readable on the maps. Where advisable, coloured prints are prepared for a modest extra cost. For large areas simplified key-maps are made in a reduced scale.

The measured areas cover the flanks of all anomalies. Often the gravity survey is further extended by a more open network, or by selected separate lines to control regional features and possible anomalies from deep-seated bodies.

A program for computer-processing of raw field data directly to printout of definitive anomaly values is in progress. A constituent program for calculation of topographic corrections on Bouguer-anomalies has been in use for some years (Karlemo, 1963; Granar, 1967). With definitive anomaly figures stored in the computer, it is only natural to develop programs for routine interpretation. So far a two-dimensional model program-system allows calculations of any magnetic or gravimetric field component, plus derivatives, field continuation, etc., for models bounded by arbitrary polygons. Further development of this system to three-dimensional models has just commenced.

Diamond drilling operations are supervised by the geological section. Where geophysical evidence has given a clear-cut picture of a deposit, a full drilling program is drawn up, intended to yield maximum additional information. In ambiguous cases geological and geophysical follow-up and replanning is accomplished concurrently with drilling.

All holes are logged with a combined inclination-meter and three-component magnetometer. The magnetic field-vector diagram of a drill hole profile is completed with measurements of D and H component on the ground. Density, susceptibility and remanent magnetization are determined on drill cores selected for chemical analysis.

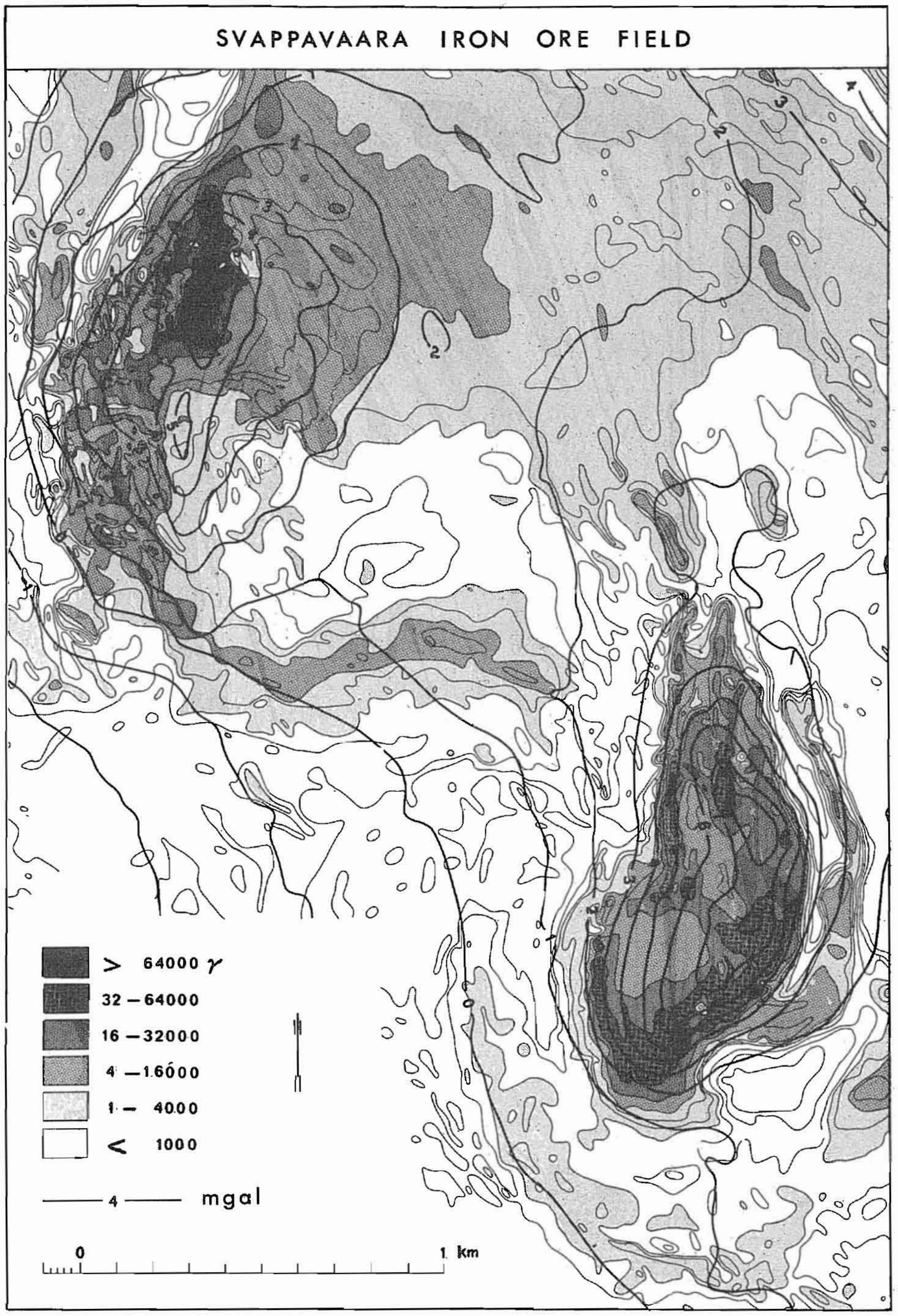

Figure 5. Combined magnetic and gravimetric anomalies over the iron ore deposits of Gruvberget (upper left) and Leveäniemi (lower right).

Special considerations. While these procedures are usually quite straightforward, two examples emphasize the importance of gravity work. From earlier surveys around Kiruna it was known that exceptional magnetic properties might be found in some of the phosphorous ores of the district. Figure 5 shows small-scale, simplified magnetic and gravimetric maps from a 1957-58 survey over the iron ore field of Svappavaara.

Of the two deposits included in the map the northernmost, Grubverget, is a N-S striking and 65° E dipping ore sheet, more than 1000 m long, 70 m wide in the centre, but thinning out toward both ends. The ore is outcropping but for a thin overburden. The vertical extent is estimated at 600-700 m. Drilling has proved 70 million metric tons of high-grade ore to a depth of 300 m. However, while the northern third of the sheet is made up of magnetite, the southern and somewhat thinner part is pure hematite. It may be noticed that the 150,000-gamma magnetic anomaly to the north completely disappears south of the narrow transition zone (the apparent continuations toward the SW are weaker, irregular anomalies over small sheets of magnetite parallel to the main orebody), while the gravimetric anomaly continues over the whole sheet.

The southern deposit, Leveäniemi, has been shown by drilling to be a very irregular, roughly syncline-shaped magnetite body, containing more than 200 million tons of ore. The eastern part, outcropping below a 6 to 14 m cover of glacial drift, is 1200 m long and up to 200 m wide. According to the magnetization normally met within the Kiruna-type magnetites, the rather weak magnetic anomaly, averaging about 40,000γ, suggests a tonnage of only 20 million tons of high-grade ore. The gravimetric anomaly, reaching a maximum of 8.8 mgal, indicates a figure of 200 million tons when converted to 60% Fe ore. The explanation for the failure of the magnetic interpretation appears to be that the magnetization of the Leveäniemi ore is ten times lower than the average for this type of ore. Apart from a martitization in the northeastern part of the deposit, characterized by a lower magnetic anomaly, it is not possible mineralogically to distinguish the Leveäniemi ore from other magnetite ores in the district.

Such experiences show that the use of gravity measurements as a standard procedure is extremely useful.

Conclusion

Considering the economic significance of iron ore mining, it is only natural that iron ore prospecting in Sweden is maintained at a rather high level of activity. In Finland and Norway prospecting efforts are stimulated by ore shortages to even higher levels than in Sweden in relation to present production.

Considerable effort is made in Scandinavia to develop and perfect new instrumentation and interpretation techniques, including automatic data processing.

The present shortage in qualified manpower, principally geophysicists, is a strong incentive to improve and rationalize all available aids of the art. In spite of the importance of the Scandinavian mining industry, education in geophysics is neglected on all levels. For instance, Denmark has the only full university chair in applied geophysics.

The need for Scandinavian cooperation, particularly to further development and research, has led to the founding of the Nordic Association for Applied Geophysics and to the launching of the periodical *Geoexploration*.

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Current research in the application of natural and induced radioactivity to mineral exploration

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Abstract. Modern techniques of exploration for uranium, thorium, and potassium are reviewed, with special emphasis on the evaluation of deposits in the field, using spectrometric techniques that until recently have been confined to the laboratory. The usefulness of the various types of radiation detectors is discussed, with methods of interpreting results.

Techniques have recently been developed for the field analysis of nonradioactive materials using various activation methods, notably the use of X-ray fluorescence and neutron activation. Elements that have been successfully analyzed at levels useful in mineral exploration include tin, copper, zinc, lead, nickel, iron, molybdenum, beryllium, aluminum, silver and possibly gold.

Résumé. L'auteur expose les techniques modernes de l'exploration de l'uranium, du thorium et de potassium et il accorde une attention spéciale à l'évaluation sur place des gisements à l'aide de techniques spectrométriques qui tout dernièrement encore étaient considérées comme des techniques de laboratoire. Il compare l'utilité des divers genres de détecteurs de radiations et les méthodes d'interprétation des résultats.

Des techniques ont tout dernièrement été mises au point pour effectuer sur le terrain l'analyse de matériaux non radioactifs à l'aide de diverses méthodes d'activation et surtout de la fluorescence par rayons-X et de l'activation par les neutrons. On a pu analyzer avec succès à des niveaux accessibles l'étain, le cuivre, le zinc, le plomb, le nickel, le fer, le molybdène, le béryllium, l'alluminium, l'argent et peut-être l'or.

The mining industry is considerably interested in the problem of efficient detection and quantitative evaluation of occurrences of the radioactive elements, particularly uranium. In the longer term, the distribution of these elements in rocks is fundamental to the solution of a variety of geological problems. The cost in expenditure and time of ordinary analytical procedures limits the number of samples that can be processed, often resulting in an inadequate or even erroneous concept of the distribution of these elements.

In this paper, an attempt will be made to review rapid, modern techniques of performing, *in situ,* quantitative analyses of the radioelement content of rocks, as well as methods involving the activation of certain nonradioactive materials.

Much of the review is also pertinent to the initial detection or location of occurrences of the radioelements, both on the ground and from the air.

Naturally radioactive isotopes

Processes of radioactive decay are accompanied by the emission of alpha and beta radiation. Both have limited powers of penetration in rocks and will not be discussed further in connection with field techniques of radioelement analysis. These nuclear processes often leave the nucleus in an excited state, and the transition to a lower energy state is accompanied by the emission of gamma radiation, emitted at energy levels characteristic of the parent nucleus. Because of their high penetrating power (Figure 1), gamma rays are of special interest in the radiometric analysis of large rock samples.

Of the many radioactive isotopes that occur in rocks, only radio-potassium and members of the uranium and thorium series are important geologic sources of gamma radiation. The radioactive decay scheme of radio-potassium (Ahrens, 1957) and simplified decay schemes for uranium and thorium (Hollander, *et al.*, 1953) are given in Figure 2, with the energies of the more important gamma rays emitted by these isotopes.

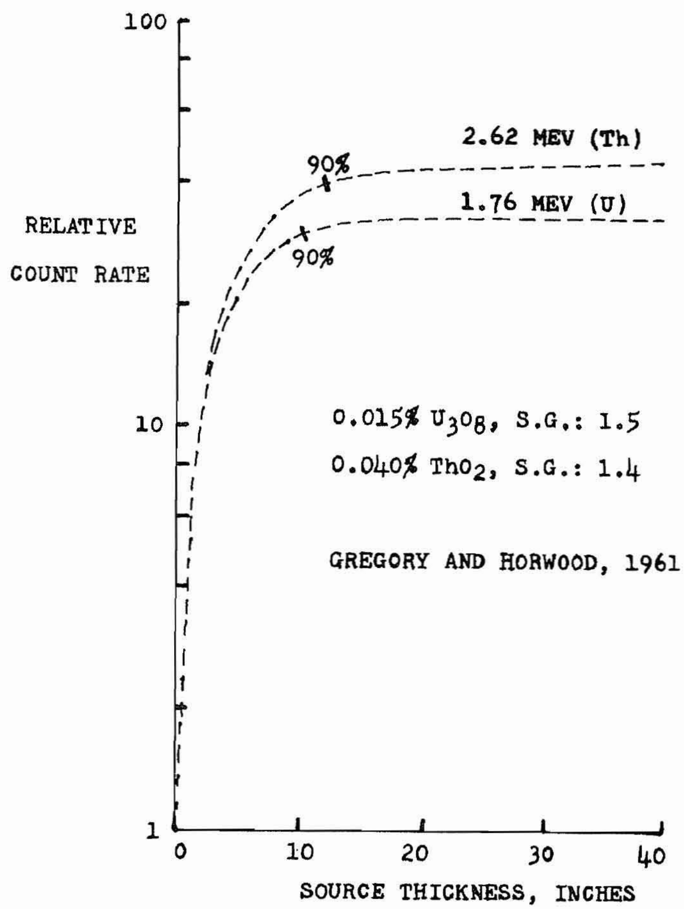


Figure 1. Variation of count rate with source thickness (Gregory and Horwood, 1961).

K^{40} (0.012% OF NATURAL K)

ELECTRON CAPTURE (10%) — BETA DECAY (90%)

Ar^{40} (1.46 MEV GAMMA) — Ca^{40}

URANIUM	THORIUM
$URANIUM^{238}$	$THORIUM^{232}$
*	*
$RADIUM^{226}$	$ACTINIUM^{228}$ (0.91, 0.96 MEV)
*	*
$RADON^{222}$	$RADON^{220}$ (THORON)
*	*
$BISMUTH^{214}$ (0.61, 1.12, 1.38, 1.76, 2.19, 2.40 MEV)	$BISMUTH^{212}$ (1.61 MEV)
*	*
	$THALLIUM^{208}$ (0.58, 2.20, 2.62 MEV)
*	*
$LEAD^{206}$	$LEAD^{208}$

Figure 2. Simplified decay schemes for K, U and Th. The asterisk indicates the omission of one or more isotopes.

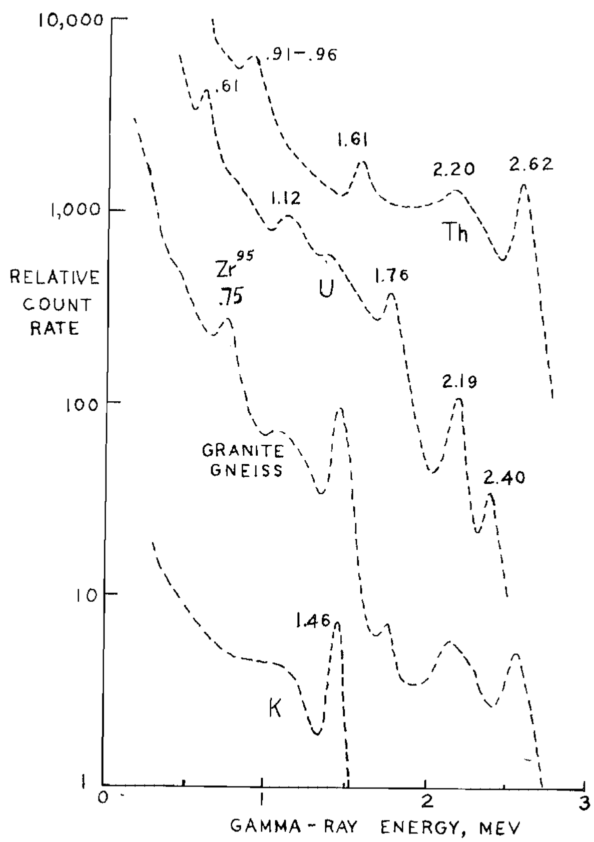


Figure 3. Spectrograms obtained from K, U and Th samples, and on a granite gneiss outcrop (3.4%K, 1.7ppm U, 5.4ppm Th).

Throughout this paper, the terms potassium, uranium and thorium will be used to refer both to these elements directly, and to their gamma-ray-emitting daughter isotopes.

In situ analysis: general principles. Methods involving the use of Geiger counters and ordinary scintillation counters to detect and estimate the total radioelement content of rocks are well documented. Modern techniques are based on equipment that is capable of measuring the spectral energy distribution of the gamma ray flux, isolating to varying degrees the gamma rays emitted by each of the radioisotopes.

The discussion that follows is based on the use of a detector of the NaI or CsI type. These are the only detectors compatible with portable equipment, offering sufficient resolution for spectrometry in the energy range of interest. Specifically, much of the numerical data was obtained using a 2 X 2-inch NaI detector, so that such data could be related directly to portable systems.

Gamma ray spectrograms of potassium, uranium and thorium are shown in Figure 3 (Gregory and Horwood, 1961, p. 15). Because of the many different gamma rays emitted by the uranium and thorium daughters, these spectrograms are especially complex. The potassium spectrogram shows only the unique 1.46 Mev photopeak and the lower energy Compton continuum. The rock spectrogram of Figure 3 was obtained in the field using a portable instrument built in our laboratory. The others were obtained from large samples, simulating field conditions. The result is a marked filling of the troughs between the peaks, especially in the lower energy regions. Both this effect and the rapid decrease in count rate with increasing energy are caused by the abundance of lower energy scattered radiation, and the decrease in the capture efficiency of the detector (NaI scintillation counter).

If the sample contained only one radioelement, measurements of gamma ray activity could be related directly to the radioelement content. For elements such as uranium or thorium, the useful gamma rays are emitted by the daughter isotopes. Radioactive equilibrium between the daughter and parent isotopes must therefore be assumed, if the gamma ray intensity is used to determine the uranium or thorium content of the sample. In the case of potassium, the radioactive isotope K^{40} makes up only 0.012% of natural potassium. In addition, only about one tenth of the K^{40} disintegrations produce gamma rays. In spectrometric analysis, these gamma rays are used to determine the total potassium content of the sample.

For samples containing more than one radioelement, measurements must be made in at least as many different regions of the spectrum as there are radioelements. It is usually possible, as will be shown, to account for the interference between these sources of radiation.

Most of the potassium, uranium and thorium peaks can be identified in the rock spectrum of Figure 3. Peaks below 1 Mev are swamped by the strong Zr^{95} fallout radiation. If the measurements are confined to the region above 1 Mev, we effectively have a sample with three sources of gamma radiation. In a general case, measurements could be made in three arbitrary regions of the spectrum. It is of course advantageous to select three regions, each of which contains radiation originating mainly from one element. It has been shown by Doig (1968) that the 1.36–1.56, 1.66–1.86 and 2.52–2.72 Mev regions are the most suitable for the *in situ* analysis of potassium, uranium and thorium. However, when samples are being measured in shielded enclosures, or in boreholes, the counting time can be considerably reduced by working at lower energy levels.

Friedmann (1960), Gregory and Horwood (1961), and Balyasnyi, *et al.* (1962), have evaluated the feasibility of the *in situ* method. Gregory and Horwood used large laboratory samples of geologic materials while Balyasnyi, *et al.*, used a truck-mounted laboratory spectrometer. Fully portable spectrometers

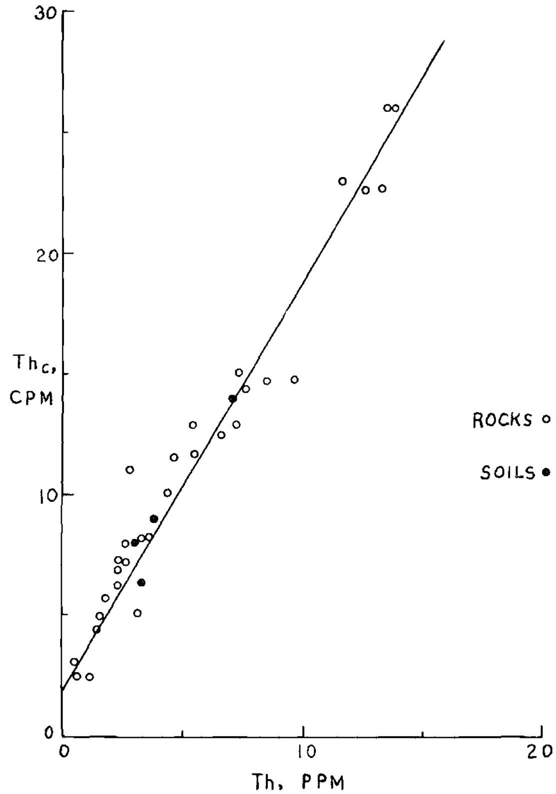


Figure 4. Total count rate in the thorium 'channel as a function of thorium content.

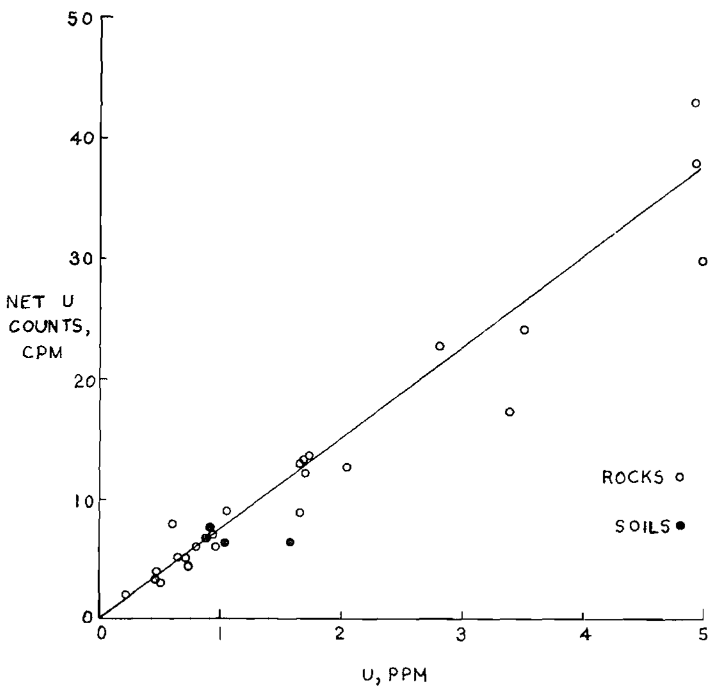


Figure 5. Stripped uranium count rate as a function of uranium content.

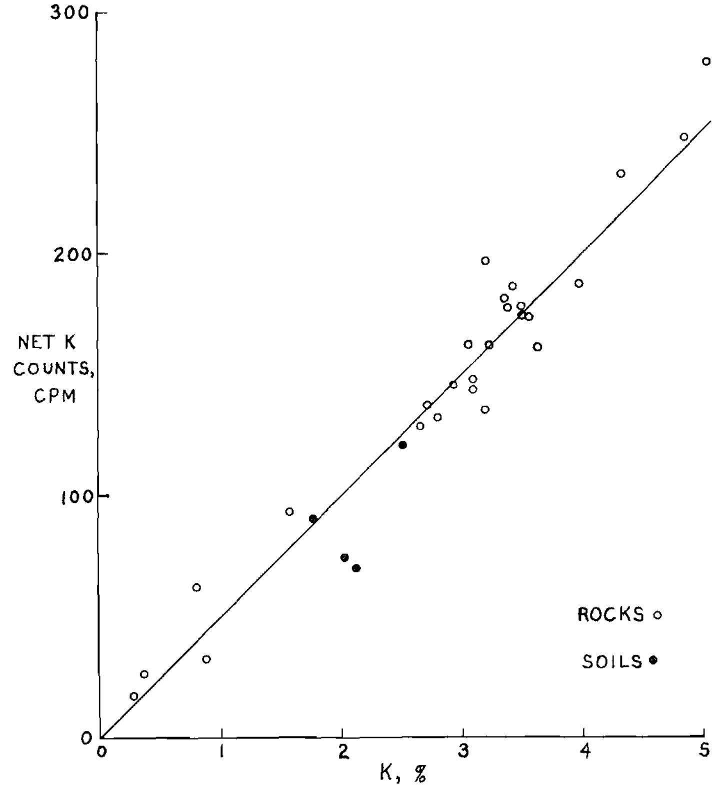


Figure 6. Stripped potassium count rate as a function of potassium content.

have been built specifically for *in situ* analysis, at Rice University (Adams and Fryer, 1964) and at McGill University (Doig, 1968).

From the 1.46, 1.76 and 2.62 Mev photopeaks, the potassium, uranium and thorium content of the rock can be related to the count rate in the three spectral regions as follows.

Because the thorium 2.62 Mev peak occurs alone there is no contribution from uranium or potassium in this channel, and we can write simply that

$$\text{Th ppm} = k_1(\text{Th}_c) \qquad 1$$

where Th ppm is the Th content in parts per million, Th_c is the count rate less background in the Th channel, and k_1 is a constant.

For uranium at 1.76 Mev there is interference from thorium, but none from potassium (see Figure 3). Hence we can write that

$$\text{U ppm} = k_2(\text{U}_c - S_1\,\text{Th}_c) \qquad 2$$

where U ppm is the U content in ppm, $S_1\,\text{Th}_c$ is the thorium contribution expressed as a stripping ratio (S_1) of the count rate in the Th channel, U_c is the count rate in the U channel less background, and k_2 is a constant relating U ppm to stripped counts in the U channel.

Finally, for potassium at 1.46 Mev there is interference from both uranium and thorium:

$$\text{K\%} = k_3(\text{K}_c - S_2(\text{U}_c - S_1\,\text{Th}_c) - S_3\,\text{Th}_c)$$

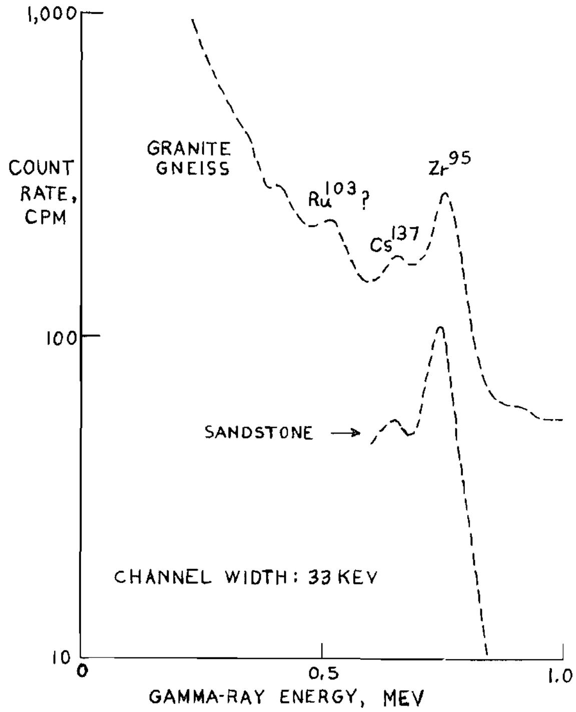


Figure 7. Gamma-ray spectrograms illustrating the fallout activity over a granite gneiss, and a sandstone.

Or the equation can be written as

$$K\% = k_3(K_c - S_2 U_s - S_3 Th_c) \qquad 3$$

where K % is the potassium content, K_c is the count rate in the K channel less background, S_2 and S_3 are stripping constants accounting for interference from U and Th, U_s is the stripped or net U count rate in the U channel, and k_3 is a constant relating K % to stripped counts in the K channel.

To calibrate the spectrometer, the constants k_1, k_2 and k_3, and the stripping ratios S_1, S_2 and S_3 must be determined. For thorium, only one sample of known composition is required. For uranium and potassium we require two and three samples, respectively. In practice, because of instrumental and sampling errors, it is best to use as many known samples (standard outcrops) as possible.

Figures 4, 5 and 6 illustrate such a calibration for the lower range of uranium and thorium concentrations, and for potassium.

The spread of points about the least squares line is due to a combination of analytical and sampling errors. This sampling error is a result of the difference in size between the field sample (up to 1 ton) and the relatively small sample collected for laboratory analysis. Because of sampling bias, the scatter of points cannot be related directly to the accuracy of the field analyses.

On an outcrop of unknown composition, measurements are made at 1.46, 1.76 and 2.62 Mev. Simple calculations using these count rates in Equations 1, 2 and 3 will yield the thorium, uranium and potassium content of the rock.

Equilibrium and leaching in surface exposures. Equilibrium between uranium and thorium and their daughter isotopes must be assumed if measurement of the activity of these daughters is to yield estimates of the uranium and thorium content of the rock. Disequilibrium occurs as a result of radon or thoron leakage, or preferential leaching of daughter isotopes.

Uranium is usually in equilibrium with its daughter products provided the uranium occurs at the concentration levels found in ordinary rocks (0 – 50 ppm) (Richardson, 1963; Doig, 1968). However, uranium of ore concentration often exhibits leaching and corresponding disequilibrium effects (Mero, 1960). These occurrences may consist of readily soluble uranium compounds in vulnerable intergranular sites. On the other hand, uranium in the common rocks occurs in minerals such as zircon, or dispersed throughout the lattices of the major mineral components.

The degree of equilibrium can be determined by comparing direct measurements of uranium to measurements of uranium as a function of its daughter Pb-214. This is usually accomplished by comparing the amplitudes of the 0.190 Mev peak (uranium daughters Th-230 and Ra-226) and the Pb-214 peak, at 0.240 Mev (Mero, 1960). It will generally be found that such equilibrium determinations are only necessary in certain metallogenic provinces. For example, the effect is common in the Gulf Coast type deposits.

Interfering sources of gamma rays. For the purposes of this discussion background radiation is defined as the gamma radiation that is not emitted by the potassium, uranium and thorium in the rock. This background would therefore include any radiation from above (cosmic or other), whatever gamma radiation that is produced by bombarding the rock with this or other sources of radiation, and whatever fallout activity that exists in the region of interest. The induced activity has been reviewed by Doig (1968), and shown to be negligible.

Cosmic radiation. The bombardment of the atmosphere by the primary cosmic rays produces a variety of secondary radiations including gamma rays. The intensity of this flux in the region of interest (1 – 3 Mev) is around 10% of the gamma ray flux measured over a granite. It is, of course, less significant when

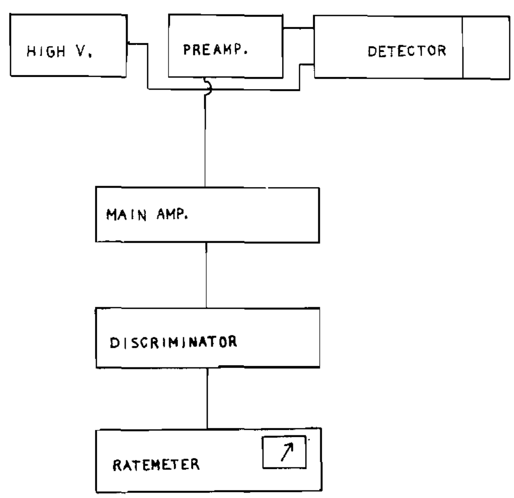


Figure 8. Block diagram of an integral-type spectrometer.

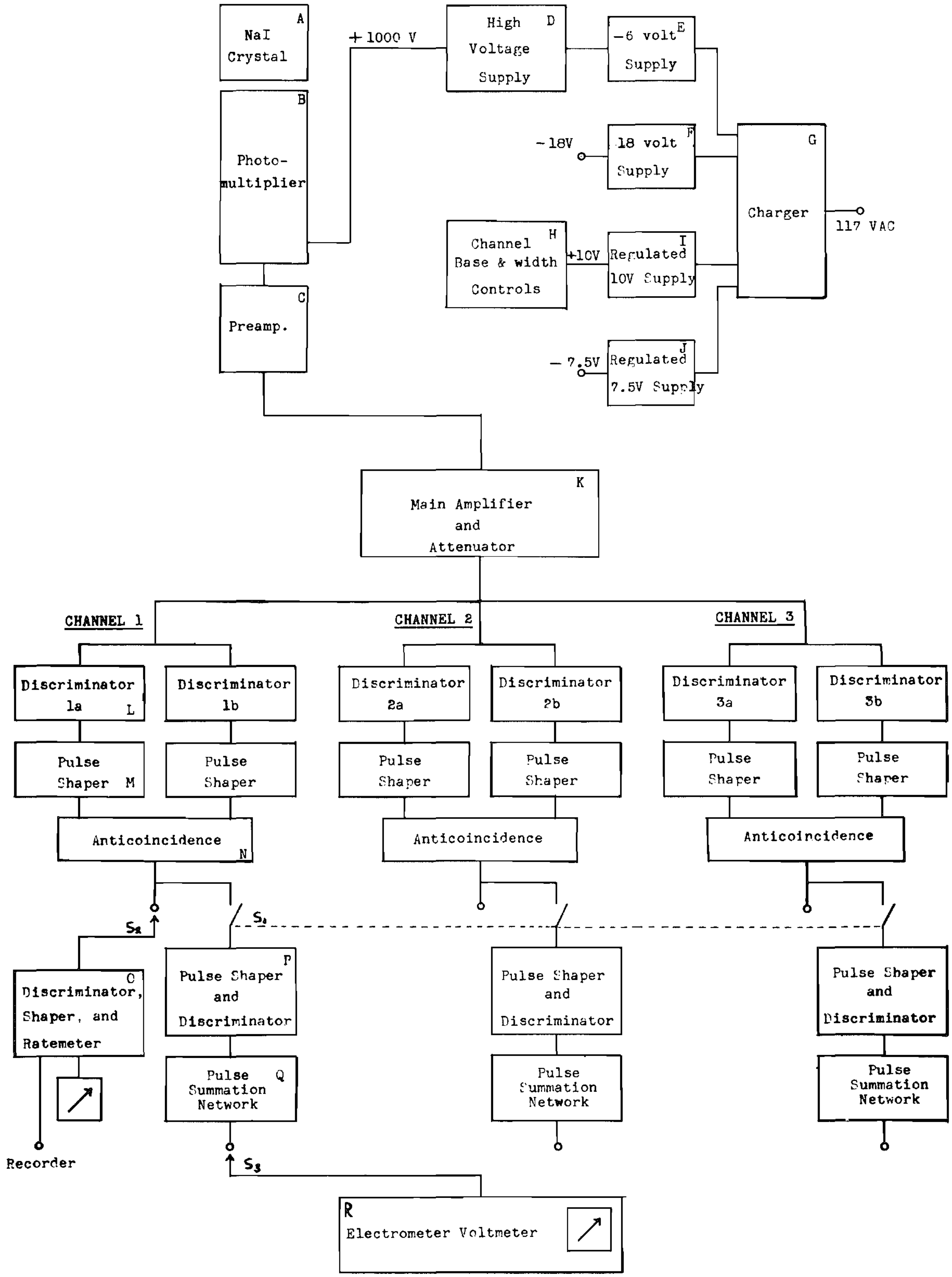


Figure 9. Block diagram of a three-channel differential spectrometer.

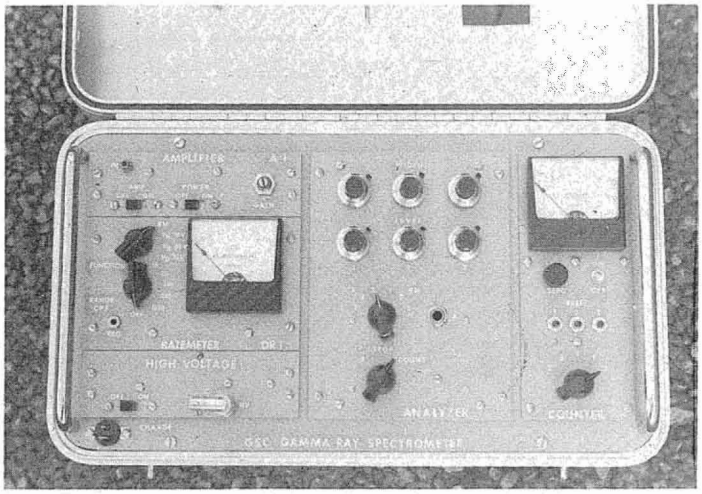


Figure 10. The prototype three-channel spectrometer.

making measurements of uranium and thorium approaching ore grade.

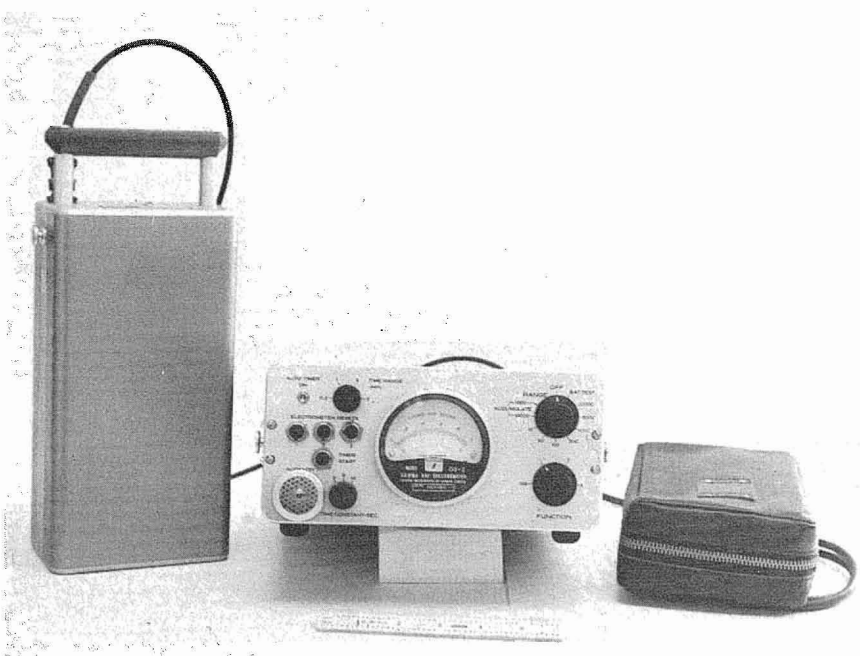
Fallout radiation. The products of nuclear explosions include gamma-ray-emitting isotopes, and most of this material eventually is deposited on the surface of the earth. Much of the long-lived gamma radiation occurs in the region 0 to 1 Mev, and is fairly well documented. Measurements of this activity relative to the potassium, uranium and thorium activity in a typical granite gneiss is shown in Figure 7 with measurements performed over a sandstone containing essentially no natural radioelements.

The Zr^{95} peak is the dominant peak in the spectrum of Figure 7. Currently, the longer-lived Cs^{137} is the dominant gamma ray emitter. The levels preclude measurements of potassium, uranium and thorium for petrologic purposes below 1 Mev. However, it is possible to evaluate uranium and thorium occurrences of economic importance using peaks in this region. Other considerations such as the unique contribution of thorium to the 2.62 Mev region and the penetrating power of the high-energy gamma rays make it advantageous to retain the analytical procedure outlined above.

Resolution and geometry effects. The resolution is a measure of the effect of nearby discontinuities in composition. The resolution determines the size of the sample that is being analyzed, or the minimum detail that can be resolved on the outcrop surface. Specifically, it will be defined as the diameter of the circular area around the probe from which 90% of the incident gamma rays are originating. It has been shown by Doig (1968) that the resolution of a 2-inch diameter NaI detector is 3, 7 and 10 feet at elevations of 2, 6 and 12 inches above the outcrop surface. Combined with the data of Figure 1, it can be shown that for an *in situ* technique, the sample is effectively very large. For detector elevation of 2 and 12 inches, and for 2.62 Mev gamma rays, equivalent laboratory samples would weigh nearly 700 and 5000 pounds, respectively. The resolution values are useful in evaluating deposits over realistic mining widths, and of course eliminate sampling bias in strictly geologic studies. Shielding can be employed to reduce the area sensed by the detector. Such shielding would usually only be necessary in evaluating underground occurrences.

On outcrops, an attempt must be made to standardize geometry, that is, position the detector so that it 'sees' a solid angle of 180°. During several seasons' field work in the Canadian Shield, no difficulty has been experienced in positioning the probe so as to approximate 180° geometry.

Figure 11. An integral spectrometer, and a three-channel instrument currently being manufactured in Canada. (Courtesy of Scintrex Limited.)



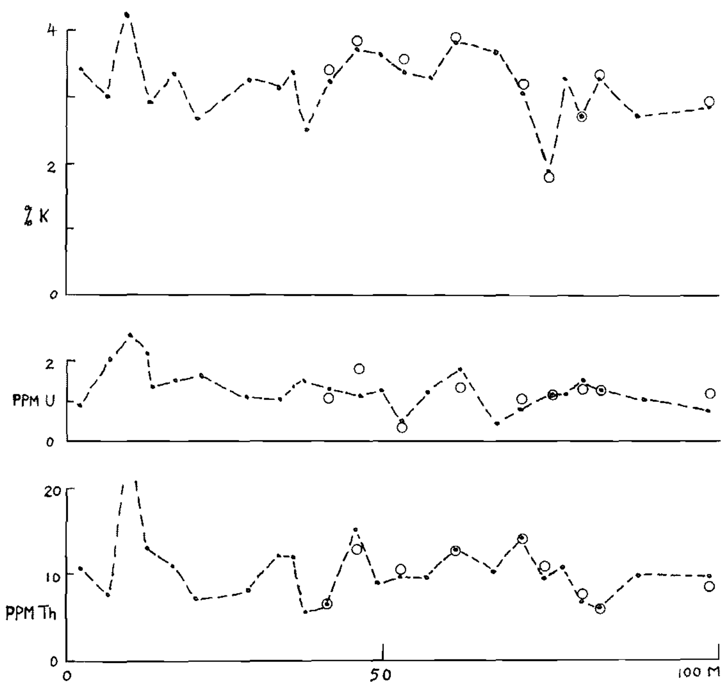


Figure 12. Replicate K, U and Th analyses, performed on a granite gneiss. Open circles represent measurements made two weeks after the detailed survey.

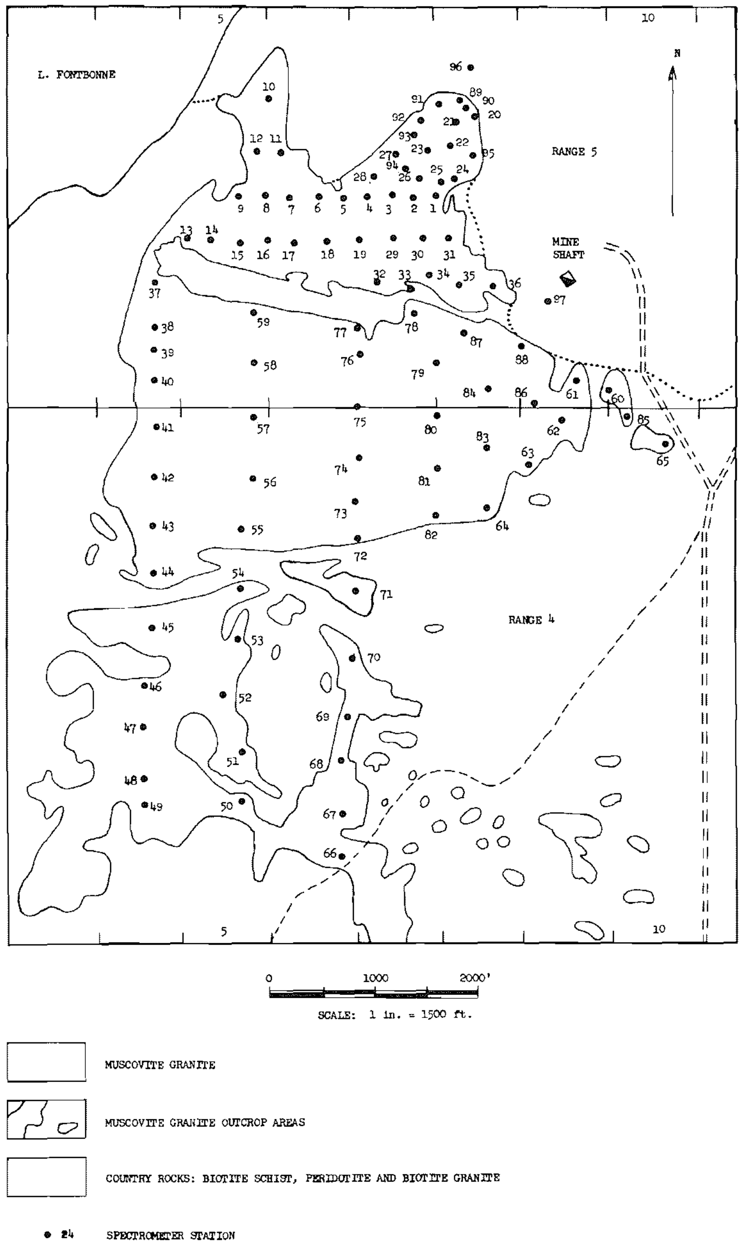


Figure 13. General geology, and spectrometer station locations, Preissac granite, Quebec.

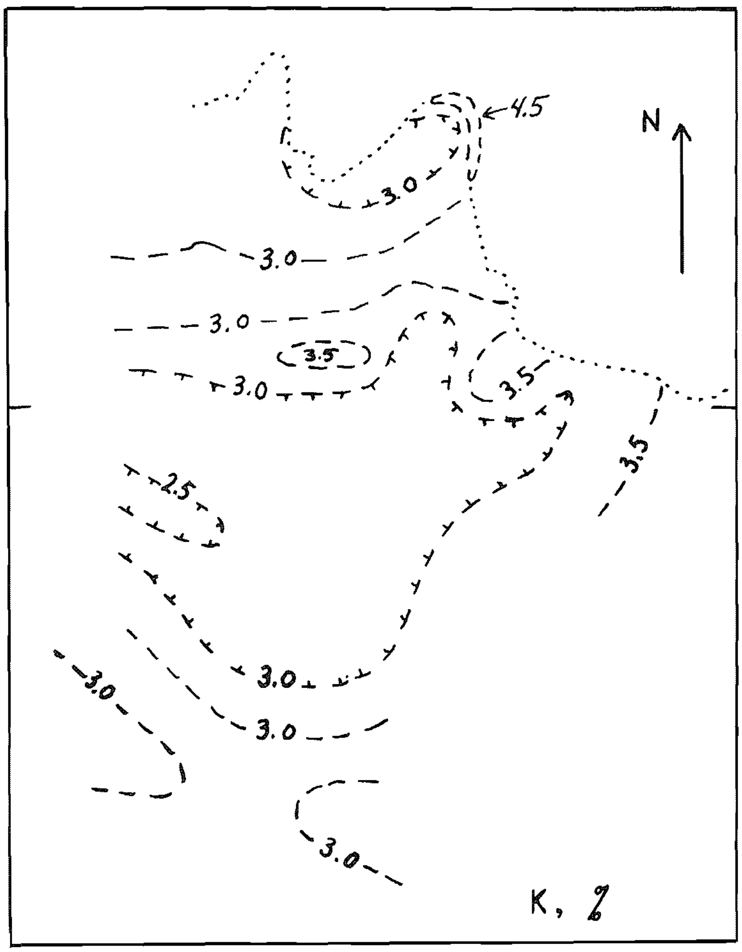


Figure 14. The distribution of potassium in the Preissac granite.

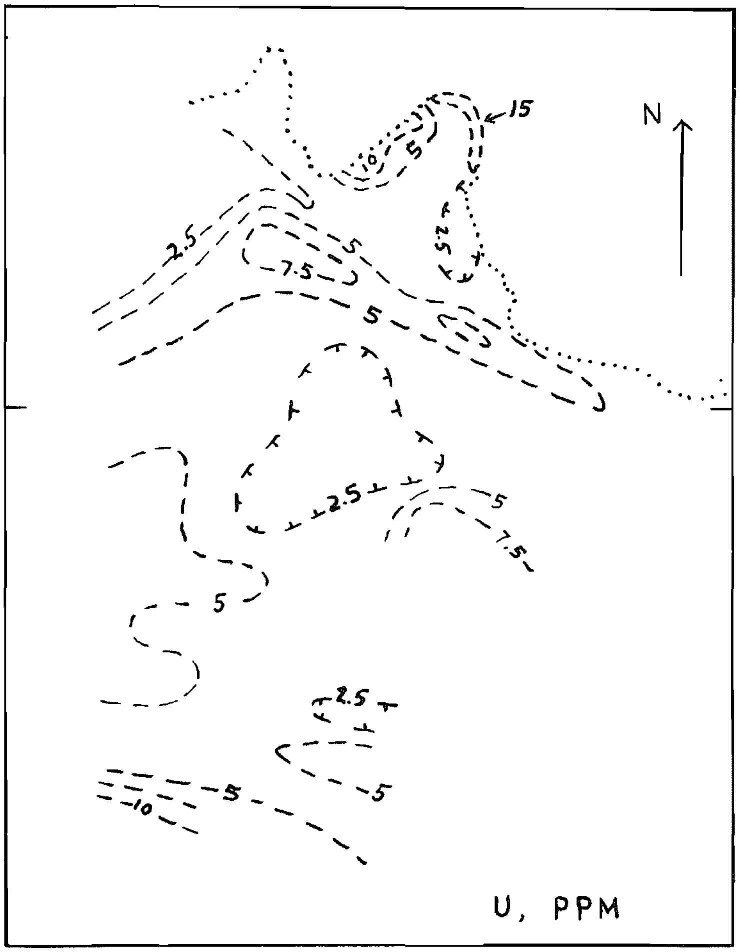


Figure 15. The distribution of uranium in the Preissac granite.

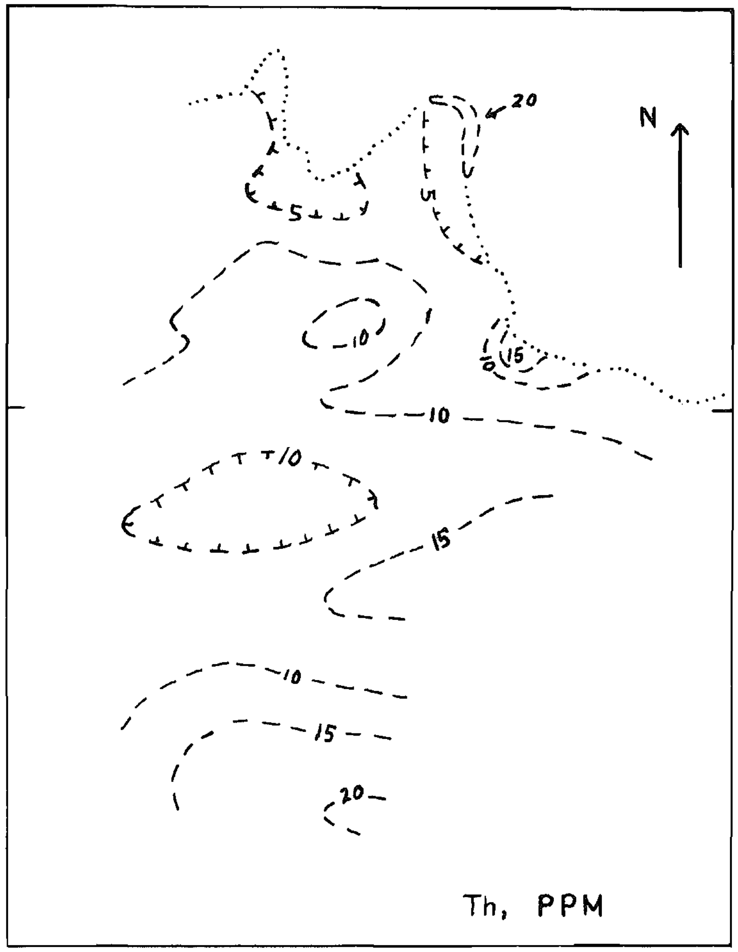


Figure 16. The distribution of thorium in the Preissac granite.

Field equipment. The detector referred to throughout the above discussion has been of the NaI (T1) type. Plastic scintillators are used to detect gamma radiation but have insufficient resolution to be used to distinguish the different radioelements. However, because of their low cost, large-diameter plastic detectors can be used as effective general prospecting tools, detecting the abundant but somewhat ambiguous low energy gamma rays. Large volume semiconductor detectors have recently become available. These detectors have excellent resolution, but must be stored and used at cryogenic temperatures to reduce both the noise level and the mobility of the doping agent (lithium).

A sodium iodide detector need not be thicker than 2 inches to effectively detect gamma rays in the range 1 to 3 Mev. The diameter of the crystal will then determine the counting time required to produce a significant analysis at a given radioelement concentration. As an example, a 2 by 2-inch crystal system will yield an analytical accuracy of better than 10% for a 5-minute counting interval for uranium, thorium and potassium levels of 2 ppm, 5 ppm and 2%, respectively. For uranium concentrations greater than 0.01%, the counting time can be reduced to as little as 10 seconds.

Figure 8 is a block diagram of an integral-type spectrometer. The single discriminator permits the operator to measure the activity of a sample above any given energy level. Quantitative analyses are obtained by setting the discriminator to three different levels, yielding three count rates from which the uranium, thorium and potassium content are calculated. A more efficient technique involves the use of an instrument with three differential channels (Figure 9). More sophisticated equipment is, of course, available, but these multichannel pulse-height analyzers can hardly be considered as field equipment. Figure 10 is a photograph of a prototype three-channel field instrument built by the writer in 1962. Figure 11 illustrates single discriminator and three-channel instruments currently being manufactured in Canada.

Examples of in situ analytical work. The prototype three-channel instrument has been used continuously over the period 1962 to 1967, in various regions of the province of Quebec (Doig, 1968), and by officers of the Geological Survey of Canada in the Elliot Lake and Bancroft areas of Ontario.

An extreme test of the reproducibility of the analyses is illustrated in Figure 12. The replicate measurements were performed some two weeks apart. The uranium level is some five hundred times below ore grade, and the thorium to uranium ratio of about 5 is unfavorable for uranium analysis.

Figures 13 to 17 illustrate the application of the method to a geologic problem. The large number of analyses that can be performed in a short time makes it possible to compute statistically significant trend surface maps of linear and higher order.

Figure 17. The distribution of values of the thorium to uranium ratio in the Preissac granite.

As in mining applications, the principal advantages of the method are its speed and versatility, and the very large sample analyzed. Complete analyses can be performed in from 10 seconds to 5 minutes, and calculations are sufficiently simple that estimates of the potassium, uranium and thorium content can be made immediately. The location of stations can therefore be adjusted continuously to suit the problem as the analyses are performed. Sampling errors are virtually eliminated because of the large mass of rock that is involved in the analysis. The sample size can be controlled by varying the altitude of the detector with respect to the outcrop surface, and this sample can be as much as a ton or more of rock. Although measurements apply only to the upper foot of rock, the values obtained are believed to be more representative of fresh rock than are the usual samples collected for conventional analysis.

Miscellaneous applications. The above discussion has been concerned mainly with the evaluation of potassium, uranium and thorium in exposed surface occurrences. The technique is equally useful in borehole work, where CsI would be a useful substitute for NaI, because of space limitations and the added danger of mechanical shock. Underground work would usually require the use of a semicircular shield, to reduce the contribution of gamma rays from other walls of the drift. Airborne techniques involving spectrometry are described in other papers in this symposium.

Individual samples (hand samples, drill core, mill heads, etc.) can be analyzed for their radioelement content provided that the geometry is standardized and that the sample and detector are adequately shielded from external sources of radiation. It is particularly advantageous to work at lower energies with these samples because of the lower total activity encountered.

A further list of applications could include the use of the well documented association of uranium and thorium with various elements, notably niobium and molybdenum. In addition to evaluating potassium ores, it may be possible to detect zones of potassium metasomatism surrounding base metal ore deposits. In groundwater studies, spectrometric techniques make it possible to employ multiple tracers. Other applications, mainly geological or petrological, have been reviewed by Doig (1968).

In situ analysis of nonradioactive geologic materials

The natural gamma ray activity of U, Th and K makes possible the rapid *in situ* analysis of these elements. To perform analyses of other elements by radiometric methods, the nucleii must be transformed to a new radioactive isotope, or the atoms must be raised to some excited state. This is usually accomplished by bombarding the target with quanta or particles such as X or gamma rays, or neutrons. The resulting activity measured (most often gamma rays) is then a function of the concentration of the element, assuming given conditions of irradiation, detector geometry and efficiency. The sensitivity of the methods depends in many cases on the effective cross sections or particle-capturing ability of the nucleus or atom.

The gamma rays or other radiation are usually emitted at definite energies characteristic of the isotopes involved. In a multicomponent sample a spectrometer is used to distinguish between the elements. Ambiguities or coincidences of energy do arise, however, and in the laboratory a crude chemical separation can be used to isolate the interfering components. The major difficulty in the field application of the methods is that a complex multicomponent system must be analyzed. In addition, the irradiating sources and sometimes complex detection systems are not always suitable for *in situ* and, in particular, borehole work.

The following discussion therefore deals mainly with those methods which conceivably can be applied under field conditions, and which yield results which are definitive in terms of the base metals relative to the common rock forming elements. Neutron activation and X-ray fluorescence techniques are the most widely applicable, but occasionally for a specific element, one of the other methods may be eminently suitable. An example is the gamma-neutron reaction used to detect beryllium.

Finally, in contrast with the foregoing section on the natural radioelements, much of the following is a review of the current literature.

Neutron activation (DC sources). Most nuclei are fairly efficient at capturing thermal (very low energy) neutrons. These extra neutrons in effect define a new isotope and the decay of the isotope usually produces gamma rays of specific energies. The cross section of a nucleus is expressed in terms of effective area (1 barn = $10^{-24} cm^2$). The larger the cross section, and the greater the irradiating flux and concentration of the element, the greater will be the induced activity. We are therefore limited by the size of the neutron source that can be used in the field or in a

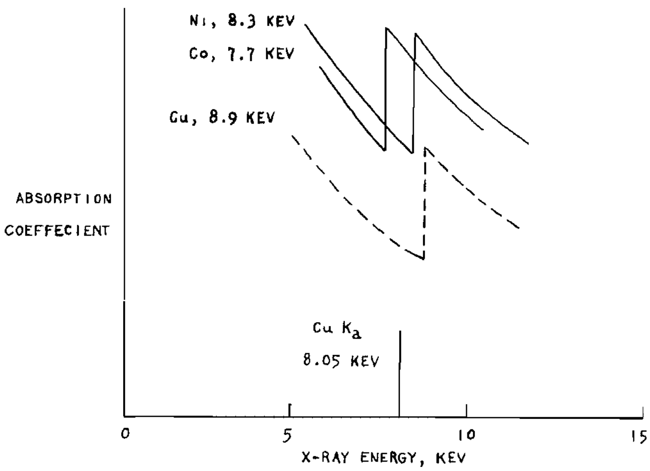


Figure 18. K-absorption edges of Ni and Co used to encompass Cu K_a radiation.

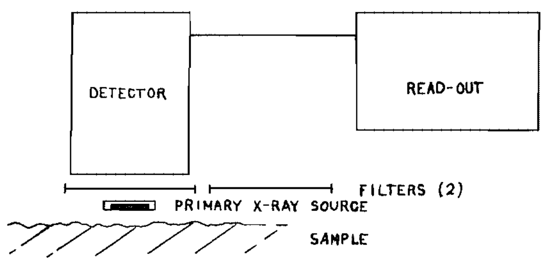


Figure 19. Block diagram illustrating a radioisotope X-ray fluorescence system using K-absorption filters.

borehole, and by the efficiency with which the target element of interest captures these neutrons.

Nuclear reactions both in samples and accelerators are used as neutron sources. In the first, a light element such as Be is mixed with an alpha emitter such as radium or plutonium. The reaction is of the form:

$$Be^9 + alpha^4 = C^{12} + neutron^1$$

To be practical, the number of neutrons produced from a reasonable amount of the high-cost alpha emitter must be large, and the alpha source must have a reasonable half-life (a few years). Suitable sources include RaBe, RaB and PuBe, yielding about 10^6-10^7 neutrons per second per curie of alpha activity.

Most accelerator sources are designed for laboratory use. The only field units available are 3 or 4 inches in diameter and could not be used in the usual diamond drill holes. The main advantage of these sources is that they yield fairly high flux densities and can be pulsed electronically.

Applications of the technique have been described by Senftle, *et al.*, (this symposium). The following is a brief summary of the general applicability of the method.

Most rock-forming elements (Al, Si, O, Ca, K, Fe) either do not emit gamma rays or the energies are such that they do not interfere with analysis of the base metals. Exceptions are Mn and Mg. Al has a very high yield and the method of neutron activation can certainly be used to evaluate bauxite deposits. Of the base metals, Cu has the highest potential in terms of gamma ray yield. Zn follows in second place (by a factor of 100) and Pb can not be activated at all, to yield gamma rays. Other materials of interest that have reasonable yields and energies in ore grade concentrations include Co, Mn, Mo, Sn, Ag, Ti, W, Li, B, V and Au. The neutron activation method has been demonstrated for Al, Cu and Ag (Lobanov, *et al.*, 1966; Hoyte, *et al.*, 1967). Sorting gold ores has been attempted by Uken, *et al.* (1966), and found to be impractical.

Neutron activation (pulsed sources). Prompt gammas emitted immediately after bombardment by neutrons (high energy) are highly characteristic of the parent material (Schrader and Stinner, 1961). However, because of the high yields from the common rock-forming elements, and the rather bulky and complex equipment required this method will not be discussed further.

X-ray fluorescence. X-rays of a suitable energy range falling on a sample dislodge electrons from the *K* ring of the atoms of the sample material. The vacancies are filled by electrons from specific energy levels in one of the *L* or *M* rings. The energy released in this process produces the characteristic X-ray fluorescence. The wavelength of the X-ray is given by 1/wavelength = $A\ Z^2$, where Z is the atomic number and the constant A can assume one of several values depending on the mode of filling the vacancy. However, there is a dominant mode, producing the K_a series of X-rays.

In addition, the X-ray absorption curve of each element has a very sharp discontinuity, again occurring at a specific energy, greater than that of the characteristic X-ray. A pair of adjacent elements in the periodic table can usually be found of which the *K*-absorption edges encompass a given K_a peak of interest, and discriminate sharply against radiation from other elements (Figure 18).

The source of X-rays is selected so as to give an adequate fluorescent response from the element of interest. The filters are selected so that their absorption edges lie on each side of the fluorescence peak. The X-rays are counted first with one filter in place, then the other, and the difference reading is related to the element content of the sample. The results are strictly quantitative only for samples prepared in a standard manner and having a matrix of similar composition.

Applicability of method. Table I lists K_a energies for virtually all elements of interest to the mining industry. Because this energy is a function of atomic number, certain important elements such as Cu and Zn yield low energy X-rays. These are difficult to detect through borehole fluids but could be detected in surface exposures or samples. Sn and Pb on the other hand produce high energy X-rays that are somewhat simpler to detect. Considering X-ray energy only, group 1 elements are nearly impossible to detect, group 2 elements are difficult, and those of group 3 are more straightforward.

X-ray sources. The choice of a source for optimum excitation of a given element has been reviewed in detail by Rhodes (1966).

Filters. Suitable filters for the more important elements of Table I are listed in Table II. Second choices are given where the availability of the ideal filter is in doubt. These filters have been selected to provide maximum discrimination against other sources of X-rays. One should note that the thickness of the filters

Table I. K_a energies for some elements of interest in mineral exploration.

	Element	A_o	K_a (Kev)
Group 1	Li	3	.052
	Be	4	.110
	Al	13	1.49
	S	16	2.31
	K	19	3.31
Group 2	Ti	22	4.51
	Cr	24	5.41
	Mn	25	5.90
	Fe	26	6.40
	Co	27	6.93
	Ni	28	7.48
	Cu	29	8.05
	Zn	30	8.64
	As	33	10.54
Group 3	Mo	42	17.48
	Ag	47	22.16
	Sn	50	25.27
	W	74	59.31
	Pt	78	66.82
	Au	79	68.79
	Hg	80	70.82
	Pb	82	74.96
	Bi	83	77.10
	U	92	98.43

determines only the degree of suppression of background (and the measured X-rays) and bears no relationship to the location of the pass band. Thicknesses must be adjusted so that the two filters are balanced in the region outside the pass band. These thicknesses are calculable but must be adjusted experimentally (Rhodes, 1962). The order of magnitude of these thicknesses are given in Table II.

From a practical point of view, some of these filters are of exotic materials and some are not available as thin foils. It is entirely permissible, however, to use a fine powder of the latter bonded to a thin plastic or beryllium sheet.

Detector system. For a portable system, and for group 2 and 3 elements (Table I), the most suitable detector is a thin (1/32 to 1/8-inch) NaI crystal, used with the filters described above. A single-discriminator, or better still, a single-channel pulse height analyzer should be used to discriminate against X-rays far away from the region of interest, where the filters are no longer balanced. The read-out device can be an expanded-scale ratemeter (Bowie, *et al.*, 1965) or a digital counter.

Table II. Filter materials suitable for performing analyses for some of the elements of Table I.

Element Analyzed	Filters		Approx. Thickness
	Lower	Upper	(inch)
Fe	Cr	Mn	.0005
Co	Mn	Fe	"
Ni	Fe	Co	"
Cu	Co	Ni	"
Zn	Ni	Cu	"
Mo	Y, Sr	Zr	.002
Ag	Ru, Mo	Rh, Pd	.003
Sn	Pd	Ag	.003
W	Hf and other rare earths		
Pb*	Os	Ir	.01

*Lead occurs in a region of the periodic table where there are few abundant elements. One or both filters may therefore be dispensed with.

Evaluation. Rhodes (1966) and Berry (1967) have reviewed the application of fluorescence techniques to analysis of geological and metallurgical materials. Briefly, the successful application of the method to analysis of ores has been documented by Bowie, *et al.* (1965) (tin), Darnley and Leamy (1966) (tin and copper), Florkowsky, *et al.* (1965a, 1965b) (copper, iron and zinc), and Niewodniczanski (1966) (copper and iron). The analysis of alloys and ores in pulverized form from a single locality is relatively uncomplicated by grain size or matrix composition effects. On the other hand, *in situ* analysis of ores can be severely limited by these effects (notably variable iron content of copper and other ores) (Bowie, *et al.*, 1965; Darnley and Leamy, 1966).

Miscellaneous methods. *X-ray absorption methods.* The sample is irradiated with X or gamma rays covering a continuous range of energies. The detector is placed so that it receives only the transmitted radiation. The spectrum then exhibits troughs or absorption bands corresponding to the fluorescence peaks discussed above. Used in a slightly different way (with higher energy gamma rays) the device essentially measures density. The method probably holds the greatest promise for Pb and may be useful for Sn, Cu, Ni and Fe (Yakubson and Nedostup, 1964; Florkowski, *et al.*, 1965b).

Alpha activation. The alpha spectrum of an irradiated sample shows energy maxima that are characteristic of the elements it contains. There are serious difficulties such as the absorption of the alphas in air and borehole fluids (Patterson, *et al.*, 1965).

Gamma-neutron reactions. (Production of epithermal neutrons by bombardment with hard gamma rays.) This is one of the first methods to be used and is well documented in connection with beryllium (Brownell, 1959; Bowie, *et al.*, 1960).

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Borehole logging methods for exploration and evaluation of uranium deposits

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Abstract. Borehole logging is the geophysical method most extensively used in the United States for exploration and evaluation of uranium deposits. Gamma-ray logs, commonly supplemented with a single-point resistance log, currently supply about 80 percent of the basic data for ore reserve calculation and much of the subsurface geologic information.

Truck-mounted rotary drilling equipment is commonly employed; holes usually have a nominal diameter of 4 1/2 inches, range from 25 to 2500 feet in depth, are seldom cased, and may be filled with air or water.

Calibration and quantitative analysis of the gross natural gamma-ray log to obtain equivalent grade and thickness of ore intersections are based on the proportionality between the area under the log curve and the product of the mean equivalent grade and thickness of a radioactive layer.

Rock density and related parameters are calculated from gamma-gamma logs. A different technique permits cancellation of natural radioactivity to obtain density data from ore zones. Calibration and correction factors for nonstandard conditions are determined for each probe in full-scale model holes. GAMLOG and RHOLOG, computer programs written in FORTRAN II for the IBM 7090 computer, are used to quantitatively analyze gamma-ray and gamma-gamma logs to obtain equivalent grade, thickness and bulk density.

Current investigations indicate that natural gamma-ray spectroscopy offers significant additional techniques for exploration and evaluation. Sodium-iodide detectors and single or multichannel pulse height analyzers are used in conjunction with the basic signal conditioning and digital pulse counting system, supplemented with automatic gain or spectrum stabilizers, to make integral or differential measurements of the gamma-ray energies. Certain characteristic photo peaks of thallium-208, bismuth-214, and potassium-40 can be adequately differentiated in spite of extensive scattering in the formation and borehole.

Résumé. La diagraphie des sondages est la méthode géophysique la plus répandue aux États-Unis pour l'exploration et l'évaluation des gisements d'uranium. Les diagrammes de rayons gamma, couramment complète par un diagramme de résistivité à point unique, fournissent généralement environ 80 p. 100 des données de base pour le calcul des réserves de minerai et une bonne parti des renseignements géologiques des couches sous-jacentes.

On utilise en général une foreuse installée sur un camion; les trous ont un diamètre de 4 1/2 po., une profondeur de 25 à 2500 pi., sont rarement tubés et sont soit vide soit remplis d'eau.

La calibration et l'analyse quantitative d'enregistrement brut naturel de rayons gamma effectués pour déterminer la qualité équivalente et l'épaisseur des intersections de minerai sont fondés sur la proportionnalité entre la surface située sous la courbe du diagramme et le produit de l'épaisseur et de la qualité équivalentes moyennes d'une couche radioactive.

La densité des roches et les paramètres connexes sont calculés à partir des enregistrements gamma-gamma. Une technique de différence permet d'annuler la radioactivité naturelle pour obtenir les données densimétriques des zones minéralifères. Les facteurs de calibrage et de correction pour des conditions anormales sont déterminés pour chaque sondage dans les trous d'essai à échelle régulière. Les programmes GAMLOG et RHOLOG écrits en FORTRAN II pour la calulatrice IBM 7090 servent à l'analyse quantitative des diagrammes de rayons gamma et des diagrammes gamma-gamma afin d'obtenir la qualité, l'épaisseur et la densité brute équivalentes.

Les recherches en cours indiquent que la spectroscopie aux rayons gamma naturels offre de nouvelles techniques supplémentaires pour l'exploration et l'évaluation des gisements. Des détecteurs d'iodure de sodium et des appareils d'analyse de tension d'impulsion à canaux simples ou multiples sont utilisés conjointement avec un système de conditionnement des signaux de base et de calcul numérique par impulsion complète par une amplification automatique ou des stabilisateurs de spectre afin de pouvoir effectuer des mesures intégrales ou différentielles des énergies des rayons gamma. Certaines pointes photographiques caractéristiques du thalium-208, du bismuth-214 et du potassium-40 peuvent être bien différenciées en dépit d'une diffusion prononcée dans la formation et dans le sondage.

Natural gamma-ray logging to detect uranium ore was first investigated in 1945. Subsequent improvements in methods and equipment by government and industry have established geophysical logging as a major part of most exploration and evaluation programs. Some 80 percent or more of the basic engineering and geological information used by the uranium mining industry and the Atomic Energy Commission to calculate ore reserves, predict extensions of deposits and for mine planning is derived from logs of non-cored holes. With the resurgence of exploration, particularly as deeper, more widely spaced and costly holes are drilled, the capabilities to extract more information from the hole will significantly assist in the economic search for new districts, new favorable environments, and the reserves and resources required by the growing demands of the nuclear fuel industry.

Borehole measurements, though fraught with problems and pitfalls, offer more than compensating technical and economic advantages. These include reduced coring, sampling and analytical costs; continuous data from which a multitude of sample intervals may be selected and statistically investigated; relatively larger sample volume; certain data may be obtained from previously drilled and cased holes; samples are relatively undisturbed; and analog records, free of subjective observations, are immediately available for qualitative evaluation and correlation.

Contemporary logging programs for uranium evaluation and exploration commonly include analog records of natural gross gamma-ray, single-point resistance, spontaneous potential (SP) and directional measurements. These records are produced by truck-mounted units operated by mining or service companies. Some major companies and individuals elect to log with semiportable equipment, without powered winches and often without benefit of chart recorders. It is possible to obtain adequate results for many applications with portable instruments if these are well designed and carefully operated. However, much of the portable instrumentation is poor and operated by untrained personnel which results in less than adequate data for quantitative analysis.

Though not in general use at this time, suitable caliper tools are available and the caliper log is probably the best method for obtaining the hole-size corrections required for quantitative log analysis. Although the feasibility of gamma-gamma logging for radioactive minerals, including ore zones, has been demonstrated by Dodd and Droullard (1965), density-porosity measurements have not been adopted by industry. Resistivity and induced polarization (IP) logs are being tested in the field but are not yet routine or developed to full capability.

Magnetic susceptibility, neutron-neutron, induction and perhaps even neutron activation or photon fluorescence logging appear to warrant research and development for the radioactive mineral industry.

This paper presents a review of a current multipurpose logging system, the principles and methods for calibration, and quantitative analysis of natural gross gamma-ray and gamma-gamma density logs.

Some preliminary observations and comments also are introduced concerning current results from a small project recently initiated by the Grand Junction Office of the U.S. Atomic Energy Commission to investigate techniques and applications of in-hole natural gamma-ray spectroscopy to exploration and evaluation of uranium resources.

General conditions and problems which influence logging

The majority of producing uranium deposits in the United States, and hence the current exploration targets, have relatively small discontinuous substratified configurations and occur in sedimentary rocks which are often poorly indurated. Orebodies are found above, below and astride the water-table. Lithologic units must be defined for correlation and ore zones for economic evaluation, which range from a few inches to tens of feet in thickness.

Rotary seismic-shot-hole type rigs are most commonly employed for drilling. The drilling media may be air, water or natural mud. The holes have nominal diameters of about 4 1/2 inches but may range from 2 to 9 inches. In most cases the holes deviate from the vertical, are rather crooked, and often rough-walled because of caving, washouts, and swelling clay seams. Because of these conditions the probes tend to ride the side and holes have a short life for logging. Not infrequently probes become lodged and must be abandoned. Multiple-purpose probes are desirable to save time in the hole, but excessively complex and costly probes may not be economic.

Although recently exploration drilling has been getting deeper, the holes seldom exceed 2500 feet and usually are 200 to 500 feet deep. Consequently, temperature and pressure conditions are not severe. Massive probes, large cables and powerful winches, such as used for most petroleum logging, are not optimum for uranium logging requirements. This permits the use of smaller and more maneuverable vehicles for logging units which must negotiate steep and narrow hill-side trails and small drill sites. Often a logging unit is expected to service several deep exploration holes per day or as many as 50 shallow holes in the case of open-pit mining sites. Portable equipment, if properly designed and operated, can meet many of the logging requirements, and indeed may be necessary for certain rugged terrain or for underground long-hole logging.

The holes may be air-filled, water-filled, or partially water-filled; and the interface is seldom encountered at the same depth on successive measurements in the same hole. Heavy muds are seldom used, mud cake is generally thin, invasion by fresh drilling water may be pronounced, and the formational waters are usually fresh to slightly saline. Hence fluid density may be assumed to be 1.0. The intensity of natural gamma radiation ranges from the equivalent of a few ppm uranium from the intrinsic uranium, thorium and potassium in the rocks, through several hundred equivalent ppm in anomalous and mineralized rock, to extreme high-grade zones containing several percent uranium and its gamma-emitting decay products. This great range in natural gamma activity causes severe problems in instrumentation design and logging procedures.

A range in magnitude of gamma activity of 10^5 cannot be adequately spanned by a single detector. To resolve slight variations of lithology or to quantitatively analyze slight anomalies equivalent to a few ppm uranium requires a sensitive detector, yielding at least 50 to 100 counts per second (cps) to achieve adequate statistical precision at reasonable logging speeds. This same detector would generate several hundred thousand cps in a high-grade ore zone of appreciable thickness, which significantly exceeds the capability of current logging instrumentation. Conversely, a detector with adequate sensitivity to measure ore-grade materials without overloading the pulse-transmission and counting instrumentation at perhaps 50,000 or even 100,000 cps would yield too low a count rate from normal lithologic units to achieve an adequate contrast and statistical precision at operational logging speeds.

A similar problem exists in gamma-gamma density logging. If an optimum combination of detector sensitivity, source strength and spacing is selected for adequate statistical accuracy in counting, then if significant additional gamma radiation is encountered in an ore zone, the total count rate may well tax or exceed the linear response capability of the system. The back-scattered radiation from the source in the probe is obscured by the natural gamma radiation from mineralized and ore zones, and special logging techniques are necessary to measure the density of ore zones.

Also, though it may be tempting to use large sensitive crystals for gamma-ray spectral measurements, it is even more imperative not to exceed the gross count rate which the system can achieve without distorting the pulse-height information.

Equipment and instrumentation

Truck-mounted geophysical unit model RD-1A

Logging unit. Figure 1 shows a truck-mounted geophysical unit developed by the Grand Junction Office of the U.S. Atomic Energy Commission for research and development in the field of borehole logging as applied to the search for and evaluation of radioactive mineral deposits. The system is more sophisticated than required for routine logging and is much more complex than units now in routine operation by the mining and service companies. It is used to make natural gamma-ray, neutron,

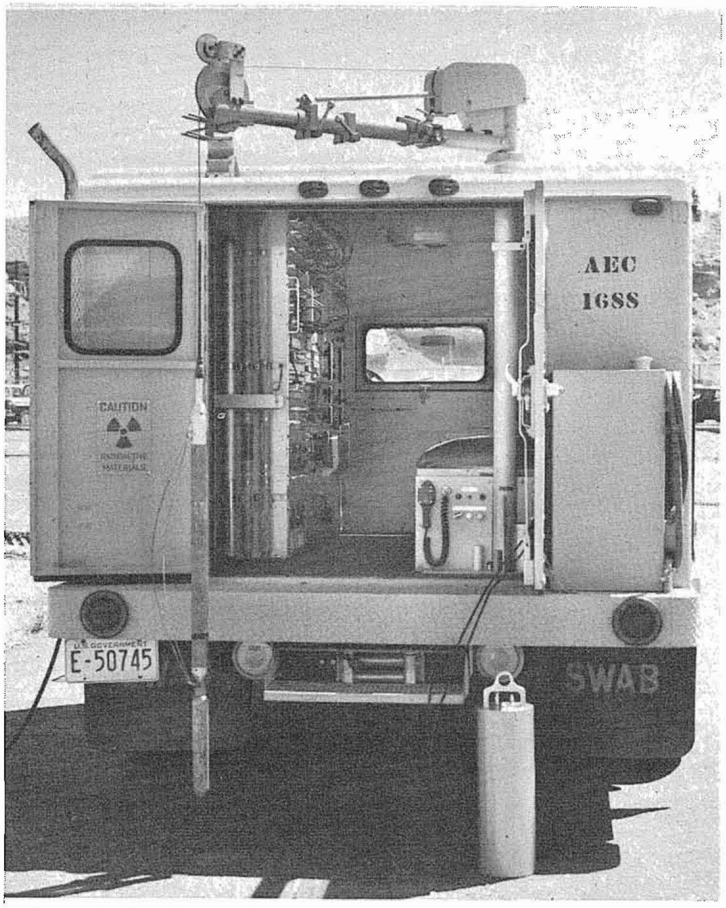


Figure 1. RD-1A multipurpose logging unit developed by U.S. Atomic Energy Commission to support raw materials programs. Down-hole probe is attached to logging cable and large detector for surface spectral measurements is on the ground.

electric, caliper and gamma-gamma density logs. As far as possible, commercially available component instruments and modules were used to assemble this multipurpose system. Primary AC power for this multipurpose system is supplied by a 4 kw generator. Figure 2 is a block diagram of the system.

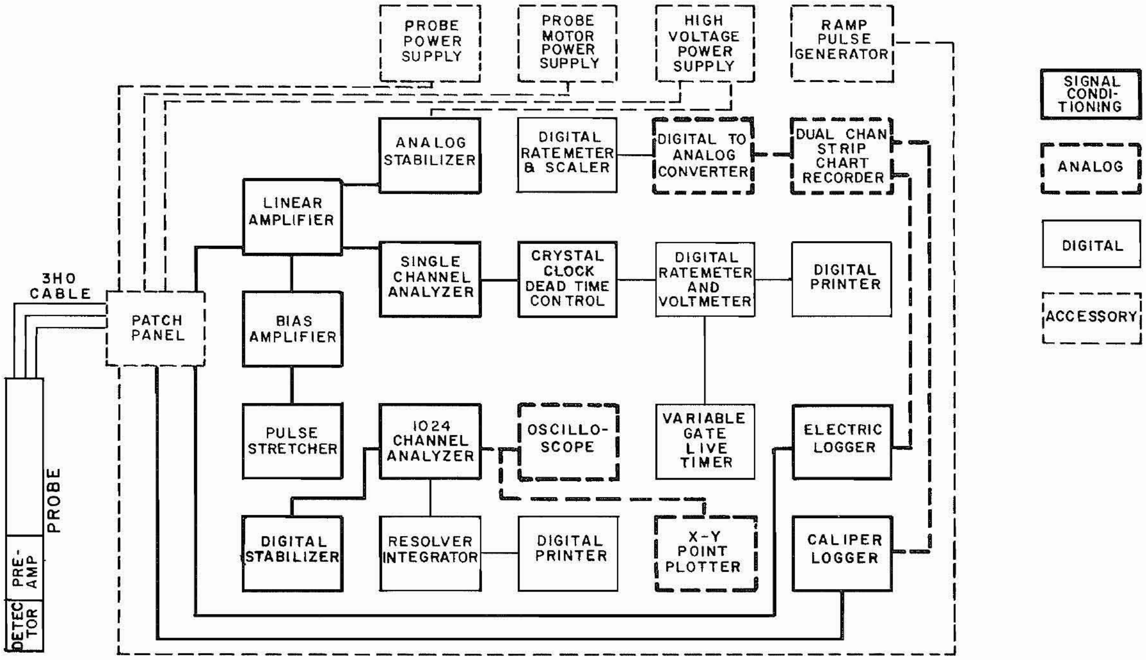
Nuclear instrumentation

Probes. Activated sodium iodide crystals, ranging in size from 1/2 X 1/2 to 5 X 4 inches, are used for the various applications of measuring gamma rays in boreholes. The crystals are optically coupled to appropriate photo-multiplier tubes, and the output pulses are coupled to the logging cable by means of an amplifier and cable driver.

Logging cable. A double-armored, three-conductor cable of the 3HO type is used for interconnecting the probe and the surface equipment.

Surface equipment (integral and differential counting). The surface end of the 3HO logging cable is connected to an impedance-matching unit which drives a multimode linear amplifier (Ortec model 410). The amplifier provides necessary gain and pulse shaping for the inputs of a single-channel analyzer (Hewlett-Packard model 5583A) and an analog spectrum stabilizer (Hamner model NC-20). The single channel analyzer is used in all three of its operating modes for various applications. Its output pulses are fed to a gating circuit which is controlled by a crystal clock. This unit establishes the dead time of the system and provides selectable dead times, in increments of 1 microsecond, from 2 to 190 microseconds; and its output pulses are used to drive the analog and digital-data readout circuits.

Figure 2. Block diagram, USAEC model RD-1A geophysical logging unit.



Pulse rate is measured with a scaler-timer (Hewlett-Packard model 5202L) operating as a digital ratemeter. Binary-coded decimal data from this unit are converted to an analog signal by means of a digital-to-analog converter (Hewlett-Packard model 580A), which drives a dual-channel strip-chart recorder (Westronics model SS-11-A/U).

Pulse-rate data for the digital readout are fed to an integrating digital voltmeter (Dymec model 2401B) operating in the frequency mode. An external combination prescaler and time base provides counts-per-second output which can be corrected for dead-time loss by means of a live-timing section controlled by gating signals from the dead-time unit. The BCD output of the digital voltmeter is coupled to a (Hewlett-Packard model 562AR) decimal printer for digital-data output.

Interval control signals for the digital readout are developed in the synchrodriven depth-measuring system through a light-activated pulse generator. Intervals of 0.1, 0.25, 0.50, or 1.00 foot may be selected by a switch.

Surface equipment (gamma-ray spectroscopy). Gamma-ray pulses from the various detectors are routed either directly to a 1024 channel analyzer (TMC model 1001) or are conditioned through the Ortec 410 amplifier followed by a bias amplifier (TMC model 343) and a pulse stretcher (Ortec model 411) prior to height analysis. A digital stabilizer (TMC model 230A) controls both the gain and the baseline of the analyzer.

Analog output from the memory section of the analyzer is viewed on an oscilloscope (Tektronix model RM-647) and readout is by an *X-Y* point plotter (Houston Omnigraphic model 6550).

A resolver-integrator (TMC model 522RA) is used to process analyzer-memory data, and digital output is recorded on a decimal printer (Franklin model 1200).

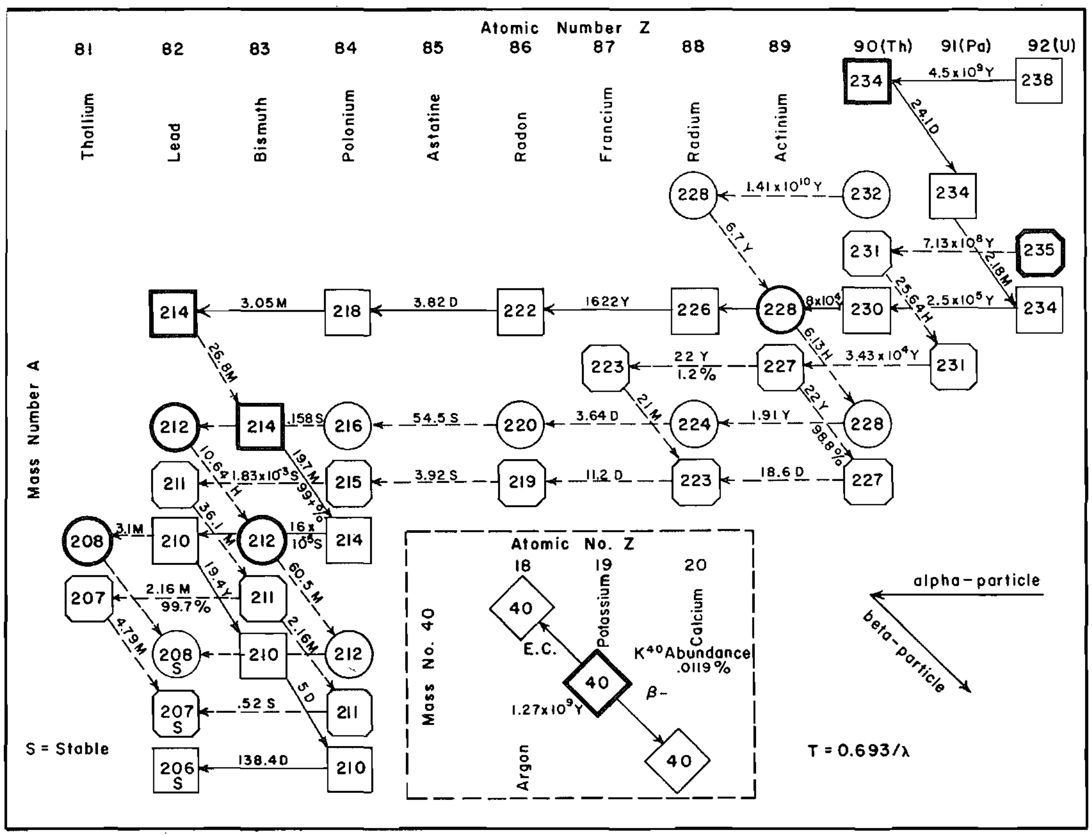
Ancillary instrumentation

Surface equipment (electric logging). Potential and current logs are made with an electric logging unit (Mount Sopris model 6-464). Either spontaneous potential or induced polarization logs can be made on the potential channel while the current channel provides either single-point resistance or short-normal resistivity logs. Analog output from this unit is coupled to the Westronics dual-channel strip-chart recorder.

Surface equipment (caliper logging). Signals from the caliper probe are coupled to the digital voltmeter (Dymec model 2401B) operating in the voltage-measuring mode. The borehole diameter is converted to a voltage which is recorded on the digital printer. Analog output is generated by measuring the voltage-to-frequency converter output of the digital voltmeter through the scaler-timer and digital-to-analog converter combination used in nuclear pulse counting.

Test equipment in the Model RD-1A geophysical logging unit includes the aforementioned digital voltmeter and oscilloscope, and a ramp pulse generator (Berkley Nucleonics model GL-3).

Figure 3. Generalized diagram of the natural decay series of uranium, thorium and potassium. Gamma-ray emitters in heavier blocks are of major interest.



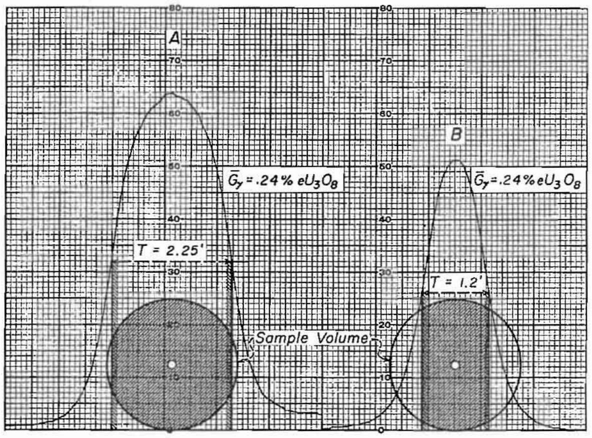


Figure 4. Count rate (amplitude of log deflection) depends on both grade and thickness.

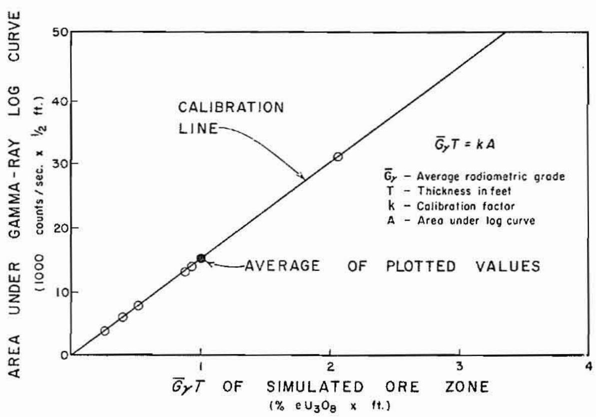


Figure 5. The area under the log trace is proportional to the grade-thickness product of the 'ore' zone as demonstrated by six model holes.

The gross natural gamma-ray log

Principle and applications. Gamma rays are emitted by the conversion of potassium-40 to argon-40, by the decay of certain members of both the thorium series, and the uranium series, notably lead-214 and bismuth-214. Figure 3 is a generalized diagram of these decay series in which the gamma-ray emitters of most significance to logging methods have been emphasized by wide-line blocks. These natural gamma rays can be quantitatively detected with logging probes. If uranium is in secular equilibrium with its gamma-emitting daughters, and if there is an insignificant contribution of gamma rays from other sources, then the concentration of uranium in the rocks immediately surrounding a borehole can be determined from a gross-count gamma-ray log with high sensitivity and practical accuracy. Because of the geochemical characteristics of the various radionuclides, these conditions are seldom, if ever, completely fulfilled. Fortunately, for many economically valuable concentrations of uranium, these conditions are sufficiently met, or data may be obtained to supply adequate corrections, to determine the thickness and mean equivalent grade of the mineralized zone from the gross gamma-ray log and, by calculation, to closely approximate the grade of incremental layers within the zone. Deposits of potassium or thorium may also be evaluated if similar conditions are fulfilled and the response of the logging system has been calibrated in terms of these elements.

In the absence of anomalous radioactivity, a sensitive gamma-ray detector will respond to the differing trace amounts of uranium-, thorium-, and potassium-bearing minerals characteristic of various lithologies; and the gamma log commonly is used to identify formational (rock) units and to correlate thin zones with considerable reliability.

Even with somewhat primitive instrumentation and methods, industry has rather successfully used the gamma log to estimate uranium reserves and to obtain related geological information. Gross-count natural gamma-ray logging is currently the major geophysical method used by the uranium mining industry. It is predicted that at least 6 million feet of borehole will be logged for uranium by this method in the western United States during 1967.

Principles of calibration and analysis

Sample volume concept. The concept of the sample volume is fundamental in devising nuclear logging systems and interpretation methods. For practical purposes, the effective sample volume surrounding a natural gamma-ray detector approximates a spheroid, which by definition contains the material contributing essentially all (some 95 or 98 percent) of the detectable gamma rays; and its radii depend on the energy spectrum of the gamma rays, the scattering and absorption by the medium and the energy threshold of the logging system.

Only when the sample volume is filled with homogeneous material, a condition seldom attained in the geological environment, is the count rate proportional to the grade. Figure 4 illustrates this effect. Logs of two models, which contain the same grade of ore, have different deflections because the 'ore' zones are not of the same thickness and do not occupy an equal sample volume.

Principle of calibration. Scott, *et al.* (1961), empirically and mathematically demonstrated that if the detector is moved up the hole at a constant rate the area under the log curve is proportional to the product of the average radiometric grade and thickness. For practical purposes, this relationship is expressed by the equation

$$\bar{G}_\gamma T = kA \qquad 1$$

where $\bar{G}_\gamma$ is the average radiometric grade in percent by weight, T is the thickness in feet, k is a constant of proportionality and A is the area under the log curve. The calibration constant k is determined from measurements in full-scale model holes with each probe and for the logging and analytical procedure that will be used. The value obtained for k depends on the sensitivity of the logging system and analytical procedures. In Figure 5 the areas under the log curve of six zones, each differing in thickness or grade, have been plotted against the product of the average grade and thicknesses of the six zones in the model holes. The values for the six ore zones all fall on the line drawn through the average and the origin, demonstrating proportionality.

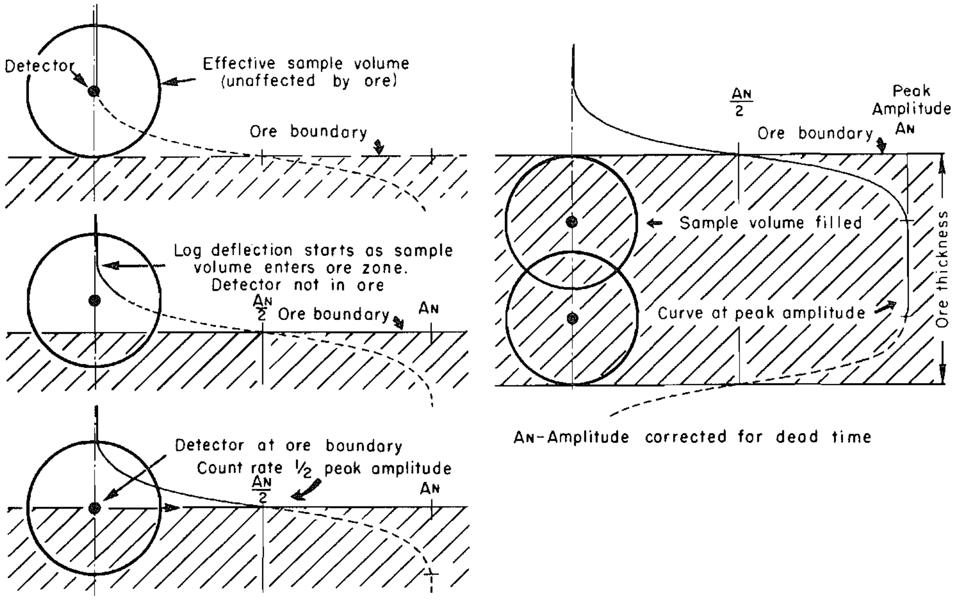


Figure 6. The ore boundary is indicated by the half-amplitude point on the anomaly.

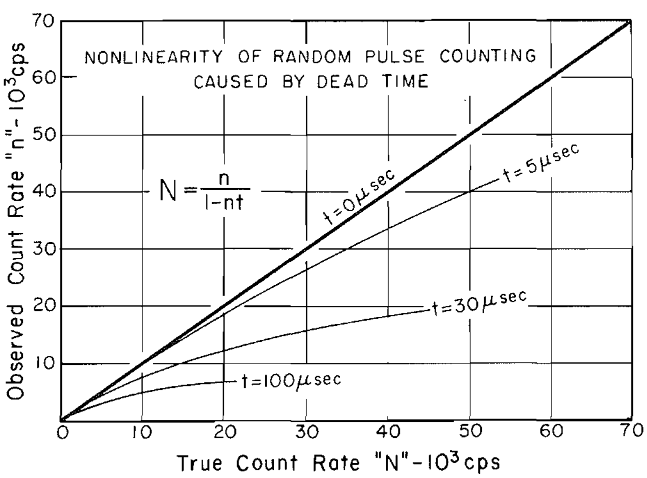


Figure 7. Nonlinearity caused by instrument dead time for typical logging systems used by the uranium industry.

Principle of analysis. From the calibration equation (1), $\bar{G}_\gamma T$ is determined by numerical integration of the response at regular intervals from background to background. The values to be integrated depend on the logging system and may be the deflection of the analog record at regular intervals or, for a digital system, the values recorded at regular intervals while logging. The precision of the integration, and therefore of the analysis, is dependent on the interval and number of the values being integrated. The average radiometric or equivalent grade $\bar{G}_\gamma$ is calculated by dividing the grade-thickness product $\bar{G}_\gamma T$ by the thickness T. The thickness is the distance between the ore or bed boundaries and may be estimated from the log.

A somewhat empirical method has been devised to estimate the thickness T from the log. The method is based on a hypothetical spherical sample volume, which is only a convenient approximation. Figure 6 illustrates the method. It shows a homogeneous ore zone having sharp boundaries, several positions of the detector and respective sample volumes, and a representative log trace. When the detector is a distance from the boundary greater than one radius of the sample volume that material in the ore zone will not cause a response. As the detector approaches to within less than one radius, part of the sample volume is occupied and the detector responds even though it may not be in the ore zone. When the detector is at the boundary of a zone which is at least one radius thick, one half of the sample volume is filled and the response will be half that of a full sample volume. For this simple case, the bed boundary is indicated by the half-amplitude point on the log trace. This is also the inflection point on the log curve representing a decrease in the rate of increase in response of the detector to the material in the ore zone.

If the sample volume is not spherical, if the boundary is gradational (or the zone is not homogeneous) and if the zone is less than one radius thick, the method cannot rigorously define the boundary. The thickness is, therefore, an empirically determined estimate which is remarkably good for thicknesses of 2 or more feet; lesser thicknesses tend to be overestimated. Fortunately this does not affect determination of $\bar{G}_\gamma T$, which represents the quantity of radioactive material; it may cause slight 'dilution' and hence underestimation of the average grade of the zone. For practical mining and reserve calculation this error in thickness, which is generally small, can be tolerated or ignored because thicknesses less than 2 feet can seldom be economically extracted without dilution. Perhaps future theoretical work will develop a rigorous technique.

Corrections. Valid quantitative analyses, based on Equation 1 described in the preceding section, depend on the proper application of corrections for nonlinearity in the logging system and for variations of the logging environment from the standard conditions of calibration.

Dead time correction. Assuming that adequate instrumentation is employed, the only significant nonlinearity in the logging system is caused by instrument dead time. If compensation for dead time is not provided in the logging system, such as the crystal clock - dead time module of the RD-1A system, then each numerical

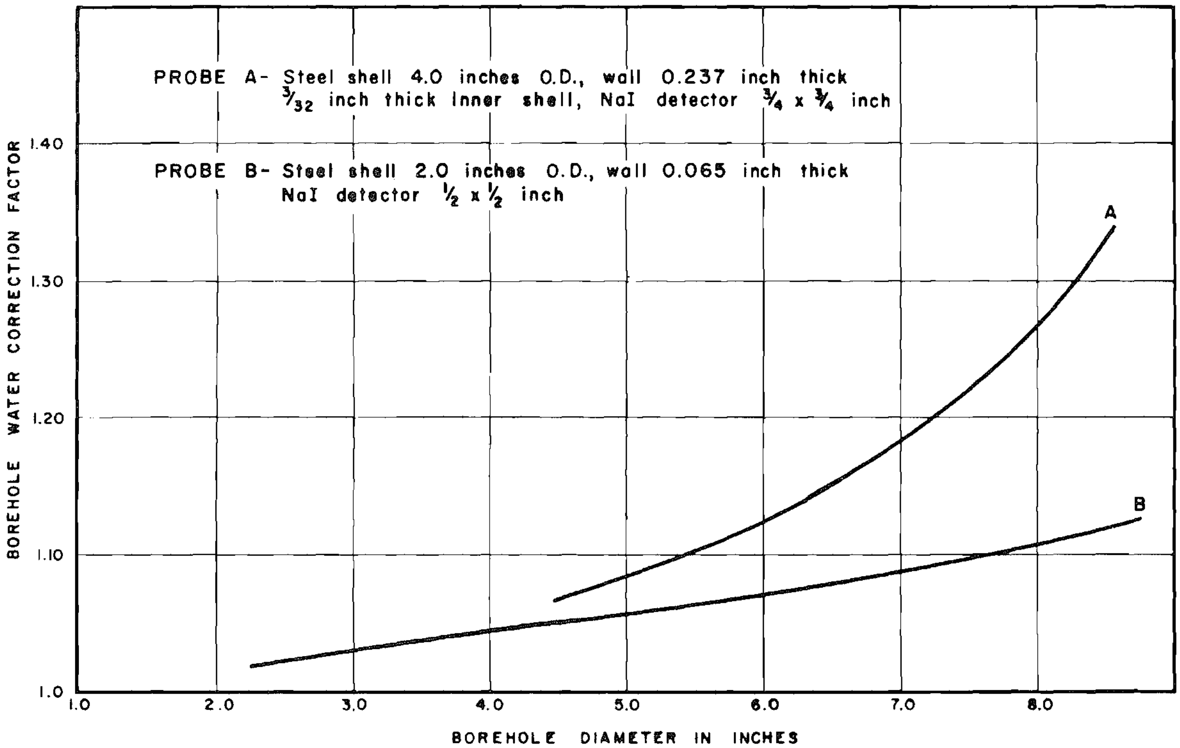


Figure 8. Correction factors for water content and diameter of borehole using typical natural gamma-ray logging probes.

value of the observed count rate n should be corrected statistically using the equation

$$N = \frac{n}{1 - nt} \qquad 2$$

where N is the corrected count rate and t is dead time. Figure 7 shows the nonlinearity caused by dead time of typical logging systems used by the uranium industry. Unless controlled and corrected, dead time will introduce significant errors in the quantitative analysis of any log based on pulse counting. In the case of the natural gamma-ray log, uncorrected dead time results in underestimating grade and overestimating thickness, particularly if very high count rates are generated by sensitive detectors or high concentrations of gamma rays.

Corrections for nonstandard borehole environments. The standard conditions under which the natural gamma-ray logging probes are calibrated have been arbitrarily selected to approximate common field conditions. Any variation in the logging environment from the conditions of calibration may require a correction to standard conditions. Variations in hole size, hole fluid, and drill rods or casing commonly introduce significant nonstandard environments.

At least in the case of gross counting, the correction of the gamma-ray log for variations in size of an air-filled hole up to 8 inches in diameter is insignificant. (For this reason 4 1/2-inch, air-filled, uncased holes have been selected as standard conditions for calibration.) However, if the hole fluid is a significant absorber of gamma rays, such as water or natural mud, then major corrections for hole fluid and size are necessary. Correction

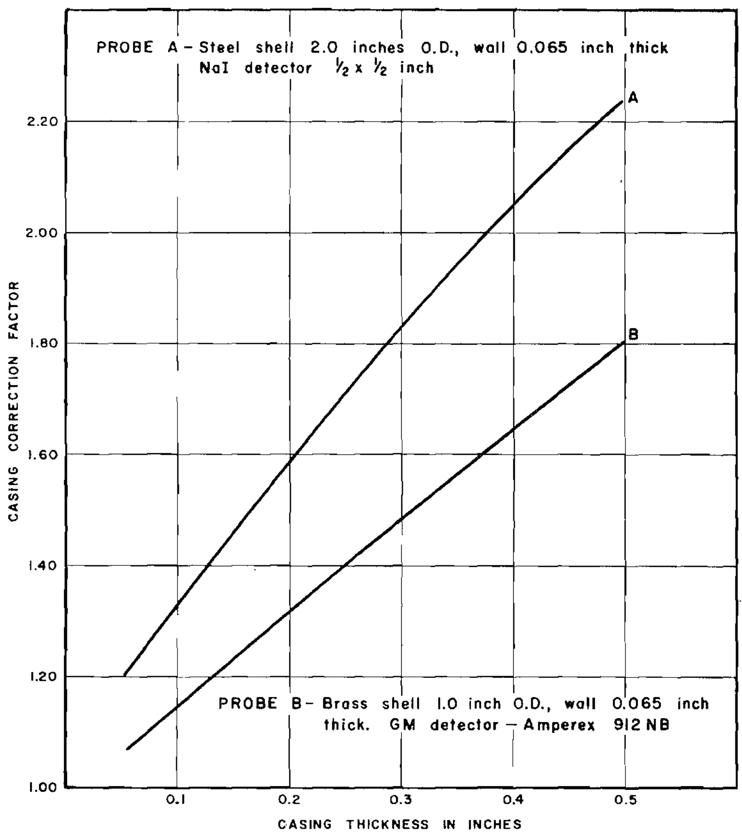


Figure 9. Correction factors for wall-thickness of casing using typical natural gamma-ray logging probes.

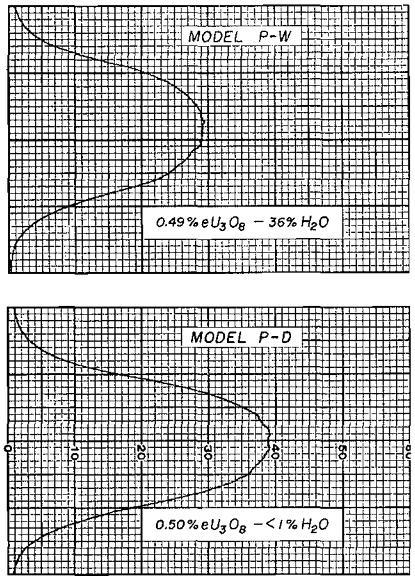


Figure 10. The attenuation effect of free water in the formation.

curves, Figure 8, are developed for each probe from full-scale models. Factors influencing the correction values are the spectral efficiency of the detector, the probe diameter and the probe shell thickness and material. Heavy barite muds introduce additional problems involving gamma-ray reactions with elements of high atomic number.

Similar curves, Figure 9, are required for each probe to correct for the absorption by casing or drill rods. For practical purposes these corrections are linear for all count rates and may be applied to the area or integrated term of the calibration and analysis equation. Appropriate corrections are indicated by the caliper log and driller's records.

Nonstandard conditions in the formation which modify, scatter and absorb natural gamma rays are less easily determined and the cumulative effects are not well evaluated. These include

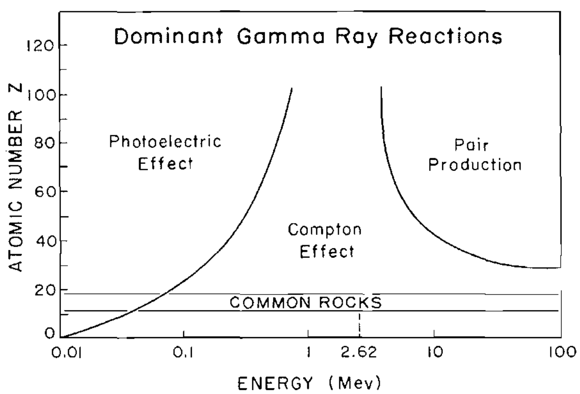


Figure 11. The type of gamma-ray reaction depends on atomic number Z and photon energy. Maximum natural gamma energy and effective atomic number of rocks, and the dominance of compton scatter are indicated by dashed lines.

intergranular fluids and unusual abundance of elements of high atomic number in the rocks.

The effect of free water in the formation is illustrated by the two logs in Figure 10. With the exception of the 36 percent by weight of water in model P-W, these models contain essentially the same materials. However, the log of the water-saturated model has a distinctly lesser amplitude and area under the curve. From empirical investigation and experience, it appears that a factor derived from the relationship

$$\text{Free water correction} = \frac{100 - \%\ \text{water in calibration}}{100 - \%\ \text{water in formation}} \qquad 3$$

adequately corrects for nonstandard free water content. The percent water in rocks below the water-table may be closely approximated from the gamma-gamma density-porosity log and it is believed that neutron-neutron methods can be developed to obtain this value for unsaturated rocks.

Figure 11 shows the fields of gamma-ray reactions in terms of the gamma-ray energy and the atomic number of the medium. Most of the common rock-forming minerals, especially those of the clastic host rocks for uranium in the western United States, have similar atomic numbers. Consequently the range of the effective atomic number of the rocks is generally narrow, averaging perhaps 15. The maximum energy of natural gamma rays is 2.62 mev. Low-energy photons, either from primary emissions or scatter, are abundant. It is these with energies of 0.14 mev or less which undergo photoelectric absorption, particularly with materials of high atomic number, and are removed from the system. This effect becomes more pronounced with the introduction of more than trace amounts of high atomic number elements, a situation generally difficult if not impossible to evaluate. The effects of nonstandard composition can be minimized by using calibration models which simulate the composition of the common rocks to be logged. Preliminary investigations also suggest that physical or electronic discrimination of low-energy gamma rays, those most influenced by variation in atomic number of the medium, will greatly reduce or largely eliminate compositional effects.

Correction for disequilibrium. In the geochemical environment the major gamma-ray-emitting daughters, such as bismuth-214, often are not in secular equilibrium with the parent uranium-238 (see Figure 3). This is particularly true of many sandstone-type uranium deposits in which the uranium or radium have been selectively transported. In this event, to estimate the true grade of the uranium, a correction must be applied to the equivalent grade indicated by gross gamma-ray measurements. The disequilibrium correction is represented by the ratio of the true grade, determined by chemical analysis, to the equivalent or radiometric grade. This ratio can be estimated by statistical analysis of chemical and 'gamma-only' assays of representative samples from the area, as described by Scott and Dodd (1960). If adequate sample data are available, a regression analysis will relate the disequilibrium ratio and grade; such an analysis indicates the 'best' correction to be applied to each equivalent grade. Lyubavin and Ovchinnikov (1961) suggested that disequilibrium could be detected by spectral logging methods. Preliminary investigations tend to confirm this idea; however, the complexity and extreme stability of the instrumentation required exceeds or seriously taxes the capability of the instrumentation currently in service.

To calculate ore reserves and make economic evaluations of a uranium deposit may require quantitative analysis of several to several hundred gamma-ray logs. These may have been obtained with more than one logging system, each requiring individual calibration and correction factors. With experience, those logs which indicate a mineralized zone of interest may be selected by inspection.

The equivalent grade and thickness of the anomalies can be determined by 'hand' interpretation methods described in detail by Scott, *et al.* (1961). Briefly, this involves: (1) selecting the zone boundaries from the half-amplitude points on the sides of the anomaly to determine the thickness T in feet; (2) obtaining the area under the log curve A by summing the count rate values, corrected for dead time, at 1/2-foot intervals between the indicated boundaries, and adding the area of the anomaly which extends outside of the zone boundaries (estimated by applying a 'tail factor' to the sum of the count rates at or adjacent to the boundaries); (3) applying appropriate correction factors to the area; (4) obtaining the grade-thickness product $\bar{G}_\gamma T$ by multiplying the area A by the calibration factor k; and (5) determining the equivalent average grade $\bar{G}_\gamma$ by dividing $\bar{G}_\gamma T$ by T. To some extent portions of anomalies may be selected for analysis to meet mining or economic requirements.

Similar techniques may be applied to determine the equivalent ppm of uranium in formations or selected lithologic units. By this method dispersed amounts of radium and its daughters, which in some cases extend well beyond the limits of the ore, can be detected from relatively wide-spaced exploration holes. However, the gross gamma log of low-intensity anomalies will be significantly influenced by the potassium and thorium content of the rocks.

GAMLOG, a computer program for quantitative analysis of gamma-ray logs was developed by Scott (1962). With subsequent modifications* it has become the standard method of analysis to obtain grade and thickness for ore reserve estimation. This program, written in FORTRAN II for the IBM 7090, utilizes 300 or more log deflection values at 1/2-foot intervals and coded control data such as type of logging equipment, k factor, dead time and correction factors to determine and print out the equivalent grade of 1/2-foot layers within the anomaly. The identification and control data are supplied on standard 80-column IBM cards. Log deflection data are digitized from copies or original analog records and punched on cards by a Gerber Digital Data Reader coupled to an IBM 026 key punch. Perforated tape records may be automatically converted to the standard card format, or digital readout on printed tape can be manually transferred to cards by the key-punch operator.

From the calibration equation (1) and the sample volume concept, for an infinitely thick, homogeneous zone, all log deflections, in units of counts per second corrected for dead time, can be shown to be, and any one can be represented by $\bar{N}$. If deflection (count rate) values are taken at 1/2-foot intervals, the number of values will be $2T$. Therefore

*Paul C. deVergie, Ore Reserves Branch, Grand Junction Office, U.S. Atomic Energy Commission, has modified the program with additional control and input data.

$$
\begin{aligned}
A &= 2\bar{N}T \\
\text{and } \bar{G}_\gamma T &= k \cdot 2\bar{N}T \\
\bar{G}_\gamma &= 2k\bar{N}
\end{aligned} \qquad 4
$$

Therefore, the grade of an anomaly representing a homogeneous, infinitely thick zone, can be determined by multiplying the deflection in corrected counts per second by twice the k factor.

By using Equation 4 the GAMLOG program makes a first approximation of the grades of 1/2-foot layers of an anomaly. Weighting factors for adjacent layers also occupying portions of the sample volume are determined from model studies and hypothetical anomalies are generated for each 1/2-foot layer. These, in turn, are composited into a total anomaly which is compared to the real anomaly. The assigned grades of the individual layers are adjusted by an iterative process until the composited anomaly matches the log anomaly, as shown by Figure 12. The program output shows grade and depth or elevation of the hypothetical layers printed in tabular form.

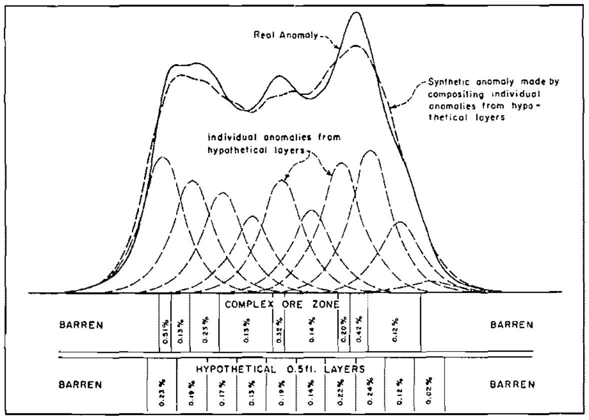


Figure 12. GAMLOG generates synthetic anomalies for hypothetical 1/2-foot layers and adjusts grade of the layers until the composited anomaly matches the log.

Subroutines have been developed to calculate count rates, corrected for dead time, from curvilinear and rectilinear logs which have been digitized in units of inches of deflection and coded range scales. The calculated grade and depth values are used as input data for several computer programs which statistically compute reserves in terms of pounds U_3O_8, tons of ore and average grade and thickness at cut-offs determined by various market prices or production costs per pound (Grundy and Meehan, 1963; Patterson, *et al.*, 1964).

Scattered gamma-ray density log

The scattered gamma-ray density log was introduced in 1951 (Faul and Tittle, 1951) and the principle has been applied to several engineering problems (Homilius, *et al.*, 1958; Roy and Winterkorn, 1957). It is used by the petroleum industry to measure porosity. The physical principles have been well described in the literature (Pickell and Heacock, 1960; Baker, 1957; Homilius and Lorch, 1957; Wahl, *et al.*, 1964; Rodermund, *et al.*, 1961). However, the method cannot be directly applied to determine the density of uranium deposits because the intensity of natural gamma radiation obscures the scattered gamma rays from the density probe.

To overcome this problem, a method of density logging has been developed which cancels the background of natural gamma radiation and measures the wet bulk density (Dodd and Droullard, 1965). Values for dry density, porosity and water content of the rocks, which are required to evaluate uranium deposits, are derived from the wet density measurement. A digital recording system and a computer program for automatic processing of the data contribute significantly to the practical application of this log.

Principle of scattered gamma-ray density logging

Electron density related to bulk density. The probe used to measure bulk density ρ_b in the borehole contains a collimated source of gamma rays which is separated from the detector. Gamma rays from the source penetrate the rock and are scattered back to the detector. Tittman and Wahl (1965), Czubek and Guitton (1965), and Czubek (1965) have shown that by using a suitable detector and gamma-ray energy the response is proportional to the Compton scattering which is controlled by the electron density ρ_e of the medium. If

$$\rho_e = N_A \ (Z/A) \ \rho_b \qquad 5$$

where N_A = Avogadro's number and Z/A is the ratio of atomic number to atomic weight, then the response is also proportional to the bulk density. Tittman and Wahl (1965), and Danes (1960) have also shown that, with the exception of hydrogen, Z/A of the common rock-forming elements is nearly constant. Therefore, by applying corrections for nonstandard Z/A, the response of the system may be calibrated in terms of ρ_b.

Porosity. Fractional porosity ϕ is calculated from the relationship

$$\phi = \frac{\rho_g - \rho_b}{\rho_g - \rho_f} \qquad 6$$

where ρ_g is the grain density and ρ_f is the fluid density.

Problems and applications in the uranium industry

Special problems. Several of the problems of scattered gamma-ray logging become especially acute when applying the method to the uranium mining industry. Foremost is the wide range and intensity of natural gamma radiation which obscures the back-scattered gamma rays from the source and which places extra demands on the pulse counting system.

The effect of hole size is critical, especially at the smaller diameters. Most holes drilled by the uranium mining industry in the western United States have nominal diameters ranging from 3 to 5 inches and normal variation within this range has a very significant effect on response. Therefore, quantitative density analysis requires accurate measurement of small changes in hole diameter to determine appropriate corrections.

Commonly, the depth to the air-water interface in the hole is unstable, which compounds the problem of correcting for effects of hole fluid.

Information sought from density logging. Dry bulk density, rather than wet density, is used in the volume-to-weight conversion for ore reserve calculations. Many deposits are evaluated by non-core drilling and logging methods, and the density log can supply the otherwise unavailable bulk-density measurement. Dry bulk density ρ_d may be used in geologic investigations and to evaluate mining problems. For a particular rock type, such as sandstone, the degree of induration or cementation, which is indicated by the density, directly affects its competence under mining stresses and its fragmentation.

Fractional porosity ϕ (Equation 6), is required to calculate ρ_d and the water content of the rock. Porosity data supplement lithologic interpretations from other logs, support geologic studies of ore controls and genesis, and may be used to evaluate water problems encountered in mining. A correction for water content of the host rock is needed to determine ore grade from natural gamma-ray logs.

Saturation S_w the fraction of the pore space occupied by water, is required to establish the fluid density ρ_f and to calculate the water content. Below the water-table 100 percent saturation may be assumed, at least in the case of rocks having interconnected pore space. Above the water-table saturation may be measured with a neutron log or estimated from experience.

Method for determining density of uranium ore zones. The following method and calculations are used to determine the dry bulk density of uranium-bearing rocks.

Dead time corrections. As in the case of natural gamma-ray or other nuclear pulse counting methods, the response of the density logging system must be corrected for instrument dead time. If not corrected by the logging system it is made by the computer program using Equation 2 and the correction becomes very significant at the high count rates generated by the combined radiation from the source and uranium ore.

Difference method using dual spacing. The intensity of the scattered gamma radiation at the detector is, within certain limits, a function of the source-to-detector spacing. Therefore for a given density, the response of a probe having a short spacing is n_S and

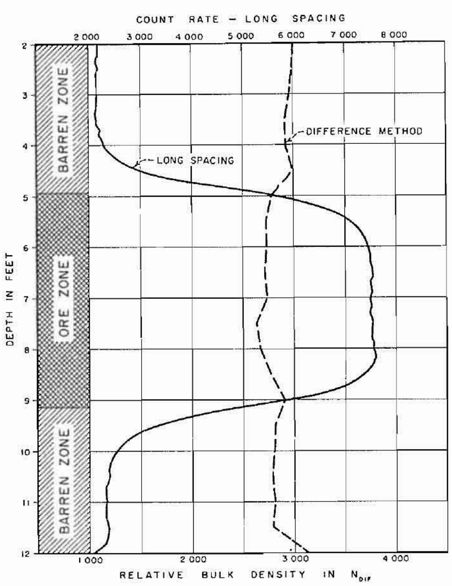


Figure 13. Comparison of density logs of an ore zone, using single spacing and difference methods.

the response for a long spacing is n_L. Corrected for dead time, these become N_S and N_L and both are a function of density. The difference $N_{DIF} = N_S - N_L$ is also a function of density (see calibration curve Figure 15). For a given position in the hole, the intensity of the natural gamma radiation at the detector is a constant which is included in N_S and N_L. This constant is eliminated by subtraction and N_{DIF} remains a function of density unaffected by background radiation (Figure 13).

Therefore, to determine density of naturally radioactive material, two logs are made with a difference in spacing of 4 or more inches. The N_S and N_L values are corrected for borehole effects and the N_{DIF} value is converted to wet bulk density by a polynomial calibration equation (11). To facilitate the difference method, the type 400 density probe has been developed which permits changing the spacing while in the hole (Figure 14).

Calculation of porosity, dry bulk density and water content

Porosity. Having measured the wet bulk density, the fractional porosity may be calculated using Equation 6. A value for grain density ρ_g is determined from the drill cuttings, either by analysis or estimated from inspection of the mineral composition. A value for fluid density ρ_f is determined as follows:

1. Below the water-table ρ_f is assumed to be 1.0 because the pore space is filled with fresh water.
2. Above the water-table ρ_f is equivalent to the water saturation, S_W, because

$$\rho_f = \frac{(\phi_W \cdot \rho_W) + (\phi_a \cdot \rho_a)}{\phi_W + \phi_a} = \frac{\phi_W}{\phi} = S_W \qquad 7$$

where ρ_W is density of water, ρ_a is density of air, ϕ_W is fractional porosity occupied by water, and ϕ_a is the fractional porosity occupied by air. A correction is applied to the ρ_f term to compensate for the A/Z of hydrogen in S_W and the porosity equation (6) is modified to the following form:

$$\phi = \frac{\rho_g - \rho_b}{\rho_g - (S_W \cdot \mathrm{Corr}_{A/Z})} \qquad 8$$

Dry bulk density. Dry bulk density ρ_d is calculated by

$$\rho_d = \rho_b - W \qquad 9$$

where W is the weight of water in grams contained in a cubic centimeter of the rock ($W = \phi \cdot S_W$).

Water content. The water content $\% W$, expesssed in percent moisture by weight, is derived from the relationship

$$\% W = \frac{W}{\rho_b} \cdot 100 \qquad 10$$

Calibration for density and borehole effects. The response of the density logging system to density and borehole effects is calibrated in full-scale model holes. The probe is calibrated for density in standard air-filled holes, 4.5 inches in diameter. The effective bulk densities of the models, which range from 1.62 to 2.85 gm/cm³, are determined by physical measurements, and are corrected to a standard A/Z of 2.0.

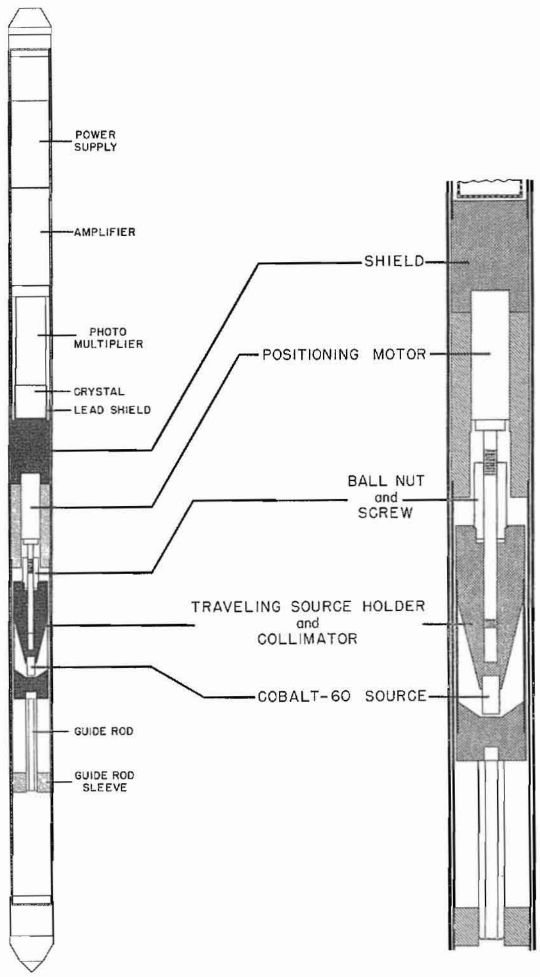


Figure 14. Sectional diagrams of type 400 density probe.

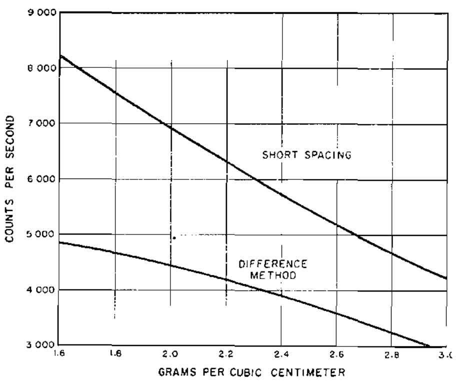
Dual spacing procedure for difference method. The count rates for the short- and long-spacing configurations are measured while the probe is held stationary against the walls of the model holes. These rates are corrected for dead time and the N_{DIF} values computed for each model are plotted versus the bulk density to derive a calibration curve (Figure 15).

WRAP*, a weighted regression analysis program for the IBM 7090 fits a curve to the points and prints out the coefficients and applicable terms of the polynomial calibration equation,

$$\rho_b = a_o\, N_{DIF}^n + a_1\, N_{DIF}^{n-1} \cdots\cdots + a_{n-1}\, N_{DIF} + a_n \qquad 11$$

Single-spacing calibration. Likewise, the corrected count rates N_S and N_L are plotted and calibration equations similar to Equation 11 are calculated by WRAP for each of the single spacing. These calibrations are used when natural radioactivity of the formation is insignificant and the more sensitive and rapid single-spacing method is satisfactory.

*WRAP, Weighted Regression Analysis Program, developed in 1961 for IBM 7090 by M.D. Fimple, Sandia Corporation, Sandia Base, Albuquerque, New Mexico.



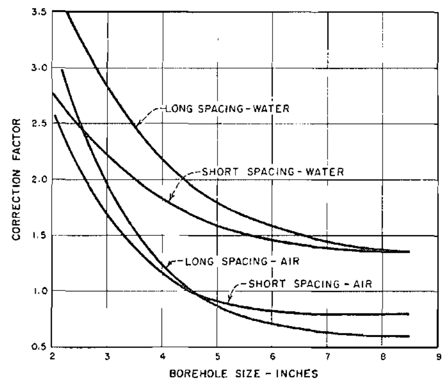


Figure 15. Typical calibration curves for type 400 density probe in standard 4.5-inch air-filled hole.

Figure 16. Typical borehole size correction curves for air- and water-filled holes.

Determination of corrections for borehole effects. A model of uniform density which contains 7 holes, ranging in diameter from 2.25 to 8.50 inches, is used to determine correction factors for borehole effects. With the probe held stationary against the wall, the count rates for air-filled and water-filled holes are measured for short and long spacing and the rates corrected for dead time. Corrections are computed to normalize the four sets of data to the standard air-filled hole, 4.5 inches in diameter. Curves showing the correction for diameter in air- and water-filled holes for short and long spacing (Figure 16) are fitted by WRAP which computes the coefficients and applicable terms of four polynomial correction equations similar to Equation 11.

Correction for source decay. The half-life of the Cobalt-60 source is 5.3 years and a correction factor for source decay at the time of logging is applied by the computer to maintain the calibration equation.

Calibration of caliper probe. The caliper system is linear through the operating range and a single-point calibration is made by placing the probe in a metal sleeve of known diameter and adjusting the voltage in the divider circuit to obtain the correct measurement.

Data processing. Automatic data processing contributes significantly to the practical application of the density logging method because many routine manipulations are required to interrelate the data from the several types of logs and to correct the data to standard calibration conditions. Additional manipulations are needed to calculate the dry density, porosity and water content at closely spaced intervals.

RHOLOG*, a computer program written in FORTRAN II for the IBM 7090, has been developed to process the data from the density and caliper logs. The computer calculates and prints out up to 2000 density and associated values in a single hole and determines the average density for zones of special interest. An error code is printed at the appropriate depth if data from associated logs are not available or have been interpolated from adjacent readings, or if they are determined to be invalid for certain portions of the hole. Logs from a given hole may be discontinuous, top and bottom depths of associated logs need not match and, in the absence of specific data, estimates of certain parameters may be used.

*The RHOLOG program was developed by Paul C. deVergie, Grand Junction Office, U.S. Atomic Energy Commission.

The density and caliper logs, including manually entered identification data, are recorded on perforated tape by the logging system. These are converted to punched cards by an IBM 047 tape-to-card converter and additional identification and control data are supplied on manually punched cards. The data cards are listed for editing before being submitted to the computer.

Gamma-ray spectroscopy

Introduction and history. As part of its program to support industry with research and development of new or improved exploration and evaluation tools, the Grand Junction Office of the U.S. Atomic Energy Commission recently initiated a small project to develop applications of gamma-ray spectroscopy to field investigations. The following comments and observations on in-hole spectral measurements are the result of preliminary and exploratory studies.

As early as 1948 and 1949 Hoftadter published on the application of NaI(TI) crystals to detect gamma energies from low-intensity sources. The technique soon became standard laboratory practice. DiGiovanni, *et al.,* (1952), in describing a scintillation logging unit designed for uranium exploration stated, "A further advantage is the fact that the sodium iodide crystal scintillation intensity is directly proportional to the absorbed energy of the incident gamma photon. This makes it possible to obtain gamma energy spectra from the material in the hole (which is extremely useful for determining the nature of the radioactive material therein)."

Laboratory, surface and airborne measurements of gamma spectra are being adapted to the search for radioactive minerals (Adams, 1964; Adams and Fryer, 1964; Pemberton and Seigel, 1966; Foote, 1967).

In spite of numerous references to spectral measurements in the literature, especially since about 1960, the uranium mining industry in the United States has made no concerted effort to adopt this potentially valuable tool for exploration and evaluation. Possibly the lack of interest has stemmed from the temporarily restricted market for uranium, possibly because reliable and stable instrumentation with spectral capability was both expensive and unproven, and possibly because the operational staffs generally considered the whole subject as 'black box' witchcraft. In any event, the advantages of down-hole spectral measurements largely remain to be developed and demonstrated.

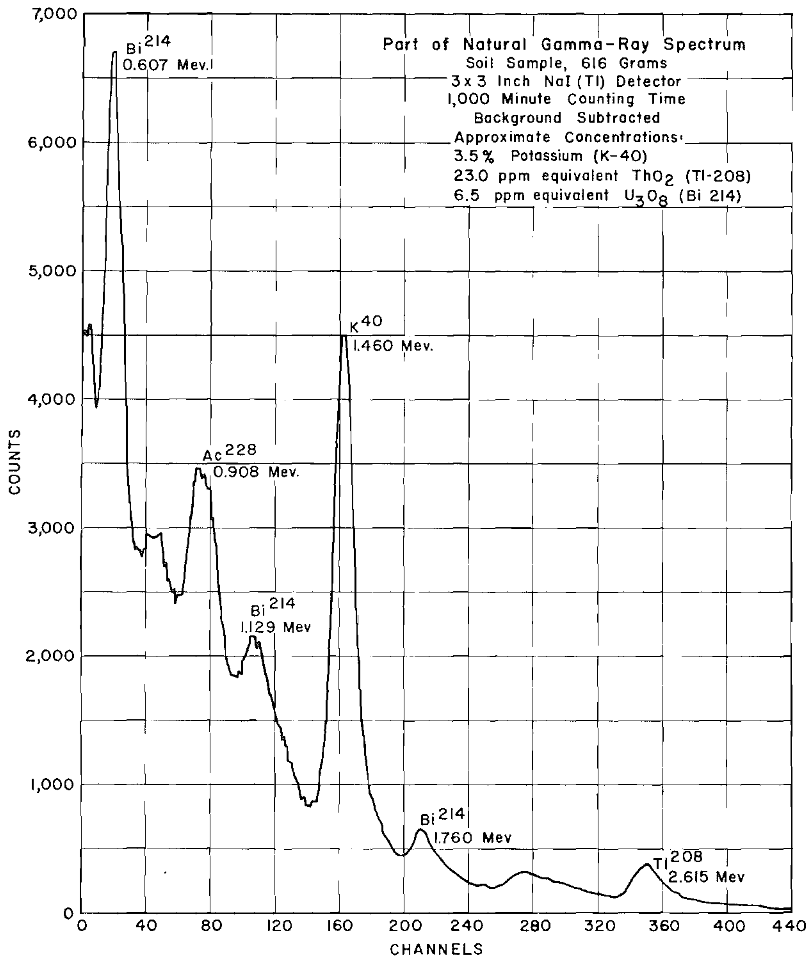


Figure 17. The high-energy portion of the natural gamma-ray spectrum contains prominent photo peaks of thallium-208, bismuth-214, and potassium-40. These can be resolved sufficiently to make spectral identifications and quantitative measurements in the borehole.

Natural gamma-ray spectra. Gamma rays are emitted by at least 24 of the 37 common natural radioisotopes of the thorium and uranium series and potassium. Several natural gamma-emitters, such as bismuth-214, emit gamma photons at many energies. Well over a hundred primary energies have been recognized, and with improved resolution in instrumentation the number is increasing. Compton scatter of the primary photons within the sample produces a more-or-less continuous spectrum of photons with energies below the photopeaks of all primary energies in the source. The gamma-ray emitters of major significance in borehole measurements are shown on the decay series diagram of Figure 3.

Figure 17 shows the high-energy portion of a spectrum for a natural soil sample containing potassium, and uranium and thorium series. The more prominent photopeaks, identified in the figure, are generally believed most useful in down-hole measurements. These include the peak of thallium-208 at 2.62 mev, which is used to indicate natural thorium-232; a bismuth-214 peak at 1.76 mev, used to indicate radium-uranium; and the potassium-40 peak at 1.46 mev, used to measure total potassium.

Problems in down-hole spectroscopy. Good down-hole spectral measurements are more difficult to achieve than those at the surface or in the laboratory. The large sample volume 'seen' by the probe causes the photopeaks of the primary energies, particularly in the low-energy region below .5 mev, to be obscured by fill-in from Compton scatter of all higher energies. As noted by Gregory and Horwood (1961), increasing sample thickness gradually obscures peaks until, for a 1-foot thickness, those peaks representing energies less than one mev are little more than barely discernible shoulders along the spectrum. Therefore, spectroscopy in the borehole based on resolution of photopeaks is restricted to the energy region generally above 1 mev. Even above 1 mev the spectra from large samples measured by the hole probes contain a larger scattered component than 500 to 1000 gm laboratory samples. However, photopeaks can be adequately resolved by a good logging system to be of practical value.

In the low-energy region below 0.5 mev, not only are the photopeaks obscured by scatter, but photoelectric absorption by high Z elements, particularly of photons less than 0.1 mev, distorts the primary spectrum; the low-energy spectrum is sensitive to composition (Kartashov, 1961). In fact, Czubek (1965) and others proposed to measure this absorption of the low-energy photons from a monoenergetic source to calculate effective Z numbers and evaluate composition.

Problems with instrumentation for quantitative spectral measurements down-hole are formidable compared to laboratory and surface work. The proportionality between photon energy and pulse height must be maintained while transmitting the signal through hundreds of feet of logging-type cables to the amplifier and analyzer. Both sensitivity and efficiency for high-energy photons increase with crystal volume. Statistically reliable counting of the selected energy bands is achieved in less time with large crystals. However, the supporting electronics system must be capable of linear response at the resulting high gross count rate. No single detector is optimum for a wide range of intensity.

Environmental factors are often rigorous. Temperature, in particular, may change rather severely and rapidly. Scintillation-type detectors employing photomultiplier tubes are particularly susceptible to changes in gain with temperature. Spectral measurements preclude operating the system on the gain plateau which overcomes the problem when gross counting. The extended time required to obtain a series of stationary or long dynamic measurements in a deep hole, particularly with fluctuating ambient temperatures, appears to require system gain stabilization.

Sample geometry and environment cannot be controlled in the borehole. Small deviations from calibration conditions may not seriously change the ratio of photons at the energies commonly selected for spectral analysis of uranium, thorium and potassium; but such deviations will affect determinations of absolute concentrations.

Applications to exploration and evaluation. The most obvious and simplest application of gamma spectroscopy is to qualitatively identify the source of gamma radiation. A gross gamma-ray anomaly, whether detected from the air, from a vehicle, on the outcrop, or from a borehole log, is unlabeled as to origin and may not indicate the element of interest. In the search for uranium deposits in sandstone it is not uncommon to find anomalies generated by minor concentrations of thorium-bearing heavy minerals or potassium-rich glauconitic zones. Relatively unsophisticated qualitative spectroscopy will usually identify the source(s) of gamma rays.

Radium haloes are, of course, important guides in uranium exploration. Broad but low-intensity radioactive anomalies, equivalent to only 10 or 15 ppm uranium, are potential targets for wide-spaced preliminary exploration drilling. However, many such apparent gross-count haloes represent facies changes involving intrinsic potassium or thorium minerals. Minor variations, either enrichment or depletion, of perhaps 5 ppm in the uranium-radium concentration, which can be readily obscured by changes in gross radioactivity, may be significant guides to favorable areas for detailed exploration. Similarly Moxham, *et al.*, (1965), found spectral measurements of uranium, thorium and potassium: thorium ratios could be applied to alteration studies as possible halo-like guides to certain copper and copper-lead-zinc deposits in Arizona.

Geological-geochemical environments may be 'fingerprinted' by characteristic ratios or changing ratios of uranium: thorium: potassium. Each of these elements reacts somewhat differently to changes in *p*H, *e*H, and to common ion concentrations. For example, because of the increased mobility of the uranyl ions, a depletion in uranium relative to thorium or potassium may indicate a current or paleooxidation environment (Adams and Weaver, 1958). For these studies the absolute concentration need not be determined with extreme accuracy, but the relative values require high precision and sensitivity.

If low-grade deposits of uranium, containing perhaps 100 ppm, become economically significant it will become necessary to quantitatively distinguish between the gamma rays emitted by the uranium decay series and those originating in the potassium or thorium minerals of the host rock. This has already become a problem in evaluation of potential resources. The mining industry should be alert to and capable of evaluating data generated while exploring for more conventional deposits. Certainly when quantitatively evaluating deposits containing 0.05 percent uranium or less by radiometric methods, it becomes advisable to eliminate any bias imposed by gamma rays from other than the uranium series. Kartashov (1961) discusses the necessity for such in-hole analyses and the probable analytical errors when using a 50 gm NaI(TI) detector and 10-minute counting time on a small anomaly containing about 50 ppm uranium, 13 ppm thorium and 2.6 percent potassium. The estimated analytical errors were 4.8 percent for uranium, 12.7 percent for thorium and 29.2 percent for potassium. For these measurements extreme sensitivity is not required, and may indeed be undesirable at higher concentrations; but excellent precision and accuracy in absolute concentration is desirable.

Under favorable conditions certain types of disequilibrium in uranium ores may be detected. The low-energy photons from thorium-234, protactinium-234 and uranium-235, which may be differentiated in the laboratory sample, are relatively more proportional to the uranium content than the total spectrum if the uranium-radium series are not in equilibrium. However, these diagnostic photons are buried in a continuum of scattered gammas in the low-energy region and cannot be selectively measured in the borehole. Lyubavin and Ovchinnikov (1961) proposed a method based on the relative fraction of gamma radiation of uranium and its decay products prior to radium and the total gamma radiation of the uranium-radium series. Blake (1965) reported encouraging results from similar preliminary field investigations based on simple ratios between the hard and total spectrum, which were measured by enclosing one of two detectors in the probe with a physical energy filter.

Electronic discrimination can sharpen the differentiation between soft and hard portions of the spectrum. These ratios, which at best yield small percentage changes with disequilibrium, are extremely sensitive to the individual measurements; and the two measurements, to be valid, must represent the same sample and, to be reliable, require instrumentation with almost perfect stability. Minor changes in borehole environment drastically affect the low-energy spectrum and, if not adequately corrected, will cause variation in ratios unrelated to disequilibrium. In spite of these problems, in-hole disequilibrium measurements would be immensely valuable and therefore intensive investigations are warranted to develop reliable operational procedures for disequilibrium logging. Closely spaced or continuous records could be integrated to obtain disequilibrium correction factors which, if applied to the gross gamma log of ore zones, would more accurately indicate the uranium concentration. Even if the disequilibrium is only qualitatively indicated, the logs would be valuable in studying the disequilibrium problem; and a series of measurements might well indicate the position of the sampled zone relative to solution roll fronts described by King and Austin (1966).

Summary

The uranium mining industry increasingly relies on analysis of logs to obtain most of the geological and engineering data from exploration and development drilling.

Natural gamma-ray logs can be quantitatively analyzed by the GAMLOG computer program to determine depth, thickness and equivalent grade of ore zones and of layers within the anomalous zone. These parameters are used in other computer programs to calculate and evaluate ore reserves. This analysis is based on the relationship between the area under the logging curve (corrected for dead time) and the grade-thickness product.

Backscattered gamma-ray logs can be quantitatively analyzed by the RHOLOG computer program to determine in-place dry bulk density, porosity, and free water in saturated rocks. These parameters are used in the volume-to-weight conversion for ore reserves, to evaluate mining problems, and to correct natural gamma-ray logs. A difference method has been developed to obtain these measurements in naturally radioactive zones.

Calibration and appropriate correction factors for non-standard conditions are obtained from full-scale model holes.

Semiautomatic digitizing of analog records and on-site automatic digital recording contribute significantly to the practical application of computer analysis.

Gamma-ray spectroscopy is being investigated; and in spite of scatter by the large sample, difficulties in linear pulse height transmission on logging cable and problems with environmental stability of spectral instrumentation, it appears to offer powerful new techniques for exploration and evaluation. The sources of high-energy gamma radiation can be identified in the borehole, the relative contribution by the several radioactive series may be evaluated, meaningful radioactive haloes may be differentiated from gross anomalies, geological-geochemical processes and environments may be 'finger-printed', and it may be possible to develop disequilibrium logging methods.

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Contents

Airborne radiometric surveying for mineral deposits

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Abstract. During the last 18 months, tens of thousands of line miles of airborne radioactive surveying have been undertaken in Canada and the United States for private industry. The primary targets of these surveys are epigenetic peneconcordant uranium deposits of late Triassic to Eocene age in the western United States, Precambrian pitchblende-bearing vein deposits of the Beaverlodge type, Proterozoic conglomerate ores of the Blind River type, and pegmatitic occurrences such as the Bancroft (Ontario) deposits.

Optimum radiometric instrumentation should be designed around the uranium-thorium ratio of each type of ore occurrence being sought as well as the radioactive elements associated with the nearby formations of host rocks. The factors affecting the optimum survey altitude, line spacing, navigation and type of aircraft to be employed include the following – the amount of exposed outcrop in an area, the topographic relief, the minimum target size of possible interest and the location and size of the area.

Practical field procedures are discussed and radiometric profiles over a variety of different radioactive mineral occurrences and rock types are presented.

No accurate quantitative evaluation of uranium, thorium or potassium content associated with any radiometric anomaly can be made from airborne data regardless of the sophistication of the instrumentation employed. Practical aspects of interpretation and the full potential and limitations of airborne radiometric surveying for economic minerals are discussed.

Résumé. Au cours des 18 derniers mois, des dizaines de milliers de milles ont été parcourus par des avions effectuant, pour le compte de l'industrie privée, un relevé aéroporté des radiations au sol sur les territoires canadien et américain. Les divers gîtes qui intéressent cette prospection sont les gîtes épigénétiques pénéconcordants d'uranium dont l'âge va de la fin du Triasique à l'Eocène dans l'ouest des Etats-Unis, les gîtes filoniens (du type Beaverlodge) de pechblende precambrienne, les minerais constitués de conglomérats du Proterozoique (du type Blind River) et les venues de pegmatite du type Bancroft (Ontario).

Pour un rendement optimum, les appareils radiométriques devraient être conçus en fonction du rapport uranium-thorium des gîtes recherches et des éléments radio-actifs associés aux formations voisines de la roche encaissante. Les facteurs qui déterminent l'altitude optimum du levé, l'espacement des lignes de vol, le système de navigation et le type d'avion à utiliser comprennent: l'étendue des affleurements dans la région, la topographie de la région, la superficie minimum à prospecter et l'emplacement et les dimensions du terrain.

Des méthodes pratiques de travail sont étudiées et plusieurs profils radiométriques qui représentent diverses venues de minéraux radioactifs et différents types de roches sont présentés.

Les données recueillies même par l'appareillage aéroporté le plus complexe ne permettent en aucun cas d'évaluer avec précision la teneur en uranium, thorium ou potassium d'une zone de roches présentant une anomalie radiométrique. Les aspects pratiques de l'interprétation seront étudiés et on passera en revue les possibilités et les limitations de la prospection radiométrique aérienne des minéraux d'intérêt économique.

The search for uranium is not an easy one. Fortunately those engaged in this pursuit today have new tools which were unavailable in the last boom period of the early fifties. With modern radiometric spectrometers they can locate many radioactive anomalies from the air and also analyze each anomaly source in terms of the dominant radioactive element causing the gamma radiation, be it potassium 40, uranium, thorium or a combination of all three. With ground radioactive spectrometers, they can go one very important step further: not only can they determine the type of radioactive source but with some highly sensitive differential spectrometers, they can measure quantitatively the amount of radioactive element down to a few parts per million. In other words, this new instrumentation permits us to undertake *in-situ* geochemical analyses of the major radioactive elements.

In uranium exploration, more than in any other type of exploration (iron, base metal or nonmetallic), we have learned the necessity of combining the disciplines of the geologist, geochemist and geophysicist. The concentration of uranium in ore can be lower than 0.1%, which in most cases can not be directly detected by the prospector, and often not even by the geologist without an instrument. Fortunately uranium has a number of daughter products or radioactive nuclides which are radioactive and can be detected by suitable instruments.

Early instruments

The first successful instrument to be used in uranium exploration was the Geiger-Mueller Tube. This gamma-counting device was a simple, inexpensive measuring tool which responded indiscriminately to all types of radiation associated with natural radioactive disintegration. Its principle drawbacks were its very low sensitivity or efficiency (1% or less) and lack of energy discrimination. Although some geiger-counters are still being used for qualitative ground exploration, more sophisticated instruments of the scintillometer type are now being employed universally.

A scintillation counter employs a scintillator which 'scintillates' or 'sparkles' when it is struck by gamma ray. It is far more efficient than the Geiger-Mueller tube (better than 90% sensitivity). A photomultiplier tube attached to the scintillator crystal actually counts the number of light flashes or photons and converts them into electrical energy.

Initially, no attempt was made to utilize energy discrimination techniques to differentiate between gamma radiation due to potassium, uranium or thorium. By the time that this could be done the initial uranium search of the fifties had come to an end in North America. However the industry is fortunate in now being able to take advantage of the great increase in basic gamma spectra-knowledge and of the remarkable advances in electronic instrumentation which have occurred within the past few years. Today the industry is employing gamma-ray spectrometers in airborne, surface and drill-hole programs. These radiometric spectrometers enable one to differentiate between the radioactive elements potassium, uranium and thorium through the analysis of the spectral energy distribution.

Table I. Potassium 40, thorium and uranium in igneous and sedimentary rocks, in ppm (from Guillou, 1964).

	Igneous Rocks		Sedimentary Rocks		
	Basaltic	Granitic	Shales	Sandstones	Carbonates
Potassium 40*					
Average	0.8	3.0	2.7	1.1	0.3
Range	0.2– 2.0	2.0– 6.0	1.6– 4.2	0.7–3.8	0.0–2.0
Thorium					
Average	4.0	12.0	12.0	1.7	1.7
Range	0.5–10.0	1.0–25.0	8.0–18.0	0.7–2.0	0.1–7.0
Uranium					
Average	1.0	*3.0*	*3.7*	*0.5*	*2.2*
Range	0.2– 4.0	1.0– 7.0	1.5– 5.5	0.2–0.6	0.1–9.0

*Chemical potassium contains 0.0119 per cent potassium 40.

Theory

All igneous and sedimentary rocks contain varying amounts of the three major and naturally occurring radioactive elements Table I (Guillou, 1964) shows the average content and range of these three major radioactive elements in parts per million in the common igneous and sedimentary rocks. Note that the average uranium content in granitic-type rocks is 3 ppm and in shales, 3.7 ppm. Lower concentrations of uranium are found in the more mafic igneous facies such as basalt, which has an average content of 1 ppm, and in other sedimentary rocks; sandstones have an average content of 0.5 ppm and carbonates 2.2 ppm. The average thorium content is generally greater than that of uranium – four times as much in granite and basalt. This U/Th ratio also holds for shales and sandstones but for carbonates it is approximately 1:1.

All natural elements with atomic numbers greater than 83 (bismuth) are radioactive. An element is radioactive when the atoms of which it is made disintegrate spontaneously. In decaying, an atom may emit one or more gamma rays or it may emit none. Regardless of the number of gamma rays emitted, each gamma photon will have a characteristic wave length or energy. Tables II and III (Mero, 1960) list the radioactive nuclides of the uranium and thorium decay series. An atom that disintegrates to form another atom is called the parent and the product is called the daughter. Radioactive equilibrium is established between a parent and a daughter when the same number of atoms of the daughter nuclide disintegrate as are formed in a unit of time. Thus in a radioactive decay series in equilibrium, the number of atoms of nuclide being formed is exactly equal to the number of atoms of that nuclide which are disintegrating. The amount of nuclides present in either uranium or the thorium decay series in equilibrium is directly proportional to the half-life of that nuclide.

A state of nonequilibrium exists when all or part of one or more of the daughter products or parents is removed from the decay series. The gas radon 222 (Tanner, 1964) is obviously quite mobile and with movement creates a state of disequilibrium. Similarly uranium 234 and radium 226 are quite soluble and may readily be moved through solution from their parents.

Figure 1 shows three spectrograms of the energy distribution of gamma radiation arising from the naturally occurring radioactive isotopes K40, U238 and Th232. Each spectrogram is different and has distinct energy peaks characteristic of gamma emission from specific radioactive disintegrations from the daughter products or nuclides listed in the tables. Between the distinct energy peaks, gammas of lower energy are found which are due to energy degradation through scattering, pair production and interaction, forming what is known as the Compton Continuum. The three spectrograms are sufficiently different to permit their use in determining the relative contributions of the

Table II. The uranium decay series (from Mero, 1960).

Name of Nuclide	Atomic Number	Nuclide	Half-Life	Energy of Gamma Rays Emitted by Nuclide (Mev)[1]
Uranium Group				
Uranium 1	92	U 238	4.5×10^9 y.	0.047 (?)
Uranium XI	90	Th 234	24.1 d.	0.093
Uranium X2	91	Pa 234	1.18 m.	0.394, 0.782, 0.806, 0.820
Uranium II	92	U 234	2.6×10^5 y.	0.060, *0.093*, 0.118
Ionium	90	Th 230	8.0×10^4 y.	0.068, 0.140, 0.190, 0.228, 0.240
Radium Group				
Radium	88	Ra 226	1,600 y.	0.188
Radon	86	*Rn* 222	3.825 d.	–
Radium A[2]	84	Po 218	3.05 m.	–
Radium B	82	Pb 214	26.8 m.	0.053, 0.242, 0.259, 0.295, 0.351
Radium C	83	*Bi 214*	17.9 m.	0.063, 0.191, 0.426, 0.498, 0.609, 0.766, 0.933, 1.120, 1.238, 1.379, 1.520, *1.761*, 1.820, 2.200, 2.420
Radium C′	84	Po 214	164×10^{-6} s.	–
Radium D	82	Pb 210	22 y.	0.007, 0.023, 0.032, 0.037, 0.043, 0.047, 0.065
Radium E	83	Bi 210	5.0 d.	–
Radium F	84	Po 210	138 d.	0.084, 0.790
Radium G	82	Pb 206	Stable	–

Table III. The thorium decay series (from Mero, 1960).

Name of Nuclide	Atomic Number	Nuclide	Half-Life	Energy of Gamma Rays Emitted by Nuclide (Mev)
Thorium	90	Th 232	1.4×10^{10}y.	0.055, 0.075
Mesothorium 1	88	Ra 228	6.7 y.	0.030
Mesothorium 2	89	Ac 228	6.13 h.	0.060, 0.135, 0.184, 0.338, 0.462, 0.533, 0.590, 0.913, 0.969
Radiothorium	90	Th 228	1.9 y.	0.087
Thorium X	88	Ra 224	3.64 d.	0.241
Thoron	86	Rn 220	54.5 s.	–
Thorium A	84	Po 216	0.16 s.	–
Thorium B	82	Pb 212	10.6 h.	0.115, 0.176, 0.238, 0.249, 0.299
Thorium C	83	Bi 212	60.5 m.	0.040, 0.144, 0.164, 0.288, 0.328, 0.432, 0.452, 0.472, 0.720, 0.830, 1.030, 1.340, 1.610, 1.810, 2.200
Thorium C′	84	Po 212	0.3×10^{-6}s.	–
Thorium C″	81	*Tl 208*	3.1 m.	0.277, 0.510, 0.582, 0.859, *2.620*
Thorium D	82	Pb 208	Stable	–

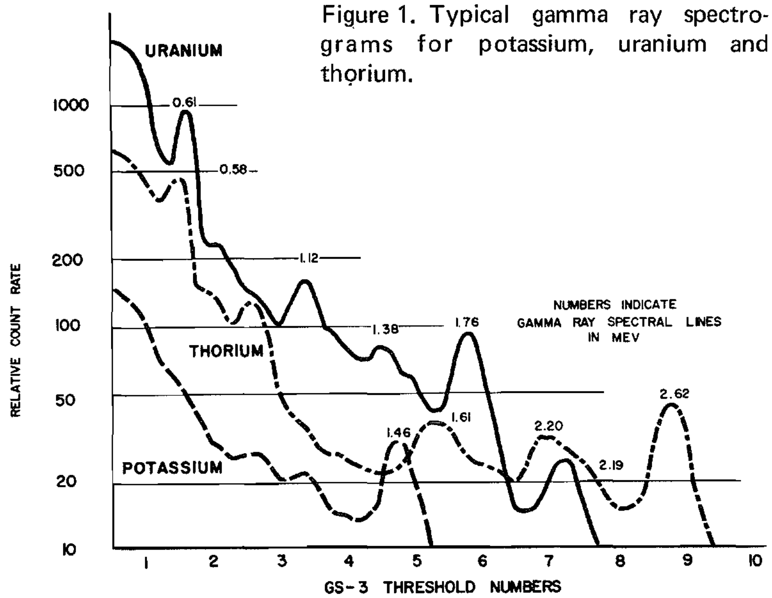


Figure 1. Typical gamma ray spectrograms for potassium, uranium and thorium.

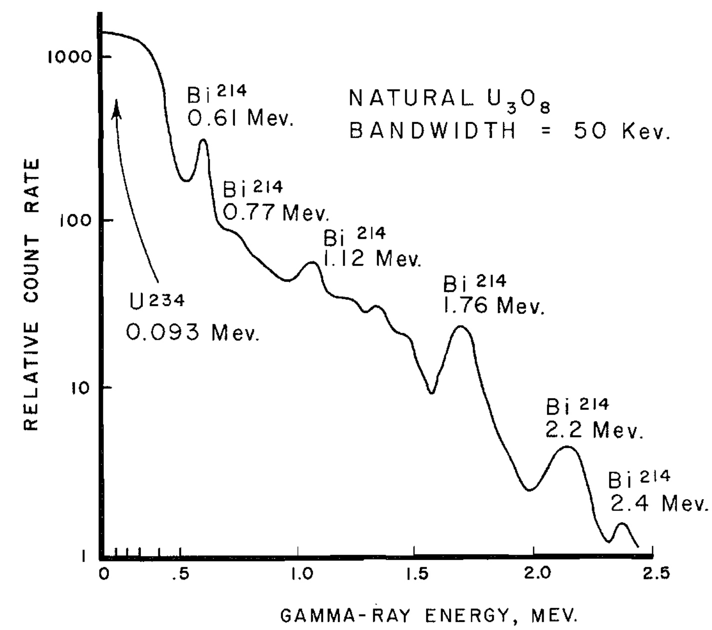


Figure 2. Spectrogram of natural Mississagi quartzite uranium ore obtained by GS-3 differential spectrometer.

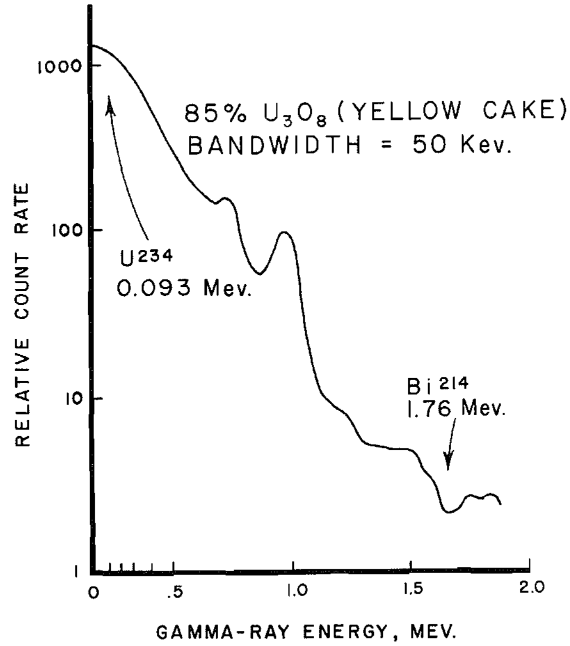


Figure 3. Spectrogram of 85% U_3O_8 (yellow cake) concentrate made from same ore as in Figure 5.

three radioactive series to an observed composite natural gamma-radiation spectrum. If a radioactive series is in equilibrium, then the relative spectral peak amplitudes will bear a nearly constant relationship.

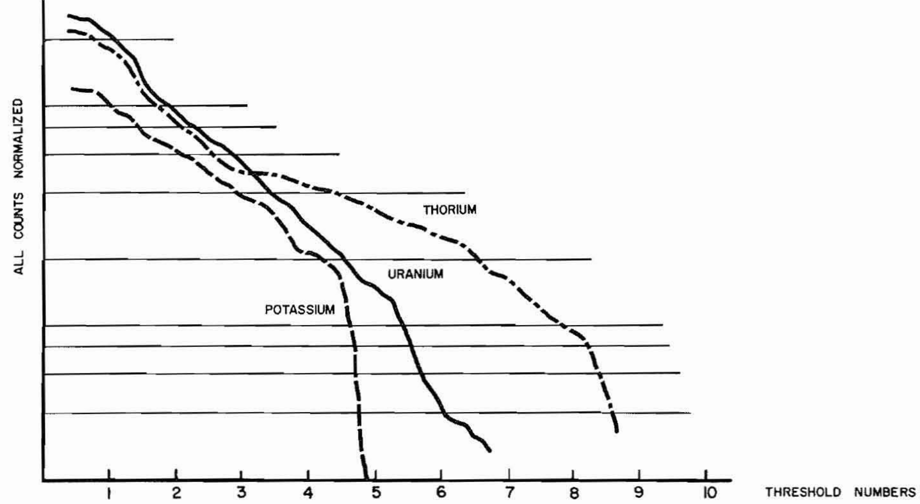
As previously mentioned, equilibrium is not always assured, because of the high mobility of radon 222 and the solubility of uranium 234 and radium 226. Thorium daughters are characterized by shorter half-lives than the uranium series and are therefore found more often in equilibrium. Figure 2 is a spectrogram of a piece of Mississagi uraninite-bearing quartzite from the Blind River area of Ontario. This ore is generally assumed to be in equilibrium. This spectrogram shows some distinct energy peaks, with the largest at 1.76 Mev due to bismuth 214. The 'yellowcake' spectrogram shown in Figure 3, is obviously out of equilibrium and has not had sufficient time to get back into equilibrium. Thus we have for the yellowcake, or uranium concentrate, a condition of disequilibrium because of the absence of bismuth 214 and other nuclides of the uranium and radium series.

Integral and differential spectrometers

Both integral and differential (single threshold and window type, respectively) spectrometers are used in the analysis of the gamma-ray spectrum. The integral spectrometer discriminates by accepting gammas of energies greater than a known but variable threshold level. By moving this threshold, an integral spectrogram may be obtained similar to Figure 4, which shows the typical integral spectrograms for potassium, uranium and thorium. When one differentiates or takes successive differences in count rates for threshold energy changes, these curves will produce data similar to the curves of Figure 1.

When one adds a second threshold above the lower threshold, it is possible to form a 'gate' or 'window' and accept only gamma energies falling within these two thresholds. The instrument then has a 'differential function'. Figure 5 shows a schematic diagram of a typical gamma-ray sensor. When a gamma-ray particle is absorbed in a thallium-activated sodium-iodide crystal its energy is converted and this results in light emission. This flash is

Figure 4. Integral spectra of potassium, uranium and thorium.



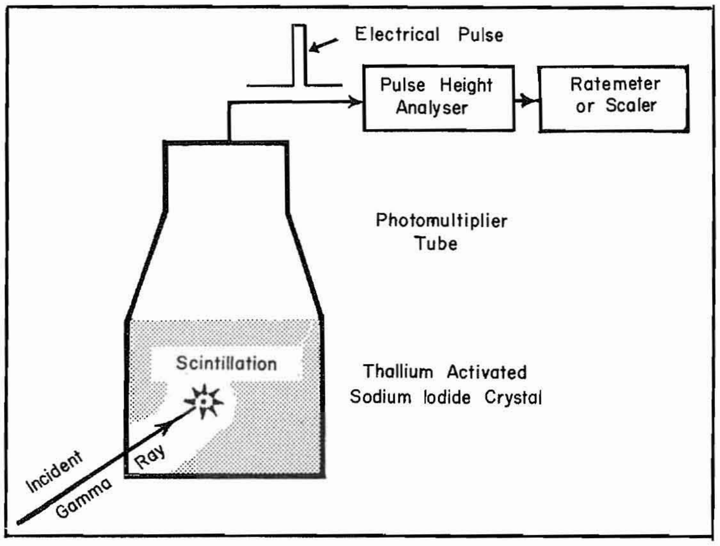


Figure 5. The gamma ray sensor.

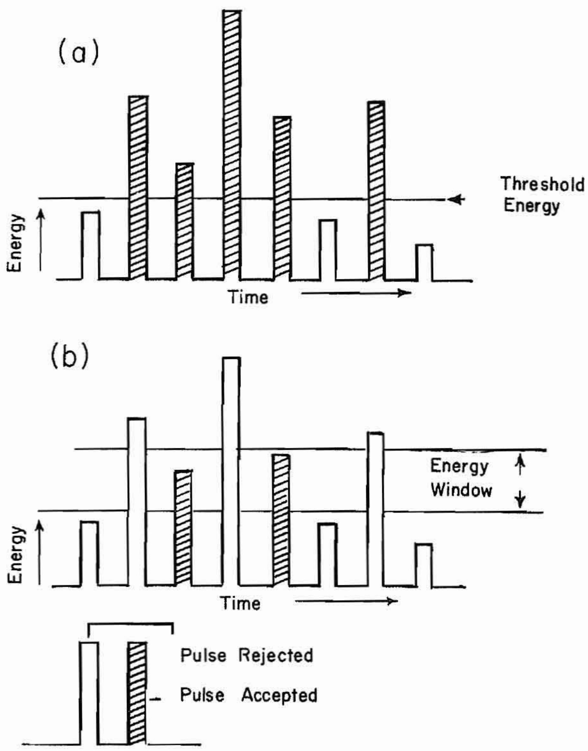


Figure 6. Spectrometer operation. (a) Integral type. (b) Differential.

detected and amplified by a photomultiplier tube, producing an electrical pulse whose amplitude is related to the energy of the incident gamma photon. This pulse passes to a pulse-height analyzer which either accepts all pulses above a selected amplitude (integral type) or with a certain range of amplitudes (differential type) (Figure 6).

The accepted pulses are either expressed in ratemeter form as counts per second or, in the case of low counts, may be progressively summed over a predetermined period of time (e.g., 5 minutes) by an integrator. The differential spectrograms of potassium, uranium and thorium of Figure 1 show two very useful features: K-40 has no energy peak above 1.46 Mev; and the uranium series has no peak above 2.42 Mev, whereas the thorium has a dominant peak at 2.62 Mev.

Thus, by providing a single threshold at about 1.65 Mev we will accept only U + Th gamma radiation, rejecting both K-40 (granitic bodies, etc.) and almost all radioactive fallout (largely below 0.75 Mev). A threshold set at about 2.5 Mev will accept only Th radiation, plus cosmic radiation (which is usually of low order). On the assumption of equilibrium of the U and Th sources, by applying constant factor subtraction using three threshold settings either consecutively with a single-channel instrument or simultaneously with a three-channel instrument, we may obtain count rates relating purely to K-40, U and Th. The assumption in this process is that the radioactive series are in

Figure 7. SC-1 single-channel variable threshold spectrometer with probe and recorder.

equilibrium. Nonequilibrium conditions may also be detected and measured by either types of discriminators. Precise measuring procedures can establish the degree of nonequilibrium and the relative proportions of the radioactive daughter products can be calculated.

Applications

Modern integral and differential spectrometers can readily be used on the ground for quantitative evaluations of the uranium, thorium and potassium 40 content of rock outcrops and surficial soils. But in the air since the geometrical size or pattern of the radiating source is not known, no quantitative estimates of the respective content of uranium, thorium or potassium 40 can be made. However, qualitative information can be extrapolated from the airborne spectrometric data. Besides their obvious application in uranium exploration airborne radioactive spectrometers may be of possible use in base metal exploration as well. Moxham, Foote and Bunker (1965) found that in the vicinity of several copper-lead deposits in Arizona there was a higher than normal potassium-thorium ratio as a result of alteration, and that around the Baghdad porphyry copper deposit there was an abnormally high uranium content, locally, in secular disequilibrium. Spectrometry can be employed in the recognition and mapping of various rock lithologies (Pitkin, *et al.*, 1964) and may, because of the association of radioactivity with other types of economic minerals, be used as a guide to the discovery of nonradioactive materials such as some of the rare earths which are known to occur in radioactive carbonatite deposits (Westrick and Parsons, 1957).

Because of the mobility of radon 222, uranium 234 and radium 226, disequilibrium conditions obviously can occur wherever conditions are favourable for the movement of these soluble nuclides. Where disequilibrium conditions occur, to rely on the bismuth 214 peak at 1.76 Mev as an indicator of U238 is dangerous to say the least. Narrow-band, multichannel analyzers can in fact be used qualitatively to give an indication of the presence or absence of equilibrium conditions, but here again in airborne work no quantitative estimates of the concentration of any of the nuclides can be made.

Mobility or solubility of some of the uranium daughter products can work to our advantage in uranium exploration in some cases, but since 10 inches of rock will effectively mask all gamma radiations from sources beneath it (Gregory and Horwood, 1961), one cannot expect to find any surface evidence from buried uraniferous deposits except for zones located within a few inches of the ground's surface. However, under favourable conditions, we can expect surface radioactivity related to uranium concentrations at considerable depth, if, in fact, some of the soluble daughter products have been taken into solution and moved to surface by means of, for example, underground water circulation along a porous formation with ultimate migration upwards along a major fracture or fault zone (Tanner, 1964). In such cases, we would expect to find, for instance, a bismuth 214 anomaly if the major daughter product in migration has been radon 222.

During the early 1950s few airborne radioactive spectrometer surveys were undertaken. Most airborne work consisted of the measurement of total gamma count wherein all gamma energies were measured on a single-channel recorder. Since K40 is a reasonably common constituent of granite and related rock facies total count anomalies due to K40 content rather than uranium or thorium were far more common, particularly in the Precambrian Shield areas. Isolated granite outcrops in swamps or granite ridges would all give reasonably intense total-count anomalies, the amplitude of which would depend on the size of the radiating granitic outcrop and the amount of radioactive K40 contained therein. Much ground follow-up was required to sort out the multitude of total-count airborne anomalies. Some were indeed due to above-average concentrations of uranium or thorium, but

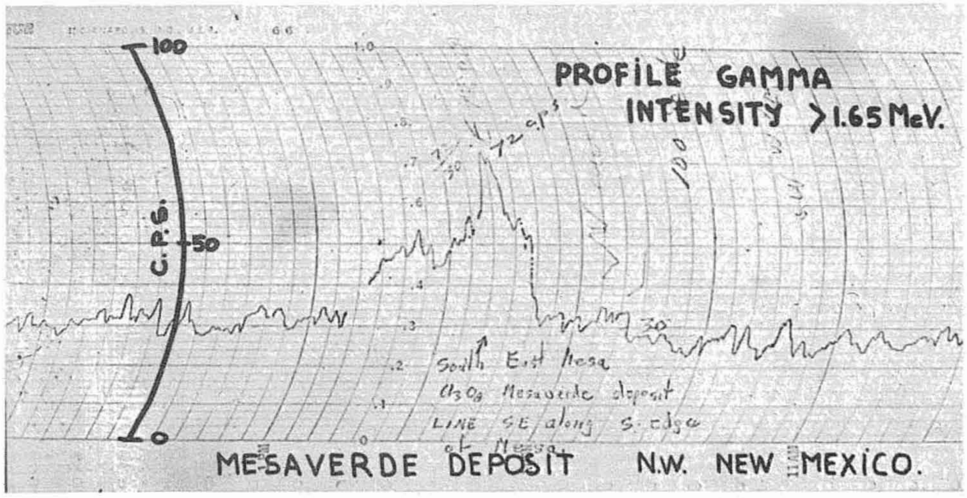


Figure 8. Radioactive airborne anomaly obtained over Mesaverde U_3O_8 deposit, NW New Mexico, with threshold set at 1.65 Mev.

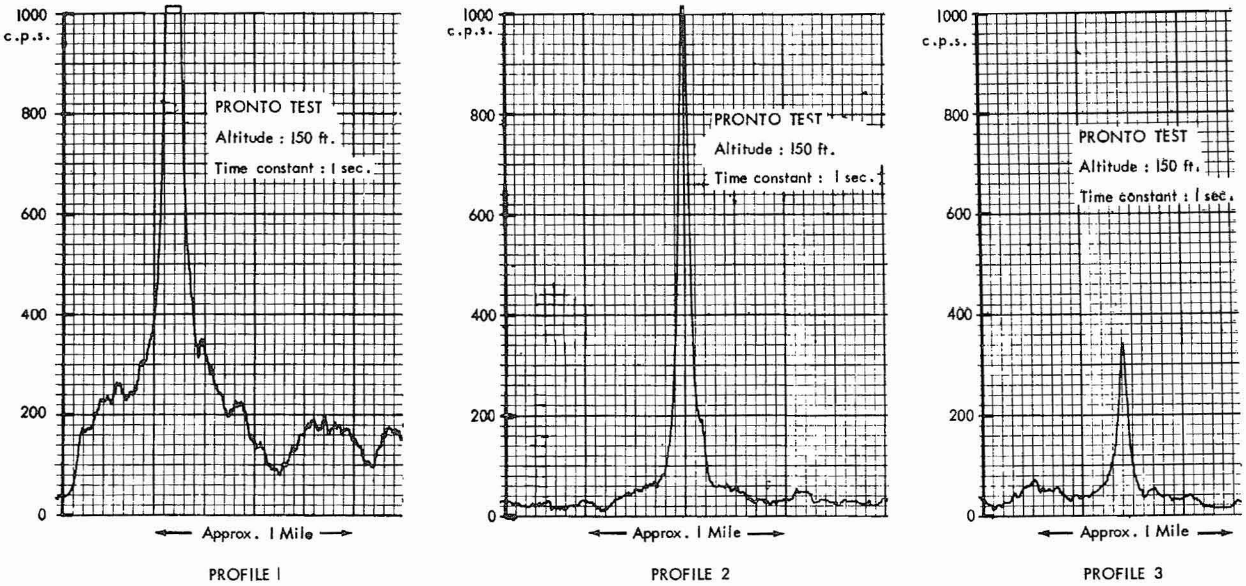


Figure 9. Variation in response at different threshold settings of 0.2 Mev, 1.65 Mev and 2.5 Mev for Profiles 1, 2 and 3.

in most cases the anomalies were due mainly to granite outcrops. Fortunately, in the recent uranium boom, airborne instrumentation has progressed hand in hand with the ground radioactive spectrometer developments.

The first commonly used airborne spectrometers were single-channel variable threshold units such as the SC-1 unit (Figure 7). This unit had an adjustable threshold which was normally set at 1.65 Mev to record uranium plus thorium gammas and eliminate lower gamma energies such as the K40 peak at 1.46 Mev. This type of system normally employed a single thallium-activated sodium-iodide crystal about 5 inches in diameter and 4 inches thick. The single-channel output from the SC-1 measuring unit could be connected to a number of single channel recorders. One such recorder which was commonly used was the Esterline Angus curvilinear clockwork recorder which required no external power. Figure 8 shows a radioactive anomaly over the Mesaverde deposit in New Mexico recorded on the EA recorder. As batteries were contained within the actual SC-1 unit itself, the entire system was completely portable and could be taken in and out of an aircraft in a matter of minutes. Since the total system weighed less than 60 pounds, it could be used in all light aircraft. Auxiliary equipment often employed in these single-channel variable threshold surveys include a continuous strip camera and a radioaltimeter. The crew generally consisted of a pilot and a geophysical operator who, in addition to his operating chores, assisted in the navigation of the aircraft on survey. At the completion of each flight, the flight film was developed and edited and the actual flight path of the aircraft during survey recovered to make sure the flying was done to the desired specifications. Anomalies could quickly be plotted on the photomosaic base maps or planimetric maps. Staking or securing of the mineral rights in and around the anomalous zones could be performed forthwith.

Figure 9 shows some airborne results over the Pronto Mine deposit in the Elliot Lake area with the threshold set at three different settings, 0.2, 1.65 and 2.5 Mev. This type of single-channel variable threshold unit has been widely used in the Pre-

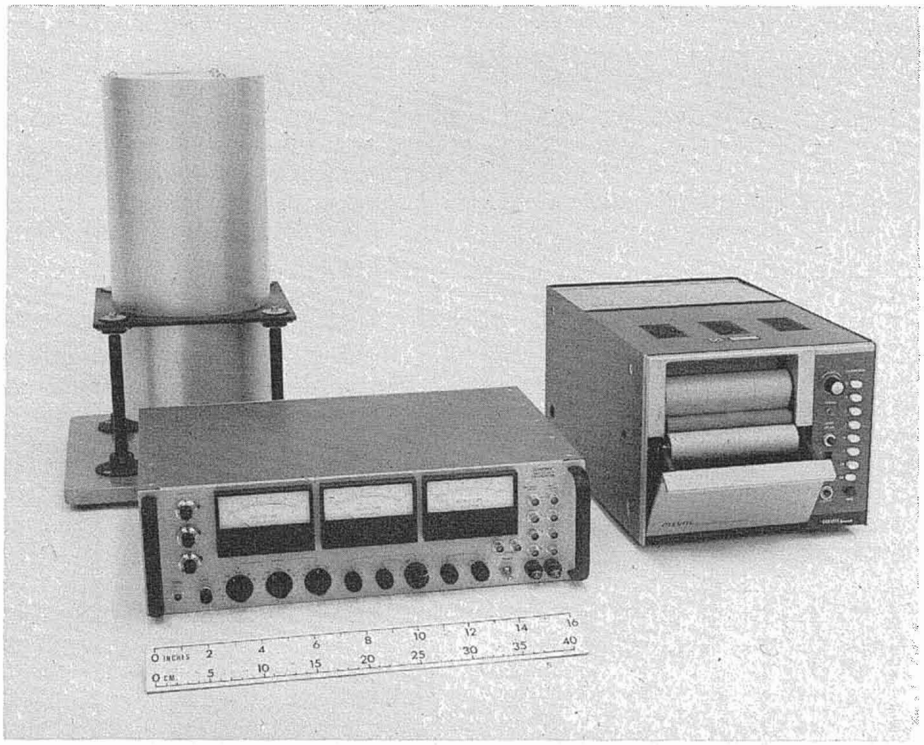


Figure 10. Four-channel radioactive spectrometer GISA-4.

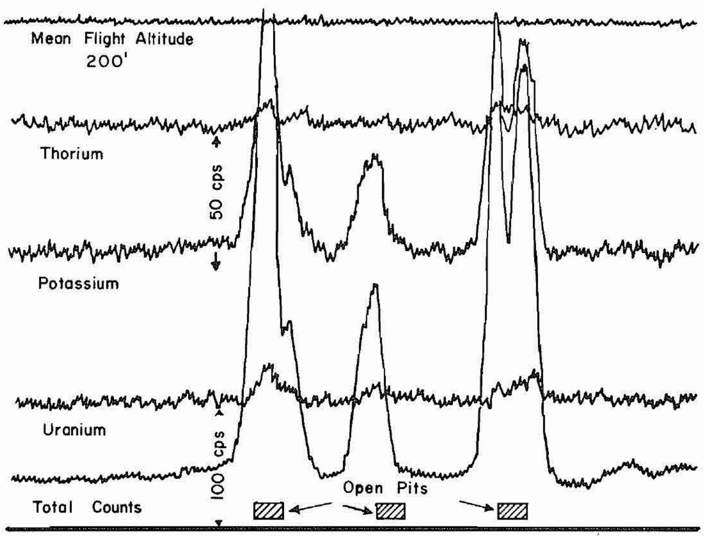


Figure 11. Airborne radiometric four-channel GISA-4 profile over three uranium open pits (Tordilla Hills area, Texas).

cambrian Shield. Its principal attribute has been its ability to eliminate all the lower-energy gamma radiations below 1.65 Mev which permits the follow-up program to concentrate on the analysis of anomalies due to uranium or thorium. Although this type of spectrometric information is a considerable advance over the total gamma measuring instruments, there are some areas in the shield, particularly in the high thorium-bearing granites, where separation of uranium and thorium is a considerable advantage. The coupling of two SC-1's has sometimes been tried. One channel records thorium only, the second records uranium plus thorium radiations. A simple subtraction of the thorium counts (multiplied by a Compton Continuum correction factor) from the counts recorded on the second channel, permits a quick calculation of the residual uranium anomaly.

Correction circuitry has been built into two such dual SC-1 systems to subtract automatically and correct for the thorium counts above 2.5 Mev and its continuum down to 1.65 Mev, so that the final output is in terms of net uranium and net thorium counts.

Four-channel radioactive spectrometers such as the GISA-4 (Figure 10) have been employed to measure the total gamma count for potassium-40, uranium and thorium. Four-channel differential units are also used – some with, and some without correction circuitry. Figure 11 shows the four-channel results over three different open pit uranium deposits in Texas. The four-channel results were particularly applicable in this area, since some of the sandstone formations, which are in reasonably close stratigraphic sequence to the main uranium-bearing sandstone, contained abnormal concentrations of glauconite which had a reasonably high K-40 content. Thorium-bearing bentonites occurred in nearby sedimentary rocks. The spectrometer permitted differentiation between the major radioactive source elements, with the ultimate result that only those anomalies due to uranium were designated for intensive ground follow-up work. During 1967, some four-channel differential airborne spectrometers were used in uranium exploration. They employed spectrum stabilization by constant monitoring of a reference radioactive source element. This constant stabilization circuitry corrects for peak voltage instability which can sometimes arise from sources such as gain drift of amplifiers, count rate hysteresis of photomultipliers, high voltage instability, temperature effects and magnetic field effects on the photomultiplier tubes. Foote (1967) has described a very sophisticated 400-channel analyzer employing six sodium iodide crystals 11 1/2 inches in diameter by 4 inches thick, along with readout of record sequence number, surface altitude and time on a high-speed magnetic tape. The magnetic tape allows computer data reduction and plotting of isoradiation maps and composite radiation profiles. A visual analog recorder also records the TL208, Bi214, K40, total count and radar altitude as well. Because of this system's size and weight, it is transported in a large-sized twin engine aircraft. It is flown at an altitude of 400 feet above the ground's surface.

Flying techniques

Although regional background radiation from the uranium-thorium content of rocks decreases only very slightly with increasing terrain clearance over the first few hundred feet, point source gamma radiation from a local concentration of high-energy uranium or thorium decreases far more rapidly (an inverse square function). For maximum probability of detection of radioactive point sources, therefore, one must attempt to maintain as small a terrain clearance as possible (Pemberton and Seigel, 1966). Altitude above the ground's surface should be no greater than 200 or 300 feet and preferably less if one is looking for very small uraniferous outcrops. To achieve a constant small mean terrain clearance in, for instance, the normal type of Precambrian topography is no easy feat. What is required is a vehicle with excellent rate of climb and descent to handle the large topographic gradients often encountered. It is also important to have a fairly low air speed to navigate accurately at these low altitudes. In a high-speed aircraft, the ground passes too quickly to enable the pilot to react to changing topography and to recognize photo-identities which he must rely upon for successful navigation.

The closer one is to the radiation source the better will be the signal-to-noise ratio over that anomaly. This noise includes both statistical (time) and geological (space) variations. Table IV shows a signal-to-noise ratio of 11:1 at 150 feet, decreasing to 2:1 at 450 feet from a point source. Even if sensitivity were increased by a factor of 10 by increasing the crystal size, we would gain little in detectability since the signal-to-noise ratio at 150 feet would still be 11:1 and 2:1 at 450 feet. Where the surface soil conditions are particularly uniform and the rocks are homogeneous there may be some advantage in increasing sensitivity, since in that some smoothing of the statistical fluctuations will result. Under these conditions an increase in sensitivity may more easily detect relatively minor radioactive concentrations. Normally the local radioactive variations which are of truly geologic origin and due to change of soil conditions introduce fluctuations of the order of a factor of 2 or more in relatively short distances.

Table IV. Signal versus altitude point source anomaly.

Flight Altitude	Background Count	Anomaly Contribution	Total Anomaly	Signal/Noise Ratio
(ft)	(cps)			
150	10	100	110	11:1
300	10	25	35	3.5:1
450	10	11	21	2.1:1

Since the peak ratemeter output for a localized radioactive source is dependent on the aircraft's velocity as well as the detector time constant and the distance between source and detector, it is obvious that the lower the air speed the better. However, equivalent results may be obtained at higher velocities using larger crystal volumes and shorter time constants. This entails greater instrumentation costs, perhaps lower safety margins, but lower operational costs per mile. The question of optimum time constant depends on the average air speed of the aircraft and the mean terrain clearance during survey. Assuming that the gamma radiation from a point source anomaly is sufficiently intense to be readily detectable at higher altitudes, a longer time constant may be employed at higher than at lower altitudes. This is because the detector remains within the gamma flux for a longer period of time, because of lateral spreading of the gamma flux with distance. The critical problem is to find the combination of terrain clearance, air speed and time constant that for a particular gamma-ray spectrometer optimizes the chances of locating uraniferous deposits of economic significance at the lowest possible cost.

The selection of optimum line spacing hinges on the analysis of the probability of detection based on the size of the target being sought in relation to the line spacing. Since the size of a surface exposure of economic interest can be as small as a few square feet, obviously the closer the spacing the better our chances of detection. However, it is seldom operationally feasible to fly closer than 400 to 500 feet. The line spacing should be closer in areas where the potential for finding new occurrences is greater and where the percentage of outcrop is low, and opened up in areas of questionable merit and considerable outcrop. In the latter case detailing at closer spacings can be done where interesting anomalous conditions are found in the original reconnaissance block flying.

Data reduction of the radiometric results may be done in various ways. Commonly the single-channel variable threshold results are plotted on a transparent overlay to a suitable scale photo-mosaic. The peak location of each anomaly is plotted along a particular flight line and identified by an *x* or closed circle. The actual extent or half-peak width of the anomaly is similarly noted on either side of the peak location. The ratio of the total amplitude of the anomaly over the average background is generally noted alongside the peak plot. The shape of the anomaly is indicated by letters *a*, *b*, *c* and *d*; with *a* being a very sharp anomaly and *d* a very broad anomaly.

Four-channel spectrometer results may be compiled in a variety of ways. The most common is to contour the total gamma count information on a transparent overlay. Each total count anomaly or closure has alongside it a box divided into four quadrants. The counts on all four channels (arising from the thorium, uranium, potassium-40, and total-count channels) are noted in the four quadrants. Other types of presentation include the actual profile plotting or stacking of profiles along each flight line. In some cases numerical plotting or contouring of various ratios are desired, such as the uranium/thorium ratio or the potassium/thorium ratio. Altitude correction of spectrometer data is sometimes undertaken before the data are reduced to isorad contours.

Limitations of airborne radiometric surveying

Airborne radiometric surveying is guided by severe limitations inherent in both the method of detection and the geological environment of uranium deposits. Some of the more important limitations are:

1. Gamma rays originating through the disintegration of radioactive nuclides are extremely limited in their penetration through rock and overburden (Gregory and Horwood, 1961). Nine inches of rock of 2.7 density will in effect inhibit the transmission, or in other words blank out, 90% of even the thallium 208 gammas emitted at an energy of 2.62 Mev. Seventeen inches of unconsolidated material of 1.4 density will blank out 90% of the gamma radiation of thallium 208 coming from below. It is essentially a surface phenomenon that we are measuring – unlike other geophysical methods such as gravity, magnetics or electromagnetics. As a result, one cannot hope to directly detect concentrations of radioactive nuclides that are buried beneath more than 1 or 2 feet of rock or soil.

2. The percentage of rock outcrop in the Precambrian Shield area is very low indeed – perhaps no more than 10% on an average. In the western United States the percentage of outcrop varies considerably, and less than 5% of the potential uranium-bearing host rocks lie within 2 feet of the ground's surface.

3. Some of the uranium minerals, such as uranium 234, radon 222 and radium 236, because of their high solubility may be leached from surface outcrop with attendant decrease in the amount of normally detectible gamma radiations which emit from uranium mineralization when in equilibrium.

4. Uranium concentrations of economic interest may be as low as 0.5% or 1 pound per ton if sufficient tonnages exist. A small-sized exposure of this concentration is a difficult target to find. The outcrop area of a uranium deposit may be very small and hence most geophysical anomalies represent 'point sources', particularly in a Precambrian environment. In such cases, the gamma flux intensity falls off approximately as the inverse square of the distance between the source and detector. This emphasizes the importance of maintaining as low a terrain clearance as possible, consistent with safety. In certain areas, particularly in the southwestern United States, where migration of some of the daughter products has taken place, the size of the radioactive anomaly or radioactive pattern may be quite extensive and accordingly, the inverse square law would not necessarily apply and the requirement for low mean terrain clearance surveys would not be as stringent.

5. The Precambrian Shield is often referred to as an ancient peneplane surface but to the exploration geologist and geophysicist it is anything but a flat surface. In the space of only a few thousand feet there are often changes in relief varying between 100 and 400 feet. These rapid topographic gradients are a challenge to the aerial survey crew attempting to maintain a mean terrain clearance of 100 to 200 feet. In an airborne survey the geophysical data are ultimately related to ground positions. Little of the Precambrian Shield area is mapped at large enough scales (1:20,000 or larger) to allow accurate navigation and accurate positioning of anomalies. None of the electronic navigation systems known today is practical or accurate enough for low-level radiometric surveys. High-frequency systems such as Hiran, Shiran or Shoran (though extremely accurate) are limited because of their line of sight requirement, while Doppler and inertial guidance are limited primarily because of off-track and along-track errors. Wherever available, aerial photographs are desirable for flight path guidance and continuous strip aerial cameras in the aircraft for flight path recovery.

6. No accurate quantitative evaluation of uranium, thorium or potassium content associated with any radiometric anomaly can be made from airborne data regardless of the sophistication of the instrumentation employed. This is primarily because the exact aerial extent or size of the radiating uraniferous source is not known before ground follow-up.

To surmount many of the aforementioned limitations one must consider more than just the problems of spectrometer instrumentation. The gamma-ray spectrometer must be flown at an altitude, at a ground speed, and at a line spacing which optimize the chance of finding the elusive radioactive target. And all this must be accomplished at a reasonable cost.

One important step prior to the survey is selection of the survey area. Where to look is the critical question in the whole uranium exploration program. The economic geologist will probably direct his search to one or more of the following areas: producing uranium camps, areas of known mineralization outside producing camps, or new areas – chosen because of geology similar to known mineralized areas.

Summary

In the air the application of modern radioactive spectrometry can speed up discovery in many ways. There are many types of both differential and integral spectrometers, no one of which is a panacea to all the problems in airborne radiometric prospecting. Effectiveness and economy, both in initial capital cost of equipment and field operations themselves, must always be kept in mind. In any particular survey planning, to get a true perspective of an aerial survey's ore-finding value one must view the total system including operational procedures rather than any one of its component parts. Even with its limitations, this method of uranium prospecting will certainly be instrumental in many new uranium discoveries.

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The application of geophysics to gold exploration in South Africa

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Abstract. Practically all the gold and uranium produced by the Republic of South Africa is won from the auriferous conglomerates of the Witwatersrand System, and exploration is oriented towards locating areas underlain by these conglomerates (reefs).

The Witwatersrand Basin is filled by sedimentary and volcanic rocks up to a total thickness of 40 to 50 thousand feet. The Witwatersrand System with a lower division of predominantly argillaceous rocks, and an upper division of arenaceous rocks, comprises about one half the rocks filling the basin. The auriferous conglomerates occur in the Upper Witwatersrand. A thick succession of lavas and sediments of the Ventersdorp System lie both conformably and unconformably on the Witwatersrand, followed by the rocks of the Transvaal System. Karroo sediments cover these rocks over large areas.

The Upper Witwatersrand beds underlie an area of some 15,000 square miles in what is generally called the Main Witwatersrand Basin. An outlier, separated by structural deformation occurs 40 miles east of the main basin outcrop, whereas the outlier is entirely covered by younger rocks.

Highly magnetic shale horizons in the Lower Witwatersrand occur in fairly constant stratigraphic relation below the conglomerates over great distances and are mapped under cover by magnetic surveys. The density contrasts, between the light granites on which the basin lies, the heavy Lower Witwatersrand, the light Upper Witwatersrand and the heavy lavas and the great thicknesses of these groups, are the cause of substantial gravity anomalies.

Geophysics and sound geological reasoning have been responsible for locating three major extensions of the gold-bearing conglomerates of the Main Witwatersrand Basin under younger cover, and for the discovery of the outlier to the east of the main basin.

Résumé. Le bassin du Witwatersrand est rempli d'une succession de roches sédimentaires et volcaniques qui atteint une épaisseur totale de quarante à cinquante mille pieds. Le système du Witwatersrand, qui se divise en une partie inférieure ou les roches argileuses prédominent et une partie supérieure à roches arénacées, comprend environ la moitié des roches qui remplissent le bassin. Une épaisse succession de laves et de sédiments du système Ventersdorp reposent avec ou sand concordance sur le Witwatersrand et laisse ensuite la place aux dolomites, aux schistes et aux quartzites du Transvaal.

Une discordance marquée constitue un fondement plat aux sédiments du Karroo qui recouvrent ces roches sur de grandes étendues. La zone d'intérêt économique est celle du Witwatersrand supérieur ou se rencontrent des conglomérats aurifères. Du point de vue géophysique, le Witwatersrand inférieur a une grande importance à cause des horizons schisteux fortement magnétiques qui demeurent en relation stratigraphique assez constante au-dessous des conglomérats sur de grandes distances. Les contrastes de densité, particulièrement entre les granites légers sous-jacents au bassin, les roches denses du Witwatersrand inférieur, celles moins denses du Witwatersrand supérieur de même que les laves lourdes et les grandes épaisseurs de ces groupes sont les causes d'anomalies gravimétriques appréciables.

Les roches du Witwatersrand supérieur sont sous-jacentes à une région d'environ 15,000 milles carrés qui fait partie de ce que l'on appelle généralement le bassin principal du Witwatersrand. En outre, une avant-butte de roches du Witwatersrand supérieur, mais séparée du bassin principal par une déformation structural, se trouve à 40 milles à l'Est du bassin principal. Environ le tiers seulement des couches du bassin principal du Witwatersrand affleure alors que l'avant-butte est entièrement recouverte de roches plus récentes.

La géophysique a joué un grand role dans la localisation, dans le bassin principal et sous des roches plus récentes, de trois étendues considérables de conglomérats aurifères. C'est aux relevés magnétiques au sol et aéroportés que nous devons la découverte de l'avant-butte à l'Est du bassin principal.

The gold mines of the Republic of South Africa produce 73 per cent of the free world's gold. The annual production is more than 30 million ounces valued at over 1 billion dollars, with in addition, a uranium output valued at over 60 million dollars. Practically all the gold and uranium is won from the auriferous conglomerates of the Witwatersrand System, and only a very small amount of the gold is produced from rocks which do not belong to this system. It is therefore appropriate that the major effort in the exploration for gold in South Africa should be orientated towards locating areas underlain by gold-bearing conglomerates of the Witwatersrand System. Geophysics has an important role in this search and gravity and magnetic surveys together with sound geological reasoning have been responsible for the discovery of four important goldfields. These four fields, the West Wits Line, the Free State Goldfield, the Klerksdorp Goldfield and the Evander Goldfield today produce 80 per cent of the gold produced in the Republic.

History

Gold was discovered in 1886 on the Witwatersrand on the farm Langlaagte now a suburb of Johannesburg. The early prospectors had not previously encountered gold in conglomerates and it was thought that they were a form of quartz reef. The name 'reef' has stuck and all conglomerates likely to be gold bearing are called reefs and were given names such as the Main Reef, Bird Reef, Leader Reef, Basal Reef, Kimberley Reef, Vaal Reef, etc.

Before the turn of the century the whole outcrop area of 36 miles in extent from Boksburg in the east to Krugersdorp in the west was being actively mined and drilling had established that the reef extended to depth towards the south. The small workers had by then disappeared and mining was being carried out by companies.

To the east beyond Boksburg, the reef disappears beneath a cover of Karroo beds and still further east under the dolomite of the Transvaal System. This area, known as the East Rand Basin,

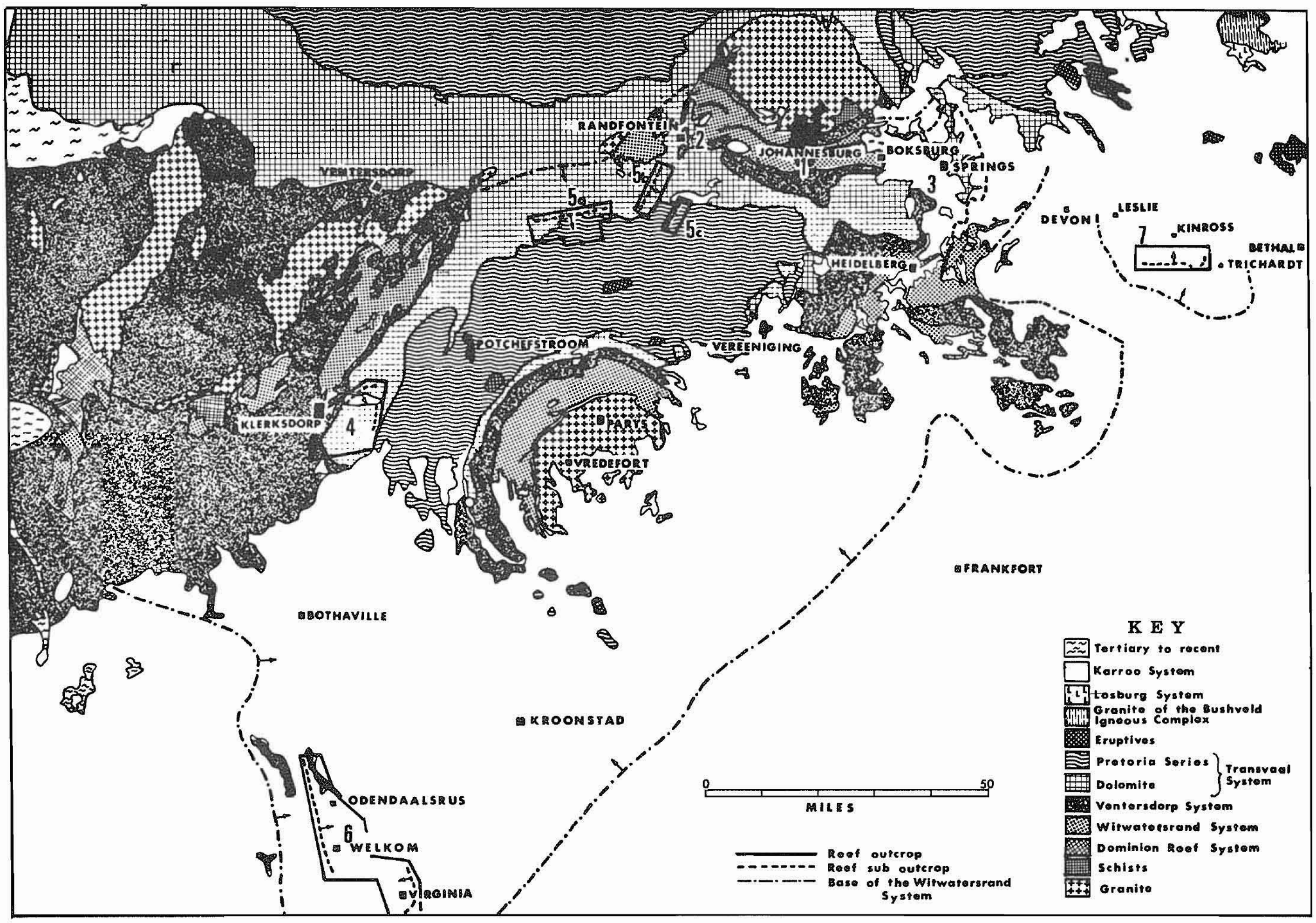


Figure 1. The geology of portion of the Transvaal and Orange Free State, Republic of South Africa, showing the extent of the Witwatersrand Basin and the location of the main gold-mining areas. 1. Central Witwatersrand or Central Rand. 2. West Rand. 3. East Rand and East Rand Basin. 4. Klerksdorp Goldfield. 5a, 5b and 5c West Wits Line. 6. Free State Goldfield. 7. Evander Goldfield on the Kinross Basin.

was prospected by drilling and because of good values and the flat dips the potential of the area was enormous. The East Rand Basin supported 26 mines at one time of which 10 are still operating. The average size of these mines (lease areas) is about 10 square miles.

One hundred miles southwest of Johannesburg near Klerksdorp gold had been discovered in 1886 only months after the discovery at Langlaagte. The Klerksdorp area did not prosper for long but when in 1932 South Africa went off the gold standard, exploration boomed, old mines were revived and new ones were started. By the 1930s gold mines were established on a 65-mile arc from north of Heidelberg in the southeast through Johannesburg to Randfontein in the west. There was a large gap of 80 miles between Randfontein and the Klerksdorp Goldfield. Along approximately half of this gap from Klerksdorp northwards only Lower Witwatersrand rocks were exposed. In the remaining half of the gap there were no outcrops of Witwatersrand rocks at all and if they did occur they were covered by the Transvaal dolomite and Pretoria series.

In 1930 Dr. R. Krahmann showed that the magnetic content of some of the Lower Witwatersrand shales made it possible to locate the position of these shale bands hidden under a thick cover, and to estimate strike and dip from the readings observed on a magnetometer. With a knowledge of the relationship of the reefs to the magnetic beds as observed from outcrops on the West Rand, it became possible to establish the more exact position, beneath the dolomite cover, of the Upper Witwatersrand beds within which the gold reefs occur. This had been roughly established some 30 years before by limited drilling. Earlier development of this field, the West Wits Line, had been prevented by technical difficulties encountered due to the enormous quantities of water contained in the overlying Transvaal dolomite.

Much thought had been given to the possibility of the Witwatersrand beds extending south from Klerksdorp into the province of the Orange Free State. Before 1900 a conglomerate was noticed on the farm Aandenk near Odendaalsrust. Although this conglomerate was barren and belonged to the Ventersdorp System which could be many thousands of feet thick, various parties from time to time insisted on reopening the workings and in 1933 a diamond drill hole was drilled down dip from the conglomerate outcrop and intersected lavas below the conglomerate. The chances of intersecting Witwatersrand beds were remote;

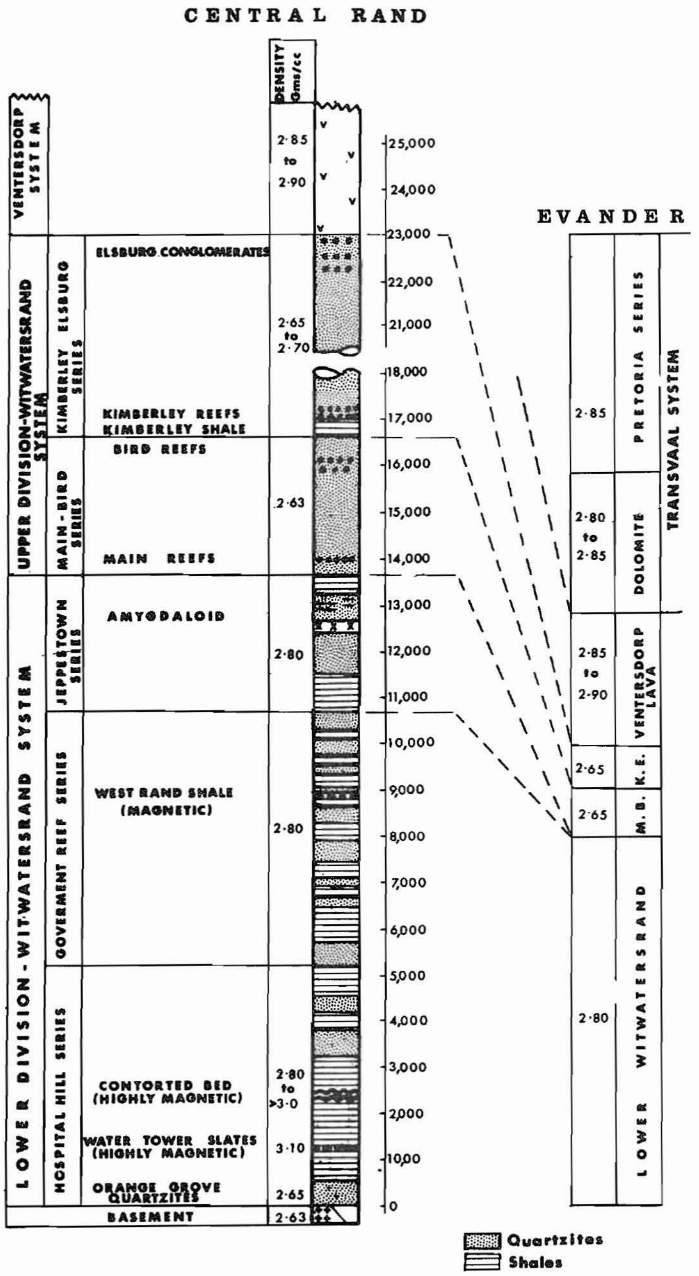


Figure 2. Diagrammatic stratigraphic column of the rocks of the Basement, Witwatersrand, Ventersdorp and Transvaal Systems in the Central Witwatersrand and Evander goldfields. The positions of the three major magnetic horizons are shown and the densities for the various suites of rocks indicated.

the nearest outcrop was 50 miles to the north. However, the hole was deepened and went out of lavas into Upper Witwatersrand rocks at 2721 feet! The hole was continued to 4046 feet but no pay values were encountered. This hole stopped some 400 feet above the Basal Reef, the 'pay' reef of the Free State which was first discovered 5 years later in a borehole 20 miles away.

Huge areas were taken up in the Orange Free State and geophysical surveys were carried out using the magnetometer, the gravimeter and the torsion balance. The object of the gravity and torsion balance surveys was to locate the light Upper Witwatersrand rocks where the cover of heavy lavas was thin. Borehole S.H.1 on the farm St. Helena was sited on a gravity low to the east of a distinct zone of north-striking magnetic anomalies lying on a gravity high. Early in 1938 this borehole intersected a reef with erratic gold values. Exploration proceeded and the first gold mine in the Free State, Saint Helena Gold Mine, was established on the Basal Reef.

There was great activity around this area and by 1946 some 300 to 400 boreholes had been drilled in the Free State Goldfield which now supports eleven mines (Area 6, Figure 1).

In the 1930s a ground magnetic survey in the Kinross area revealed magnetic anomalies due to Lower Witwatersrand rocks. Twenty boreholes were drilled without discovering reef.

Structural difficulties in the area northeast of Klerksdorp suggested the use of geophysics to establish the nature of the ground below the lavas and dolomites. In 1947 B.D. Maree located a gravity low on the farm Stilfontein. He suggested that this could be due to light Witwatersrand quartzites close to the surface beneath the dolomites. O. Weiss carried out a gravity survey on the farms Stilfontein, Rietfontein and Hessie for the Strathmore group. Six boreholes sited on the gravity low all intersected the Vaal Reef conglomerate. The mines of Stilfontein, Buffelsfontein, Hartebeestfontein, Vaal Reefs, Zandpan and Western Reefs are now operating on this zone.

In 1948 the Oscar Weiss organisation flew the first airborne magnetometer survey for Union Corporation using a fluxgate magnetometer mounted inboard on a DC3 aircraft. Some 42,000 profile miles were flown on this survey. During 1948-1949 certain areas were detailed with airborne magnetometer for Union Corporation and other groups.

In 1949 interest was reawakened in the Kinross area by Union Corporation who carried out aerial magnetic, ground magnetic and gravity surveys in the area and after extensive drilling established the first mine, Winkelhaak Gold Mine, which started operating in 1956. This area, now known as the Evander Goldfield, supports four gold mines, Winkelhaak, Leslie, Bracken and Kinross.

At the present time there are 54 gold mines operating on Witwatersrand reefs. The most recent mines to be established are Kinross (1964) on the Evander Field and Kloof (1964) and Elsburg (1967) both in the West Wits area.

Location and geology

The location and extent of the Witwatersrand Basin is shown in Figure 1. The Witwatersrand Basin is filled by a thick succession of sedimentary and volcanic rocks up to a total thickness of 40 to 50 thousand feet. Rocks filling the basin belong to the Dominion Reef, Witwatersrand, Ventersdorp, Transvaal and Karroo Systems. The Witwatersrand System which is divided into a lower division of predominantly argillaceous rocks and an upper division of mainly arenaceous rocks, comprises about half the rocks filling the basin. A thick succession of lavas and sediments of the Ventersdorp System lies both conformably and unconformably on the Witwatersrand System and is followed by the dolomites, shales and quartzites of the Transvaal System. Closely associated with the Witwatersrand System at its base is the Dominion Reef System. Any one of these groups of rocks can lie on the basement of old granites or basement complex made up of

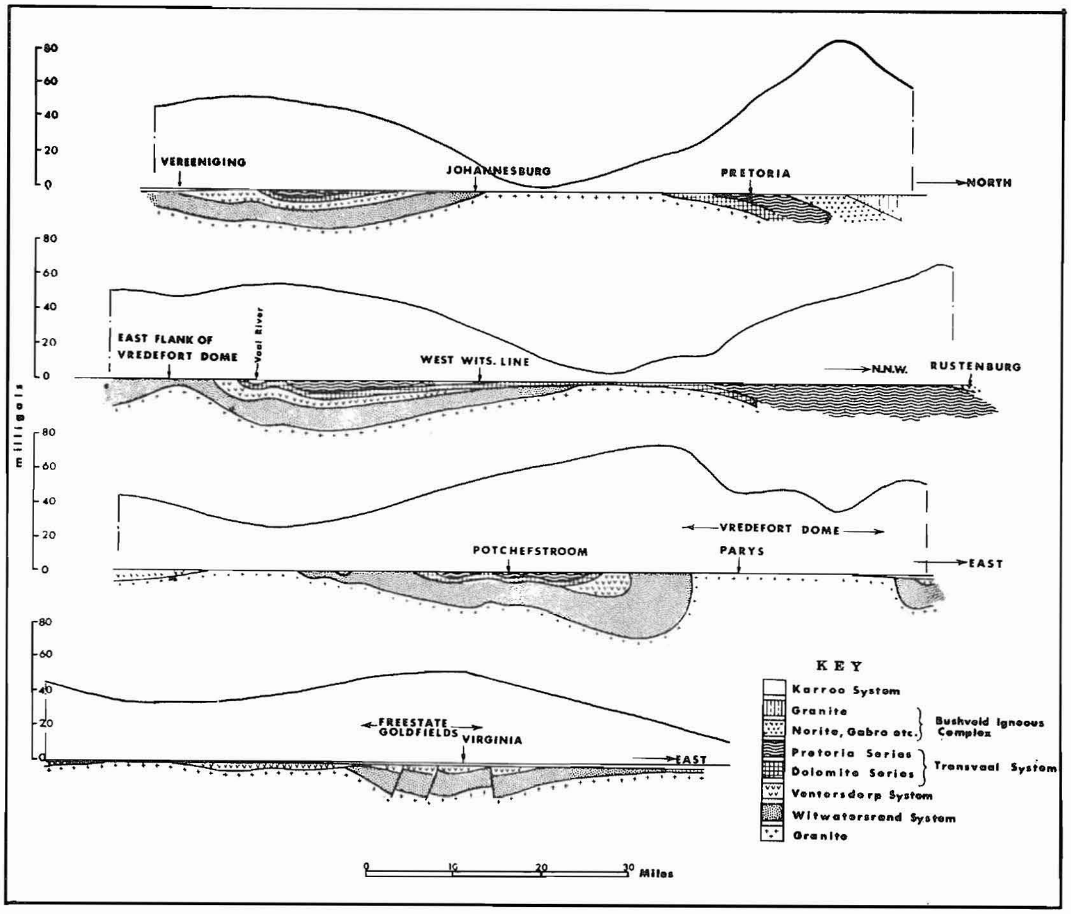


Figure 3. The Witwatersrand Basin. Geological sections and gravity profiles across the basin.

rocks of the Swaziland System or other pre-Witwatersrand rocks. A marked unconformity forms the comparatively flat floor of the Karroo sediments which overlie these rocks over a large area. The Karroo sediments were laid down in Carboniferous to Jurassic times whereas all the other rocks under discussion are Pre-cambrian.

The Witwatersrand System is characterised by the remarkable persistence over great distances of even very thin beds. The zone of economic interest is the Upper Witwatersrand in which the gold-bearing conglomerates occur. Uranium is often associated with the gold in these conglomerates.

Only a small portion of the rocks contained in the Witwatersrand Basin is exposed at the surface, the remainder is concealed beneath a cover of younger rocks, notably by the Karroo sediments and the Transvaal dolomite. Of the 600 miles of strike length along the rim of the basin and on the flanks of the Vredefort dome only 180 miles of actual outcrop of Witwatersrand rocks occur. The Vredefort dome is a granite boss near the centre of the basin. The Witwatersrand and Ventersdorp beds around the boss have vertical to overturned dips.

The Upper Witwatersrand beds underlie an area of some 15,000 square miles in what is generally known as the Main Witwatersrand Basin or Rand Basin. The north-south axis of this basin (Upper Witwatersrand) is 180 miles long and the east-west axis is 80 miles long. In addition, an outlier of Upper Witwatersrand rocks, separated from the Main Basin by structural deformation occurs 40 miles to the east of the Main Basin. This outlier is known as the Kinross Basin and is entirely covered by younger rocks. The Evander Goldfield is on the Kinross Basin (Area 7, Figure 1).

Figure 2 summarises the stratigraphy of the Witwatersrand and Ventersdorp Systems and Figure 3 shows some typical sections across the basin. As mentioned, the Upper Witwatersrand contains the very important gold reefs. On the other hand, the Lower Witwatersrand is barren of gold except in a few isolated places but is of great importance in that the highly magnetic horizons of this division provide the means of detecting the system beneath thick cover. As with almost all the other horizons of the Witwatersrand System these magnetic beds are remarkably persistent over very large distances and remain in fairly constant stratigraphic relation below the conglomerates. Krahmann (1936) identified nine magnetic anomalies caused by magnetic shale bands on the West Rand. Of these he labelled five as major anomalies. However, it is now believed that possibly two of the major anomalies were the result of repetition due to faulting.

Geophysical exploration

Basic criteria. The gravity and magnetic methods have been used almost to the exclusion of all others in the exploration for Witwatersrand reefs. Both these methods are indirect in that neither locate the reefs themselves. This is in contrast to most methods of mining geophysics where the contrasting physical

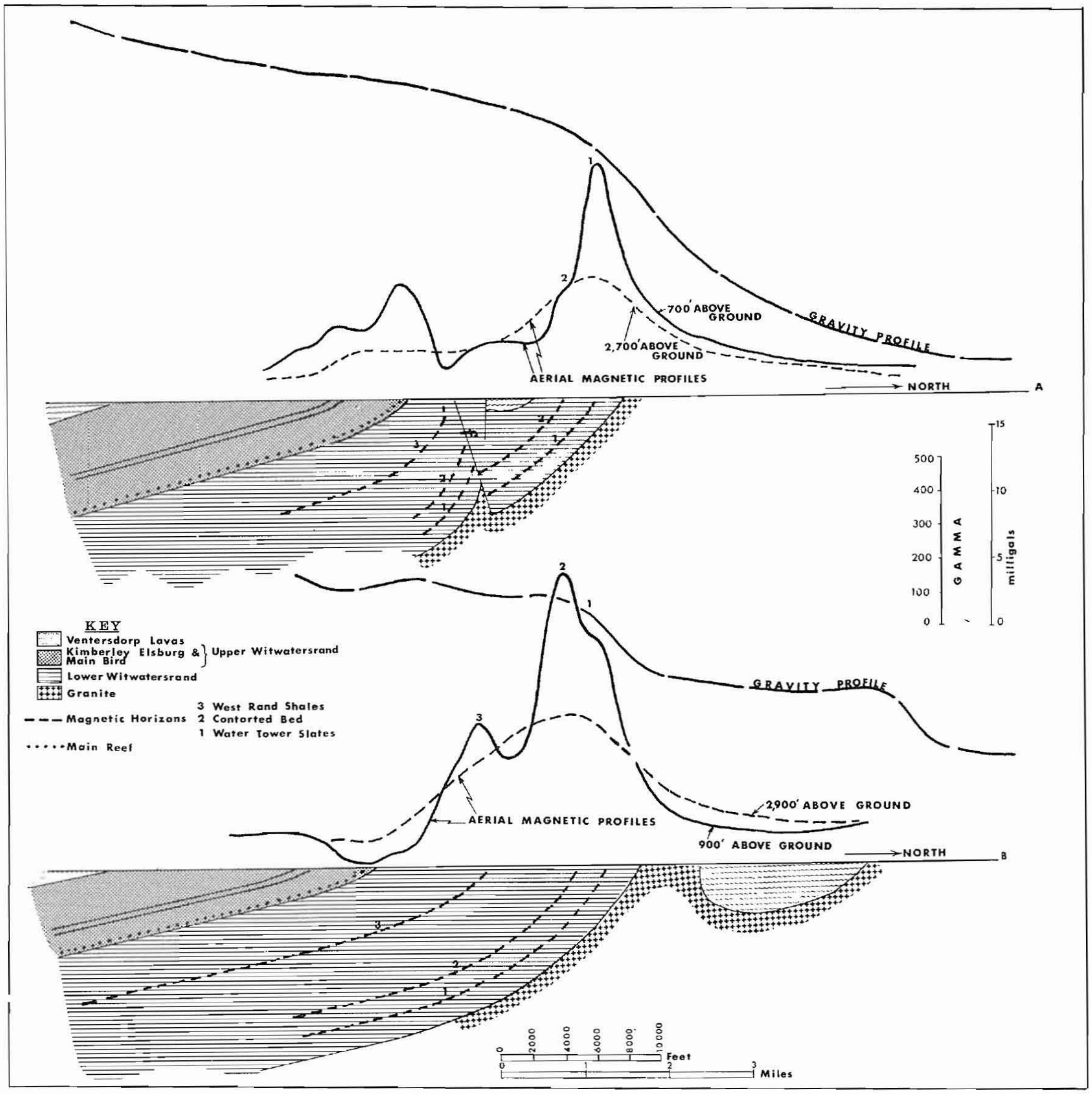


Figure 4. The Central Witwatersrand. Aerial magnetic profiles, gravity profiles and geological sections across southerly dipping Witwatersrand beds. A. Through the eastern suburbs of Johannesburg. B. Across the eastern edge of the outcrop area 11 miles east of Johannesburg.

properties of the ore and the surrounding rock provide the means of detecting the ore by gravity, electrical, magnetic or radioactive methods, or a marker horizon in close proximity to the ore is detected by one or other of these methods. Although the gold reefs are often radioactive and contain high percentages of pyrite, their presence can only be detected by radiation detectors under negligible cover or by electrical methods at comparatively shallow depth. This is of no interest to the prospector simply because the strike of the reefs is so extensive that if they do occur at shallow depth they must inevitably be outcropping close by and would have been followed in the normal course of mining or drilling. No geophysical or geochemical method is capable of indicating the presence of the gold in a hidden reef. The tenor of the gold is very low and the richest reef which may contain as much as 80 ounces per ton in places (Carbon Leader, West Wits Line) will only have a width of up to 2 inches. The percentage gold is never higher than 0.5 per cent. In the thicker reefs which may be several feet thick the gold content may be of the order of 10 dwt/ton or about 20 parts per million.

The gravity and magnetic methods only detect the formations of which the reefs or conglomerates form a very small part in a total thickness of up to 20,000 feet of rock. In fact, the magnetometer detects horizons which are several thousands of feet below the economic horizons and under favourable circumstances the gravimeter may detect the 5 to 10 thousand foot thick Upper Witwatersrand quartzites within which the conglomerates occur. The presence of gold-bearing conglomerates within these formations can only be established by drilling. Geophysically the problem is one of detecting formations and establishing structure and in this regard it is more akin to oil geophysics than mining geophysics.

Provided the grade is high enough, it is economically feasible to mine gold from reefs at great depths. Three gold mines are currently mining from depths in excess of 10,000 feet and one, Western Deep Levels on the West Wits Line, only starts mining on

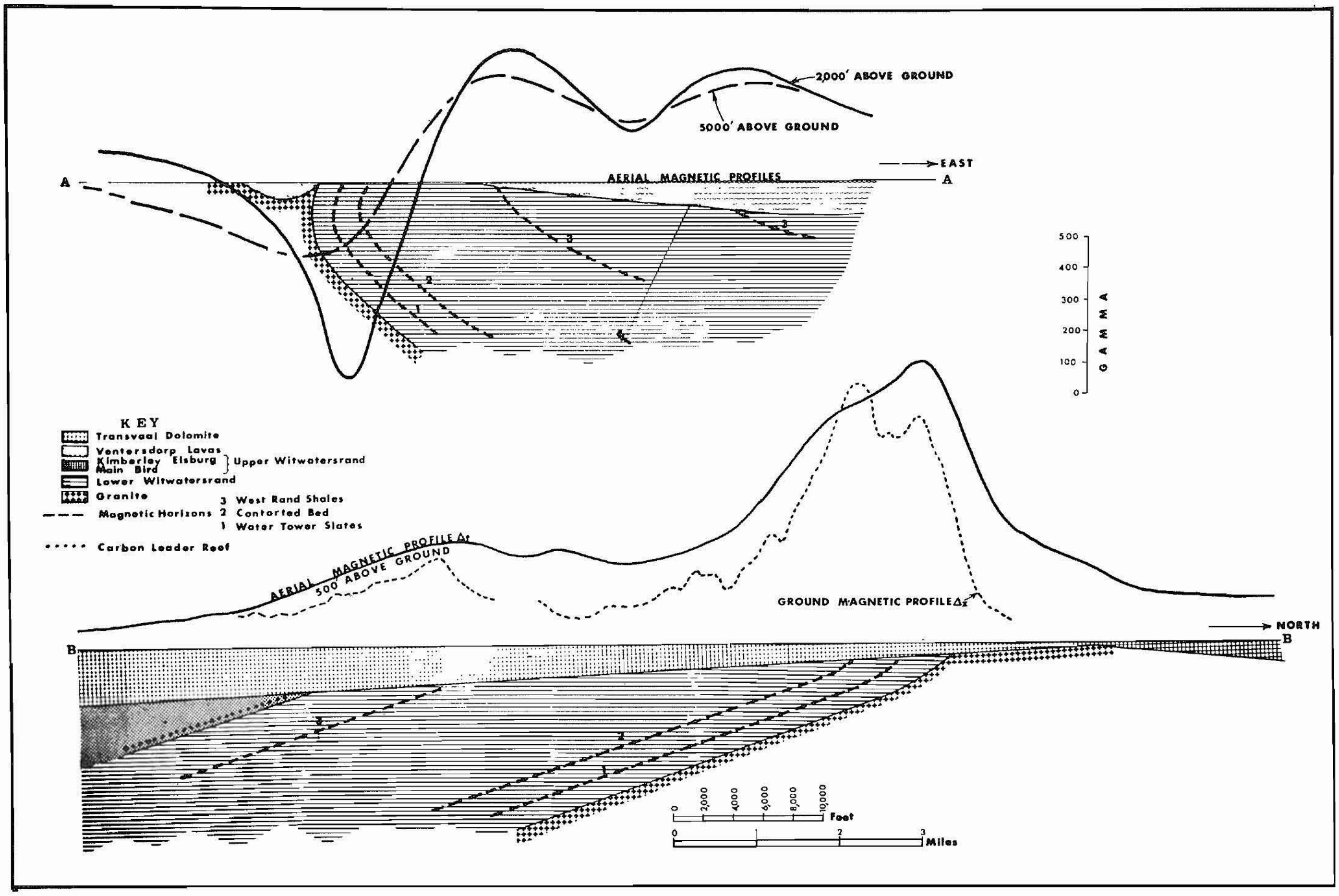


Figure 5. Magnetic profiles across the Witwatersrand System. A. Across overturned Lower Witwatersrand beds striking north northeast 12 miles south of Ventersdorp. B. Across the West Wits Line (Area 5a, Figure 1).

reef at 5200 feet. The shallowest mine in the Free State starts at 700 feet, the deepest at over 4000 feet. Therefore it is quite logical that extensions of the Witwatersrand System could be sought which are covered by several hundreds to several thousands of feet of younger rocks.

Magnetic method. Within the Lower Witwatersrand are several magnetic shales. The most important of these are the Water Tower slates, the Contorted bed, a highly contorted magnetite rich banded shale, and the West Rand shales. All three are sufficiently magnetic to be detected at depths of several thousand feet by moderately sensitive magnetometers. Figure 4 shows magnetic profiles flown at different heights over outcropping areas of the Central Rand. In Figure 4B the profile at 900 feet clearly shows the Water Tower slate (1), Contorted bed (2) and West Rand shale (3) anomalies. In Figure 4A the West Rand shale anomaly is not clearly defined, probably because of complicated faulting in this zone. The geological section is an oversimplification. At greater heights the Water Tower slates and Contorted bed anomalies merge completely to form one anomaly and the two effects are not resolved. In fact, if dips are steep and the distance below flight level approaches the separation of the magnetic beds all three anomalies become one anomaly (see aerial magnetic profile at 2900 feet above ground, Figure 4B).

Figure 2 shows the relative positions of these beds in the stratigraphic column. The lower one, the Water Tower slates, is some 1000 feet above the contact of the lowest member, the Orange Grove quartzites, with the basement. The position of this anomaly occurs therefore very close to the base of the Witwatersrand System and a magnetic map of an area underlain by Witwatersrand rocks will show an alignment of magnetic anomalies corresponding closely to the suboutcrop trace of the base of the system. Down dip further alignments of anomalies will correspond to the Contorted bed and to the West Rand shales. The polarity, shape and degree of resolution of these anomalies will depend on the magnetic nature of the beds, the strata dips and strikes and the depths below observation level. The determination of dips from the magnetic anomalies is difficult largely because the two major anomalies are usually superimposed and the magnetism is remanent and its direction generally not known. It is usually not important to know the dips of the magnetic beds to any precision, because in the zone of economic interest the dips will be flatter, very often considerably flatter, than at the edge of the basin. Consequently the usually steep dips of the Water Tower slates and Contorted bed if determined from their anomalies would give an erroneous position of the Upper Witwatersrand beds and reef horizons. Strike faulting is commonplace throughout the Witwatersrand System and repetition of anomalies often occur down dip. Further, strike faulting within the Upper Witwatersrand beds in general will not be indicated by a magnetic anomaly as the magnetic beds are already too deep to indicate the presence of the fault, or if manifested, the anomaly would be so broad as to be worthless for positioning the fault from the magnetic map. Therefore as a consequence of strike faulting the position of the reef horizons could not be established with any degree of certainty even if the dips were established from the shape of the magnetic anomalies.

Up to this point it has been implied that the Lower Witwatersrand has a reasonably constant thickness, that the magnetic beds are continuous throughout and that they bear a fixed stratigraphic relationship to the conglomerate reefs in the Upper Witwatersrand. Although this appears to be true over large distances and is certainly true on the outcrop area of the Central Rand, there is sufficient evidence from boreholes and mining operations to show that the Upper Witwatersrand beds vary in thickness and there is every reason to believe that the Lower Witwatersrand beds behave similarly. The Upper Witwatersrand at the Evander Goldfield 70 miles east of Johannesburg has thinned to less than 3000 feet and the Lower Witwatersrand is evidently not more than 8000 feet thick. Unfortunately there is a very limited footage drilled into Lower Witwatersrand rocks simply because they occur below the economic horizons and therefore very little is known about these rocks outside the outcrop areas. The probable variation in thickness and relative position of the magnetic horizons relative to each other and the conglomerates adds further to the uncertainty of the position of the conglomerates relative to the anomalies of the magnetic map. It is possible that one or more of the major magnetic horizons could be entirely missing. From the foregoing it would appear that the interpretation of the magnetic map is largely empirical and the effectiveness of the interpretation depends on the available local knowledge of the structure. Even if a magnetic zone only indicates the possible presence of Witwatersrand rocks and the direction of their dips, progress has been made.

Depth determinations can be made on profiles using both the horizontal slope distance of the maximum slope, or Peters' method of the distance between tangents of the half maximum slope. These are subject to gross errors as they are influenced by the superposition of the two important anomalies and by adjacent interfering effects whether from deep seated or shallow causes. Standard profiles obtained by flying over known areas with various conditions of dip and strike are catalogued and compared with the profiles obtained on survey. A number of attempts have been made by the author's group to establish depth by flying at multiple levels. This is not really satisfactory unless the complete grid is flown at selected levels. The survey then becomes excessively costly.

Gravity method. The granite on which the Witwatersrand System generally rests has a density of 2.63 gm/cc. The rocks comprising the Lower Witwatersrand are shales, quartzites and intrusives with densities of 2.63 gm/cc for the quartzites, 2.8 to 3.85 gm/cc for the shales and slates and 2.8 to 3.0 gm/cc for the intrusives. The shales make up about 60 per cent, the quartzites 30 to 40 per cent and the intrusives 2 to 10 per cent. The mean density for the group varies between 2.75 and 2.83 gm/cc, thus making it denser than the granite by 0.12 to 0.20 gm/cc. The total thickness of the formation can be as much as 20,000 feet and is probably nowhere less than 6000 feet, and thus represents a large relatively heavy mass compared with the granite. The Upper Witwatersrand is comprised predominantly of quartzites with some minor shale bands, conglomerates and intrusive sills. With the quartzites and conglomerates making up 90 per cent of the Upper Witwatersrand rocks the mean density is 2.63 to 2.66 gm/cc. The thickness of the Upper Witwatersrand can vary from a few thousand feet to 10 thousand feet and thus represents a light mass compared with the Lower Witwatersrand.

Lying both conformably and unconformably on the Witwatersrand System is the Ventersdorp System, comprised largely of great thicknesses of andesitic lavas of a density of 2.8 to 2.9 gm/cc, and usually lesser thicknesses of sediments predominantly quartzites and conglomerates. High up in the succession are porphyritic lavas with lower density than the andesitic lavas. The andesitic or basic lavas can be many thousands of feet thick and, contrasting in density by 0.2 to 0.3 gm/cc with the granite and the Witwatersrand quartzites, they form an appreciable heavy mass compared with the lighter rocks.

The Transvaal dolomite which can lie on any of the older formations has a density of 2.85 to 2.89 gm/cc and reaches a thickness of some 5000 feet. The Pretoria series, conformable with the Transvaal dolomite, has a mean density of around 2.85 to 2.90 gm/cc.

Because of these enormous thicknesses of material and the contrast in densities of around 0.15 to 0.3 gm/cc these formations produce appreciable gravity anomalies.

A Gravity Map of the Republic of South Africa with 10 milligal contours superimposed on the geology (scale 1:1,000,000) is published by the Geological Survey. An extensive network of stations was observed along roads at station intervals between 1 to 10 miles. This map used in conjunction with reconnaissance aerial magnetic surveys can form a useful starting point in exploration. The Witwatersrand Basin shows an anomalous gravity in excess of 40 milligals due to the heavy rocks of the Witwatersrand, Ventersdorp and Transvaal Systems filling the basin. High gravity is not confined to the Witwatersrand Basin only; deep basins of rocks belonging to the Ventersdorp, Transvaal and other systems where no Witwatersrand rocks are present also produce substantial gravity highs. The extensive occurrence of volcanic and intrusive rocks of the Bushveld igneous complex are the cause of the largest gravity anomalies in the country.

Figure 3 shows gravity profiles and geological sections derived from the gravity map of the Republic of South Africa and adequately illustrates the gravity effect caused by these formations.

The usefulness of the gravity method is twofold, first to establish the existence of a basin of predominantly heavy rocks beneath a cover of younger rocks, usually of Karroo age, and secondly to detail the structure within the basin. In particular changes of gradient and gravity lows can be indicative of the presence of the lighter Upper Witwatersrand quartzites sandwiched between the heavy Lower Witwatersrand and Ventersdorp rocks (Figures 6 and 7). Where heavy Ventersdorp lavas and Transvaal dolomite cover Witwatersrand formations gravity lows can occur where the Upper Witwatersrand quartzites are present below a shallow cover of these rocks (Figures 8 and 9).

The gravity and magnetic methods are complementary to each other. Magnetic anomalies can be due to other causes than the magnetic Lower Witwatersrand beds. If the magnetic anomalies occur on the edge of an extensive gravity high then the

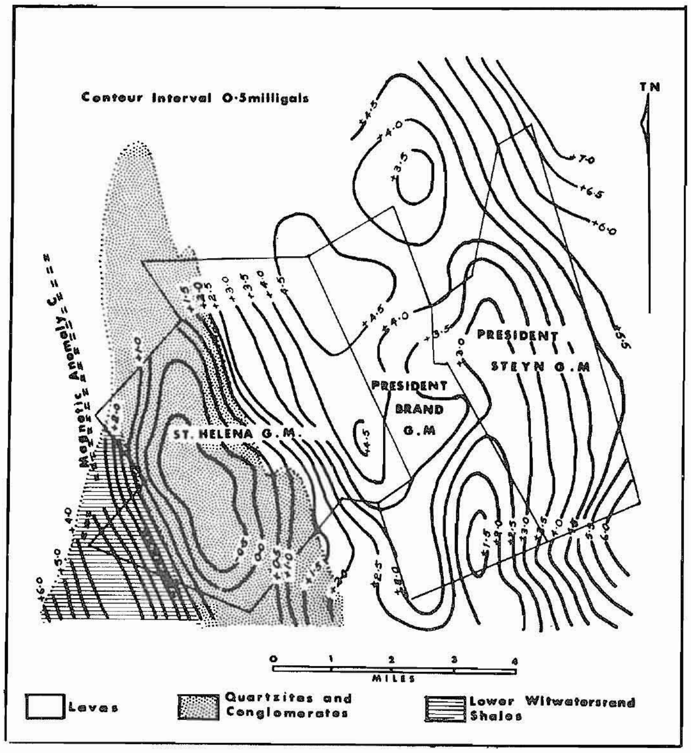


Figure 6. St. Helena. Gravity contours of portion of the Free State Goldfield and pre-Karroo geology showing the gravity low which lead to the discovery of the St. Helena Gold Mine.

chances that the magnetics are due to Lower Witwatersrand are greatly improved. Certain characteristics of magnetic anomalies based largely on type profiles over known areas strengthen the interpretation.

Although the initial interpretation of the magnetic map is largely empirical the geophysicist is able to make more specific deductions as to structure by comparing the data of the magnetic and gravity maps. A borehole site is selected on the basis of this interpretation and is sited to intersect reef. The reef may be some 6000 feet above the nearest magnetic horizon and if the dips of the formations are, say, 25 degrees the borehole site will be some 3 miles ahead of the peak of the anomaly and the chances therefore of intersecting reef in the first borehole are not high. Nevertheless useful stratigraphic information is obtained if the reef itself is not intersected and interpretation will be modified accordingly. This type of exploration is based entirely on geological theory with a thorough knowledge of local geology using the magnetic and gravity methods and the diamond drill to work out the details of the hidden structure. Continual collaboration between the geologist and geophysicist is absolutely essential.

Geophysical surveys

The West Wits Line. In the early 1900s boreholes drilled southwards from Randfontein intersected good gold values (Area 5b, Figure 1) and geological reasoning indicated that the Witwatersrand System must run somewhere beneath the dolomite towards the outcrop area southeast of Ventersdorp (Figure 1).

Dr. R. Krahmann (1936) demonstrated that the magnetic beds of the Lower Witwatersrand series could be followed even under a reasonably thick cover of the dolomite. A magnetic survey was conducted by Dr. Krahmann in collaboration with Dr. L. Reinecke for Goldfields of South Africa covering an area of 380 square miles involving over 100,000 observations on nearly 1500 miles of traverse. This was the first application of geophysics to the search for Witwatersrand reefs.

Borehole sites were selected by calculating the position of the reef from the position of the magnetic anomaly representing the highest magnetic horizon (the West Rand shales) after making certain assumptions as to dips of the dolomite and Witwatersrand beds and the thickness of the Witwatersrand beds between the highest magnetic horizon and the reef. These assumptions were based largely on outcrop and borehole information south of Randfontein.

A ground magnetic profile after Krahmann and an aerial magnetic profile across the West Wits Line is shown in Figure 5. These profiles show the three magnetic anomalies due to the Water Tower slates (A), the Contorted bed (B) and the West Rand shales (C).

Seven gold mines are producing in this area including the richest gold mine in the world, West Driefontein.

St. Helena. The second geophysical success, that of St. Helena Gold Mine in the Free State was due to a combined application of geology, gravity and magnetics. A. Frost (Frost, *et al.*, 1946), Consulting Geologist for Union Corporation Limited, theorised that the normal succession of Witwatersrand and Ventersdorp rocks could occur somewhere in the Orange Free State at shallow depth accessible to mining. O. Weiss (Frost, *et al.*, 1946) suggested that if the Upper Witwatersrand quartzites occurred anywhere at shallow depth they would, by virtue of their thickness and their lower density (lava 2.85 gm/cc, quartzites 2.65 gm/cc), cause a detectable gravity low. The heavy Lower Witwatersrand rocks would be indicated by a gravity high with associated magnetic anomalies and the lavas by a gravity high with no magnetic anomalies.

Large areas in the Orange Free State were covered by the torsion balance and magnetometer and indicated that the lava cover was thick. Union Corporation Limited, in collaboration with Western Holdings Limited, then covered an area of ground held by Western Holdings which included the farm St. Helena.

Figure 6 shows gravity contours over a portion of the Free State Goldfield and Figure 7 shows a gravity and magnetic profile across St. Helena Gold Mine. The contours are according to Weiss and clearly show a closed gravity low of about 3 milligals. The gravity low occurs to the east of a zone of magnetic anomalies corresponding to anomalies A, B and C in Figure 7. These magnetic anomalies lie on a zone of high gravity. The interpretation was that the magnetic anomalies and the associated high gravity was due to Lower Witwatersrand rocks, that the gravity low was due to Upper Witwatersrand quartzites dipping eastwards, and that the increase of gravity east of the gravity low was caused by Ventersdorp lavas increasing in thickness to the east. Borehole S.H.1 was drilled about the middle of this low and after cutting through 991 feet of Karroo rocks, was drilled through 6081 feet of quartzites, where it intersected an auriferous reef. However, subsequent drilling showed that this hole was in the footwall of the Basal Reef but still in the Upper Witwatersrand division.

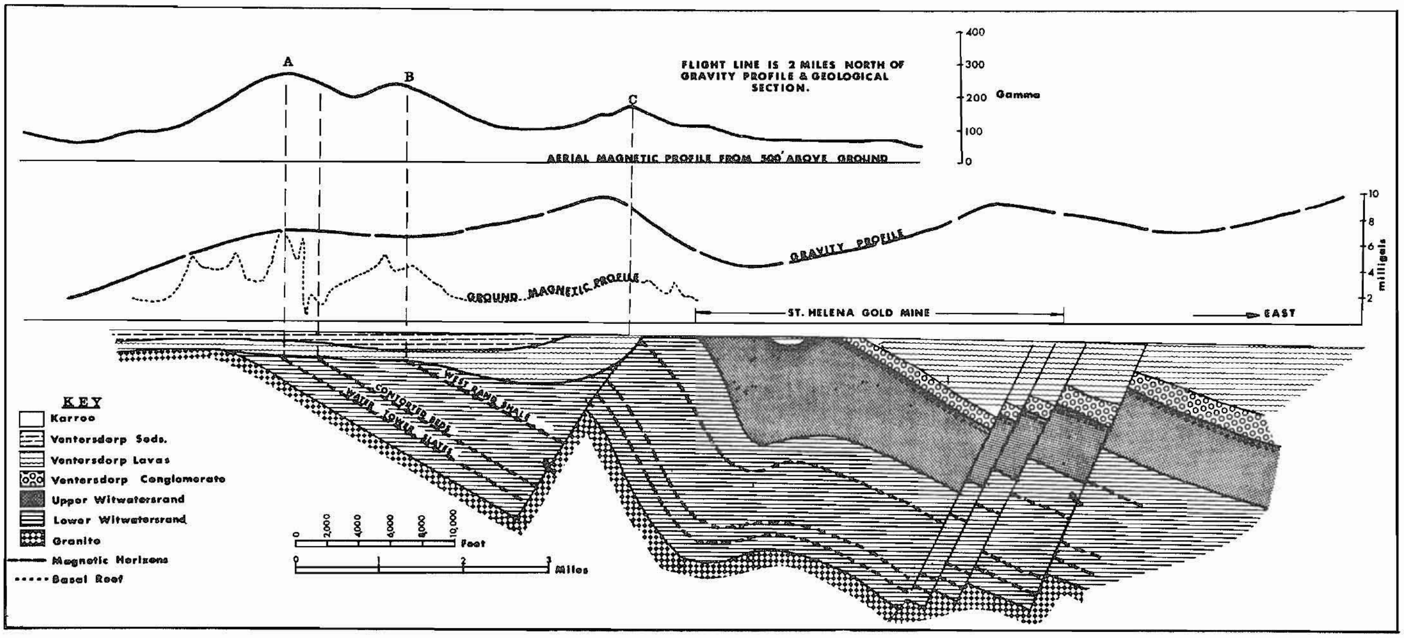


Figure 7. St. Helena. Gravity, ground magnetic and aerial magnetic profiles and geological section across St. Helena Gold Mine and environs.

A feature of the magnetics in this area is the way that the anomalies disappear on strike and reappear again. This is thought to be due to a deep lava trough which cuts across the strike of the anomalies, putting the magnetic beds at depth too deep to register at the surface. This trough is shown ahead and to the east of the anomalies in the section of Figure 7. Note the advantage of the aerial magnetic profile over the ground profile. Surface dolerite sills and dykes in the Karroo beds are the cause of the noisy results whereas these effects are largely eliminated from the air.

The geophysical interpretation is not as straightforward as this example may suggest it to be. From the extensive gravity work in the Free State Goldfield gravity lows can be found which are due not to Upper Witwatersrand quartzites, but to Ventersdorp sediments or in the one case to a deep Karroo trough (Karroo sandstone and shales have densities of 2.45 to 2.65 gm/cc). Likewise the best and most persistent magnetic anomalies which occur north of the Free State Goldfield suggest shallow magnetic beds, yet drilling down dip revealed deep lava in excess of 6000 feet. The explanation is that the magnetic beds are relatively shallow but that the dips are very steep and the Ventersdorp unconformity is such that the lavas deepen rapidly, cutting out the Upper Witwatersrand beds.

Stilfontein. Figure 8 shows the gravity contours (Weiss, 1951) of the Stilfontein area which lies some 10 miles northeast of Klerksdorp. The area of the gravity map lies wholly on dolomite and falls within the area No. 4 of Figure 1. To the west of the area are the outcrops of the Lower Witwatersrand System which dip eastwards. Early boreholes east of this outcrop in the dolomite area had stopped in Lower Witwatersrand rocks. The gravity low suggested that light Upper Witwatersrand quartzites could occur at shallow depth below the dolomite. Aerial magnetic data indicated that the gravity low area was magnetically flat, whereas to the north magnetic anomalies suggested the presence of Lower Witwatersrand rocks below the dolomite. Nine boreholes drilled into the gravity low intersected Upper Witwatersrand rocks at depths ranging from 1913 to 4039 feet. Six of these holes intersected the Vaal Reef. The sections in Figure 9 clearly illustrate the correlation between the gravity and the geology.

This area covered by the dolomite now has six operating gold mines. To the north of the area drilling and geophysical surveys have failed to indicate the presence of Upper Witwatersrand rocks beneath the dolomite. Steep faulting and folding is responsible

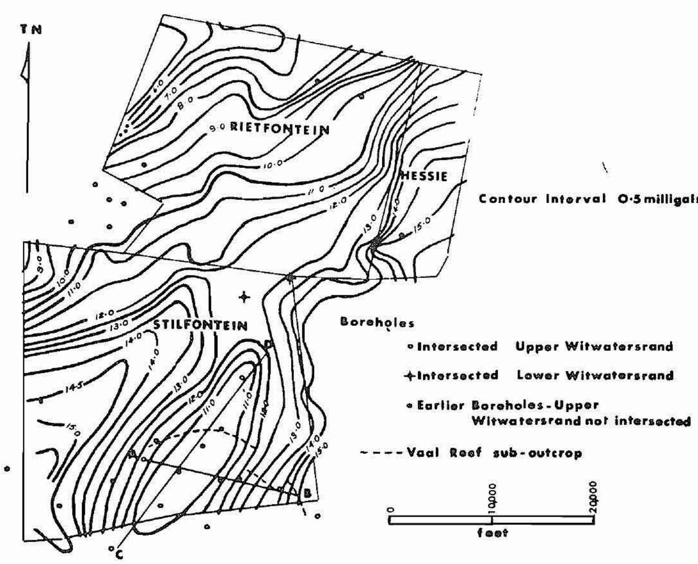


Figure 8. Stilfontein. Gravity contours on the farms Stilfontein, Hessie and Rietfontein showing the gravity low which led to the discovery of the Stilfontein Gold Mine in the Klerksdorp goldfield (Area 4, Figure 1).

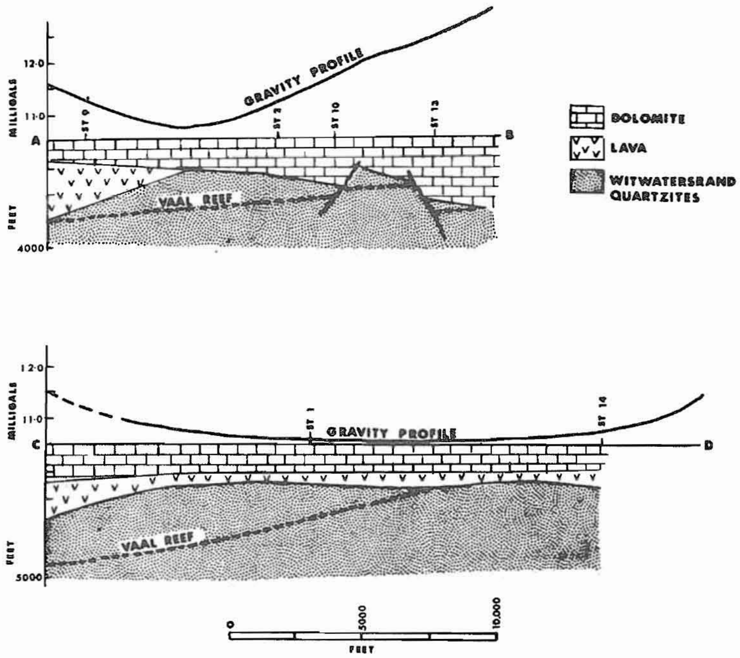


Figure 9. Stilfontein. Geological sections and gravity profiles on lines *AB* and *CD* of Figure 8.

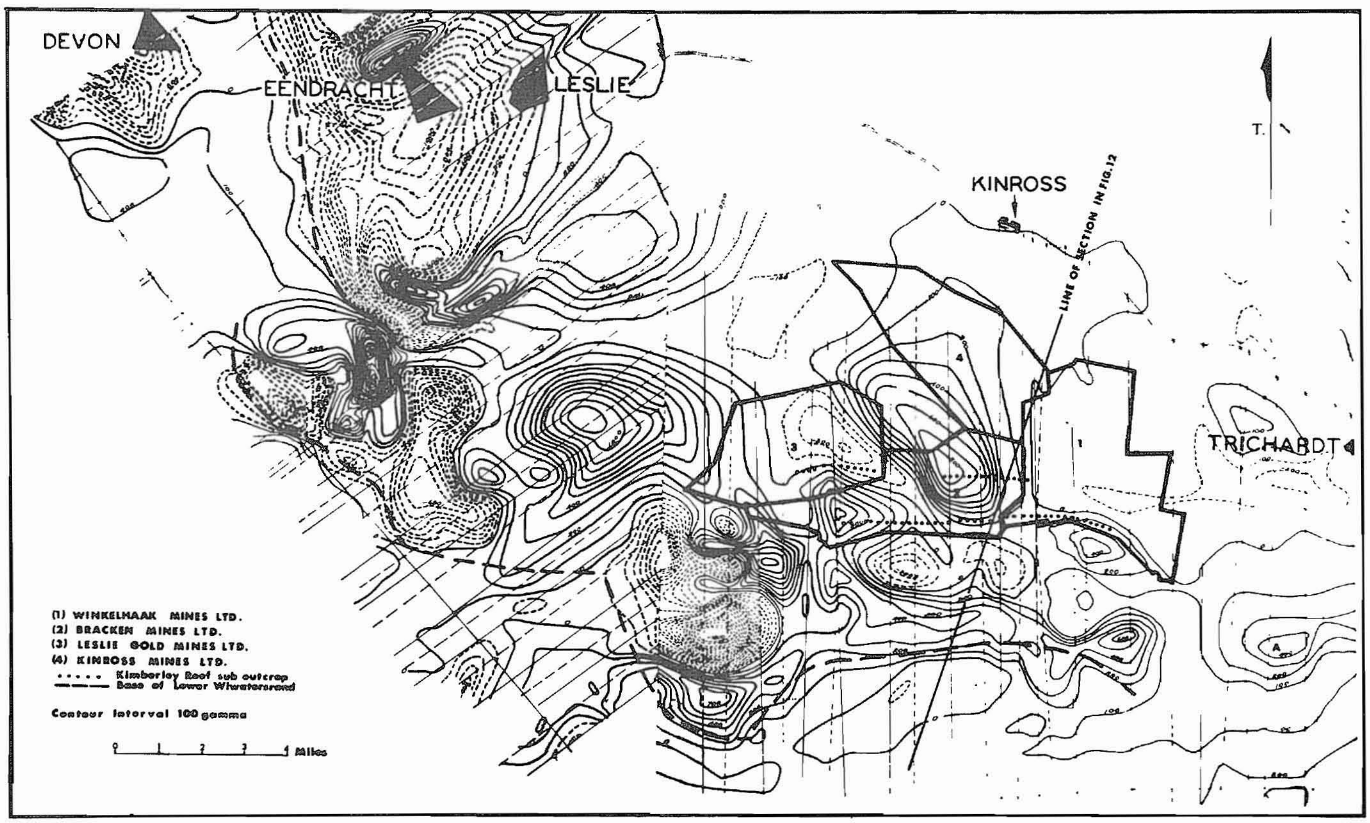
for bringing the Lower Witwatersrand rocks to suboutcrop apparently across the whole area of the dolomite. By the time the dolomite dips below the Pretoria series the dolomite is already 5000 feet thick and together with a varying thickness of Ventersdorp lavas the depth to reef would be considerable.

Geophysical case history: the discovery of the Evander Goldfield

The history of this field goes back to before 1933 when Lower Witwatersrand rocks were recognised in a borehole which was drilled to investigate gas emissions in the area (Area 7, Figure 1). In 1933 Fox started an investigation of the Far East Rand between Springs and Bethal (Fox, 1939). A ground magnetic survey involving 53,209 stations on 1240 miles of traverse was carried out in an area from north of Devon in the west, to near Trichardt in the east. This survey revealed magnetic anomalies forming a crescent striking south between Devon and Leslie and swinging to an easterly strike 10 miles south of Kinross. Fox postulated that these anomalies were due to Lower Witwatersrand beds. A vertical hole sited on the most intense of these anomalies near Leslie (20,000 gammas) intersected the highly magnetic Contorted bed of the Lower Witwatersrand below 477 feet of Karroo rocks (Fox, 1936).

The direction of the regional dip was interpreted as being inwards from the arc of magnetic anomalies, that is, northerly and easterly. Twenty boreholes were drilled in the area on the assumption that the Upper Witwatersrand beds would develop east and north from the magnetic anomaly arc. In not one of

Figure 10. The Evander Goldfield. Aerial magnetic contours.



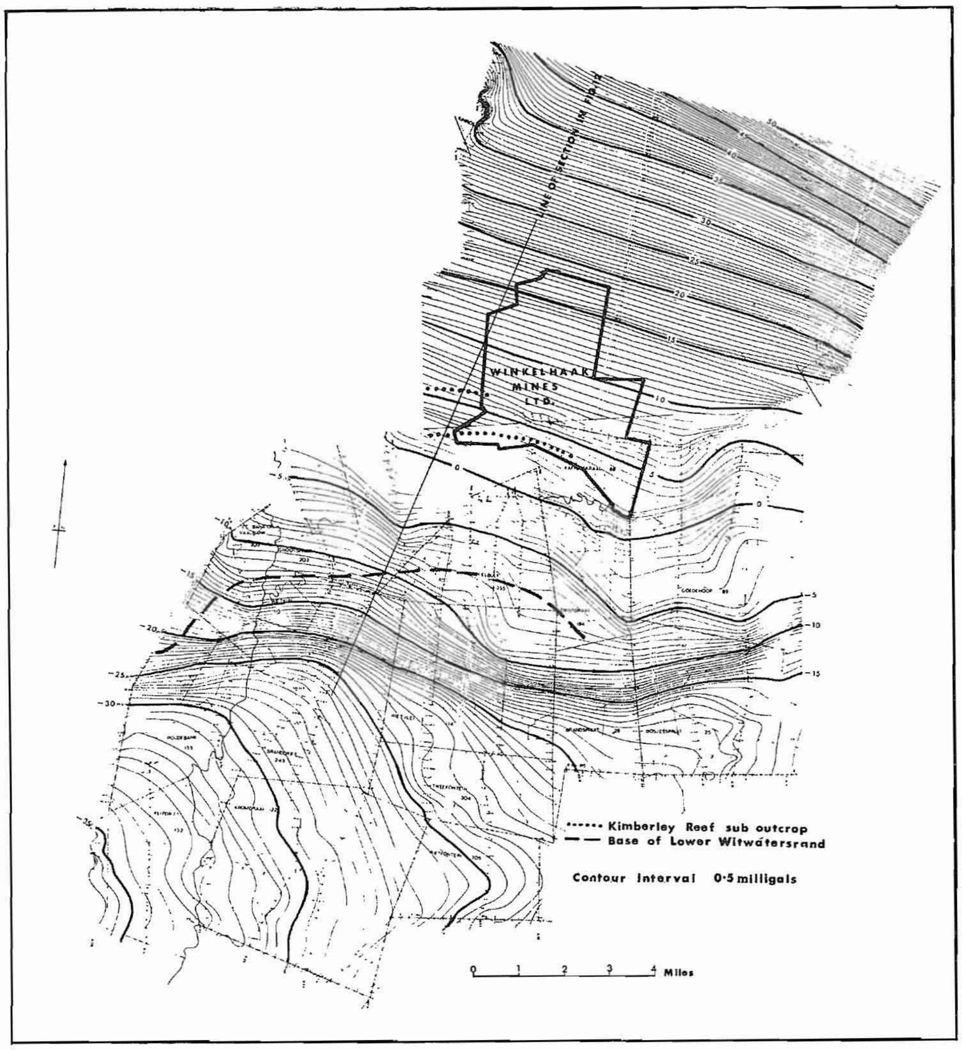


Figure 11. The Evander Goldfield. Gravity contours of portion of the Evander Goldfield.

these boreholes was the Main Reef or Kimberley Reef found or recognised. Exploration ceased in 1936.

Interest in the area remained dormant until 1948 when the Union Corporation started an investigation of the area. The area formed part of a regional airborne magnetic survey and during the course of this survey the area was covered by a wide-spaced grid at approximately 5-mile intervals. The results of this survey showed anomalies extending farther eastwards and indicated the magnetic relationship of this area to the known areas to the west. Although the magnetic anomalies pointed to northerly dips, it seemed more probable from geological considerations that the beds were dipping south and that they formed a part of the northern rim of the main basin displaced into the position indicated by the magnetic anomalies by faulting. On this basis a company, Capital Mining Areas, was formed and ground was taken under option on and to the south of the magnetic anomalies. Ground magnetometer and gravity surveys in this area indicated that the beds were in fact dipping north and ground was taken up to the north of the anomalies. This interpretation was based largely on the gravity survey (Figure 11) which showed an increase of gravity northwards with a steep gradient immediately south of the magnetic anomalies (Figure 12). The low gravity south of this steep gradient was virtually devoid of magnetic anomalies and was interpreted as being underlain by granite beneath the Karroo cover. The high gravity to the north was interpreted as being due to heavy rocks of the Witwatersrand System, lavas of the Ventersdorp System and Transvaal dolomite increasing in thickness beneath the cover of Karroo rocks. This interpretation was in accordance with a gravity profile through Johannesburg where the rocks of the various systems are exposed at surface (Figure 4).

A gravity traverse was run northwards along a road through Trichardt and showed a gravity peak of 90 milligals, 8 miles north of the town. This anomaly and the gradients over the Capital Mining Area were in excess of anything previously experienced in Witwatersrand basin studies and could only be accounted for by introducing both Pretoria beds and Bushveld igneous complex rocks all dipping north. The steep gradient in the area of interest was bothersome as it was difficult to remove to obtain residuals that would be sufficiently meaningful. At this stage only the steeper gradient south of the magnetic anomalies could be used to establish the base of the Witwatersrand beds. (As it turned out later, this steep gradient occurred at the base of the schist below the Witwatersrand beds.)

There were a number of puzzling features about the magnetic anomalies particularly south of Trichardt (Anomaly A in Figure

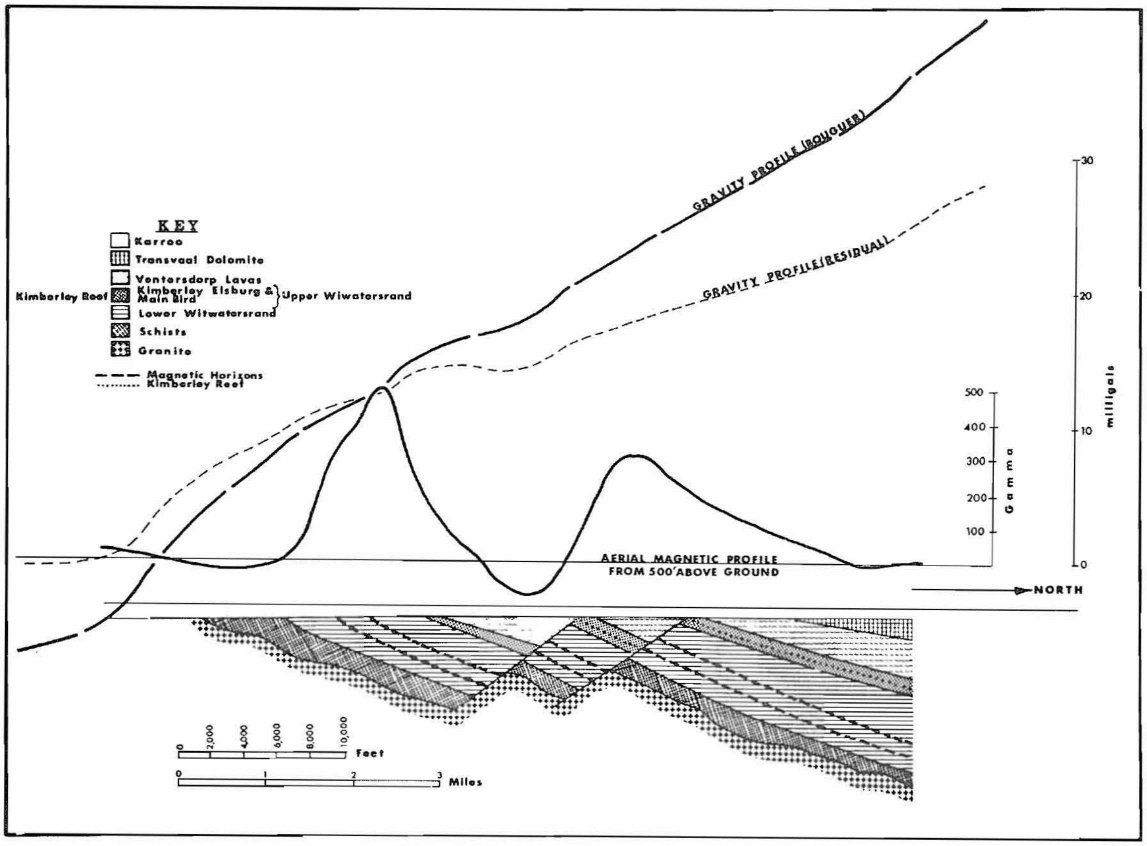


Figure 12. The Evander Goldfield. Gravity and aerial magnetic profiles and geological section on section line shown in Figures 11 and 12.

10). Here the magnetics showed only one anomaly and not the expected three anomalies of the Water Tower slates, Contorted bed and West Rand shales. To explain this a fault was postulated coinciding with the peak of the magnetic anomalies so that the northern side of the fault was downthrown and all three magnetic horizons butted up against this fault thus resulting in a single anomaly. On the basis of this interpretation a borehole, UC57, was sited immediately ahead of the anomaly peak in the hopes of intersecting Upper Witwatersrand beds.

This borehole commenced drilling in February 1950 and intersected Basement Schists below 695 feet of Karroo rocks. This was the first setback and forced a reassessment of the geophysical data. Although the schists in the borehole core were only slightly magnetic, it seemed possible that more highly magnetic schists could occur at greater depth and that the magnetic anomaly was in all probability due to schists. A second hole, UC60, was drilled 8000 feet north of the first and again intersected schists. It was then realised that drilling was in a structurally complicated area and a site for the third borehole was selected on the farm Winkelhaak some 7 1/2 miles northwest of the first hole. This borehole was the first success in that it established the existence of Upper Witwatersrand beds lying between Ventersdorp lavas at the top and Lower Witwatersrand beds at the bottom. A number of reef zones were intersected including the Kimberley Reef but the gold values were low. The drilling program was now concentrated on establishing the extensions of this reef on strike and down dip and to find values upon which a mine might be established.

In August 1952 six drills were in progress and ten holes had been completed of which seven had intersected the Kimberley Reef.

In March of 1952 after six boreholes had been completed a detailed aerial magnetic survey was flown over an area from Devon in the west to Breyten in the east. Two thousand profile miles were flown over an area of some 1300 square miles at 1/2-mile and 1-mile intervals.

Figure 10 shows the aerial magnetic contours of part of this survey over the area of the Evander Goldfield. The complexity of the pattern of the magnetic anomalies becomes apparent. The advantage of the aerial magnetics over ground magnetics in this area, apart from speed, was that the noisy background caused by surface dolerites of the Karroo System was eliminated.

By the time the results of the aerial magnetic survey were delivered, drilling had established that the Upper Witwatersrand System was considerably thinner than on the East Rand. There was also reason to believe that most of the Jeppestown Series was missing (Figure 2). This accounted for the fact that the Kimberley Reef suboutcrop was not as far down dip from the nearest magnetic anomaly as is usual on the East Rand, Central Rand and West Rand. Another unusual feature was that magnetic anomalies also occurred down dip from the reef suboutcrop. These anomalies were originally considered to be due to the West Rand shales before drilling proved this wrong. As drilling progressed it became evident that strike faulting occurred with upthrows on the north side resulting in the reef being brought back to suboutcrop. These faults were also responsible for bringing the magnetic horizons closer to the surface. To add to the complication of interpretation, a number of these faults have a particularly flat dip (Figure 12) and therefore the position of the magnetic anomaly depends on this angle, as well as on the usual angle of dip of the beds and the stratigraphic position of the magnetic horizon. All that could be said was that strike faulting had caused repetition of the reef and the magnetic anomalies, and beyond that no more precise interpretation was attempted. From the end of 1952 until recently upward of 80 per cent of the boreholes were drilled for values and the remaining less than 20 per cent for structure. The close pattern of the drilling was such that geophysics could not substantially contribute to the evaluation of local structure. However, the reassessment of geophysical data as borehole information came to hand continued to guide the drilling in the wider exploration of the field.

Figure 12 shows the magnetic and gravity profiles with a generalised geological section. The dolomite, Ventersdorp lava, and Kimberley Elsburg and Main Bird Series quartzites are well established by drilling and except for a few minor faults this picture of the Kimberley Reef horizon is true. No closer drilling would substantially alter the section as shown. There are so few holes that have intersected Lower Witwatersrand beds that the section in the Lower Witwatersrand remains conjectural. However it becomes apparent that there are only two major magnetic horizons (probably the Water Tower slates and Contorted bed) and that the West Rand shales are probably absent. It is also apparent that the most northerly magnetic anomaly on this section is not due to a third magnetic horizon such as the West Rand shales but is caused by the lower magnetic horizons being brought closer to the surface on the north side of the flat dipping fault. A further point that these profiles bring to light is that the sharp increase of gravity south of the most southerly magnetic anomaly is apparently not caused by the Lower Witwatersrand-granite contact at this point, but is due to schists which underlie the Lower Witwatersrand rocks. The schists have the same mean density and from a gravity point of view form one unit with the Lower Witwatersrand.

As the rocks of the Main Bird and Kimberley Elsburg Series are considerably thinner than for other areas of the Witwatersrand Basin, they do not create a gravity low of the same order. Nevertheless there is a sufficient thickness of the quartzites to be the cause of anomalies of sufficient size to be diagnostic of faulting particularly where lavas are downthrown against these rocks. Difficulty arises when faulting as illustrated in the section occurs. The nature of the faulting is such that the effect of the light granite coming closer to the surface compensates for a wedge of heavy lava near the surface. Gravity lows caused by the uplift in the granite could be mistaken for lows due to quartzites. In spite of these difficulties, the gravimeter can be used to effect, particularly now that so much is known about the general and detailed structure and the thicknesses of the beds, particularly of the quartzites.

General

Experimental seismic surveys have been done both at St. Helena and on the East Rand in an effort to establish structures. These experiments proved expensive and slow and the records lacked resolution. High velocities in the Witwatersrand and Ventersdorp rocks resulted in loss of signal in the ground role because of short travel times. The state of the art has advanced enormously since these experiments were carried out some 17 years ago and it would seem feasible with modern techniques to produce a meaningful seismic section across faulted beds of the Witwatersrand System under a thick cover of Karroo rocks. Density contrasts of up to 0.2 gm/cc exist between the shales and quartzites and velocities vary from 16,000 ft/sec to 19,000 ft/sec. One of the problems would be multiple reflections from the many dolerite sills in the Karroo System. The cost of seismic surveys seems prohibitively high particularly when it is realised that one month's survey is the equivalent of nearly 10,000 feet of core drilling. Only drilling can establish the existence of a reef and once this has been done the drilling that follows is largely to establish the zones of payable reef during the course of which the structure is established. Circumstances nevertheless could arise where seismic surveys might be warranted.

A brief mention of geophysical methods used down hole is appropriate here although these methods play no part in the exploration stage.

Radiometric logs (gamma logs) are taken down boreholes. Their use in detecting uranium-bearing reefs is of limited importance as the cores of all reefs are assayed for both gold and uranium. Simpson (1951; 1952) showed that certain beds and reefs of the Witwatersrand and Ventersdorp Systems could be correlated over long distances from the character of the radiometric logs.

Temperature surveys down boreholes have assisted in establishing the geothermal step (feet/°F) in various parts of the country. Deep level mining on the Witwatersrand is possible because of the high geothermal step (160-200 feet/°F) but a thick cover of Karroo beds can severely limit the depth to which ore can be economically mined. The geothermal step in the Karroo is 70-135 feet/°F.

Conclusions

Magnetic and gravity surveys have made a major contribution towards the discovery of new goldfields and the extensions of existing goldfields. Falling into the first category are the Free State and the Evander goldfields and into the second, the West Wits Line and the northeastern portion of the Klerksdorp goldfield. Both gravity and magnetic surveys were employed in three of these programs whereas in the prospecting for the West Wits Line, gravity played no part. The major contribution to the discovery of the Stilfontein gold mine in the Klerksdorp area was made by gravity, and gravity played the more important role in the discovery of St. Helena in the Free State goldfields. Nevertheless if magnetic anomalies had not occurred up dip from the gravity lows the interpretation would not have been conclusive and certainly in the case of St. Helena the gravity low would probably not have been drilled.

The airborne magnetometer, because of its flexibility, speed of operation and freedom from noise caused by the dolerites of the Karroo System has greatly advanced the ease with which magnetic surveys can be accomplished.

Gravity surveys are hampered by the need to acquire ground if the desired detail is to be achieved, and the tendency is to limit gravity surveys to public roads. This limitation does not apply to the airborne magnetometer.

It is becoming more difficult to find new goldfields. No new goldfields have been found since drilling proved the geophysical indications of the Evander Goldfield in 1951. Since then all new gold mines have been established on immediate extensions of existing gold-mining areas. The airborne magnetometer's last and only contribution as far as is known was towards the discovery of the Evander Goldfield. There have been some technical successes in locating Lower Witwatersrand beds but drilling has either failed to find the Upper Witwatersrand beds, or where they were present, no payable reefs were intersected.

The search goes on and gravity and magnetic surveys remain the only geophysical methods used. The advent of more sensitive magnetometers, magnetic gradiometers and digital processing in recent years is unlikely to make a major contribution to exploration in this field. No major breakthrough is foreseen whereby the auriferous reefs themselves can be directly detected.

The application of geophysics to establishing local structures in existing goldfields and during the opening up of new goldfields is an area in which little work has been done. A wider use of the gravimeter with more sophisticated treatment of the gravity data and the application of seismic methods call for further research.

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Contents

Diamond prospecting by geophysical methods—a review of current practice

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Abstract. The main application of geophysics to the exploration for diamonds has been in the search for kimberlite pipes. Kimberlite is a rock with variable physical characteristics, none of which is unique.

Magnetic, resistivity and gravity anomalies have been found over known kimberlites during local trials, but geophysical prospecting has been confined chiefly to magnetometer surveys.

Résumé. La principale utilisation de la géophysique dans l'exploration des diamants a consisté de la recherche de cheminées de kimberlite. La kimberlite est une roche qui possède des caractéristiques physiques variables dont aucune n'est particulière.

On a trouvé des anomalies magnétiques, gravimétriques et de résistivité au-dessus de kimberlites connues au cours d'essais locaux, mais la prospection géophysique a consisté surtout des relevés au magnétomètre.

Economic concentrations of diamonds occur either in alluvial deposits or in the ultrabasic rock kimberlite. There is no geophysical method by which diamonds can be detected directly and consequently the application of geophysics to prospecting for diamonds is confined to the location of the primary kimberlite source rock.

The classical method of searching for kimberlite depends on the recognition of heavy mineral dispersion haloes which usually surround kimberlites. The most useful heavy minerals are magnesian ilmenite and pyrope garnet. These anomalies can be many times larger than the area of the body from which the minerals were derived and this makes the method particularly useful during reconnaissance prospecting. With such a relatively simple and direct method of reconnaissance, geophysics has found only limited application during this phase of prospecting.

When the prospecting becomes more detailed and the target is a single pipe rather than a group of pipes, geophysical methods may be used to assist other means of prospecting or may even become the only method used.

When compared to its application in base metal prospecting geophysics has played a relatively minor part in the search for kimberlite diamond deposits. This is largely because kimberlite is a rock with variable characteristics which can be set in any number of different geological environments. This makes it difficult to predict the kind of results which can be expected during a geophysical survey.

The geology of kimberlite

The economically most significant occurrences of kimberlite are on the African continent south of the Sahara and in the Yakutsk Republic of the U.S.S.R. Nearly all the other kimberlites found to date have been of little or no economic value. Kimberlites occur as intrusive dykes or volcanic pipes which range in age from 80 million years to 1130 million years.

Kimberlite dykes. Kimberlite dykes vary in width from a few centimetres to several metres. They occur in zones which may extend for several tens of kilometres. Individual dykes in such zones are often arranged *en echelon*. A few dykes are being profitably mined in South Africa but because of their smaller volumes they are not of as much value as pipes.

Kimberlite pipes. There are about one thousand pipes known. Less than 2 percent of these are of any economic significance since the majority are entirely barren or contain very few diamonds.

Pipes usually occur in groups which may number less than ten or as many as fifty or sixty. The most famous group is undoubtedly the celebrated one at Kimberley in South Africa where mining has now been in progress almost continuously for over eighty years.

Most kimberlite pipes are conical bodies which taper off in depth. Diameters at surface range from a few metres to over 1 kilometre. The majority of the economically significant pipes are between 400 and 1000 metres in diameter at surface.

The physical characteristics of kimberlite

Kimberlite is an ultrabasic rock which consists chiefly of olivine or olivine and phlogopite mica. It occurs as tuff, volcanic breccias and intrusives which are usually more or less serpentinized and often carbonatized.

The physical characteristics of kimberlite are dependent on its mineral composition and its state of weathering. According to Fairbairn and Robertson (1966), kimberlite rock alters to the clay minerals nontronite and montmorillonite in the zone of weathering.

Specific gravity. The specific gravity of kimberlite is largely controlled by its degree of serpentinization and weathering. Fresh dyke kimberlites in Sierra Leone collected at a depth of 300 feet below surface have specific gravities between 2.71 and 3.12 while the kimberlite from a pipe at the same level averages 2.55 and at 18 feet below surface only 2.47.

In the South African diamond mines specific gravities between 2.64 and 2.98 with an average of 2.75 are encountered below the zone of surface weathering.

Lower densities are encountered in Yakutia, for example Men'shikov (1957) gives an average of only 2.35 for kimberlites of the Mir pipe.

Magnetic susceptibility. Kimberlite derives its magnetic characteristics from the magnetite and ilmenite it contains. Both these minerals occur as primary constituents but magnetite is also

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formed as a secondary mineral during the serpentinization of kimberlite. Scant information is available about the amounts of these minerals present but Litinskii (1963) gives a range of 1 – 8% for magnetite.

No published information is available on the magnetic susceptibility of the African kimberlites. The kimberlites of Yakutia have susceptibilities between 100 and 6000 $\times$ 10^{-6} emu/cm^3 according to Litinskii.

Resistivity. There appears to be very little information available about the resistivity of kimberlite. De Magnee (1950) and his colleagues encountered values of less than 20 to about 150 ohm metres in the Congo.

General experience shows that kimberlites have resistivities usually lower than that of the surrounding rock. In Sierra Leone for instance this was found, even where the surrounding granite was decomposed to clay. This is probably because the montmorillonite in the kimberlite-derived clay has a lower resistance than the kaolinite in the granite-derived clay.

Geophysical fieldwork

Gravity surveys. *U.S.S.R.* – According to Balashin (1964), precision gravimetric surveys were used in the southwestern part of the Daldino-Alakitsky region of Yakutia to locate kimberlite pipes under a continuous trap cover. Calculations showed that a kimberlite pipe can cause a clear gravity anomaly in excess of 0.3 mg providing it is not covered by more than 100 metres of trap. It is claimed that this is three times the mean square error of the survey. The main factor influencing the gravitational field was found to be the irregular thickness of the traps. Experimental work, using resistivity probing, points to a way of determining the thickness of the trap layer. From the results of the resistivity survey an isopach map of the traps was drawn and by using this map, corrections could be made for the gravitational influence of the trap.

Trial gravimetric surveys were also carried out by Romanov and Romanova (1961) over a pipe which was partly covered by trap lava. The main features of local relief in the area surveyed are several escarpments up to 6 metres in height formed by the edge of a trap plateau.

The position and approximate outline of the pipe were obtained from a magnetic survey and from drilling. Three rock types are in the survey area, which measured 1 $\times$ 1.5 km. These differ in density. The kimberlite has a density of 2.3 gm/cm^3, the surrounding limestone 2.5 gm/cm^3 and the overlying trap 2.8 gm/cm^3. Calculations showed that gravitational anomalies over the kimberlite pipe must be about 1 milligal.

The survey was conducted on a 50 $\times$ 50-metre grid. There is an abrupt change in the regional gradient caused by the change in trap thickness. Residual or local anomalies were separated from the regional effect by a method of second derivative calculation which took into consideration the values for groups of eight stations. Treated in this way the data revealed an anomaly over the kimberlite pipe of 1.5 mg below background.

Tanzania – Edwards and Howkins (1966) state that there are more than two hundred kimberlite occurrences now known in Tanzania. Many of these kimberlites are represented at the surface by small structural basins of sediments which occupy craters connected with the underlying pipes.

In the case of Mwadui pipe this sedimentary basin is about 300 metres deep but in the majority it is less than 30 metres.

In 1958 and 1960 the Geophysical Division of the Overseas Geological Survey of Great Britain carried out gravimetric surveys over the Mwadui and several other kimberlite occurrences in Tanzania.

The following information was obtained from a report by Dr. Mason-Smith who conducted these surveys (Mason-Smith, 1960).

There is a regional gradient of about 1.5 mg per mile in a northwesterly direction in the Mwadui area. When the regional gradient has been removed the anomaly appears as a circular negative zone centred over the pipe. The maximum anomaly at the centre is about −6 milligal. This striking anomaly is due to the appreciable contrast in density between the sedimentary beds in the crater and the surrounding granite/schist countryrock. This difference is around 0.3 – 0.6 gm/cc^3 (see Figure 1).

Following the success of a trial survey over the Mwadui pipe a number of other kimberlite occurrences were also surveyed. Anomalies were obtained wherever a pipe structure was present.

As a result of these surveys Mason-Smith concludes, in part, as follows:

"1. All the larger proven kimberlite pipes produce well-defined closed negative anomalies of similar character.

2. The weathered upper parts of the pipes have a roughly circular margin with steeply plunging walls. The absence of a broad ring of positive anomaly shows that the unweathered feeder to the upper part of the pipe has a relatively small cross section. There is evidence that high density material occurs near the surface close to some of the small pipes.

3. The maximum anomaly is roughly proportional to the diameter of the pipe – about 1 mg/200 yards of diameter.

4. Most of the pipe anomalies are superimposed on slowly varying regional anomalies of deeper origin. After correction for regional effects the margin of the pipe occurs at the 'half maximum' anomaly.

5. If an indication of the proximity of kimberlite has been obtained by sampling, a gravity survey team (one gravimeter) can establish the existence or nonexistence of a pipe and delineate its margins in one or two days."

This gravity method has not received much attention to date but it would seem that under appropriate conditions such surveys could be of use in the location of kimberlite pipes. In areas like Tanzania where the lack of magnetic contrast between the kimberlite and the countryrock precludes the use of the magnetometer the choice of geophysical methods lies between gravity and resistivity surveys.

Magnetic surveys. *United States of America* – The earliest account of the application of magnetometer surveys in prospecting for diamond-bearing pipes is that given by Stearn (1932). He obtained an anomaly exceeding 2000 gammas over the Prairie Creek peridotite pipe near Murfreesboro, Arkansas.

During more recent work by the Selection Trust Exploration Ltd. with a JALANDER fluxgate magnetometer it was found that other peridotite breccia pipes in the area did not give rise to any significant magnetic anomalies. It is, therefore, assumed that the Prairie Creek anomaly is caused by the presence of the intrusive peridotite in one part of the pipe which is otherwise occupied by tuffs and breccias.

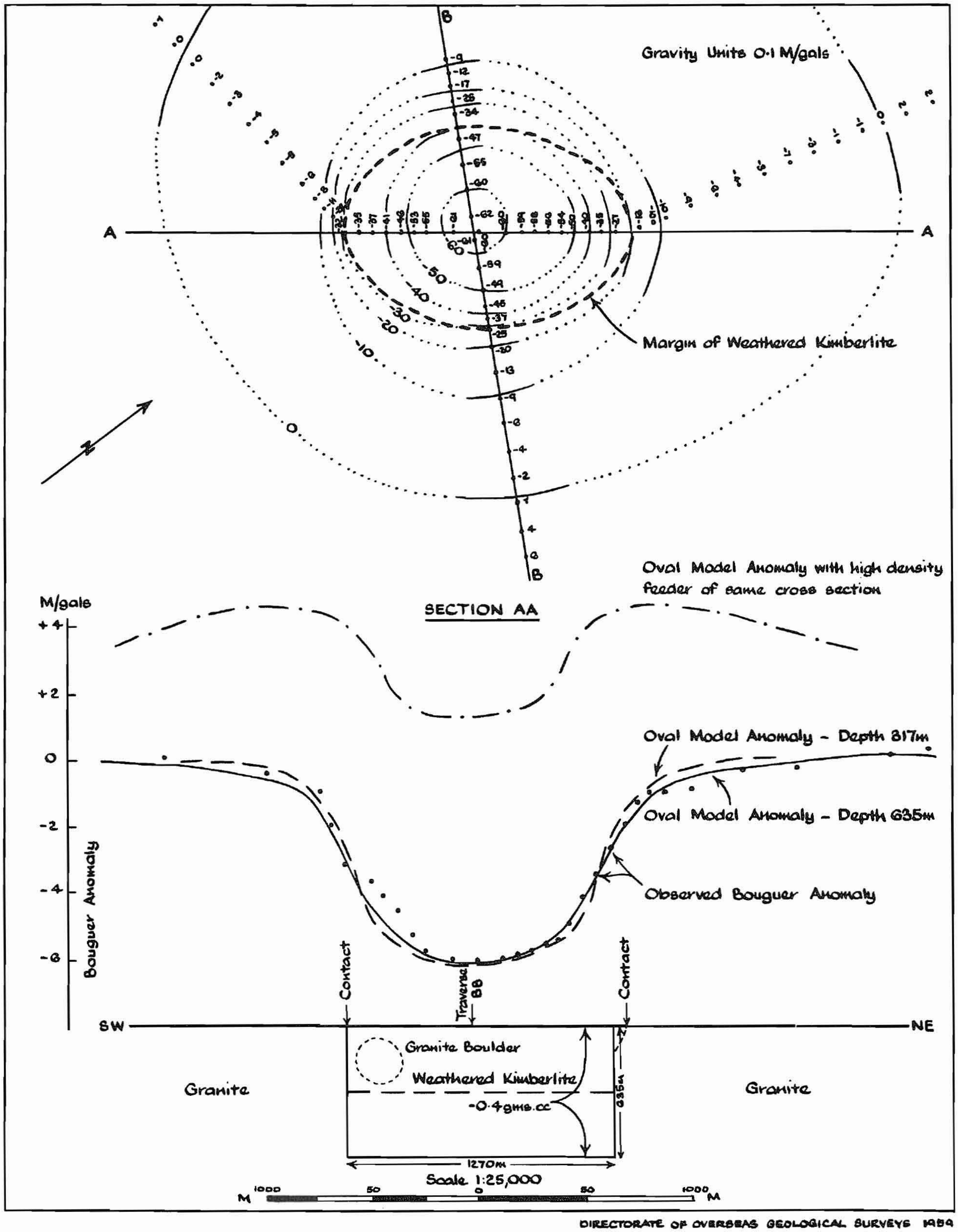

Figure 1. Gravity survey, Mwadui Mine, Tanzania.

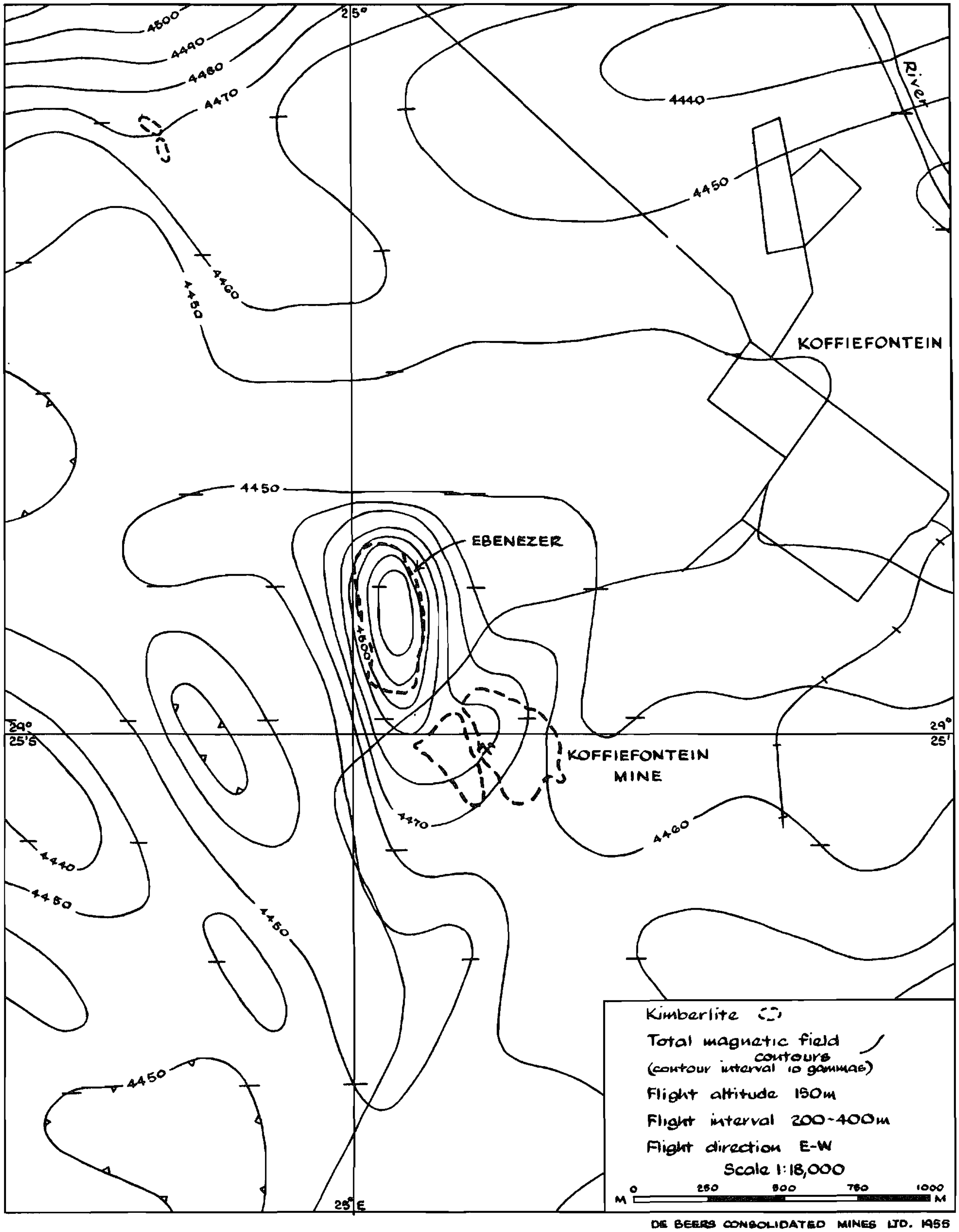

Figure 2. Aeromagnetic map Koffiefontein area, South Africa.

U.S.S.R. – During the intensive diamond prospecting campaign carried out in Yakutia, magnetometer surveys have been more generally used in the search for kimberlite than anywhere else. Particularly favourable conditions prevail in the areas where the countryrocks are flatlying calcareous strata with a magnetic susceptibility of virtually zero. Litinskii (1963) states that the magnetic susceptibility of the kimberlites ranges from 100 – 6000×10^{-6} emu/cm^3.

Men'shikov (1957) indicates that ground magnetometer surveys showed a wide range of anomalies from five to three thousand gammas with highly irregular oscillations from several hundreds of gammas negative up to 2500 gammas positive.

Trial airborne surveys were carried out at heights of 200, 400 and 600 metres over selected pipes to determine vertical magnetic gradients and optimum flying heights. At a height of 600 metres the anomalies disappear or become indistinct. Vertical gradients encountered were relatively steep and vary with different pipes from 120 to 1000 gammas per 100 metres and from 180 to 1500 gammas per 200 metres. At a height of 100 metres the magnetic intensity falls off to 1/2 – 1/5 of the value on the ground and at 200 metres to 1/6 – 1/11, depending on the magnetism of the pipe. Most pipes could be easily detected at a height of 400 metres.

Men'shikov claims that at a survey height of 100 metres anomalies are twice as wide as on the ground and airborne surveys can therefore be regarded as twice as effective as ground surveys. Since the intensity of the anomaly is reduced at this height to as little as 1/5 of the surface value this claim is open to doubt.

Barygin (1962) discussed the prospecting of kimberlite pipes from the air. He recommends a flying height of 50 to 100 metres and a line spacing of 250 metres. Barygin states that aerial magnetic prospecting for kimberlite pipes gives good results but he also notes the following drawbacks:

1. In some places anomalies caused by trap rocks are indistinguishable from those caused by kimberlites.
2. Some pipes are only slightly magnetic causing anomalies barely distinguishable from the general background.
3. Some pipes are small relative to the flight line spacing and may consequently be missed altogether.
4. The particular magnetometer (ASGN-25 array) sometimes recorded nonexistent anomalies.

In conclusion Barygin recommends the following prospecting procedure:

1. Visual observation from the air.
2. Air magnetic survey.
3. Preparation and interpretation of the data from 2.
4. Air photographic survey.
5. Laboratory interpretation of the air photographs.
6. Coordination of the data from the aeromagnetic survey with those of the air photo survey.
7. Aeromagnetic selective resurvey.
8. Working out of the supplementary data from the aeromagnetic resurvey and coordination of them with pre-existing information with the production of a final basis for ground operations.
9. Field geological interpretation of the air photographs and testing of the magnetic anomalies.
10. Geophysical work on the ground.

Litinskii (1963) describes an interesting magnetic prospecting method referred to as Kappametry.

The objective of this method is to determine the pattern of magnetite and ilmenite distribution in the soil and stream sediments over and around kimberlite pipes. The Kappametric survey is carried out by taking soil samples on a regular grid and measuring their magnetic susceptibility with a portable instrument.

Weathering disperses the kimberlite minerals from the pipes causing dispersion haloes which may be many times larger in area than the pipes. These haloes may be displaced downstream of the source but this does not appear to be serious under ordinary circumstances.

The advantage claimed for the method is that it gives more rapid results than either geochemical sampling or ordinary heavy mineral sampling. Geochemistry requires a laboratory and results are not immediately available. Heavy mineral sampling requires water for panning and in Yakutia this could mean carrying samples for considerable distances.

It would appear that this method could only be applied in areas where the countryrock contained very little or no magnetic minerals and where kimberlite was the main intrusive rock present.

Africa – In South Africa the De Beers Company carried out trial airborne magnetometer surveys over a number of pipes. The flight altitude was 150 metres in all cases. Not all the pipes over which surveys were conducted could be detected. Where anomalies were obtained they did not exceed 60 gammas over the background. Figure 2 is an example of results obtained. Ground magnetometer surveys carried out by the De Beers Company and by Selection Trust Exploration staff have confirmed that variable results can be expected in South Africa. Some pipes may give rise to anomalies exceeding 500 gammas while many cause no detectable anomalies at all.

In Tanzania very disappointing results were obtained with the magnetometer. Trials carried out with the airborne instrument over several pipes, including the Mwadui pipe, failed to reveal detectable anomalies. It is possible that the presence of nearby magnetic basic dykes may in some cases have complicated the magnetic field thus masking any effect the kimberlite may have had. However, detailed ground surveys also proved equally disappointing.

In similar pre-Cambrian terrain in Sierra Leone results have been equally disappointing. A number of small kimberlite pipes and numerous narrow kimberlite dykes are present on the leases of the Sierra Leone Selection Trust Ltd. Detailed ground magnetometer surveys over selected areas have indicated that the kimberlites are not sufficiently magnetic to cause consistent anomalies.

One part of Africa where good results were obtained with the magnetometer is Mali in West Africa. From 1963 to 1966 the Selection Trust Exploration Company prospected for diamonds in the southwestern part of Mali. Kimberlites were known in the area and trial surveys indicated that the pipes gave very characteristic and well defined anomalies. Figure 3 illustrates a typical pipe anomaly.

Regional ground surveys were carried out with the SHARPE MF1 Fluxgate magnetometer over areas where alluvium precluded the use of heavy mineral surveys.

Convenient sized blocks of ground were surveyed on a 200 X 50-metre grid by relatively unskilled operators under supervision

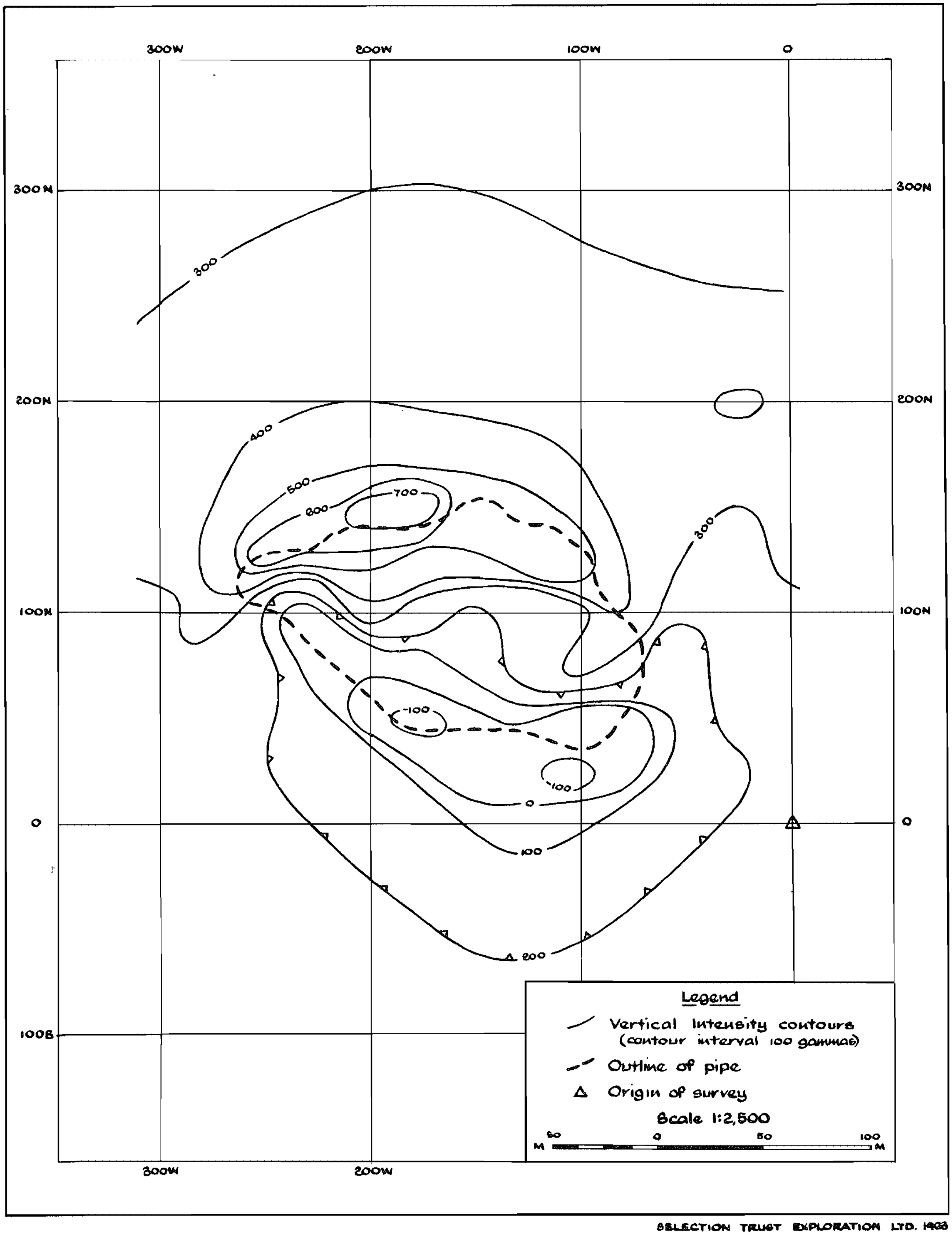

Figure 3. Magnetic anomaly over kimberlite, Mali, West Africa.

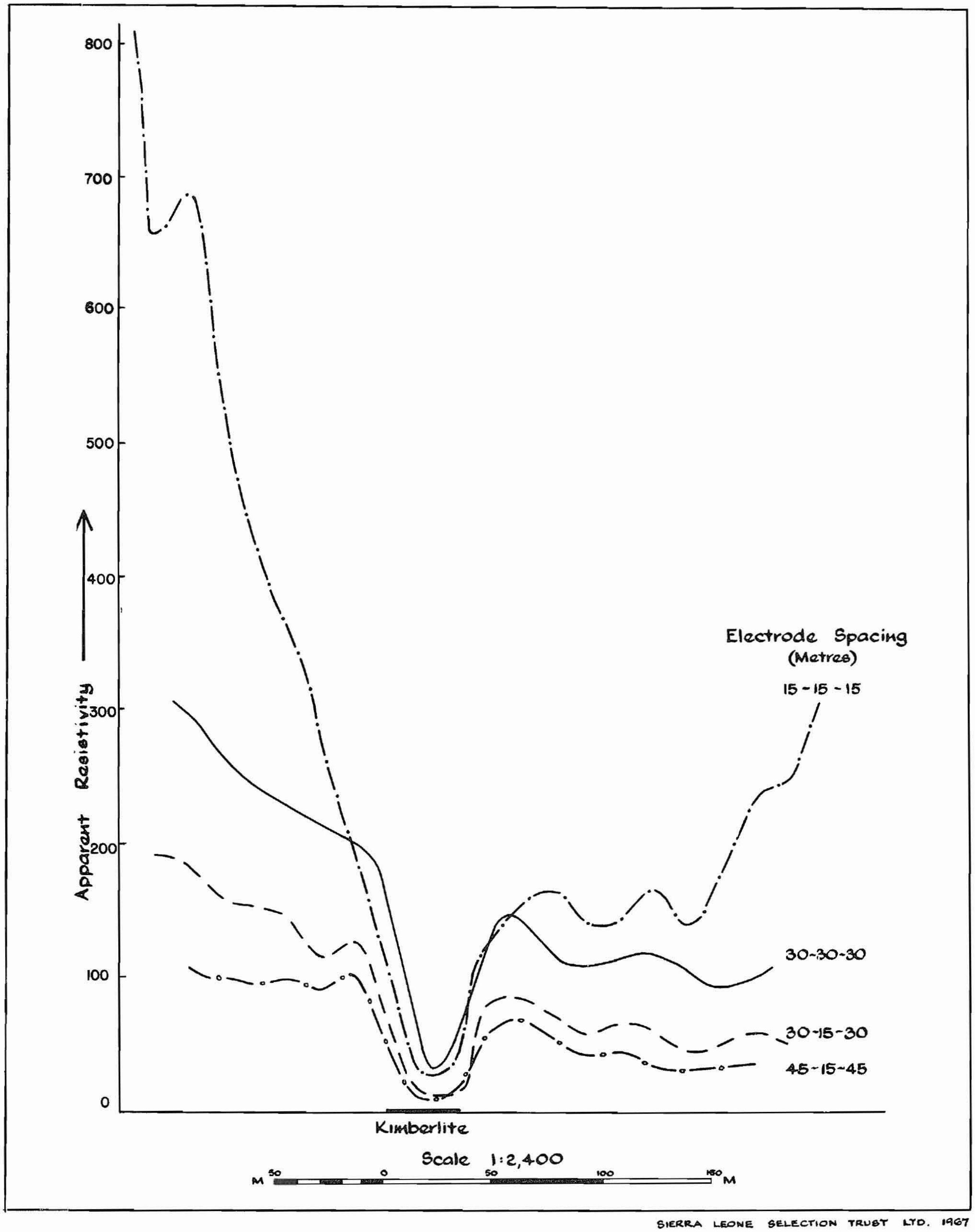

Figure 4. Resistivity profile over kimberlite pipe, Sierra Leone, West Africa.

of a senior member of the field staff. Since the objectives were local rather than regional anomalies it was found convenient to disregard the diurnal variation which amounted to about 60 gammas. Anomalies were screened and only those resembling the pipe type were checked by more detailed surveys and pitting or drilling where necessary.

In addition to the regional surveys the magnetometer was also used locally to locate pipes where heavy mineral anomalies indicated the presence of kimberlite.

Some problems were encountered locally, particularly where magnetic laterite caused erratic readings. However, the presence of the laterite was usually obvious and this could then be taken into consideration when analysing results.

The magnetic surveys in Mali were successful because of the adequate magnetic contrast which exists between the schist and sandstone countryrock and the kimberlite pipes. No magnetic susceptibilities were determined but pipe anomalies displayed maxima of between 200 and 1550 gammas above background and associated minima of 200 to 900 gammas below background.

Resistivity Surveys, Africa. The first published resistivity survey of a kimberlite pipe was carried out by de Magnée and his colleagues at Bakwanga in the Kasai in 1946 (de Magnée, 1950).

This survey was conducted in an attempt to locate the source of local alluvial diamonds. The source area was thought to be a hill consisting partly of silicified limestone. A thick cover of sandy loam and the presence of large amounts of groundwater made normal prospect pitting difficult.

Resistivity probing was first carried out to determine the overburden thickness and the best electrode spacing to use. Spacings of 20 and 40 metres were adopted (Wenner configuration). Surveys with both these spacings indicated the presence of a low resistivity body measuring some 400 X 600 metres. Pitting proved the presence of a kimberlite pipe.

The sandy loam overburden had resistivities of 800 to 1500 ohm metres. The limestone countryrock measured some 400 ohm metres while the decomposed and waterlogged kimberlite gave values lower than 20 ohm metres.

In Tanzania a number of surveys indicated that here, too, the kimberlites displayed resistivities significantly lower than the surrounding countryrock. However, the method was not generally applied in prospecting.

In Sierra Leone trial surveys carried out on the Sierra Leone Selection Trust mining lease at Yengema indicated that kimberlite pipes would give detectable low resistivity anomalies. The profile shown in Figure 4 illustrates the kind of results obtained.

Regional surveys are currently in progress in an attempt to discover kimberlite pipes which may not be revealed by other types of prospecting.

Two problems have been encountered during the survey. During the dry season the contact resistance of electrodes can be high and give rise to erratic results with the ordinary alternating current instrument. This difficulty is overcome by confining dry season work to the valleys which retain sufficient surface moisture to ensure good electrode contacts.

The second problem is caused by deep weathering in some valleys or parts of valleys. These areas often give rise to anomalies similar to those found over kimberlite. In the case of large pipes resistivity surveys with different electrode spacings would probably be able to distinguish pipes from weathered bedrock but unfortunately the pipes so far found in Sierra Leone do not exceed 100 metres in diameter and drilling is usually required to investigate the bedrock.

Summary and conclusions

It is clear from the amount of published literature that the magnetic method of prospecting for kimberlite has been most favoured especially in Siberia. It is the only airborne method with which positive results have been obtained and consequently the only method that has been applied over relatively large areas. Kimberlites, are, however, not uniquely magnetic and poor results have been obtained in areas of pre-Cambrian rocks, particularly migmatites.

Gravimetric and resistivity surveys have both had a limited application although these methods have been useful on a local scale.

Geophysics may not be generally applicable to the prospecting for kimberlites but it is, nevertheless, of practical use when applied sensibly under suitable conditions.

Acknowledgments

Acknowledgment is made of the cooperation of the following organizations and persons who kindly supplied data which would not otherwise have been available: the management of Selection Trust Exploration Ltd., Sierra Leone Selection Trust Limited and Williamson Diamonds Limited; Dr. D.J. Mason-Smith of the Overseas Geological Survey of Great Britain and Dr. L.G. Murray of the Anglo-American Corporation of South Africa.

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Exploration for marine placer deposits of diamonds

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Abstract. Marine placer deposits are localized concentrations of transported heavy minerals generally restricted to the inner part of continental shelves off mineralized areas such as ancient shields.

Characteristic of these deposits are: (1) emplacement by the combined effect of winnowing action by waves and transport by longshore currents; (2) enriched zones parallel to shore caused by temporary still-stands in Pleistocene regressive and transgressive movements of the surf-zone; (3) concentrations in topographic lows formed by river beds and surf gullies usually oriented at right angles to the coastline; and (4) association with materials of hydraulically equivalent size such as other heavy minerals and (basal) gravels.

Economical exploration consists of planned sampling traverses utilizing indirect geophysical methods followed by direct sampling in selected areas. Continuous acoustic profiling has been most successful in outlining sediment bodies of thickness suitable for mining purposes and in locating ancient strandlines, topographic traps and promising gravel patches. High definition profilers are preferred to those giving deep penetration because only limited thicknesses of sediments can presently be mined at a profit. On account of the extremely patchy distribution of precious minerals, precise navigation is of great importance for exact relocation. Selected geophysical methods, surveying systems and illustrated case histories are briefly discussed.

Résumé. Les dépôts d'alluvion marine sont des concentrations localisées de minerais lourds charriés, généralement restreintes à la partie interne des plates-formes continentales au large des régions minéralisées comme les anciens boucliers.

Les traits dominants de ces dépôts sont: (1) l'emplacement attribuable à l'effet combiné de l'action de vannage par les vagues et du charriage par les courants qui longent les plages; (2) les zones enrichies parallèles à la rive attribuables aux arrêts temporaires dans les mouvements régressifs et transgressifs du pleistocene dans la zone des brisants; (3) les concentrations dans les lieux topographiques surbaissés formés par les lits de rivières et des ravins attribuables aux brisants ordinairement orientés à angle droit avec la côte; et (4) l'association avec des matériaux de dimensions équivalentes, en termes d'hydraulique, à celles d'autres minéraux lourds et de graviers (de fond).

La recherche économique consiste dans les cheminements d'échantillonage planifié, utilisant des méthodes géophysiques indirectes, suivis d'échantillonage direct dans des régions choisies. Les profils acoustiques ininterrompus ont donné les plus heureux résultats dans le traçage des contours de massifs de sédiments d'épaisseur appropriée aux fins de l'exploitation minière et dans la localisation d'anciennes lignes de grèves, de pièges topographiques et de prometteuses fosses de gravier. Les profileurs à haute définition sont préférés à ceux qui donnent une profondeur pénétration parce qu'une épaisseur limitée seulement des sédiments peut être actuellement exploités avec profit. En raison de la répartition extrêmement inégale des minéraux précieux, une navigation précise s'impose si l'on veut retrouver l'endroit exact. L'auteur présente brièvement des méthodes géophysiques choisies, des systèmes de levés et des cas précis illustrés d'exemples.

Whereas man's concern with mineral exploration and mining dates back at least six millennia, only very recently has he realized that the sea could be used as a source of minerals. Undoubtedly the dangers and complications of marine operations impeded development of marine mining, but once imaginative people dared to break the taboo and embark on sea mining ventures, it was found that mining at sea – besides presenting even more complications than had been anticipated – offered several redeeming advantages over terrestrial mining.

For example, the acquisition of concession rights is generally easier; transportation of bulk material is cheaper; prospecting is greatly facilitated by special, newly developed geophysical techniques which cannot be used on land; and mining can be done with relatively simple equipment and few worries about disposal of tailings.

Probably the earliest marine placer mineral to be mined in quantity was cassiterite, off Malaya and Indonesia, where dredging operations date back several decades. Recent exploration methods and results in this area are discussed by Van Overeem (1960a,b,c). Mining for marine diamonds started off Southwest Africa in 1961 and operations have expanded considerably since that time. A summary of marine diamond mining and other offshore mining methods is given by Wilson (1965b).

This paper deals chiefly with exploration for marine diamonds and is based on the author's experience as a staff geologist of Ocean Science and Engineering from 1963 - 1965 when this company conducted an extensive offshore exploration and evaluation program on behalf of the De Beers Consolidated Mines. Comparison of the few published reports available on marine mining indicates a great similarity in occurrence and exploration methods between marine diamonds and other marine placer deposits. Therefore, it is the author's contention that conclusions made on the basis of studies of marine diamond occurrences can be generalized and applied to all marine placer minerals.

Classification of marine mineral deposits

Marine mineral deposits can be classified in several ways and many types of occurrence are sufficiently similar to terrestrial deposits that they fit the 'classical' genetic classifications of Lindgren (1933) and Bateman (1952). Bateman uses composition as a guide line in the organization of his textbook and separates the minerals into two main categories: metals and nonmetals. Mero (1964), in the first text dealing exclusively with mineral resources of the sea, uses the area of deposition as the chief criterion of classification. He recognizes five marine mineral regions: marine beaches, sea water itself, continental shelves, surficial sediments and the hard rock beneath the surficial sea-floor sediments.

This paper is concerned with marine placer deposits, which consist of heavy minerals, either metallic or nonmetallic, and which may occur in at least two of the five regions Mero discusses. Consequently, marine placer deposits do not fit satisfactorily in classification schemes based either on composition or on area of deposition. However, they are very closely related genetically in that they are all secondary minerals, which means that they have been formed elsewhere and have subsequently been transported for considerable distances as distinct particles. In this respect they differ from many types of other marine mineral deposits, because the bulk of sea-floor deposits has been formed *in situ* by precipitation from various solutions.

This suggests the use of a bipartite genetic classification for marine minerals based on the physical state in which they reached their deposition site. A variety of terms has been suggested for each of the two main categories of deposits and though each of the terms may have slightly different connotations, the essence is whether the mineral (1) was formed in its present location (or close to it) by precipitation, or (2) existed as such in particulate form before and has been transported some considerable distance.

The former category are *primary minerals*: they may be magmatic, metamorphic, hydrothermal, hydrogenous or biogenous depending on type and temperature of the solution from which they precipitated. The lack of transport in particulate form is denoted by such adjectives as: autochthonous, autigenic, (bio-)chemical and dissolved. These minerals include those occurring on land under similar circumstances as well as those characteristic of the marine environment. Examples of typically marine primary minerals – each of which may constitute a potential 'ore' – are manganese nodules and phosphate nodules; calcium carbonate in the form of coral-algal reefs, shell beds and globigerina oozes; certain clays*; silica in diatom and radiolorian oozes; evaporites, and minerals contained in sea water such as magnesium, iodine and bromine.

Secondary minerals are transported physically or mechanically, that is, in the form of distinct particles; they are allochthonous or allogenic, and usually land-derived (terrigenous). Quartz is the most abundant amongst the marine secondary minerals: it is mined for such uses as beach replenishment (Taney, 1965). Other examples are the placer minerals which comprise all minerals of specific gravity exceeding 2.85 and of sufficient durability to become concentrated by the sorting action of rivers, waves and currents.

This paper deals exclusively with the exploration for this last type of secondary minerals, the marine placer deposits.

Marine placer deposits

Because exploration for marine placer deposits is expensive, it should be preceded by preliminary geological studies to suggest favorable areas and eliminate others from further consideration. For example, from the following factors the nearshore area off Southwest Africa appears to be a very favorable prospecting locale for marine diamonds

1. There is a *source* of diamonds inland: diamondiferous kimberlite pipes of Cretaceous age.

*Other clays may be better classified in a third category, namely minerals originally belonging to category (1), primary, or category (2), secondary, which have subsequently undergone significant alteration.

2. There is an obvious *transporting agent* leading to the sea: the Orange River.
3. There are some very effective *concentrating mechanisms*: strong surf and longshore currents.
4. The bedrock forms excellent *sediment traps*: cracks, potholes, drowned riverbeds and bays.
5. Since diamonds have been mined for years from raised beaches along this coast, knowledge of *Pleistocene sea-level changes* suggests the existence of analogous deposits in drowned beaches offshore.

Each of these points will be briefly discussed, but by virtue of their special importance, Pleistocene sea level changes will be dealt with in more detail in the next section.

Source of placer minerals. Many minerals are commonly associated with certain diagnostic rock types. In the case of diamonds, this is ultrabasic kimberlite. By contrast, cassiterite, the chief tin ore, is closely associated with silicic granites (Van Overeem, 1960b; Beckmann, *et al*., 1962). Occurrences of primary gold show good correlation with intrusive rocks.

In many cases such diagnostic rocks characterize the mineralized areas of exposed ancient shields, for example, in Canada, Scandinavia and South Africa. These regions are intensively mined and obviously may constitute good sources of placer minerals. The placer deposits themselves are almost exclusively restricted to late Tertiary and Quaternary sediments. Typical areas of actual and potential marine placer deposits are shown in Figure 1.

High relief of the source area and especially rejuvenation will enhance erosion of source rocks. It requires removal of vast thicknesses of rocks to provide worthwhile quantities of placer minerals, especially if the original grade is low.

Although a certain amount of submarine erosion does take place (Dill, 1964), it is unlikely that marine diamonds were derived from erosion of submarine kimberlite pipes. This alternative hypothesis on the origin of marine diamonds was based mainly on the widespread occurrence of post-Karroo ultrabasic pipes. Although submarine pipes ranked high among geophysical exploration targets off Southwest Africa, none has been found to date.

Transporting agents. With the exception of minor contributions by cliff erosion, and by gravity, wind and glacier action, rivers are the only significant agents introducing placer minerals into the sea.

Although the rate of transport of heavy minerals in rivers is variable, it is in general extremely slow. Because of their higher specific gravity, the heavy minerals will be trapped in riffles, potholes or in the inner bends of meanders, thus forming river placers. According to Van Overeem (1960b, p. 461), discussing cassiterite mining results off Billiton, Indonesia: . . . "gullies contain the largest amount of tin. They are especially rich in the concave undercut parts of their bends. In these places the rivers have often excavated local depressions in their beds."

After a placer mineral has been trapped in a topographic low, it may take thousands of years before rejuvenation or a change in river course carries the mineral farther seaward. If the total travel path is long, a certain amount of concentration will take place, because the placer minerals are more resistant to attrition than other minerals of the bed load.

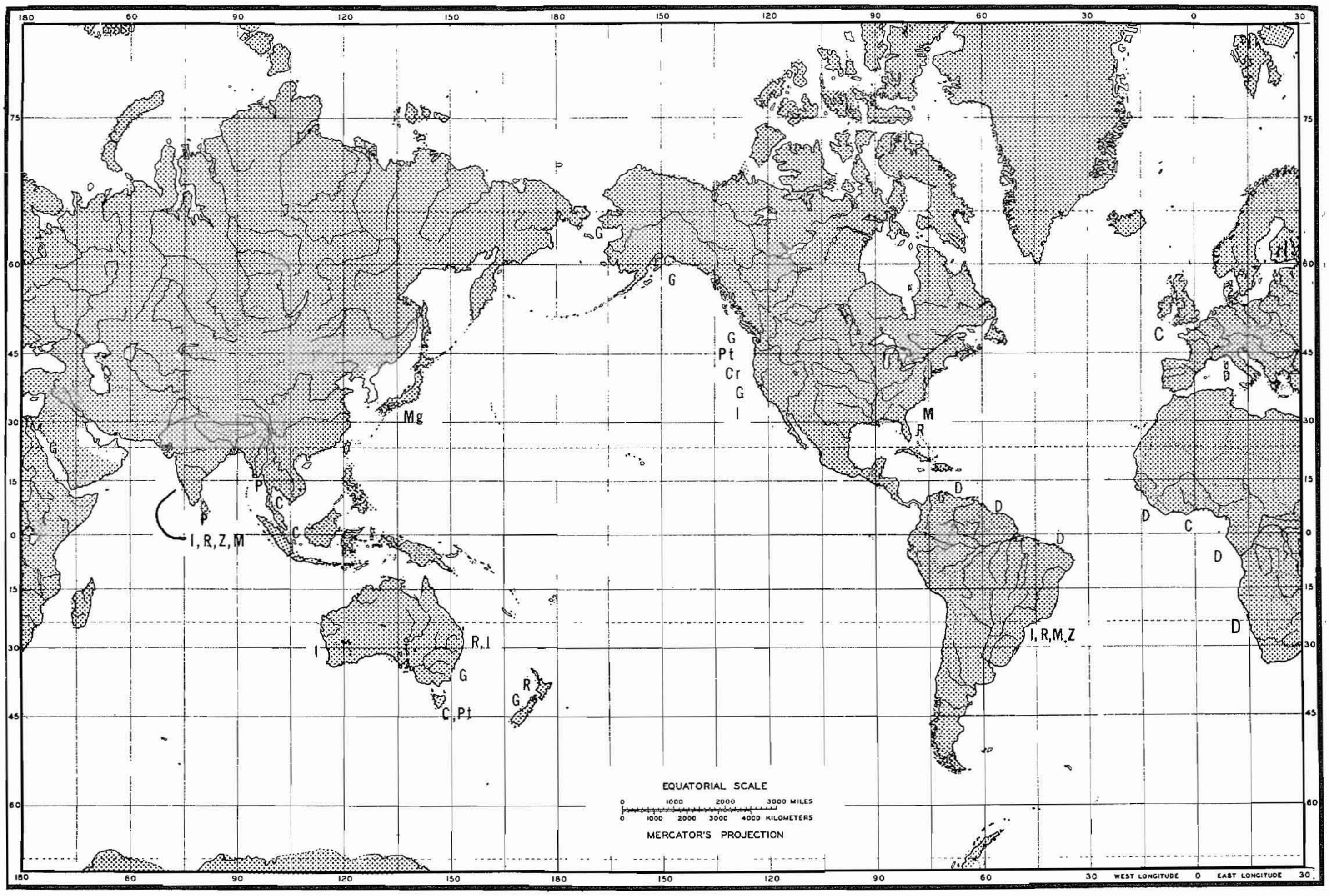


Figure 1. Actual and potential marine placer deposits. C. cassiterite, Cr. chromite, D. diamonds, G. gold, I. ilmenite, M. monazite, Mg. magnetite, P. precious stones, Pt. platinum, R. rutile, Z. zircon.

The principal marine transporting agents are surf and currents; the combined transport and concentrating action in the surf zone is discussed in the following paragraphs. One special type of marine transporting agent deserves brief mention, because it undoubtedly carries some placer minerals out to deep waters. This is the mass movement of marine sediments effected by turbidity or density currents. Specifically, sediments moving along shore may be intercepted in submarine canyon heads and carried out into deeper water by mass movement (Shepard, 1951a,b; Chamberlin, 1960). This transport mechanism suggests possible locations of placer minerals where submarine canyons debouch on the deep sea floor. Mining of this 'sink' for placer minerals is beyond the scope of present techniques.

Concentrating mechanisms. After any mechanical stirring of a mass of sediment, the heaviest particles will settle first and fill the low spots. The net downward movement of heavy minerals will, therefore, be enhanced by frequent repetition of a cycle consisting of stirring followed by a period of rest, during which some of the particles can settle.

Thus sea waves, which have a typical period around 8 seconds, cause a very efficient jigging action on shallow sea-floor sediments in which heavy minerals, together with coarser sizes of minerals of average specific gravity, will collect at the bottom of the stirred-up sediment column.

If a current, even a very weak one, is superposed on this up-and-down motion, particles with average specific gravity will be picked up earlier, travel faster, and settle later than those with high specific gravity, resulting in horizontal, in addition to vertical, separation.

Combination of these two effects – waves and longshore currents – makes the surf zone the locus of one of the best natural concentrators. The efficiency of concentration depends chiefly on the wave height and on the angle between the coastline and incident wave crests.

In Southwest Africa, average breaker height exceeds 6 feet, and longshore currents of 3 knots have been measured. The considerable alongshore movement of boulders and cobbles derived from coastal mining dumps suggests that the major movement of diamonds may take place in the surf zone. Furthermore, the fact that the average size of diamonds found in raised terraces decreases over distances of tens of miles north and south away from the Orange River suggests not only that this river is the source, but it also attests to the effectiveness of longshore currents.

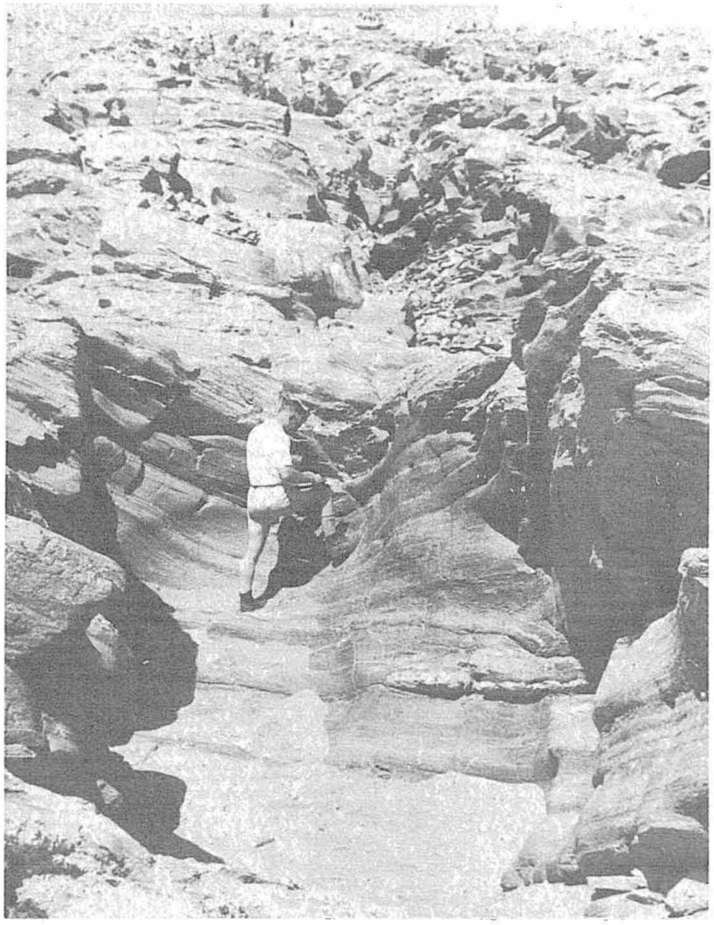


Figure 2. Gullies in raised marine terraces, north of the Orange River, Southwest Africa (photo Allen McKinzie).

The effects of the mechanisms discussed above are not restricted to diamonds, but also apply to any other placer minerals.

Sediment traps. Heavy minerals tend to collect in topographic depressions; more generally, sediments will settle wherever currents become too weak to transport them. Places on the sea floor which obstruct current flow will, therefore, act as sediment traps. Examples of such traps are embayments, drowned river beds, submarine cliffs, potholes and surf gullies (Wright, 1964; Oostdam, 1964).

Off Southwest Africa large areas of bedrock consist of schists, which form considerable micro relief. Mining of similar areas on land (Figure 2) demonstrated that diamonds and gravel are relatively more abundant within depressions than between. An identical observation was made by Van Overeem (1960b) regarding the occurrence of cassiterite off Billiton, Indonesia.

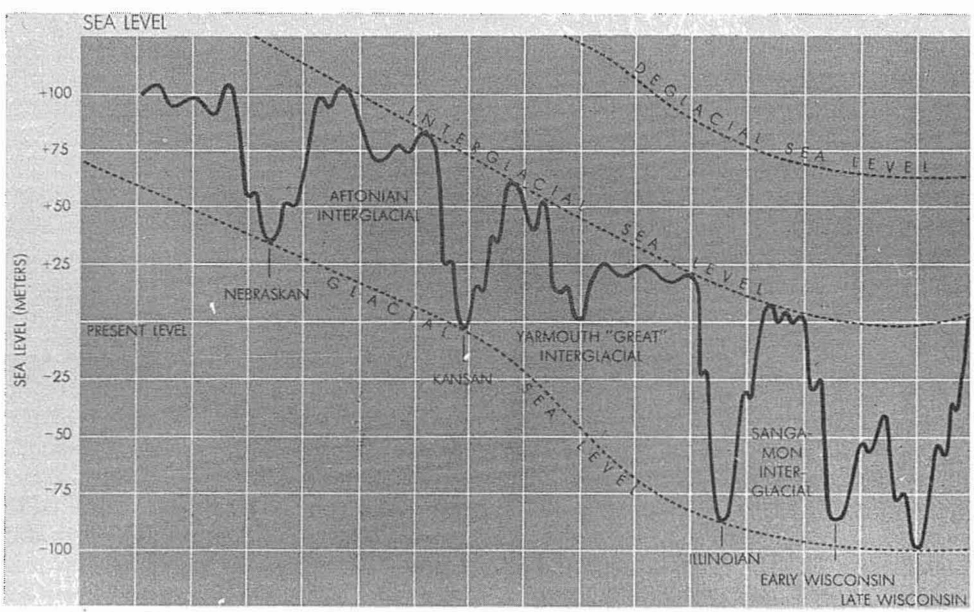
Influence of Pleistocene sea level changes on the distribution of marine placer deposits

In the preceding section we discussed how the processes at work in the surf zone concentrate placer minerals in topographic depressions. The present-day surf zone occupies a relatively narrow band and has a small depth range so that it almost forms a linear feature. In the recent geological past, however, the surf zone has been actively moving now landward, then seaward, in a series of transgressions and regressions of the sea, thus adding a second and third dimension to the working scope of the surf.

During the glacial ages, growth of the polar ice masses caused the withdrawal of water from the oceans, and sea level was lowered. In turn, this water was released by melting of the ice during interglacial ages with a resulting rise in sea level.

The amplitude of these changes amounts to several hundred feet and is illustrated in Figure 3, which shows the four major transgressions and regressions, and the approximate relation between present-day sea level and that at any time during the last 400,000 years. It should be pointed out that there is no agreement yet about the exact positions of the eustatic sea level.

Figure 3. Pleistocene sea-level changes (after Fairbridge, 1961).



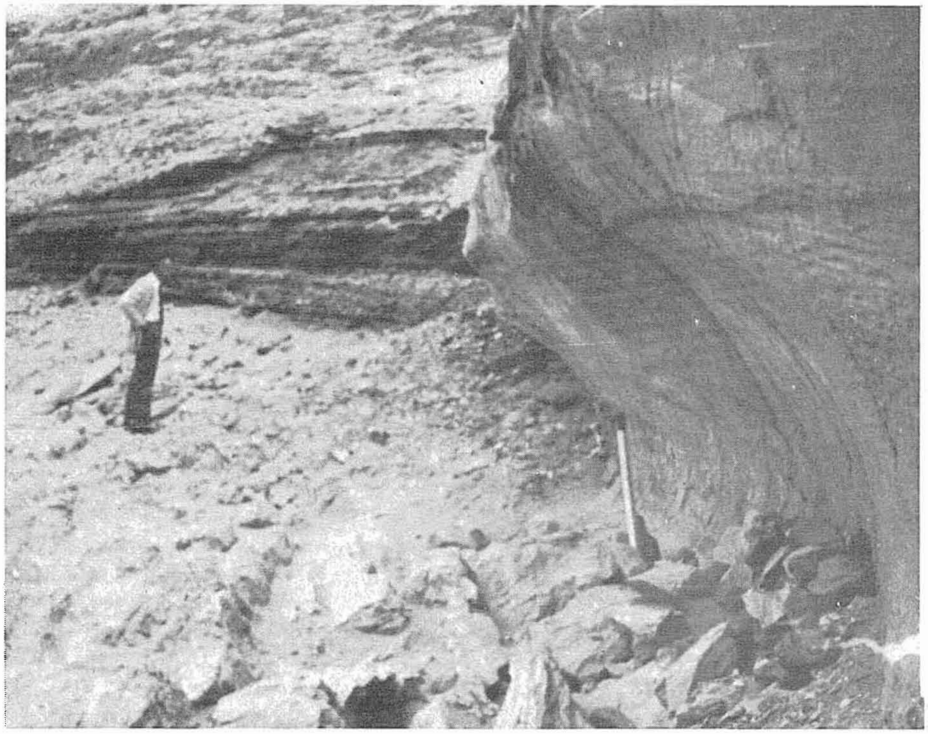


Figure 4. Surf-notches at top of raised marine terrace, north of the Orange River, Southwest Africa.

The interested reader is referred to articles by Ewing and Donn (1956), Curray (1960, 1961) and Fairbridge (1960, 1961) for detailed discussion on this subject.

The importance of Pleistocene sea-level changes to the distribution of marine placer deposits cannot be overemphasized. The effect of a transgressing surf zone has been aptly compared to the action of a bulldozer (Dietz, 1963). Most of the beach materials will be swept upward and inland, but many of the placer minerals may be left behind in protected depressions, where they may later be covered by marine deposits.

Any halt in transgression of the sea may cause development of a terrace or beach, with or without sea cliff. In turn, that beach or the surf gullies cut in the terrace may become loci of new placer deposits. The chief factors which determine the degree of coastal modification are: (a) the length of *time* the sea level remained at essentially the same location, (b) the *energy level*, that is, the effective power expended by waves and currents, and (c) the *materials* involved, mainly in terms of the resistance of the rocks to erosion, and the quantity as well as quality of the sediments present.

When the sea recedes, terraces and beaches are left exposed on land, where they may subsequently be covered by thick terrestrial deposits. Such raised beaches, with characteristic features as wave-cut cliffs, surf notches (Figure 4), sea stacks and basal gravels are presently mined for diamonds along the coast of Southwest Africa. In addition, a regressive sea causes lowering of base level, with attendant increase in erosion and in supply of sediments to the sea. The effect of temporary halts in a regression is identical to that of a transgression, as discussed above.

Alternation of regressions and transgressions greatly complicates the geology of coastal regions and undoubtedly influences the distribution of placer deposits. This is illustrated by the fact that the average size of diamonds along the African coast decreases from the upper raised terrace to the submerged deposits mined at a depth of about 50 feet. With the exception of the upper raised terrace and the lowest submerged beach, all terraces have been reworked at least once. In connection with sea-level changes and reworking of sediments, Van Overeem reports that off Billiton the major concentration of cassiterite is close to bedrock and that overlying transgressive sediments are usually low-grade and always contain very fine grained cassiterite (1960b, p. 462). Also, the lowest marine terrace off this island (depth below sea level, 90 feet) consists almost entirely of bare bedrock with the exception of some drowned river beds. The latter are completely filled with predominantly fresh-water deposits, to such extent that they do not show on bathymetric maps (1960a, p. 455).

Because these sea-level changes have been world-wide, similar effects can be expected for all marine placer deposits. In addition, geologic evidence of local diastrophic movements should be carefully studied for clues to the possible distribution of placer deposits: it may not be a coincidence that, along the coast of Southwest Africa, a very rich marine diamond deposit was discovered where a down-warped raised terrace reached sea level.

Exploration program for marine placer deposits

A good marine exploration program consists of a well planned sequence of steps designed to successively narrow down the territory to be investigated by rejecting undesirable areas until the final target areas are defined in which an (expensive) mining vessel can be put to work with a minimal risk of loss.

An ideal procedure for a marine exploration program is schematically presented in Table I, and the following remarks should be read after examination of this outline. If the purpose of the exploration is an evaluation of the entire territory, the program will differ only in the emphasis on some of the steps.

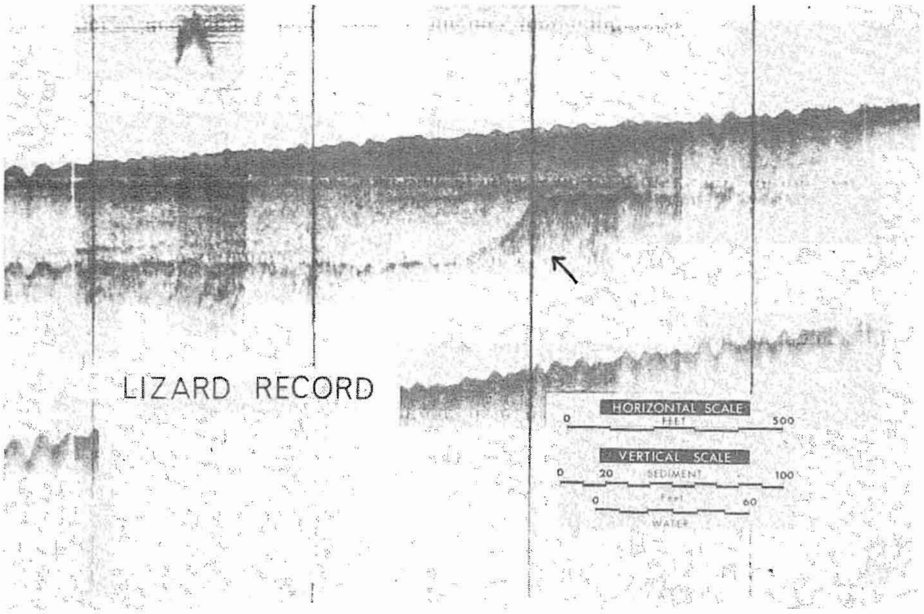


Figure 5. "Lizard" record showing buried seacliff, off Southwest Africa.

1. The selection of a sampling territory will depend primarily on direct or indirect geological evidence that the area is a potential mine. Direct evidence consists of actual samples of placer minerals with a sufficiently high grade to warrant further investigation. Indirect evidence may consist of geological studies indicating the presence of a source of the placer mineral, transporting agents, effective concentrating mechanisms, and sediment traps in the bedrock. Almost unmistakable indirect evidence is provided whenever successful mining is done on nearby raised terraces.

Other obvious controlling factors in the selection of a sampling region are whether mining concessions can be obtained, and whether funds and facilities will be available, first for test-mining and later for full-scale mining operations.

Table I. Schematic outline of marine exploration program.

1. Selection of Sampling Area
2. Definition of Target Areas
3. Choice of Instrumentation, Vessel and Personnel
4. Determination of Sampling Design
5. Reconnaissance Survey
6. Interpretation of Results and Definition of New Targets
7. Detailed Geophysical Surveys
8. Sampling of Selected Sites
9. Test-Mining Operations
10. Evaluation

2. The definition of target areas is in first instance determined by the available mining techniques. Mining in waters below a certain water depth or in sediments more than a critical thickness may be impossible or unprofitable, so that initial target areas should be those that are physically accessible. Within those areas, geophysical records may show certain desirable features which are generally associated with placer minerals (Figures 5, 6 and 7). Unfortunately, as geophysical records never seem to show the placer minerals themselves (with the possible exception of magnetite), the search must be based on associated features.

Continuous seismic profilers may display, for example, drowned beaches or terraces, sea cliffs (Figure 5), drowned river beds or surf gullies, potholes and other micro-relief, or basal gravels (Figure 6) (c.f. Van Overeem, 1960b, p. 461). A

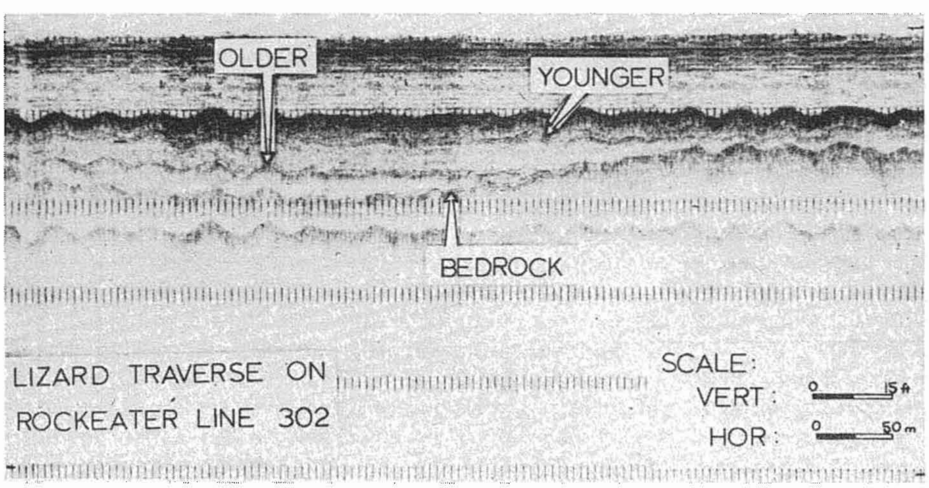
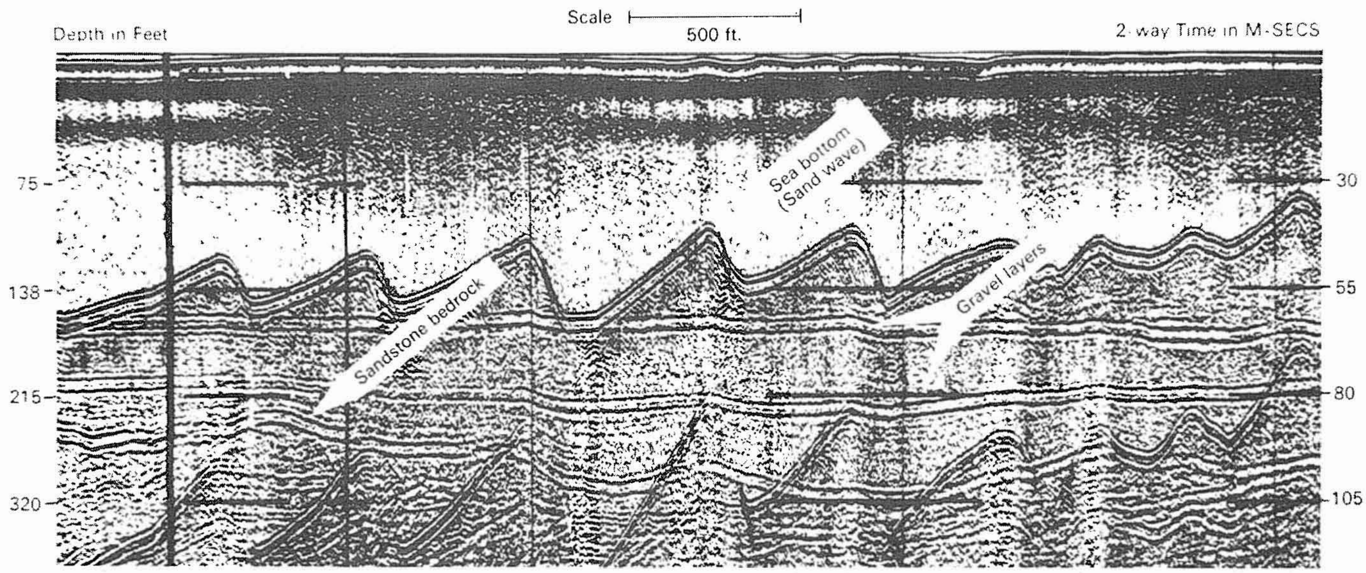
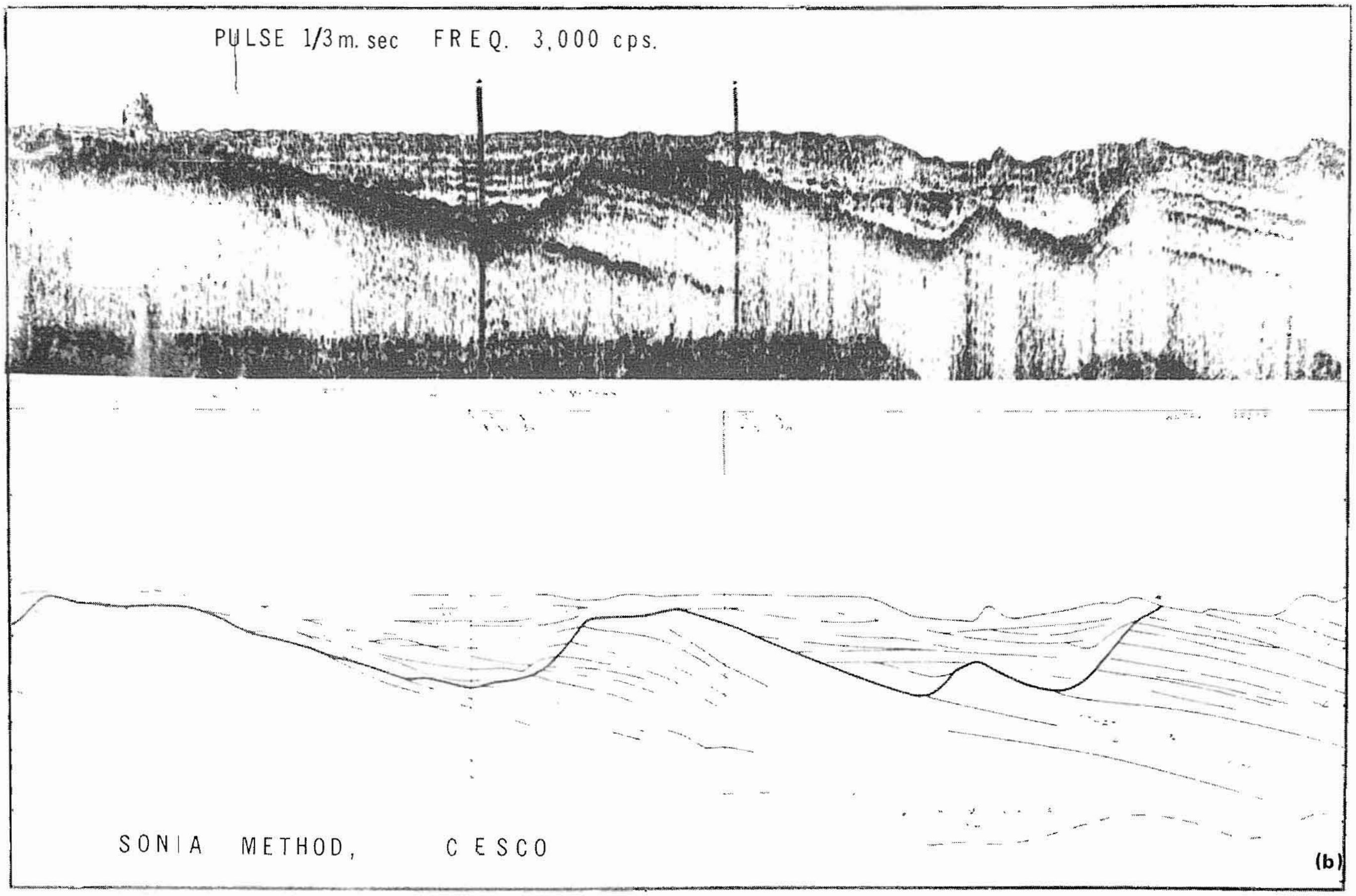


Figure 6. "Lizard" record showing basal gravel layer (marked "older") overlying bedrock, off Southwest Africa.



Hydrosonde System Mark 2A with spark source, Minas Basin, Bay of Fundy.
Record shows striking example of sand waves of amplitude up to 50 feet and period up to 500 feet. Two gravel horizons lie from 0-50 feet below bottom, the upper one forming bottom at one sand-wave trough and at left of record. Sandstone bedrock lies a maximum of 130 feet below main sea bottom.

(a)



(b)

Figure 7. Examples of high resolution records suitable for detailed geophysical exploration in connection with marine placer mining. (a) (Bay of Fundy) Hydrosonde Mark 2A, Huntec, Toronto. (b) (Dover Strait, two filled-in pockets on Cretaceous bedrock) Sonia Recorder, Cesco, The Hague, 1965.

magnetometer will record the presence of concentrations of magnetite, which is an associate mineral of gold and platinum. A gravity meter may pick up such anomalies as submerged kimberlite pipes, possible sources of diamonds. These and similar occurrences constitute desirable targets for detailed exploration, because they may possibly be mined at a profit.

3. The choice of instrumentation, vessel and personnel depends first on the budget for the exploration program. Minimum instrumentation should definitely include (1) a continuous seismic profiler, (2) one or more sampling devices which can penetrate into bedrock and take controlled samples, and (3) proper navigation instruments, preferably including both electronic and optical types. In addition, the use of a magnetometer and a gravimeter is recommended in conjunction with the seismic profiler.

If time is an important factor, three or more ships may operate simultaneously in the exploration program: one medium-sized vessel to perform the reconnaissance survey, one small vessel to do the detailed geophysical survey and another ship to take actual core or drill samples. For several reasons, the latter two vessels should work close together; one reason is that shore-party support can be minimized.

In the final steps of the exploration program, the use of a mining vessel will be required. To provide the best possible evaluation, this barge should be identical to the units which will be used for actual mining operations.

Of paramount importance to successful operations are various supporting vessels, aircraft and vehicles as well as a perfectly functioning communication network.

Finally, the most important selection of all is that of reliable and competent personnel, capable of acting as a team and willing to work more than 8 hours a day under adverse conditions whenever necessary.

4. The sampling design involves both the layout of the geophysical tracks and the selection of sites for actual sediment sampling. Since time and money are usually limited it is of paramount importance to discuss the sampling procedures with a statistician – preferably one who knows how to compromise between management and marine operators. This should be done very early, not at the end of a program when a vast amount of data has already been collected. The critical selection of sampling programs – most likely variations on stratified random sampling procedures – are especially important in the initial phases of the program.

5. The intention of the reconnaissance survey is the rapid inspection of an extensive region. If at all feasible, the survey vessel should concurrently use a fathometer, a continuous seismic profiler, a magnetometer and a gravity meter. In addition, navigational fixes should be provided at least once every 5 minutes. To save time, collection of sediment samples should be limited to the bare minimum at this stage. 'Feedback' of sample analyses to the statistician will enable translation of this vague term into an actual minimum number of samples required.

6. Records of the reconnaissance survey should be monitored continuously while they appear, and preliminary mapping should be done early so that the geologist in charge can judiciously modify the original program if desired. The semifinal interpretation of the records should lead to the outlining of targets for the detailed survey.

7 and 8. In the detailed survey, good resolution of the geophysical records is more important than deep penetration. Individual layers as well as bedrock relief of less than 2 feet should be clearly distinguishable on the records. Positioning should be of comparable accuracy, preferably within half a ship's length. Sediment sampling methods should be selected on the basis of their suitability for quantitative evaluation of the deposit. Specifically, they should be capable of complete penetration to and preferably into bedrock, since placer minerals will be chiefly concentrated there. No single satisfactory sampling method has been adapted for use at sea at this time, so that two or more devices used in conjunction are generally required. A drill with an airlift system, for example, will pick up all material and even grind into bedrock, but slumping will cause some contamination. To assess the amount of this contamination, various corers should be used because they will show the layering of the sediments and thus allow adjustments to be made. This aspect of marine-sampling operations needs considerable study as well as development of new techniques.

If two vessels are available, it will be a great advantage to closely integrate the detailed geophysical survey and the sediment sampling. The benefit of taking cores or drill samples at the exact site for which geophysical records have just been run is readily apparent. The 'feedback' provided by inspection of cores aids tremendously in the interpretation of geophysical records.

9. An even better feedback can be realized by test-mining of a carefully measured area which has just been sampled. This will not only provide a measure of the efficiency of the sampling tool and in this way improve the evaluation of the deposit, but it will also help in the interpretation of the geophysical records. Some excellent examples of correlation between mining, core-sampling and geophysical records are presented by Van Overeem (1960a). Relations between cores and seismic profilers are given by McClure, *et al.* (1958, Figure 9) and Beckmann *et al.* (1959).*

10. Evaluation of marine placer deposits is a tricky subject, especially in the case of marine diamonds. Because of their high value and scarcity, many or large samples may have to be processed to yield just one stone. In this respect there is a profound difference between diamond and gold placers. Gold may occur in very finely divided form and thus will allow determination of a finite grade, however low, for many samples. By contrast, diamonds do not occur as 'dust', so that many samples will prove barren and a few may show a 'jackpot' effect. This extremely skewed distribution pattern of diamonds makes evaluation extremely difficult.

To the author's knowledge, there are no papers dealing specifically with the evaluation of marine placer deposits. Some benefit may be derived from perusal of the following references on mine evaluation: Dorenfeld (1964); Krige (1951); Matheron (1963); Rodionov (1963); Sichel (1952); Sichel and Rowland (1961); and de Wijs (1951, 1953).

*No effort is made to discuss the many types of sampling devices and ancillary equipment. A few selected references are: Alpine (1966); Bader and Paquette (1955); Hough (1939); Hvorslev and Stetson (1946); Isaacs and Iselin (1952); Kudinov (1957); Kullenberg (1947, 1955); Ocean Industry (1966); Rechnitzer (1966, 1967); Taney (1965); and Yules and Edgerton (1964).

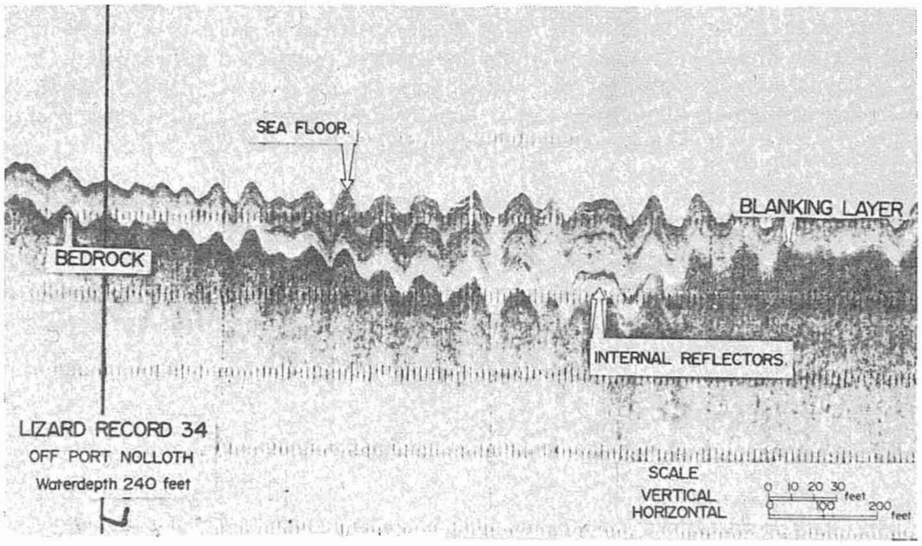


Figure 8. Example of "Acoustic Blanking Layer" on "Lizard" record, caused by presence of gases in sediments.

Geophysical methods and instruments

For extensive marine surveys, only those geophysical methods are suitable which can be made continuously while the ship is underway. There are three types of such instrument systems available: gravity meters, magnetometers, and seismic profilers. Each system measures and records variations in some physical property of the sediments or bedrock. Since these instruments and methods are described in detail in the State of the Art section of this volume – gravity methods by W.E. Strange, magnetic methods by P.J. Hood and seismic methods by G.D. Hobson – they will just be touched on here.

The main problem in gravity measurements at sea is the requirement to measure changes in the gravitational attraction on a suspended beam which are of the order of 5 milligals – whereas surface ships are exposed to wave accelerations which often exceed 10,000 milligals. Detailed descriptions of the LaCoste-Romberg surface-ship gravity meter and the Graf sea gravimeter which are used for this purpose are given by Worzel and Harrison (1963).

The disadvantage of gravimeters in general is that results are often open to more than one interpretation and therefore, concurrent use of two or more geophysical systems is highly recommended.

Three types of instruments are used to measure the total magnetic fieldstrength at sea: fluxgate, proton-precession, and optically pumped and monitored magnetometers. Partly because it does not require calibration, the proton-precession magnetometer is used most. The sensitivity and absolute accuracy of the instrument is ± 1 gamma, whereas the Earth's field averages 50,000 gammas. The more recently developed optically pumped rubidium, cesium and helium magnetometers have sensitivities around 0.1 gamma.

The seismic profiler is the most effective method and a large variety of systems is available on the market. Although the continuous profiler can well be used by itself, it is advantageous to combine it with other systems.

Since the thickness of any sediment layer is proportional to the time interval between the arrivals of waves reflected from the top and the bottom of that layer, the thickness can be accurately measured once the velocity of sound in that particular layer is known. This velocity can be determined from actual samples of the sediment, or by seismic refraction techniques, for which the same profiler can be used (McGuinness, *et al.*, 1962). For general purposes, mean sound velocities of 4800 or 4890 ft/sec are used for sea water, and 5500 ft/sec for unconsolidated sediments.

In contrast to the deep penetration seismic profiles required in the oil industry, the demand of present-day marine-mining operations is for geophysical records showing good resolution. Resolution improves with increasing sound frequency, with a theoretical maximum around one tenth of the wave length. For example, a sound wave with a frequency of 300 cps traveling through sediments with a characteristic velocity of 6000 ft/sec will have a wave length of 20 feet and a resolution of 2 feet.

Navigation systems

Improvement of vertical control by increased definition of geophysical records is of little use if horizontal control is inadequate. Therefore, positioning should become more precise and accurate with successive steps in an exploration program. Since detailed surveying depends mainly on the quality of the navigation system employed, it is incorrect to space survey lines closer than (or even close to) the mean radius of error of the system.

Positioning may be done by optical or by electronic methods. The development of electronic navigation has been greatly emphasized and the standard survey methods of the pre-World War II era apparently tend to be ridiculed. Based on the author's experience, however, there seems to be an inverse relationship between the degree of sophistication of a newly developed system and its reliability. Frequently old-fashioned methods may save hours of down-time when elaborate electronic systems break down or give erratic results. This suggests the redundancy concept, which means carrying at least two complete electronic navigation systems – including well trained electronic technicians – as well as a standard complement of sextants on board and two or three theodolites or transits with the shore party.

Because most placer deposits are relatively close inshore, both visual and electronic positioning methods can be used. Celestial navigation will probably be limited to the first stage of the exploration program, when exact positioning is not too important. In some cases it may be advantageous to lay accurately positioned buoys and use them as markers for further navigation.

The importance of accurately locating and identifying shore beacons used for navigation cannot be emphasized too much. For detailed surveys in remote areas setting a new network of beacons is highly recommended, rather than using doubtful existing ones.

Optical methods. Pelorus bearings from a magnetic or gyro compass to prominent points on shore are only useful in preliminary surveys. For detailed work, two sextants can be used simultaneously to shoot horizontal angles between three markers. Plotting is done by station pointer or three-arm protractor; plotting the course immediately is recommended, so that the helmsman can be instructed to adjust his heading when necessary. In cases where range poles are set up, only one sextant reading need be made.

More accurate positioning can be achieved by using two shore-based theodolites. In this case, continuous radio contact should be possible between ship and shore party. Best procedure is for the ship navigator to give a countdown every 3 or 5 minutes, after which the theodolite men in turn report their reading.

Table II. Survey of electronic positioning systems (after Bowditch, 1958 and Laurila, 1963).

System	Company or Agency	Stations: Ship	Stations: Shore	Type of Measurement	Frequency	Range	Accuracy	Remarks
Consol		Ordinary medium-frequency receiver	3 transmitters	Direction, by counting number of dots and dashes between equisignals of 30 or 60 seconds.	250 - 350 kc	Up to 1200 miles by night over water	Insufficient for accurate surveys	Although this is in principle a hyperbolic system, the use of a short baseline makes this system essentially directional
Radar								
Primary		Transmitter	Natural, passive reflectors	Primarily distance, but in addition, approx. direction can be obtained; measures roundtrip travel time		Min. 50 yards. Max. is range of radar-horizon, which is equal to visible horizon +15%		Gives map-like presentation on radar scope
Secondary		Transmitter	3 transponder beacons	Same	Several bands, from 225 to 56,000 mc	Function of height of shipboard and shore beacon antennas	150 yards	Also see Marine Geophysical International (1966)
Shoran (Short-range navigation)	Offshore Navigation Co.	Transmitter	1 receiver 1 transmitter	Distance, by pulse-type circular system	90 and 300 mc	50 - 75 miles	Standard error of one line; measurement ±7 meters	
Hiran (High accurate Shoran)	Offshore Navigation Co.	Transmitter	1 receiver 1 transmitter	Distance, by pulse-type circular system	230 - 310 mc or 90 mc	50 - 75 miles	Standard error of one line measurement ±2 meters	Modification of Shoran
EPI (Electronic Position Indicator)	Coast & Geodetic Survey; Litton Systems	Transmitter	2 transponders	Time-lapse between transmitted and received pulse	1850 kc	400 miles	±40 meters	Can only be used by one vessel at a time
Loran (Long Range Navigation)		1 passive receiver	3 or more transmitters	Difference in distance, by measuring time between reception of pulse-modulated synchronized signals from transmitters				Can be used by many ships simultaneously; shipboard problems are proper identification of waves and correct matching of signals on scope
A (standard)	RCA Sperry				2 mc	500 - 700 miles over water; in excess of 1500 miles if using skywave	Few thousand feet	

Table II. Survey of electronic positioning systems (concluded).

Systems	Company or Agency	Stations		Type of Measurement	Frequency	Range	Accuracy	Remarks
		Ship	Shore					
B		1 receiver	3 or more transmitters	Difference in distance by phase comparison	2 mc	300 miles	±15 to ±100 meters	
C	Sperry Gyroscope Co.	1 receiver	3 or more transmitters	Difference in distance, by continuous wave-phase comparison	100 kc	1700 miles over water; up to 4000 miles using sky-wave	±15 to ±100 meters	Allows extension of baseline up to 1000 miles, which improves relative accuracy of points far from beacons
Decca	Decca Navigator Co.	1 receiver	3 ground-stations (master, green slave and red slave)	Difference in distance, by continuous wave-phase comparison	Resp. 88,516 c 118,021 c and 132,774 c	300 miles	±4 meters on baseline and 4 meters multiplied by cosec (1/2α) anywhere else (α is subtended angle at which baseline can be seen from given point)	Can be used by many ships simultaneously. For errors, see discussion in Maries and Beckmann (1961, p. 272 - 3)
Hi-Fix		1 receiver	3 stations	Distance or difference in distance by phase comparison	2 mc	5 - 35 miles	±3 ft. on baseline	Can use either circular or hyperbolic geometry; shipboard display on counter-type indicators circular Hi-Fix is single user; hyperbolic Hi-Fix multi-user
Lorac (Long Range Accuracy)	Seismograph Service Corp.	1 receiver	3 ground-stations	Difference in distance by phase comparison of beat frequencies	1700 - 2500 kc transmission frequency plus 100 - 600 c audio frequency	200 miles	3 ft. along baseline	Can be used by several ships simultaneously. Since no lane identification is provided, ship must start from a known position
Hyperbolic Raydist (five types N)	Hastings Instrument Co.	1 receiver	3 transmitters	Difference in distance by heterodyne continuous-wave system	1,600 - 2,500 kc, carrier freq. plus 200 - 400 c audio freq.	250 miles	25 ft. at 50 miles	Can be used by several ships simultaneously. Since no lane identification is provided, ship must start from a known position
DM		1 receiver	2 ground-stations				±2 meters on baseline	One ground station generates circular pattern, the other hyperbolic pattern; only one vessel at a time can use Raydist DM; portable system
Hydrodist MRB 2	Telluro-meter (Pty), Ltd.	2 master units	2 remote units	Distance expressed in time differences of millimicro-seconds	2800 to 3200 mc, carrier frequency; modulation frequencies approx. 1.4 mc	40 kms	±1.5 meters	Has built-in velocity based on refractive index of 1.000330; shipboard display on counter-type indicators; only one ship at a time

Use of optical methods obviously depends on weather conditions. Although visual surveying is commonly restricted to daytime use, it can also be done by night. In fact, it is often easier for a theodolite man to sight on a light.

Electronic navigation systems. In contrast to the optical positioning methods which involve measurements of angles, or triangulation, most electronic navigation systems work on the principle of trilateration, that is, by measuring distances. Exceptions are the measurement of directions by radio direction finders and consol, and measurement of speed in such essentially dead-reckoning systems as Doppler and inertial navigation. Since these systems have limited use in detailed surveying, they will not be discussed: details are given in Bowditch (1958). Use of laser and maser beams and of satellites for navigation purposes is under active development, but such systems are presently too expensive and not generally available.

There are two basic methods to measure the distance between a ship and certain (passive) reflectors or (active) transponder beacons: it can be calculated directly from the round-trip travel time of an electromagnetic wave transmitted by the ship, or it can be obtained indirectly by measuring the difference in distance between the ship and three or more transmitting shore stations.

Examples of the direct *distance measuring systems* are two variations of radar: primary radar, involving reflections from a passive reflector (for example, land masses, buildings, other vessels), and secondary radar, in which a transponder beacon is triggered by the very short pulse transmitted by the ship, and responds by emitting its own signal. Shoran, Hiran and Electronic Position Indicator (Table II) are systems which work on the same principle as secondary radar. Raydist and Decca are variations in which the distance is measured as a function of the phase difference between signals. This requires transmitters and receivers both on the ship and on the shore station. The above systems have in common that each shore beacon generates a position circle; commonly two of these circles suffice to plot a ship's position, although three beacons are preferred.

In the *distance-difference measuring systems*, on the other hand, a minimum of three shore stations are required to obtain a position, but no active transmission of the ship is required. Because points of equal difference in distance to two fixed points lie on hyperbolas, these systems are known as hyperbolic systems. Each two shore stations generate a family of hyperbolic lines of position which can be preplotted on maps for each configuration of beacons. If a chain of beacons is set up, three beacons will allow the ship's position to be plotted at the intersection of two hyperbolas. Accuracy of the position depends, among other things, on the length of the baseline, the spacing of successive hyperbolas, and the subtended angle. It is expressed in terms of the area of the error parallelogram. The often-used term 'lane' refers to the distance along the baseline between two adjacent hyperbolas; in phase-difference systems this distance equals one half wave length.

Hyperbolic systems include Decca, Loran, Hyperbolic Raydist and Sofar; the latter system uses sound waves instead of electromagnetic waves. Details of commonly used systems are given in Table II, which is mainly based on data from Bowditch (1958) and Laurila (1963). Rapid developments in the field of electronic navigation make it advisable to request latest information directly from manufacturers.

Case histories

For proprietary reasons, very few case histories are available of marine placer exploration and mining. This is regrettable, because much could be learned from type records and case histories without needing to know the jealously guarded exact location of their site of origin.

Some of the earliest and most detailed case histories of offshore tin-mining operations in Indonesia appear in three articles by Van Overeem (1960a,b,c). A brief article on geophysical exploration off Thailand, also for tin, was published by Beckmann, *et al.* (1962) of Alpine Geophysical Associates. Officers of this company, as well as of Edgerton, Germeshausen and Grier, have written numerous case histories on marine geophysical prospecting, though not specifically on placer exploration.

Ocean Science and Engineering's prospecting program off south and southwest Africa involved the use of several geophysical systems. In the initial exploration during 1963/4, a Sparker was used to outline sediment bodies less than 20 feet thick, because this was considered the economic mining cut-off thickness. Preliminary lines averaging 6 miles long were run perpendicular to the coast at 1-mile intervals, interspersed with several lines up to 40 miles offshore. The exploration territory extended approximately 700 miles from the Olifants River, South Africa, to a point just south of Walvis Bay, a South African enclave in southwest Africa. Navigation was done by a modification of Decca radar using three or more shore beacons (Marine Geophysical, 1966).

Subsequently, during 1964/5, detailed geophysical surveys were run at 200-meter spacing in the primary target areas defined by the Sparker. During this phase, Ocean Science's specially designed high-definition Lizard profiler was used in conjunction with the drilling operations of the sampling ship *Rockeater*. Positioning was effected by a prototype Hydrofix system and by shore-based theodolites, using helicopters to transport the shore party from one beacon to the next in the inaccessible Namib Desert. Because of the high antennas required for the Hydrofix, this system offered some problems (which have reportedly been remedied since). We therefore had to rely on visual fixes. Although the Namib coast has a bad reputation for weather, with haze reported for 200 days per year, the amount of time lost due to bad visibility was surprisingly small. Even in dense fogs one could often get a brief glimpse of the ship and during such time an experienced theodolite man could manage to get a shot in.

For detailed work around the mining barges, the Marine Diamond Corporation briefly used a Sonoprobe system. Presently the company is using a high-definition boomer for all its geophysical exploration work. Positioning of mining barges is done by Hydrodist.

In determining the specific features associated with diamonds we were guided by the experience of geologists and mining engineers who had been actively engaged for years in diamond prospecting and mining operations on shore. Intensive studies of the modes of occurrence of diamonds mined from the raised marine terraces north of the Orange River (Stocken, 1962) proved of great interest because they undoubtedly apply not only to the distribution of submerged placer deposits, but of all other placer minerals. Other useful publications are by Reuning (1931), Dutoit (1954) and Hallam (1959).

The decision came easy to look at geophysical records for structures analogous to the ones which, on land, showed good correlation with diamonds. Such analogies include the following:

1. Associations of heavy minerals with basal gravel and conglomerates on land suggested a search for reflections from gravel layers on seismic profiles. An example of a distinct basal gravel layer is shown on the Lizard record in Figure 6.

2. On land, sea caves are a sure sign of the upper part of a raised terrace (Figure 4). The detection of marine terraces may be more difficult, but is facilitated greatly if successive survey lines keep crossing features illustrated in Figure 5, which is most likely a drowned sea cliff. It could also be a normal fault, but even in that case it forms a possible trap for diamonds.

3. Surf gullies, most spectacularly displayed on raised terraces from which the overburden has been carefully removed (Figure 2) have their counterparts on bare bedrock areas of to-day's continental shelf, where they have been inspected by divers. Undoubtedly, many of these gullies are buried under sediments, but they may well be picked up by high-resolution geophysical profilers with a narrow sound cone or with transducers towed in a bottom sled.

4. Finally, just as river beds on land, submerged drainage systems are loci for placer minerals. This was demonstrated vividly by two maps of the same offshore area drawn independently, one showing drill sites and number of diamonds recovered, and the other presenting the bedrock topography based on geophysical records, and including a particularly sinuous submerged drainage system. Superposition of these two maps showed that all diamonds occurred in the river beds, and none between! It must be pointed out, however, that subsequent mining may discover diamonds between river courses, too. Similar relationships, however, were brought out by Van Overeem (1960b, p. 461) in the case of cassiterite.

In conclusion a brief example is given of a less desirable feature which may be encountered in some marine geophysical operations, particularly in areas of upwelling. Because of oceanic and atmospheric circulation, such areas occur characteristically in midlatitudes on the east side of ocean basins. Upwelling brings nutrient-rich intermediate waters into the upper, euphotic zone, resulting in great productivity of algae, and in turn to large plankton populations and a rich fish stock. The large number of dead organisms raining to the seafloor uses up most of the oxygen dissolved in the sea water in the process of rotting, or oxidation. This leads to an oxygen minimum (Stander, 1964) and deposition of azoic muds with incompletely oxidized organic remains. Certain sulphate-reducing bacteria thrive in this environment, acting as oxidizing agents and setting free considerable amounts of hydrogen sulphide. This, or any other gas in sediments prevents sound penetration, so that structures below this 'acoustic blanking layer' will not be detectable (Figure 7) seismically. Possibly a major increase in energy output will offer a solution to this problem, provided the layer is not too thick. Fortunately, the areal distribution of the azoic muds is rather patchy, so that windows in the blanking layer provide data on layering and depth to bedrock.

A similar occurrence is reported and illustrated by Edgerton and Payson (1964, p. 879,880, and Figure 5) in Boston Harbor, where a thin layer, 3 to 4 inches thick, of black carbonaceous mud completely masked structures in the clay bottom which are well visible less than 100 feet away from the mud.

Summary

Marine placer deposits consist of resistant heavy minerals which have been concentrated by wave and current action. They occur typically in late Tertiary and Quaternary sediments off mineralized territories and are trapped in topographic depressions such as drowned riverbeds, surf gullies, potholes and in drowned beaches. Their areal distribution has been greatly influenced by Pleistocene sea-level changes.

In the exploration for marine placer deposits the continuous seismic profiler has proven the most effective single prospecting system, but a magnetometer and gravity meter should be towed simultaneously. Rapid exploratory surveys, with wide spacing between lines, serve to outline target areas for detailed surveying and to reject areas where sediments are too thick for profitable mining. Subsequent detailed geophysical surveys require a profiling system capable of high definition rather than deep penetration. Sampling operations are best run in conjunction with detailed geophysical work to provide feedback in interpretation of the records. The sampling system should provide reliable quantitative data throughout the entire sediment column. To improve evaluation it is recommended that sampling devices be calibrated with the mining system to be used in the exploitation of the deposit.

Especially in detailed surveying, the accuracy of positioning methods should receive emphasis. Numerous suitable electronic navigation systems are available (see Table II) but direct optical methods—preferably shore-based theodolites—can often be employed because offshore placer deposits lie relatively close inshore.

Basic reasoning and experience from mining operations on raised marine terraces suggest a search of geophysical records for those features commonly associated with placers. These include basal gravels and conglomerates, drowned drainage systems and surf gullies, buried beaches and sea cliffs, and areas of high relief.

Conclusions

The old adage that expert advice is cheap certainly holds in the field of marine surveying operations, where the expense of running a ship dwarfs any consulting fee. A team of recognized experts can save large amounts of time, funds and frustration. Geologists can suggest target areas on the basis of geologic inference, and statisticians can determine the best sampling plan with the least number of survey lines or sample sites. Close cooperation between marine mining engineers, geophysicists and marine operators is required for selection of the right combination of survey vessels, geophysical sampling and navigation systems, as well as personnel. Especially critical is the reliability of each of the systems, because breakdown of one system may hold up an entire survey. This suggests use of the redundancy concept, involving duplication of systems or carrying of alternate systems.

Although the technique of continuous seismic profiling is hardly one decade old, several near-perfect systems are available, providing sufficient penetration and detail for use in marine mining. The status of navigation systems is less favorable, but improving. Considerable improvement is required in sampling methods; specifically, a marine sampling device is needed, capable of complete sampling of the entire sediment column and the top of the bedrock. The sample should be free of contamination, so that it can be used for quantitative purposes such as determining the general grade as well as vertical variations in grade.

Experience in exploration for diamonds and comparison of the few case histories available for other placer deposits indicates a great similarity in occurrence of marine placer minerals. Evaluation of diamond deposits, however, is undoubtedly more difficult than for any other placer mineral because of the small number and high value of diamonds and their extremely skewed distribution.

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Neutron activation techniques for precious metal exploration

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Abstract. A feasibility study has shown that an *in situ* irradiation of the ground with neutrons can produce sufficient induced radioactivity in some 30 elements to make detection and identification relatively easy. Extensive tests and two prototype field detectors for the detection of silver show encouraging results. A mobile 150-kev positive ion accelerator is used as a source of 3-Mev or 14-Mev neutrons. The induced radioactivity is analyzed by a multichannel analyzer, and element identification is made on the basis of both energy and half-life.

A similar study made on the precious and semiprecious metals indicates that no one technique is satisfactory for all the metals. Rather than build a practical field exploration device for the precious metals, a mobile neutron activation laboratory has been built to investigate the various parameters and techniques which can be used. Field tests have been made using both thermal and fast neutron reactions to detect gold. Two of the more promising methods are described and preliminary field results are shown.

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Résumé. Une étude expérimentale a démontré que l'irradiation sur place du terrain par des neutrons peut produire suffisamment de radioactivité provoquée dans une trentaine d'éléments pour en rendre la détection et l'identification relativement faciles. Deux prototypes de détecteurs sur le terrain destinés à la recherche de l'argent ont été soumis à des essais intensifs et les résultats sont encourageants. Un accélérateur mobile d'ions positifs de 150 kev sert de source de neutrons de 3 ou 14 Mev. La radioactivité provoquée est analysée par un appareil à canaux multiples et l'identification de l'élément se fait à la fois d'après l'énergie et la période radioactive.

Une étude semblable faite sur des métaux précieux et semi-précieux démontre qu'aucune méthode n'est satisfaisante pour tous les métaux. Au lieu de construire un appareil pratique pour l'exploration des métaux précieux, on se sert d'un laboratoire mobile d'activation par neutrons pour étudier les divers paramètres et techniques qui peuvent être utilisés. Dans des essais sur le terrain, on s'est servi à la fois des réactions aux neutrons rapides et aux neutrons thermiques pour déceler de l'or. L'auteur décrit deux des méthodes les plus prometteuses et donne les résultats préliminaires obtenus sur le terrain.

A recent study (Senftle and Hoyte, 1966) has been made by the U. S. Geological Survey on the feasibility of using *in situ* neutron activation for the purpose of mineral exploration. The study shows that with a thermal neutron source of $10^8 n/cm^2/sec$ the activity in more than 30 elements can be easily detected, by *in situ* irradiation, and that among the precious metals the induced radioactivity of silver and rhodium are particularly high. On the basis of this investigation, two mobile silver detectors were constructed and field tested. The results of these tests (Hoyte, Martinez and Senftle, 1967) showed that silver ores as low as 1.5 oz per ton could be easily detected in place in a period of a few minutes. It is the purpose of this paper to review the state of the art and to examine the possibility of using similar techniques for exploration of the precious metals.

Silver detection

Figure 1 shows an over-all view of the first prototype instrument. The unshielded neutron generator is mounted on the rear of a trailer drawn by a rugged field vehicle in which is mounted the control and detector electronic equipment. The neutron generator is a 150-kv, positive ion, Cockcroft-Walton accelerator using a sealed target tube. This generator was capable of producing a flux of 5×10^9 14-Mev neutrons/cm^2/sec at the target when a tritium target was used, or about 10^7 3-Mev neutrons/cm^2/sec when a deuterium target was used. When neutrons of thermal energies were required, a piece of paraffin was used between the target and the ground to slow down the neutrons before they entered the ground. A 2 $\times$ 2 inch NaI(T1) scintillation crystal was used as the detector. Because the crystal would become activated if it was allowed to remain near the target during the irradiation, it was mounted on a light spring-loaded boom which swung out about 120° from the rest position so as to place the crystal about 20 feet from the target during the irradiation. As soon as the neutron flux was cut off the boom was released and swung the crystal into the counting position in about 6 seconds. The vehicle containing the associated electronic equipment was detached from the trailer and moved to a distance of about 150 feet before the irradiation. This was necessary to circumvent the use of a heavy neutron shield, and to

Figure 1. First experimental silver detector. 14-Mev neutron generator and boom carrying scintillation detector are in the trailer; vehicle carries control and readout equipment.

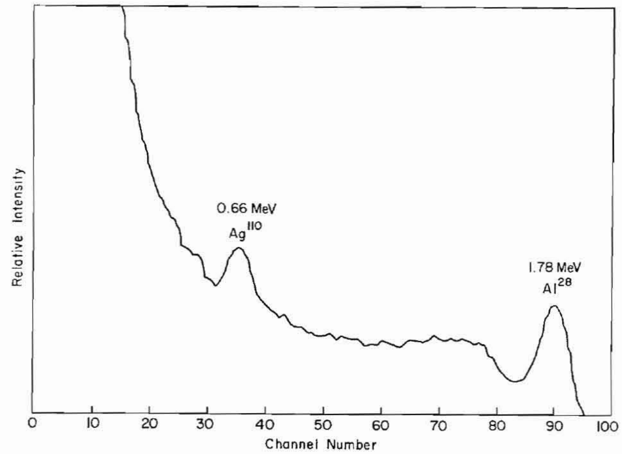


Figure 2. Spectrum of similated 15-oz-per-ton silver ore after irradiation with 14-Mev neutrons through 7.5 inches of paraffin moderator. From Hoyte, Martinez, and Senftle (1).

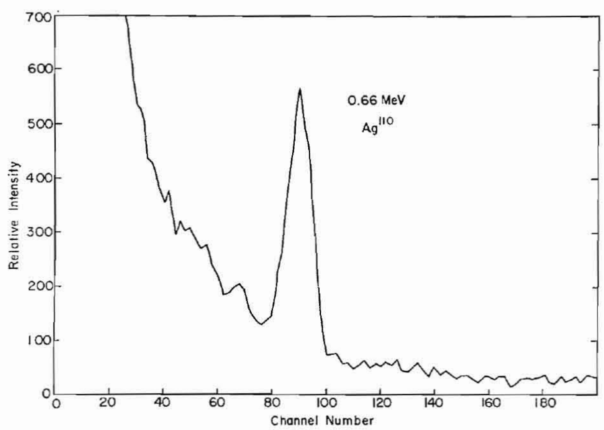
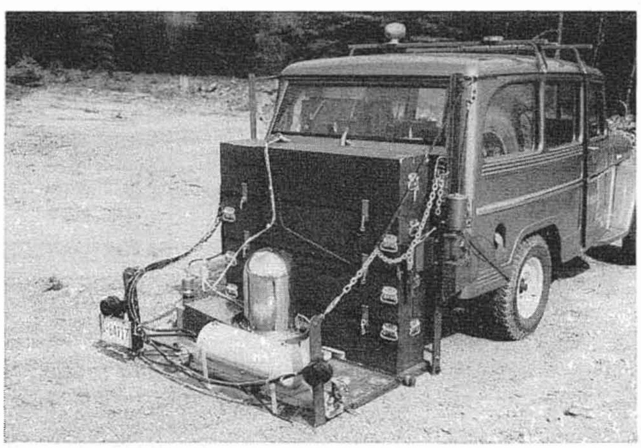


Figure 3. Spectrum of simulated 22-oz-per-ton ore after irradiation with 3-Mev neutrons through 1/2 inch of paraffin moderator. From Hoyte, Martinez, and Senftle (1).



allow the operator to be at a safe distance when 14-Mev neutrons were used. Obviously, this was a clumsy piece of equipment, but in spite of this much valuable information was obtained. For instance it was learned that 3-Mev neutrons were superior to 14-Mev neutrons for silver detection even though the neutron flux was nearly two orders of magnitude less. This enhancement was due to the increase in signal-to-noise ratio, i.e., the background interference from high-energy reactions was much less with the lower-energy neutrons.

Figure 2 shows the silver peak over a simulated 15-oz-per-ton silver ore after irradiation with 14-Mev neutrons. Note the Al^{28} peak due to the $Si^{28}(n,p)Al^{28}$ reaction and the rather severe background underlying the silver peak due to Compton scattering. A similar spectrum is shown in Figure 3 taken over a simulated 22-oz-per-ton silver ore after irradiation with 3-Mev neutrons. The Al^{28} shown in the former spectrum is a high-energy reaction and, as the threshold of the reaction is about 3 Mev, it did not cause a significant interference when 3-Mev neutrons were used. Based on the information learned with this unit, the detector was rebuilt as shown in Figure 4. The trailer was eliminated. By adding a paraffin shield and using only 3-Mev neutrons, the operators were able to stay safely inside the vehicle. Both the neutron generator and a 3 X 4 inch NaI(T1) crystal were mounted on the tailgate so that they could be raised or lowered. In addition they were mounted on the opposite ends of a paraffin-cadmium shield which rolled on tracks across the tailgate. During the irradiation the generator was in a position directly over a 10-inch-diameter hole in the tailgate. As soon as the generator was turned off, the assembly shuttled automatically across the tailgate, thus placing the crystal detector over the same hole. The shuttle device was hydraulically controlled and could be adjusted so the detector would be moved to the generator position in 2.5 seconds. It was thus possible to take advantage of any short-lived induced radioactivity. While this device was not a practical exploration tool, it was many times better than the first unit.

A spectrum taken with this device over the ore dumps of an old pyrite mine in Virginia is shown in Figure 5. Subsequent chemical analysis showed a silver concentration of 1.5 oz per ton. These experiments pointed out one thing: *in situ* neutron activation with proper engineering was feasible as an exploration tool for certain elements. It was apparent, however, that each element presents different problems and that a single piece of equipment cannot be used efficiently for all the elements. A mobile neutron irradiation and detection laboratory was therefore constructed to study the field problems, irradiation and detection techniques, etc. A 200-kv positive ion accelerator was mounted on the lift gate of a 6 X 6 army vehicle as shown in Figure 6. The scintillation detector was mounted on a boom swung from the side of the truck as shown. The boom was attached to the lift-gate mechanism and swung into the counting position in 6 seconds as the lift gate went up. The multichannel analyzer and other electronic circuits associated with the detector were mounted inside the van. Provision has also been made to use

Figure 4. Second experimental silver detector. 3-Mev neutron generator and detector are fixed to a shuttle which moves across the tailgate shown in irradiation position.

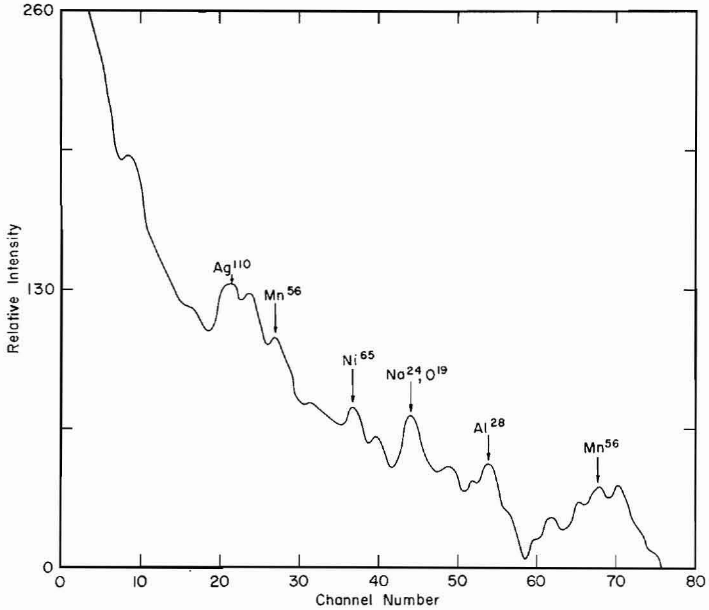


Figure 5. Spectrum taken over pyrite concentrate containing about 1.5 oz silver per ton at Arminius mine, Mineral, Virginia. Probable isotope assignments are shown for several of the more prominent peaks. The silver peak was identified by its fast decay as well as by its energy. From Hoyte, Martinez, and Senftle (1).

Figure 6. Mobile neutron activation laboratory showing 200-kev accelerator on tailgate in irradiation position and crystal on automatically operated boom.

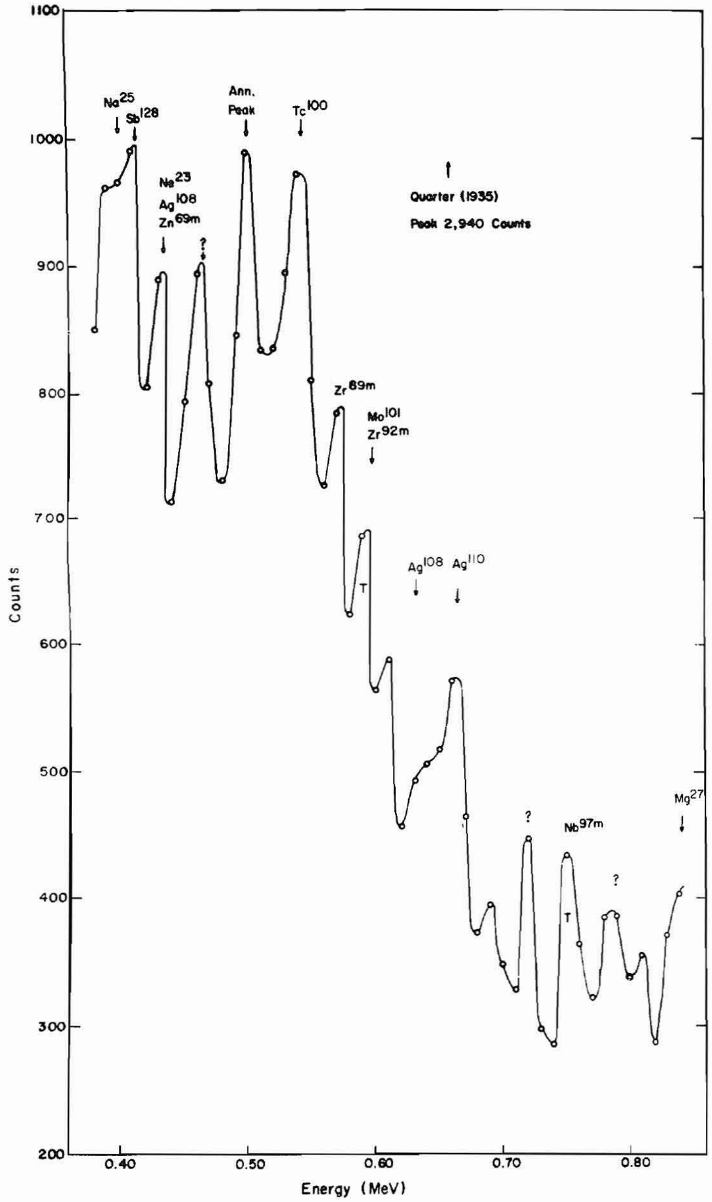


Figure 7. Gamma spectrum taken over silver ore (1.5 oz Ag/ton) after 100-sec neutron irradiation. Note the count in the Ag^{110} peak at the same location when a silver quarter was placed on the surface.

a solid-state detector using an Si(Li) crystal instead of the scintillation detector. Using this laboratory we have been able to study various nuclear reactions that may be used for exploration and optimize the parameters to give maximum sensitivity.

With successive irradiations, proper background subtraction techniques, and adjusting the irradiation and counting times to give maximum counting rates, one can enhance the useful induced activity in a particular element. For instance, the spectrum shown in Figure 7 was taken over silver ore running 1.5 oz Ag per ton. The spectrum is considerably better than that taken over ore of similar silver concentration with less sophisticated equipment used to take the data in Figure 5. Both Ag^{108} and Ag^{110} are clearly visible. For contrast a silver quarter was thrown on the surface and a repeat run was made. The Ag^{110} peak reached 2940 counts as indicated in the figure. Thus, by optimizing the activation and counting procedures, the sensitivity of this method was increased from 1.5 oz Ag per ton to less than 0.1 - 0.2 oz Ag per ton.

Precious metal detector

The first group of elements which have been studied in some detail are the precious and semiprecious metals. The initial investigation centered about the thermal neutron reactions,

Table I. Calculated thermal neutron-induced (n,γ) radioactivity of precious metal radionuclides which may be used for mineral exploration.

Parent Nuclide	Isotopic Relative Abundance(%)	Cross section (barns)	Product Nuclide	Half-Life	γ-Energy Mev	Activity/g/100 sec irradiation (dis/sec)*	Activity/g/100 sec irradiation after 6 sec delay
Ru		Insensitive to (n,γ) reactions					
Rh-103	100	11 138	Rh-104m Rh-104	4.4m 42s	.052, .077 .56(2%) 1.24(0.1%)	1.56×10^6 6.64×10^7	1.56×10^6 6.3×10^7
Pd-106 Pd-108	27.33 26.71	.1 ** .1 **	Pd-107m Pd-109m	22s 4.8m	0.216 0.19	1.48×10^4 1.35×10^4	1.23×10^4 1.33×10^4
Ag-107	51.82	35	Ag-108	2.4m	.63(1%) .43(2%)	4.01×10^6	4.01×10^6
Ag-109	48.18	89	Ag-110	23.5s	0.66	2.47×10^7	2.12×10^7
Re-187	62.93	1.3	Re-188m	17.9m	.064, .105	1.70×10^3	1.65×10^3
Os-189	16.1	0.008	Os-190m	10m	.62, .51, .356 .186	4.58×10^2	4.58×10^2
Ir-191 Ir-193	37.3 62.7	250 110	Ir-192m Ir-194m	1.4m 0.05s	0.058(99%) 0.115	1.69×10^7 2.22×10^7	1.68×10^7 nil
Pt-196 Pt-198	25.3 7.21	0.05 0.03	Pt-197m Pt-199m	82m 14s	0.337 0.032, .393	5.68x10 6.85×10^2	5.68x10 5.35×10^2
Au-197	100	98.8	Au-198	2.7d	0.41, 0.68, 1.09	9.30×10^3	9.30×10^3

*Based on thermal flux of 10^8 n/cm^2/sec/gram of element and an irradiation time of 100 sec. **Actual values not known. Assume value of 0.1 barns.

particularly those yielding nuclides which have short half-lives. A comparison of the expected radioactivity for various nuclides induced in one gram of precious metal when irradiated for 100 seconds in a thermal neutron flux of 10^8 neutrons/cm^2/sec is shown in Table I. As previously shown, the activity induced into silver is more than sufficient for exploration purposes; hence we use the value 2.47×10^7 dis/sec shown for Ag-110 (seventh column) as a rough criterion for the other nuclides. Rh-103, Ir-191 and Ir-193 have comparable induced activities, but they also have some associated disadvantages. Rh-104 decays by gamma emission only 1 to 2 percent of the time and thus has a comparatively low specific emission. Ir-192m emits only a 58-kev gamma which is difficult to resolve from the noise with a scintillation detector and is easily absorbed in the ground. Ir-194m has a somewhat higher energy of emission but the half-life is so short that it is difficult to detect. While these three nuclides are possible to use for detecting rhodium and iridium, special techniques must be developed to cope with these problems. The small concentrations of these elements even in ore-grade occurrences require sensitivity difficult to achieve in practice. The induced radioactivity of the other radionuclides shown in the table is relatively low and will be easily masked by the radioactivity induced in the gangue elements. Silver thus appears to be the only metal in the group which admits of easy detection by thermal neutron activation.

It is unfortunate that gold, because of its economic importance, does not have a higher activity for a short irradiation time. However, the gold half-life is considerably longer than any of the other precious metals, and this fact suggests an alternative technique. If the irradiation time were extended to 10 minutes the activity per gram of gold would be 5.3×10^4 dis/sec. After several days the activity of many of the other short-lived gangue elements would have decayed to a low level, but gold due to its long half-life (2.5 days) would still have an activity of about 2.5×10^4 dis/sec/gm. Other than W^{187}, Zn^{69m}, and Cd^{115}, we do not know of any nuclides of the common elements with similar half-lives and with gamma rays within 0.1 Mev of the 0.417-Mev gamma of Au^{198}. One should therefore be able to resolve the gold photopeak from interfering elements using this method.

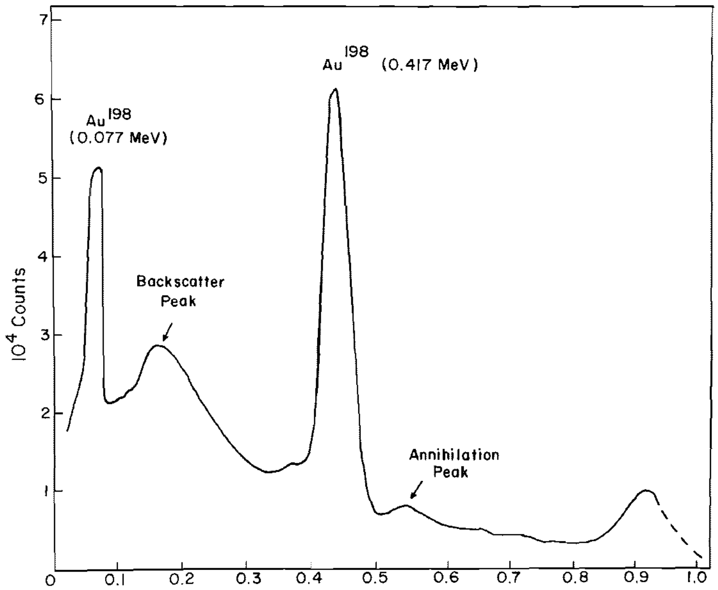


Figure 8. Gamma spectrum of gold foil on surface of 10-inch square box of ferruginous soil (≈40 pounds) 2 hours after 5-minute irradiation of 14-Mev neutrons.

Preliminary laboratory experiments using the 0.417-Mev gamma photopeak were made to solve some of the problems before attempting field tests. As it was planned to make the measurements after the short-lived activities had decayed to a negligible level, 14-Mev neutron irradiation was used to obtain the highest possible flux of neutrons. Using 1.5 inches of paraffin moderator, a 4.3-gram gold foil was sandwiched between the moderator and a 10-inch square paper box filled with ferruginous soil. After a 5-minute irradiation, the activity was so high that no meaningful data could be recorded for at least 25 minutes. After two hours the spectrum shown in Figure 8 was recorded. The 0.417-Mev photopeak of gold is prominent. Of course this represents a large amount of gold. If the box represented the total sample irradiated in a typical field irradiation, the concentration would be about 7 oz per ton. When the foil was counted through the soil, as shown in Figure 9, the gold peak was barely visible. This gives a rough indication of the depth of detection for the .417-Mev gamma ray of gold. To get some idea of the activation of gold at depth, a similar foil was placed between two similar 10-inch square boxes of soil and placed such that the neutrons passed through 10 inches of soil (Box #1) before striking the gold foil. After irradiation under the same conditions as used previously, the spectrum shown in Figure 10 was obtained by removing Box #2 and observing the foil and bottom of Box #1. The gold photopeak is present but much lower than when on the surface. These experiments show that this technique can be used to detect gold but that the depth of penetration does not extend much below 10 inches.

Field tests were made in the Crown Mountain area in northern Georgia where gold has been found. Twenty-five test irradiations using both 14-Mev and 3-Mev neutrons were made. In almost every case a small peak was observed at about 0.41 Mev after a decay period of at least 12 hours. However, there is a small peak in the natural background which occurs within a few hundredths of an Mev of the same energy. At the time these measurements were made, we did not have provision for automatic spectrum stabilization and the results were inconclusive. In one case, however, the neutron generator was run for 8 minutes at peak current generating 3-Mev neutrons. The spectrum taken 16 hours after the irradiation at a spot on strike with some old gold diggings on Crown Mountain is shown in Figure 11. There is a peak at about 0.41 Mev which appears to be gold but could be due in part to zinc. Zn^{69} has a gamma ray energy of 0.44 Mev. Analyses of grab samples taken in the vicinity ran from <0.1 to 1.5 ppm gold. Assuming a concentration of 1 ppm, and activation of a 300-pound sample, the detector would be looking at a little over 0.1 gram of gold. The activity of this amount of gold under the given irradiation conditions would be of the order of 10^3 disintegrations per

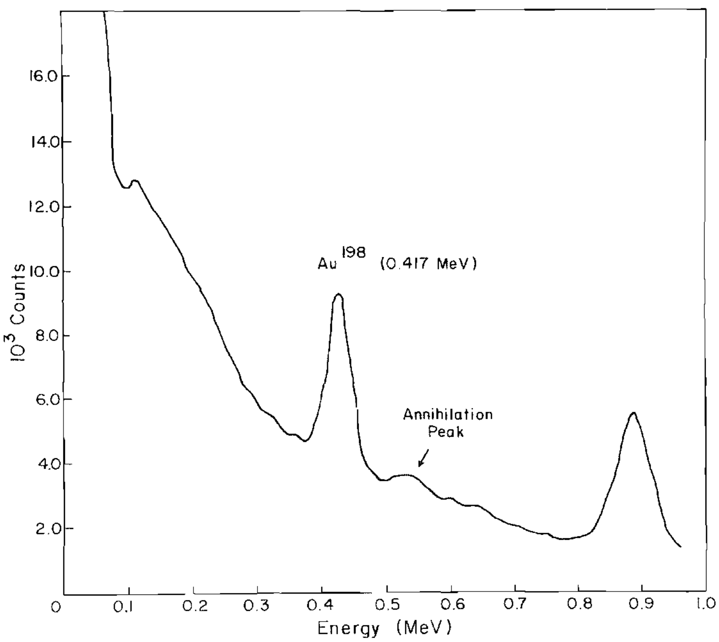


Figure 10. Gamma spectrum of gold foil placed between two 10-inch square boxes of soil and irradiated for 5 minutes with 14-Mev neutrons through 10 inches of soil.

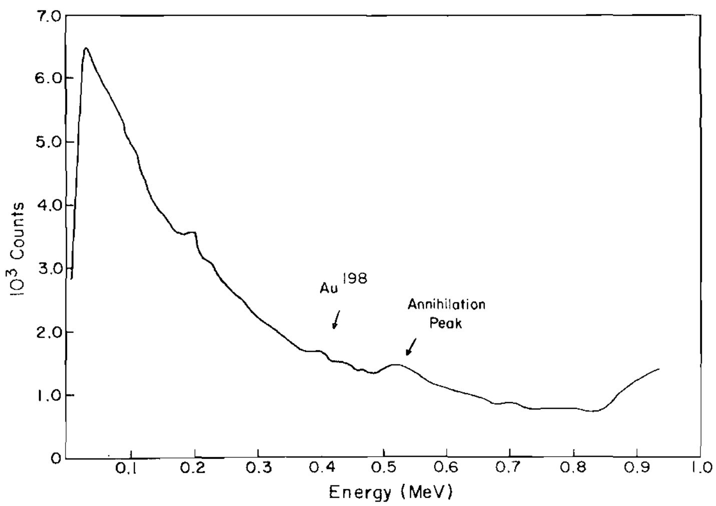


Figure 9. Gamma spectrum of same sample as shown in Figure 8, except taken through 10 inches of soil.

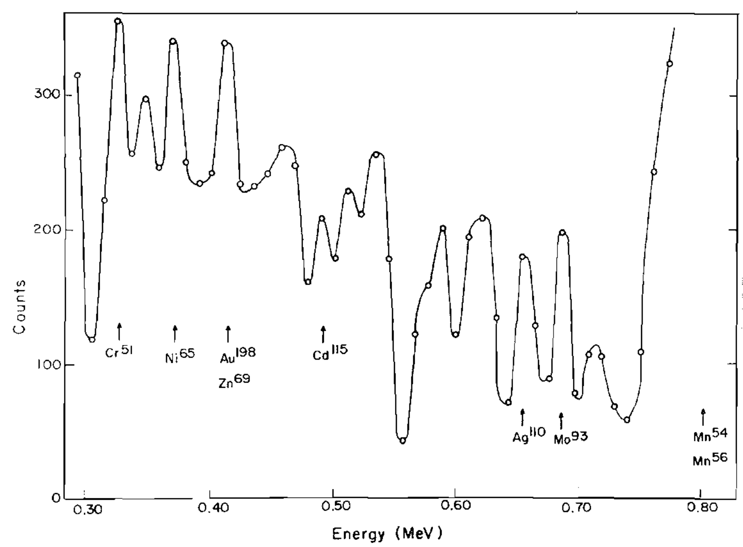


Figure 11. Gamma spectrum taken 16 hours after 3-Mev neutron irradiation at Crown Mountain, Georgia.

second in the 0.417-Mev peak. This would be further reduced by absorption in the ground depending on the depth and the counting geometry, but would still be high enough to detect. The results indicate that this thermal neutron technique for gold exploration is feasible and we are currently attempting to improve it. With the relatively crude equipment used in these experiments, the sensitivity is probably about 0.1-0.5 oz Au/ton, but we feel that this can be reduced to less than 0.05 oz Au/ton with stronger neutron source and a somewhat more sophisticated readout and background stripping device which is currently being developed.

The possibility of using high-energy or fast-neutron reactions for activation has also been studied. Here we are concerned with fast-neutron reactions of the type (n,p) and $(n,2n)$, which in the case of some of the precious metals have not been studied as well as may be desired. From the information available we have calculated the expected activity for the above fast-neutron reactions similar to the data in Table I. Because of the low-capture cross sections and in some cases long half-lives, the highest activity for any of the precious elements falls several orders of magnitude lower than that needed for a feasible exploration technique. For this reason we have abandoned the idea of using high-energy neutron reactions as a means to produce induced activation for precious metal exploration. For some of the base metals this is not the case, and high-energy neutrons can be used to produce substantial activities.

In addition to a fast-neutron reaction, however, there is another type of interaction which may take place with fast neutrons. A fast neutron may suffer a 'billiard ball' or inelastic collision with an atom and hence impart some energy to the atom without actually being captured. The excited atom subsequently returns to the ground state by emitting a γ-ray. These $(n,n'\gamma)$ reactions, as they are called, generally emit the γ almost immediately, but for some nuclear species the excited atom is in a metastable state and decays after a short delay. Those $(n,n'\gamma)$ reactions which are known to form metastable states among the precious elements generally emit γ-rays which are undesirably low in energy (less than 0.1 Mev; see Table II). Osmium, iridium and gold are exceptions. Au^{197m}, the most studied of these elements, has a half-life of 7.3 seconds, emits a 0.28-Mev and a 0.13-Mev gamma, and has a relatively large cross section of 1.3 barns. The cross sections for most of the other reactions in the tables are not known.

Instead of using a 100-second irradiation as used for the calculations in Table I, one can reach over 97 percent of the saturation activity of Au^{197m} in a 40-second irradiation. Using a flux of 10^8 3-Mev neutrons/cm^2/sec, this would amount to about 4×10^5 disintegrations per second per gram of gold. Compared with a 100-second irradiation of silver as shown in Table I, this is a relatively low activity. However if a short irradiation time is

Table II. List of $(n,n'\gamma)$ reactions of the precious metal isotopes.

Parent Nuclide	Isotopic Relative Abundance (%)	Cross section (barns)	Product Nuclide	Half-life	γ-Energy (Mev)
Rh-103	100	*	Rh-103m	57 m	0.04
Ag-107	51.82	0.53	Ag-107m	44 s	0.093
Ag-109	48.18		Ag-109m	40 s	0.088
Os-189	16.1	*	Os-189m	5.7 h	0.031
Os-190	26.4	*	Os-190m	9.5 m	0.51, 0.61, 0.36, 0.19, 0.04
Ir-191	37.3	0.51	Ir-191m	4.9 s	0.14, 0.042
Ir-193	62.7	*	Ir-193m	11.9 d	0.08
Pt-195	33.8	*	Pt-195m	3.5 d	0.031
Au-197	100	1.3	Au-197m	7.3 s	0.28, 0.13

* Not known.

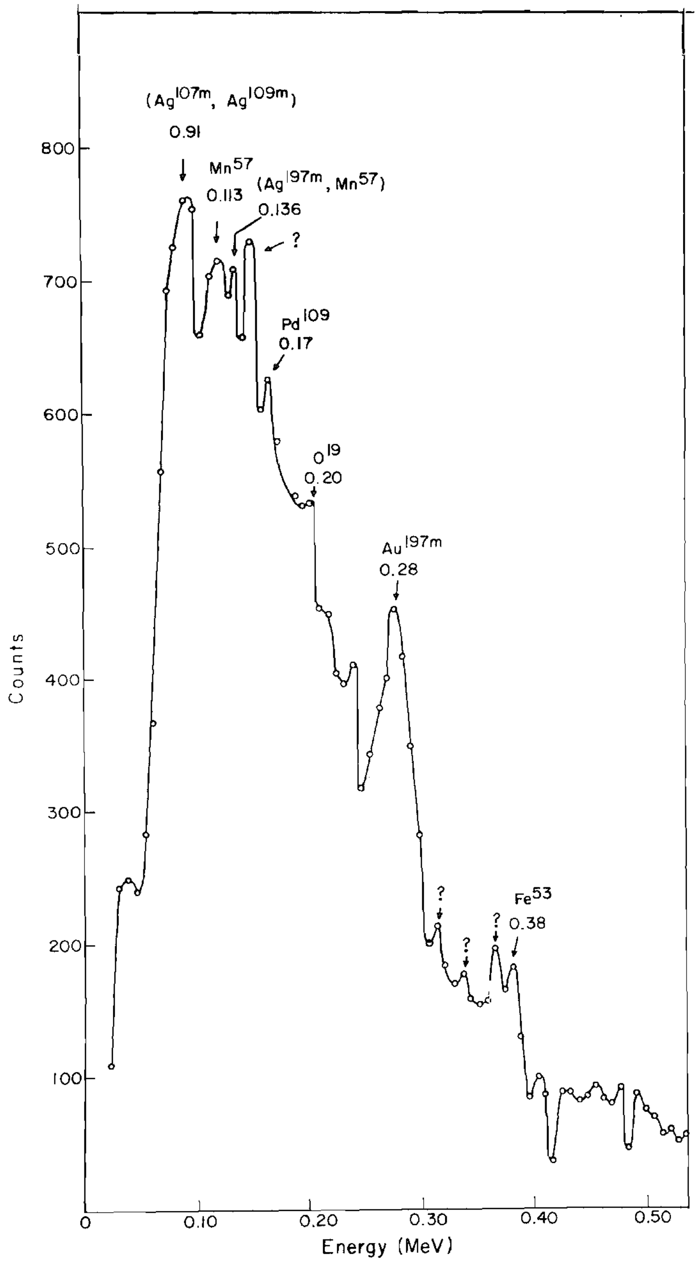


Figure 12. Gamma spectrum taken within 24 seconds after irradiation of synthetic gold and silver deposit (60 ppm Au and 250 ppm Ag) using thermalized neutrons.

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used, the background, which has a relatively long effective half-life, will not increase significantly. Thus, one may obtain a signal-to-noise ratio comparable with that of activated silver and hence a practical exploration technique for gold might be devised.

Using the swinging boom arrangement to quickly position the crystal detector, we irradiated the ground at a spot which had previously been salted with a gold foil. Based on the irradiation of about 300 pounds of soil, the concentration was 60 ppm gold. After 21 seconds of irradiation with 3-Mev neutrons through a 1.5-inch polyethylene moderator and a 24-second counting period, we obtained the spectra shown in Figure 12. Both 0.13-Mev and 0.28-Mev peaks of gold are observed, the latter being well resolved from the rest of the spectra. The height of the 0.28-Mev photopeak of Au^{197} may be maximized by choosing the proper irradiation time and counting period. In the particular case cited here no attempt was made to maximize these parameters.

Encouraged by this initial result we are currently investigating further refinements. Figure 13 shows the induced background activity (curve 1) in the gold photopeak window for different periods of irradiation with 3-Mev neutrons. The induced background activity from the matrix elements is superimposed on the natural U, Th, and K background activity, which can be subtracted electronically. Curve 2 is the gold activity plus background activity calculated from the cross-section and half-life data and normalized to the experimental point corresponding to a 21-second irradiation. Experimental points for other periods of irradiation are also shown. From this figure one can see that there will be a certain period of irradiation which will produce the greatest ratio of gold activity to induced background activity. It can be shown that this period t can be calculated from

$$t = \frac{\ln A_s\lambda - \ln A_s'\lambda'}{\lambda - \lambda'} \approx \frac{\ln A_s\lambda - \ln S}{\lambda}$$

where A_s and A_s' are respectively the saturation activities for the amount of gold present and for the soil or rock matrix elements. λ is the decay constant for gold, and λ' is the effective decay constant for the matrix elements taken collectively. As the effective decay constant of the matrix is small compared with that of gold, one can make the approximation as shown in the equation. S or $A_s'\lambda$ is simply the slope of the background build-up curve 1. It is clear from this expression that the irradiation time needed to give the maximum ratio of gold to background activity will become shorter as the concentration of gold becomes less. For instance in the experiment described above, the maximum irradiation time should have been about 11 seconds instead of the 21 seconds actually used. However, 60 ppm is a high concentration for gold, and in practice it would be advisable to use much shorter periods of irradiation.

Using the same analytical technique, one can show that the counting time which will give the maximum number of counts in the gold peak is the same as the critical irradiation time determined above, i.e., the counting and irradiation periods should be the same if possible. It therefore appears that a useful gold detector which would be capable of seeing small concentrations should be based on a pulsed neutron technique with interpulse counting.

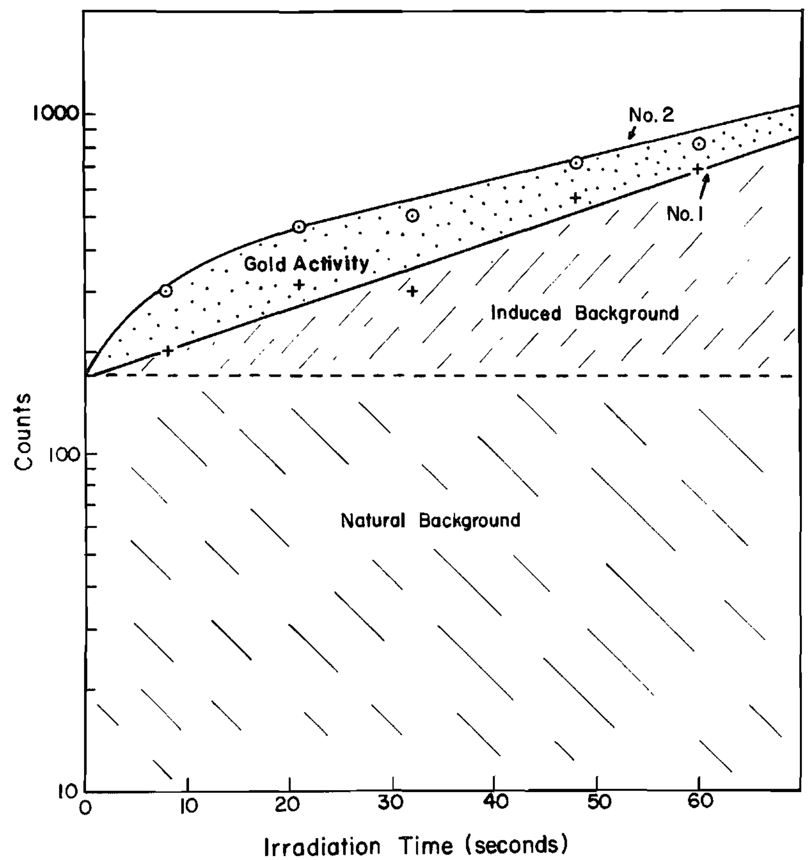

Figure 13. Experimental data taken over synthetic gold and silver deposit. For increasing times of irradiation, curve 1 is induced background count under the gold peak, and curve 2 is the counts in the gold peak due to gold plus background.

Our present equipment is not readily adapted for short burst irradiations and we have simply tried to irradiate 35 to 40 seconds to saturate the Au^{197m} activity, count for a 6-second interval in an accumulate mode, and follow this immediately for a second 6-second counting period in a subtract mode. The net count in the gold channel in this short counting period was obviously low, and this procedure had to be repeated several times to obtain meaningful statistics where the gold concentrations are low. For instance, tests made over ore containing 0.32 oz Au/ton yielded a signal-to-noise ratio of only about two. These unsatisfactory results were due to some extent to the 6- to 7-second delay between the end of the irradiation and the start of the count. Half the gold activity was gone before the count time had started. With some experience we found that the crystal detector acquired no significant activity if it was buried just below the surface even as close as 1 1/2 feet from 'ground zero'. This allowed us to eliminate the boom system with its 6-second delay, and we were able to start the count period immediately. This significantly enhanced our sensitivity as shown in Figure 14. There is little doubt as to the presence of gold. This approach requires further study and we are planning to develop it further.

By repeating the irradiation and counting procedure at a given site for several short but gradually increasing periods of irradiation similar to the data in Figure 13, one can calculate an average saturation activity for gold. As this activity is directly proportional to the amount of gold present for a given geometry and absorption, the gold concentration could be determined semiquantitatively with the help of a few calibration experiments. The concentration determined in this way, however, would not be absolute. The calibration would probably be made with homogeneous samples, and, as the distribution of gold is unknown, the absorption and scattering of the gammas would vary and only an equivalent gold concentration could be determined.

This study indicates that *in situ* neutron activation is a feasible exploration method for silver and gold. In addition, it may be quite useful for several of the other precious metals with more sophisticated equipment. The most practical technique for gold is not entirely clear and further work is being done to evaluate the various approaches to the problem. Once this has been determined, it will be necessary to engineer the proper equipment for field use.

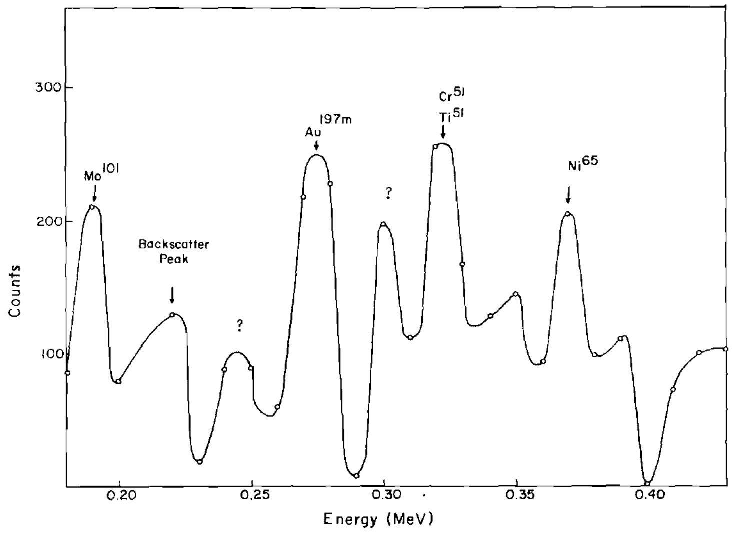

Figure 14. Gamma spectrum of gold ore (0.32 oz Au/ton) taken immediately after 38-second irradiation with 3-Mev neutrons.

Acknowledgment

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Contents

The application of geophysical methods in the exploration for bauxite deposits

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Abstract. No known geophysical method has a direct application in the search for bauxite deposits. In certain types of buried bauxite deposits, geophysical methods have been of value in pinpointing areas which would justify exploration by conventional drilling methods and, at the same time, serve as a useful tool in eliminating large areas from further costly drill exploration. A case in point is the coastal belt of Guyana where bauxite deposits, formed on topographic highs of a mid-Tertiary drainage system, were subsequently buried under late Tertiary and Quaternary sediments. Seismic surveys instituted in 1965 on lease areas held by the Demerara Bauxite Company, a subsidiary of Alcan, have been successful in delineating such basement highs and subsequent drilling has located bauxite on some of them. The data collected have been of additional value in eliminating areas in which the basement, including any such highs, is too deeply buried to permit economic open-cast mining, now or in the future.

Résumé. Aucune méthode géophysique connue ne peut s'appliquer directement à la recherche de gisements de bauxite. Dans certains cas de gisements de bauxite enfouis, les méthodes géophysiques peuvent servir à délimiter les régions où les forages par les procédés classiques pourraient se justifier tout en éliminant de vastes régions où des forages d'exploration coûteaux seraient inutiles. Un bon exemple est la zone côtière de la Guyane où des gisements de bauxite formés sur les plateaux d'un réseau de drainage du tertiaire moyen ont été par la suite enfouies sous des sédiments du tertiaire récent et du quaternaire. Les relevés séismiques entrepris en 1965 sur des propriétés de la Demerara Bauxite Company, filiale de l'Alcan, ont permis de localiser ces crêtes infouies et, par les travaux de forage entrepris par la suite, de retrouver quelques-uns de ces gisements. Les données recueillies ont aussi servi à éliminer les régions où ces crêtes sont enfouies à trop grandes profondeurs pour permettre aujourd'hui ou dans un avenir prévisible l'exploitation à ciel ouvert des gisements.

There have been several references recently to the use of various geophysical methods in the search for bauxite. This paper attempts to assess, to the extent of our present knowledge, their applicability for this purpose. In the following we will first briefly describe the occurrence of bauxite on a global basis, the most generally accepted theory as to its origin, and the more common types of orebodies, especially their positioning in relation to present-day land surfaces, since these factors limit the usefulness of geophysical methods. This is followed by a brief description of Alcan's experience in the application of geophysics to the search for bauxite and in particular the applicability of seismic methods.

Seismic methods are currently being used in Guyana, South America, by Alcan's subsidiary, Demerara Bauxite Company Limited, and the equipment and methods employed are described in some detail. A general statement on the results obtained is given.

Bauxite – mineralogy and occurrence

Bauxite, the most widely used ore of aluminum, is not a specific chemical compound but is composed essentially of hydrated aluminum oxides, either in the trihydrate form, gibbsite, or as the monohydrate, boehmite, or in varying mixtures of both. Iron oxides, titanium oxides and silica are the other major constituents. The iron is usually present as goethite, which is sometimes associated with lesser amounts of hematite, magnetite or siderite. Titania may be present as rutile or leucoxene, the alteration produce of ilmenite. Silica occurs either as free quartz or in a combined form as the clay mineral, kaolinite. Chemically, bauxite may show a fairly broad range in composition from one bauxite field to another, within the limits of, say, 40 to 60% Al_2O_3, 1 to 25% Fe_2O_3 and 1 to 15% SiO_2, although most bauxites in use today are much lower in iron and silica than the higher limits given above. Variation in chemical composition also occurs within individual deposits. The ore may vary from hard to soft and from dense to porous and all ranges are found, sometimes within a single deposit. Pisolitic varieties have a wide distribution in certain parts of the world.

Although several theories have been proposed for the origin of bauxite, it is generally accepted today that most of the major bauxite occurrences in the world are residual in origin. It is believed that they result from the *in situ* chemical weathering and leaching of rocks of various origins and compositions, which took place in areas of low local relief under tropical climatic conditions and in areas having heavy intermittent wet and dry seasons. The parent rocks from which bauxites are thought to have been derived include those of igneous and sedimentary origin, as well as their metamorphosed derivatives. The sedimentary rocks may have been consolidated or unconsolidated. Since the ore is a product of weathering, it necessarily forms at, or close to, the drainage surface existing at the time of its formation. There are several major bauxite areas where the deposits appear to be very closely related to present-day drainage systems, such as those of Western and Eastern Ghats of India, Southern Malaysia and in the Cape York area of Australia. A study of these deposits suggests that bauxite deposits of this type formed initially as a capping or blanket on the topographic highs or domes between major drainage systems in an advanced stage of maturity. Subsequently, changes in isostatic level or in climatic conditions may halt the chemical leaching and bauxitization process, with mechanical erosion then becoming a dominant factor. This results in the degradation of the primary bauxite deposit with transport of the erosion products down the adjacent slopes or for some distance beyond the primary deposit, giving rise to reconcentrated, or 'secondary', bauxite deposits. These may be considered to be a second type of deposit, and examples are known in Arkansas in the United States, in Guinea and in Malaysia. Another variation of the first, or blanket, type of deposit are those in which the bauxite either forms on, or is transported and deposited upon, a karst topography developed on limestone. The Jamaican, Haitian and Istrian deposits are typical examples. In these instances, as a result of the solution and karstification of a dominantly limestone basement, the bauxite fills sinks and pockets in the limestone, and locally may even cover ridges between adjacent sinks.

Both the karst and the more predominant blanket-type deposits, along with their related 'secondary' or detrital deposits, if formed during earlier geologic periods, may have subsequently been covered by more recent sedimentary formations as a result of crustal down-warping which, in some cases, may have been accompanied or followed by folding and faulting. The deposits of southern France and Dalmatia are examples of karst-type bauxites which have been subsequently covered by later sediments and then folded and faulted. Some of the Arkansas deposits, as well as many of those in Guyana and some in Surinam may be considered examples of blanket-type deposits which were down-warped and covered by later sediments, but did not suffer subsequent deformation.

From the foregoing it is evident that there are several forms in which bauxite deposits may occur:

1. As extensive blanket or dome-shaped bodies under little or no soil cover, the locations of which are related to heights of land at the heads of ancient and prolonged drainage systems;
2. As residual pockets and partial blanket deposits forming residuals on karsted limestone surfaces;
3. As secondary deposits arising from erosion and redeposition of the first and second types;
4. As buried deposits of the first, second and third types which, through down-warping and the deposition of younger sediments, have been protected from erosion; or
5. As buried deposits of the fourth type which have subsequently suffered deformation and, to some extent, metamorphism through regional folding and faulting, with later uplift and erosion generally exposing the deposits, in part or in whole.

Geophysics in relation to bauxite

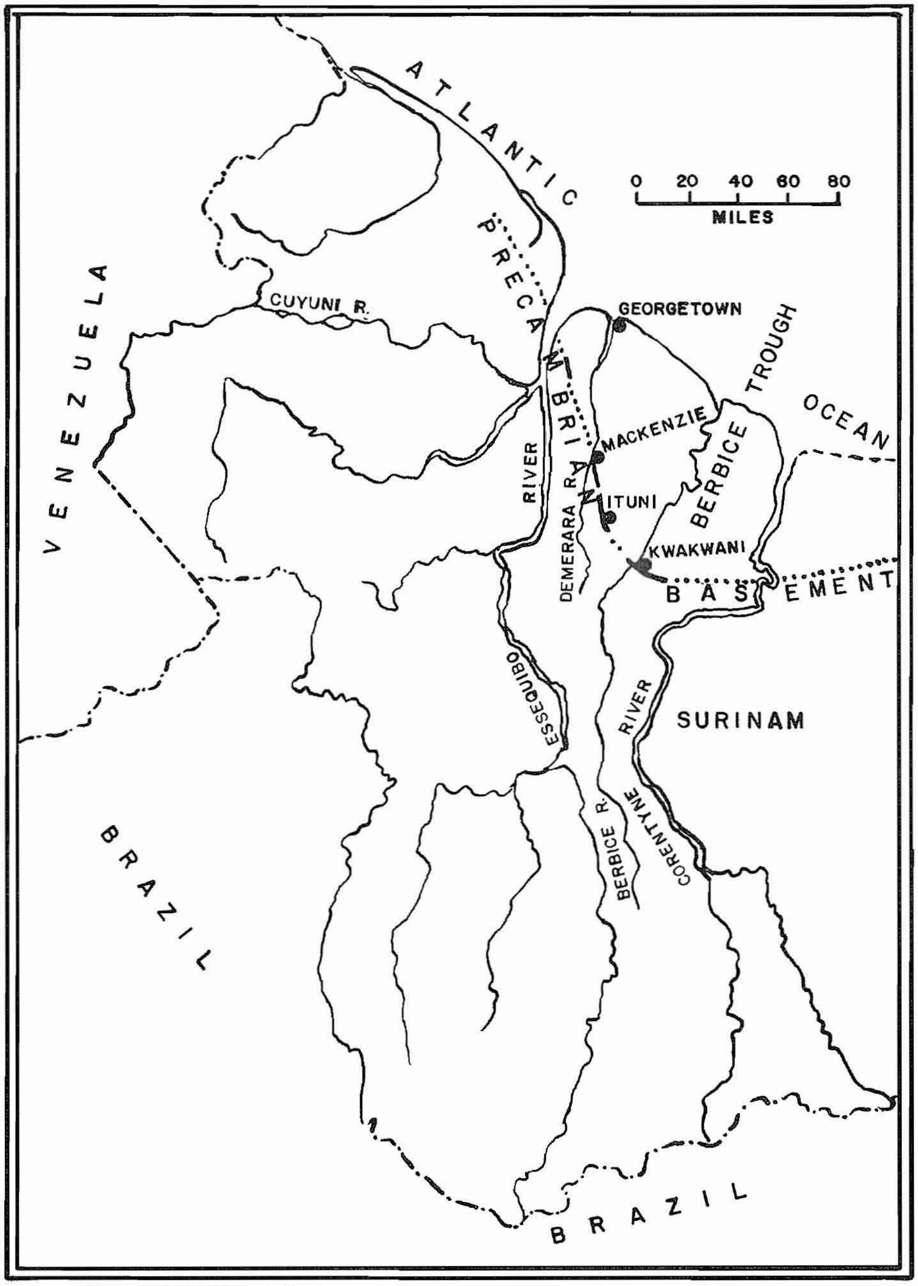
To assess where geophysics can be used advantageously in the search for bauxite certain types of occurrences where these methods are not applicable can be eliminated.

The types of deposits classified as 1, 2 and 3 above occur either widely exposed at surface or partially exposed by erosion along the flanks of valleys, or else their presence may be inferred from the occurrence of bauxite gravel in nearby stream beds. Because such bauxite deposits are visible and because their lateral and vertical extents may be defined, relatively inexpensively, by surface mapping and shallow drilling, there would be little or no justification to resort to geophysical methods to obtain data on their areal extent. Furthermore, since none of the geophysical methods in current use are capable of providing qualitative information as to the chemical composition or grade of bauxite, drilling or test-pitting is required in any case to obtain samples for analyses necessary for evaluation purposes. Such drilling or test-pitting also serves to delineate the particular deposit under examination.

Under certain circumstances, geophysics could be applied usefully in a rapid determination of the volume of material in bauxite deposits of the karst type, where there is a sufficiently sharp contrast between the density and electrical conductivity of the bauxite and of the enclosing waste rock to permit the location of the contact between them. This could be done by seismic or resistivity methods. However, here again these methods would give no idea of grade or quality and would need to be followed by pattern drilling and sampling to obtain such information. Nevertheless, if the aim were simply to establish the potential tonnage of a deposit, say, prior to its purchase, these methods, in combination with limited drilling, would provide sufficient preliminary data on which to base a decision on whether or not to purchase. The necessary pattern drilling for grade establishment purposes could then be completed at leisure, after acquisition. Numerous observations indicate that the fourth type, or buried bauxites deriving from the first or blanket type, are normally closely related to an underlying cushion of residual clay of varying thickness, whether derived from the weathering of an unconsolidated sediment or a crystalline basement rock. Thus the fourth type or buried deposit lies within an envelope of unconsolidated material consisting of residual clays below and sands, clays and other sediments above. To our knowledge no known geophysical method is capable of differentiating between bauxite or its high-iron equivalent, laterite, on the one hand and clays, sands and other unconsolidated sediments surrounding it, on the other. Their physical properties, such as magnetic susceptibility, density, electrical resistivity and ability to transmit or refract seismic waves are too nearly similar to allow any of the geophysical methods based on the use of these phenomena to be used directly in distinguishing between laterite, bauxite or the enclosing unconsolidated material.

However, when a primary bauxite deposit forms through the chemical decomposition of a crystalline basement, the shape of the deposit will reflect the shape and topography of the drainage divide along which the bauxite forms. In turn, the contact between the residual clay underlying the bauxite and the crystalline basement will reflect the overlying topography and in fact tends to be amplified since the depth of weathering will be less under the topographic high than under the adjacent stream beds. Therefore a topographic high will be reflected at depth by an amplified bedrock high. The above generalization has been observed in many exposed blanket-type deposits, not only in Guyana but also in Guinea, Brazil, India and Malaysia. Because of the known relationship between bedrock highs and bauxite or laterite shown by surface bauxites, the same relationship can be expected between buried bauxites and the underlying crystalline basement, and a more precise knowledge of the topography of the bedrock will give a lead in the search for a buried or fourth-type bauxite. While several geophysical methods are capable of outlining bedrock topography, our experience suggests that the seismic method provides the best answer to this problem when dealing with depths of from 200 to 1000 feet.

As far as we know, the only major bauxite area where this method has been successfully applied to the conditions outlined above is in the so-called 'bauxite belt' in Guyana (Figure 1) near the northern coast of South America. Here, bauxite deposits, which formed during a Tertiary or earlier age on a land surface resulting from the deep weathering of hard, dense crystalline Precambrian rocks, were preserved under a cover of unconsolidated late Tertiary and Quaternary sediments. Similar conditions may exist elsewhere along the outer edge of the



— —APPROXIMATE LINE OF EMERGENCE OF EARLY TERTIARY BAUXITE SURFACE

·····PROJECTED EXTENSION OF LINE OF EMERGENCE

Figure 1. Guyana – showing approximate trace of bauxite belt.

Guyana shield, possibly in the Surinam extension of the Guyana belt. The only other known area offering generally similar conditions is the Arkansas bauxite field where the Tertiary Eocene transgression covered bauxite formed through weathering of a pre-Eocene nepheline syenite (Gordon and Tracey, 1952).

Role of the seismic method as applied in Guyana

In Guyana bauxite occurs in discontinuous groups of deposits at the surface or at varying depths below. The deposits are in a belt (Figure 1) which extends from a point on the right bank of the Essequibo River northeast of Bartica, southward through Mackenzie and Ituni, the Demerara Bauxite Company's mining areas, after which it swings east-southeastward to Kwakwani on the Berbice River (deposits of Reynolds Guyana Mines Ltd.); presumably it then continues easterly into Surinam. This probably includes the bauxite deposits in the Paranam and Moengo areas. The belt lies just to the east and north of the line of emergence of the crystalline Precambrian basement rocks from beneath the late overlap of Cretaceous to recent sediments, which marks the western flank of the Berbice Trough, or syncline.

The results of exploration work which the Demerara Bauxite Company has carried out in the part of the belt located on the western flank of the Berbice Trough from the Essequibo to the Berbice rivers, indicate that the bauxite in this area was derived from the deep weathering of a mid-Tertiary erosion surface which was underlain by various intrusive to metamorphic Precambrian rocks.

The Upper Eocene to Oligocene erosional unconformity on which the bauxite formed appears to represent a prolonged period of chemical weathering of the basement rocks, because the weathered zone extends to depths of 75 to 150 feet below the bauxite layer which, itself, may be up to about 40 feet in thickness. During or following the latter stages of bauxitization, the land surface began to rise and the resultant renewed downward incision of the drainage pattern destroyed or removed much of the bauxite capping except along the higher points between the drainage basins. A second submergence of the Berbice Trough, from late Oligocene through to Pleistocene time, resulted in the deposition of the White Sand series of clays and interbedded lignites and sands within this syncline, first filling in the valleys between the bauxite remnants and eventually covering these cappings themselves. Gradual uplift in late Pleistocene was followed by renewed erosion partly along pre-White Sand drainage channels on the west flank of the Berbice Trough. The erosion exposed portions of the buried bauxite cappings along the emergent edge of the Trough. During this period of emergence, deposition of the Quaternary Demerara clays continued in the seaward portions of the Trough.

Erosion of the western flank of the Berbice Trough has cut through 100 to 200 feet of unconsolidated sediments of the White Sand series along the present course of the Demerara River and its tributaries, and has exposed bauxite lying at, or above, river level. However, eastward and northeastward, down the flank of the Trough, any pre-White Sand bauxite cappings which remain are covered by a progressively greater thickness of the White Sand series. It is here, in the search for these buried occurrences, that the value of seismic methods of prospecting has proven to be of value. As stated previously, the bauxite, at least in the landward portions of the Trough, formed as the uppermost part of the residual mantle and was preserved in areas underlain by basement highs, which also represent topographic highs on the old erosion surface. Drilling by Demba justifies the assumption that this relationship will follow the same pattern as these basement highs, since the contacts between basement rock and weathered rock are traced down the flank of the Trough.

The sharp change in velocity of seismic waves, where the physical constants of elasticity of material change abruptly from a low to a higher velocity at depth, provides an excellent point of measurement, and this is more or less the case at the transition point between weathered rock and relatively fresh basement rock. Therefore seismic methods, by providing contours of the old basement surface in the area bordering the mapped line of bauxite outcrops, serve to outline basement highs which, in turn, can be expected to reflect an overlying bauxite or laterite capping. This assumption, of course, holds true only as long as the bauxite is residual from the crystalline basement.

It was mentioned earlier that the Guyana bauxite is thought to have originated during a late Eocene to Oligocene period of emergence, but that down-warping and the deposition of sediments in the Berbice Trough first occurred in late Cretaceous time. Therefore, there is a possibility that sediments of Cretaceous to Eocene age were also bauxitized locally along drainage divides which existed during this emergence. This may be so in some of the Surinam deposits. In Guyana such deposits, if present, would occur farther down the Trough, toward the axis of the syncline. However, unless these occurrences reflected both original basement highs and overlying late-Eocene-Oligocene surface highs, seismic methods would not be likely to give any indication of their possible presence. Otherwise, such deposits could only be found, fortuitously, by wildcat drilling.

By indicating the general depth to bedrock and thus, indirectly, the approximate depth at which bauxite is likely to occur, seismic work serves as a most important aid in the elimination of certain areas for further prospecting. Since present mining equipment is not considered capable of allowing economic stripping and working of buried deposits under more than approximately 300 feet of unconsolidated overburden, areas of more than about 500 feet to the crystalline basement may be eliminated.

Current geophysical program in Guyana

Because of the foregoing theories, seismic prospecting was introduced in Guyana by the Demerara Bauxite Company in August 1965. As a preliminary, tests were carried out in an area in which drilling had provided some basement data and where bauxite had previously been located over topographic highs in the basement. The seismic results compared favourably with those obtained from the drilling. The seismic program was then extended beyond the area of known basement topography and, at the same time, a follow-up drilling program was mounted to check the new seismic data to make sure that the first check was not just a coincidence. This program lasted for a three-month period and gave sufficiently encouraging results to justify the adoption of the seismic method as a part of the annual exploration program.

Largely because of climatic conditions, the seismic program was confined to a six-month period in each of the years 1966 and 1967. It was thought that during the rainy seasons there would be considerable interference with transport conditions and in background interference noise from wind and rain. This was not as serious as anticipated. It was also felt that six months' seismic work would provide sufficient data to keep the exploration drill equipment busy for the full year. This has more than proved to be the case, and drilling is now considerably behind in checking up on the seismic data. However, as seismic work proceeds toward the Berbice River, with the expected deepening of the pre-Eocene basement, it is foreseen that the seismic results will be of use in providing negative data where excessive depths of the unconsolidated cover would render any underlying bauxite commercially unexploitable.

Traverse lines in the original test program were laid out in an east-west direction, first at 1200-foot intervals and later at 3600-foot intervals. As a result of this work, it was decided that the 1200-foot interval provided more detail than was necessary, whereas the 3600-foot interval yielded too little information and that basement contouring on this basis left too much to the imagination. In 1966 all east-west lines were spaced at 2400-foot intervals with a few north-south tie-in lines. This work provided sufficient information on the trends of the basement highs along

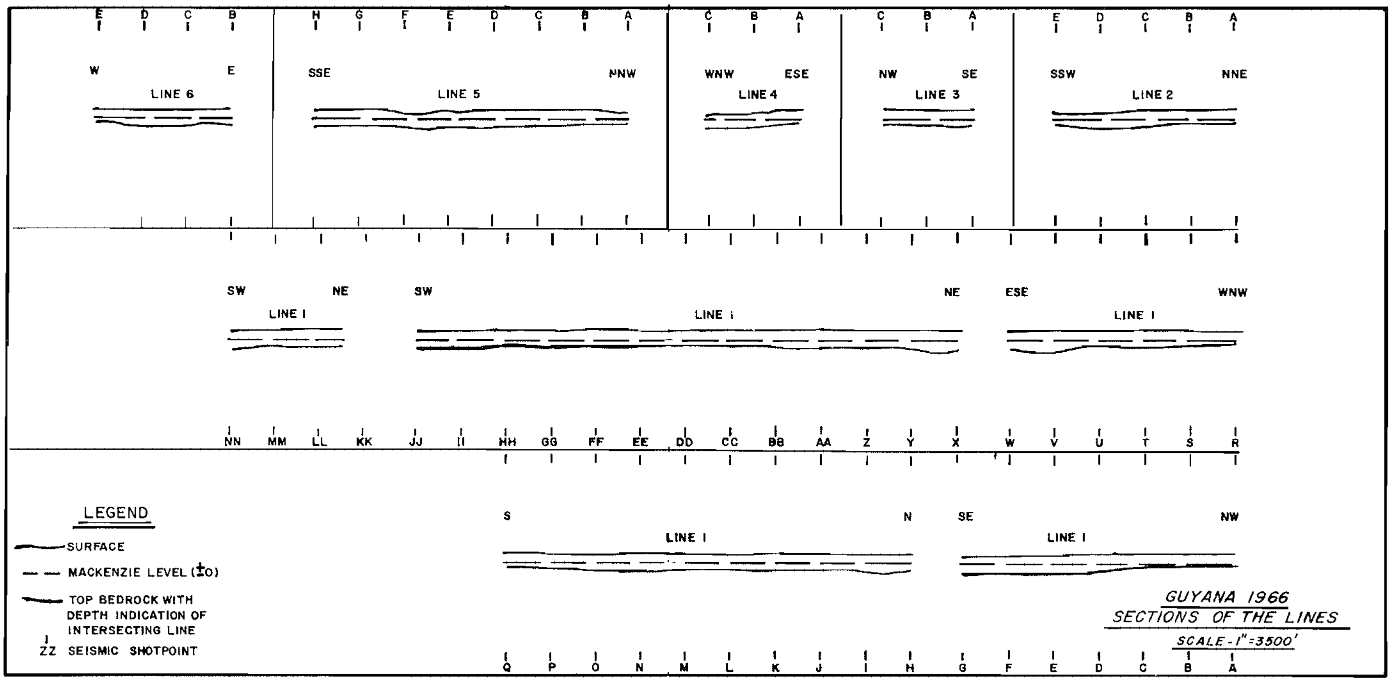


Figure 2. Vertical sections along several lines plotted from topographic and seismic field observations.

the west flank of the Berbice Trough to suggest that the line pattern should be somewhat altered. Consequently, during 1967 north-south lines were spaced first at 10,000-foot intervals and later followed up with a number of east-west lines at 3600-foot intervals or closer wherever the north-south lines showed basement highs warranting further study.

The seismic work is being carried out under contract by Seismos, of Hannover, Germany. The recording equipment is mounted in a Land Rover. The equipment was built by Seismos with fully transistorized amplifiers for 24 traces. The instrument has automatic gain control, presuppression, filtering and mixing. A magnetic tape recorder is used and the film is developed in the field.

In the initial test period, the refraction method yielded excellent results while the reflection method did not provide positive interpretational data. In the latter case, trace spacing was reduced from 50 feet to 25 feet without any improvement being observed in the records. The refraction method was therefore adopted as the standard method for our work. After testing, an optimum filter setting of 12 to 100 cps was selected for all refraction recordings. As far as shooting techniques are concerned, 24 miniature geophones were planted per trace, but this was later modified to 18 per trace. The explosive charges were laid just below the surface, in hand-dug holes, at a depth of approximately 3 feet.

The prospecting areas in Guyana are densely forested, and extensive line cutting and road making is required well ahead of time to permit the seismic survey to operate under optimum conditions. Seismic profiling along the traverse lines, under these latter conditions, averages 5000 feet per day.

While statistics are not yet available for the 1967 field work during the period August 1965 to July 1966, a seismic profile distance of 172 miles was covered, embracing an area of some 40,000 acres. Explosive consumption averaged 390 pounds per mile of line traversed, increasing to 452 pounds per mile in 1967.

The records obtained have been generally very good and the quality of the first 'breaks' excellent. Occasionally, the noise level from wind, rain or various pieces of equipment caused some deterioration in the quality of the records with delays in the operation. In all areas surveyed one refractor, with a velocity varying from 4500 to 6500 meters per second, could be read continuously. This represents the subweathered layer. Velocities in bedrock average 17,000 to 19,600 feet per second. In interpreting the results, the observed 'first breaks' or, in other words, the arrival times of the refractive waves, were taken from the records, plotted and represented as time-distance curves for each spread. For velocity and depth calculations the plus-minus method was used and applied as a basic tool. All observed data were referred to the true surface level. Figure 2 shows the results obtained along several lines, plotted in section at a scale of 1 inch = 500 feet. The upper line represents the surface topography, the middle dashed line Zero Elevation Mackenzie Datum and the lower heavy line the top of bedrock.

Conclusions

In the special case of the Berbice-Essequibo area in Guyana, a knowledge of the basement topography is a useful tool in the location of buried bauxite occurrences because of the indicated relationship in this area between bauxite and basement 'highs'. While it does not directly indicate the presence of bauxite, and although all highs are not expected to be overlain by a bauxitized horizon, such information helps to eliminate large areas from costly and time-consuming deep drilling. As our knowledge of the relationship between elevations of the basement rock and elevations of bauxitized surfaces increases over a broader area, it is believed that this work may provide a knowledge of controlling elevations which would allow more accurate spotting of areas which are likely to yield bauxite on drilling. It is again emphasized that the relationships in question refer only to bauxites which have formed from, or as part of, autochthonous residual clays on crystalline basement rocks.

Acknowledgments

The writer is indebted to Alcan Aluminium Limited for permission to publish the foregoing and to the Demerara Bauxite Company, Limited for permission to include data from their area of operations. Mr. E. Anderson, the latter's Chief Geologist, was most helpful in various verbal discussions, and portions of his paper (Anderson, 1966) dealing with the current program in Guyana, were freely used. The writer also wishes to express his deep appreciation to Dr. R. Grimes-Graeme for useful discussions and help in editing the foregoing.

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Contents

The application of geophysics to exploration for chromite and tungsten

V.A. Klichnikov and V.I. Segalovich

U.S.S.R.

Abstract. Gradiometers and precise gravimeters have been used in the southern Urals and in Kazakhstan to locate chromite orebodies. Quantitative interpretations of gravimetric surveys over ultrabasic rocks and aeromagnetic surveys over basic rocks are used to delineate these rocks, with which chromite deposits may be associated.

Density, magnetic and radioactive contracts are used to delimit granitic areas with which tungsten deposits may be associated. Geochemical, electrical and magnetic methods are also used in the search for rare-metal deposits.

Résumé. Des gradiomètres, gravimètres précis ont été utilisés dans le sud de l'Oural et au Kazakhstan pour localiser des gîtes de chromite. L'interprétation quantitative de mesures gravimétriques sur des roches ultrabasiques a permis de cartographier les roches auquelles les dépôts de chromite sont associées.

Les contrastes de densité, de propriétés magnétiques et de radioactivité sont utilisés pour la cartographie des zones granitiques auquelles les dépôts de tungstène sont associés. Les méthodes géochimique, électrique et magnétique sont aussi utilisées dans la recherche des métaux précieux.

Chromite and tungsten deposits belong to different genetical types and different geophysical methods are used for their exploration.

Chromite deposits

Since 1929 geophysical methods, first of all gravity methods, have been successfully used for the exploration of chromite in the Urals and Kazakhstan (Andreev, 1937; Yunkov, 1937). In the last decade, owing to the use of highly efficient gradiometers and precise gravimeters, the exploration has been carried out on extensive areas. Especially good practical results have been achieved in the Urals in the region of intrusion of ultrabasic rocks.

The intrusion is formed by peridotitic serpentinites, in which dunite occurs in the form of schlieren and as bands of varying thickness. In the intermediate zones between the above mentioned rocks pyroxenitic dunites are embedded. Besides rocks of the vein complex, principally gabbro-diabases and also pyroxenites and hornblendites are abundant in this intrusion.

Productive chromite deposits are located as a rule in dunitic serpentinites in the southeastern part of the intrusion and are represented by groups of orebodies spaced 200 to 300 m from one another. The orebodies concentrate in the linear zones of the submeridional strike. They are lenticular and egg-shaped and their size is about tens by hundreds of metres. The orebodies are of a richly disseminated type and have a density of 3.2 to 4.6 gr/cm^3. The contact of these bodies with host serpentinites is usually sharply marked.

The high density of chromite and the large size of orebodies predetermine the choice of gravity prospecting as the principal method used for the search of chromite deposits. The flat terrain or slight relief favour the advantageous use of the gravity method. The gravity effect of topography in this region does not exceed 0.1 mgal. The density variations and the variations of the thickness and composition of the overburden, as well as the gravity effect of deeply buried masses ('regional background') impede and complicate gravity surveying. The consideration of these factors is one of the important requirements for the effective application of gravity methods for the search of chromite deposits.

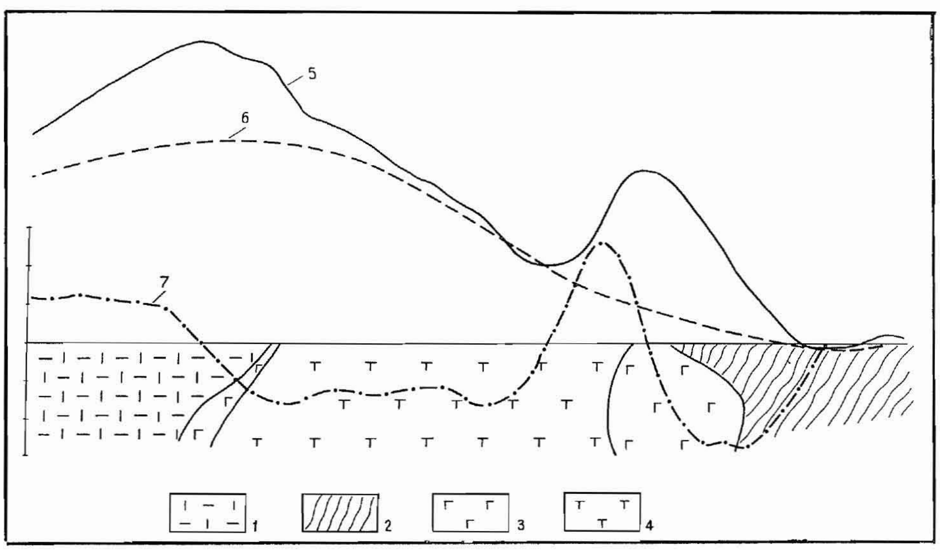

Figure 1. Curves of observed Δg (solid line), regional background (dashed line) and second gravity potential derivative U_{xz} (dotted-dashed line) along the profile intersecting the northern part of the intrusion. 1 – ancient crystalline schists and gneisses; 2 – upper Cambrian metamorphic schists and tuffaceous sedimentary rocks; 3 – gabbros and amphibolites; 4 – serpentinites.

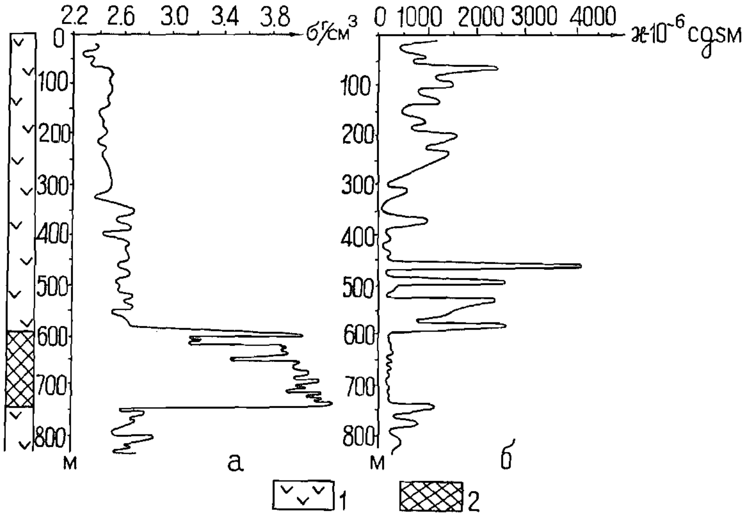

Figure 2. Curves of density (a) and magnetic susceptibility (b) variations at a chromite deposit. 1 — serpentinites; 2 — chromite.

The average density of dunite and peridotite serpentinites is 2.40 – 2.53 gr/cm³. The density of gabbroid (2.83 gr/cm³) and that of metamorphic schists (2.65 gr/cm³) in which the intrusion is embedded is greater than that of serpentinized rocks in the intrusion itself. For this reason near the exocontact of the intrusion gravity 'steps' having an amplitude of 2 to 4 mgal and local anomalies due to gabbroids are observed (Figure 1).

The density of serpentinites near the surface of the earth is 2.40 gr/cm³ and it increases with depth up to 2.58 gr/cm³ owing to the decreasing rate of serpentinization of ultrabasic rocks. In contrast to serpentinites, gabbro-diabases and pyroxenites have an effective density of 0.3 – 0.4 gr/cm³ at depth and 0.7 – 1.0 gr/cm³ near the surface of the earth. In the latter case the effective density of gabbro-diabase and pyroxenite is comparable to that of chromite in relation to serpentinite host rocks. But the gravity anomalies of gabbro-diabase dykes have a latitudinal strike which discriminates them from anomalies due to orebodies having an isometric or elongated form in the meridional direction.

The magnetic susceptibility of chromite ores is, as a rule, hundreds of ppm (CGS) and decreases with depth owing to the decrease of the content of secondary magnetite. Zones of higher magnetic susceptibility due to serpentinites are sometimes observed adjacent to chromite ore (Figure 2). On the whole the ore-bearing serpentinites are characterized by a low magnetic field but in the vicinity of the contacts of the ultrabasic intrusion with gabbroid and other rocks the magnetic susceptibility may be relatively high and this makes possible the application of magnetic methods for the delineation of the contracts of the ultrabasic intrusion and also for mapping gabbro-diabase dykes. In the direct search for chromite magnetic methods cannot be used.

Gravimetric and magnetic surveys conducted with the aim of mapping the intrusions of ultrabasic rocks and for structural investigations are carried out on the scale of 1:50,000. The gravity fields in the northern and in the southern parts of the intrusion are quite different. The northern part of the intrusion has a positive anomaly, the maximum of which corresponds to gabbroid and metamorphic schists adjacent to the ultrabasic rocks. The central part of the intrusion has a negative gravity anomaly while the southeastern part has an intensive positive one. The above mentioned north, central and southeast parts of the intrusion are separated by linear zones of gabbroid dykes indicated by bands of positive gravity anomalies, having values of 2 to 4 mgal and widths up to 1.5 to 2.0 km.

The south and north regional positive gravity anomalies are probably due to deep intrusions of nonserpentinized ultrabasic rocks. The thickness of the serpentinized part of the Kempirsay intrusion according to gravity data is approximately 1.5 km.

Because of gravimetric data it has been possible to establish that the intrusion in the southeast has a steep boundary and a relatively smooth dip in the northwest, its vertical thickness being not less than 5 km.

The intensity of the magnetic field in the southeastern part of the intrusion is somewhat lower than that in other parts of the intrusion (some hundreds of gammas). The decreased magnetic susceptibility and decreased density of ultrabasic rocks in the southeastern part of the intrusion is due to the low content of

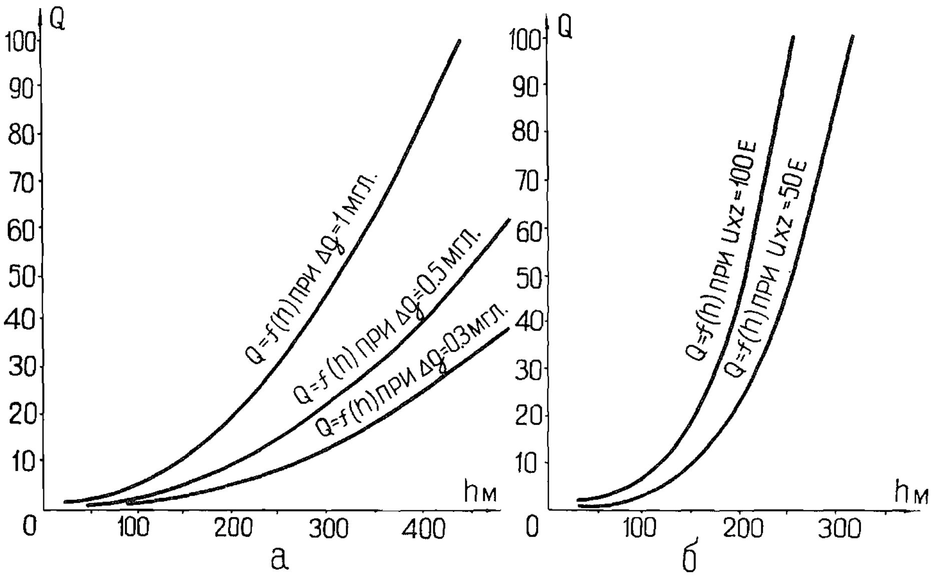

Figure 3. Curves showing the dependence of the effective spherical body mass (in millions of tons) on the depth of the centre of the body (in metres) for certain anomalies of Δg (a) and U_{xz} (b).

secondary magnetite and iron, in general, in these rocks. Petrochemical investigations (Pavlov, 1959) indicate a genetic relation between magnesium chromite deposits and ultrabasic rocks having a low iron content. Consequently the above mentioned physical properties of rocks and appropriate characteristics of the gravitational and magnetic fields may be used for the selection of chromite areas. In regions adjacent to the intrusion gravimetric and magnetic surveys were conducted on scales from 1:200,000 to 1:50,000 with the purpose of discovering ultrabasic intrusions.

Gravity anomalies due to chromite ores have as a rule an intensity of not more than 2 mgal and their areas range from 0.1 to 0.2 km^2. In the first years of prospecting for orebodies in the district, variometer surveys were made and later on detailed gradiometric surveys which were conducted along latitudinal profiles over a grid of 100 X 20 m (a station density of 500 per square km). Such a grid provided the discovery of deposits at a depth of 50-100 m having minimal economic reserves. In recent years gravimetric surveys were used for the exploration of deeply buried orebodies, these surveys being made over a grid of 200 X 50 m or a grid 100 X 100 m. The survey error was 0.04 – 0.06 mgal. The gravity effect of density variations of host rocks is 0.02 – 0.04 mgal. Hence for reliable interpretation the intensity of gravity anomalies must be not less than 0.3 mgal. While measuring the second derivative of the gravity potential in the southeastern part of the intrusion the noise level was ±20 E. Therefore orebodies can be reliably detected only when the intensity of the gradient anomaly is not less than 50 to 60 E.

Using the above mentioned minimum values of the anomalies, it is possible to estimate the depth of investigations when the surveys are made with gravimeters and gradiometers. Theoretical calculations have been made for the case of a spherical body having an effective density of 0.5 gr/cm^3. Figure 3 represents curves of effective body masses (in millions of tons) versus the depth of the center of these bodies for some predetermined values of gravimetric and gradiometric anomalies. Assuming that the minimum values of the effective body mass approximately correspond to ore reserves of 10 to 15 million tons, we estimate the depth limit of exploration to be 300 to 500 m for gravimetric and 150 to 200 m for gradiometric surveys.

The calculated value of the depth of investigation is practically attainable when all kinds of noises (regional background included) are taken into account.

In the interpretation of the variometrical surveys residual anomalies have been detected for years by subtracting from the measured vectors, the average vector corresponding to the area under investigation. But very often the investigation area was not larger than the area of the orebodies themselves and this way of interpretation had the result that some anomalies were missed and the depth of investigation reduced.

At present the detection of residual anomalies is achieved by subtracting from the measured vectors the average vectors calculated by averaging the results around every station of the survey. The averaging is done by using 1 km squares, which are slightly larger than the area of ore anomalies. Sometimes, for the purpose of increasing the precision of the results, the evaluation of gravity values is made using areas of different size (in which the average data are determined).

Moreover, the interpretation of data measured by variometers and gradiometers comprises a recalculation of the second derivative of gravitational potential into its first derivative. As a result, integration maps of gravity anomalies having a contour interval of 0.20 or 0.25 mgal are obtained. All chromite deposits of the region are shown on these maps. In one of such areas after the interpretation, a distinct anomaly was revealed and a new chromite orebody was discovered by drilling.

Maps of vectors and contour lines of gravity data for this area are represented in Figure 4. Surveys with gradiometer GRB-2 were made in 1960 and according to data obtained in the northern part of the area shown in Figure 4 chromite orebodies at

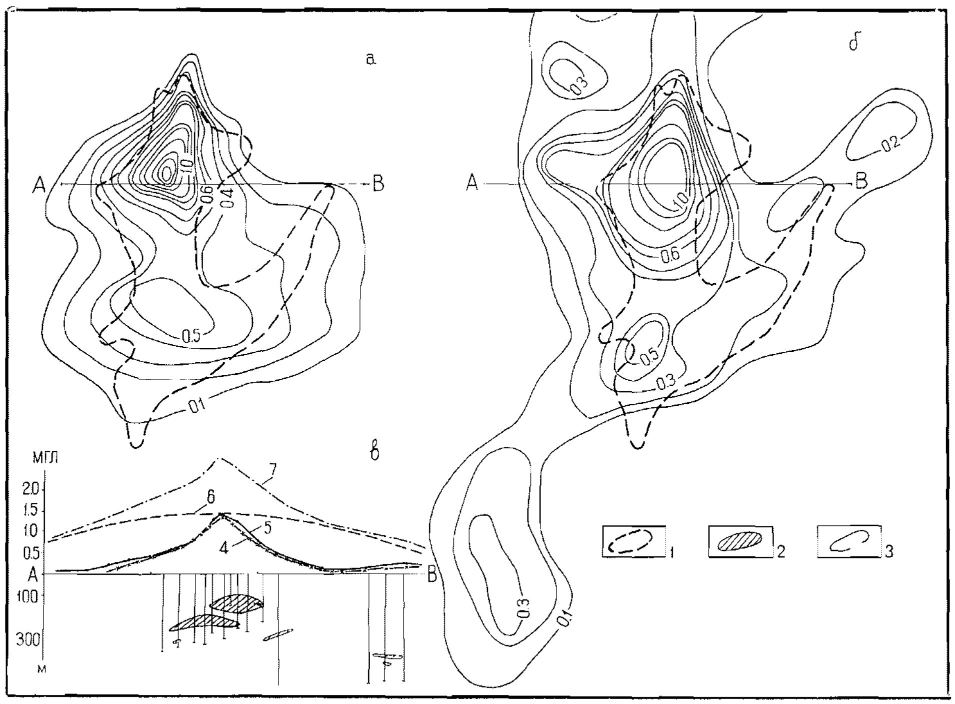

Figure 4. A contour map of calculated Δg (a) and observed Δg (b) and also curves of Δg along a profile laid over the chromite deposit. 1 – the contour of the chromite deposit (a plan view); 2 – the contour of orebody (a sectional view); 3 – the contour lines of a gravity anomaly; 4 – the calculated Δg; 5 – the residual Δg; 6 – the regional Δg; 7 – the measured Δg.

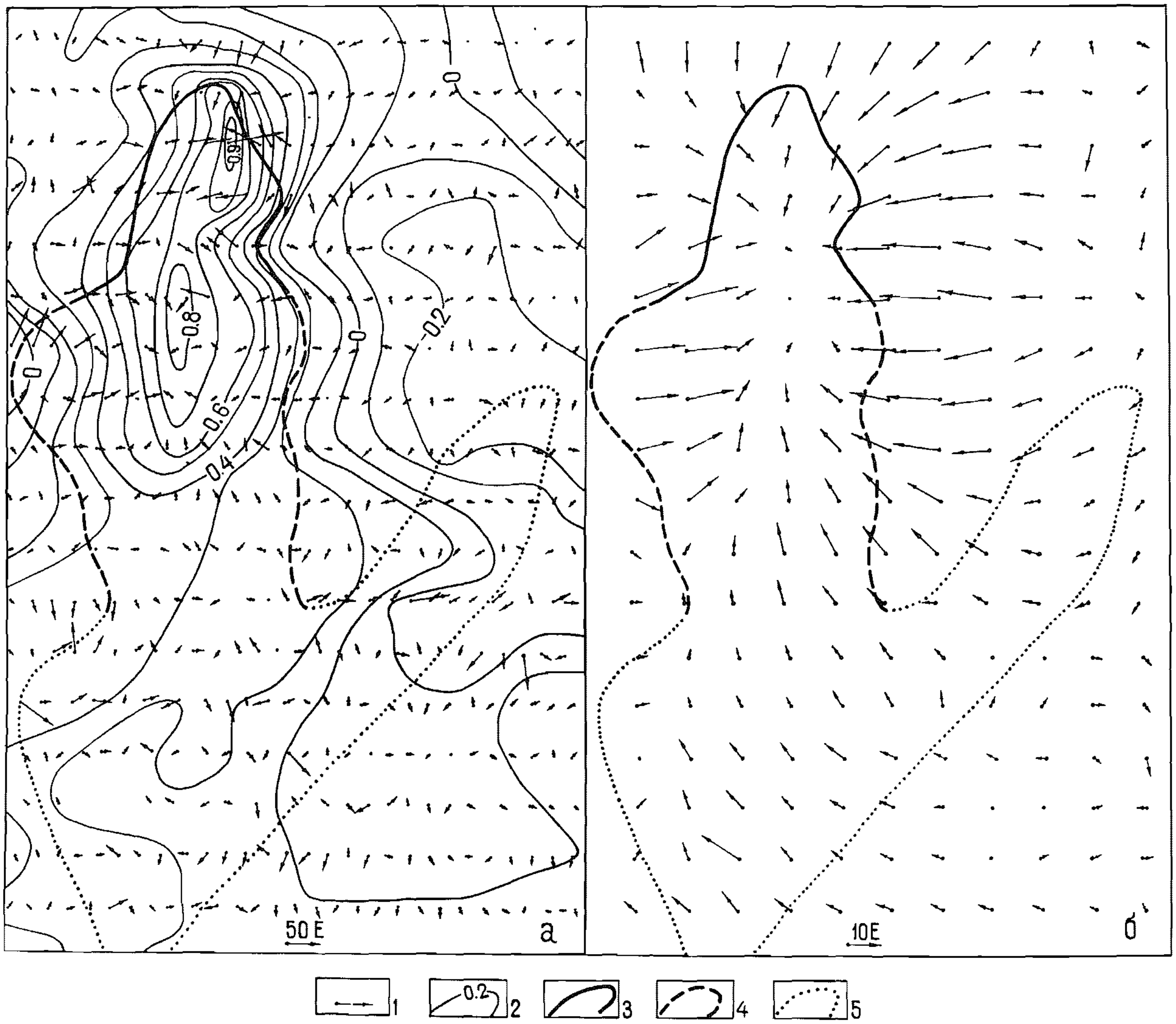

Figure 5. Plots of measured (a) and residual (b) vectors over the chromite deposit. 1 — the vector U_{sz}; 2 — the contour line of a gravity anomaly; 3 — the generalized contour of orebodies up to a depth of 50 m; 4 — up to a depth of 150 m; 5 — up to a depth of 500 m.

a depth of 150 m were revealed. Later on an integration of the measured gradient of gravity was made and it resulted in establishing the extension of the anomaly to the south and a new, deeply buried, large body was discovered.

When searching for deeply buried deposits high-precise gravimetric surveys are used as well. Due to gravimeter surveys in the described region, new chromite deposits were discovered. An example is shown in Figure 5. In the right-hand side of the figure contour lines of the observed gravity anomaly are shown and in the left-hand side contour lines of the calculated gravity anomaly for bodies are shown on the cross section in the lower part of Figure 5.

The second example is given in Figure 6. In the right-hand side of the figure a graph of Δg is given. In this particular case the regional background is considered to be linear and a residual anomaly of Δg can be detected with the precision of 0.1 mgal. The intensity of the local anomaly of Δg (as seen in the left-hand side of Figure 5) is 0.7 mgal and the deposit is clearly outlined.

It must be noted that quantitative interpretation of gravimetric anomalies is very important for locating the sites and for determining the depth of bore-holes. The interpretation is as a rule made by calculating graphs of gravity anomalies or by calculating gradient anomalies for predetermined positions of the bodies, various shapes, and effective density. The selection of the shape, size and depth of orebodies is based on the known features in this region. After drilling test holes over gravity anomalies, curves corresponding to revealed ore anomalies are computed and the observed field curves are compared with calculated curves. The difference between these curves sometimes serves as an additional anomaly curve, indicating the presence of new orebodies not exposed by drilling. This method of interpretation of measured data is most effective in the search for new orebodies on the flanks of explored deposits.

Geochemical methods on the whole have not found wide application for the search of chromite deposits because no indicator-elements have been found as yet for chromite ore.

Thus gravity surveys remain the principal method used for locating deeply buried chromite ore in the South Urals.

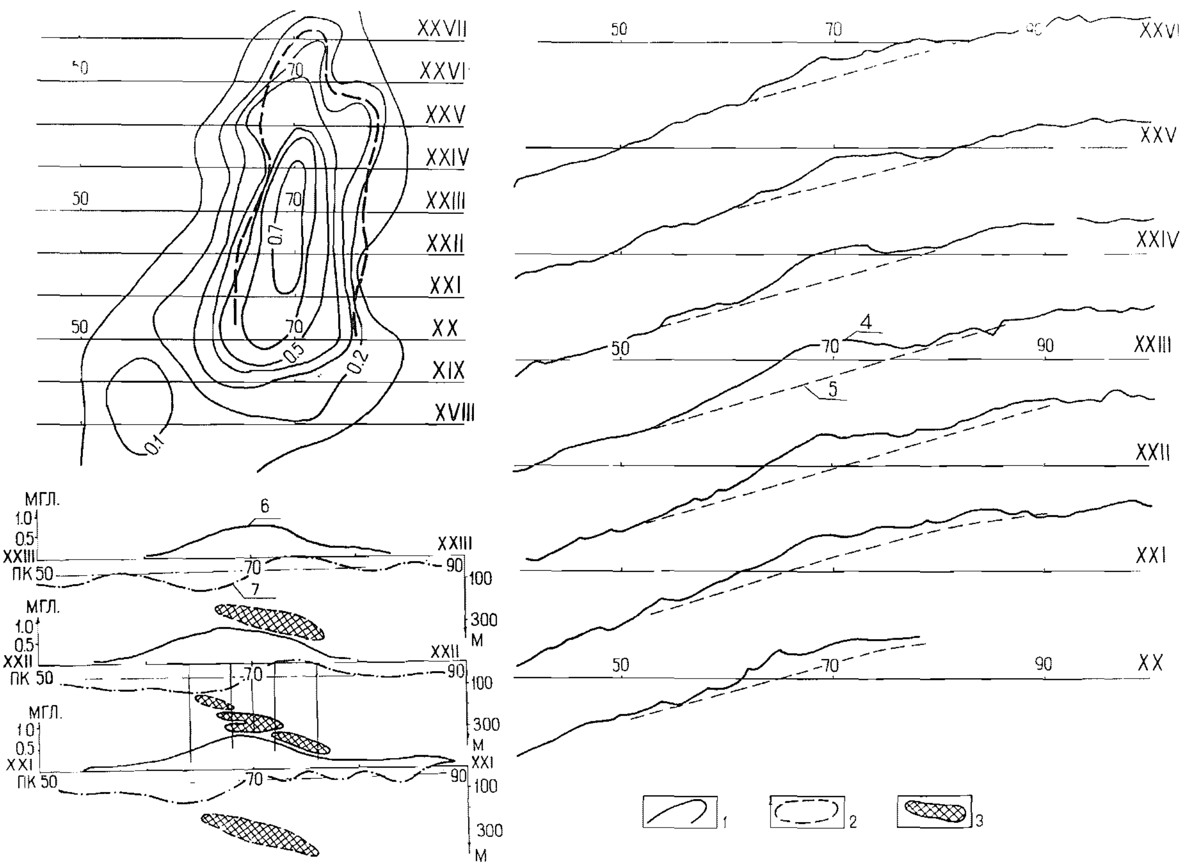

Figure 6. Contour lines of a gravity anomaly, diagrams of U_{xz} along a number of profiles and the geological section at a chromite deposit. 1 – contour lines of residual Δg; 2 – the outlines of the deposit (a plan view); 3 – the outlines of the orebodies (a sectional view); 4 – curves of measured Δg; 5 – curves of regional background; 6 – curves of residual Δg; 7 – curves of measured Δg.

Tungsten ore deposits

Geophysical methods are used for making regional surveys with the purpose of locating promising areas. Principally gravity and magnetic surveys are made and these usually on a scale of 1:200,000 and smaller scales.

Deposits associating with acid magmas (leucocrate mineralization) occur in regions of deep geosynclinal sinking, where negative gravity anomalies have been noted (Andreev, 1960). The gravity minimum is explained (Andreev, 1958; Kazanly, 1958; Shcherba and Popov, 1962) by an increase of thickness of the earth's crust. The increase in thickness of the earth's crust in this region is confirmed by deep seismic soundings.

The above mentioned regularities are noted in other regions of the U.S.S.R. The classification of regions according to the endogenic metallogenic principle is probably based on the peculiarities of their structure at great depth. The study of the latter problem is the task of regional surveys, carried out on a scale of 1:200,000 and smaller scales.

The possibility of locating promising areas for tungsten ores is based on the connection of rare metal deposits with leucocratic and moderately acid granite. Quartz-vein deposits are generally located within granitic intrusions or on their exocontacts. Stockwork deposits occur over intrusive zones. Both types of deposits are often within a single ore field. As a rule the ores are complex; they contain wolframite, scheelite, cassiterite, molybdenite, beryl, bismuthinite and other minerals. The ores often contain a large amount of pyrite.

A zonal structure is noted in some deposits: the molybdenum mineralization occurs closer to the mother intrusion than the tungsten mineralization.

In Kazakhstan gravity methods on a survey scale of 1:200,000 to 1:50,000 and magnetic and radioactive methods on the scale of 1:50,000 to 1:25,000 were used for mapping ore controlling granite intrusion.

The application of the gravity method is based on the density contrast between granites and rocks surrounding the intrusion, the density being 2.50 to 2.58 gr/cm³ for granite and 2.67 to 2.70 gr/cm³ for host rocks. Predominantly all known deposits are associated with gravity minima (Figure 7). Many deposits occur in the area of minor values of gravity and are associated with the dome of the intrusion, others are somewhat displaced towards the sides probably in the direction of ore-controlling structures. An interesting regularity was found in Kazakhstan: separate but large deposits of tungsten ores are confined to relatively small domes (their area is about units or first tens of square km), whereas large domes (having several tens of square km) are accompanied by many small occurrences. Some intrusions are characterized by deep erosional sections and have practically no rare metal occurrences.

Contents

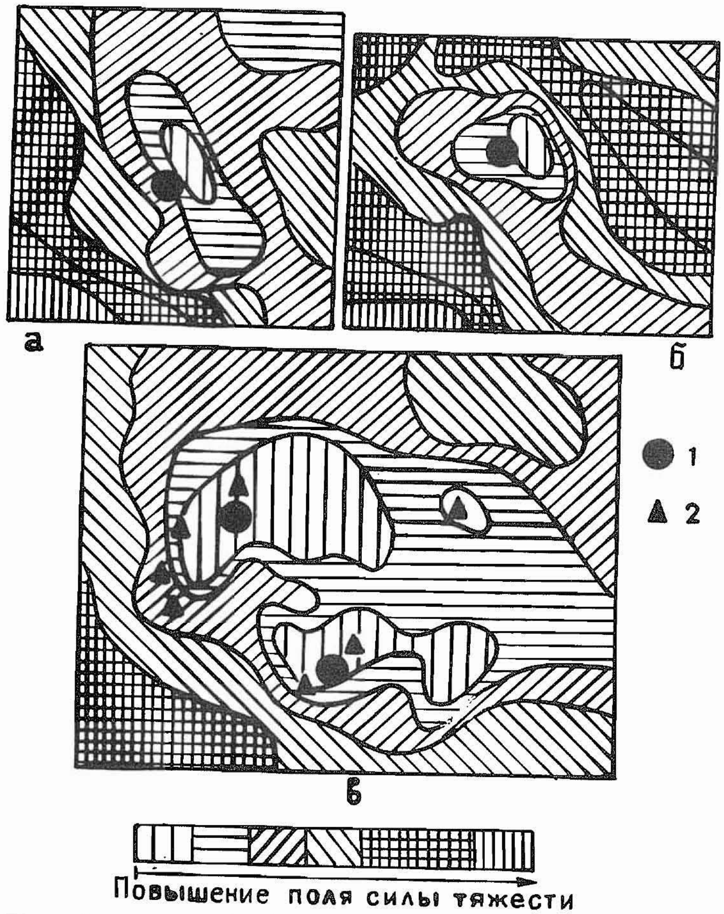

Figure 7. A schematic plot of the gravity anomaly distribution in three regions that have molybdenum-tungsten deposits (according to Moiseenko, 1959). 1 — deposits; 2 — ore mineralization.

Magnetic and radioactive methods may be used in searching tungsten ores because granites have a relatively low magnetic susceptibility (not more than 100.10^{-6} CGS) and a high radioactivity (about 25 mcR/h with a background of 5 to 12 mcR/h when flying at the height of 50 m). The host leucocratic granites may be located by reason of their lower magnetic field intensity and higher radioactivity. On the other hand, in Central Kazakhstan non-ore-bearing leucocratic and alaskitic granites are accompanied by an increase of magnetic field, which is associated with accessory magnetite that has a magnetic susceptibility as high as $(500\text{-}640)10^{-6}$ CGS.

Detection of low magnetic field intrusions and zones overlying intrusions is sometimes rendered easy owing to the contact metamorphism zones, which occur on the intrusion margins. These marginal zones have a high magnetic susceptibility up to several thousands 10^{-6} CGS. Intensive magnetic anomalies are noted over these intrusions (Figure 8). Radioactive surveys mentioned above give additional information facilitating the detection of relatively young ore-bearing intrusions. The position of rare metal ore mineralization and radioactive anomalies in Altai is shown in Figure 9. Tungsten ores as a rule have low radioactivity and deposits of these minerals cannot be distinguished by radioactive anomalies.

Geochemical, electrical and magnetic methods are of major importance in the search for rare metal deposits. Magnetic and electrical methods are indirect methods. Their successful application depends on the genetic relation of wolframite and scheelite with magnetite, pyrite and other minerals, which gives rise to magnetic and electrical anomalies. Wolframite-magnetite skarns are most favorable for geophysical methods, including magnetic, induced polarization, resistivity and spontaneous polarization methods. Quartz-wolframite veins and stockworks are more difficult objects for geophysical methods. Magnetic methods are

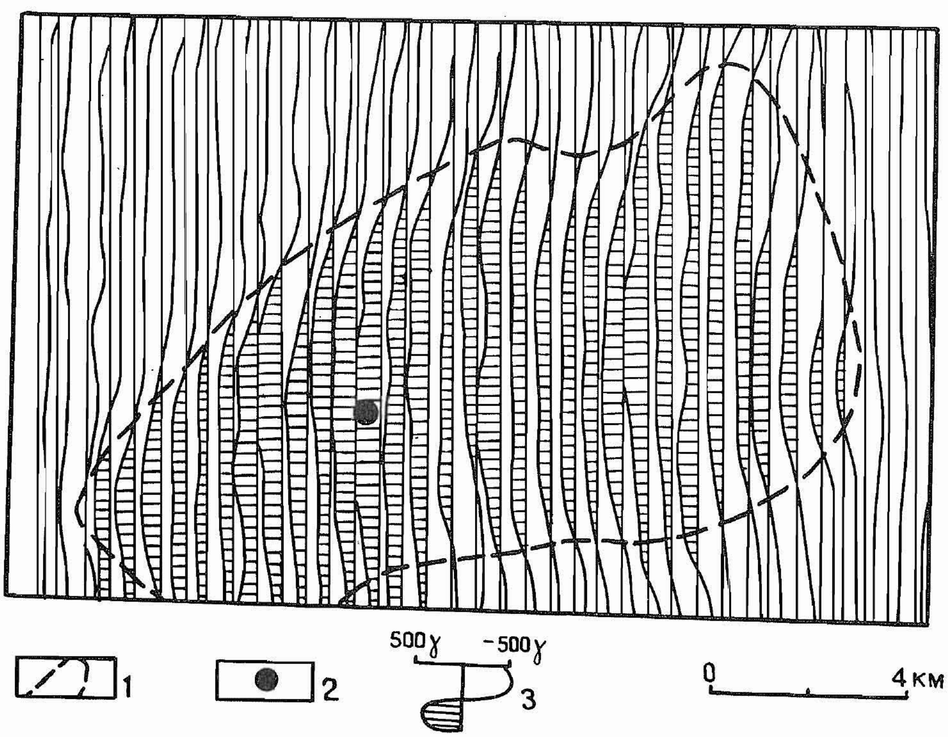

Figure 8. A plan of curves of ΔT in the area of a tungsten-bearing stockwork. 1 — the outlines of the zone overlying the intrusion; 2 — a tungsten deposit; 3 — the vertical scale of the curves of ΔT.

Figure 9. A plan of the distribution of the gamma-field and rare metal mineralization in Altai (according to Smilkstin, 1962). 1 — mineralization; 2 — the intensity scale of the gamma-field: from 5 to 9 microroentgen per hour; from 9 to 14 mcR/h; from 15 to 22 mcR/h; from 22 to 30 mcR/h.

chiefly used to locate these deposits and their successful application depends on the degree of the hydrothermal alternation of ore-bearing rocks that greatly affect the magnetic susceptibility. Hydrothermal alteration of rocks is mostly exhibited in the zone adjacent to the exocontact where greisenization has taken place. Molybdenum deposits occur in these zones as well as tungsten deposits together with deposits of other minerals. Under favorable conditions distinct negative magnetic anomalies are noted which correlate well with the deposits. An example of such a magnetic anomaly is shown in right-hand side of Figure 10. The contours of greisenization and pyritization zones, the position of ore veinlets and bore-holes intersecting ores may also be seen in this drawing. No magnetic anomalies directly connected with orebodies are noted. Under these conditions electric methods are of the greatest importance and first of all the induced polarization method. Large amounts of pyrite in these

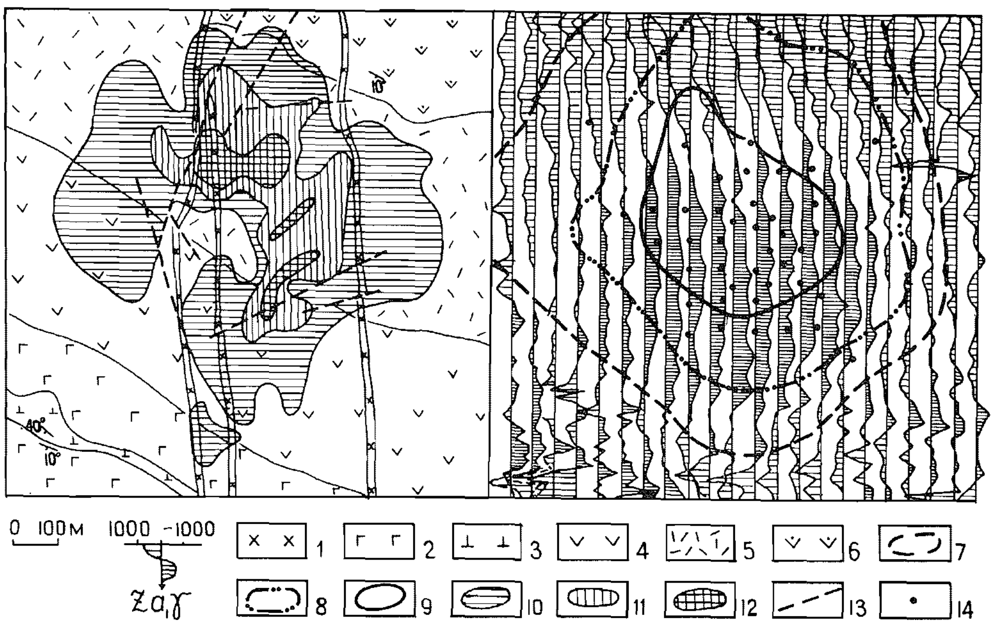

Figure 10. Plans of geochemical (left) and magnetic (right) anomalies at the stockwork rare metal deposit. 1 — granodiorite porphyries; 2 — andesite porphyries and their tuffs; 3 — basaltic porphyries; 4 — tuffs of liparite porphyries; 5 — dacitic porphyries; 6 — agglomerate tuffs of dacitic porphyries; 7 — the outline of the zone of pyritization; 8 — the outline of the zone of spread of ore veinlets; 9 — the outline of the zone of greisenization; 10 — the zone of tungsten-content in diluvium from 0.005% to 0.01%; 11 — from 0.01 to 0.4%; 12 — from 0.04 to 0.07%; 13 — tectonic dislocations; 14 — exploratory drill holes.

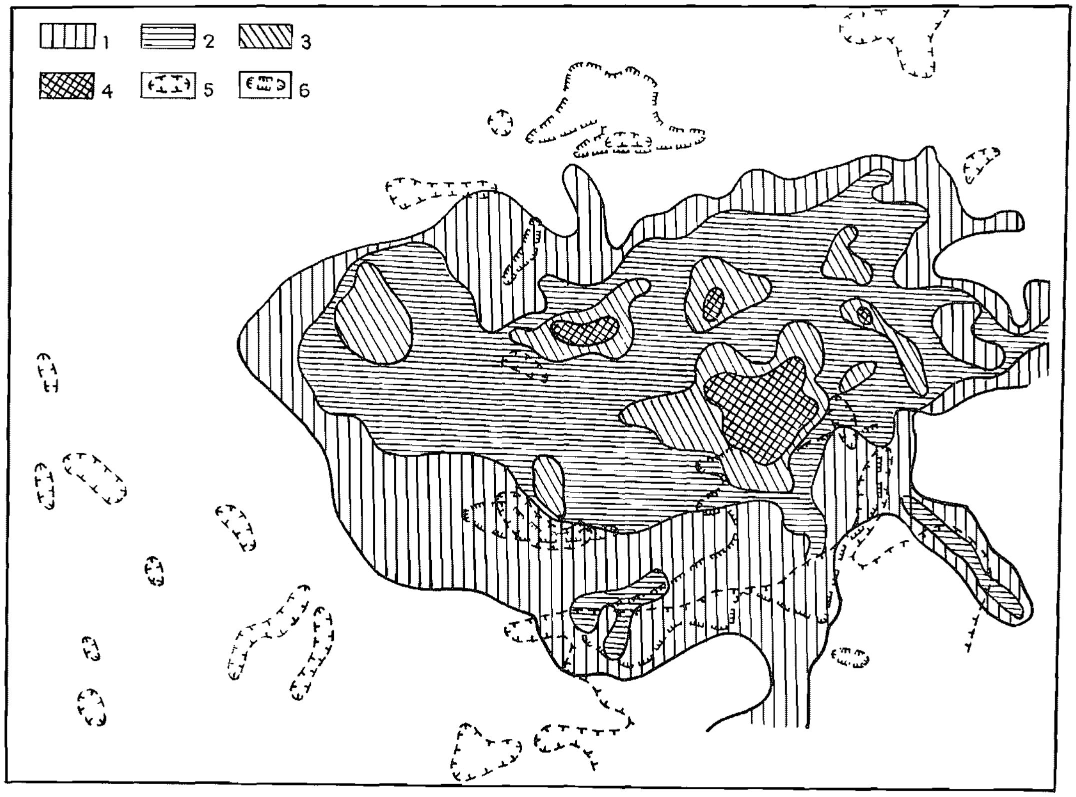

Figure 11. Plan of geochemical anomalies at the tungsten deposit (according to Miller, 1962). 1 – the zone of tungsten content from 0.005 to 0.01%; 2 – from 0.01 to 0.02%; 3 – from 0.02 to 0.04%; 4 – from 0.04 to 0.3%; 5 – the zone of lead-content from 0.1 to 0.15%; 6 – the zone of copper-content from 0.07 to 0.3%.

ore zones account for the successful application of the IP method. Pyritized rocks give rise to distinct IP anomalies sometimes even where the orebodies, surrounded by pyritized rocks, occur at great depth. Rare-metal ore fields are usually large and the induced polarization on a scale of 1:50,000 (over a grid of 500 X 50 m) is used for their search. In the detailing of induced polarization anomalies the grid is up to 250 X 50 m or even more. Along with induced polarization, resistivity measurements are made. Using curves of apparent resistivity it is possible to delineate the zones of tectonic disturbances and quartz veins, and to solve other problems of geological mapping.

Geophysical surveys permit the detection of ore-controlling intrusions and promising areas over intrusions in their vicinity. Geochemical and metallogenic surveys give a direct indication of the presence of the metals being prospected. When searching for tungsten deposits the principal element-indicator is tungsten, which occurs in geochemical haloes surrounding these deposits. In these haloes tungsten as a rule associates with molybdenum, tin, bismuth, beryllium, lead, zinc and copper. Samples are usually taken from diluvium. The quantity of elements depends on geological conditions; the thickness, composition and genesis of unconsolidated rocks. The anomalous content for tungsten, molybdenum, tin and beryllium is one thousandth of a percent. For lead, zinc and copper – one hundredth of a percent. The content of above mentioned elements in samples of diluvium, is usually lower than its content in host rocks. An example of the geochemical surveys is given in the left-hand side of Figure 10.

The complicated form is characteristic for haloes if disseminated tungsten and the displacement of haloes towards ore outcrops is not large even for rough relief. Geochemical surveys permit the outlining of marginal zones and the evaluation of the amount of mineralization (Solovov, 1959). In one of the Kazakhstan regions it has been found possible to properly guide the search for large tungsten stockworks by means of geochemical surveys on a scale of 1:10,000. Prior to the heavy concentrate analysis the narrow band, having a meridional strike, was considered promising. But geochemical anomalies have latitudinal strike and further prospecting was successfully carried out in the areas corresponding to anomalous contents of tungsten in diluvium (Figure 11).

The pattern of rare metal distribution in ores is reflected in the zonality of geochemical anomalies. The anomalous content of molybdenum is associated with a stockwork of granite-porphyry, while that of tungsten with the periphery of the stockwork. Further from the stockwork and on its periphery anomalous contents of lead, copper and zinc were observed. All these features are shown in the map of the deposit (Figure 11). The taking into consideration of this zoning of metallometric data serves to predict the depth of the erosional section of the deposits prospected and the probable alteration of ore composition with depth.

All tungsten deposits located by geochemical surveys are in regions with small thickness of overburden. The integral application of geophysical and geochemical methods results in many discoveries of deposits of tungsten ores in regions having no thick overburden. But these methods have also proved effective to some extent in regions with relatively thick overburden.

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Geophysics and asbestos exploration

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Abstract. This paper treats only exploration for chrysotile asbestos in ultrabasic rocks.

Magnetic surveys remain the principal geophysical tool for discovery, delineation and structural study of ultrabasic bodies. Interpretation of rock types, fault structure, and associated anomalies, followed by drilling through overburden, has resulted in the discovery of a number of asbestos prospects. Electromagnetic surveys have produced erratic conductor patterns difficult to explain. Brief case histories with diagrams provide examples of both types of surveys.

Ultrabasic bodies are commonly assumed to be magmatic intrusions. An extrusive volcanic origin for many ultrabasic rocks, especially within volcanic piles, now appears probable to the writer. This hypothesis provides numerous geological possibilities in connection with petrology, emplacement, age relations, and ore genesis. It broadens the scope for correlating geophysical results with ore occurrences.

Résumé. L'auteur traite seulement de l'exploration de l'amiante chrysotile dans les roches ultrabasiques.

Les relevés magnétiques demeurent le principal outil géophysique employé dans la recherche des massifs ultrabasiques et dans l'étude de leur forme et de leur structure. L'interprétation des genres de roches, des structures des failles et des anomalies associées, suivie de forage au hasard à travers les morts-terrains, a conduit à la découverte d'un certain nombre de gisements d'amiante. Les relevés électromagnétiques ont donné des réseaux conducteurs erratiques difficiles à expliquer. L'auteur donne des exemples des deux genres de relevés à l'aide de cas précis et de diagrammes.

On suppose généralement que les massifs ultrabasiques sont des intrusions magmatiques. L'auteur pense maintenant que plusieurs roches ultrabasiques et surtout celles qui se trouvent dans des piliers volcaniques seraient d'origine volcanique extrusive. Cette hypothèse fournit de nombreuses possibilités géologiques relativement à la pétrologie, la mise en place, les relations d'âge et la formation des minerais. Elle ouvre de nouveaux horizons dans la corrélation des résultats géophysiques avec les venues de minerai.

This paper briefly describes some geophysical instruments, procedures and interpretation used in exploration for chrysotile asbestos deposits by Canadian Johns-Manville Company, Limited. Magnetic survey methods are paramount. Electromagnetic surveys have limited application and are usually a byproduct of base metal search. Shallow seismic techniques show some promise.

The purpose of magnetic surveys is:

1. To locate and delineate magnetic bodies of presumed serpentinite;
2. To segregate, if present, the facies or layers in composite basic-ultrabasic bodies, i.e., gabbro, pyroxenite, peridotite, dunite, associated carbonate rock; and
3. To discover anomalous features within the favorable layer (usually a serpentinized peridotite).

Interpretation of the data has been largely empirical. It is based on geologic knowledge of the habits of ultrabasic bodies encountered during widespread asbestos exploration.

Instruments and procedures: Magnetic surveys

The types of magnetic instruments and surveys procedures are amply described in a number of publications (Westrick, 1957; Smellie and Faessler, 1957; Scott, 1957; Dobrin, 1960). In the field, dip needles were replaced by Schmidt-type vertical balances which, in turn, have given way largely to fluxgate magnetometers. The vertical balances require a tripod set-up, levelling, orientation and adjustment of a compensating magnet. The fluxgate type magnetometers are suspended from a neck strap, do not require orientation or compensation and are much lighter (about 3 pounds). More rapid ground coverage is feasible with fluxgate equipment. The slight loss in accuracy is acceptable in surveys of ultrabasic rocks.

Ground magnetic surveys consist of a base control line parallel to the projected trend of the ultrabasic body. Cross lines are placed at intervals ranging from 1000 feet for reconnaissance work to 50 feet for detailed work. Stations are normally located at 50- to 100-foot intervals, with fill-in stations in zones of high magnetic gradient.

Corrections made to station readings include diurnal and day to day corrections by regular checks on magnetic control base stations.

A working zero level is established in the field by adding an arbitrary figure to each reading. A convenient method is to adjust the zero level so that country rocks adjacent to the ultrabasic body read in the 1000-gamma range.

Airborne magnetic surveys are still widely conducted using the venerable Gulf fluxgate type unit. Recent new sensing devices reported are atomic spin precession and an optical pumping type. Greater sensitivity and lighter weight (suitable for use in small aircraft) are indicated advantages.

Survey control for airborne work is often based on air photo mosaics roughly controlled to available topographic or planimetric maps. Flight lines are plotted on the mosaics and on transparent overlays, using 35 millimeter strip camera film to identify topographic control points. Simultaneous fiducial marks on the profile recording instrument are triggered by the strip camera target shots. These fiducials are given numbers corresponding to those on the film. This datum ties the magnetic profiles to topographic features on the mosaic. Flight lines are usually at one eighth to one quarter mile intervals and are planned, if possible, across the 'geologic grain' of the survey area.

Airborne magnetic surveys record variations in the total field. Although they give low resolution of magnetic features in comparison with ground surveys, they provide an advantage in the form of continuous magnetic profiles. Low cost per unit of area makes such surveys ideal for reconnaissance over large areas to locate ultrabasic bodies.

Contents

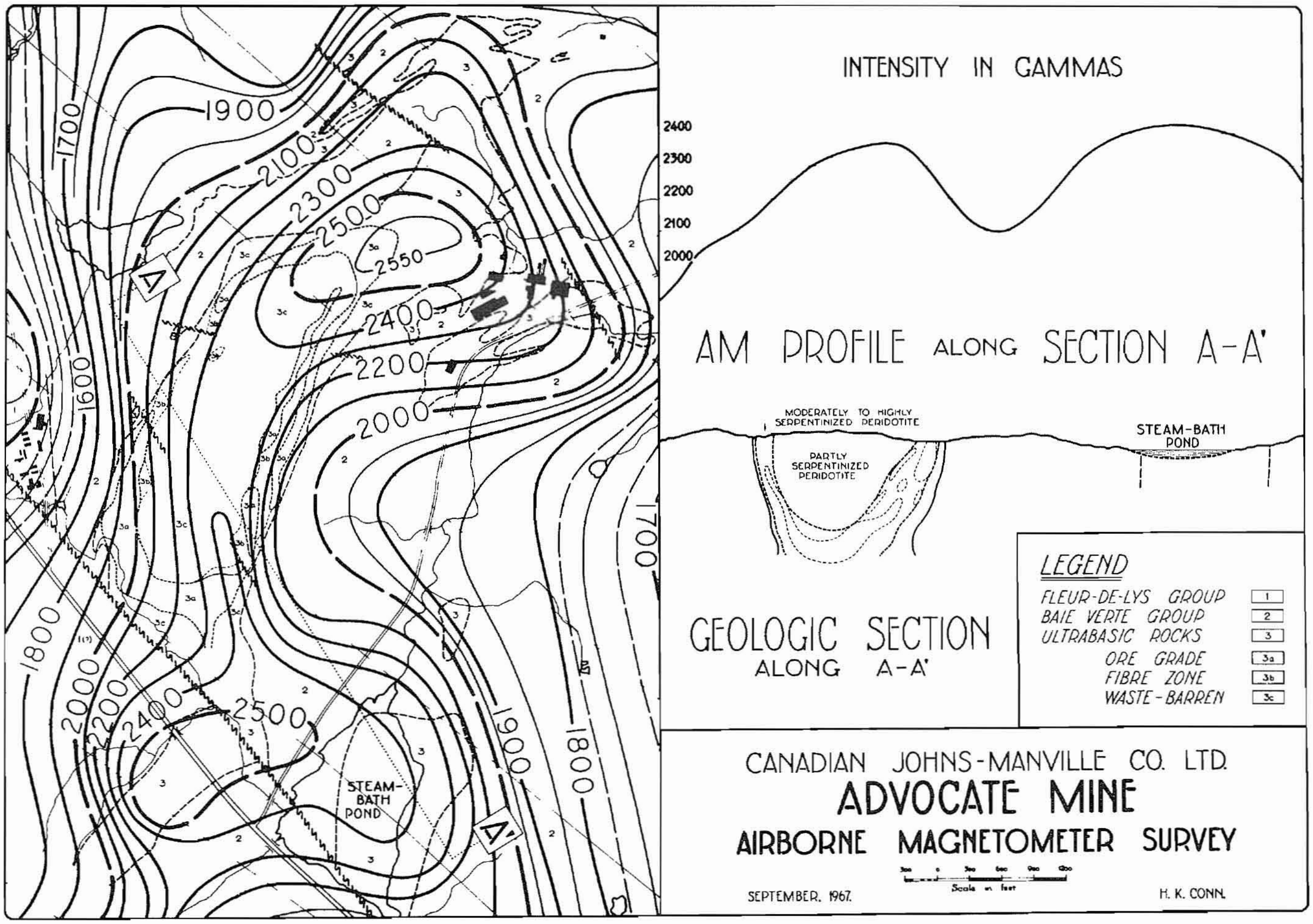

Figure 1. Advocate Mine, airborne magnetic map and profile.

Interpretation

Geophysical surveys are performed essentially as a means of measuring physical contrasts in the bedrock. Anomalous magnetic effects over ultrabasic bodies are caused by many factors, including variations in, and alterations of, bedrock, remanant magnetism, faulting, irregular depth of overburden, etc.

Geologic background. Theories and empirical observations relating to origin, mode of emplacement and alteration of ultrabasic bodies and associated chrysotile veins (Low, 1957; Conn, 1957) tend to govern exploration methods. Ultrabasic (and composite basic to ultrabasic) bodies are commonly assumed to be intrusive rocks of magmatic origin. The author now believes that many such strata-controlled ultrabasic bodies, particularly where associated with basaltic volcanic piles are, in fact, extrusive flows with associated agglomerate breccia and tuff (Conn, unpublished). This concept gives rise to potential geologic conditions which differ materially from the conventional assumptions, relating structure, composition and ore deposition that have been used in most geophysical interpretations. Some potential conditions are:

1. Surface weathering at the time of deposition, causing oxidation and silicification (especially in post-Precambrian age ultrabasic rocks);

2. Surface erosion of the volcanic terrain and deposition, between extrusive surges, of local sediments which may contain syngenetic graphite and iron sulphide beds;

3. Intermittent fumerolic activity, including silica and carbonate deposition and alteration of surfaces and channelways;

4. Nickel iron sulphide surface flows, gravity controlled; and

5. Ultrabasic pillow lavas and cooling joints which could provide favorable structural loci for the development of chrysotile veins.

The location of chrysotile deposits within ultrabasic rocks, and their general association with certain magnetite-rich and highly serpentinized sections of peridotite bodies, is well known to the exploration fraternity. These facts have caused magnetic surveys to dominate asbestos exploration. The increased magnetite content is caused by more intense serpentinization, which alters the original, usually iron-rich olivine, and iron-poor pyroxenes to a matte of serpentine minerals, resulting in the crystallization of the contained iron as magnetite in the form of dust, globules and veinlets.

The degree of serpentinization, found in ultrabasic rocks, is believed to result from several factors:

1. Original composition of the host rock, e.g., dunite, essentially an original olivine rock;

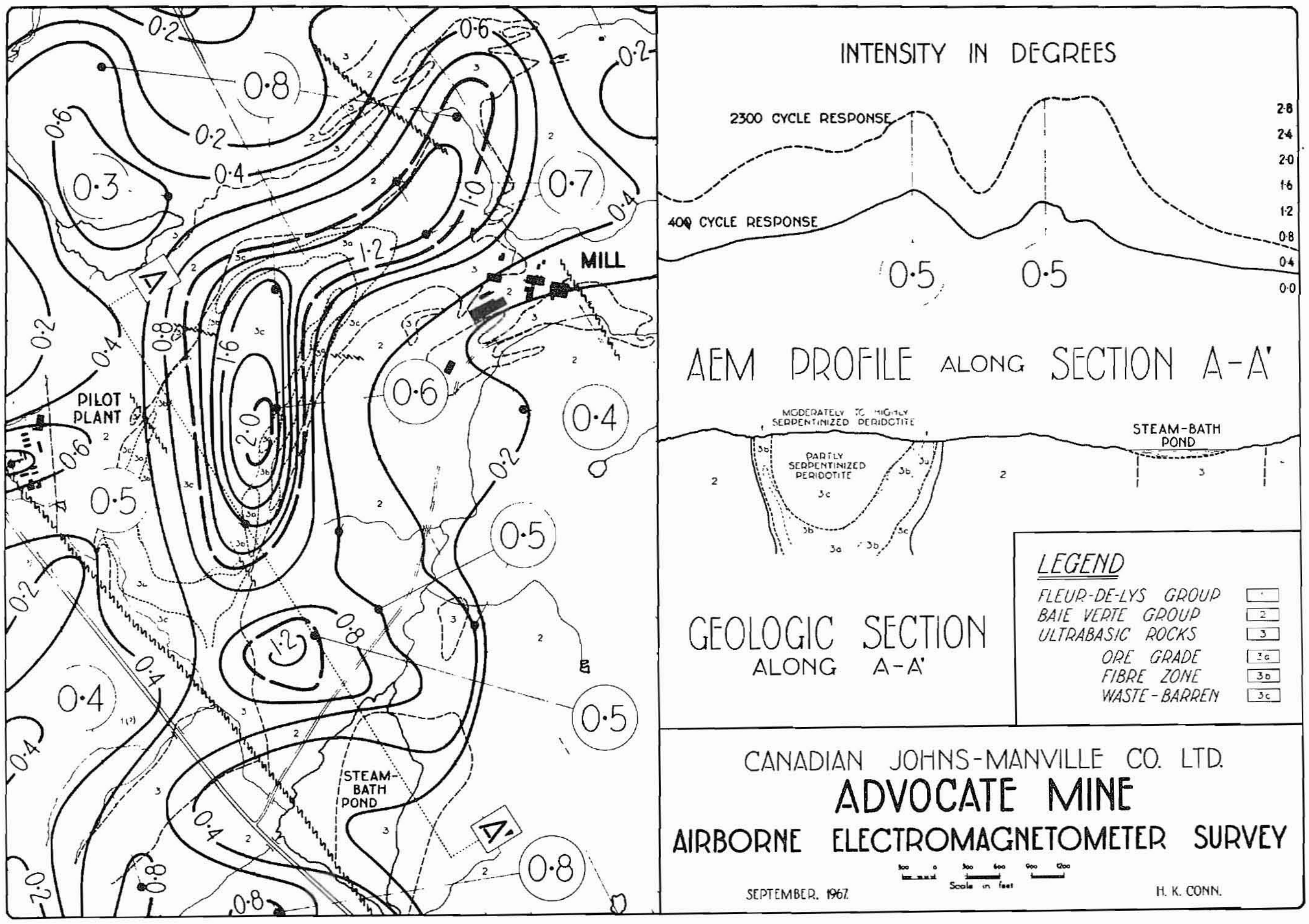

Figure 2. Advocate Mine, airborne electromagnetic map and profile.

2. Regional metamorphism. This seems to control the degree of serpentinization of gross segments of some ultrabasic belts, e.g., Eastern Townships of Quebec. Availability of water may be a requirement;

3. Local dynamic metamorphism resulting from shearing; and

4. Geologic age. The degree of 'whole rock' serpentinization appears to increase from Mesozoic to Archean time.

Remanant magnetism. Recent work with the fluxgate magnetometer has shown rapid reversals in the local magnetic field on outcrops of magnetite iron formation. Some of these reversals are attributed to remanant magnetism (Hood and Sangster, 1965).

Similar features can be expected in other magnetite bearing rocks. For example, rhythmic banding of the regional Stillwater (Montana) and Bushveld (South Africa) basic-ultrabasic intrusive sheets suggests recurrent precipitation of specific mineral assemblages in the magma chambers.

Gravity-controlled layering is believed to have produced a rudely horizontal attitude at the time of deposition. The magnetite as it cools below the Curie point is assumed to acquire a magnetization parallel to the direction of the earth's local magnetic field at that specific period of geologic time.

Post-deposition orogenies which tilt or fold these basic-ultrabasic complexes may result in such layers displaying magnetic anomalies divergent to the earth's field, because of remnant magnetism.

This interpretation assumes that orogeny or deep burial does not again raise the temperature of the magnetite above the Curie point and that associated earthquake shocks do not rearrange the original magnetic fields of the magnetite-rich layers (Birch, *et al.*, 1942).

Similar magnetic features may be present in other basic-ultrabasic bodies of probable extrusive origin.

Faulting. In the opinion of the writer, faulting tends to break up what otherwise might be a more uniform magnetic field. A simple demonstration is the breaking of a bar magnet. This results in two magnetic fields with poles of opposite sign across the break. Analogy with a cross-faulted sheet-like ultrabasic body is obvious. Cross-faulting, strike-faulting and probably major jointing, fracture such bodies to produce a large number of irregular blocks, with opposing magnetic poles across the fractures. This is one reasonable cause for a complex pattern of magnetic contours commonly observed.

Overburden thickness. The variable thickness of overburden over many ultrabasic bodies gives rise to numerous problems of interpretation. Rock outcrops or bedrock with shallow over-

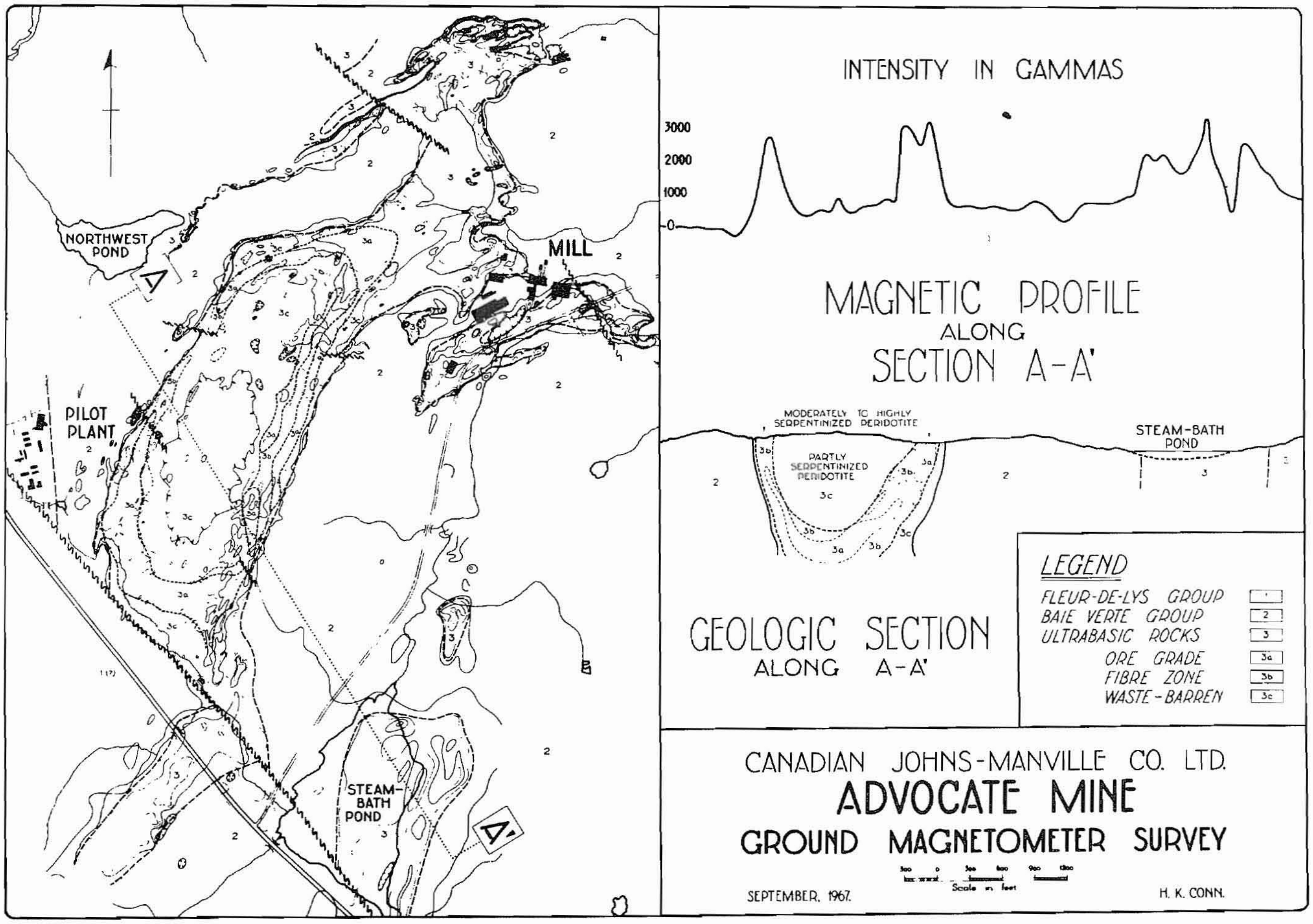

Figure 3. Advocate Mine, geologic map and ground magnetic profile.

burden have been observed adjacent to buried valleys with overburden depths in the range of 25 to 200 feet. Since magnetic intensity tends to decrease inversely with the square of the distance from the source, abrupt changes in the magnetic field are common across the margins of such buried topographic features. Thus, magnetic anomalies of apparent significance may be caused solely from sudden reduction in the depth of overburden. The reverse situation also occurs. 'Less favorable' magnetic patterns caused by deeply buried cross-cutting valleys, have been known to contain ore zones.

Shallow seismic surveys have been used successfully to determine the actual thickness of overburden. This information has definitely improved interpretation of magnetic results in certain properties containing deep and continuous overburden of varying depth, e.g., southwest McCool township, Ontario.

Latitude factor. The earth's magnetic field is approximately horizontal at the Equator and dips vertically at the magnetic poles. The 'lower pole' effect of steeply dipping, ultrabasic bodies in the higher magnetic latitudes such as Canada, is not usually a significant factor in preliminary interpretation, i.e., location of geologic contacts from inflection points on the magnetic profile. The 'lower pole' effect becomes a more prominent factor in magnetic interpretation of ultrabasic bodies nearer the Equator (using a vertical field magnetometer).

A body observed in Colombia displayed an apparent sub-horizontal dipole effect between its northern and southern margins. Neglecting any remanant magnetism, a reasonable interpretation of the contact locations from magnetic data was possible with moderate geologic control. At this location local magnetic effects caused by mountainous terrain, irregular depth of tropical weathering, and thick talus slopes, mitigated against effective detailed interpretation.

Case histories

The following two case histories describe airborne magnetic and electromagnetic surveys, and ground magnetic surveys over two asbestos mines. These are the Advocate Mines Limited mine, a few miles north of Baie Verte, Newfoundland, and the Reeves Mine of Johns-Manville Mining and Trading Corporation, some 50 miles southwest of Timmins, Ontario. The geologic age of Advocate rocks is Post-Ordovician (Paleozoic); the Reeves rocks are Archean (Precambrian).

Advocate Mines Limited. The airborne magnetic survey (Figure 1) was flown by the Aeromagnetic Survey Division of the Photo-

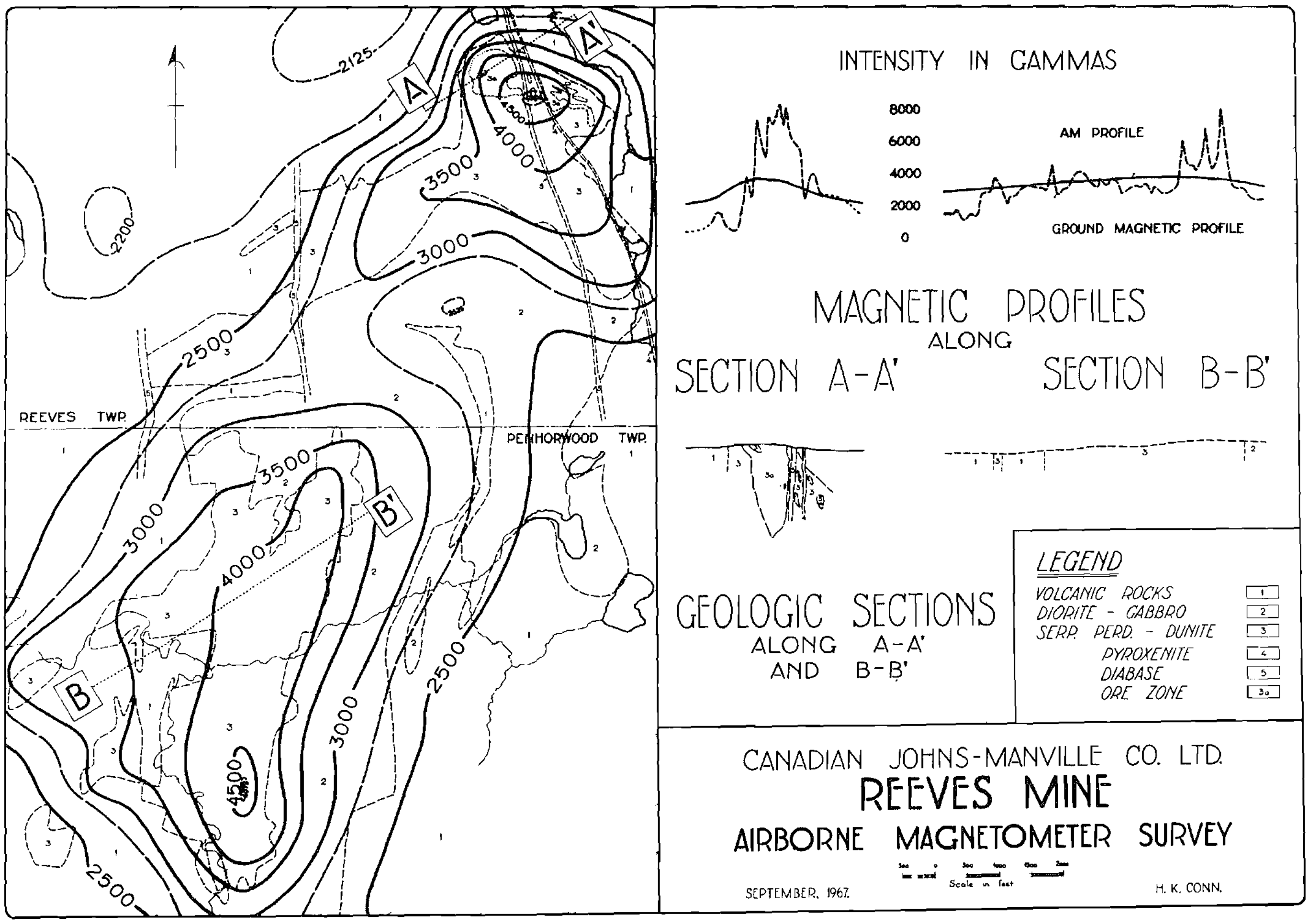

Figure 4. Reeves Mine, airborne magnetic map and profiles.

graphic Survey Corporation in 1950 on behalf of the Newfoundland Government. The instrument used was a modified Gulf type magnetometer.

The airborne electromagnetic survey was flown by Aeromagnetic Surveys Limited in 1956 using a dual frequency, out-of-phase measuring electromagnetic system.

Both surveys used a Canso aircraft with average flying height of 500 feet above ground. The flight line interval was approximately one quarter mile. Control was provided from flight line plots on rough laydown photo mosaics.

The contour plan of the airborne magnetic survey defines the peridotite body and its extensions in a reasonably satisfactory manner.

The anomaly peaks (over 2400 gammas) at the northeastern and southwestern ends of the body correspond to surface and near-surface exposures of highly serpentinized peridotite. The geologic structure simulates a doubly-plunging syncline. The central section between the peaks is composed principally of slightly to moderately serpentinized peridotite. The geological features of potential economic significance are clearly distinguishable in this survey. Limited geologic ground control is essential for correct interpretation.

The airborne electromagnetic survey is depicted in Figure 2. The low frequency (400 cps) contours are superimposed on the geologic map. Profiles of the low frequency and high frequency (2300 cps) and underlying geology, are shown in a section.

A major anomaly peak overlies the main ultrabasic body and contained orebody. Ratio peaks of low frequency to high frequency (0.5, 0.6 and 0.8) adjoin the surface expression of the orebody. Poor control and uncertain scale factors from the laydown mosaic may have displaced these peaks an appreciable amount. The writer suspects that they are actually located on the margins of the body, along the heavily sheared contact.

Ultrabasic bodies elsewhere on the Advocate Concession display a similar distinctive low frequency anomaly pattern. The cause is not known to the writer, although some serpentine minerals are reported to be conductive.

The ground electromagnetic survey grid has been omitted. The ultrabasic bodies were well defined by the survey. Geological mapping and drilling have confirmed most of the contacts.

The magnetic contour pattern and intensity clearly distinguishes the moderately to highly serpentinized zones of the main ultrabasic body. Known asbestos orebodies are located exclusively within these zones. However, all such zones do not contain fibre.

An original reconnaissance ground magnetic survey provided essentially the same general picture as this airborne survey. Interpretation of the former work, based on scattered surface

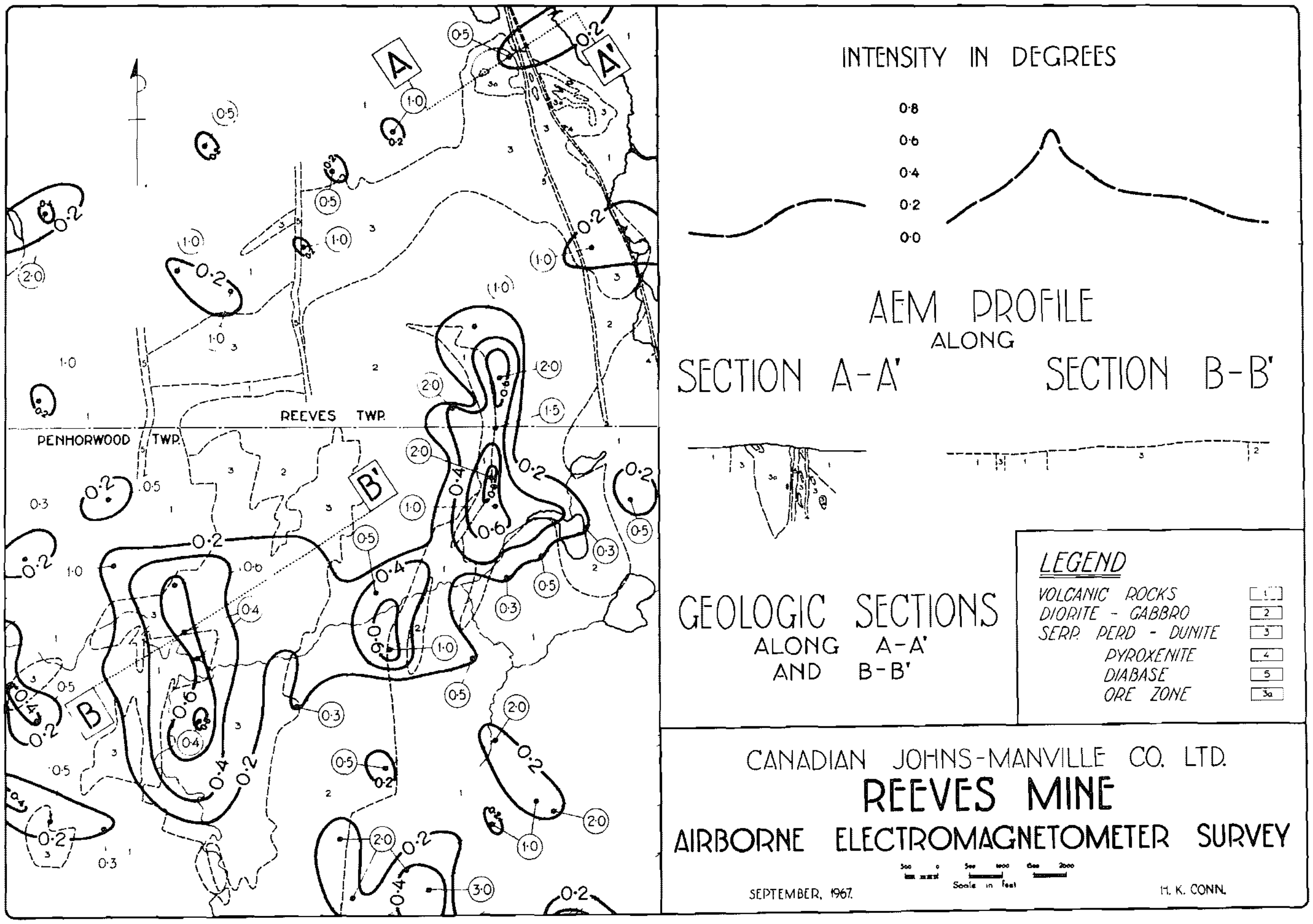

Figure 5. Reeves Mine, airborne electromagnetic map and profiles.

fibre discoveries, effectively outlined the fibre zone and contained orebodies, as determined by later drilling and mining (Figure 3).

Reeves Mine. A generalized contour plan of the aeromagnetic survey, superimposed on a geological map, is contained in Figure 4.

The survey was flown by Aeromagnetic Surveys Limited in 1956, using a Canso aircraft equipped with a modified Gulf type magnetometer and a dual frequency out-of-phase measuring electromagnetic unit. Flight lines were at one-eighth mile intervals with a flying height of 500 feet.

The boundaries of the ultrabasic bodies are moderately well defined by this survey. The detailed contacts are a product of combined geological mapping and ground magnetic work.

The ultrabasic bodies, of early Precambrian age, are composed of highly serpentinized peridotite, with some dunite. Locally, large sections are partly altered to carbonate rock. These altered sections are located primarily in the southwestern part of the Reeves township ultrabasic body and the northwestern part of the Penhorwood township ultrabasic body. The aeromagnetic contour pattern reflects these zones of carbonate; a more precise picture was obtained from ground magnetic surveys.

The magnetic profiles on Figure 4 combine aeromagnetic and ground magnetic data. Several feet of overburden originally masked the orebody. Ground magnetic stations, in consequence, gave highly erratic readings as may be noted from the profile. Use of a common scale in the section has suppressed the ore zone anomaly on the aeromagnetic profile. It is evident on the contour plan with a peak of 4830 gammas.

The structure of the ultrabasic body in the vicinity of the orebody is dome-like. Dips are steep to the northwest, and moderate to the northeast and east, beneath the Keewatin type volcanic rocks, and moderate to the south beneath the gabbro-diorite. Geologic contacts with enclosing rocks are conformable. The south and east dips are well indicated from the magnetic contours; the north dip is poorly indicated, partly because of the lower pole effect.

The diabase dyke, cutting the orebody and all other rocks, was traced readily by ground magnetic work. It produced a relatively 'low' pattern within the ultrabasic and a moderate 'high' within the greenstone volcanic rocks. It has caused the 'shoulder' on the right-hand side of the main ground magnetic anomaly, as depicted in Section A-A^1 of Figure 4.

Figure 5 portrays plan and profile of the airborne electromagnetic survey superimposed on the same geological map as in

Figure 4. Contours for the low frequency response (400 cps) are shown. The ratio of low frequency to high frequency provides a measure of the significance of the conductor. Ratios 0.5 and greater are usually legitimate bedrock source conductors.

The strong conductor with good ratios crossing the township boundary in a northerly direction was detailed with ground electromagnetic surveys and drilled at several locations.

The holes intersected numerous bands of a graphite-pyrrhotite and pyrite-rich sedimentary rock of obscure origin, interbanded with andesite volcanics, carbonated gabbro and massive serpentinized peridotite and serpentinite layers.

The large, low frequency anomaly with a poor ratio (0.4) covering the southwestern margin of the Penhorwood ultrabasic, has no satisfactory explanation. Drill holes in the vicinity intersected a normal serpentinite with more or less carbonate alteration. However, detailed ground electromagnetic surveys were not done and a target may be present, distant from the drill holes.

A small, low frequency anomaly with a 0.5 ratio, overlies a portion of the orebody. The anomaly peak plots on or very near a deeply oxidized carbonated shear zone, along the northern margin of the orebody.

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Logging the Prairie evaporite formation in Saskatchewan

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Abstract. The use of well-log data for the estimation of sylvite, carnallite, halite and clay content has been made on many exploration and development potash projects. A recently introduced Sidewall Epithermal Neutron (SNP) device will aid the basic program. The effect of well-bore variables and the presence of chlorine is diminished with this device. The effect of these variables on the SNP system and upon older well logs is discussed. A guide to the use of older logs is included.

Résumé. On s'est servi des diagraphies de puits pour déterminer la teneur en sylvite, en carnalite, en halite et en argile à plusieurs sites d'exploration et d'exploitation de potasse. Un nouvel appareil à neutrons qui sert à mesurer la porosité des parois (Sidewall Epithermal Neutron) apportera une aide précieuse au programme de base. Cet appareil réduit l'effet des variables qu'apportent le trou et la présence de chlorine. Il est question de l'effet de ces variables sur le système de mesure de la porosité des parois à l'aide de neutrons, ainsi que sur les anciennes diagraphies. On donne également un exemple de l'emploi des anciennes diagraphies.

Earlier authors (Alger and Crain, 1965; Crain and Anderson, 1966; Dewan and Greenwood, 1955) have outlined the use of geophysical logs in the evaluation of the Prairie evaporite formation. This evaluation can be provided at the drill site by use of nomographs and hand calculation. Subsequently the specific amounts of constituent minerals, sylvite, carnallite, insolubles and halite, may be calculated by electronic computer using the data from geophysical logs and techniques common in the oil industry (Savre, 1963). A recent development in neutron logging, the Sidewall Ephithermal Neutron Device (SNP) (Tittman, *et al.*, 1966), has been compared with the 'long spacing' neutron-gamma system previously used for this analysis. This paper will review the theoretical basis for log evaluation and compare results obtained using the SNP neutron with those from the neutron-gamma system.

A section is devoted to the use of well-log data from the older exploratory drill holes in the potash basin, to give some approximation to potash content and grade. The basin is dotted with old exploratory drill holes. The older logs run in these wells can provide some approximation of potash content and grade. The general theory presented plus a section devoted to old logs, provides a guide to the use of these surveys.

Theory

Alger, Crain and Anderson have shown that potash minerals can be effectively identified and assayed through the use of geophysical logs. The gamma ray, *GR*, log provides the prime indication of K_2O content and is augmented by neutron, N, and sonic, S, logs to give the carnallite and clay content, respectively. This analysis is based on these premises:

1. It is assumed that the minerals present are halite, W, sylvite, X, carnallite, Y, and clay Z.

$$W + X + Y + Z = 100 \qquad 1$$

2. The gamma ray emission in the evaporite section is related to the concentration of the isotope K^{40} of potassium (3) (a fixed proportion, 12 per cent of the total potassium concentration) plus the emission emanating from the potassium, thorium and uranium constituents of the clay content.

$$0.63X + 0.17Y + 0.05Z = K_2O_{app} \qquad 2$$

(The result is labelled "apparent" K_2O content because the insoluble content of the formation generally is slightly radioactive.)

3. The neutron log-determined hydrogen index ϕ_N is that contributed by the water of crystallization of carnallite plus the water in the clay.

$$0.65Y + 0.30Z = \phi_N \qquad 3$$

4. The recorded sonic interval travel time ($\Delta t_{\log}g$) in microseconds per foot is the algebraic sum of the Δt of the constituent minerals in proportion of their presence (4).

$$67W + 74X + 78Y + 120Z = 100\Delta t_{\log} \qquad 4$$

Reducing these equations accounts for the individual effect of the minerals W, X, Y, Z on the logs *GR*, N and S and provides a solution in terms of W, X, Y and Z.

$$\text{Insoluble } Z = 2.07\,\Delta t_{\log} - 0.23\,K_2O_{app} - 0.29\,\phi_N - 138.91 \qquad 5$$

$$\text{Carnallite } Y = 1.54\,\phi_N - 0.46Z \qquad 6$$

$$\text{Sylvite } X = 1.59\,K_2O_{app} - 0.41\,\phi_N + 0.04Z \qquad 7$$

$$\text{Halite } W = 100 - X - Y - X \qquad 8$$

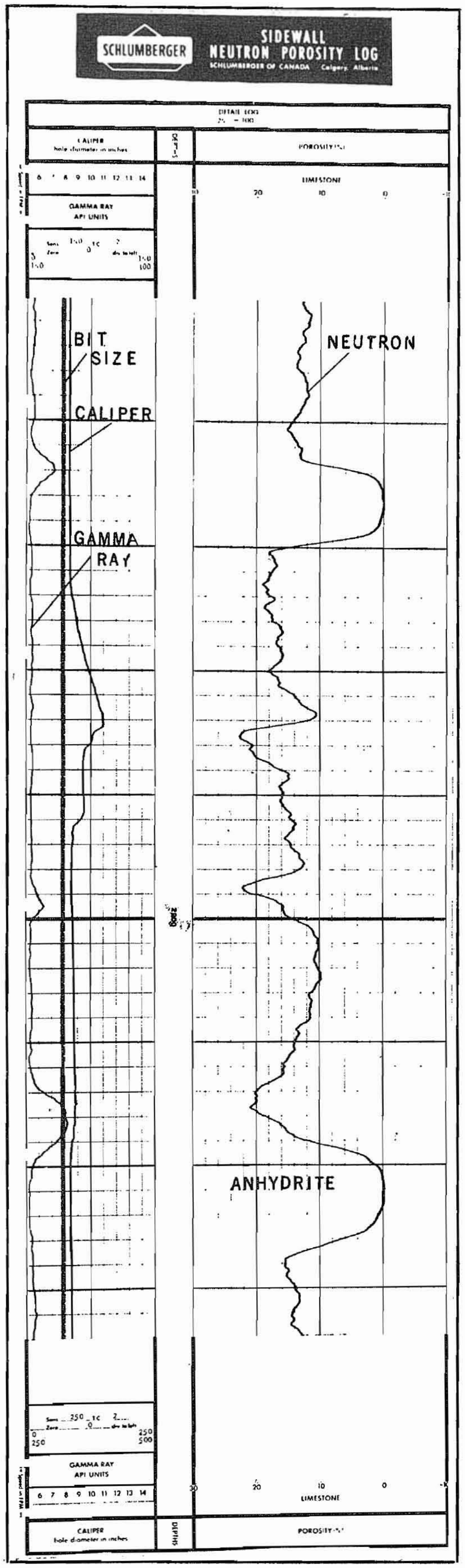

Figure 1. Sidewall neutron porosity log.

To convert from a proportion to K_2O equivalent the final analysis follows:

$$K_2O_{total} = K_2O_{app} - 0.05Z \quad (9)$$

$$K_2O_{sylvite} = 0.63X \quad (10)$$

$$K_2O_{carnallite} = 0.17Y \quad (11)$$

This evaluation, aided by nomographs, can be performed for key intervals in the field. Subsequent detailed electronic computer analysis gives both tabular and graphic plots of the constituent minerals.

This program has been successfully run in both exploratory and development holes. Where discrepancies with core analyses have been apparent the authors believe the error to lie in borehole variables not in the basic premises. The SNP, by system and design, removes the effect of many of these variables.

Variables

Hole size. A drill hole filled with either oil or salt mud constitutes a large hydrogen-rich volume. As the formation porosity decreases, as in the evaporite sequence, the variation in hole size becomes of greater significance. Caliper data can be used to correct measured neutron count levels by the standard charts used in this analysis. However, oval-shaped holes and the effect of sonde position increases the limit of possible error.

The SNP (5) is a skid-mounted sidewall neutron device that is pressed against the ore face by a caliper recording arm. Any residual hole size effect is further diminished by a caliper-controlled computer. This effectively removes the influence of borehole environment over a range 6 to 16 inches in diameter.

Matrix effect. The neutron-gamma systems which were used to provide the information in earlier work had a strong matrix component in their response. In this type of tool fast neutrons (100,000 ev) are emitted from the source, and degrade by collision with formation atoms. They go through the epithermal (0.5 ev) to the thermal (0.25 ev) level where they are captured by hydrogen or chlorine with the consequent production of a gamma ray of capture that is then monitored by the counter.

The SNP system is an epithermal device, i.e., fast neutrons are emitted and are detected as they pass through the epithermal energy level. Hence, the chlorine-effected capture stage is eliminated. This system is largely hydrogen sensitive and the role of chlorine is minimized.

Temperature/pressure. Conventional neutron systems are affected by borehole temperature and pressure and require, after logging, chart corrections before normalized data are provided. The SNP incorporates an environmental computer to provide output data that are ready for immediate computation.

Presentation

The neutron-gamma system (linear count rate) generates a scale that is logarithmic in response to porosity. This causes difficulty in assignment of zero porosity and in addition there is a decrease in resolution in zones of high carnallite concentration.

The SNP system produces a linear porosity scale with a preset zero (Figure 1). This allows direct use of log data, without

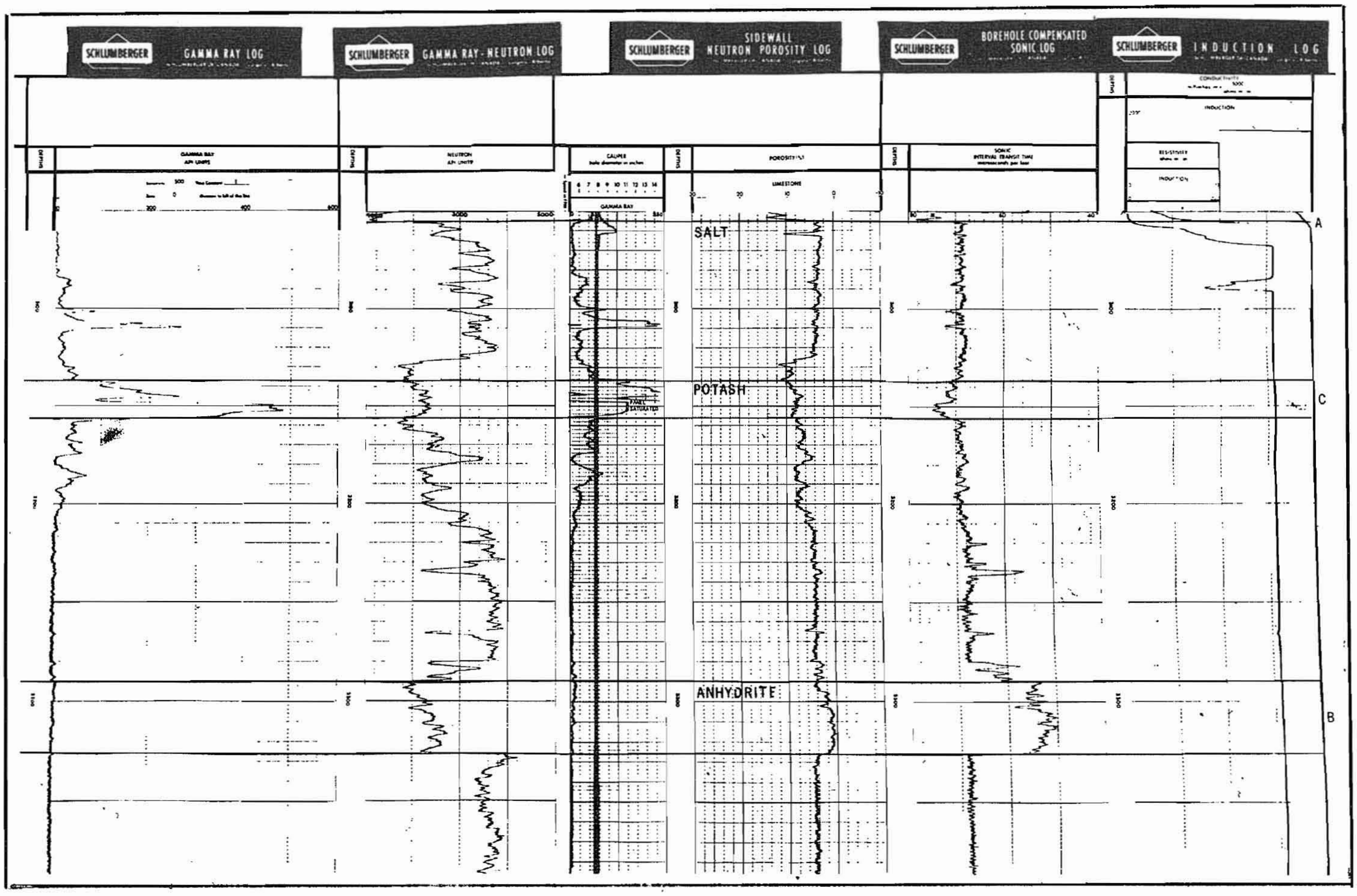

Figure 2. Gamma ray, gamma ray neutron, sidewall neutron porosity, compensated sonic, and induction-resistivity logs for the top section of the prairie evaporites.

reference to logarithmic tables, which speeds field analysis, simplifies computer use, and provides more meaningful visual information.

Potash evaluation with SNP neutron log

The SNP porosity recorded in the salt is a reflection of the included water. This can be used to modify the existing equations to refine the analysis.

1. If V is the included water as indicated by the SNP in the upper and lower salt sections, (generally 3 to 4 per cent) then

$$V + W + X + Y + Z = 100t \qquad \text{1a}$$

2. The included water has zero gamma ray emission so Equation 2 remains unchanged:

$$0.63X + 0.17Y + 0.05Z = K_2O_{app} \qquad \text{2a}$$

3. The porosity is read directly by the SNP; hence Equation 3 becomes

$$1.00V + 0.65Y + 0.30Z = \phi_{SNP} \qquad \text{3a}$$

4. The effect on Δt of varying amounts of included water is under current study. For the present, a refined evaluation is possible by applying a moderator (m) to the log values. Using normalized sonic data, Equation 4 remains the same:

$$67W + 74X + 78Y + 120Z + m = 100\Delta t_{log} \qquad \text{4a}$$

Where $m = \Delta t_{log}$ salt -67

Reduction of these equations results in:

$$Z = 2.07\,(\Delta t_{log} - m)\ 0.23\ K_2O_{app} - 0.29\,(\phi_{SNP} - V) - 138.91 \qquad \text{5a}$$

$$Y = 1.54\,(\phi_N - V) - 0.46Z \qquad \text{6a}$$

$$X = 1.59\,K_2O_{app} - 0.41\,(\phi_N - V) - 0.04Z \qquad \text{7a}$$

$$W = 100 - X - Y - Z \qquad \text{8a}$$

when V is considered part of W. Conversion to K_2O equivalent remains the same:

$$K_2O \text{ total} = K_2O_{app} - 0.05Z \qquad \text{9}$$

$$K_2O \text{ sylvite} = 0.63X \qquad \text{10}$$

$$K_2O \text{ carnallite} = 0.17Y \qquad \text{11}$$

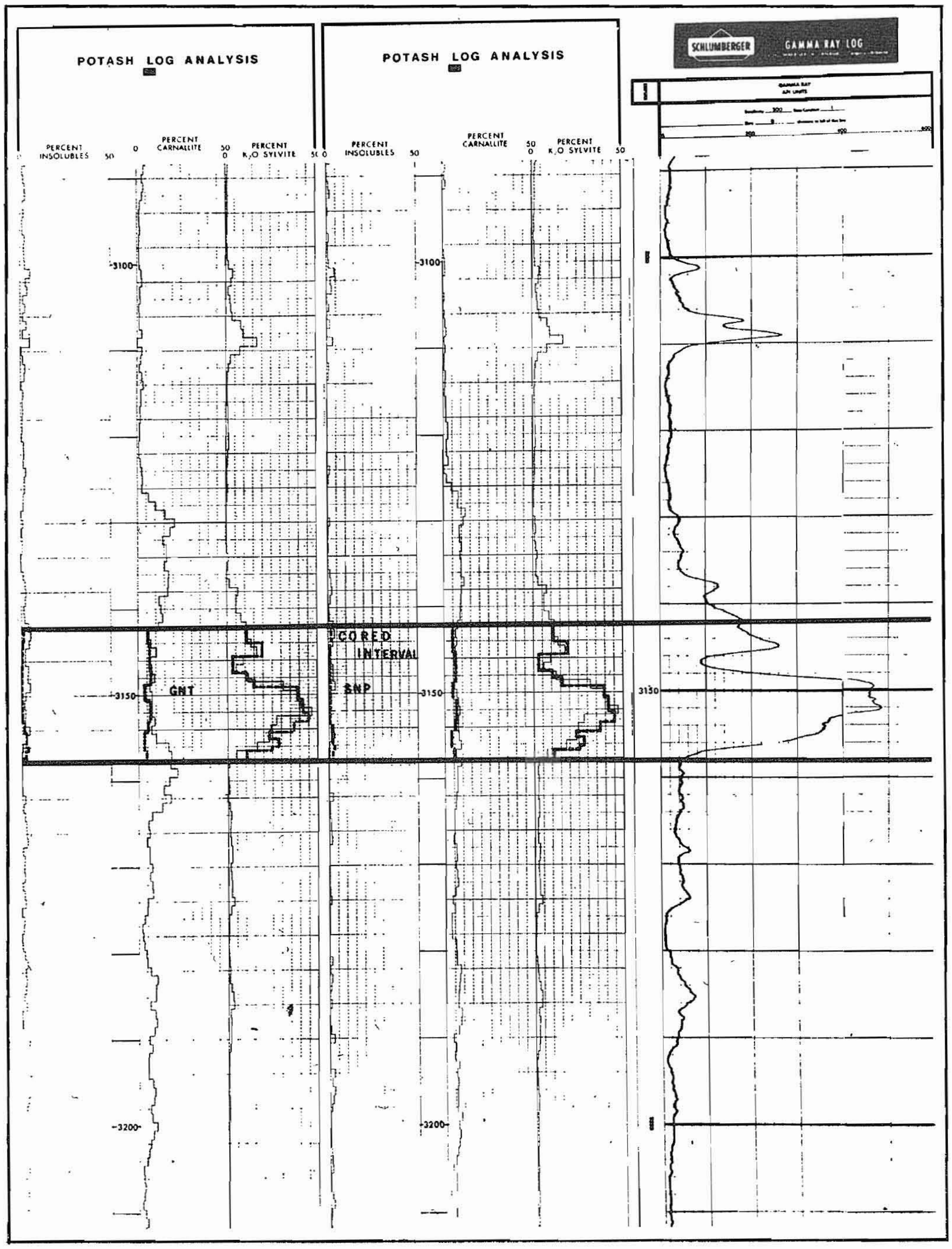

Figure 3. Gamma ray and computed potash analysis logs.

Application

The recording of induction resistivity, gamma ray, Borehole Compensated (BHC) sonic, neutron-gamma, and SNP neutron logs, plus core data allows the following comparison (Figure 2).

The suite of geophysical logs clearly indicates the top of the Prairie Evaporite at 3055 feet and the contrast with the overlying red shale bed is seen as: (1) a dramatic increase in resistivity, (2) a decrease in gamma ray level, (3) an increase in GNT neutron counts, (4) a decrease in SNP ϕ and (5) a decrease in sonic Δt.

The gamma ray gives the indication of K_2O present. The maximum deflection (at a depth of 3152 feet) represents a K_2O content of 48.4 per cent, as determined either by nomograph or computation.

The sonic log adds some basic lithological information by dramatically separating the anhydrite (50 μ sec) at 3290 to 3326 feet from the salts (67 to 78 μ sec).

The neutron-gamma type neutron log displays the chlorine effect. The count rates in the halite that are greater than in anhydrite are due to the high-energy gamma rays of capture by chlorine atoms. This masks the ability of the gamma ray neutron system to assess carnallite.

The SNP neutron log assesses 0 to 1 per cent ϕ in the anhydrite section (probably due to impurities) and 3 per cent ϕ in the halite Assuming the included water to be uniform throughout the section, any increase in apparent ϕ in the section would be due to carnallite or shale.

A comparison of computer printout of the neutron-gamma with the SNP log shows a much higher halite fraction in the upper salt (Section A averaged 98 per cent using SNP versus 95 per cent with gamma ray neutron). The comparison of the cored interval (Figure 3) shows the gamma ray BHC SNP system to equal the gamma ray BHC neutron-gamma in sylvite assessment. The gamma ray BHC SNP system shows improved insoluble response throughout the cored interval.

As expected, the gamma ray BHC SNP system gives a marked improvement in carnallite assessment, particularly at the bottom of the cored section.

Potash exploration using older logs

While it is not possible to measure K_2O content with the same accuracy using older logs they can be used qualitatively for potash exploration. The logs available were made on wells drilled as petroleum prospects. The evaporite section is usually badly caved and under these conditions all factors affecting log response act to reduce the apparent K_2O. Such factors are as follows.

Differential solution. When a salt section is drilled, solution of the salt continues until the mud becomes saturated. Further drilling with the salt-saturated mud will cause little enlargement. Should a potash bed be encountered, however, potash will go into solution. This results in caving and, if the potash bed is thin, the logging tool is held away from the ore by the adjacent salt beds. The recorded radioactivity and, hence, the apparent K_2O content are reduced. A neutron log run over the interval will show increased porosity and hence increased apparent carnallite in the caved zone. If a caliper log is not available the analyst would tend to interpret the caved sylvite bed as a carnallite bed.

Tool response. Early gamma logs were run with geiger type counters. While the count rate increases linearly with increasing gamma ray emission in most zones, this is not true in zones of high radioactivity where the response tends to fall off. In practice this means that high-grade ores will appear poorer than they actually are.

Unscaled logs. Some of the logs available in the potash basin are unscaled. An approximate scaling can be applied using the reading in salt and in the second red beds as calibration points. A study of 25 logs shows that the average radioactivity level in the second red beds is 4 micrograms. The difference in radioactive levels between the salt and the red beds is 3.3 micrograms. This scaling, when applied to the potash section, is a drastic extrapolation. Hence this evaluation must be taken only as a guide to the zone's richness.

Conclusion

The system of evaluating potash zones using common geophysical logs has been improved by the introduction of the SNP neutron system.

The assessment of sylvite, carnallite, clay and halite can be obtained at the wellsite by nomograph and hand calculation using the data provided by gamma ray, SNP neutron, and BHC sonic logs. Subsequent machine computation gives detailed printout and graphic plots of these constituent minerals. The old logs from the potash basin can, to a lesser degree, provide a guide to the presence and richness of potash.

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Geophysical investigations of evaporites in Nova Scotia

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Abstract. The major evaporite deposits in Nova Scotia occur in a marine sequence in the Upper Mississippian (Dinantian). Salt, anhydrite, gypsum, dolomite, limestone and potash are present in that approximate order of abundance. Of these minerals, all except potash are presently being exploited.

Geophysical exploration has been successful in locating evaporites. The major structures cause large negative gravity anomalies which are primarily due to rock salt. A number of these structures have curious magnetic anomalies associated with them. Seismic reflection surveys have been partially successful in delineating the shapes. Gamma ray logging of exploratory bore holes has supplemented continuous coring in finding potash.

Gravity and electrical explorations have outlined shallow anhydrite and gypsum occurrences. Seismic refraction work has been used to outline a limestone deposit.

The work demonstrates that in areas with a complicated geology and thick glacial till, geophysical techniques can provide important additional information required for successful exploration of industrial minerals.

Résumé. Les principaux dépôts d'évaporites en Nouvelle-Écosse se trouvent dans une série marine du mississipien supérieur (dinantien). Le sel, l'anhydrite, le gypse, la dolomite, le calcaire et la potasse s'y trouvent à peu près dans l'ordre d'abondance indiqué ci-dessus. Tous ces minéraux sauf la potasse sont actuellement exploités.

On a réussi à localiser des dépôts d'évaporites par des méthodes d'exploration géophysique. Les principales structures causent d'importantes anomalies gravimétriques négatives qui sont dues surtout à la présence de sel gemme. Un certain nombre de ces structures présentent des anomalies magnétiques assez curieuses. Des relevés par réflexion séismique ont permis avec un certain succès d'en déterminer les formes. La diagraphie des sondages d'exploration par rayons gamma a permis d'obtenir l'analyse continue des carottes dans la recherche de la potasse.

Les explorations gravimétriques et électriques ont permis de délimiter des venues peu profondes d'anhydrite et de gypse. La réfraction séismique a servi à délimiter un gisement de calcaire.

L'étude démontre que dans les régions à géologie complexe et où se trouve un till glaciaire épais, les techniques géophysiques peuvent fournir d'importances données supplémentaires nécessaires à une exploration fructueuse des minéraux des industriels.

Nova Scotia is situated in eastern Canada, bordering the Atlantic Ocean for some 300 miles. The two deep-water ice-free ports at Halifax and the Strait of Canso enhance the economics of industrial mineral production in Nova Scotia. The eastern United States forms a natural market and Boston is in closer proximity to Halifax than Montreal (Figure 1).

Geology. The southwestern part of Nova Scotia is composed of Palaeozoic slates, quartzites and argillites intruded by major granite masses; the general structural trend is SW-NE. The same rocks continue up the Atlantic shore to the Strait of Canso with a swing to an easterly trend.

Marine sedimentation earlier in the Palaeozoic ended in the Lower Mississippian when the continental shales and arenaceous rocks of the Horton Group were deposited (Roliff, 1962). A marine transgression in the Upper Mississippian filled the shallow depressions, and the high temperatures and arid climate caused evaporite deposits to form. These Windsor rocks include limestone, gypsum, anhydrite, salt and potash. Continental conditions returned in the Pennsylvanian and coal seams of economic value were laid down.

Younger sediments and lavas of Triassic age occur along the coastal region of the Bay of Fundy. Glacial deposits mantle much of the inland area, obscuring the geology.

Windsor group. The Windsor rocks outcrop in central and northern Nova Scotia (Figure 1), forming low-lying ground. Boundaries with the older rocks are often faulted and the relatively incompetent nature of much of the Windsor group results in complex structures. Recent studies by Schenk (1967), Moore (1967) and Take (personal communication) have revised the detailed stratigraphy and paleographical interpretation of the Windsor.

Three thousand feet of Windsor rocks are present 35 miles north of Halifax, but Take (personal communication) reports about 10,000 feet in central Cape Breton. The soluble nature of the evaporites in the Windsor succession make it difficult to determine a true thickness in surface deposits which are subjected to weathering.

The broken and disconnected nature of the Windsor outcrop is attributed by Take to the effects of major thrusting and transcurrent faulting.

Evaporites. The evaporites within the Windsor group contain large amounts of salt and some associated potash. Salt springs occur in a number of locations (Pearson, 1963). Salt is currently being crystallized from brine obtained from drill holes at Nappan, and salt is mined at Pugwash. Annual salt production for domestic, chemical and highway use runs at 477,389 net tons (Province of Nova Scotia, 1966) and the market for highway salt is expanding at about 10% each year.

Potash is not produced commercially but is known to occur in the existing salt mine at Pugwash, and to have occurred in the former salt mine at Malagash where 80,000 tons of 8% KCL were estimated with a probable further reserve of 145,000 tons. The potash grade reached 11% in KCL in some locations and was reported to increase with depth.

The Nova Scotia Research Foundation analyzed the bromine content of salt samples from a number of locations in Nova Scotia to assess the probability of potash formation. Baar's reports (1966) indicate that brine concentrations sufficient to form potash did occur at certain periods in the Windsor.

Contents

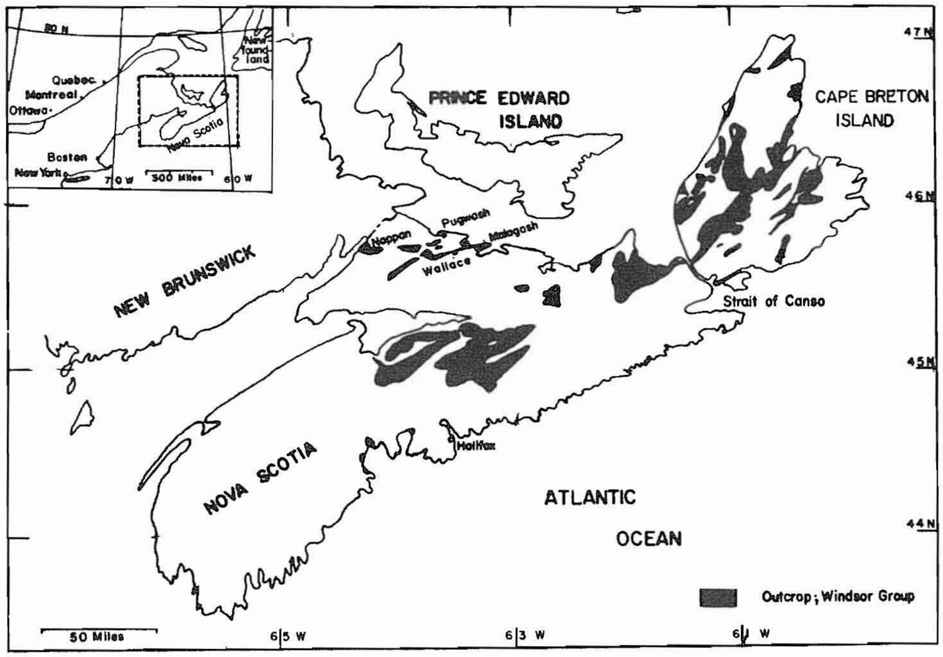


Figure 1. Windsor group outcrops in Nova Scotia.

Geophysics. A torsion balance survey was carried out in the area adjacent to Malagash Mine in 1934 by the Dominion Observatory and the Geological Survey of Canada (Miller and Norman, 1936).

The survey extending to nearly a mile from the mine occupied some 233 stations. A negative anomaly of about 3 milligals was detected.

Systematic gravity surveys were commenced in 1955 and today the Nova Scotia Research Foundation is measuring some 4000 gravity stations a year using Worden and Sharpe gravity meters. Stations are located on roads, tracks and cut lines at about 1000-foot spacing. Elevations determined by precise levelling are referred to the geodetic datum. The gravity observations are tied to the network of Dominion Observatory bench marks.

Since 1966 data has been reduced by IBM computer. The principal facts for each station including latitude and Bouguer gravity are compiled from the field data. At present the information is stored on punch cards but a magnetic tape file is being established and should be in service in 1968. All new data is handled in this way, older data is being systematically checked and recompiled to a common datum. Additional aids to interpretation including terrain corrections, plotting and automatic contouring are being developed.

Gravity coverage exists for most of northern Nova Scotia and is available in the form of 2 inches and 1 inch to 1 mile map sheets. Gravity compilation maps are available for certain areas.

Gravity surveys over areas underlain by rocks of the Windsor group exhibit negative anomaly patterns. These gravity 'lows' are typically 2 to 5 miles across, and from 5 to 15 milligals in magnitude. The steepest gradients and lowest gravity occur in areas where rocks of relatively high density adjoin the Windsor. The spacing between adjacent gravity lows is of the order of 12 to 15 miles in areas underlain by the thicker sections of the Windsor.

There is little doubt that these negative gravity anomalies are caused by large masses of salt. The only other low-density material which is common in the Windsor succession is gypsum, but this inverts at the pressures found at a few thousand feet to the higher-density mineral anhydrite, and cannot produce features of the magnitude of these gravity anomalies.

Many of the gravity anomalies show elongation, parallel to known faults or thrusts where the intrusive salt bodies appear to have penetrated along structural planes of weakness.

Geophysical investigations, Wallace area, Nova Scotia

Regional gravity surveys indicated the presence of a large negative anomaly in the Wallace area. This area is close to the former salt mine at Malagash where potash had been reported, and within 12 miles of the producing salt mine at Pugwash (Figure 1).

The favourable marketing prospects for salt and potash in eastern Canada and U.S.A. encouraged an intensive investigation of this area, financed jointly by the Provincial Government of Nova Scotia and the Atlantic Development Board and carried out by the provincial Department of Mines and the Nova Scotia Research Foundation.

Gravity. Regional gravimeter surveys by the Nova Scotia Research Foundation in 1957 and 1958 were supplemented by a regular grid composed of 840 stations spaced 500 feet apart on lines separated by 1000 feet. The resulting Bouguer anomaly map (Figure 2) shows a double negative anomaly composed of a larger western part centred south of Wallace Harbour and about 10 milligals in magnitude, and a smaller eastern part centred just south of the former salt mine at Malagash with a magnitude of about 6 milligals. A general east-west trend is evident in the anomalies with the eastern anomaly offset to the south.

Preliminary interpretations of the gravity were made using simple geometric models. In Figure 3 there is good agreement between the observed gravity along the section line N-S. and the gravity anomaly produced by a simple prismatic model 900 feet below the surface and extending to a depth of about 8000 feet with a gravity contrast of 0.22 g/cc. The choice of density

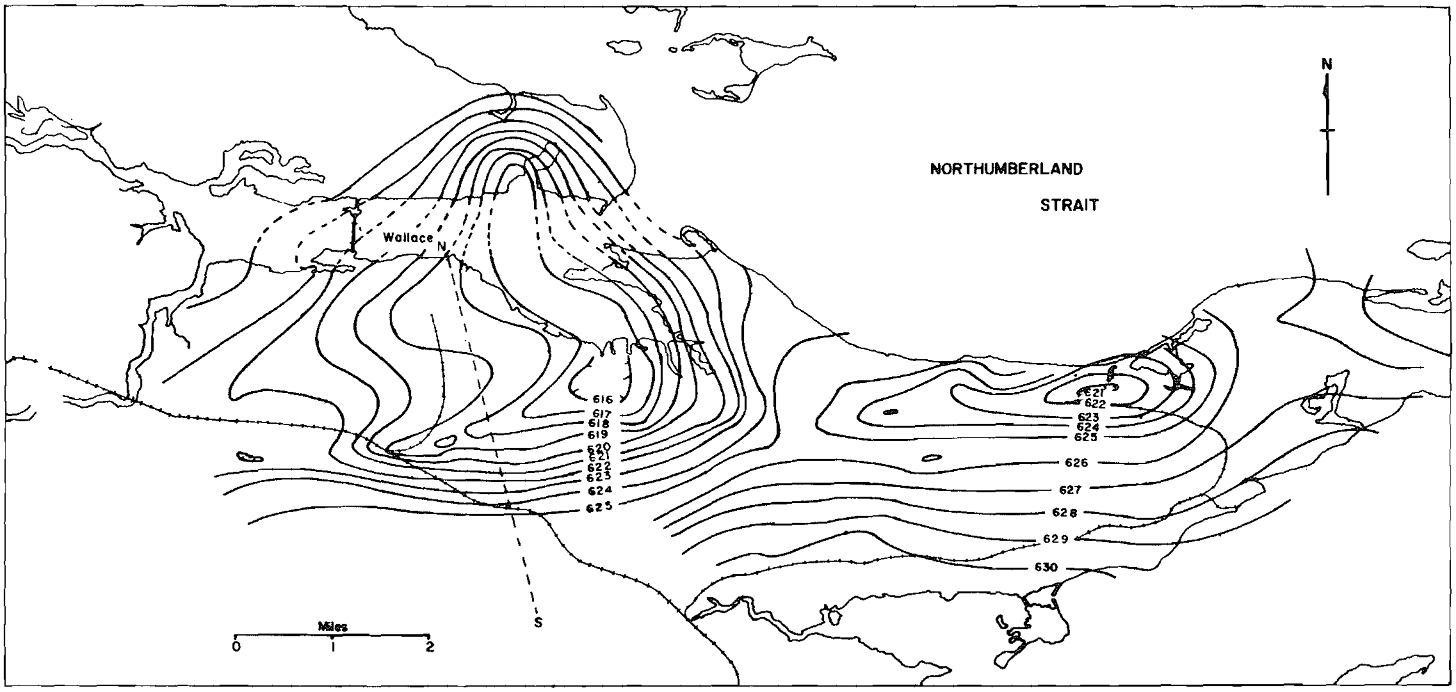


Figure 2. Bouguer gravity of Wallace area. Gravity contours at 1 milligal interval. N-S position of gravity and seismic profile.

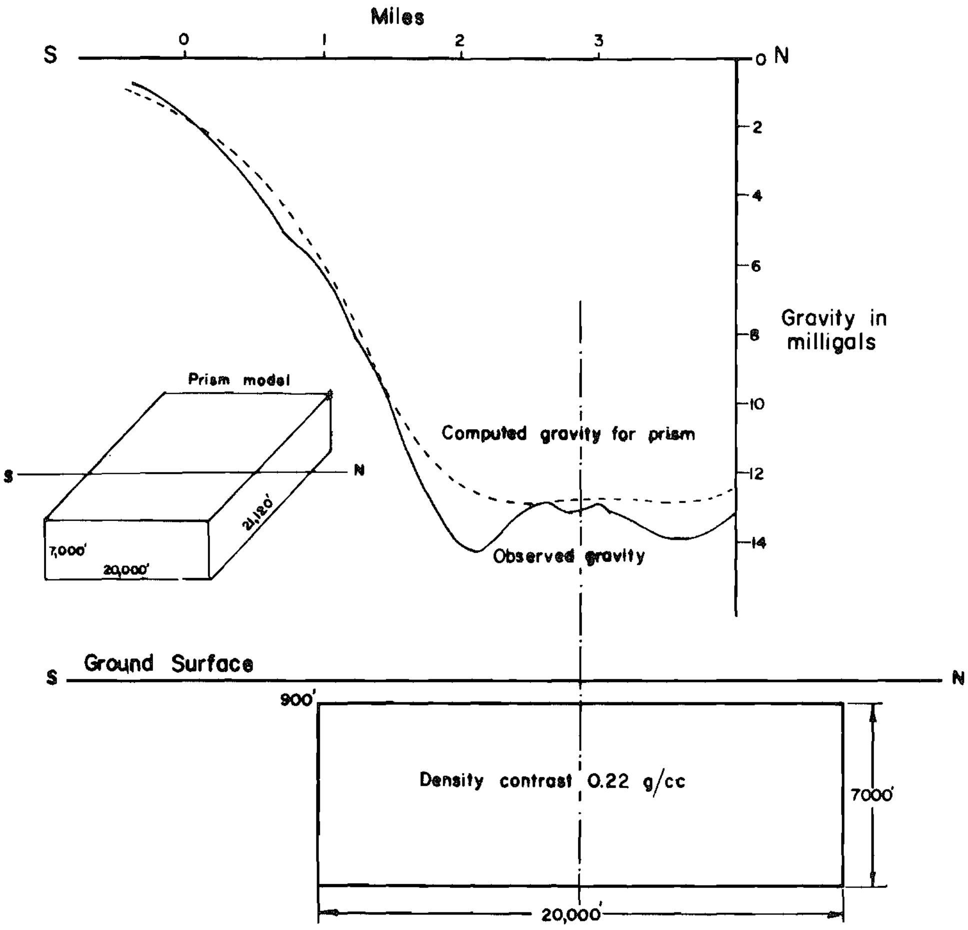


Figure 3. Observed and computed gravity along profile N-S for simple prismatic body.

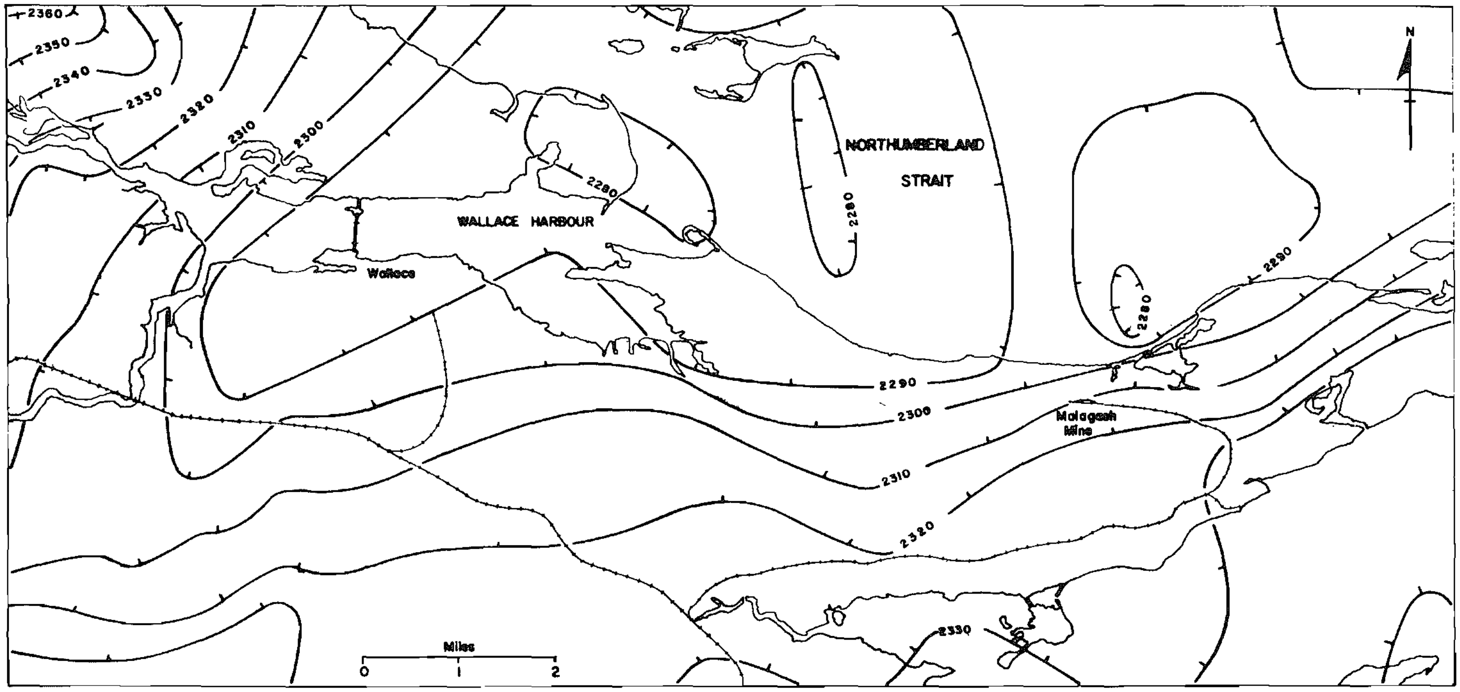


Figure 4. Aeromagnetic map of Wallace area. Magnetic contours at 10 γ interval, after the Geological Survey of Canada.

contrast is critical in this type of gravity model and the value used is an estimate of the contrast to be expected between Windsor evaporites (2.20–2.25 g/cc) and Mississippian rocks (2.40–2.50 g/cc). Higher contrasts can occur if a thick mass of pure salt is present, on the other hand the presence of substantial amounts of anhydrite (2.90 g/cc) within the salt would reduce the density contrast.

Magnetic. The airborne magnetic maps for this area published by the Geological Survey of Canada (Figure 4) show widely spaced contours characteristic of a thick sequence of sedimentary rock.

A ground magnetometer survey was carried out by the provincial Department of Mines, using the same line and station spacing as the gravity survey (Figure 5). Superimposed on the general east-west trend of the airborne magnetic survey, the ground survey shows a number of additional features. In the west is a NNW-SSE trend, in the vicinity of Wallace. Over the eastern gravity low, south of Wallace Harbour, the magnetic trend is WNW-ESE in both ground and airborne surveys, giving place to a predominantly E-W. or WSW-ESE trend in the area east of Malagash Mine. The salt intrusions near Wallace are in an area where the magnetic features are broad; small scale features and steeper gradients occur away from the salt body.

The salt contains small amounts of the magnetic minerals haematite in the form of red coloration, and the ferrous chloride mineral Rinneite. But susceptibility measurements on drill cores gave low to very low values, with no apparent correlation with lithology. Model calculations suggest the source of the magnetic anomalies lies at, or close to the top of the salt, and may therefore be due to local concentrations of magnetic minerals probably secondary deposits from circulating water.

Seismic. The results from a reflection seismic survey by the Beaver Exploration Co. along the line N-S are shown in the unmigrated section of Figure 2.

Good reflections were obtained from a number of horizons away from the salt intrusion (Figure 6). The interpretation shows a thrust at depth cut by a fault in the vicinity of the salt

Table I. Table of formations.

Age	Rock Units	Thickness (feet)	Rock Structures
Upper Penn.	Pictou group. Sandstone, shale, occasional thin coal seams	3400 +	Open folds, occasional faults, gently dipping beds
Lower Penn.	Boss Point formation. Predominantly grey to greenish grey, medium grained, cross bedded sandstone	2800 +	
	Claremont formation. Red-brown, poorly sorted conglomerate interbedded with thin shale and sandstone	800	Large folds and faults, gently to steeply dipping beds
Miss.-Penn.?	Middleborough group. Thinly bedded, chocolate to red shale and sandstone (?) unconformity(?)	370 +	
Upper Miss.	Windsor group. Gypsum, salt, limestone, dolomite, some shale and sandstone	Thickness unknown	Complex of folds and faults, steeply dipping beds, piercement structures

Geology after Cameron.

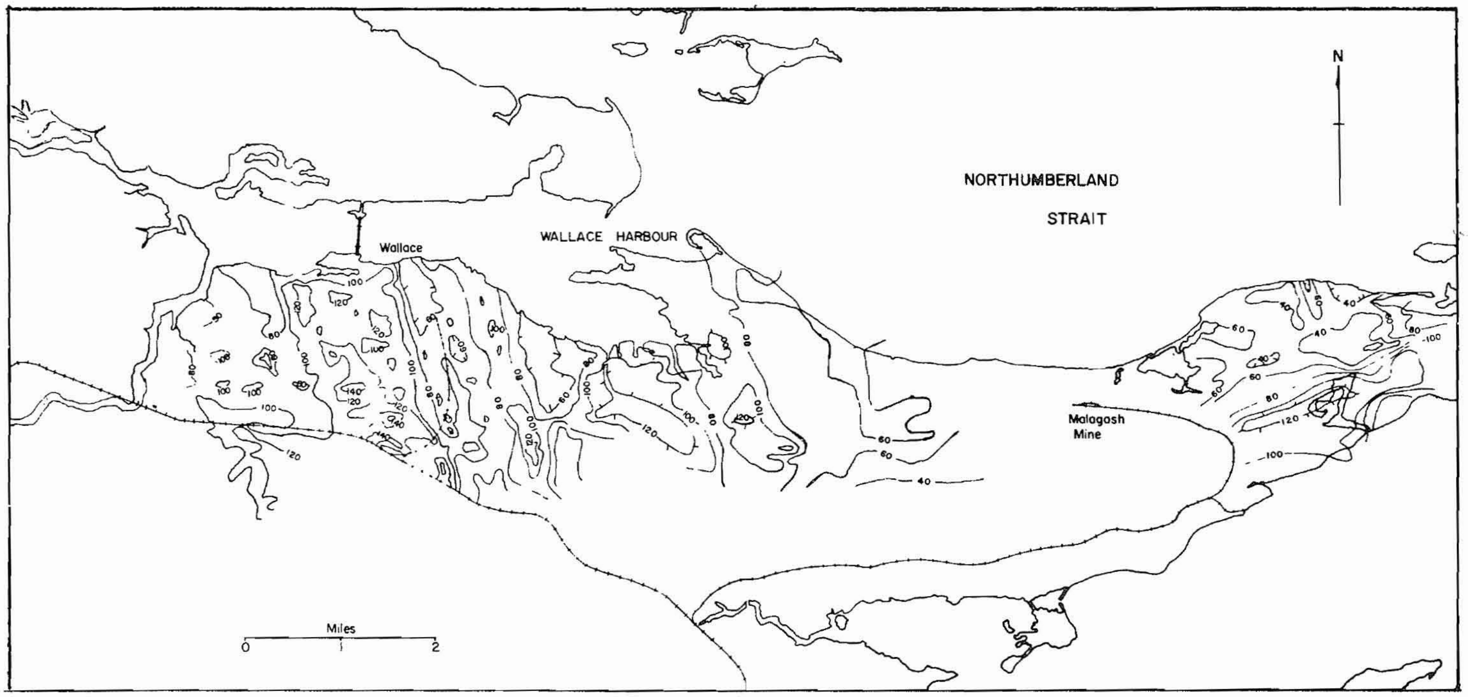
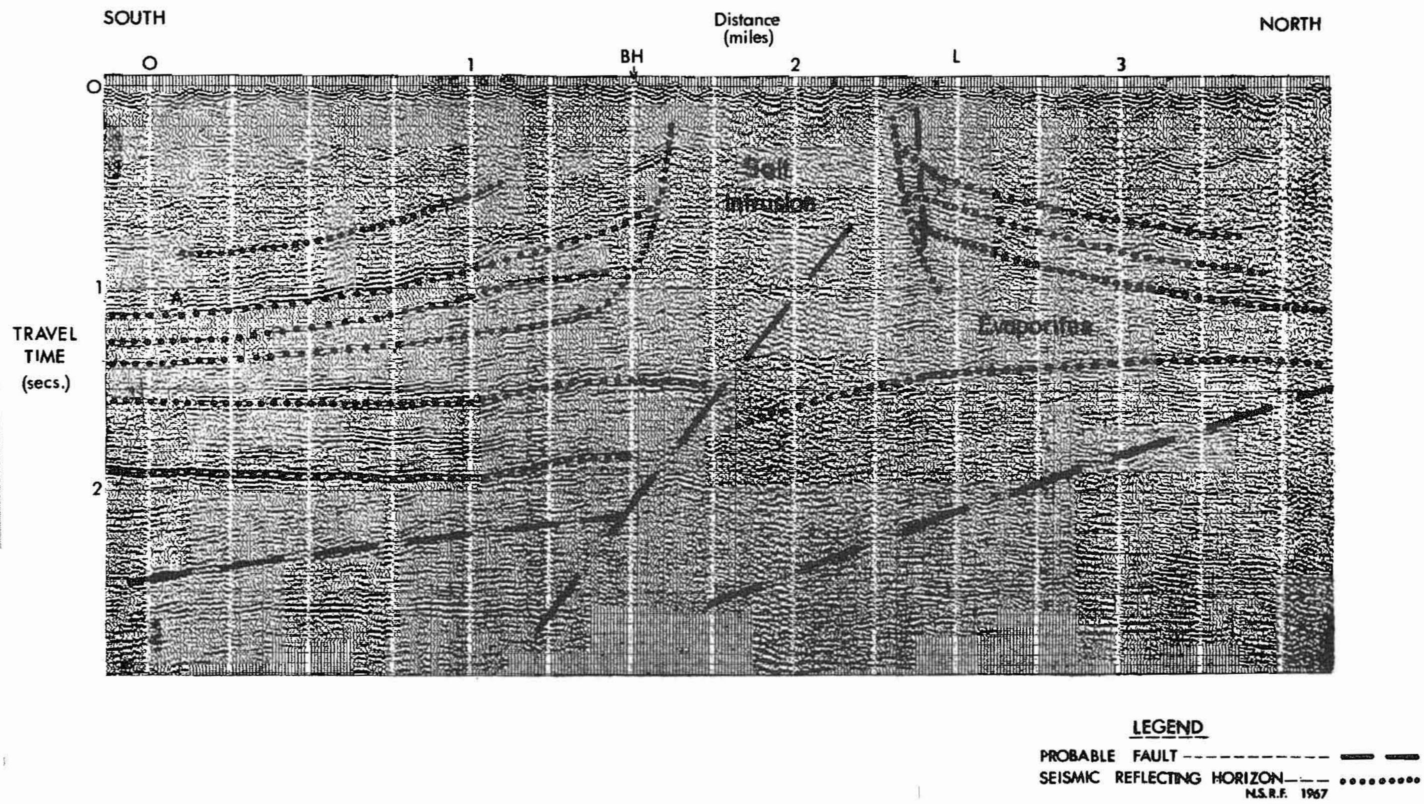


Figure 5. Ground magnetic survey map of Wallace area. Magnetic contours at 20 γ interval after Nova Scotia Department of Mines.

Figure 6. Seismic section, no correction for migration.



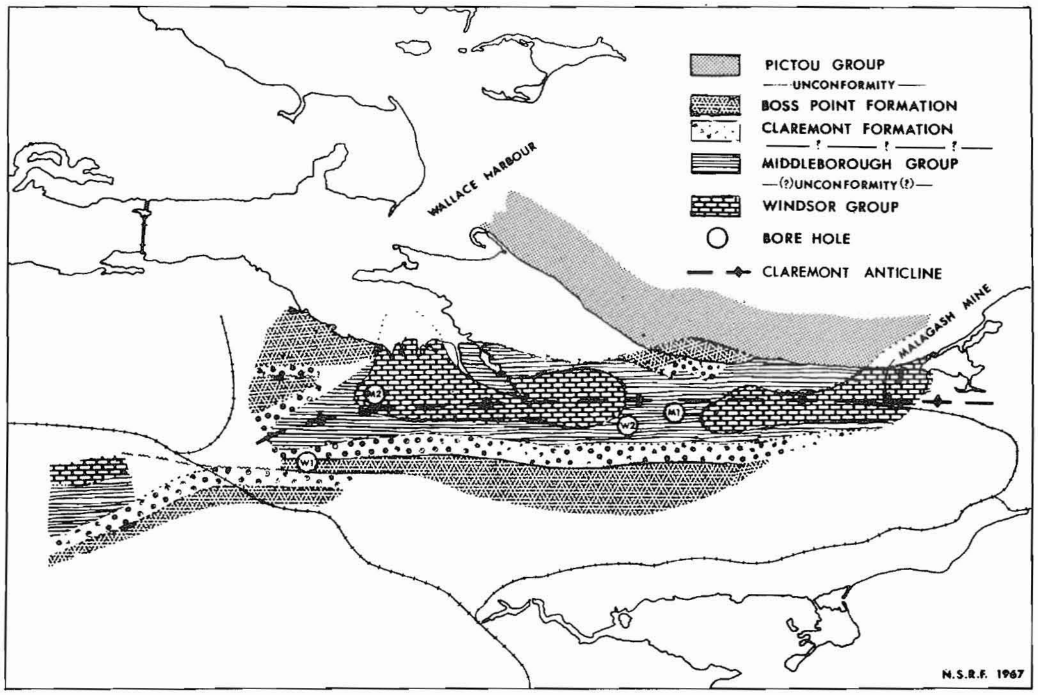


Figure 7. Geology of Wallace area.

intrusion. Strata thickens towards the intrusion presumably because of an expanded salt sequence and the overlying rocks are tilted by the intrusion with dips increasing to about 50°. There is also some evidence of minor faulting.

In the absence of good velocity control, depths are uncertain. However, if a velocity of about 14,000 ft/sec is assumed for the upper part of the sequence the depth to the first prominent interface A is around 7000 feet at the south end of the section.

Geology. The surface geology of the area was detailed by Cameron (1967). A simplified version of his map is shown in Figure 7. Surface outcrops are generally poor except in coastal or stream sections. However, the presence of Windsor rocks is often indicated by the development of Karst topography.

The east-west structure of the Clairmont Anticline is complicated by additional folding and thrusting. Dips are high and often irregular towards the centre of the structure, suggesting local folding due to the uprising salt.

The lithology and thickness of the main rock groups are tabulated in Table I together with the prevailing structural features in each.

Drilling. The presence of salt was confirmed in the wire line hole (M1 in Figure 7) drilled by the Department of Mines. Salt was first encountered as cement in brecciated siltstone at 800 feet. This gave way to massive salt at 900 feet, which continued to the hole bottom of 1000 feet.

In the summer of 1966 two rotary holes were drilled to depths of 4011 feet (W1) and 2619 feet (W2). In W1 salt was first encountered at 2746 feet, the overlying rocks were measured as dipping at 55 to 60°; W2 ran into evaporite at 1206 feet, extending to 1866 feet. A second evaporite section occurred at 1866 feet consisting of salt and anhydrite which continued to hole bottom.

Core samples revealed potash minerals veining the salt at several levels. Gamma ray logs of the holes by the Nova Scotia Research Foundation indicated several zones within the salt with high gamma ray activity up to a potash equivalent of 7% K_2O. Subsequent chemical tests on core samples confirmed these findings. The potash-bearing horizons ranged up to 100 feet in thickness averaging 5.8% K_2O and a best analysis of 8.3% K_2O. In Figure 8 the irregular nature of the gamma ray log in the potash sections contrasts with the low readings obtained in massive salt without potash; shale and siltstone bands also give increased gamma ray count, but the peaks are usually lower than those due to potash minerals.

Discussion

The presence of two major salt intrusions in the Wallace area was indicated by the gravity surveys and has been proved in bore holes. The seismic reflection profile indicates a depth to the bottom of the salt of about 8000 feet and the gravity model based on this depth shows good agreement with the observed data.

The intrusion of the salt was probably controlled in part by the fault indicated on the seismic profile, the pressure of the overlying rocks forcing the plastic salt along the bedding and up towards the surface. The potash mineralization occurs as veining and replacement of the salt and may represent material redeposited by circulating water.

The seismic profile suggests that the Windsor group in the Wallace area has a considerably greater thickness than has previously been supposed from surface geological studies.

Conclusions

Gravity surveys form an effective way of locating intrusive salt masses. Seismic data appears to confirm that faulting and thrusting are a major factor in the emplacement of salt structures

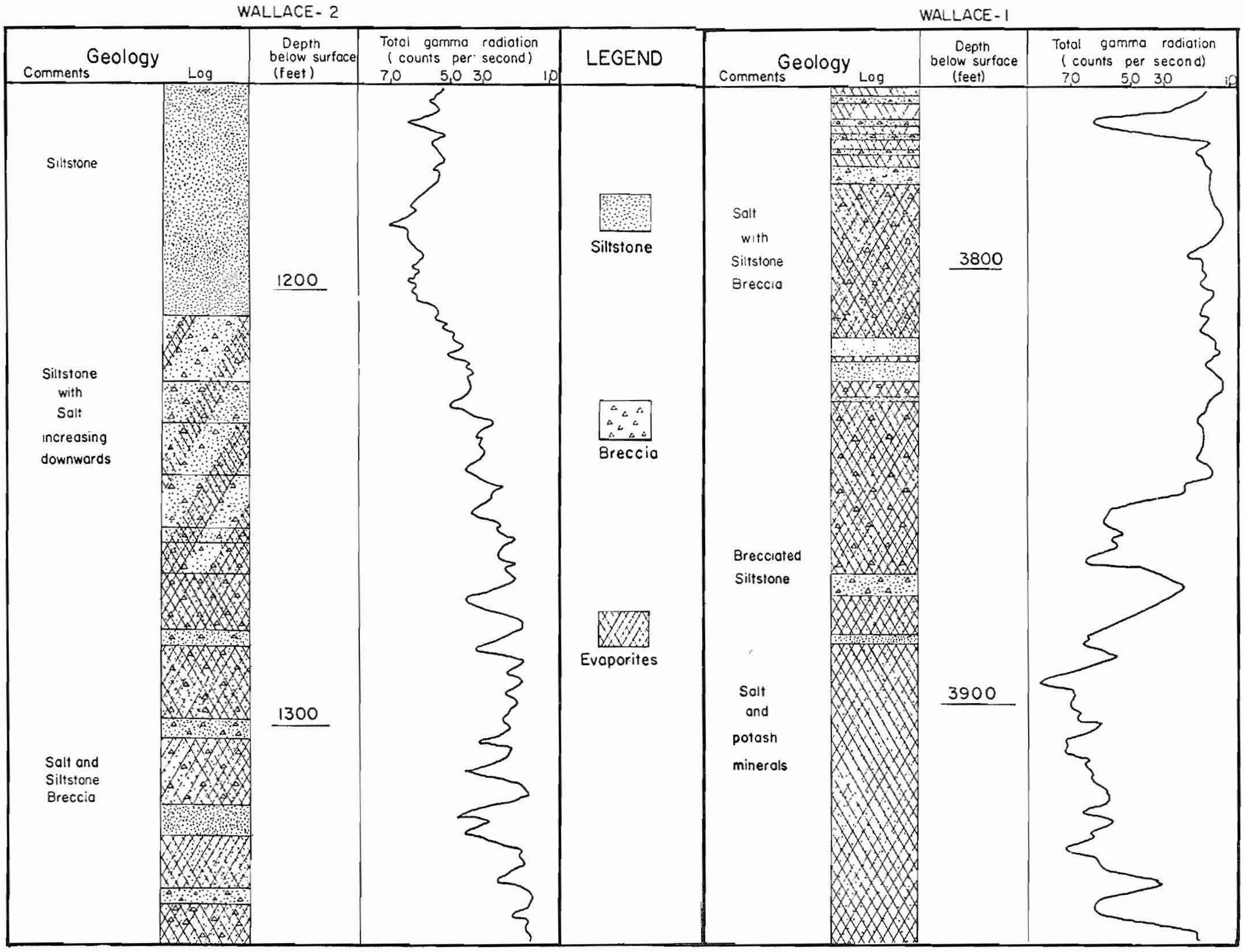


Figure 8. Bore hole and gamma ray logs.

in Nova Scotia. These salt bodies have more in common with those found in the Rhine Graben of Germany, than the salt bodies of the Gulf Coast.

Within the salt intrusions, high dips and isoclinal folding is to be expected and have been found in drill cores and by the work of Evans (1967) in the Pugwash salt mine. Fragments of anhydrite and limestone carried up within the rising salt would account for the irregular seismic reflections of the salt.

Potash mineralization when found, is irregularly distributed within the salt; it is possible that secondary mineralization is responsible with the soluble potash minerals being leached out and then redeposited by circulating water. If this is the case fracture and fault zones within and marginal to the salt could play an important part in controlling potash mineralization. Analogous deposits in the Rhine (Borchert and Muir, 1964) show the best potash concentrations away from the domes, anticlines and fracture zones where preferential leaching has taken place. Applying this to Nova Scotia the preferred areas for potash would be on the flanks away from the centre of the salt intrusions, where the rock is less disturbed but not at excessive depth.

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