2. AN OVERVIEW OF MINING GEOPHYSICS

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Abstract

The technology of mining geophysics is advancing rapidly in methodology, instrumentation and interpretation techniques. A surprising diversity of approach exists in a number of methods, because of differences in the local geological, geophysical, topographic or even socio-political setting.

A general trend is towards the simultaneous gathering of increasingly large amounts of independent geophysical data in airborne, ground or borehole surveys. The resultant challenge is to extract the maximum amount of useful geological information from the mass of field data generated by these surveys. Increasingly, computers perform the task of routine interpretation, using either direct inversion programs or automatic selection from a family of theoretical models.

Minicomputers are routinely employed in the control of multisensor airborne systems and in the recording of their output in digital form on magnetic tape. Some simple data manipulation is even being done by such minicomputers in real time prior to recording.

Microprocessors are being increasingly incorporated into field portable geophysical instruments for surface and borehole surveys.

Résumé

L'application de la géophysique à l'extraction minière connaît une évolution rapide tant au niveau de la méthodologie et de l'instrumentation que des techniques d'interprétation. Il existe des approches étonnamment variées à certaines méthodes à cause des différences sur les plans géologique, géophysique, topographique ou même socio-politique au niveau local.

De façon générale, la géophysique tend à s'orienter vers la collecte simultanée d'une quantité de plus en plus grande de données géophysiques indépendantes recueillies par des levés aériens, au sol ou par sondage. Le défi est alors d'extraire le plus grand nombre possible de données géologiques utiles de la masse de données obtenues par des levés sur le terrain. On fait de plus en plus appel aux ordinateurs pour les tâches d'interprétation courantes, en utilisant soit des programmes d'inversion directe ou de choix automatique à partir d'une famille de modèles théoriques.

On emploie couramment des mini-ordinateurs pour le contrôle des systèmes aéroportés à détecteurs multiples et pour l'enregistrement des résultats obtenus sous forme numérique sur des rubans magnétiques. On utilise même quelquefois ces mini-ordinateurs en temps réel lorsqu'il s'agit de manipulation simple de données, avant l'enregistrement.

De plus en plus, on incorpore les microprocesseurs aux appareils géophysiques transportables pour les levés en surface et par sondage.

INTRODUCTION

The science of geophysics applied to mineral exploration includes a kaleidoscope of methods and techniques, many of which are in a state of rapid flux. At least eighteen fundamentally different methods are in major or minor use in mining geophysics around the world, some being employed in up to twenty variants.

There is a zestful difference of opinion on the relative merits of methods, techniques and instrumental approaches, not only between the two main centres of development in North America and the U.S.S.R., but also among the scientists in each centre. These differences of opinion have, through scientific or commercial competition, been instrumental in stimulating advances in the art in both centres.

In my opinion, the most significant factor at present in mining geophysics is the data explosion. Through the miracles of 1977 microelectronics we can now endow a man or an aircraft with far more geophysical data gathering capability than would have been dreamed of only a few years ago. For example, airborne radiometric systems record 256 to 1024 channels of data simultaneously, whereas only a year or two ago four channels were standard and ten years ago only a single channel. Airborne electromagnetic systems today rarely gather fewer than six channels of data and many more channels are contemplated. Ground induced-polarization receivers commonly produce six channels of data and one even makes one thousand channels available. Computer controlled data acquisition systems are increasingly being used in airborne surveying as are microprocessors in ground based equipment, to facilitate the gathering and manipulation of multichannel data.

As a typical example of an integrated airborne geophysical system designed for multi-resource mapping at low level, we may find six audio frequency electromagnetic channels, two VLF EM channels, four gamma-ray spectrometer channels and a magnetometer channel. The thirteen independent geophysical channels in all are recorded digitally on magnetic tape every half second, or every thirty metres on the ground. Figure 2.1 shows a computer printout of a section of the digital tape from such a survey, with the various geophysical data streams, the altimeter output and the fiducial numbers identified. Eight sets of plans of stacked profiles or contours are normally produced by computer from these various data. This great volume of data strains the human capability to correlate and fully utilize its potential at the present time.

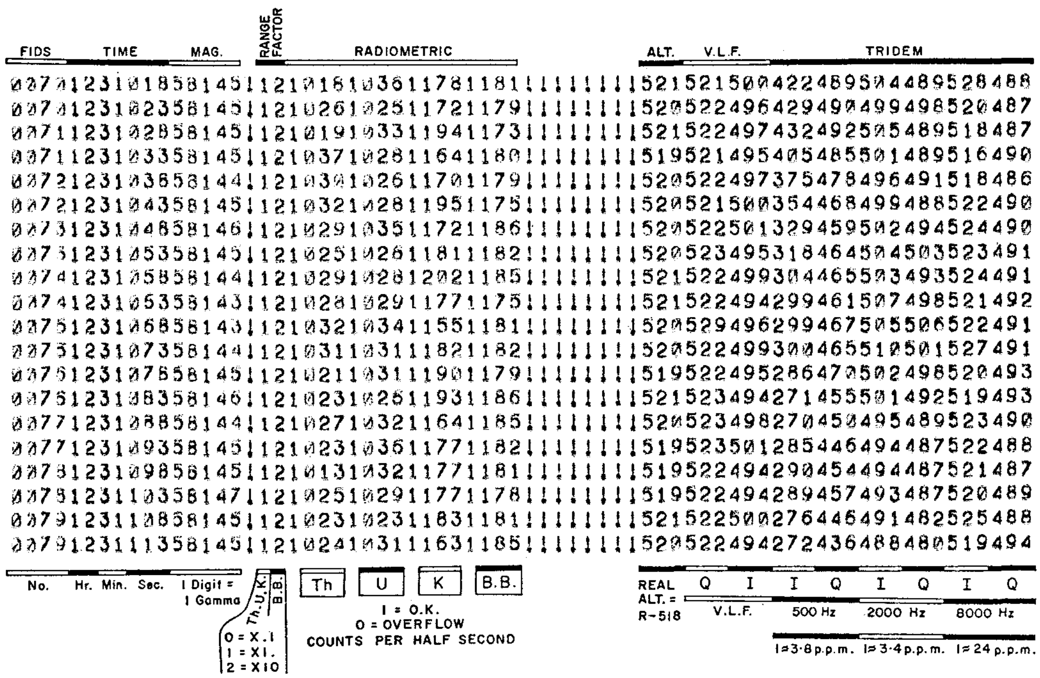

Figure 2.1. *Computer printout of typical multimethod airborne geophysical magnetic tape. (Courtesy Scintrex Limited)*

In fact, the greatest challenge now facing mining geophysicists is the distillation of the maximum amount of useful geological information from the mass of independent data currently arising from surveys embodying single or multiple methods. If this is to be done on a routine basis, it will clearly have to be carried out by the computer.

Computer processing and machine presentations of data have been already, of necessity, taken over from human hands and minds in the case of complex airborne-generated data of the type shown in Figure 2.1. Total "hands off" processing of such data is still not practiced in most low-level surveys, however, because the flight path is still recovered using tracking cameras due to the shortcomings of present radio navigational devices (such as Doppler). Navigational devices which are moderate in cost, light enough to be used in the relatively small aircraft employed in mining geophysical surveys and still give the high positioning accuracy required (±25 m) are not yet available. Transponder systems (e.g. Motorola, Raydist and Decca), using fixed stations, have acceptable accuracy and weight but their cost and inconvenience precludes their general use.

The use of the computer has permitted some fundamental advances to be made in the quantitative interpretation of many types of geophysical data, particularly of a multichannel nature. The direct inversion of data for purposes of interpretation is now practical in resistivity, IP (e.g. Pelton et al., 1977) and electromagnetic surveys (e.g. Sternberg, 1977). Where direct inversion is too demanding of computer time, the computer still serves as a fast and economical means of selecting the best fit from a family of simplified models for which it has derived the forward solution.

In order to provide a broad perspective on this complex field and to place the various methods in their proper context, I propose to structure this discussion by geological objective. The broader features of each more important method will be considered as it is encountered in its major geological application.

REGIONAL GEOLOGICAL MAPPING

In the field of basic geological mapping, the magnetometer remains the primary airborne geophysical tool, indicating the distribution of the various rock types and minerals through their variation in magnetic susceptibility and remanent magnetization. However, the gamma-ray spectrometer is now almost a constant companion of the magnetometer for regional airborne geophysical surveys, providing a classification of rock or soil types based on their content of potassium, uranium and thorium.

A third mapping parameter, namely conductivity, utilizing one of several airborne electromagnetic devices is now available. For this application, multiple frequency measurements or multichannel transient measurements are commonly made in order to cover a broad range of earth conductivities.

Radio transmission measurements using VLF and broadcast band stations as source and measuring the ratio of electric and magnetic field components, can also map near-surface conductivities. These are quantitatively discriminating only in a somewhat lower range of conductivities than those mentioned above since their basic operating frequencies are high by normal airborne electromagnetic standards.

The Airborne Magnetometer

The proton magnetometer is the most commonly used airborne magnetometer. In a stable, well-compensated installation, the best of these can now achieve a useful sensitivity of about 0.1 gamma (at one reading per second). Some high sensitivity (cesium, rubidium or helium) optically-pumped magnetometers are also being used for identification of subtle features in areas of low magnetic activity and as vertical gradiometers.

Surprisingly enough, many total field self-orienting fluxgate magnetometers are still in operation, mostly in the East, but also in the West because the smooth analog profile data is still preferred by many interpreters.

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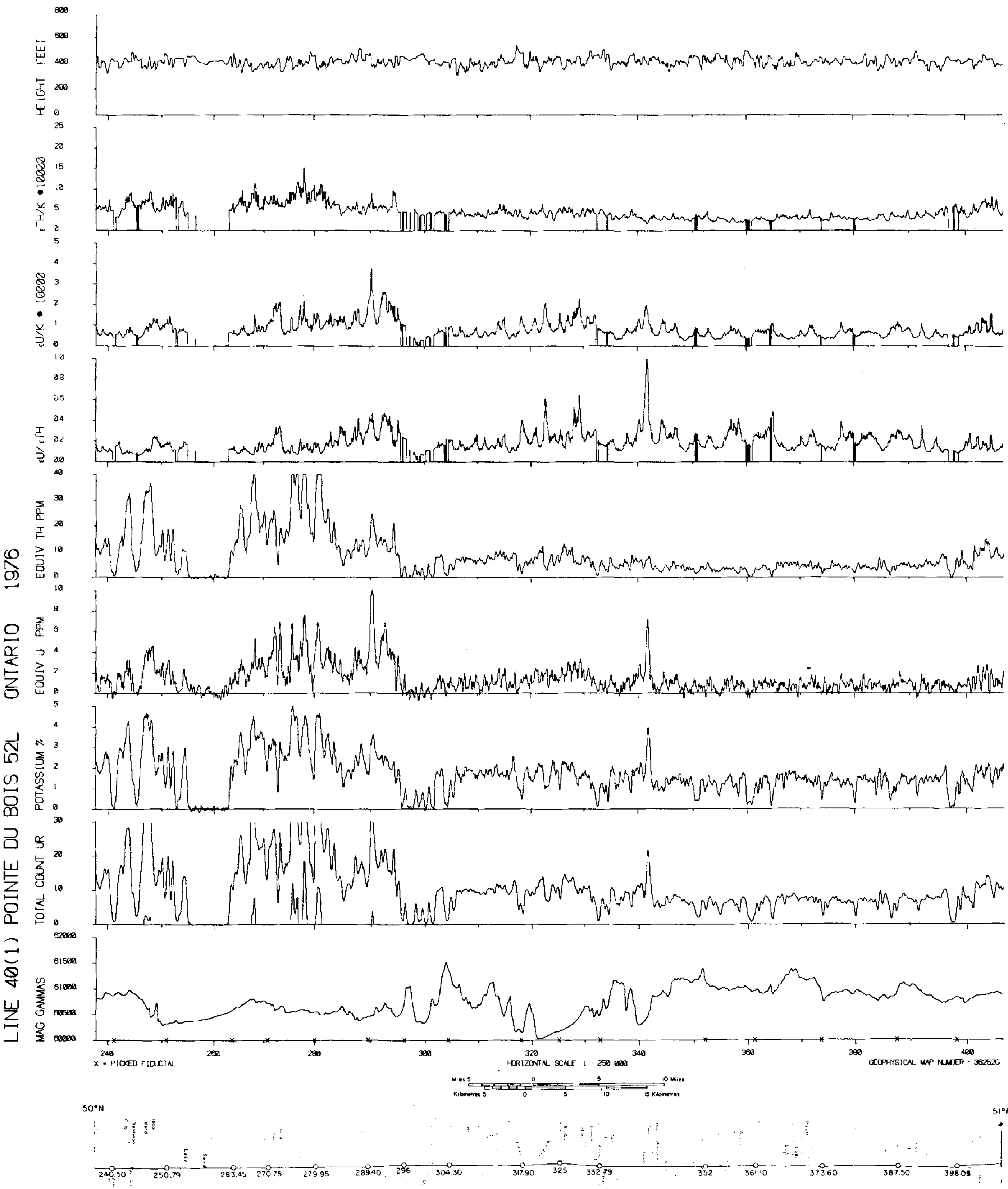

Figure 2.2. *Computer plot of stacked airborne radiometric data in four channel profiles and elemental ratios. Pointe du Bois, Ontario, Canada. (Courtesy of Ontario Ministry of Natural Resources and Department of Energy, Mines and Resources, Ottawa).*

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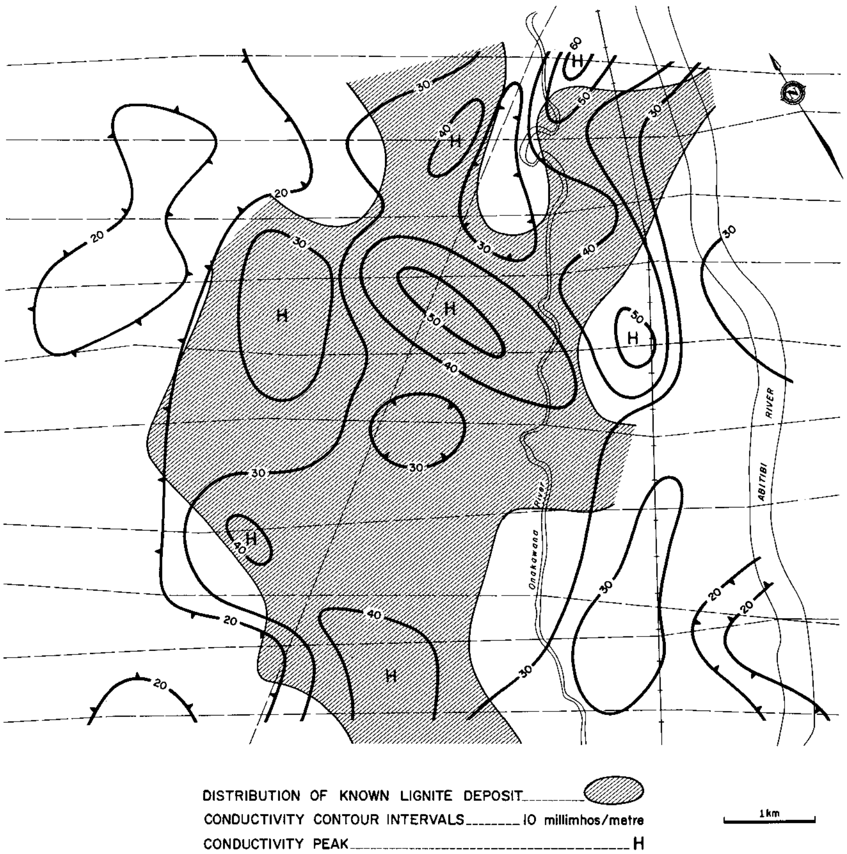

Figure 2.3. *Computer interpretation of lower layer conductivity derived from Tridem airborne electromagnetic data. Onakawana lignite deposit, Ontario. (Courtesy Ontario Ministry of Natural Resources)*

Regional aeromagnetic surveys for mapping purposes are normally flown at a mean terrain clearance of about 150 to 300 m (terrain permitting) and with line spacings depending on the ultimate plotting scale. For example, if the plotting scale is to be about 1:50 000 the line spacing may be 500 m (or 0.25 mile) and for 1:100 000 the line spacing may be 1 km (or 0.5 mile) etc. Surveys for specific exploration targets will have line spacings dependent on the expected target dimensions.

Compilation of the resultant aeromagnetic data, most of which are now digitally recorded, is now mostly carried out using computer techniques.

The Gamma-Ray Spectrometer

Until recently, sodium iodide crystal volumes for aerial gamma-ray spectrometry rarely exceeded 1000 cu. in. (16.4 L) and at most four channels or windows of gamma radiation were measured. Now it is common to employ up to 3000 cu. in. (49.2 L) for first order aerial mapping. The specifications for such high sensitivity surveys commonly call for about 200 cc of crystal per km/h of ground speed of the aircraft (or 20 cu. in. per mile per hour). With such large crystals, yielding much higher count rates than before, it has become meaningful to break the spectrum into more than four channels. For example, in the current Canadian or U.S. government-type specifications, the natural spectrum from 0 to 3 MeV is recorded in 256 channels on magnetic tape. In addition, cosmic-ray activity in the 3 to 6 MeV range is monitored in 256 channels. The local level of atmospheric (radon) and cosmic radiation is separately measured by an upward-looking crystal which is lead-shielded from gamma radiation of terrestrial origin. Five hundred and twelve channels of gamma radiation may be similarly recorded from this upward-looking crystal.

At least theoretically, the recording of the resulting 1024 channels of radiometric data permits corrections for the effect of atmospheric radon and cosmic radiation into the natural terrestrial spectrum, rock-type identification through absolute levels of uranium, thorium and potassium, as well as their ratios, and an independent check on the energy calibration of the gamma-ray spectrometer at all times. Some attempts are being made to recognize spectrum changes due to overburden attenuation and soil moisture changes, but with as yet uncertain success (e.g. Geodata, 1978).

The copious results of such multichannel surveys cannot possibly be compiled and presented in their entirety. In practice, they are corrected for terrain clearance variations, cosmic and atmospheric background and then grouped into four channels, one being "total count" and the other three centred about the primary gamma peak for each of K, U and Th. Corrections are made for Compton interference of the elements so that three "stripped" elemental channels are presented, one for each of K, U and Th, as well as total count. These elemental channel values may be presented directly, or as ratios, in profile or contour form.

Figure 2.2 shows typical stacked profiles of total count, K, U and Th. Each has been corrected for altitude (to 120 m) and background variations and each has been averaged over three adjacent one-second sampling periods. The K, U and Th are expressed in equivalent per cent or ppm of each element, assuming an infinite source area, having been "stripped" of Compton interference effects. Also presented in stacked profile form are the ratios eU/eTh, eU/K and eTh/K, as well as the altimeter and magnetometer profiles. In order to avoid statistically meaningless ratios the ratio values are based on running averages of successive readings over intervals where the numerator and denominator each exceed 100 counts.

Both types of profiles (elemental and ratio) may be meaningful in rock-type identification and in mineral exploration. The latter application is commonly restricted to prospecting for deposits of uranium, thorium, potash and phosphates (uranium rich) and those minerals associated with alkali complexes (e.g. columbium and tantalum), at least in the West. In the U.S.S.R., the ratio values are also used for the recognition of rock alteration associated with a variety of deposits of non-radioactive elements including bauxite, molybdenum and tin, etc. (Zietz et al., 1976).

Airborne Conductivity Mapping

Details of airborne electromagnetic systems for conductivity mapping will be found in the section of this paper on base metal exploration, for which they are more commonly employed. As an example of such conductivity mapping for other applications, consider Figure 2.3. This shows the mapping, by a multifrequency in-phase/quadrature system, of a lignite deposit which is buried under 10 m to 40 m of glacial clays and tills. In this case, the lignite and its associated fire clay horizon has a significantly higher

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conductivity (25 to 60 millimhos/m) than that of the overlying materials (about 5 to 10 millimhos/m). The conductivities of this contour plan were derived by computer interpretation using techniques described more fully in Seigel and Pitcher (1978).

The optimum terrain clearance may be different for each type of mapping survey. As a rule, prospecting-type radiometric surveys should be flown as close to the ground as possible (75 m or less) for improved detection of small targets. Aeromagnetic surveys may be flown somewhat higher (e.g. 150 m). Electromagnetic surveys must also be flown at a minimum terrain clearance. However, low terrain clearance means more severe turbulence, more difficult flight path recovery and higher unit costs. Thus, combined magnetic-radiometric mapping surveys are often flown at terrain clearances which are in excess of those desirable for the most effective radiometric prospecting purposes.

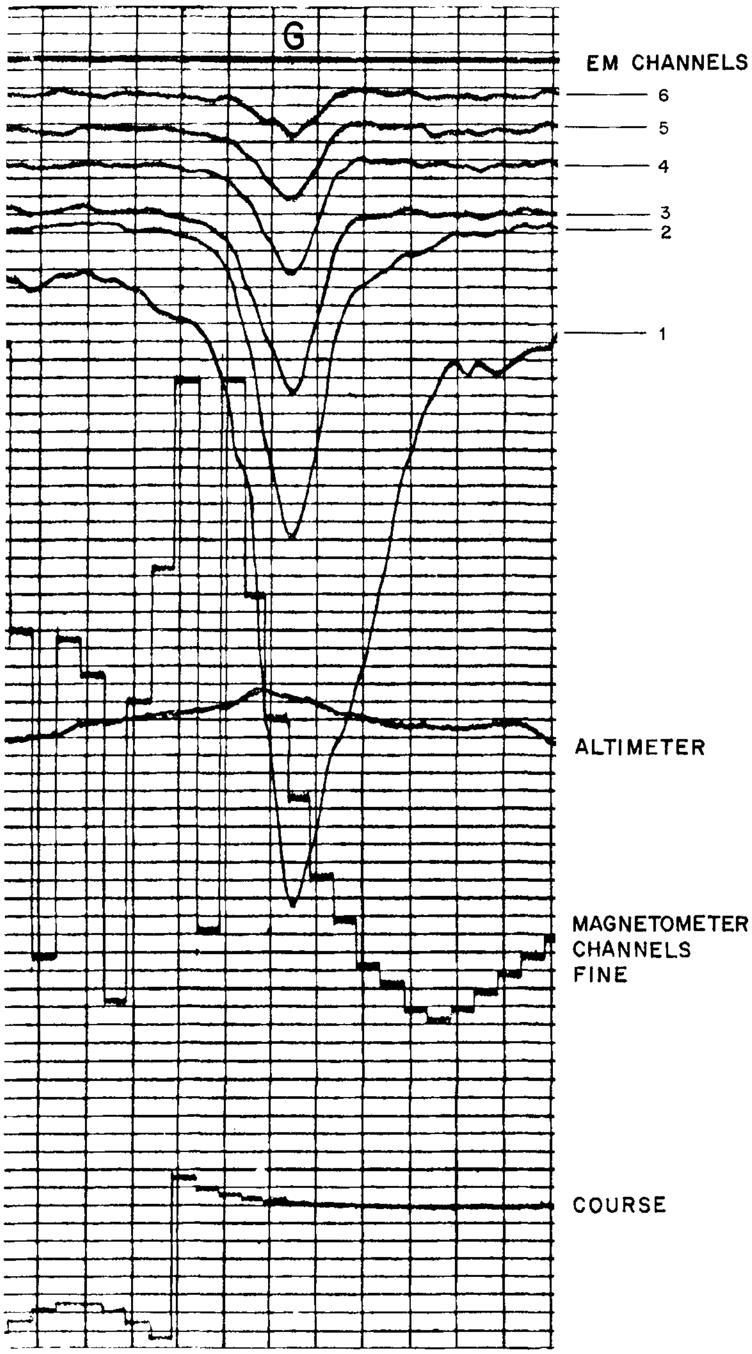

Figure 2.4. *Input AEM traces over a bedrock conductor under 85 m of overburden. Sheraton Township, Ontario, Canada. (Courtesy of Questor Surveys Limited)*

Similarly, fixed-wing airborne electromagnetic systems in which the receiver is mounted in a towed bird must fly (for safety reasons) at 115-130 m terrain clearance. This renders them only marginally suitable for those simultaneous radiometric surveys where uranium prospecting is a major objective. Totally on-board airborne electromagnetic systems are normally flown at very low terrain clearances and are therefore relatively compatible with radiometric surveys for uranium prospecting.

BASE METAL EXPLORATION

Mining geophysicists have been highly successful in the discovery of buried base metal orebodies of many types and in many environments. The most successful primary methods have been the electromagnetic induction technique for massive sulphide bodies and induced polarization for disseminated sulphide bodies.

Massive sulphide bodies commonly have electrical conductivities (1000-10 000 millimhos/m) which are two to four orders of magnitude higher than those of their host rocks. Thus, in most geological environments, the orebodies can be resolved from their host rocks by electromagnetic induction methods. Where large areas of favourable rock types are to be explored, it is now the accepted practice to employ a suitable airborne electromagnetic method for reconnaissance detection, followed by ground electromagnetic investigations and other ground-based methods for detail.

Airborne electromagnetic methods have been particularly cost-effective where they can be applied, because of their low unit cost, which is still of the order of \$15-\$30 per km surveyed. This is not to imply that the probability of success with these methods has been high. The ratio of base metal orebodies to total "conductors" has been found to be rather low, usually of the order of 1/500 to 1/1000. Despite this, the low unit conductor discovery cost and the high average orebody return have made this type of exploration approach highly rewarding in the search for stratabound copper-zinc and lead-zinc deposits, particularly in Precambrian environments. Similar success has been recorded in the exploration for nickeliferous pyrrhotite deposits associated with ultrabasic intrusives.

The high quality of modern airborne electromagnetic and magnetic data leaves little additional information to be gleaned from their counterpart ground surveys except greater precision of location, which is desirable for drilling purposes. Useful complementary information may be afforded from geological mapping and geochemical sampling of the conductor location, depending on the nature of the soil cover in the survey area. In the Canadian Shield, where outcrops are few and the soils are of transported glacial origin, the geophysical data alone may have to be relied upon for a drilling decision.

Gravimeter traverses are often useful in such areas to resolve conductors due to graphite from those due to massive sulphides. Both induced polarization and gravity (to a lesser extent) have proven useful in resolving conductors of ionic origin (bedrock troughs and shear zones) from those of electronic origin (sulphides or graphite).

The IP method has been particularly useful as a ground follow-up technique in areas of tropical weathering, particularly in semiarid environments (e.g. Australia).

For a fuller discussion of ground follow-up philosophy and methods, the reader is referred to Seigel (1972).

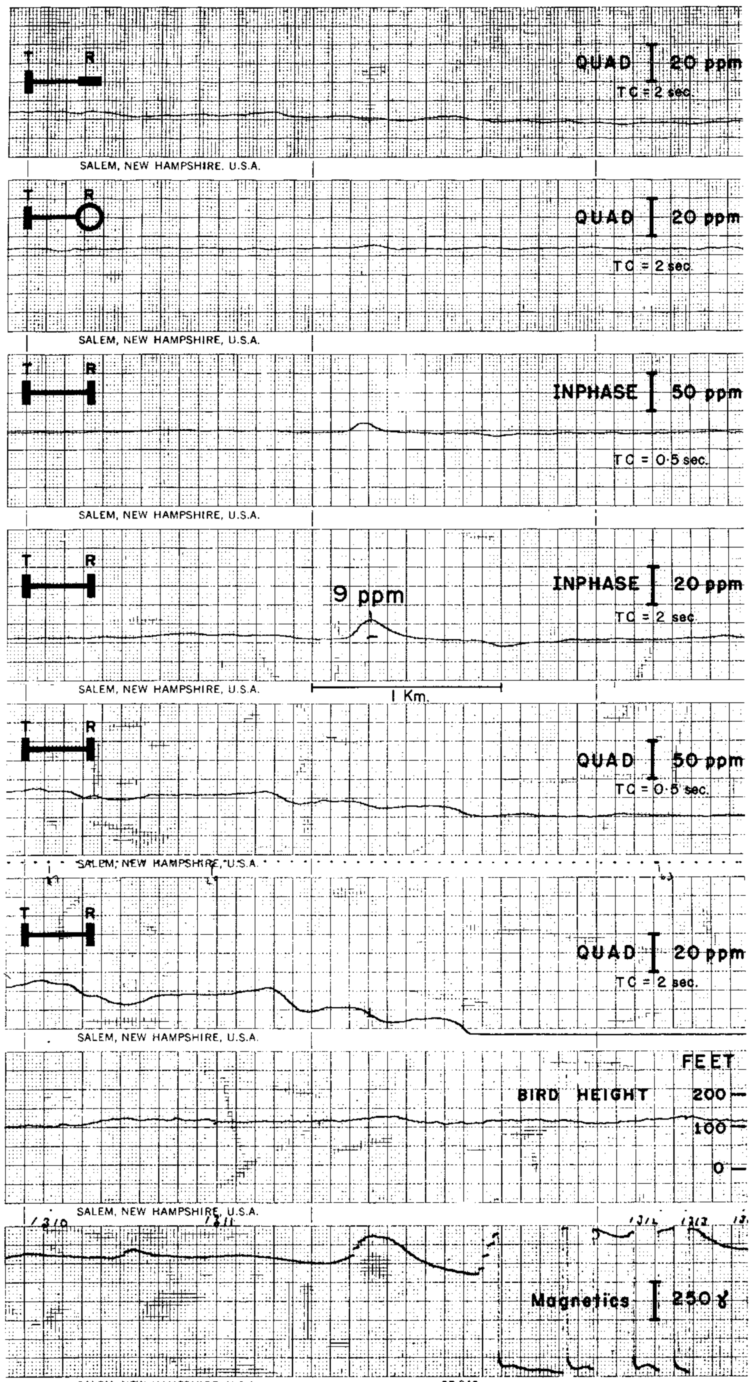

Figure 2.5. *Multichannel single-frequency Dighem helicopter electromagnetic discovery profile over nickel/copper deposit. Montcalm Township, Ontario, Canada. (Courtesy of Geophysical Engineering Ltd.)*

The Airborne Electromagnetic Method

At present, about seven basically different airborne electromagnetic (AEM) methods are in active use throughout the world. Most of these were first developed and utilized in Canada, because of various technical and historical reasons, although increasingly these are now being manufactured abroad, for example, in Sweden, Finland, U.S.S.R., India and China. A fuller description of AEM systems may be found in Ward (1970).

Recent airborne electromagnetic developments have been directed towards expanding the data-gathering capabilities of the systems, leading to the detection and resolution of a broader range of geological conductors, as well as to improvement in signal to noise ratios. The latter objective, when achieved, will automatically result in an increased depth of exploration as well as higher spatial resolution for near surface targets through a reduction of time constants.

It is common today for an airborne electromagnetic system to produce between 6 and 9 simultaneous channels of data (perhaps not all of it truly independent) for different (transient) times, different frequencies, or different coil configurations. The interpretative possibilities of this wealth of data are large. Some computer interpretations based on simple geological models have been developed by the operators of these systems and are now being applied on a routine basis.

Perhaps the most widely-used AEM system at the present time is the transient system known as Input (e.g. Lazenby, 1973). It measures six slices of the electromagnetic transient decay at various times out to 2.3 s^{-3} following a 1.1 s^{-3} primary pulse. In this way, it is able to detect a wide range of geological conductors.

Figure 2.4 shows an Input AEM test profile flown across a bedrock conductor consisting of a mixed graphite/sulphide body in Precambrian rocks, under 85 m of relatively poorly conducting overburden. The figure illustrates the exploration depth capability of the Input AEM system under the existing conditions of this test.

Multi-frequency continuous-wave AEM systems, measuring in-phase and quadrature disturbances simultaneously at several frequencies (e.g. Tridem, operating at 500, 2000 and 8000 Hz; see Seigel and Pitcher, 1978), have come into use for the same reasons.

Some AEM systems employ several transmitter and receiver coil configurations in order to obtain information about geological conductors having a variety of geometries relative to the survey line. For example, the Dighem helicopter system (see Fraser, 1978) employs three receivers, one coaxial and two orthogonal to the transmitter coil, with an operating frequency of 918 Hz and a coil separation of 9 m.

Figure 2.5 shows an actual Dighem discovery traverse over a body of pyrrhotite, pentlandite and chalcopyrite in a Precambrian gabbro intrusive, lying under about 20 m of glacially derived soil cover.

The struggle for greater useful depth of penetration has been frustrating. Because of the immutable laws of physics, the signal from a conducting body drops off, at best, as the inverse third power of the elevation of the airborne electromagnetic system and at worst as the inverse fifth power, depending on the relative parameters of the conductor and the system employed. Noise due to the aircraft being a conductor cannot be totally eliminated and moreover, the geological noise associated with undesirable earth conductors cannot be eliminated at all. These factors

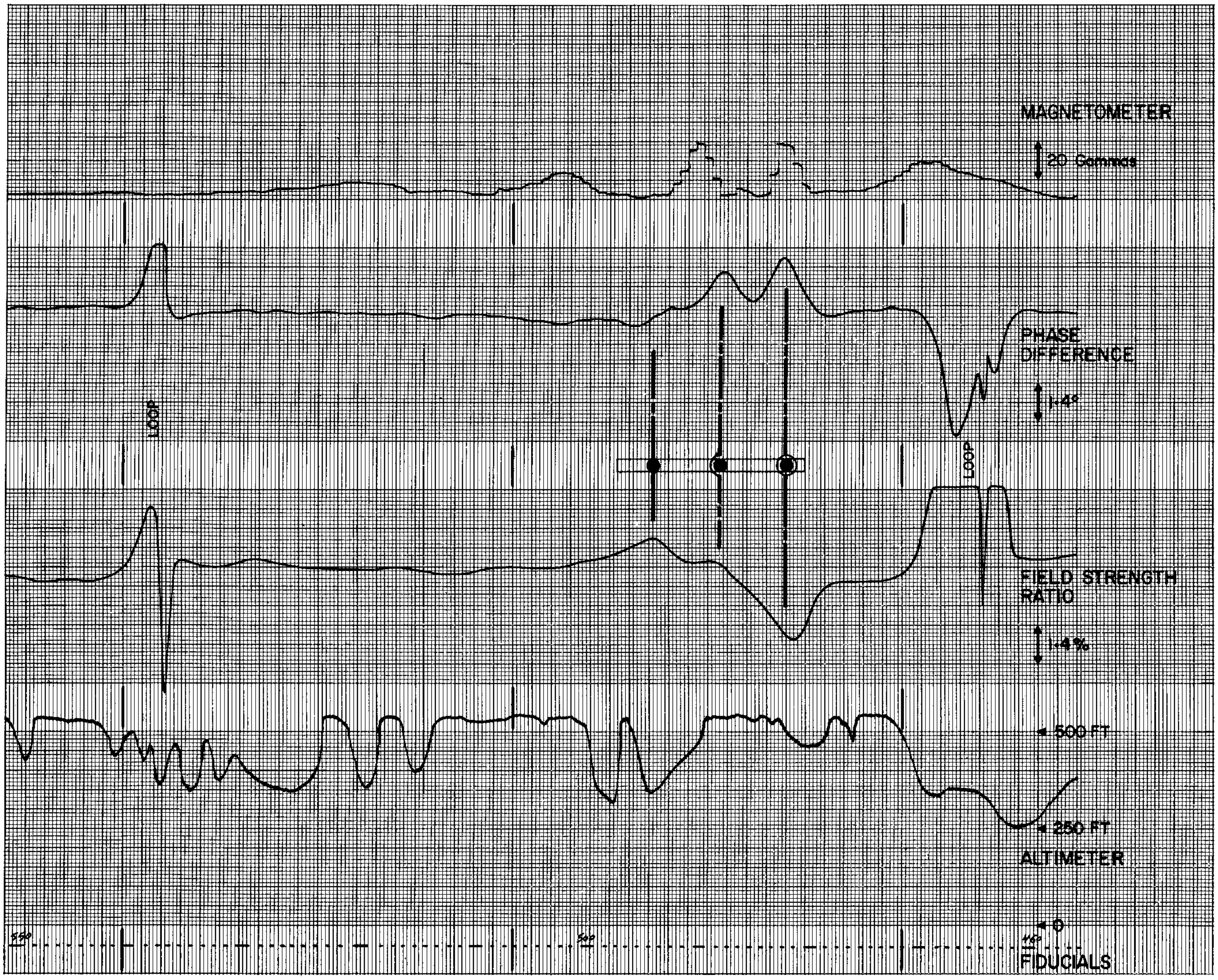

Figure 2.6. *Turair semiairborne profile over conductor in mountainous area. Operating frequency 400 Hz. Western Canada. (Courtesy of Scintrex Limited)*

put practical limits on the effective depth penetration of present day fully-airborne electromagnetic systems of between 100 and 125 m under most circumstances, despite the exceptional case which may be documented from time to time.

For this reason, semiairborne systems have been developed in the U.S.S.R. and Canada, to achieve much greater potential depth of penetration. These systems employ large, ground-based energizing loops or grounded cables, usually 4-10 km in dimension, as primary field sources. The mechanics of laying such large field sources by helicopter have been achieved in Canada. The use of these semiairborne electromagnetic systems has been especially rewarding in very mountainous areas, where it is difficult to maintain the relatively small terrain clearance necessary for wholly airborne electromagnetic surveys and yet the geological noise is often small. Such systems have demonstrated detection of conductors under as much as 200 m of cover under these conditions.

Figure 2.6 shows a profile generated by the Turair semiairborne, helicopter-supported system, in a particularly rugged section of the Canadian Cordillera. A conductor zone was revealed by this profile despite the fact that the helicopter, at the time, was flying at a height greater than 150 m above the ground surface. Since there was over 1000 m of local topographic relief, these conditions precluded the use of fixed wing aircraft and restricted the effectiveness of helicopter-borne totally-airborne electromagnetic systems. The figure shows also the effect of the loop sides, where the field gradients are too rapid for useful measurements to be made.

To utilize the airborne electromagnetic data from a particular system quantitatively, it is necessary for its calibration and zero levels to be well established. This has not always been sufficiently tied down by the operators. At present, however, much greater attention is being given to these factors, to the obvious benefit of both the systems and the users. As a result, the potential use of AEM systems has been broadened from the simple role of base metal anomaly hunting into the quantitative field of conductivity mapping.

One interesting aspect of recent airborne electromagnetic experience in Canada clearly illustrates the large element of chance (or statistical probability), involved in this type of exploration approach. The known base metal mining camps in eastern Canada have been flown and reflown by airborne electromagnetic systems since the first introduction of such surveys in Canada in 1951. Nevertheless, new base metal mines continue to be found by new surveys in these areas. Still we cannot say that these fresh discoveries occur at greater depths than were possible using the older systems, or were achieved because they did not show up earlier through some technical limitation of the older (and therefore presumably inferior) systems. Of five relatively recent discoveries, two had been missed by earlier surveys because they had a very short strike length and probably lay between the lines of the earlier survey. One had been previously found and drilled inadequately so that its nature had not been properly investigated. The other two were previously known to be conductors but had not been followed up because of inadequate geophysical-geological reasoning. Their combination of electrical and magnetic properties was such as to relegate them to the rank of uninteresting conductors. It remained for new prospectors with better geological reasoning (or was it less reliance on conventional geophysical reasoning?) to take the trouble to investigate these conductors and to reveal their ore potential.

As Slichter (1955) and others have pointed out, geophysical surveying is a statistical procedure and there is a relationship between the line spacing, the probable orebody length and the probability of discovery of the orebody. On the basis of such arguments, one may select the line spacing so as to optimize the cost effectiveness or prospecting profit ratio of the geophysical program. Ground investigation costs, including line cutting, geophysics and drilling, have escalated far more rapidly than those of airborne surveying in the past decade. As a result, the cost-effectiveness of an integrated exploration program, which includes airborne and ground phases, will be improved by flying more closely spaced lines today than was done ten years ago. As an example of this trend to closer line spacing, our company (Scintrex) has recently flown large blocks of mineralogically favourable country in Saskatchewan at 120 m (400 ft.) line separation with an integrated airborne system and has computer plotted the results on the scale of 1:5000. These line separations and plotting scales were formerly reserved for ground surveys.

It is interesting that plotting on such large scales clearly reveals any tiny uncertainty in the flight path recovery or in the mosaic preparation. A positioning error equivalent to only one half second in time produces the most remarkable "herringboning" in the contours.

The success ratio of airborne electromagnetic surveying around the world has been highly variable. In temperate and arctic areas the geophysical conditions are generally relatively good, with little oxidation and only moderately conducting soils. The Canadian Shield and particularly the Baltic Shield provide good geophysical and physiographic environments for this exploration technique and many major stratabound base metal bodies, usually of the copper-zinc types, as well as copper-nickel sulphide bodies, have been found using AEM techniques.

The application of these techniques in areas of tropical weathering, particularly in arid or semiarid conditions (e.g. Australia and the southwestern United States), has been far less rewarding to date because of a number of fundamental, adverse factors. Such weathering may easily oxidize a massive sulphide body to 50 m depth, whereas conductors of graphitic, serpentine and saline origin may persist through to the ground surface. In addition, semiarid and tropical soils are often highly conducting. In other words, the geological noise level is usually increased and the orebody signal level decreased in electromagnetic prospecting under conditions of tropical weathering and arid and semiarid desert terrain. This is not to say that airborne electromagnetic methods are of no value in such areas. In fact, there are successful case histories which prove the contrary. It just means that the odds for discovery are less under these conditions and one has to be more cautious in the use of AEM in areas of tropical weathering and arid and semiarid terrain.

The Induced Polarization Method

In ground exploration for base metal deposits, the induced polarization method is the primary electrical exploration tool for porphyry coppers, for contact metamorphic copper deposits and even for stratabound copper or lead-zinc deposits. It is often used as the preferred exploration tool in the search for massive copper-zinc or nickeliferous sulphide deposits, in areas with highly conducting surficial deposits, such as Australia, South Africa and in many wet tropical countries. As was mentioned earlier, the method is being used, with good reason, as a ground follow-up tool for airborne electromagnetic surveys in such areas. A volume by Sumner (1976) summarized much of the development that has occurred in IP in recent years.

The IP method, as presently practiced, exists in a number of possible methods of measurement and quantities measured. These fall into two main categories, viz. the frequency-domain (continuous wave) and time-domain (or transient) systems.

Most commonly, the electric fields associated with polarization current flows in the ground are measured between two potential electrodes (EIP). More recently (Seigel, 1974) there has developed an approach (MIP or Magnetic Induced Polarization) wherein the magnetic fields associated with polarization current flow are measured by a sensitivity magnetometer. The nature of EIP and MIP responses are very different in theory and practice and two methods appear to be complementary (i.e. advantageous for different problems) rather than competitive.

Within the frequency-domain systems, there are a number of possible methods of measurements and quantities measured. Traditionally, the percentage change of apparent resistivity with frequency (PFE) has been measured as the IP characteristic. More recently, the phase shift between the measured voltage and the primary current waveforms has been used to yield equivalent information (e.g. Hallof, 1974). Some workers now measure complex resistivities and their change with frequency to obtain IP information (e.g. Zonge and Wynn, 1975).

Both time-domain and frequency-domain IP systems are in use and the formerly heated conflict between proponents of the two different approaches has now died away. It is generally appreciated that, in IP as in EM, the time-domain or transient method has the advantages of higher potential sensitivity. Since transient measurements are made after the inducing current pulse has been cut off, they are "absolute" measurements. Thus, one may improve the signal-to-noise of such measurements by increasing the transmitter power, thereby also increasing the sensitivity of the measurement for low IP responses. In addition, many channels of data which are obtained simultaneously may give useful information relating to a range of polarizable materials. The low inherent frequencies commonly employed in time-domain surveys generally result in lower electromagnetic induction problems (at least at later decay times) although the earlier decay times may be markedly distorted by EM coupling effects.

The frequency-domain approach has the advantage of better signal-to-noise, or lower primary power, if you prefer. This can be very significant in areas of high magnetotelluric

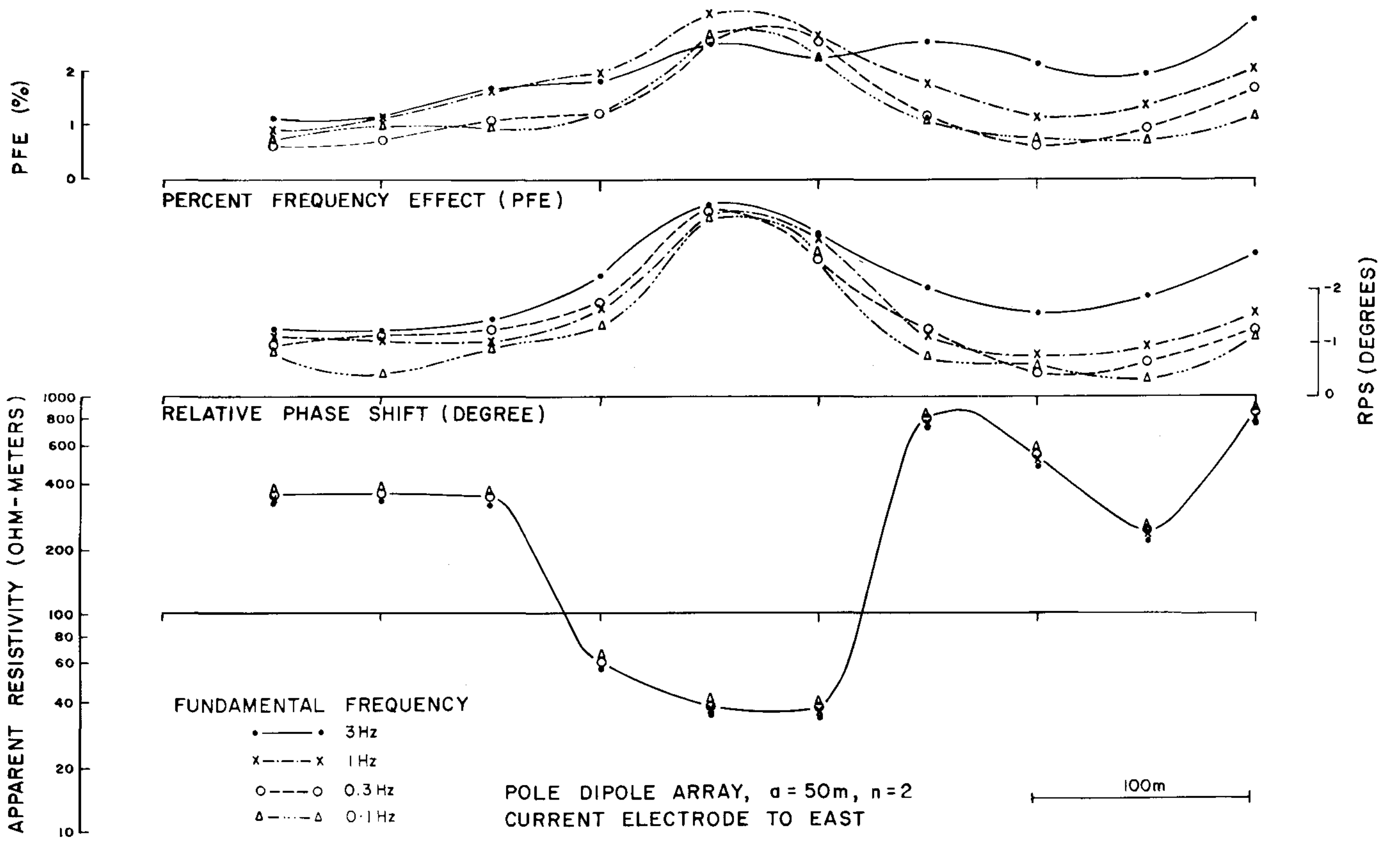

Figure 2.7. *Scintrex IPRF-2 complex resistivity pole-dipole traverses at fundamental frequencies 0.1, 0.3, 1 and 3 Hz. State of Goias, Brazil. (Courtesy of Departamento Nacional Da Producao Mineral, Brazil)*

or industrial noise activity. Being a "relative" method, its sensitivity is usually restricted by the stability of the transmitted wave form, regardless of the power transmitted.

Over the past few years the trend in IP measurements has been towards the gathering of more information on a routine basis. In the time-domain a number of channels, usually 3 to 6, of transient data, are measured simultaneously, in order to obtain the shape as well as the amplitude of the transient curve. In the frequency domain, complex resistivities may be measured at a number of frequencies in the range of 0.01 to 100 Hz.

Figure 2.7 shows the results of multi-frequency, frequency-domain EIP complex resistivity measurements in a tropical environment. Pole-dipole traverses were run over the same line with a comparator type of receiver which automatically compares the resistivity amplitudes (PFE) and phase shifts (RPS) at the fundamental and third harmonic resulting from a single transmitted square-wave current form. Base frequencies of 0.1, 0.3, 1 and 3 Hz were employed. It is noteworthy that the high polarization/low resistivity zone in the central part of the profile shows up more clearly as the operating frequency is decreased. In addition, the RPS, which has a measure of inherent EM suppression, has a better geological signal/noise than the PFE at the higher frequencies employed.

Figure 2.8 presents three of six transient traces measured by a six-channel time-domain receiver in Western Australia. A typical interrupted square-wave current pulse of two-seconds on-and-off time was employed. Each channel represents a time integral of the transient (IP) signal over 260 ms. The survey in this instance is actually an MIP survey over a nickeliferous pyrrhotite body in ultrabasic rocks, under about 30 m of oxidation. The various channels have already been normalized with respect to the "Newmont" universal decay curve, which is a transient IP decay curve form obtained by averaging a large number of such curves from many geological environments. Among other significant features of this profile is the divergence in decay curve form between various stations. The interior current flow appears to be characterized by an abnormally long time constant, which is consistent with the rather "massive" nature of the sulphide lenses in this deposit.

There is an awareness that in the frequency domain the phase angle measurement allows a simple, first-order removal of electromagnetic induction effects and that it is even possible to make a relative phase shift measurement which is automatically stripped of electromagnetic effects to this approximation (Seigel, 1974; Hallof, 1974). This is based on the fact, which has been theoretically predicted and experimentally observed in the field, that the phase shift in low frequency IP measurements varies very slowly with frequency, possibly less than 50 per cent per decade of frequency. At the same low frequencies, however, any phase shifts due to EM inductive effects increase almost proportionately with the frequency. Thus, the measurement of phase angles at two frequencies provides a simple means of correcting for EM effects.

Armed with the new tools that can obtain response curve shape information in the time or frequency domains, many workers are attempting to derive criteria for distinguishing one type of IP source from another. The

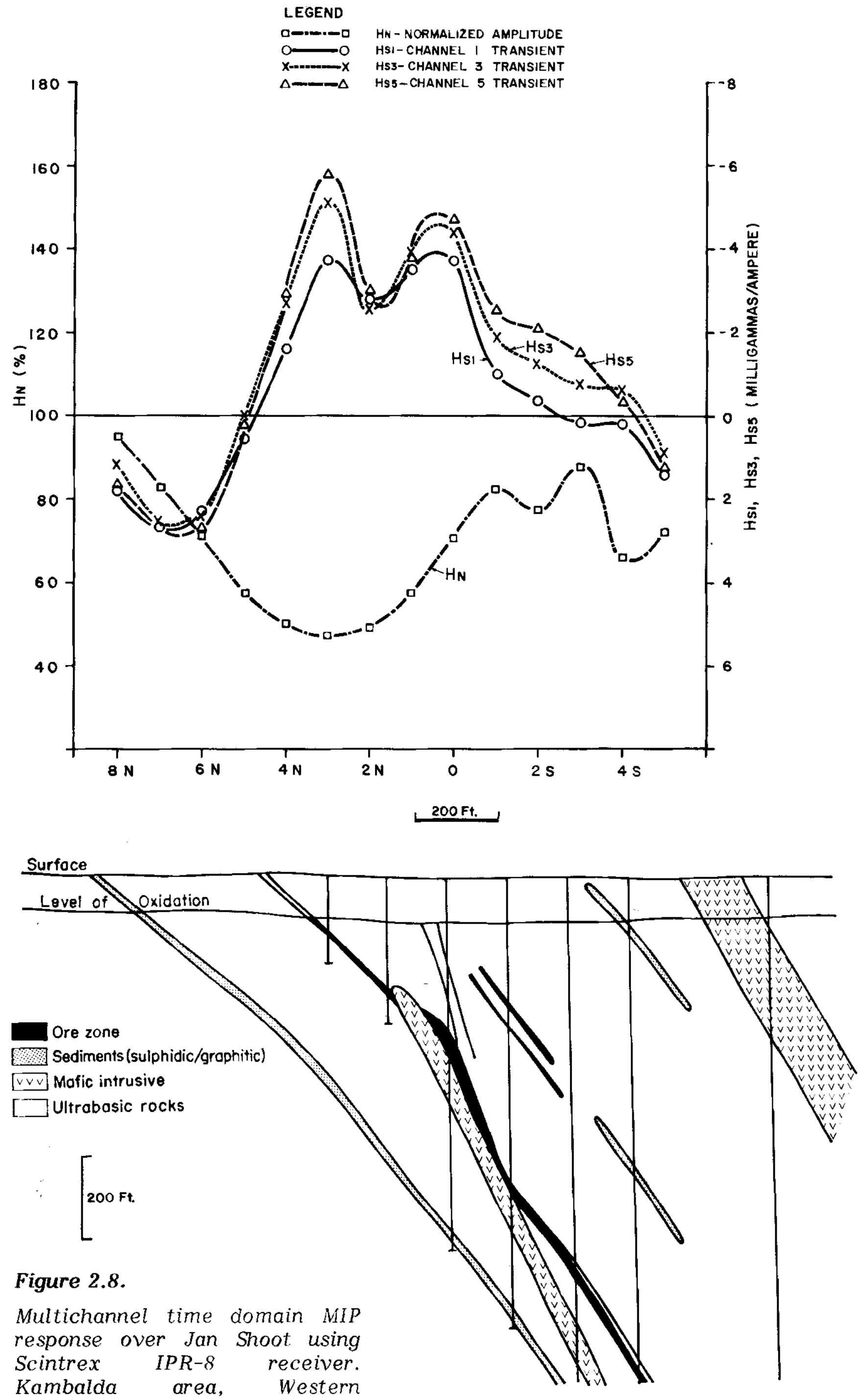

Figure 2.8.

Multichannel time domain MIP response over Jan Shoot using Scintrex IPR-8 receiver. Kambalda area, Western Australia. (Courtesy of Western Mines Limited)

dependence of the IP response curve shape on the size distribution of the metallic particles has been known for 25 years. This permits the differentiation of sources of small average particle size e.g. graphitic shales, from sources of larger average particle size, e.g. sulphide grains. The former commonly give rise to relatively short time-constant transients, whereas the latter give rise to relatively long time-constant transients.

Some workers (e.g. Zonge and Wynn, 1975) have claimed ability to differentiate one metallic sulphide from another through differences in their IP response curves. These claims have become somewhat muted in time as particular field cases arise which do not conform to the original hypothesis. In addition, the results of other investigations tend to refute this claim (e.g. Angoran and Madden, 1977).

In my own experience, IP curve-shape information can be valuable in resolving source ambiguities in a particular area, but only after the appropriate local experience has been obtained. Generalizations from one area to another, or from one geological environment to another may be dangerous.

Microprocessor-based receivers have started to appear. These can be programmed to record complete complex waveforms in a large number of channels (e.g. 1000) and to process these waveforms to derive factors of IP significance in either the time or frequency domains. The cost/benefit of these new receivers remains to be established.

The MIP method has been mostly used to date in Australia. This method can detect an induced polarization source through a conducting overburden layer which would normally seriously reduce the electric field IP effects of the source. In addition, it permits IP measurements to be made in areas of loose sand or permafrost, where electrical contact with the ground is difficult or even impossible.

For those IP receivers producing 10 or more channels of simultaneous information, there is a trend to having their data fed into a cassette-type magnetic tape recorder in the field for storage and later processing, by computer.

Ground Electromagnetic Systems

There are three basic types of continuous-wave (CW) ground electromagnetic systems in active use in the field today, viz. the vertical-loop or tilt system, the slingram or horizontal loop and the Turam, or fixed source gradient systems. All of these have been used for over 25 years and still remain in use because each fulfills its own useful functions. The vertical-loop system is primarily used for ground follow-up of airborne electromagnetic indications, particularly in forested areas and areas of high topographic relief, because it can operate without cutting lines. The horizontal-loop method has been improved in recent years with the addition of multiple frequencies -- up to five in one unit, and greater intercoil separation -- up to 240 m. The horizontal-loop technique is probably the preferred ground electromagnetic method for the majority of conducting base metal deposits, except for the very deep ones (in excess of 100 m) and except for areas of rugged topography.

The Turam method finds its best areas of application in the search for deeply buried conductors, or in rugged topography. Detection of sulphide bodies under more than 150 m of cover by the Turam method has been achieved in practice. The number of operating frequencies available

Contents

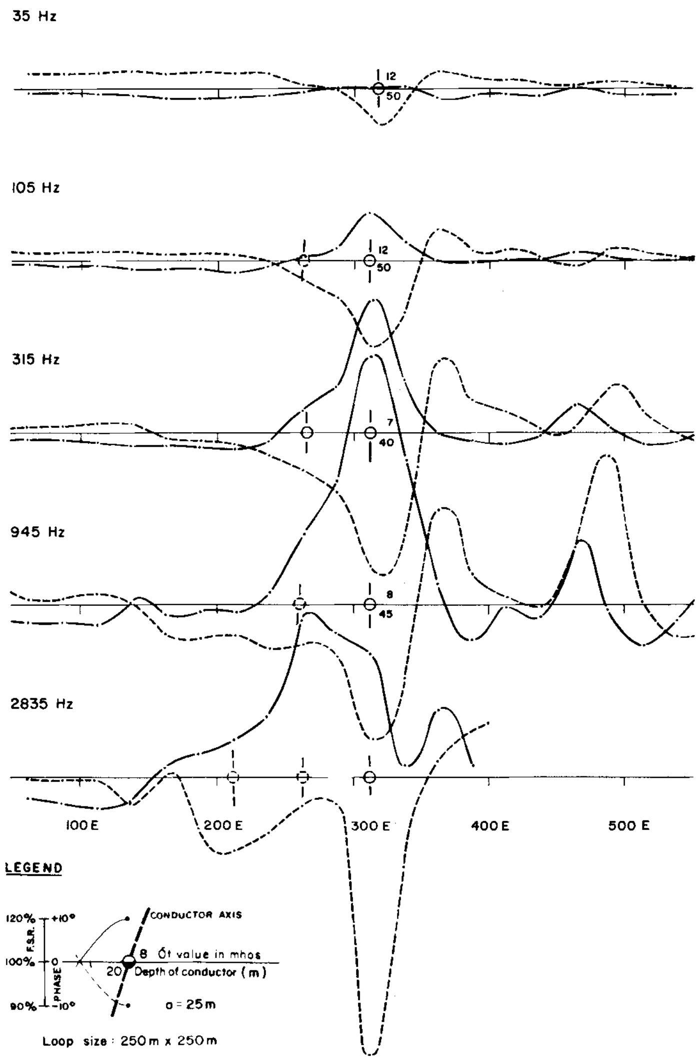

Figure 2.9. *Scintrex SE-77 Turam-type ground electromagnetic response over buried conductor. State of Goias, Brazil. (Courtesy of Departamento Nacional Da Producao Mineral, Brazil)*

today in standard production units has increased to five and the range of frequencies increased as well to cover both poorly and highly conducting environments.

Figure 2.9 shows the results of a five-frequency, Turam-type system, employed on ground follow-up of airborne electromagnetic surveys, in a tropical environment. The operating frequencies increase by factors of three, from 35 Hz to 2835 Hz. An examination of these results indicates that whereas a single, well-defined conductor axis is apparent on the lowest frequency employed, the response pattern is distorted by flanking, weaker conductors on the highest frequency.

Transient ground electromagnetic prospecting, long an exclusively Russian domain, has spread to the west and two models of multichannel transient systems are now in use in North America. Their increasing popularity is due to the broad range of conductors which can be detected and resolved simultaneously, as well as their lack of sensitivity to topographic relief. Of course there is the usual requirement for higher power or longer signal averaging times than in comparable CW systems. Both horizontal-loop and Turam configurations are being used, the latter requiring but a single horizontal receiving coil.

More recently, EM systems are being developed which may combine the broad conductor response of the transient systems and the lower power requirements of the CW systems. These newer systems employ complex waveforms which are repetitive but include a number of components of differing frequencies, often harmonically related. These include the square wave, the saw-toothed waveform of UTEM (ref. Lamontagne and West, 1973) and the pseudo-random waveform (Edwards, 1976). Coherent detection is employed using synchronized crystal clocks or radio links for time reference. Microprocessors may be employed for control of the receiver. With such systems the measurements may be made in terms of the earth impedance vs. frequency spectrum or as its step-function or impulse function response. The multichannel data are usually stored in digital form on magnetic tape cassettes. These data may be transformed, for greater ease of interpretation, from the frequency to the time domain, or vice versa, by computer or even by programmable calculator. Thus, in due course, the advent of these complex waveform EM systems will remove the distinction between time-domain and frequency-domain systems that presently exists.

Figure 2.10 presents the measurements made by an eight-channel, time-domain ground electromagnetic system, over a copper-zinc-gold sulphide orebody in a semiarid environment. Dual vertical-axis transmitter and receiver coils were employed with centres 50 m apart. A current pulse with an on/off time of 10.8 ms was employed. The eight channels of transient electromagnetic decay signals measured range in a logarithmic fashion from 0.15 ms (channel 1) to 8 ms (channel 8) in delay times. The orebody is in Cretaceous andesites and basalts, under 30-40 m of oxidation and soil cover. It is noteworthy that the orebody shows up best on the intermediate channels. The shortest time channel (1) does not distinguish the orebody response from geological noise. The longest time channel (8) gives only a low order orebody response.

The long wave VLF radio transmissions, primarily in the 15-30 kHz region, are employed as sources for one-man electromagnetic prospecting units. These units usually measure field amplitudes or inclinations. They are attractive from the standpoint of cost, weight and speed of measurement. They suffer from a number of limitations, the chief of which is their lack of conductor discrimination because of the high operating frequencies and distant source geometry. Nevertheless, VLF-measuring devices are in use in those areas where geologic noise, particularly overburden is minimal.

The magnetotelluric method, first proposed by Cagniard for deep sounding for petroleum exploration, has now been adapted for shallow sounding in mining geophysics, as well as permafrost problems, etc. In order to respond to shallow structures, in the first few hundred metres of the ground surface, frequencies in the audio or near audio range (1-10 000 Hz) are used. The resultant method is sometimes termed Audio Frequency Magnetotellurics or AMT (see Strangway et al., 1973).

Figure 2.11 is an AMT profile which presents the resistivities calculated from crossed E and H measurements at four irregularly-spaced frequencies in the range of 1-3000 Hz. The profile is over the Cluff Lake, Saskatchewan uranium orebody which is associated with a fracture zone in Precambrian rocks. Apparently this zone is highly conducting and extends almost to the present ground surface, for the resistivity decreases progressively as the frequency increases.

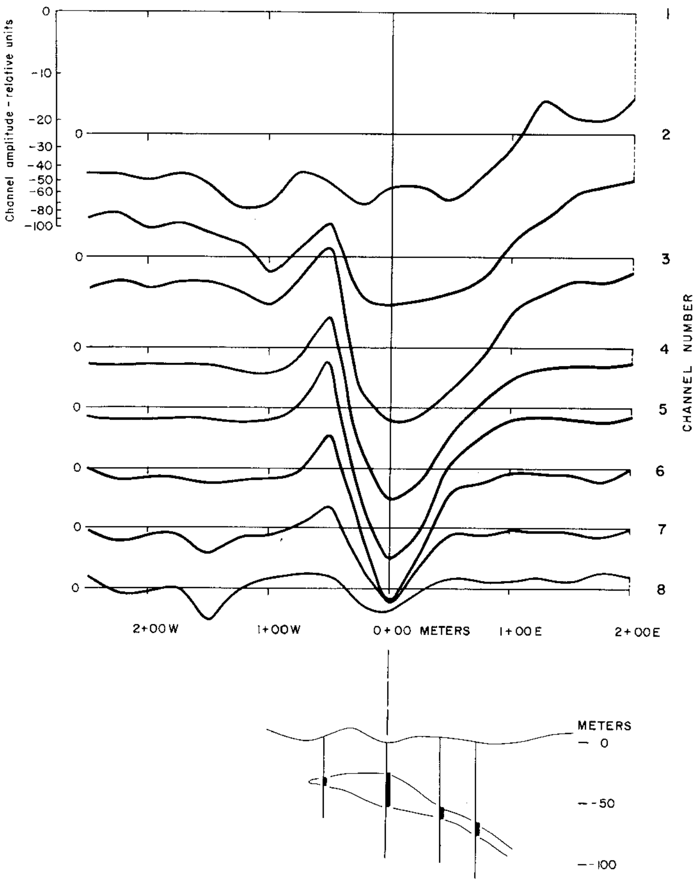

Figure 2.10. *Crone PEM 8 channel time domain ground electromagnetic profile over Cu, Zn, Au orebody. Sultanate of Oman. (Courtesy of Sultanate of Oman)*

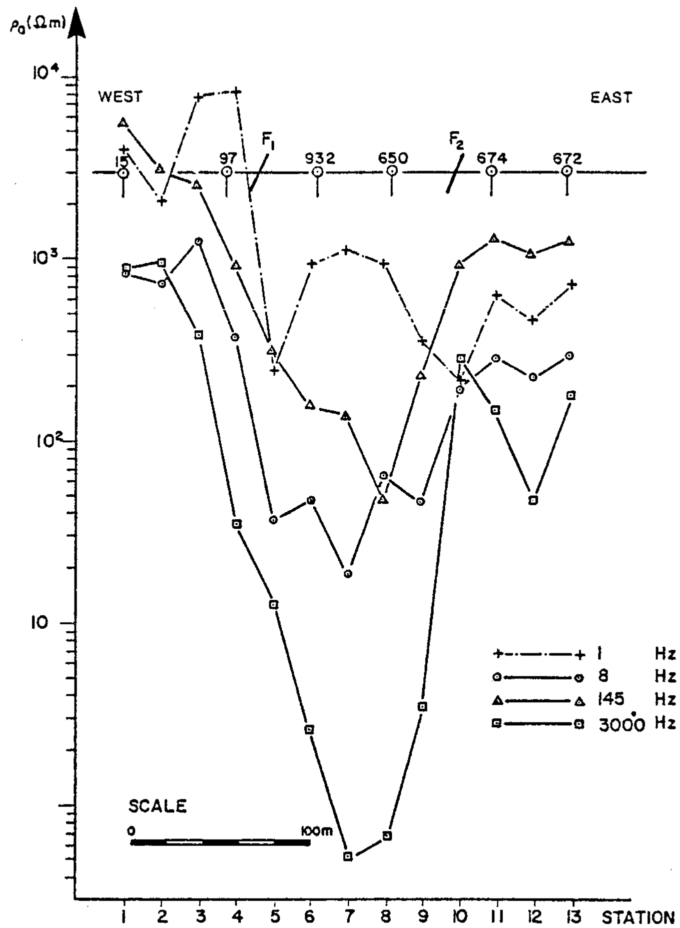

Figure 2.11. *Audio frequency magnetotelluric traverse over uranium deposit. Cluff Lake, Saskatchewan, Canada. (Courtesy of Mineral Exploration Research Institute, Montreal and Amok Limited)*

Almost four orders of magnitude resistivity contrast is to be seen between the high frequency derived resistivity over the zone and the more resistive rocks to the west.

Drillhole Logging Methods

There is currently a minor upsurge of interest in drillhole electromagnetic methods for base metal exploration. At least three different systems are in use in North America, including a fixed-source time-domain unit, a fixed-source CW multifrequency unit and a single frequency moving, coaxial, transmitter-receiver system.

Figure 2.12 shows the results of a five-frequency CW electromagnetic log of an exploration hole which passes within about 50-60 m of a nickel-copper massive pyrrhotite body of the typical Sudbury (Canada) type. In this system the field source is a large, closed loop laid out on the ground, primarily on one side of the collar of the hole. A down-hole coil, coaxial with the hole, compares the magnetic field in that direction, in phase and amplitude, with that measured by a coil which remains fixed in a location near the collar. The field strength ratio in this example has been normalized for the normal field geometric changes through division by the lowest frequency field strength data, smoothed for the obvious local disturbance near 1000-foot depth in the hole.

From these results, it is clear that the range of detection of sulphide targets through the use of electromagnetic logs in exploratory boreholes is similar to that achieved through the use of the equivalent surface technique. The latter usually suffers from somewhat greater geological noise, due to surface conduction problems.

Despite such favourable results, it still cannot be said that it has become standard practice in the West to log by EM (or any other technique) all base metal exploration holes, even after at least two decades of educational effort by the geophysical community. In the U.S.S.R. and China, it does appear to be commonplace to log pairs of base metal exploration holes with the high frequency (0.15 to 40 MHz) "radio shadow" technique (Zietz et al., 1976). For example, in the Tongling, China copper area, an excellent discovery of a contact metamorphic copper deposit at 300 m depth was made with help from this technique, using a 1 MHz transmitter (pers. comm.).

A number of other geophysical logging techniques suitable for base metal exploration are used sporadically as well, including induced polarization, resistivity, mise à la masse, and three component magnetometer, usually to solve a specific local geological problem. All of these logging techniques are being used for remote detection purposes and are adaptations and extensions of techniques and apparatus developed for surface exploration.

The mining industry, unlike the petroleum industry, is accustomed to core drilling its exploration holes. Thus the mining industry is, in general, disinterested in the short range, or "at hole" physical property information provided by

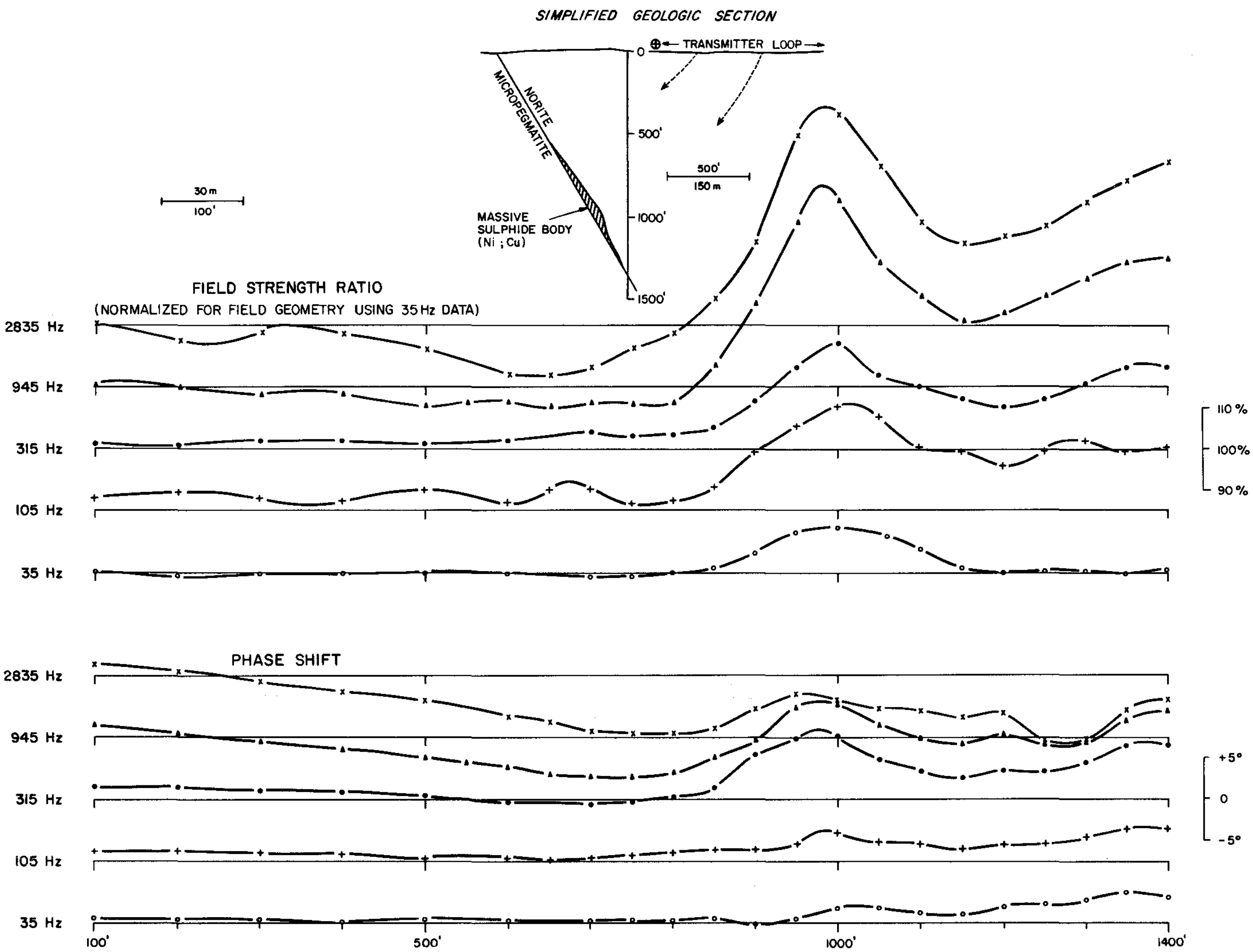

Figure 2.12. Scintrex DHEM-5 drillhole electromagnetic log showing nearby Ni/Cu deposit. Sudbury, Ontario, Canada. (Courtesy of Geological Survey of Canada and International Nickel Company of Canada Limited)

the broad array of logging tools (density, resistivity, SP, caliper, etc.) developed for the oil industry. For certain types of base metal exploration and in uranium exploration (see next section), specific short range logging tools are, however, being employed, because they can yield quantitative grade information with a resultant saving in overall exploration cost and time.

In situ grade information may be obtained through a variety of nuclear techniques including: simple natural gamma-ray spectral measurements in the case of K, U and Th, radioisotope source XRF measurements for a broad range of elements, neutron activation (delayed and prompt gamma measurements) for a variety of elements, gamma-neutron measurements for beryllium and delayed fission neutron measurements for uranium.

All of these techniques attempt to determine quantitatively the mean grade of specific elements in the vicinity of a borehole. They share a common problem in attempting to achieve acceptance by the mining geologist in that in order to establish their validity, their results are compared with chemical assays of cores or chip samples from the same borehole sections. Depending on the degree of heterogeneity of the elemental distribution in the specific deposit, there may be little correlation between these two sets of data (e.g. Czubek, 1976), particularly since they may present the analysis of far different volumes of rock.

Portable XRF analyzers using a radioisotope source for excitation and balanced "Compton edge" filters for energy selection have been in use in the West for about ten years (e.g. Clayton, 1976). They are employed for surface analysis and, to a lesser degree, for borehole analysis of a range of metals of economic interest. For borehole use they require a dry, clean hole because of the low penetrating power of the primary and secondary X-radiation employed.

One nuclear logging system of sufficiently high penetrating power to give a "bulk sample" analysis (500 kg or more per assay) is that employing a neutron source (e.g. ^{252}Cf) and measuring prompt gamma radiation resulting from neutron capture in the nuclei of the elements round the hole (Nargolwalla and Seigel, 1977). This system called Metalog by the manufacturers, Scintrex Limited, has been employed to determine the grade of Ni, Fe and Si in the lateritic nickel environment, copper in the porphyry copper environment and S and ash content of coal, through in situ borehole measurements.

Figure 2.13 presents experimental correlation charts between the Metalog values for Ni and Fe and bulk sample grades in a lateritic nickel test.

Figure 2.14 shows similar experimental correlation charts for S and ash in a coal field test. In this instance, the comparative chemical analysis was obtained from core samples, as bulk sampling was not feasible.

Other Ground Methods

I have briefly reviewed the primary methods currently in use in base metal exploration. Other methods are also in use, in the East or West, to a lesser extent and for the solution of special problems. The seismic method, for example, finds indirect application in situations where the definition of geological structure will be of value in the location of ore deposits. The method is also employed in the U.S.S.R., using two boreholes and is called the "acoustic shadow" method. It locates inhomogeneities lying between the two boreholes (ref. Zietz et al., 1976).

A piezoelectric method has been developed and used in the U.S.S.R. for exploring for quartz veins and quartz-rich pegmatites (ref. Zietz et al., 1976).

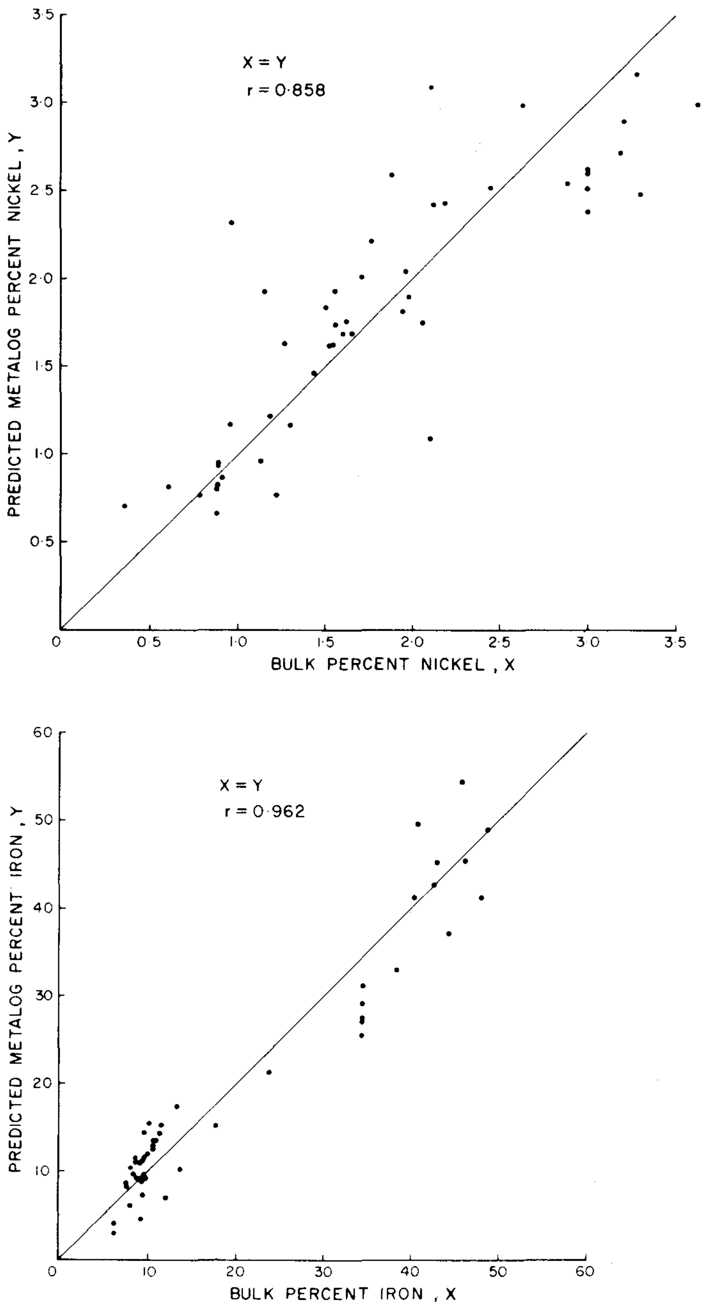

Figure 2.13. *Metalog neutron-prompt gamma bulk sample comparison charts for Ni and Fe in a lateritic nickel deposit. (Courtesy of Scintrex Limited)*

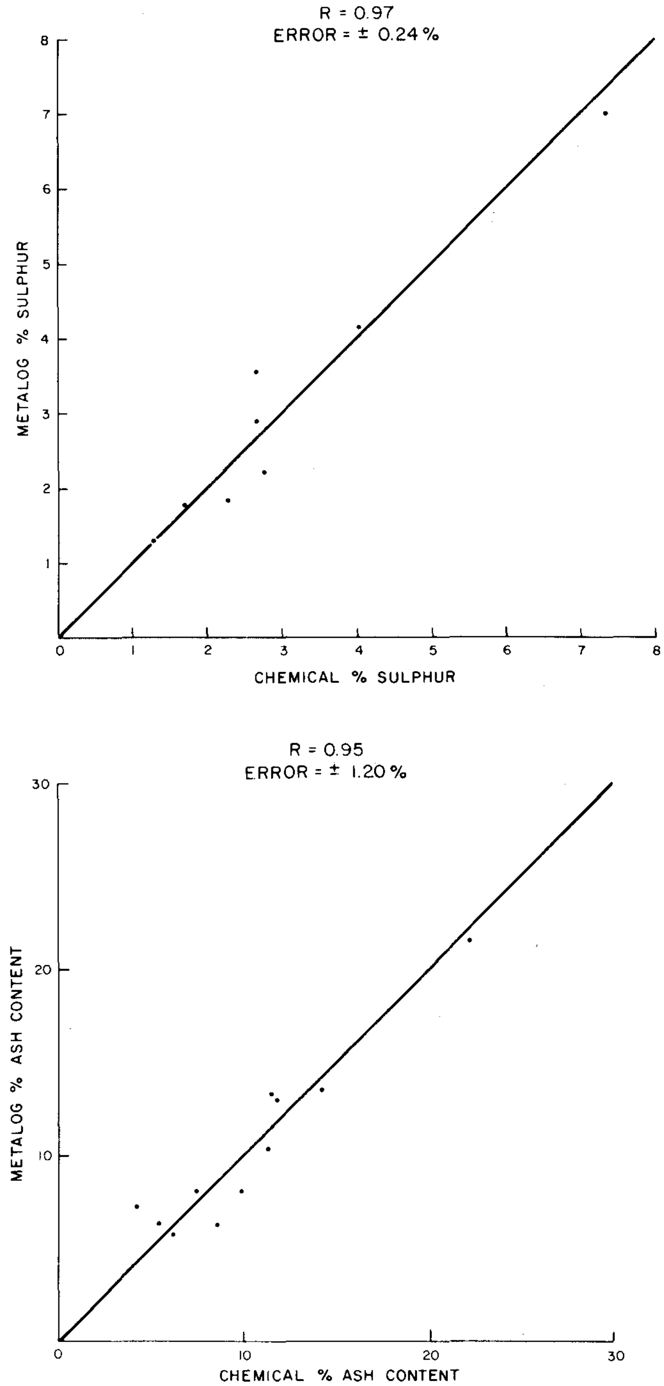

Figure 2.14. *Metalog neutron-prompt gamma core sample comparison charts for S and ash in coal seams. (Courtesy of Shell Research and British Coal Board)*

URANIUM EXPLORATION

Uranium exploration, presently a very important area of involvement of mining geophysicists around the world, involves airborne, ground, and borehole activities. In this search, geophysicists have the unique advantage of having at their disposal a powerful tool which is so direct that it can yield actual U grades and yet is rapid and inexpensive in execution. This is, of course, gamma-ray spectroscopy. Using adequate volumes of NaI(Tl) crystals as detectors, with properly calibrated and stabilized electronic pulse-height analyzers, we can quantitatively determine the average equivalent grade of uranium in rocks or soils. There is some question as to whether or not this method is properly denoted as a geophysical or geochemical one, but, since the devices are most often operated by technicians who are neither geophysicists nor geochemists, the controversy in fact should not arise.

The 2.62 MeV energy gamma-ray peak uniquely denotes the presence and amount of Th. The 1.76 MeV gamma-ray peak, after suitable correction for the Compton continuum of

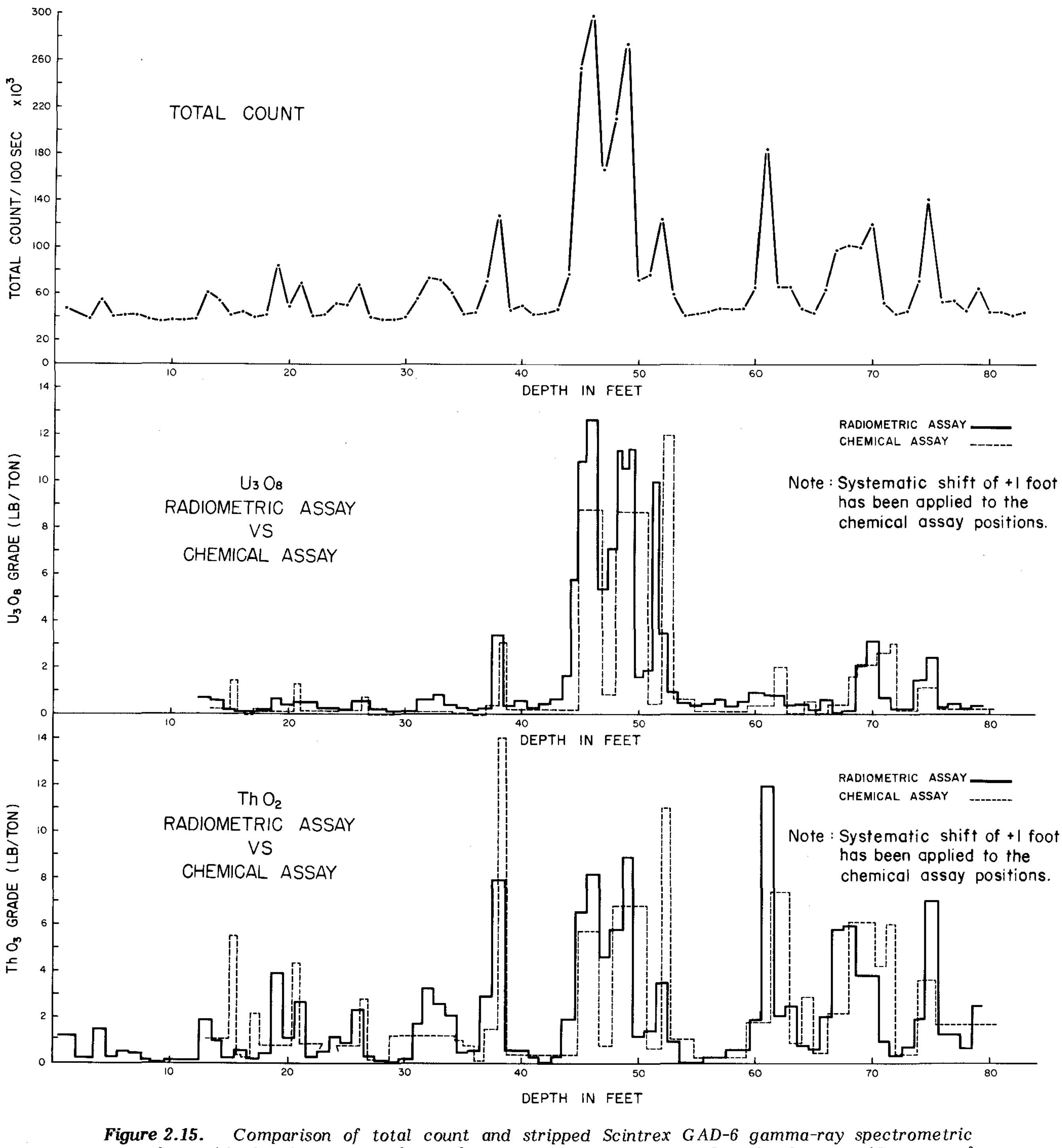

Figure 2.15. *Comparison of total count and stripped Scintrex GAD-6 gamma-ray spectrometric assay logs with chemical assays of core for U and Th. Lake Agnew, Ontario, Canada. (Courtesy of Agnew Lake Mines)*

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Th, is specific for the presence and amount of ^{214}Bi, which is a daughter product of ^{238}U. Under those conditions where the ^{238}U is in equilibrium with this daughter product, then the 1.76 MeV peak (after correction) is specific for ^{238}U. Similarly the 1.46 MeV peak, after suitable Compton corrections, is related quantitatively to the ^{40}K radioisotope.

The current trend in gamma-ray spectrometric measurements is to tightly control the calibration and stabilization of the measuring devices so that quantitative eK, eU and eTh grade values may be deduced from such measurements, whether they are derived from airborne, ground or borehole surveys. The assumption of equilibrium, so necessary for U determinations, is, unfortunately, often invalid, particularly in porous or highly weathered rocks. Even fresh-looking, low-porosity Precambrian sediments and intrusives, scoured clean by glacial action only 10 000 years ago, may be in U disequilibrium in the first 50 cm or so, from where almost all the gamma radiation detectable at surface arises. Ignoring, for the moment, the disequilibrium problem, one can apply corrections to the observed data for the outcrop geometry (if known) and for the gamma radiation due to radon in the atmosphere and cosmic ray activity, to obtain eK, eU and eTh.

I have already briefly reviewed the state-of-the-art in airborne radiometric exploration (Fig. 2.2). The airborne techniques and instrumentation are not very different whether the geological objective is radiochemical mapping or the search for uranium deposits. The line spacing and survey height tend to be smaller in the uranium search. Of course, four-channel systems, with smaller crystal volumes, are also being used to good effect in light aircraft and helicopters, at elevations of 30-60 m, in the search for uranium. A good review of airborne radiometric considerations is to be found in a paper by Darnley (1973).

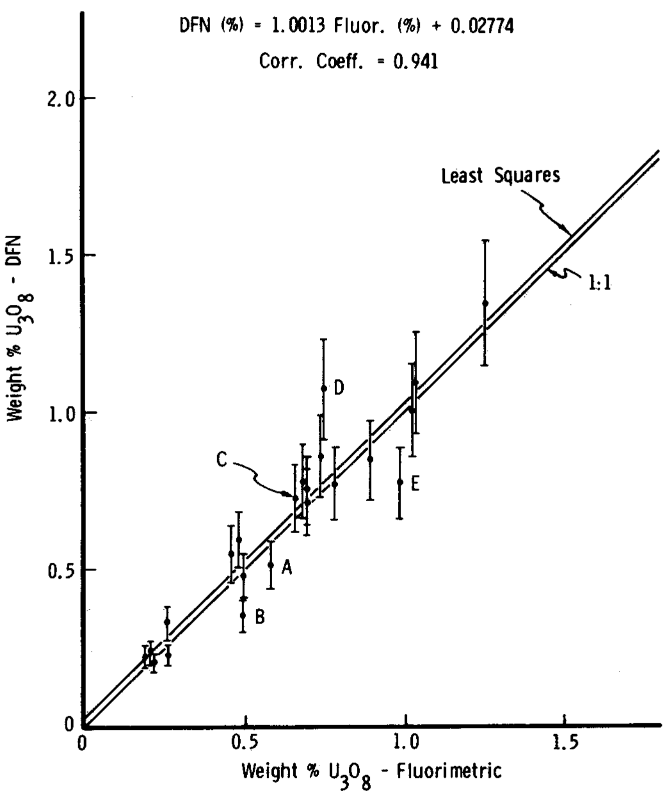

Figure 2.16. *Comparison chart of delayed fission neutron assays and fluorimetric core assays for uranium. (Courtesy of Geophysics; after Givens et al., 1976)*

For ground uranium prospecting, a broad range of portable gamma-ray detectors are employed, from simple, nondiscriminating scintillation counters to four-channel differential spectrometers with automatic Compton stripping and spectral stabilization, etc. Some of these are excellent examples of compact modern electronic engineering. Crystal volumes on ground instruments may range from 30 cm^3 for rough anomaly hunting, to over 1200 cm^3, for radiochemical mapping. The best of these spectrometers enable determinations to be made of the grade of U and Th in outcrops and rock samples, providing that radioactive equilibrium exists and that proper corrections are made for the outcrop or sample geometry.

In borehole logging for uranium, the natural gamma scintillation counters or spectrometers are mainly used, yielding at least semiquantitative results. With careful calibration against chemically-established grades of U and Th in test boreholes (either natural or man-made, e.g. Geological Survey of Canada pads outside of Ottawa or Department of Energy facilities near Grand Junction, Colorado) and with radioisotopic stabilization, for example using a ^{133}Ba source, U and Th grades of satisfactory accuracy may be determined. This assumes equilibrium conditions for U, which is normally valid in tight Precambrian rocks beneath the weathered zone.

Figure 2.15 is an example of a stabilized gamma-spectrometric log of an underground borehole which has been drilled to provide guidance for underground mining in an established uranium mine. Both U and Th are present in this mine, in highly variable relative proportions, in Precambrian sediments. The results of the radiometric log are presented as total count eU and eTh. Chemical assays for U and Th of core samples are shown for comparison purposes. The degree of correlation between the radiometric and chemical assays is deemed to be good, despite the limitations, mentioned above, pertaining to such correlations.

In areas where disequilibrium of U is known to be a significant problem, for example in the Colorado Plateau area of the Western United States, the natural gamma spectrum can be misleading and a more direct tool, such as prompt or delayed fission neutron (DFN) logging, is employed for more quantitative results. A comprehensive description of the latter variant, now being used on an operational scale in the West, is given by Givens et al. (1976). In DFN logging the rock around the hole is bombarded with 14 MeV neutrons from a pulsed neutron generator, producing 2 pulses per second. Since the half life of the DFN due to U is about 4 seconds, there will be a build up with time of the DFN levels. For quantitative U-grade determinations, correction to the DFN measurements are made for the effects of fluid salinity, strong thermal absorbers, borehole size and formation density.

Figure 2.16 shows a direct comparison of DFN assays and fluorimetric assays for U made on the core. The correlation coefficient is high (0.94).

Radon soil gas measurements based on alpha detection is a popular uranium exploration method, used in the hope of expanding the range of detection of buried deposits. Both short term and long term (or integrated) sampling techniques are employed (e.g. see Warren, 1977). The former use either an ionization chamber or zinc sulphide scintillator for measurement. The latter use fission track or solid-state alpha detectors, left in a hole in the ground for up to several weeks. The detection of buried uranium deposits by means of soil radon gas measurements is a well accepted technique. There is, however, some controversy about the effective depth of detection of this approach, since the short half life (3.8 days) of radon and its expected diffusion rates are incompatible with the 100 m or so depth detection claimed. Nondiffusion transport mechanisms for radon or its precursors appear necessary to account for the observed field results.

Because of its diversity of methods, mining geophysics gives great scope for creative originality on the part of its practitioners. I believe that is one of the secrets of its fascination for those of us who have made it our life's work. It also makes the task of compressing a comprehensive review of mining geophysics into a few pages a most difficult one.

ACKNOWLEDGMENTS

The author is indebted to a number of sources for permission to publish the various figures of this paper. An acknowledgment to the appropriate source has been made in respect of each figure, in its caption.

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