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Exploration for massive sulphides in the Canadian Shield

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Abstract. The physical environment of the Canadian Shield is such that EM and gravity methods are well suited to the exploration for massive sulphides.

A number of instrumental systems and survey methods, both airborne and ground, have evolved to meet the particular requirements of the area. The choice of primary method or combination of methods depends principally on location and local environment. Follow-up methods usually consider the nature of the orebody sought.

Specific exploration programs, both regional and local, show examples of the successful application of geophysics in the Canadian Shield.

Résumé. Le milieu physique qui caractérise le Bouclier canadien convient bien à l'exploration des amas de minérais sulfurés par des méthodes électromagnétiques et gravimétriques.

Un certain nombre d'appareils et de méthodes pour utilisation à la fois au sol et à bord d'avions ont été mis au point répondre aux exigences particulières de cette région. Le choix d'une première méthode ou d'une combinaison de méthodes dépend surtout de l'endroit et du milieu à explorer. Les méthodes utilisées par la suite dépendent de la nature du gisement que l'on recherche.

Des programmes d'exploration précis à la fois régionaux et locaux servent d'exemples du succès que remporte l'utilisation de la géophysique dans le Bouclier canadien.

The Canadian Shield

The Canadian Shield was defined by H.C. Cooke in 1947 as "The great region of Precambrian Rocks that constitutes the central backbone of Canada. It is a crudely shield-shaped area with its face on the Arctic Ocean and narrowing to a point in the United States south of Lake Superior. Its position and boundaries are indicated on Figure 1. Its area is approximately 1,800,000 square miles or about half of all Canada." While the area of the Shield has remained unchanged since 1947, new methods of exploration have made it possible to prospect under water and under relatively thick sections of Paleozoic and younger formations. To what Cooke regarded as the Canadian Shield, the exploration geologist must now add a fringe area overlapping the interior plains, the arctic plains and the Hudson Bay and St. Lawrence lowlands.

Physiographically, the Canadian Shield is a peneplain which after uplift in Middle or Late Paleocene time has been dissected and scoured by the combined action of glacial and stream erosion. The characteristic topography of the Shield is flat and monotonous, local topographic variations seldom exceeding a few hundred feet. However, around its rim particularly along the Ungava-Labrador-St. Lawrence River coastline, the mountains reach an altitude of 6000 feet and are cut by deep, glacially scoured valleys.

The effect of glaciation throughout the interior of the Shield was to remove all soil and weathered rock, including all placer deposits and secondarily enriched zones that may have formed by centuries of weathering. Some of the debris remained on the Shield in lake beds, stream valleys and elevated ridges and hills. The effect of this was to create a multitude of new lakes and rivers so abundant that in places they constitute 35% of the total land area. Further uplift of the Shield left large areas covered by lake beds such as the Clay Belt of northern Ontario and Quebec. Whereas vast areas of the Shield, notably the areas of the Northwest Territories, Baffin Island and Ungava have very little overburden cover, in general the Shield is buried by a mantle of overburden averaging about 30 to 50 feet thick. Locally, particularly in the areas of old lake beds, the thickness amounts to several hundred feet.

Forest cover is heavy in the south, thinning and disappearing completely towards the open barrens of Ungava and the Northwest Territories. Tree height even in the heavily timbered areas seldom exceeds 100 feet; over most of the Shield, average tree height is less than 40 feet.

Access in the Canadian Shield is predominantly by aircraft. All-weather airstrips are available over most of the southern half of the area. Farther north, airstrips are several hundred miles apart and transportation is done between lakes using floats in the

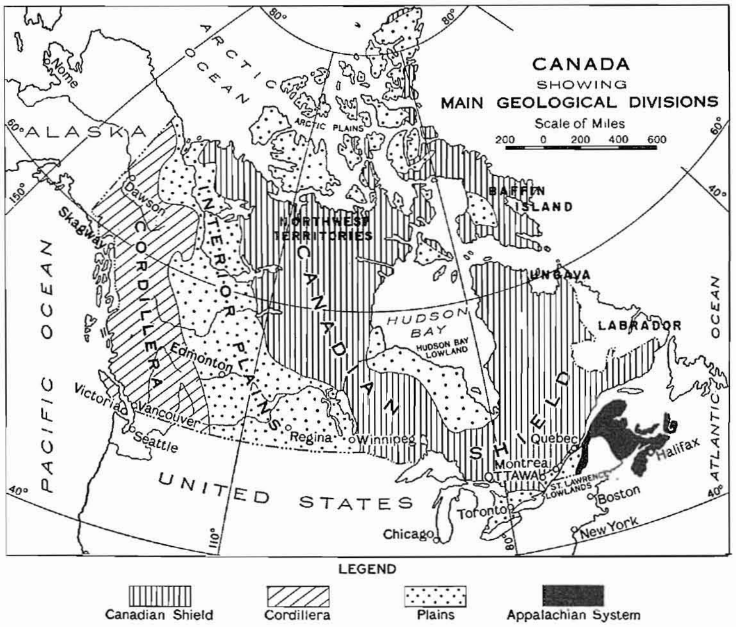

Figure 1. Location of Canadian Shield.

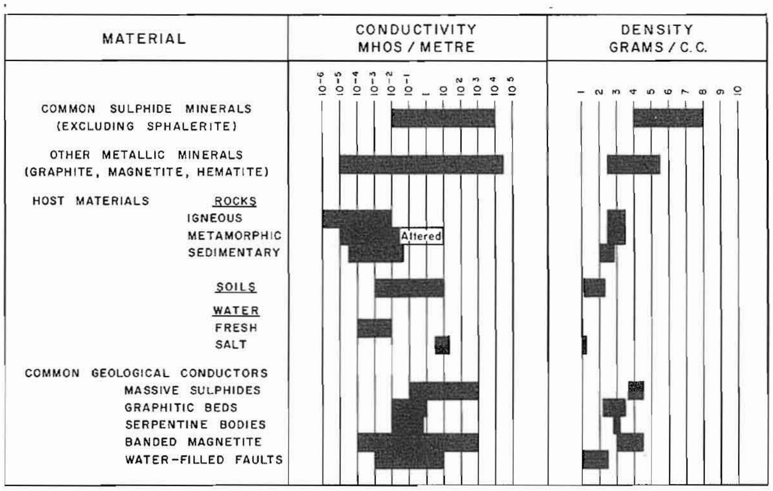

Figure 2. Summary of important data on the physical properties of massive sulphides and their environment.

summer time and skis in the winter. Roads and railroads are making their way gradually northward, generally (as in the case of the Pine Point and Labrador railroads) because of important mineral discoveries.

Climatically, the Shield is cold-continental to subpolar. Freezing temperatures prevail for at least four months of the year; the ground is covered by snow from January to April in the south and from November to June in the north; in the northern half of the Shield the ground is permanently frozen to depths of several tens of feet. Annual rainfall varies from 4 inches in the north to 30 inches in the south, averaging about 16 inches over all.

Massive sulphides

In his introduction to the chapter "The Search for Massive Sulphides" in *Mining Geophysics*, Vol. I, Ward (1966) advises geophysicists to avoid geological definitions and consider massive sulphides in terms of their "simple physical attributes". Accepting the conclusion of the Symposium on Massive Sulphides in Canada held in April 1959, a massive sulphide body must consist of a single mass of at least 1000 square feet extent, containing a minimum of 50 to 80% sulphides (opinion differed) by volume. Let us use this rather broad definition as a starting-off place for the consideration of massive sulphide deposits in the environment of the Canadian Shield.

The effectiveness of geophysical methods depends not only on the properties of the orebodies of interest but also on those of the host rocks and other earth materials constituting the orebody environment. We have examined some of the geographic and topographic features of the Canadian Shield; let us now look at the physical attributes as they may affect geophysical prospecting methods.

The Shield consists mainly of granite and granitoid gneiss, but includes belts of severely deformed and altered volcanic and sedimentary rocks. It is within these belts, which are sometimes tens of miles wide and more than a hundred miles long, that most geophysical prospecting has been carried out. All of these rocks are extremely ancient, the youngest being the Late Precambrian (Proterozoic) volcanic and sedimentary rocks which overlie the Early Precambrian (Archaean) basement in a number of scattered localities. These include the folded Keweenawan and Huronian belts of the Blind River/Sudbury/Cobalt/Mistassini regions; the Coppermine and Athabasca formations of the Northwest Territories; and the flat-lying sheets of volcanic and sedimentary rocks on the east shore of Hudson Bay and parts of the Arctic islands. Diabase dikes and sills of the same age cut the Archaean rocks over most of the Shield area.

Overlying the Shield along its flanks are younger sedimentary rocks, mainly Early Paleozoic in age, through which geophysical prospecting is being carried out with ever-increasing success. These formations, together with the overburden materials and waters surrounding and overlying them, constitute the environment in which prospecting takes place.

Ward (1966), West (1960), Bosschart (1961), and the writer (1961) reported on the physical properties of the massive sulphide deposits in the Canadian Shield. Data on the physical properties of rocks, soils and water have been gathered by the writer from field measurements and published references. Figure 2 presents the more important data gleaned from these various sources of information.

A quick examination of Figure 2 shows that the common sulphide minerals have both densities and electrical conductivities strongly in contrast with those of the host rocks and other host materials. Magnetic susceptibility, except in the case of pyrrhotite, would not seem to be a significant property.

Massive sulphide bodies likewise contrast strongly with unmineralized host rocks in density and conductivity, but overlap in conductivity with other host materials and some common geological conductors. Based on very similar considerations, Ward (1966) concludes that for massive sulphide assemblages excluding sphalerite and hematite the electrical conductivity is typically very high; and that for assemblages including pyrrhotite or magnetite, the magnetic susceptibility is typically higher than that of the host rocks. To this we should add that massive sulphide bodies are exclusively higher in density than unmineralized host rocks and other host materials.

It follows from the preceding argument that electrical and gravity methods are a natural combination in searching for massive sulphide bodies in the Canadian Shield. Magnetic methods can also be used effectively if the sulphide body of interest typically contains pyrrhotite or magnetite. This is normally the case with nickeliferous ores, and it may prove to be the case with massive sulphide bodies generally, though we know of a few important exceptions.

Not enough statistics are available to determine the percentage of non-nickeliferous sulphide bodies that contain pyrrhotite or magnetite in significant quantities; however, in the writer's experience it would seem that such bodies form a very small minority. On the other hand, most massive sulphide *orebodies* do in our experience produce a distinguishable magnetic anomaly. The writer and D.G. MacKay (1960) show this to be a fact in the Mattagami area, Quebec. Magnetite apparently is a common constituent of massive sulphide bodies containing chalcopyrite; galena and sphalerite bodies are often found without magnetic association. In the Canadian Shield, copper and nickel being the metals of prime interest, the magnetic criterion seems to be a logical one.

Exploration methods

A variety of exploration philosophies have been used in prospecting campaigns in the Canadian Shield. These vary from metallogenic-tectonic studies followed by surface prospecting and drilling on the one extreme, to 'saturation' prospecting by geophysical methods on the other. The former has been effective in locating several new metalliferous areas and some minable orebodies. The latter has located numerous orebodies but has added little to our knowledge of the Shield as a mineral environment.

Between these two extremes many well guided exploration programs have been carried out based on roughly the following sequence of steps: (1) regional geological studies; (2) aeromagnetic survey and interpretation; (3) airborne EM (with or without simultaneous aeromagnetics and radiometrics) and interpretation; (4) ground follow-up by EM and magnetic methods, accompanied by geological anomaly examination; and (5) detailed ground geophysical surveys, geological mapping and drilling.

Regional geological studies. With the exception of a small region of the Arctic islands, the entire Canadian Shield has been mapped geologically at a scale of 1 inch to 8 miles. Mapping at a scale of 1 inch to 4 miles and larger is in progress by both the federal and provincial governments, most of the mineral belts having been covered to this date. In addition to these surveys, geotectonic and metallogenic studies have been carried out by various government departments and universities, with the result that a great body of information is now available to the prospector.

Aeromagnetic survey. Aeromagnetic survey data have been available over much of the Canadian Shield since the mid-1950s. An intensification of the program on a federal/provincial basis began in 1962, and the Shield is now roughly two-thirds covered by aeromagnetics at a scale of 1 inch to 1 mile; the remaining areas are scheduled for completion by 1974. While these maps cannot be used directly for massive sulphide exploration, they are used to supplement available geological maps in selecting areas of geological interest.

The writer (1962) and Stam (1960) demonstrated the effectiveness of aeromagnetics in mapping geology in areas covered by overburden or water. Proper interpretation of available aeromagnetic data probably would have saved many millions of dollars and speeded up mine development in Canada if the interpretation had been done before the initiation of major field programs. An aeromagnetic map is a geological map drawn in invisible ink. Interpretation of the data should be carried out immediately after map compilation, otherwise interest shifts to another area and the data gather dust in the files. Most successful exploration programs have used carefully interpreted aeromagnetic data, frequently in association with geological air photo interpretation. Aerial photography exists over 80% of the Canadian Shield at a scale of about 1:50,000; low-level photography at scale 1:25,000 or better is available in about 1% of the Shield, concentrating on the populated areas. Regional geological-aeromagnetic interpretation programs have been carried out over most of the southern one third of the Canadian Shield. These studies, combining the first two steps of the previously mentioned exploration sequence, have formed the basis for numerous effective exploration programs and mine discoveries.

Airborne EM. Following the selection of a favourable area for massive sulphide exploration, the next logical step is to use the most efficient means possible of locating orebodies directly. Fortunately, as shown, massive sulphide deposits in the Canadian Shield environment afford satisfactory conditions for direct detection by both electrical and gravity means. The most efficient and least ambiguous of electrical methods is that of airborne electromagnetics (EM). The writer (1966) reviews airborne EM surveying in Canada in the period 1955 to 1959 and includes Table I. By now at least 250,000 square miles have probably been surveyed by this method in the whole of Canada, some 200,000 of which would be on the Canadian Shield. (These figures are based on estimates provided by contractors – most mining companies prefer to keep their information confidential. The figures shown are probably on the low side.)

The writer and MacKay (1960), the writer (1966), Pemberton (1961) and White (1966) describe airborne EM programs in various parts of the Canadian Shield. These are but a few of the score of similar programs that have been undertaken on the Shield since 1945. Pemberton (1966) lists 113 orebodies discovered by, or with the assistance of, geophysical methods during this period. Sixty-six of the 95 direct discoveries are in Canada, where geophysics has obviously played a leading role in mining exploration. Forty-two of the 66 Canadian discoveries are in the Canadian Shield; of these 27 are massive sulphide deposits and 19 were found by airborne or ground EM methods. Almost one half of the total world discoveries by geophysics have been in the Canadian Shield. Does this reflect geological and geographical conditions more favourable than other areas of the world, or is Canada fortunate in having received greater attention than other countries? The writer believes that whereas conditions are indeed favourable in the Canadian Shield, exploration carried out on a similar world-wide scale would have resulted by this time in many hundreds of mine discoveries and a greatly accelerated industrial-

Table I. Exploration statistics – after the writer (1966). All of Canada, 1955 – 1959.

Square miles surveyed*	125,000 square miles
Line miles of EM	500,000 line miles
EM anomalies located	100,000
EM anomalies selected**	10,000
EM anomalies followed up on the ground	3,000
EM anomalies drilled	1,000
Sulphide bodies found	800
Potential orebodies found	16

* Includes some areas flown more than once. ** Anomalies selected as probably significant by a process of interpretation or 'skimming.'

ization of the developing countries. The airborne EM method is not directly applicable to all Shield areas; nevertheless, vast areas of Precambrian Shield do exist where the techniques tried and proven in Canada can be used without major modification. Current programs in India, Africa, South America, Southeast Asia and Australia attest to this fact.

Skillful interpretation of airborne EM results is essential before ground work is carried out. Many programs were carried out in the 1950s without the aid of quantitative interpretation methods. Selection of anomalies for ground investigation was done by rule of thumb and good geological judgment. Strong economic pressures and a shortage of experienced geophysicists delayed the development of better interpretation techniques, and it was not until 1960 that geophysicists began classifying airborne EM anomalies routinely on a quantitative basis. Methods such as those of the writer (1961), White (1966) and Weiduwilt (1962), developed in each case for a particular airborne EM system, became widely used, with a noticeable effect on the success rate in exploration programs.

Philosophies differ concerning interpretation and ground investigation of airborne EM. On the one hand, some select only the most favourable anomalies for ground investigation, preferring to conserve exploration funds for application in other areas; on the other hand, some justify investigating and even drilling the most unlikely anomalies because economics dictates that an orebody must be found in a particular area. In either case, it is important that interpretation be carried out so that ground investigation is performed systematically, employing the most suitable methods.

Aeromagnetic and airborne radiometric surveys are usually carried out in conjunction with airborne EM in the Canadian Shield. The extra cost of carrying these instruments and performing the data reduction is small in comparison with the total survey cost. The data are mainly used to assist in the geological interpretation of the environment in which airborne EM anomalies are located. Direct magnetic or radiometric association may be significant in some cases. Direct magnetic association, as mentioned earlier is often considered to be a favourable factor. In addition, the magnetic and radiometric data may reveal other geological features of interest such as magnetite bodies, carbonatite intrusives and pegmatite dikes.

Ground follow-up. Ground investigation of airborne geophysical anomalies follows various patterns, depending on the location, access and amount of rock exposure. A few general rules, however, nearly always apply:

1. The anomalies are investigated in descending order of probable economic importance.
2. Regardless of the amount of outcrop, a ground geophysical instrument should be used that responds to the same parameters as those which caused the airborne geophysical anomalies.
3. An examination of the surface geology (including overburden) and topography is absolutely essential.
4. Sufficient ground geophysical work is done to facilitate the identification of the source of the anomaly before a decision is taken to drill or abandon it.

A great many exploration programs have failed because of inadequate emphasis on ground investigation. Experience has shown that in the Canadian Shield, the cost of ground geophysics, geology and exploratory drilling is from four to fourteen times that of an airborne survey. Operators unwilling to budget sums of this magnitude have been known to abandon programs, leaving large numbers of first-grade airborne EM anomalies uninvestigated. Early discouragement through a discovery of barren sulphides or graphite is frequently the cause. In other cases, the ground geophysics failed to locate the airborne anomaly either through excessive depth of burial, difficulty in recovering location, or a poor choice of ground geophysical methods.

A fair amount of statistics is now available on the results of ground investigation of airborne geophysical anomalies. Table II lists the results of a program carried out with a two-frequency, quadrature system at a line spacing of one quarter mile in an area of 1700 square miles in northwestern Quebec. More than 90% of the ground was covered by heavy overburden, much of it consisting of highly conductive clays. One hundred and ninety-eight anomalies were selected as having possible economic significance, of which 42 were considered to be probably due to overburden. The anomalies were located on the ground by vertical loop EM, with a depth penetration roughly equivalent to that of the airborne system. At the date of compiling Table II, 120 anomalies had been investigated on the ground. Gravity methods were used to help select the most favourable anomalies for drilling. All 22 of those drilled intersected metallic conductors and 20 of these

Table II. Interpretation and follow-up statistics, after airborne EM survey, northwestern Quebec.

	A anomalies (first grade)	B anomalies (second grade)	C anomalies (third grade)	Anomalies where overburden suspected	Totals
Investigated by reconnaissance ground survey	12	30	45	33	120
Confirmed and further work planned or carried out	12	26	31	8	77
Confirmed but no further work planned	-	-	-	4	4
Not confirmed	-	4	14	21	39

found massive sulphides. In other programs, conducted under better overburden conditions, interpretation methods have proven to be better than 90% reliable in distinguishing anomalies due to metallic conductors. It was privately reported to the writer by the late Dr. A.R. Clark that with the aid of response curves such as those published by the writer (1961), he was able to select large numbers of anomalies that had been detected but rejected in previous airborne EM surveys, and had investigated these with success on the ground. The writer also knows of cases where anomalies were abandoned after a cursory ground examination had revealed graphite and magnetite in the vicinity of the conductor; later ground surveys showed an imperfect correlation between the conductors and the suspected causes and, upon drilling, the anomalies were found to be caused by massive sulphides.

Therefore detailed interpretation and ground follow-up are vital factors in the economics of integrated massive sulphide exploration programs.

Detailed surveys. Detailed ground geophysical surveys are not always required before an anomaly is drilled. Economic or logistic factors may favour the rapid identification of an anomaly by drilling one centre of conductivity. Such a procedure, however, frequently leads to ambiguous results; the anomaly is not satisfactorily explained or, in some cases, the wrong explanation is given to it. Complete definition of an anomaly by systematic ground survey will not only ensure that the best portion of the conductor is drilled, but will also assist in resolving any ambiguities that may arise out of the drilling program. Nevertheless, there may be occasions when literally tens of miles of first-grade EM conductor require investigation; in such cases, scattered groups of ground EM profiles will be adequate to define a sufficient number of targets for drilling.

A combination of several different ground geophysical methods may result in a better identification of the cause of an airborne anomaly and consequently increase the success rate in drilling. Ground magnetometer profiles can be used to advantage in recognizing conductors due to banded magnetite and to serpentine. Magnetic data can also be used to help interpret depth to bedrock. Gravity survey is useful in resolving conductors due to wet shear zones, faults, and buried ridges and valleys beneath conductive overburden. Gravity has also been used extensively to differentiate graphitic conductors from those due to massive sulphides. In some areas these are the most troublesome conductors, as they have electrical characteristics almost indistinguishable from those of massive sulphides. As a rule, gravity is effective where overburden is less than 50 feet thick, though profiling by seismics or resistivity is sometimes required to resolve the effects of bedrock topography. Where overburden is thicker than 50 feet, the gravity anomaly may be too small to be reliably distinguished from the effects of lateral density variations and bedrock topography. The amount of geophysical work done before drilling depends again on various geological, economic and logistic factors.

Detailed ground geophysical surveys are frequently carried out after drilling to help outline a conductive body and minimize the amount of exploratory drilling required. The writer (1957) cites a case where four different surface techniques and two down-hole techniques were used to effectively supplement a surface drilling program. An induced polarization survey was carried out later on the same orebody, providing additional information that helped to guide development drilling.

Ground surveys. So far we have dealt with integrated exploration programs comprising regional surveying and ground follow-up. Whereas such programs account for a large part of the exploration effort in the Canadian Shield and have been responsible for most of the major discoveries, the place of the surface program should not be overlooked. Such programs are necessarily restricted in area and therefore must be based on more precise area selection for target definition. Often this is done by reconnaissance geological mapping, as in the case of current work in the Coppermine River area of the Northwest Territories. Frequently, however, the areas are based on information gained through programs carried out previously, often by other mining companies. For example, the Mattagami discovery led to claim staking and ground exploration programs by dozens of mining companies who had no knowledge of the airborne survey results. The investigation of such properties then becomes a matter very similar to the airborne program already discussed, but on a smaller scale. As with airborne surveys, EM methods are favoured for the reasons already given; but on the ground IP has lately found some popularity even when massive sulphides are the object of the search.

Hallof (1967) described some massive sulphide bodies that cannot be detected by EM. Most of these appear to fall short of the 50% concentration figure that we have used as minimum in our definition of massive sulphides. Perhaps a better argument for the use of IP is that in particular situations the effects of electrolytic conduction can obscure or distort the effects of a weak massive sulphide conductor. These are most common when a conductor is buried at great depth below conductive overburden or sedimentary rocks. Electrolytic conduction in overburden can normally be resolved by multifrequency in- and out-of-phase EM measurements. Nevertheless, electrolytic conductors do overlap massive sulphides in the conductivity scale, and a combination of a metallic conductor in an electrolytic environment is a difficult one to unravel by EM methods alone. In such situations IP is often to be preferred.

Combinations of methods have the same advantages in surface exploration programs as they do in follow-up programs after airborne surveys. A ground magnetometer survey costs very little if done at the same time as a ground EM or IP survey, and it can yield very useful data. Gravity may be used in special cases to improve identification of better conductors.

Geophysical instruments and techniques

A great deal of controversy surrounds the process of selection of instruments and survey techniques for both airborne and ground phases of massive sulphide exploration. No area of geophysics brings forth stronger opinions from both designer and user alike. The writer attributes this controversy principally to the great success of geophysical methods in massive sulphide exploration in recent years. Geophysicist and owner alike are bound to take more than a casual interest in a system that finds them a mine; and they are understandably critical of a system that fails to do so while their colleagues, using other systems, are locating mines to the right and left of them.

References already quoted by the writer (1961), Pemberton (1961), Podolsky (1966), and Weiduwilt (1962) describe various

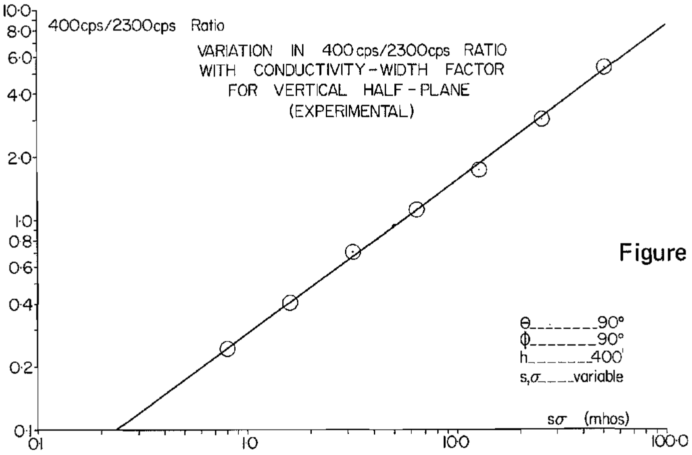

Figure 3

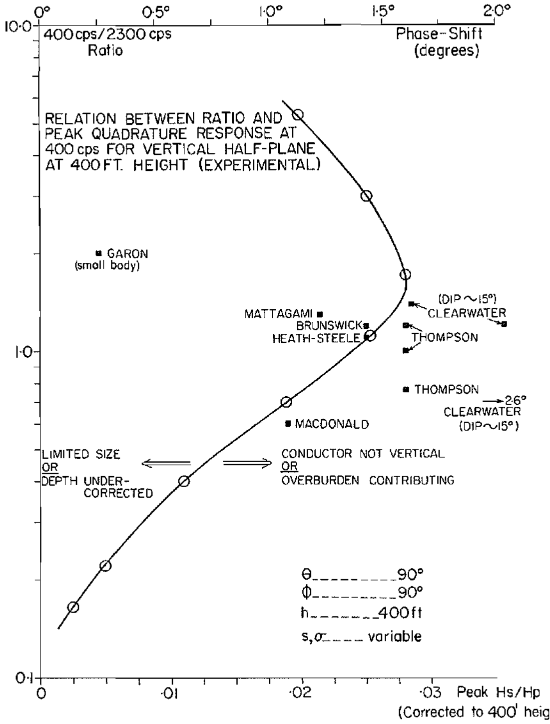

Figure 4

Figures 3, 4. Airborne EM interpretation curves — after the writer (1961).

airborne EM systems, all of which have been responsible for major massive sulphide discoveries. Comparisons of airborne EM systems have been published by Roux (1959), Makowiecki, *et al.* (1965), Pemberton (1962), and Ward (1967). Barringer (1967) describes the INPUT system, an airborne EM instrument working in the time domain.

Ground EM systems commonly used in the Canadian Shield are described by Bosschart and Seigel (1966), Crone (1966), Bergmann (1960), and Ward and Gledhill (1957). In addition to these references that deal mainly with the instruments and field applications, comprehensive discussions of methods of quantitative interpretation, with special reference to the Canadian Shield, have been published by Bosschart (1964), West (1960) and Grant and West (1965).

Gravity methods and instruments have been described in the literature; their application to massive sulphide prospecting is described by Pemberton (1957).

Airborne and ground magnetometer methods and instruments are likewise well known; recent reviews by Hood (this volume) cover the field very thoroughly.

Some case histories have been published describing massive sulphide exploration programs in the Canadian Shield. Papers by Bosschart (1961), the writer and MacKay (1960), the writer (1957; 1966), Pemberton (1961) and Podolsky (1966) have already been mentioned; Bergey (1957), Seigel (1957), McMurry (1957), Clayton (1966), Hallof (1966), White (1966), and Dowsett (1967) describe other massive sulphide exploration programs.

The following remarks are intended to complement the references cited above, and present the writer's personal views based mainly on experience with the different systems and methods in Canada.

Airborne EM methods. The writer has obtained most of his experience with two airborne EM systems operated by the Hunting group of companies (now Lockwood Survey Corporation Ltd.) in Canada, and is therefore biased in favour of these systems or systems measuring similar parameters. The two methods are: the two-frequency quadrature system (the writer, 1961) used chiefly for reconnaissance surveys; and the in- and out-of-phase system (the writer, 1961a) used with a helicopter normally for detail surveys or surveys in mountainous terrain.

Most published comparisons of airborne EM methods have been based on limited field testing and subjective (and often erroneous) reasoning. Whereas such comparisons may have been necessary during the 1950s, EM interpretation theory has now advanced to the point where a purely objective analysis can be made. McLaughlin (1967) and Ward (1967) have made such analyses which, though incidental to their main purpose, have exposed some of the myths surrounding airborne EM surveying.

A modern airborne EM system must do two things: (1) *Locate conductors.* Penetration, sensitivity, resolution, accuracy of positioning, etc. are important. (2) *Provide a measure of conductivity-width.* The effects of strike, dip, height, etc., must be distinguishable from those of conductivity-width; simplicity and the degree of dependence on the above factors are important.

In the Canadian Shield environment, the following general observations seem to apply:

1. Massive sulphide bodies of interest vary in size, geometry, depth and conductivity between very broad limits; the best EM system, therefore, is the one that is sensitive to, but is least affected by variations in, the above set of parameters. It is important that the system respond to flat-lying, as well as steeply dipping conductors; and, despite statements to the contrary, all working airborne EM systems do in fact respond very nearly equally to finite bodies of both these attitudes.
2. Over the large majority of the Canadian Shield, distances are typically large; depth to orebodies is often great because of overlying lakes and thick deposits of overburden or sedimentary rocks. An economical, long-range, fixed-wing aircraft, equipped with a system of high sensitivity both downwards and laterally, is most suitable for these conditions.
3. 'Closely-coupled' EM systems such as most light plane, fixed-wing systems, and all helicopter systems, are preferred in regions of steep topography and for detailed surveys in areas where the overburden is shallow.

Table III. Comparison of six fixed-array frequency airborne EM systems – after McLaughlin (1967).

System (common name)	Coil Array	Coil sep.	Aircraft (typical)	Fre-quency	Coil Ht. (typical)	Noise envelope (typ.)	Traverse Speed	Vertical dike response						Horiz. dike response	
								$\sigma t = 200$		$\sigma t = 500$		$\sigma t = 1000.$		$\sigma t = 2$	
								α	β	α	β	α	β	α	β
Newmontaero	XX	60′	S - 55	400	150′	20 ppm	60 mph	300	200	400	170	500	100	600	1100
T.G.S.	XX	50′	G - 2	400	150′	15 ppm	60 mph	150	110	200	110	220	80	340	600
Hunting (now Lockwood)	XX	30′	G - 2A G - 3	4000	120′	6 ppm	60 mph	180	40	200	15	210	0	110	220
Sharpe	XX	30′	Hughes Turbine	1600	120′	2-3 ppm (4)	100 mph	100	60	180	45	200	25	25	110
Barringer	XZ (or XY)	30′	S - 55 or equal (3)	400	120′	3 ppm (2) (4)	60+mph	?	?	?	?	200 (1)?	150 (1)?	–	8 (1)
Mullard	YY	62′	Otter	320	180′	40 ppm	120 mph	200	130	350	120	500	80		

Definitions:
σt = thickness x conductivity in mhos feet/meter
α = in phase (in ppm)
β = quadrature (in ppm)

Coil arrays: X, Y, Z represent coil axis directions, X in direction of flight
(1) Values obtained by rather risky extrapolation
(2) Referenced to axial field
(3) Probably also compatible with turbine helicopters
(4) Claimed by manufacturer

4. Exploration programs in the far north are frequently based on surface geological mapping and reconnaissance geochemistry, using helicopters for transportation. In such cases, for example in Ungava and Baffin Island, the helicopter is sometimes equipped with an EM system, permitting simultaneous airborne EM to be carried out on a systematic or on a patchwork basis.

5. Massive sulphide bodies in the Canadian Shield have conductivity-width factors (Figure 2) overlapping those of some other geological formations and structures. In particular, graphitic beds, serpentine bodies, clay formations and water-filled shear zones, may provide an EM response indistinguishable from that of a massive sulphide body. Therefore the EM system should be designed to provide maximum resolution of the conductor, enabling the interpreter to determine true width and recognize the effects of banded or multiple conductors. This requirement conflicts with that of deep penetration, so the choice of EM system is at best a compromise.

6. On the basis of numerous anomaly examinations, the writer has found that by and large, massive sulphide bodies containing economic minerals, particularly the ores of copper, lead and zinc, have a lower bulk conductivity than those composed of barren sulphides. Typically, orebody conductivities appear to be in the range of 0.1 to 0.4 mhos per metre; barren sulphide bodies, mainly pyrite, are usually in the range of 0.4 to 0.9 mhos per metre; bodies largely composed of pyrrhotite normally have conductivities in excess of 0.9 mhos per metre. Graphitic schists usually have conductivities less than 0.3 mhos per metre, and are therefore difficult to distinguish from economic orebodies. Serpentine bodies likewise have conductivities similar to those of orebodies. Unique solution of conductor width is seldom possible, even with very high resolution airborne EM equipment; recognition of sulphides as distinct from other geological formations normally of greater width is usually done with the aid of simultaneous aeromagnetic data, together with a careful geological appraisal of the anomaly in relation to its lithologic and structural environment.

7. The methods of operations research have been applied to maximize the probable gain from exploration programs in various parts of the world. Allais (1957) describes such a case in Algeria, where not only the search pattern (line spacing) but the combination of methods and the extent of the different phases of the program were considered. Agocs (1955) and Hammond (1961) deal primarily with the line spacing, using examples from the Canadian Shield.

As far as the writer knows, no such procedure has been applied to massive sulphide exploration in the Canadian Shield, though line spacing has been selected on occasions through the use of Buffon's equation.

For a survey line spacing of 1/4 mile (most commonly used for reconnaissance airborne EM in Canada), a detection probability of 48% is obtained for randomly oriented bodies 1000 feet long.

Airborne EM systems possessing the characteristics required for regional exploration include the Hunting (now Lockwood) two-frequency quadrature system (the writer, 1961), the Barringer INPUT system (Barringer, 1967), and the International Nickel differential system (Dowsett, 1967). These systems employ similar coil configurations, and because they are not sensitive to fields in phase with the primary field, are able to use towed receiving coils and consequently achieve deep penetration and high sensitivity. Whereas the quadrature system records only two channels representing the conductor response at 400 cps and 2300 cps, the INPUT system now records six or more channels, with an effective response down to 100 cps. The extra information is useful where there are adjacent conductors of different conductivities, such as massive sulphides underlying clay beds. However, the three systems provide comparable information and should be judged on the basis of sensitivity which, in the case of equivalent coil configurations, is a function of background noise level only.

Quantitative interpretation of quadrature data is done on the basis of curves such as those in Figures 3 and 4 published by the

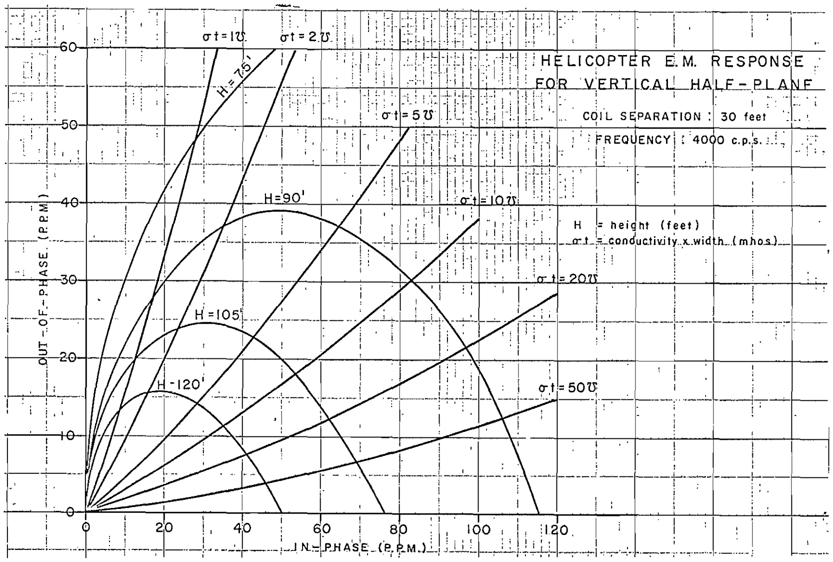

Figure 5. Helicopter EM interpretation curves.

writer (1961). Equivalent curves for the INPUT and differential systems have not yet been published.

For detailed airborne EM surveys, a variety of roughly equivalent systems have been used from both fixed-wing aircraft and helicopters. Table III lists those that have been used most widely in the Canadian Shield, and compares their response at normal flying height to vertical sheet-like conductors at surface and at a depth of 100 feet. It may be observed that the systems possessing the greatest coil separations improve in relation to the others with increasing depth to the conductor; sensitivity is a function of coil separation, background noise and frequency; discrimination against nonmetallic conductors improves (up to a point) with decreasing frequency.

Several of the above systems have been successful in locating economic deposits of massive sulphides. The choice of system should be based on such factors as the cost per mile, the ability to maintain a constant height above ground, sensitivity to bodies of the type sought, and discrimination against other geological conductors. Enough details are available regarding the above systems that a choice can be made on a purely objective basis.

It is worth noting that with the decrease in coil separation (as compared with the towed bird systems), effective conductivity is increased, as a smaller portion of the conductor is being sampled. Larger conductivity-width factors are therefore normal, and this should be taken into consideration in judging both sensitivity and discrimination. Nevertheless, it is the writer's opinion that the factors listed by McLaughlin (1967) in Table III are at least one order of magnitude too high for massive sulphide bodies in the Canadian Shield.

Quantitative interpretation is possible with all of the above systems, using the methods of Weiduwilt (1962) as applied by Grant and West (1965). Figure 5 is a phasor diagram for the Hunting (now Lockwood) helicopter EM system described by the writer (1961a).

Ground EM methods. In ground follow-up work after airborne surveys, the following criteria apply in the choice of instruments and methods:

1. The equipment should be light and exceedingly portable, allowing easy transportation and convenient operation through heavy bush on a blazed traverse line.
2. The method should have a good response to conductors of the type producing the airborne EM anomalies.
3. The method should have good depth penetration, preferably as deep as that of the airborne EM system.
4. It is advantageous to use a system that will yield information on both conductivity and width of the conductor.

The first three criteria are most easily satisfied by the relatively simple vertical loop (dip angle) EM systems, which were developed in Canada for use in massive sulphide exploration in the Canadian Shield. Deep penetration, high-power versions similar to those that appeared first in the late 1940s, are still favoured by some mining companies because of their deep penetration and reliability. Where shallow overburden is expected or where the airborne EM survey penetrated no more than 150 feet below ground, light-weight, transistorized systems with coil separations of about 400 feet may be used. Crone (1966) describes work done with one such lightweight system.

The above systems are capable of locating and roughly defining a buried conductor, but do not yield reliable information regarding either conductivity or width. Systems measuring both in-phase and out-of-phase components have this capability but obtain deep penetration only at the expense of portability and survey convenience. The Turam method (Bosschart and Seigel, 1966) has been used for ground follow-up in some difficult areas, but is both slow and inefficient for this purpose. The horizontal loop method (Bergmann, 1960), meets all of the above requirements providing depth is less than 150 feet, and is the method preferred by the writer. Though conventional systems are not quite as portable or simple as the modern vertical loop systems, these disadvantages are offset by the ability to estimate the conductivity and width of the conductor. This is done with the aid of curves such as those published by Grant and West (1965) and shown in Figure 6. Thus normally metallic conductors on the one hand can be separated from other geological conductors on the other, the former usually possessing higher conductivity and smaller width. Drilling recommendations can therefore be made without recourse to gravity or to detail surveys with another ground EM method.

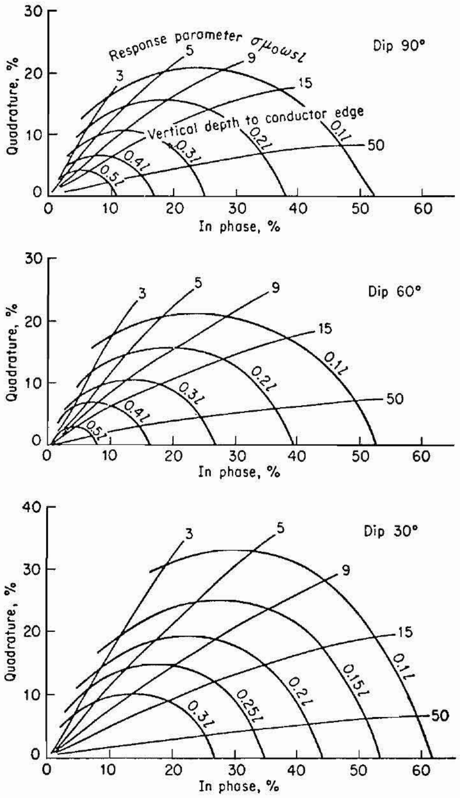

Figure 6. Horizontal loop ground EM interpretation curves.

New horizontal loop EM equipment is available (the writer, 1968) with improved portability, sensitivity and depth penetration. Equipment of this type is expected to play an important role in ground EM surveying, both as a follow-up method and for detailing before and after drilling.

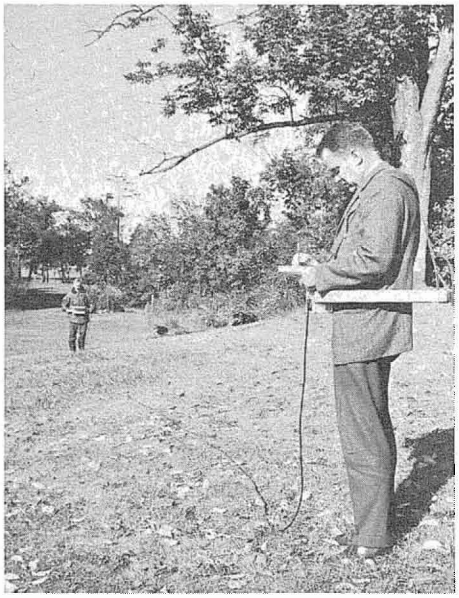

Figure 7. Deep penetration horizontal loop ground EM system.

Ground EM surveys carried out as a primary reconnaissance method employ basically the same set of systems. Table IV compares the most common systems in terms of speed, economy, depth penetration and discrimination (including the ability to measure conductivity and width).

Of these systems the high-power vertical loop method has probably been most widely used in the Canadian Shield, though horizontal loop systems have become more popular since 1956. Lightweight vertical loop systems are not used as extensively for reconnaissance surveying as they are for detailing and ground follow-up. Turam is used for reconnaissance in areas of deep

Table IV. Comparison of typical ground EM systems.

Manufacturer	Type	Frequency cps	Max. coil sep. (ft)	Size of Crew	Depth (3) Penetration	Interpretability
McPhar SS15	Vertical loop	1000/5000	2000	2	1/3 to 1/2 of .coil separation	Fair (1)
Sharpe SE300	-do-	400/1600	1000	″	-do-	″
McPhar REM	-do-	1000/5000	600	″	-do-	″
Crone JEM	-do-	480/1800	400	″	-do-	″
McPhar VHEM	Vertical loop Horizontal loop	600/2400 600/2400	500 300	″ ″	-do- -do-	″ Good
Sharpe SE600	Vertical loop Horizontal loop	1600 1600	1000 300	″ ″	-do- -do-	Poor Good
Huntec Ronka Mk III	Horizontal loop	876/2300	300	″	-do-	Good
Huntec HUNTEMATIC	-do-	500/1000/2000	500	″	-do-	″
Geonics Ronka 16	Vertical field components	18k - 24k	–	1	100 - 1000 ft(2)	Fair
McPhar AFMAG	Dip angle	130/475	–	1	500 - 1500 ft(2)	Poor
Sharpe TURAM	Fixed source loop frame	200/400/800	–	3	400 - 600 ft	Good

(1) Used at two frequencies.
(2) Depending on ground conductivity.
(3) Figures represent conditions typical of Canadian Shield unless otherwise noted.

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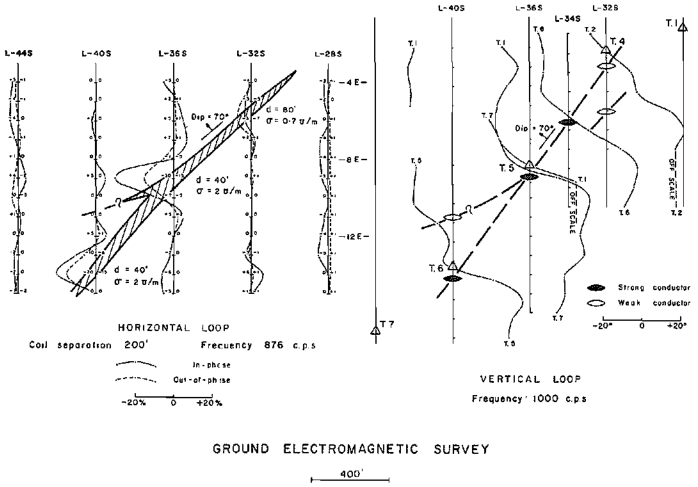


Figure 8. Comparison of horizontal and vertical loop ground EM surveys, northern Ontario.

overburden (or sedimentary cover), and for detail surveys after other geophysical methods. New horizontal loop EM equipment with penetration of 250 feet or more (Figure 7), is expected to gain rapidly in popularity.

Time domain (pulse) ground EM systems have not been routinely applied in the Canadian Shield, though they have gained great popularity in Russia (Velikin, 1967). Systems employing natural fields (AFMAG) and distant radio transmissions have been used effectively in the Canadian Shield but are not as interpretable as other EM systems. Where deep penetration is of prime interest, these systems may be used to advantage; but conductor resolution and discrimination appear to suffer seriously.

For ground EM follow-up, and for both detail and reconnaissance ground EM surveying, the writer favours a combination of horizontal loop and Turam EM. Choice of coil separation and frequency (or frequencies) should be made on the basis of local geological environment and the type of conductor sought. Line spacing can be based on probability theory; for most purposes a reconnaissance spacing of 400 feet, followed by detailing at 200-foot and 100-foot intervals, has been found satisfactory. Figure 8 presents horizontal and vertical loop EM results over a massive sulphide body in northern Ontario, showing interpretations typical for each method. The extra information obtainable from the horizontal loop survey is obvious.

The Turam method can be used effectively to depths of 400 feet or more, but requires the laying out of a primary loop or cable, reducing the efficiency and economy of the survey. The writer agrees with Bosschart and Seigel (1966) regarding the advantages of the primary loop method over the grounded cable method for resolving and diagnosing conductors. The grounded cable method has seen little use in Canada in the last five years, as it has been virtually impossible to discriminate between metallic and nonmetallic conductors when using this technique. Similar conclusions have been formed in other parts of the world, and therefore it is strange that the grounded cable method is still widely used outside Canada.

Examples. Most of the references quoted above provide excellent examples of the application of EM methods to massive sulphide exploration in the Canadian Shield. Figures 8 to 16 illustrate

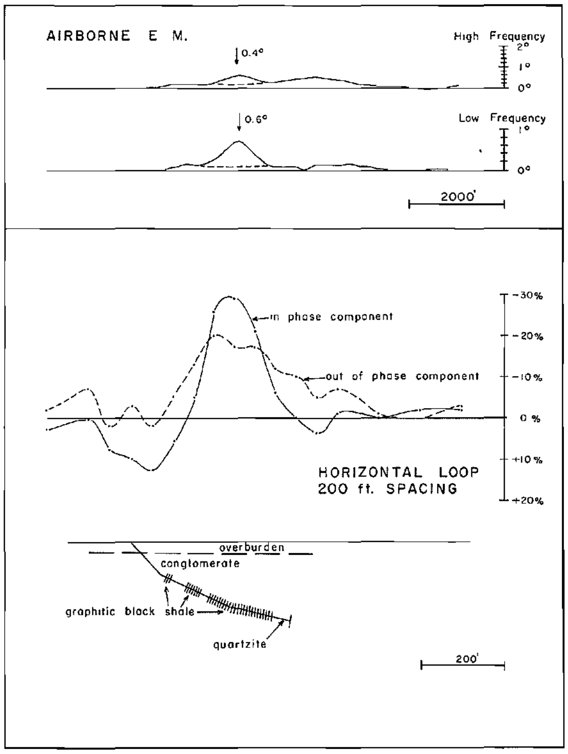


Figure 9

Figures 9 - 16. Airborne EM and ground geophysical profiles, northern Ontario.

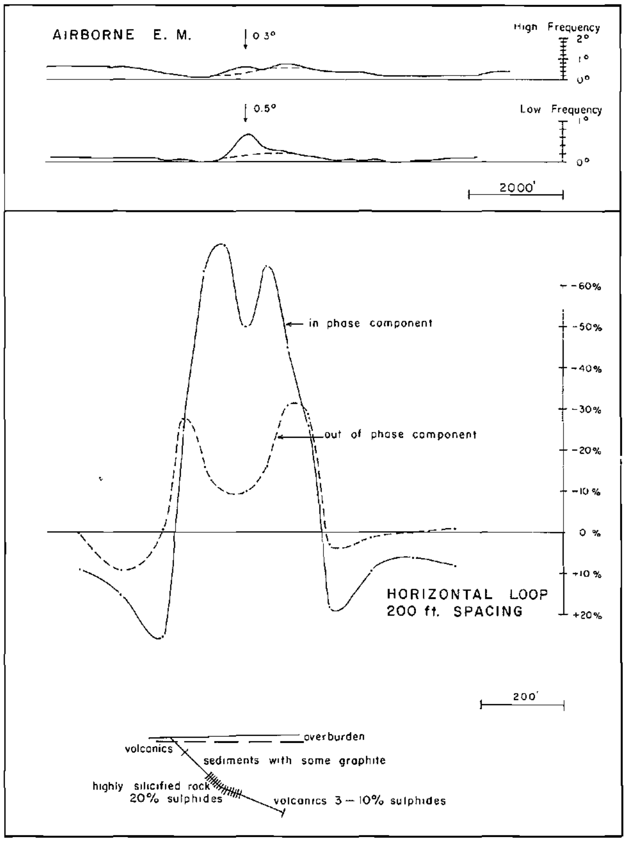


Figure 10

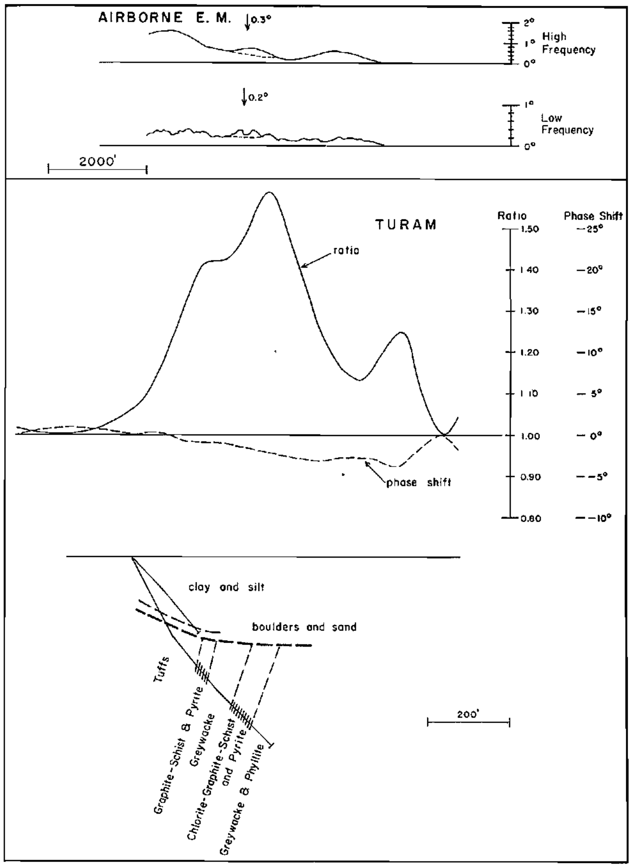


Figure 11

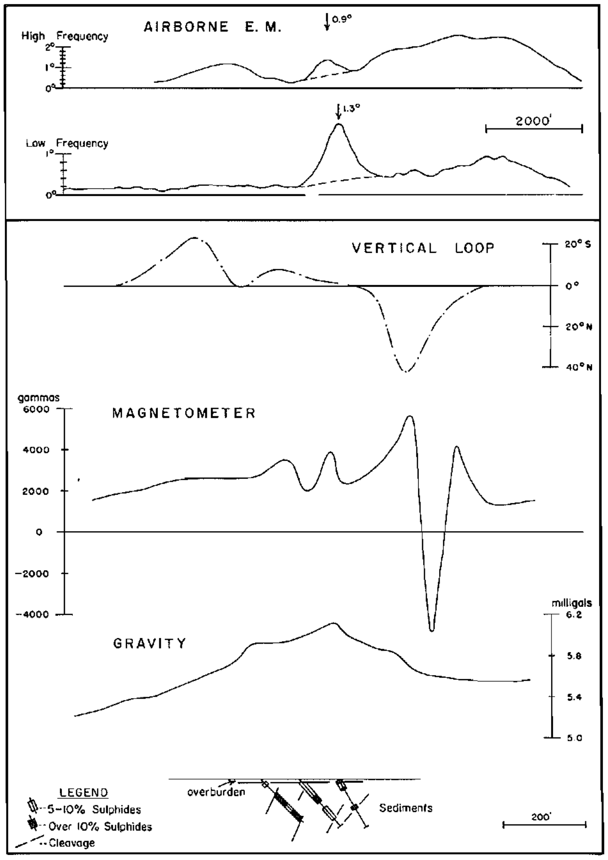


Figure 12

Figure 14

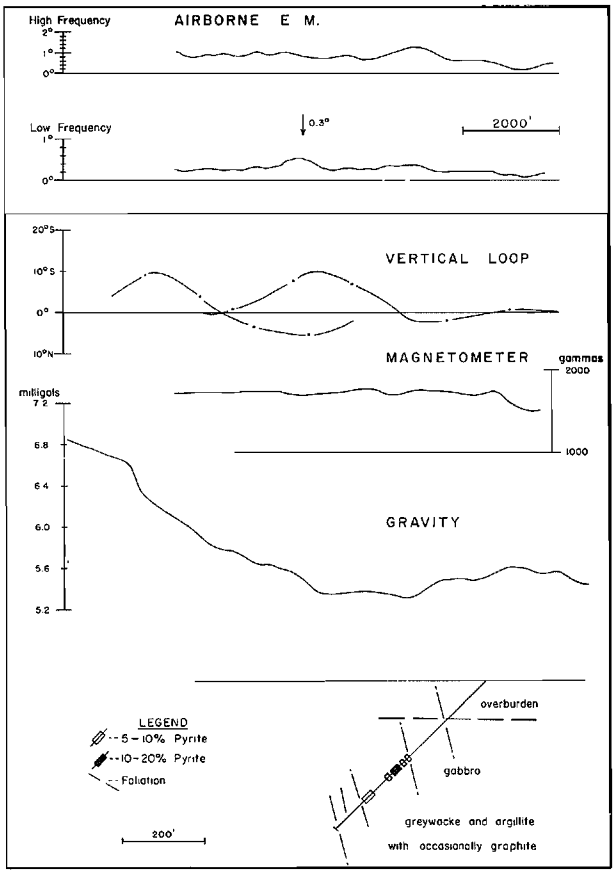
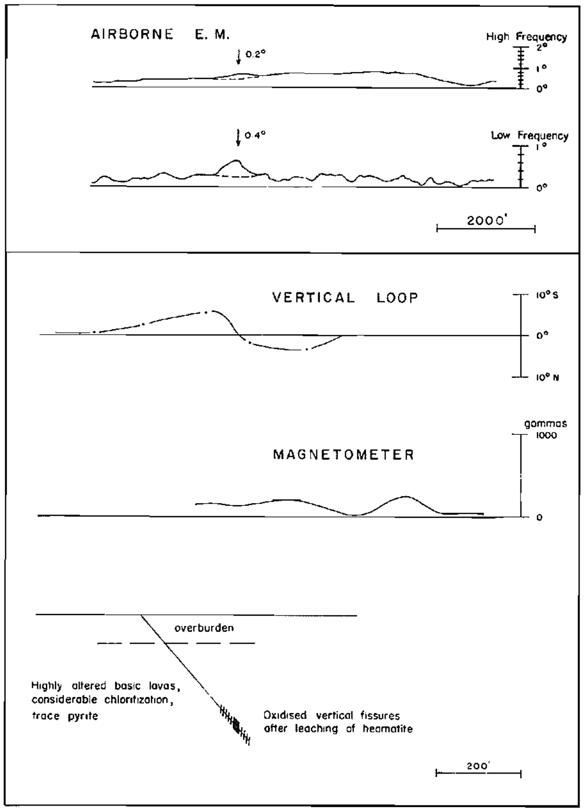


Figure 13



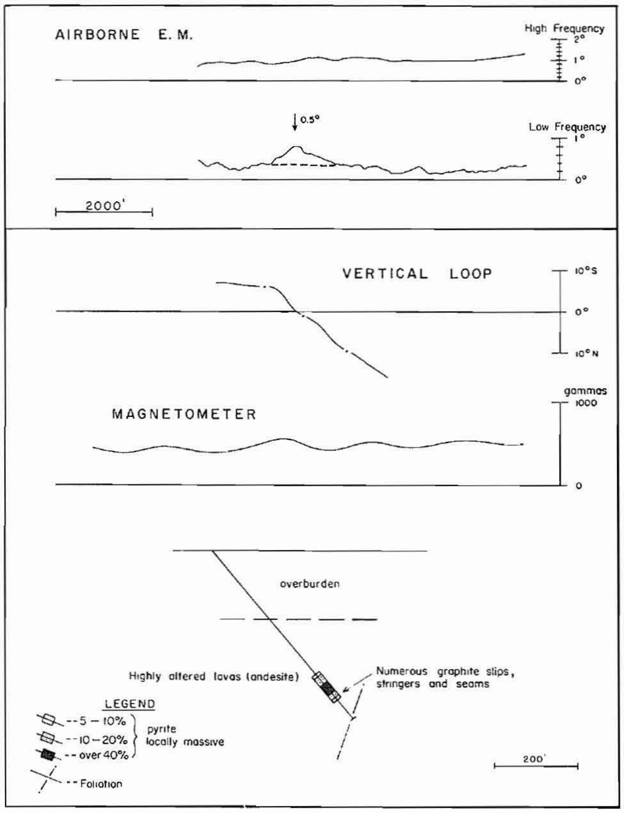
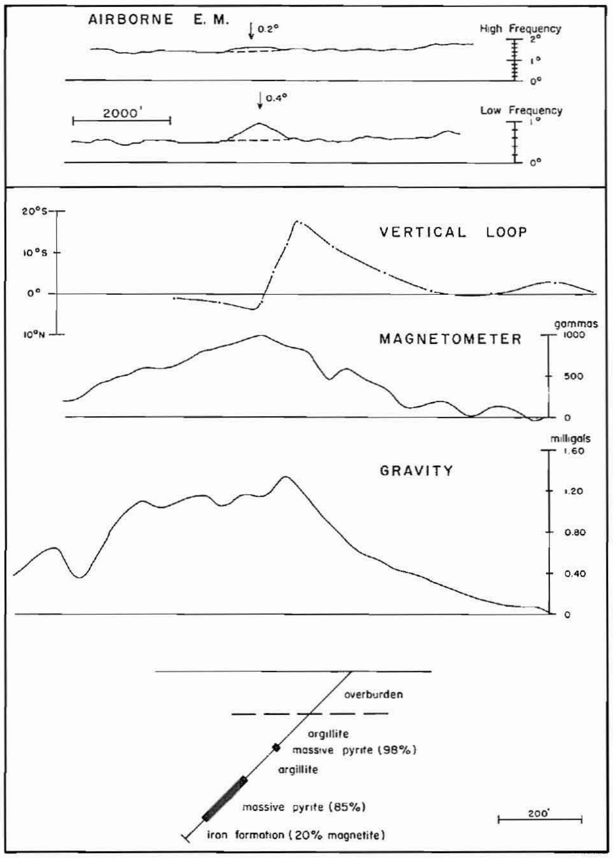


Figure 15

Figure 16



cases not previously published where both airborne and ground methods were applied before drilling. The airborne EM method in all cases was the Hunting (now Lockwood) quadrature system; a variety of methods and combinations of methods were used for the follow-up work, the results of which were used in part in the compilation of Table II.

The examples are believed to be representative of surveys in the Canadian Shield, in terms of both the methods used and the conditions encountered. Overburden effects are well illustrated, deep overburden having the dual effects of reducing the anomaly size and increasing the 'geological noise'. Vertical loop and Turam methods are clearly more effective for deep penetration work than the conventional horizontal loops; gravity methods are effective only if the overburden is shallow or the mineralization very heavy. Some of the sulphide bodies are magnetic while others are not.

The reader is referred to case histories already cited for detailed examples of massive sulphide exploration programs.

Summary and conclusions

The evolution of instrumental systems and survey methods for massive sulphide exploration in the Canadian Shield has been influenced by two factors: the physical and geological environment of the Shield and the physical properties of the massive sulphide bodies in the area.

Methods and instruments have developed rapidly in Canada with the result that this country has experienced more than its proper proportion of mine discoveries. The economics of massive sulphide exploration in the Canadian Shield is extremely favourable.

The writer and his colleagues have been involved in recent years in similar exploration programs in other Shield areas of the world, notably those of the Middle East, Africa, South America and Australia. Whereas specific techniques will require modification, and the relative emphasis of the different components of the program may be altered, the general approach used in the Canadian Shield seems to be applicable in much of the world. It is to be hoped that the lessons learned so painstakingly in Canada will be of assistance in planning and executing the surveys to come.

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Discussion on Exploration for Massive Sulphides in the Canadian Shield, by N.R. Paterson.

Maurice Magee, Tennessee Copper, U.S.A. Has any company been doing some kind of cheap geophysical or geochemical mapping of long conductive zones which could pinpoint the best sections to drill? In most cases, drilling of the full length would be very expensive and yet a body of commercial value could lie somewhere along this conductor.

N.R. Paterson, Huntec Ltd., Canada. I think that is a very good question, one for those of you who are disturbed by the problem of long conductors (the ones that stretch for miles and miles), similar to those in the Thompson area. These are a problem because, although it becomes apparent very quickly that these long conductors may be due to pyrrhotite, pyrite, or even graphite, there is no reason why there shouldn't be economic copper, nickel or other base metals along with these noneconomic minerals, at different locations along their strike. In fact, there is every reason for there to be, because here you have a situation where there has been hydrothermal action and we all know that copper bodies and other base metal bodies frequently find themselves in association with graphite, with iron formation or with other noneconomic conductors. The use of geochemistry to try and locate the interesting minerals along the strike of these long conductors has been raised a number of times. I think this has been used in New Brunswick effectively to the best of my knowledge. I think it has also been attempted and successfully applied in the Northwest Territories. I don't know if it would apply in the region of northern Quebec, northern Ontario and northern Manitoba where we have thick sections of glacial overburden. Here geochemistry has had extremely doubtful results and I can think of a few cases where we actually augured holes down to a depth of 30 feet or more to bedrock surface in order to take geochemical samplings. These were right over economic orebodies and still we got no geochemical results. It doesn't take very much glacial clay to insulate the sample from the material in which you are interested. A geophysical approach rather than a geochemical approach would appear to be more effective within the Canadian Shield.

Edwin Gaucher, Soquem, Canada. In the case of a long conductor showing rather uniform geophysics along strike I presume drilling at given intervals would be the best approach? What interval would you suggest?

Paterson. Yes, I'd agree with that. I think it's a question for a geologist more than for a geophysicist and my only suggestion in this regard would be to try to sample the conductor at various points where it does something a little peculiar: where it takes a bend, or where there is faulting, where there is a local intrusion, where the magnetics or the geology show some structural anomaly which might have caused some change in the habit of the orebearing solutions. I don't know what interval this might be, but I would think that 1000 feet is much too small. Conductors I am thinking of stretch for miles and I would think every 5000 feet or so might be much more appropriate.

Howard McMurray, New Jersey Zinc, U.S.A. Do you think there is any merit in crossing these things with gravity, for instance, at maybe a lot closer intervals than 5000 feet and that perhaps you might check with seismic data to make sure you don't have a bedrock expression.

Paterson. I think what you are talking about is separating the graphitic and overburden conductors from sulphides. The question originally put by Dr. Gaucher was concerned more with separating the barren sulphides from the copper-bearing sulphides.

I would agree with you in connection with separating graphitic conductors that gravity can be used in this context, particularly if one does it on a systematic basis, so that you have more than one sampling; and of course it is a lot less expensive than drilling. It is also a very useful technique for unravelling the overburden anomalies, providing one interprets it properly and possibly uses seismics along with it, as you suggested. This has been done, and is being done in the Canadian Shield now – gravity checking of conductors with simultaneous seismics. We did a job just last week doing this very thing and I would say that it is a fairly common technique. The problem of unravelling the barren sulphides from economic sulphides is a much more difficult one.

William Dolan, Newmont Mining, Canada. One of the things I frequently encounter, which I am sure you have too, is that in the one dimensional sense, the profile sense, we quite frequently get excellent magnetic expression, either sharply negative or sharply positive, associated with the conductor. But upon introducing the second dimension, namely along strike, they do not remain coincident. If they did not remain coincident during the duration along strike you do not have a valid sulphide conductor. What is your experience, which is surely more extensive than mine?

Paterson. Our experience on this is that we look for one-to-one coincidence between EM and magnetics or we upgrade the EM conductor in a priority listing. When I say one-to-one I mean along strike as well as on the cross section. Just because an EM anomaly happens to fall on the side of magnetic anomaly, it doesn't mean a thing – it could be a dyke, or any kind of situation. So in the remarks column, one could say the EM anomaly lies in the general area of a magnetic high and perhaps go one step further and say we think this magnetic high is a volcanic band, or a dyke, or perhaps an intrusive or what have you. But this becomes more the geological setting than saying what we think the conductor is. In order to upgrade the anomaly, because it is magnetic, you've got to have perfect coincidence all the way along the strike. I would add the further comment that although I can think of numerous orebodies in the Canadian Shield that are nonmagnetic, and Texas Gulf is one prime example, my experience has been that there are more that are magnetic by far than that are not magnetic. Now I won't say the same for sulphide bodies. I think if you looked at sulphide bodies as a whole you would have to say that a lot more sulphide bodies are nonmagnetic than are magnetic by maybe a factor of ten to one. But if they contain interesting and economic minerals, they tend to have coincident magnetic anomalies. This is usually because of magnetite, not pyrrhotite.

D.W. Wagg, Geoterrex Ltd., Canada. I am not sure I would totally agree with the last point – but if it were valid, it would be a fairly significant criterion. I would like to make one or two comments here. One is on the enquiry over here about general conductivity in different areas of Canada. In our experience, we have found in a number of areas a rather widespread, fairly highly conductive overburden. Mattagami area is one example, and the Timmins area another. Large parts of eastern Manitoba appear to be this way. There is interesting conjecture on the nature of the sources of high-conductivity overburden. Secondly, Dr. Paterson mentioned deep geochemical sampling and he said it had not been successful in his experience. I know that it has been succesful in some cases and it may, although not always, add some criteria for long conductors. A final point that may be of interest is that while the Texas Gulf body itself is nonmagnetic, it does have geophysically associated with it a pyrrhotite zone which is very definitely magnetic. Had you not known this in advance, you certainly would be interested in the part of the body which was apparently magnetic, from airborne work.

Paterson. I would say that having seen the aeromagnetic results over the Texas Gulf body, I would not have classified it in the way Mr. Dolan and I classified coincident magnetic expressions. The thing falls on the flank of a basic intrusive, which is quite obvious on the magnetics, and this small peridotite zone may, if you examine it closely enough, have a magnetic expression. Pursuing that point just one step further, the bodies that I am thinking of that don't have magnetic expressions are mostly of the lead-zinc variety, the ones with copper almost always have magnetic expression, and the ones with nickel all do. John Dowsett may be able to quote examples where they don't, but I don't know of one.

J.S. Dowsett, International Nickel Company, Canada. You're quite right.

Paterson. I think it is a very interesting point that maybe this is an added criterion which should be fed more seriously into our operational methods. In doing exploration we use the magnetic expression as the least significant factor in classifying the importance of the anomaly for follow-up. I think we should be giving it more importance than that. The reason we haven't is that we've seen so many sulphide bodies that don't have magnetic expression, and I still think that ten to one is a conservative estimate in that regard.

Wagg. Thank you very much. I won't belabour the magnetic association of the Texas Gulf body. Another thing I want to add: there can be errors made by all of us who are interested in finding base metals when we apply certain criteria since these are usually subjective. Certainly not always, and hopefully the end result is objective anyway. For example, I consider that practically the top criteria is short strike length.

Paterson. If we use strike line as a criterion I think we would be throwing away most of our orebodies right now. I don't feel that is a very reliable one, bearing in mind that what is causing the conductivity very frequently isn't the ore, but is parallel banded iron formation, or graphite, or in many cases barren sulphides that extend for miles. Yes I feel more comfortable, when I see a short strike length but I don't think you can use it as a quantitative criterion. I think much more important, is the conductivity/width factor and the geological environment, and another factor, too, is the depth to which it extends. I would rather see the thing cut off at depth rather than cut off along the strike. As a matter of fact I have seen the airborne EM results over the Thompson and my analysis of that was that it cut off at depth and the anomaly had all the appearance of a horizontal ribbon rather than a horizontal half-plane.

Dowsett. I'm curious to know at what depth you think the Thompson body terminates?

Paterson. That was a long time ago, but in order to resolve a ribbon from a sheet, it has to be reasonably shallow, the order of a few hundred feet; once it gets to be 1000 you can't tell whether it's 2000, so it must have been two or three hundred feet. Now the feeling, and this was substantiated by the fact that we flew over it at several altitudes, was that the response seemed to be much more that of a ribbon. The fall-off in height, of course, is quite different for a ribbon than it is for a sheet both for the magnetic and the EM. I can remember very distinctly the magnetic anomaly falling off as a line of dipoles as opposed to a line of poles, which meant that whatever was causing the magnetic anomalies seemed to have very definite limits.

Contents

Some recent geoelectrical measurements in the Swedish sulphide ore fields illustrating scope and limitations of the methods concerned

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Abstract. Until 1955 prospecting in the Swedish sulphide ore fields was dominated by the electromagnetic group of methods. However, during recent years increasing emphasis has been placed on galvanoelectric or potential methods.

Resistivity measurements have been highly successful in the mapping of geological structures and details of ore suboutcrops, even beneath highly conductive overburden which masked the orebodies from electromagnetic methods.

Extensive IP measurements have been made in Sweden but the experience so far is that every IP indication is accompanied by a resistivity indication and vice versa. No distinct advantage of the IP method has been discernible in these tests.

Some recent research on the SP method has shown remarkable long-term consistency of results and suggests that with the application of a 'telluric correction' valid anomalies of less than 50 mV may be defined by this cheap but neglected method. SP borehole measurements as high as several hundred millivolts have been observed at depths of 200 metres which should dispel the notion that weathering is responsible for SP anomalies.

Recently Boliden has made considerable use of the mise-à-la-masse technique in which one current electrode of a pair is placed in a conducting mineral occurrence and the potential distribution studies in boreholes and on the surface. The resulting three-dimensional picture has succeeded in delineating ore zones with a high degree of accuracy.

Boliden Aktiebolag believes that no single geoelectric method is the answer to all prospecting problems.

Résumé. La prospection des terrains sulfurifères en Suède a été dominée jusqu'en 1955 par le groupe des méthodes électromagnétiques. Au cours de ces dernières années, cependant, les techniques galvanoélectriques ou potentielles ont pris un essor croissant.

Les mesures électriques ont connu un grand succès dans le relevé des structures géologiques et des détails des gisements sous-affleurants, même si ceux-ci ont un recouvrement très conducteur empêchant la détection des gisements par méthode électromagnétique.

De nombreuses recherches ont été faites en Suède, au moyen de la méthode de la polarisation provoquée, mais l'expérience a prouvé que chaque indication PP est doublée d'une indication sur la résistivité et vice-versa. Il ne s'est déduit de ces essais aucun avantage en faveur de la méthode PP.

De récents travaux portant sur la méthode AP ont mis en relief une remarquable homogénéité de résultats et permettent de déduire qu'il doit être possible, en pratiquant une 'correction tellurique', de définir des anomalies certaines, inférieures à 50 mV, au moyen de cette méthode bon marché mais négligée. Il a été donné de relever, dans des forages, des valeurs atteignant plusieurs centaines de millivolts à des profondeurs de l'ordre de 200 mètres, ce qui infirme la théorie suivant laquelle l'intempérisme serait la cause des anomalies AP.

Boliden a récemment fait un emploi intensif de la technique de la mise à la masse qui consiste à placer une des deux électrodes du système au sein d'un gîte minéral conducteur et d'étudier la répartition de la tension dans des forages et en surface. Les données tri-dimensionnelles qui en résultent ont permis avec succès de déterminer les limites précises des zones minières.

Aucune méthode géoélectrique prise séparément ne peut répondre, d'après Boliden Akteibolag, à tous les problèmes de prospection.

Until about 1955 prospecting in the Swedish sulphide ore fields was dominated by the electromagnetic group of methods. However, recently increasing emphasis has been placed on galvanoelectric or potential methods. This short contribution discusses the results of some resistivity, IP, SP and mise-à-la-masse surveys.

Resistivity measurements in Boliden's prospecting campaigns have generally been carried out using fixed current electrodes and mobile potential probes with a very small mutual separation (gradient mapping). Elsewhere in Scandinavia, in Finland, for example, the dipole-dipole array has been used. The gradient mapping system appears, however, to be four to five times cheaper and also more convenient from the safety point of view, for routine surveys.

Resistivity measurements have been highly successful in the Swedish sulphide ore fields in the mapping of geological structures and details of ore suboutcrops. Almost-vertical, sheet-like ores as thin as 10 to 20 metres have been successfully and accurately mapped by the gradient method. All the above favourable experience contradicts the statement made in a recent theoretical geophysics text that the resistivity method 'is quite insensitive to local deformities'.

The resistivity method has also succeeded in penetrating below the overburden where the electromagnetic method failed completely on account of the high conductivity of the overburden.

A limiting factor in the application of the resistivity method is the wealth of anomaly detail obtained, particularly the anomalies of weathered zones and troughs of crushed rocks. IP measurements in the areas concerned have failed to distinguish these anomalies from 'potentially productive' anomalies.

Extensive IP measurements have been undertaken in the Swedish sulphide ore fields but the experience so far is that every IP indication is accompanied by a resistivity indication and vice versa. No distinct advantage of the IP method has so far been discernible in these tests.

A certain amount of work on SP has been carried out at Boliden by Dr. D. Malmqvist and the author. The simple and

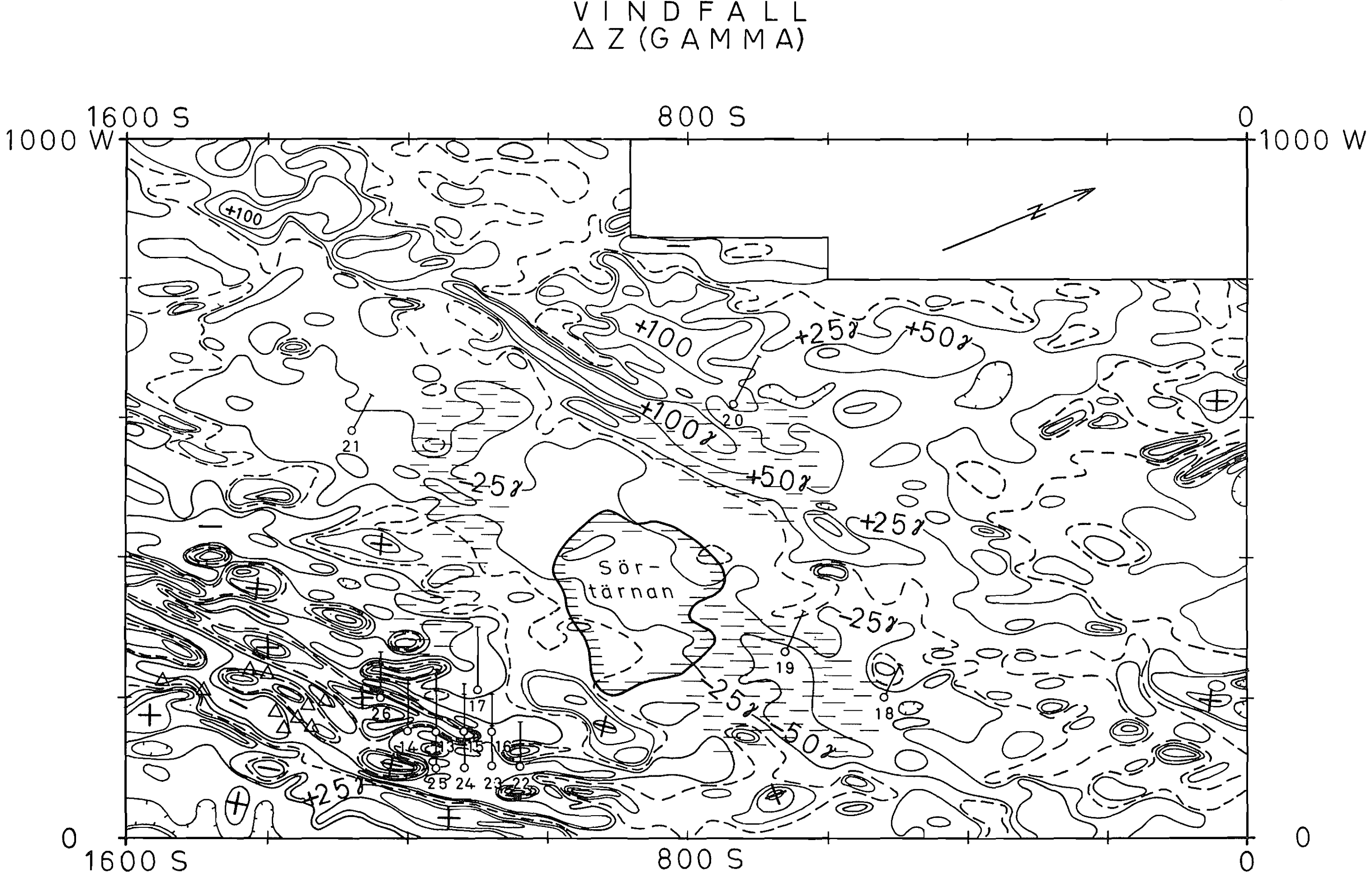

Figure 1. Magnetic map of part of the Vindfall area, central Sweden. (Scale in this and other figures is in metres.)

cheap SP method seems to be almost totally neglected nowadays by geophysicists. SP anomalies can be highly diagnostic of fissures and cracks in the bedrock, incidentally an observation of no small value to hydrology. The successful application of the SP method calls for careful attention to these and other such potentials. The temporal stability of even weak SP anomalies (50 mV and less) in areas which are by no means ill-drained is remarkable. In one test area the stability has been followed over a period of 8 years, measurements being made twice every year (generally in spring and autumn). In accurate SP work we apply the 'telluric correction', whereby all SP readings are referred not only to one particular reference point but also to a particular epoch. We hope that this research will lead us to a more optimal application of the SP method and extricate it from the disfavour into which it has presently fallen among geophysicists.

Measurements of SP in boreholes have been undertaken at Boliden. SP anomalies as high as several hundred millivolts have been observed in compact pyrite zones as deep down as a couple of hundred metres. Such observations, and similar ones on graphitic shales, should suffice to dispel the notion, still widely prevalent despite the work of Sato and Mooney, that weathering of orebodies is responsible for sulphide self-potentials.

Of late, Boliden has often used the so-called mise-à-la-masse method and developed the technique further. The principle of this method is to earth 1 current electrode of a pair in a conducting mineral show (in a borehole, an outcrop, etc.) and study the resulting potential distribution on the surface as well as in boreholes. Three-dimensional measurements have shown that the method can establish correlation between different parts of an orebody, isolate different ore lenses, determine the dip and plunge of an orebody, follow broadly the variations in the shape of the cross section and the strike of an ore lens from one level to another and in some circumstances estimate the depth extent of the ore lens.

Thus, the geoelectrical work at Boliden Aktiebolag is diverse. We do not believe that a single method, be it IP or EM, is the answer to all prospecting problems.

Potential versus EM methods

This contribution discusses briefly the results of some resistivity, IP, SP and mise-à-la-masse surveys in the Swedish sulphide ore fields.

The sulphide ore fields of Sweden have been the birthplace of many geoelectrical prospecting techniques since the 1920s. From the very beginning, the success of the electromagnetic methods, in particular, has been striking in north Sweden. It depended greatly on a combination of several favourable circumstances such as the relatively high moraine resistivity, the very low ore resistivity, the generally uniform and fairly shallow (10 to 30 metres thick) moraine cover and the gentle topography. Con-

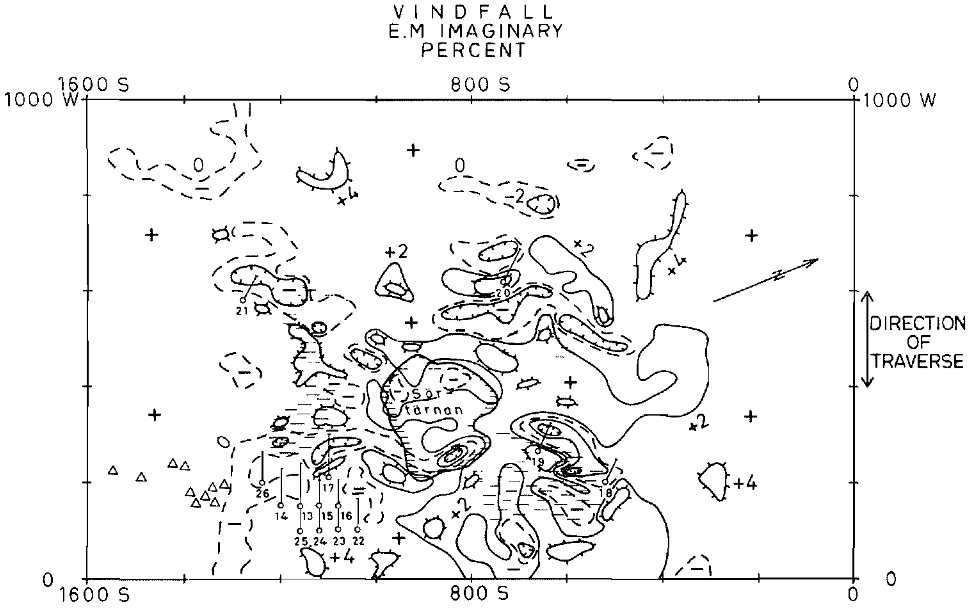

Figure 2. Electromagnetic imaginary component map of part of the Vindfall area. Moving source-receiver system, horizontal coils (vertical dipoles), 60-metre coil separation, frequency 3600 c/s. Contours in percent normal field.

sequently, ore prospecting in the Swedish sulphide fields has been dominated until now by electromagnetic methods, even though quite extensive campaigns with the potential methods were also undertaken in the early days, particularly with the equipotential method. However, since about 1955 increasing emphasis is being placed on the potential methods of prospecting such as the resistivity, induced polarization, self-potential and recently, the mise-à-la-masse methods.

Geophysicists are now well aware of the relative advantages and disadvantages of the EM and resistivity methods but it will not be out of place to recapitulate them briefly to highlight the gradual shift of emphasis in the Swedish ore fields.

The electromagnetic response of the ground within the 'range' of EM equipment is generally dominated by the good conductors. In the juxtaposition of a good and a relatively poor conductor, the poor conductor is subject to a screening field and may even remain undetected. On the other hand, once a conductor is detected the electromagnetic methods offer a fairly reliable possibility of discriminating the quality of the conductor as well as obtaining its depth and dip.

The potential methods on the other hand are highly sensitive to small changes in the resistivity of the ground and can map the details of resistivity variations in the subsurface very efficiently. However, because of the so-called saturation effect, they cannot distinguish between a good and a very good conductor or a poor and a very poor conductor. Also, the estimates of dip, depth and other geometrical parameters obtained from resistivity anomalies are often much more uncertain than those obtained from electromagnetic ones.

The main course of the ore-bearing formations in the Swedish sulphide districts was known from prospecting campaigns between about 1920 and 1955, and as the limitations of the electromagnetic methods became increasingly more apparent, it was natural to turn attention to the potential methods of geoelectricity. In 1955, the need for structural mapping in areas with virtually no bedrock outcrops also grew keener and this gave an added impetus to the use of the resistivity method in prospecting work.

Success of resistivity mapping in Boliden's campaigns

Practically all resistivity measurements in the prospecting campaigns of Boliden Aktiebolag have been carried out using the so-called gradient array, which we have often preferred to call the modified Schlumberger system. Typically, our current electrodes have consisted of long lines of bare copper wire pegged down to the ground every 5 or 10 metres by long nails. Two such equally long parallel electrodes, a few hundred to several hundred metres in length, are laid out approximately along the geological strike in the area and measurements of the gradient of the electric field are made along profiles at right angles to the current lines. The distance between the current electrodes is, say, 2000 or 3000 metres, that between the potential probes may be 20 or 40 metres.

Conditions for the valid use of linear current electrodes and the theoretical aspects of the system have been dealt with in detail elsewhere (Parasnis, 1965). If the validity conditions for linear electrodes are not satisfied, point current electrodes must be used. The quantity ultimately calculated in our work is an 'apparent resistivity' defined by

$$\rho_a = \frac{1}{IG'(x)} \frac{dV}{dx}$$

where I is the current, $G'(x)$ a geometrical factor, x the distance along the profile and V the electric potential. Being entangled for a long time in the Wenner configuration, North American workers often fail to appreciate the usefulness and the advantage of the apparent resistivity defined as above, namely a normalized gradient between fixed current electrodes.

The main reason why we use linear, instead of point, current electrodes is that (provided the electrodes are not unduly long) the field operations are faster, cheaper and more convenient. Elsewhere in Scandinavia, in Finland, the dipole-dipole configuration has been used but it has been found to be far more expensive. Also, the dipole-dipole configuration requires a maximum-source output voltage of several hundred volts, which is undesirable from the safety point of view. The fixed current

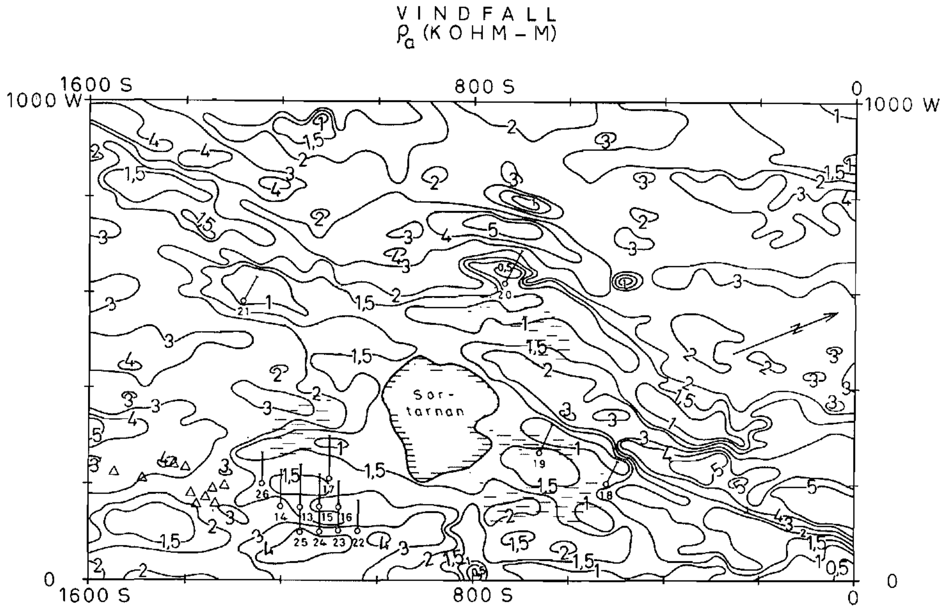

Figure 3. Apparent resistivity (normalized gradient between fixed current electrodes 3000 metres apart) in the Vindfall area, central Sweden. Contours are labelled in kohm-metres.

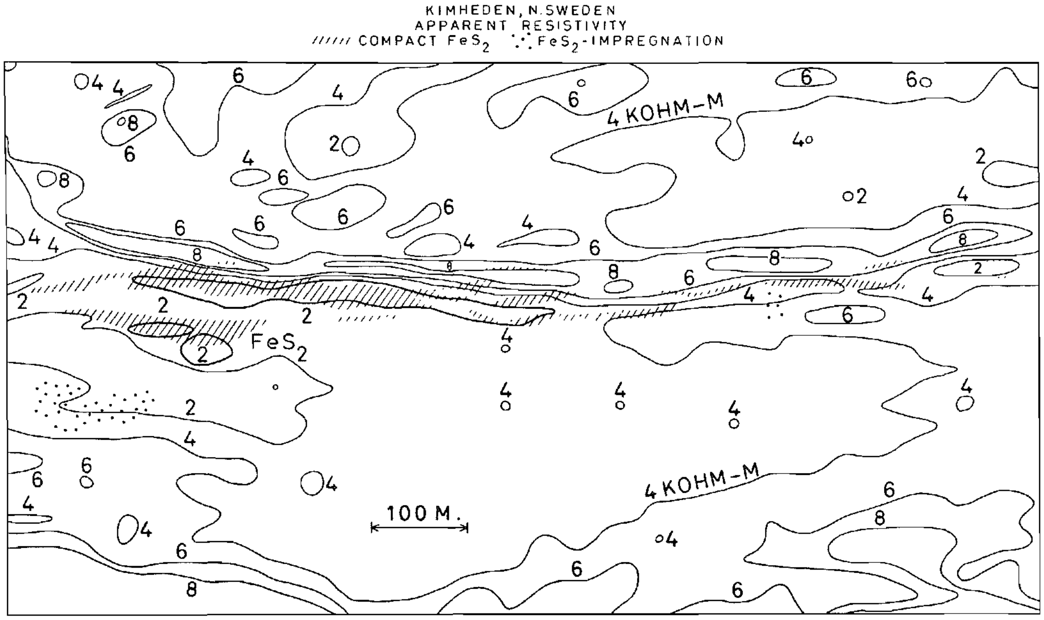

Figure 4. Mapping the suboutcrop of the Kimheden orebody, northern Sweden by apparent resistivity (normalized gradient between fixed current electrodes 1000 metres apart).

electrodes-gradient system can easily manage with about 200 volts under Scandinavian conditions.

A striking example of the advantage of resistivity methods in mapping structural details is afforded by the geophysical measurements in the Vindfall area in central Sweden. We shall start with Figure 1 which is the magnetic map of a part of that area. Magnetically the area is of a fairly low relief (generally within ±100 gammas) except for an anomaly complex in the south. The complicated pattern here with relatively strong magnetic anomalies is due to greenstone rocks. A small lead-zinc-copper deposit occurs in these rocks. The drill holes marked on the map will give an indication of the position of the deposit.

The magnetic map shows two distinct strike directions, one approximately NE-SW, the other approximately NNE-SSW.

Figure 2 shows the electromagnetic imaginary component map of the same area obtained with a moving source-receiver system. Practically everywhere, the anomalies are less than ±2 percent but what is more, they do not show any kind of pattern. The real component map is even more featureless. Detailed interpretation shows that the EM anomalies can be ascribed almost entirely to the variations in the thickness and the resistivity of the swampy moraine overburden. The overburden of the area, about 5 to 10 metres average thickness, has a rather low resistivity of about 65 to 100 ohm-metres and hence it is completely screening the bedrock from the primary electromagnetic field. Vertical loop EM method (coil separation 60 metres) was tried but met with no better success.

Figure 3 shows the apparent resistivity map of the area obtained by using fixed linear current electrodes 3000 metres (about 10,000 feet) apart. It is at once evident that the resistivity anomalies fall into a significant pattern which coincides in all its essential details with the pattern shown by the magnetic

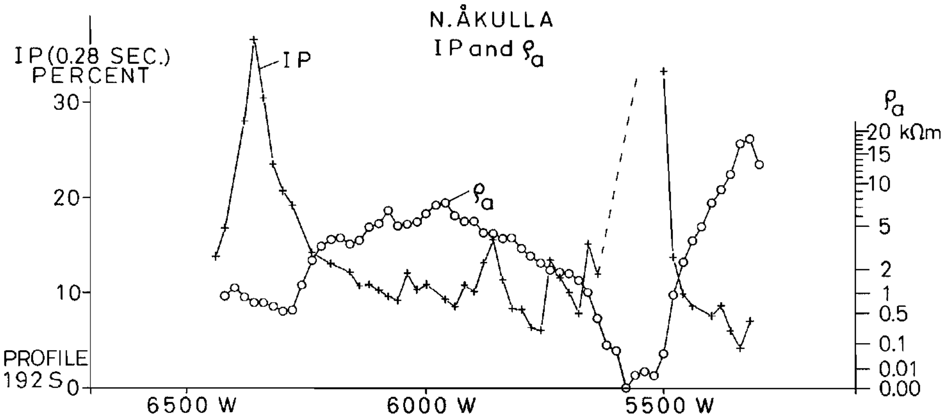

Figure 5. Apparent resistivity and time-domain IP along profile 192S in the Åkulla area, northern Sweden. Ordinates on the resistivity scale (right-hand side) are proportional to the cube root of ρ_a. Length of current pulse 13 sec. Time delay after current cut-off 0.23 sec. Integration time 0.1 sec (0.23 – 0.33 sec). IP expressed as secondary voltage, centred at 0.28 sec, in percent of primary voltage.

anomalies. For example, we again find the two predominant strike directions, one NE-SW and the other NNE-SSW. There is no doubt that the resistivity map is, to a very large extent, reflecting structures within the bedrock. The technique used has thus succeeded in penetrating below the highly conductive overburden, where the electromagnetic method failed. Subsequent drillings have shown that the bedrock surface in the area is quite flat, so that the resistivity variations cannot have been due to the topographic undulations in the bedrock.

At the time when the resistivity survey was finished the ore deposit had not been located although its possible existence had been suspected because of boulder floats of galena and sphalerite found in the moraine (marked by triangles in Figure 3). We did not expect the orebody (presumed to be a poor conductor) to show up on the resistivity map, and indeed it is not possible to isolate unambiguously any resistivity anomaly due to the orebody. Nevertheless, the very first drill hole within the area of Figure 3 (No. 13), sunk on the basis of a weak resistivity indication (a low of 1 kohm-metre) around 1160S/200W and the course of the boulder train, struck ore.

The resistivity contrast between the ore, the bedrock and the moraine is not favourable for the orebody to be delineated by resistivity contours. However, in appropriate circumstances it may be possible to accurately map the suboutcrop of an ore sheet even as thin as 10 to 20 metres by resistivity, as Figure 4 shows. Here, the contour of the almost-vertical, thin, cupriferous pyrite ore sheet fits in very well with the apparent resistivity contour of 2 kohm-metres. The contact of the ore with the bedrock on the northern side comes out as a sharp gradient in the resistivity contours. On the southern side the contact is not sharp and the apparent resistivity values rise only gradually to 4 kohm-metres. This difference is now known to be due to the bedrock north of the ore which is a hard, fresh quartzite while that south of the ore is considerably weathered in parts and sericitized.

Another instance of the accurate mapping of an ore suboutcrop in Sweden will be found in Parasnis (1966, p. 180-181).

Examples of successful structural mapping by resistivity are ample in the geophysical work at Boliden Aktiebolag. We find that, provided the current electrode configuration is properly selected, the resistivity method is second only to the magnetic method in the wealth of structural detail obtained. Therefore it is rather surprising to find that a recent theoretical text on applied geophysics (Grant and West, 1965) states that the resistivity method "is quite insensitive to local deformities".

Failure of IP to yield extra information

Induced polarization measurements with the pulse as well as the frequency system have been undertaken in the Swedish sulphide ore fields by Boliden Aktiebolag and, on a smaller scale, by the Swedish Geological Survey (only pulse system). In Finland the Outokumpu OY have extensively used the dipole-dipole frequency method. In their areas the geological, mineralogical, structural and other conditions are very similar to those in the northern Swedish sulphide ore fields. A comparison between the Finnish dipole-dipole work and our gradient work shows that the dipole-dipole technique is between four and five times as expensive as the gradient one (under Scandinavian geological and wage conditions).

While there is no doubt about the reality and the complexity of the IP phenomenon, I must confess that our experience of IP anomalies has been largely disappointing to date. We find, in the areas so far tested by us in Sweden, that every IP indication has its counterpart in a resistivity indication and vice versa. A low apparent resistivity value is accompanied by a high IP value, a high resistivity value is accompanied by a low IP value. In the work at Boliden this general 'mirror image effect' has been found to be true even when the resistivity low is due, not to electronic conductors, but to crushed and weathered bedrock zones containing no appreciable clay minerals. Thus it has not been possible to eliminate potentially 'barren anomalies' in planning exploratory drilling.

Mining geophysical literature and brochures are full of successful exploration case histories while there is surprising silence about failures in exploration. It always provokes thought to take a look at failures as well, so that one does not become too complacent about a technique. I am, therefore, going to present instances in our work where the IP method has failed in one sense or another.

Figure 5 is a typical example of a time-domain IP profile in the Scandinavian shield areas. Above the mineralized zone around 5500W the apparent resistivity values are very low (about 3 ohm-metres) and the IP values are high. Outside the zone the resistivity values are high and IP ones low. In the present case the mineralization consists of pyrite impregnation in Precambrian volcanic rocks. Figure 6 shows another IP and resistivity profile, where the mineralization consists of very finely disseminated galena in Eocambrian sandstone. In this profile too, the general correlation between IP and resistivity indications cannot be mistaken.

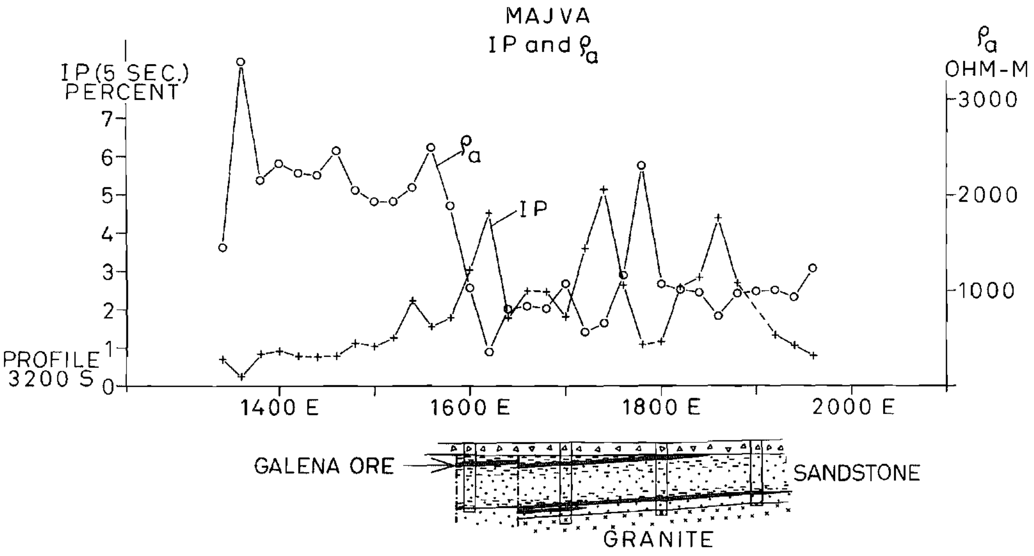

Figure 6. Apparent resistivity and time-domain IP along profile 3200S in the Majva area, northern Sweden. Length of current pulse 120 sec. IP expressed as instantaneous voltage, 5 sec after current cut-off, in percent of primary voltage.

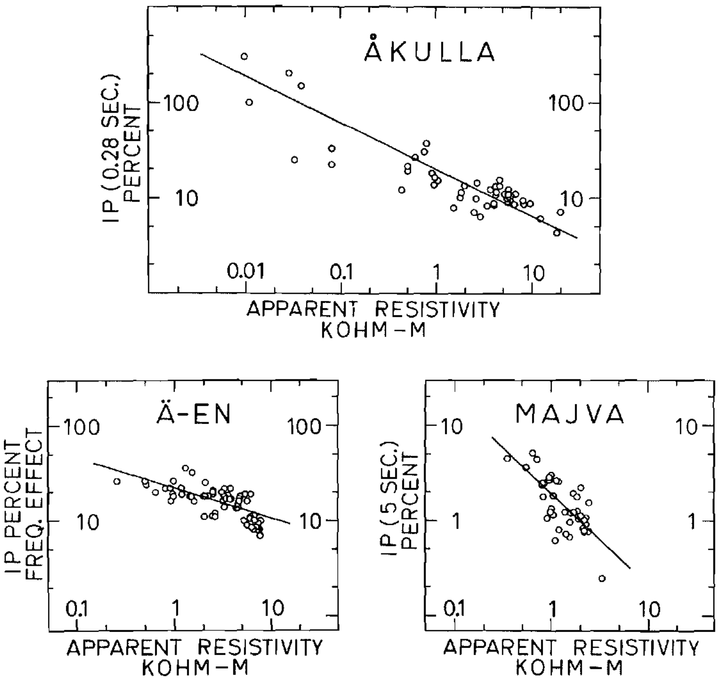

Figure 7. Functional relationship between IP and apparent resistivity. The least-squares lines shown on the log-log scale yield the following equations: Åkulla, IP = $19.85\rho_a^{-0.4990}$; Ä-en, IP = $21.46\rho_a^{-0.3138}$; Majva, IP = $1.954\rho_a^{-0.9662}$. All the relations are significant according to standard statistical tests. The Ä-en observations were made with the frequencies 0.3 and 10 cps. For details of times see captions to Figures 5 and 6.

Examples such as those in Figures 5 and 6 are the rule, to date without exception as far as I have analyzed, in the Swedish sulphide fields. Further, a definite functional relationship seems to exist between an IP value and the apparent resistivity at the measured point (see Figure 7), which, incidentally, is equally true of the so-called metal factor. One must conclude that, at least in the Swedish sulphide fields and similar areas, IP fails to give extra information above that already inherent in the much simpler and cheaper resistivity measurement.

One of the favourite objects for IP is ore of the impregnation type, particularly porphyry copper. Figure 8 shows the results of resistivity and IP frequency domain measurements on a recently discovered ore deposit in the Skellefte district of Sweden. This impregnation deposit, containing 2 to 15 percent finely divided sulphides in gabbro, is in some ways reminiscent of a porphyry copper deposit, although it is not one of that type.

The resistivity indication (a low of about 1 kohm-metre and less, in a background of 5 to 10 kohm-metres) is continuous all the way in Figure 8 with a break between bh16 and bh18 whereas the IP indication presents a patchy and irregular picture. The many drillings on this deposit show that the sulphide impregnation is uniform and regular over the entire stretch and that the resistivity indication delineates it more faithfully than the IP. The patchiness of the IP picture is almost certainly the effect of near-surface inhomogeneities and it is difficult to see what extra information IP is yielding in this case. In fact it seems that the information to be obtained in the present example from IP is a much deteriorated version of that given by the apparent resistivity.

Finally, Figure 9 is an example of the apparent success of IP. This shows a resistivity and IP time-domain profile across another disseminated ore, a lead-zinc-copper ore in central Sweden. The host rock consists of granulite, amphibolite, pegmatite, greenstones and granite. The ore contains about 2 to 5 percent galena.

It would be tempting to argue that the maximum between 550W and 600W is indicating the ore and proves the success of IP. However, the IP map of the area is cluttered with maxima and minima of the relief on this profile (geologic IP noise) and it is doubtful whether this particular indication could have been singled out for drilling on the basis of IP alone. (The IP was measured in November 1966. The ore was known by drillings in June 1964.) The resistivity shows a shallow minimum between 520W and 680W but resistivity minima of this order are common in the area (see Figure 3). Note also the strong IP indication between 420W and 460W. There is considerable evidence that this maximum and the corresponding resistivity minimum are due to brecciated bedrock, notably granite. Typical clay minerals have not been detected in the relevant drillings.

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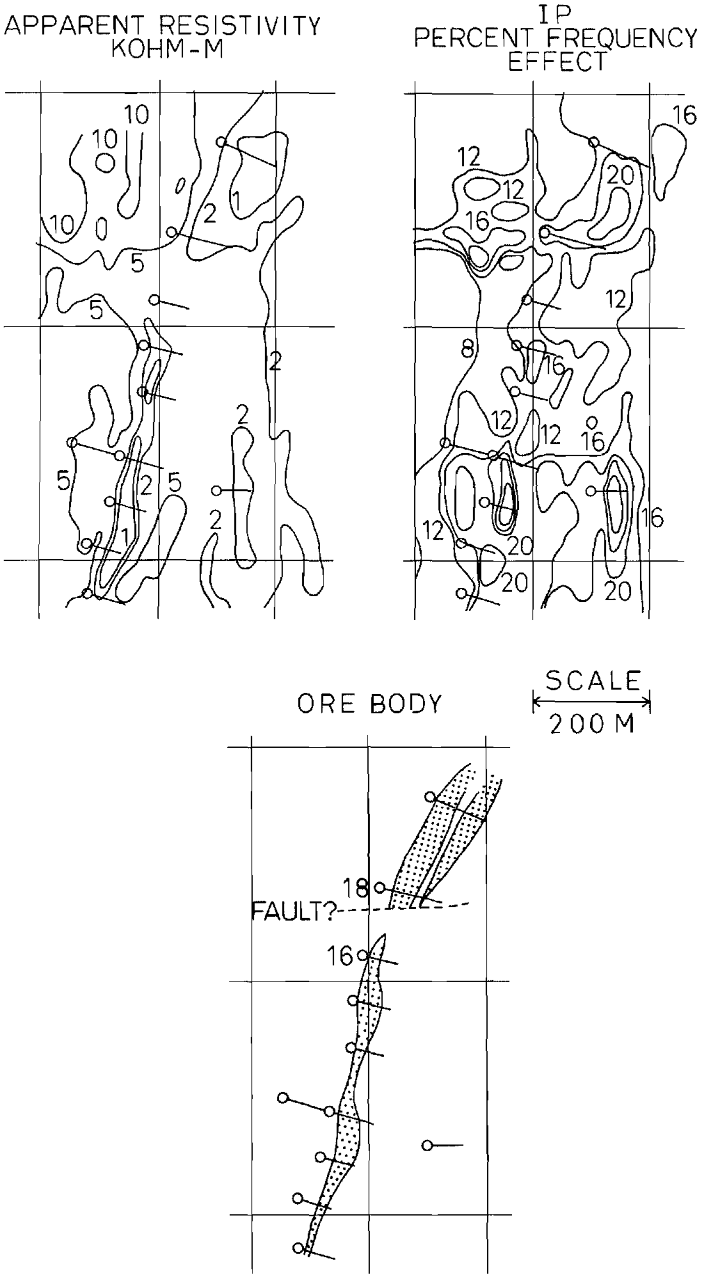


Figure 8. Resistivity and frequency-domain (0.3, 10 c/s) IP maps of the Ä-en ore (sulphide impregnation in gabbro) in northern Sweden, showing that the resistivity delineates the ore more faithfully.

In fairness I must mention that there is no statistically significant correlation between IP and ρ_a on the profile in Figure 9.

The conclusion drawn from IP and resistivity measurements in the Swedish sulphide fields is that IP is not always a satisfactory method to solve exploration problems, even those concerning disseminated ores, and certainly not by itself. Also, the apparent resistivity maps the geologic and structural details better than IP.

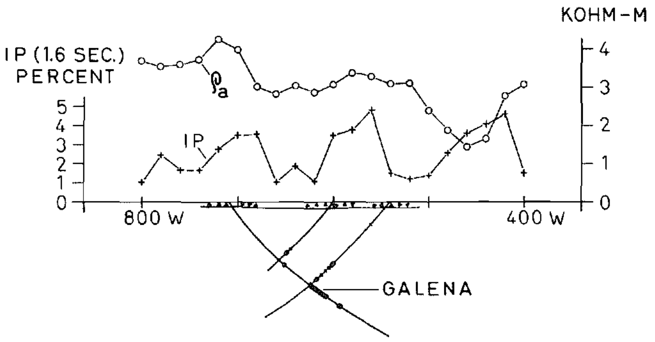


Figure 9. Resistivity and IP along profile 2680S across the Vindfall disseminated galena ore in central Sweden. Note the high geologic IP noise. Length of current pulse 10 sec. Secondary voltage measured 1.6 sec after current cut-off. Integration time 60 milliseconds. IP expressed as secondary voltage in percent of primary voltage.

Revival of the self-potential method at Boliden

One of the easiest and cheapest geophysical methods is the self-potential method. However, it is almost totally neglected nowadays in exploration. Therefore it seems desirable to touch briefly on some of the work Dr. D. Malmqvist and I have carried out at Boliden with this method.

The principal mechanism of the self-potentials such as those observed above certain sulphide ores is now well understood from the work of Sato and Mooney (1960), who account for these potentials in terms of electric currents in the host rock rather than in terms of the oxidation of an orebody. However, these currents are the result of differences in the oxidation potentials (*Eh*) of the upper and the deeper levels of the subsurface. They concentrate preferentially into a good electronic conductor such as a sulphide body and produce the familiar SP centres. A corollary of the theory of Sato and Mooney is that self-potentials should be observable under a somewhat different variety of climatic and geological circumstances than those admitted by the older theories.

The typical ore self-potentials, which are about one hundred to a few hundred millivolts, are extremely stable in time. To test the temporal stability of small self-potentials, of around 10 to 50 mV, which, as a rule, cannot be ascribed to electronic conductors, we have followed the self-potentials in a test area in northern Sweden continuously for the last 8 years. The observations have generally been taken twice a year, once in the spring or early summer and once in the autumn.

Figure 10 shows the SP along one of the test profiles. These measurements were made using nonpolarizable calomel-KCl electrodes. We see that not only are anomaly features with a fairly large SP relief, 50 mV and more, found to be stable but in many cases small wiggles having amplitudes of about only 10 or 20 mV can also be followed in the same position from year to year. It is remarkable that several cycles of snow, frozen ground, thaw, rain and dry periods have not managed to disturb the pattern of these small potentials. The drainage in the area is good and hence the observed self-potentials cannot be electrolytic

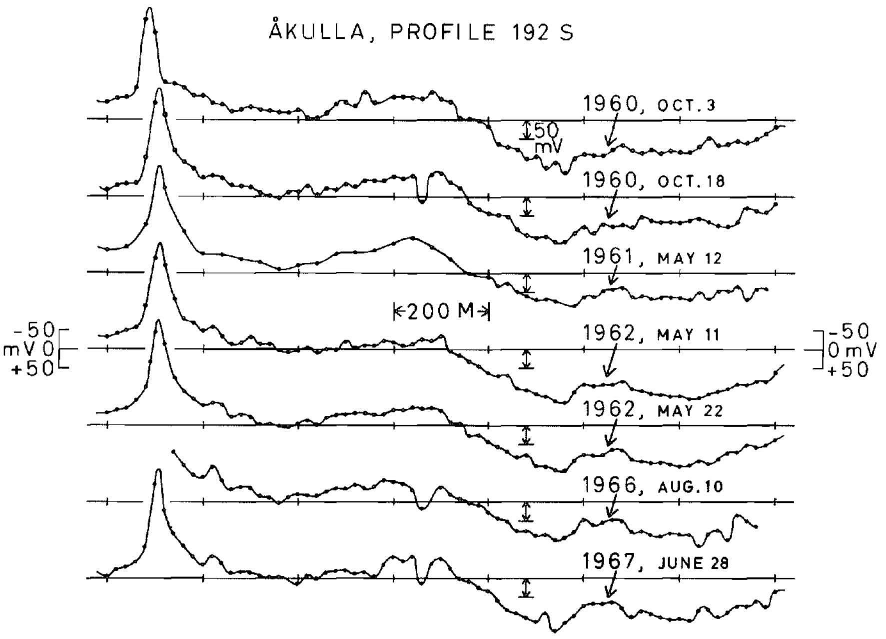


Figure 10. Stability of SP in the Åkulla, region, northern Sweden.

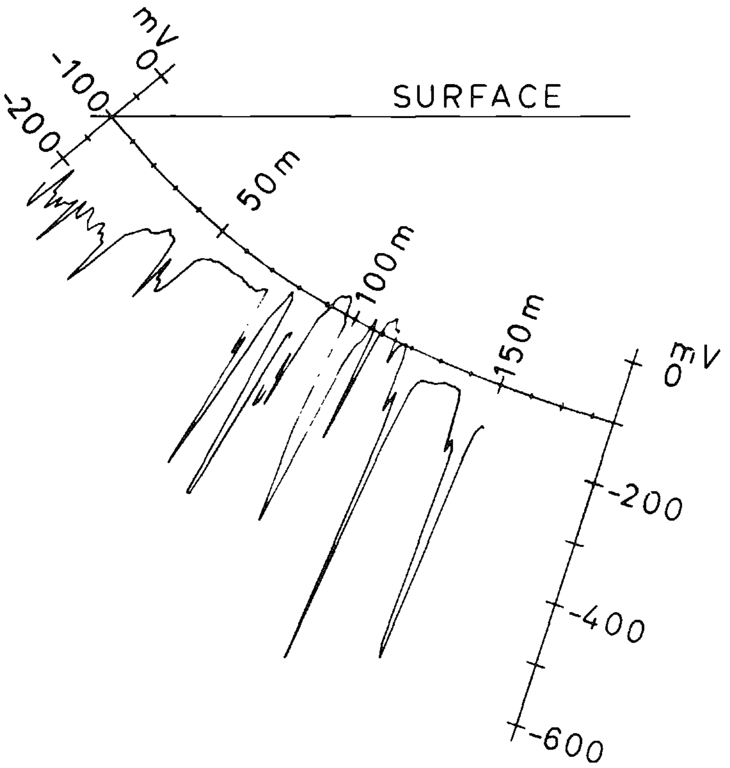


Figure 11. SP measurements in borehole 65 intersecting the Kimheden orebody in Figure 4.

concentration potentials in the soil and moraine. It is far more likely that they represent stable telluric conditions and as such their pattern is associated with structures in the bedrock.

Our work in other areas has shown that it is possible to map fissures, cracks and shear zones in the bedrock by means of SP. Findings such as these are evidently of significance to hydrological geophysics.

One aspect of SP research that has hitherto been given little attention is the streaming potential or the chemical zeta potential. When water is forced through a capillary a potential difference is developed between the ends of the capillary, the high pressure end becoming more negative. Laboratory experiments indicate that certain soils and clays can develop potential differences of around 25 mV per metre head of water (Schuch, 1963). In areas with undulating topography such effects must be appreciable. If a correction for them can be estimated and applied to observed self-potentials, some progress could, I believe, be made in the interpretation of SP anomalies.

We have also undertaken extensive SP measurements in boreholes to investigate the natural electric conditions around sulphide orebodies. An example is shown in Figure 11. From about 5 to about 80 metres drilling depth in this hole (except between 40 and 50 metres) the SP values are observed in magnetite impregnation while the values between 40 and 50 and those below 70 metres depth are in cupriferous pyrite. Between 65 and 70 there is a shear zone. Deep down in this hole there exist self-potentials of about several hundred millivolt. Thus at 122 metres drilling depth we have a potential of −628 mV and at 145 metres, one of −570 mV. It is difficult to believe that oxidation of ore is going on at these depths, especially as the water-table is only a few metres below the ground surface and the ore is completely submerged under water. These observations should suffice to dispel the notion, still widely prevalent despite the work of Sato and Mooney, that oxidation of ores is the main agent responsible for sulphide self-potentials.

In our SP work we like to apply what I shall call the 'telluric correction'. If the mean strength of telluric currents in an area

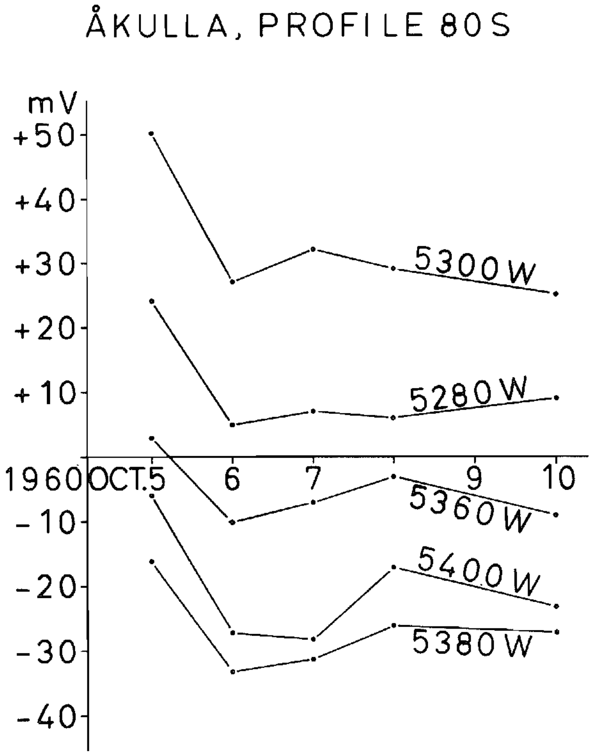


Figure 12. Daily check of SP at some points in the Åkulla region, northern Sweden.

varies from day to day the natural potential between two points on the ground will vary proportionately. Being a regional scale effect, such variation will be roughly the same at all points in the area. That such an effect exists is shown in Figure 12, where the potentials measured every morning at five control points with respect to a fixed base point are plotted. It will be seen that the variations are roughly parallel at all the points. I may add that the effect cannot be ascribed to electrode potentials, since the stability of the mutual potential difference of the calomel electrodes employed was checked every morning after placing them in a standard 1 *N* aqueous solution of chemically pure KCl.

Thus in accurate SP work apparently all measured potentials must be referred not only to a particular base point but also to a particular epoch. We submit that this aspect has not been adequately recognized by geophysicists. We hope that our researches sketched here will lead us to a better understanding of the various components of the natural potentials in the ground and extricate the SP method from the disfavour into which it has currently fallen among geophysicists.

Mise-à-la-masse surveys: a new development

Lately, we have often used the so-called mise-à-la-masse method and developed the technique further. The principle of this method is to earth 1 current electrode of a pair in a conducting mineral show (in a borehole, an outcrop, etc.) while the other electrode is at infinity, and study the resulting potential distribution on the surface as well as in boreholes. If the conducting mineral show forms part of a large mass the potential picture will be expected to be different from the one if the mineral show is a very small isolated occurrence. This is schematically shown in Figure 13, where the left-hand part shows the equipotentials around a point current electrode in a semi-infinite, homogeneous, isotropic earth, and the right-hand part of the distorted equipotentials in the presence of a conducting ore lens.

Considerable information about the geometry of an ore mass can be obtained from mise-à-la-masse potentials, and by making these measurements at an early stage it is possible to guide the exploratory drilling program in a more rational, efficient and economic manner than would otherwise be the case. Obviously, the mise-à-la-masse method is not a reconnaissance method but rather a method for detailed study.

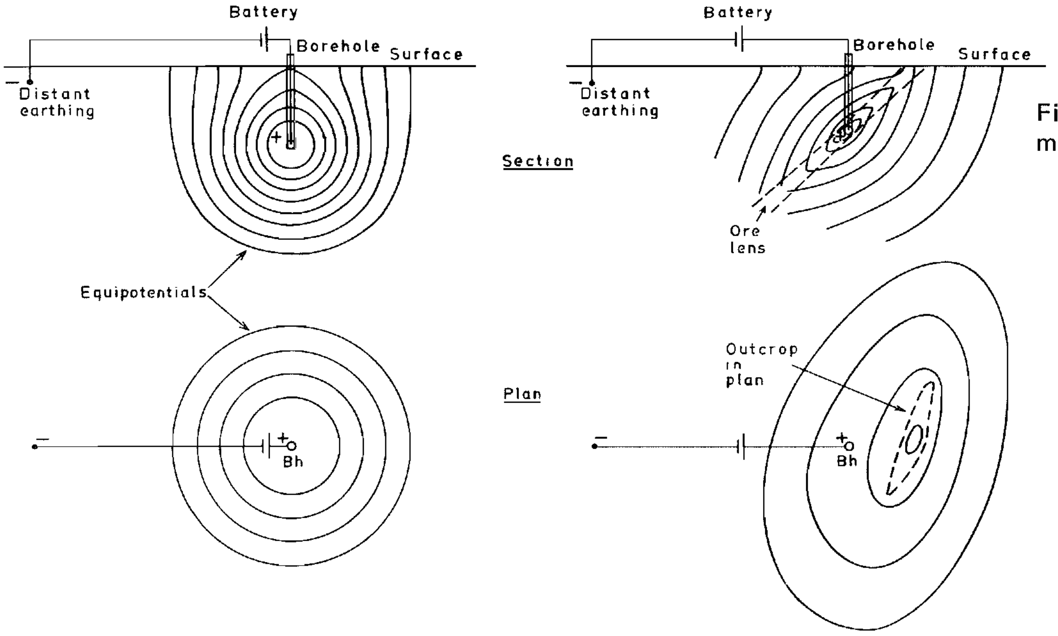


Figure 13. Principle of the mise-à-la-masse method.

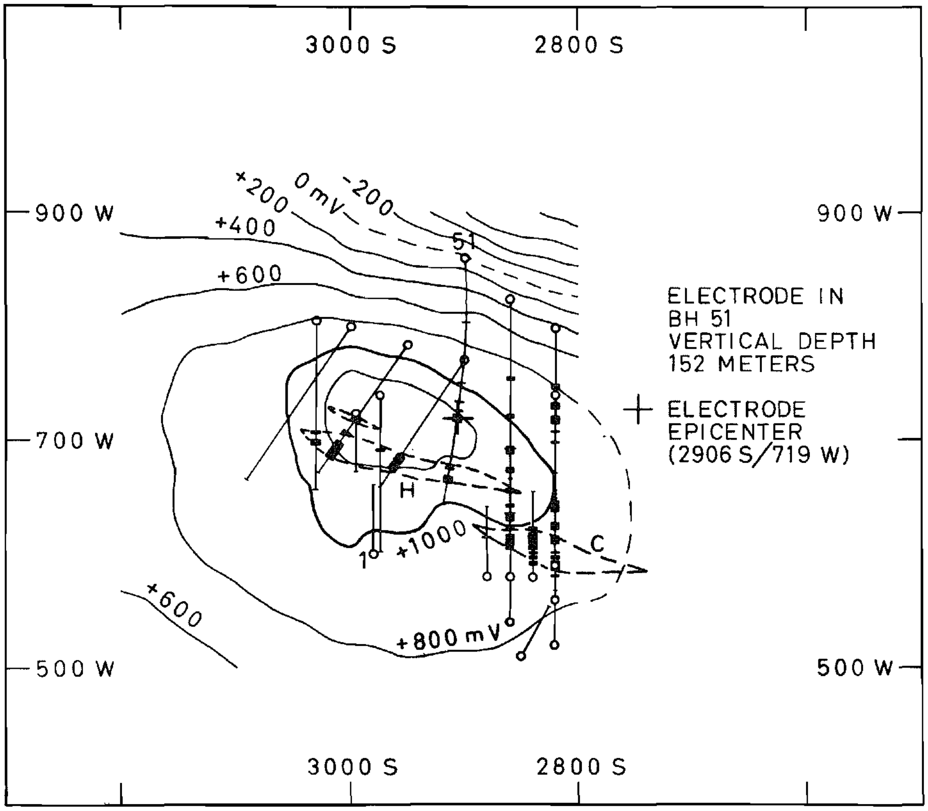
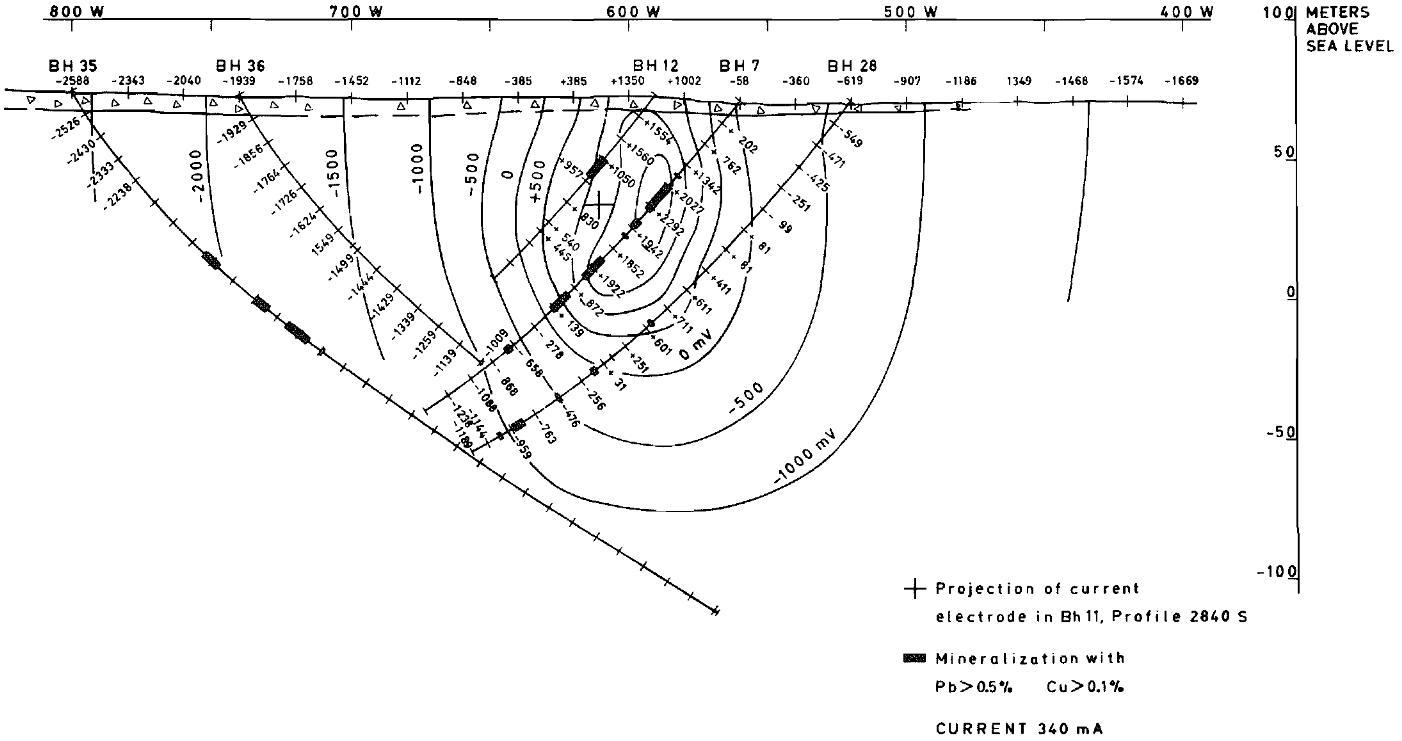


Figure 14. Mise-à-la-masse potentials of lens *H* in the Vindfall area in central Sweden.

Figure 15. Mise-à-la-masse potentials in the vertical plane through profile 2820S in the area of Figure 14. (Current electrode in lens *C*.)



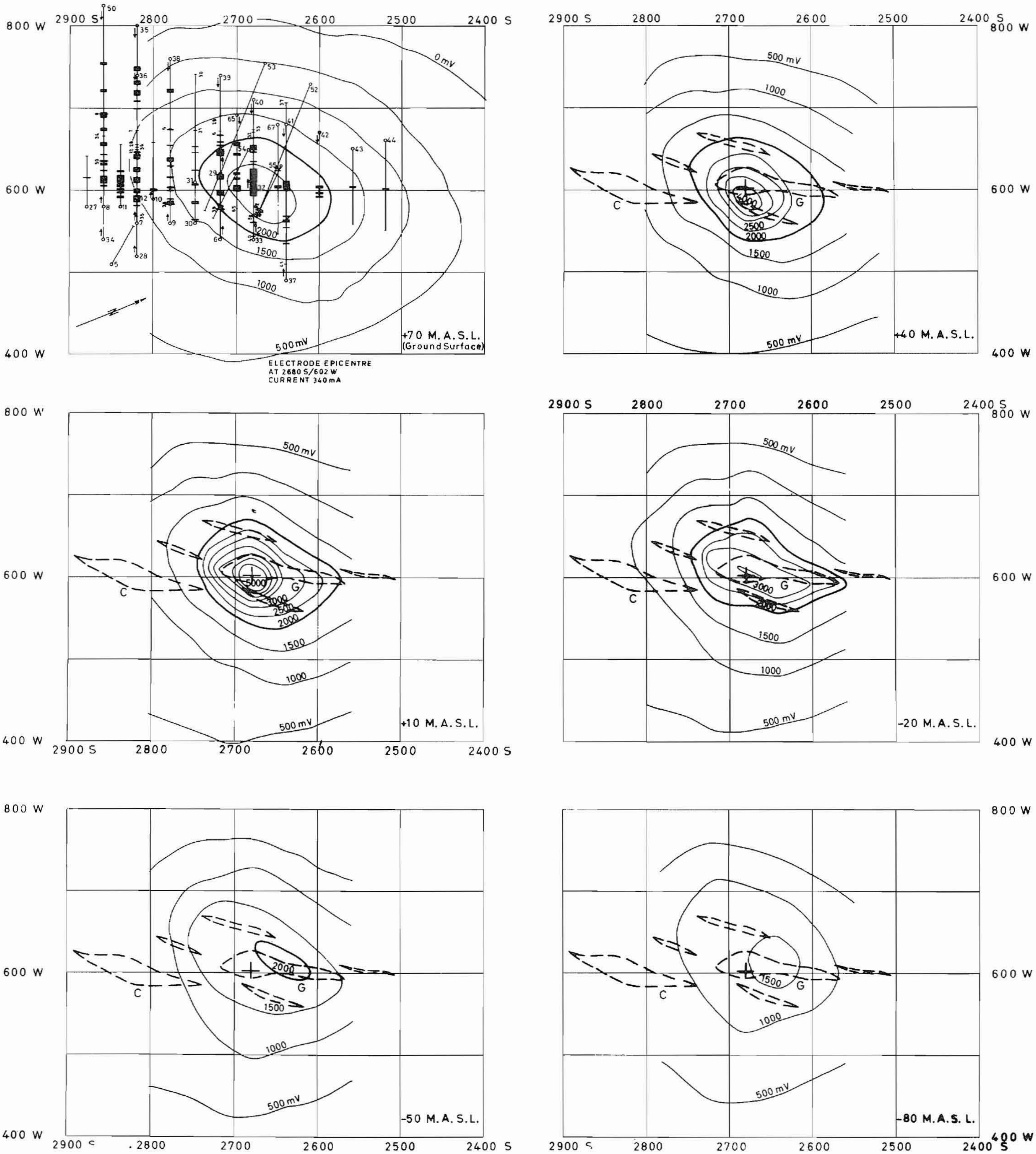


Figure 16. Mise-à-la-masse equipotentials on different levels. Current electrode is situated at a vertical depth 90 metres below ground surface (20 metres bsl) beneath the grid coordinate 2680S/602W.

Figure 14 shows the map of surface potentials obtained by earthing a current electrode in a conducting galena ore show at 208 metres drilling depth in a borehole (152 metres vertical depth below ground surface). The current used was 340 mA. The ore lens marked by the dotted contour *C* had been previously delineated by drillings and by mise-à-la-masse measurements, and the question was whether another ore lens could be expected south of *C*. Hole 51, drilled to investigate this question, showed stringers of galena and sphalerite ore. A mise-à-la-masse survey was then undertaken. This survey clearly shows that an ore lens exists south of bh 51 and also gives an indication of its strike.

It must be added that all the drill holes south of bh 51 (except one, No. 1) were drilled *after* the mise-à-la-masse survey. They delineated the ore lens marked by the dashed contour *H*. Borehole 1 had not encountered any ore. It should also be noted that bh 1 is drilled from the east while the other holes intersecting lens *H* are drilled from the west. The decision of drilling from the west was taken because mise-à-la-masse measurements in the holes intersecting lens *C* as well as those intersecting lens *G*, 140 metres north of *C*, had shown a distinct dip towards the west and not towards the east as initially presumed (Figure 15).

When a sufficient number of drill holes become available, a three-dimensional picture of the mise-à-la-masse potentials, or rather several pictures with earthings in different places, can be obtained. Such measurements have been found to serve very well to establish correlation between different parts of an ore deposit, isolate different ore lenses, determine the dip and plunge of an orebody, follow broadly the variations in the shape of the cross section and those in the strike of an ore lens from one level to another and in certain circumstances estimate the depth extent of the ore lens (Parasnis, 1967). All such information is extremely valuable for subsequent development and exploitation decisions. Two of the points above are effectively illustrated in Figure 16, which shows the equipotentials on six different levels, constructed from surface and drill hole mise-à-la-masse measurements.

Evidently the shape of the contours varies considerably in the present case from level to level. On the levels 40 metres above sea level and 10 metres asl the 'inner' contours are almost circular in shape suggesting that, on the upper levels, the lens in question (*G*) has approximately the same linear dimensions in all the horizontal directions. Lower down, the lens becomes elongated and its strike also varies somewhat. The principal dashed contour between the profiles 2600S and 2700S is the inferred cross section of lens *G* (referred to earlier) on the level 20 metres below sea level (90 metres below ground surface).

Fixing our attention on a particular contour, say +2000 mV, we find that the area enclosed by it decreases very considerably from 20 to 50 metres bsl, which could be because the lens peters out between these two levels or, possibly, somewhat below 50 metres bsl (120 metres below ground surface). Four boreholes drilled *after* the mise-à-la-masse survey to ascertain the depth extent of the lens *G* have not encountered any ore corresponding to *G* and deeper than 120 metres below ground surface.

The utility of mise-à-la-masse surveys in our work has been proved beyond doubt and we now intend to carry out such measurements more regularly in our prospecting. Towards this end we have constructed a mise-à-la-masse outfit that enables a potential measurement to be made at an observation point with earthings 'simultaneously' in four different places (in boreholes or outcrops). The operator presses one of four buttons on the panel of a small pocket-sized box carried by him. This triggers by remote control the first current electrode, and a predetermined constant current is passed through the ground for 10 seconds by a current generator which may be placed several hundred metres (or even a couple of kilometres) away. During this time the potential at the observation point with respect to a base point is read. After 10 seconds the current is automatically cut off and then restarted at the operator's will, this time by pressing some other button so that the current generator shifts its output terminal to the relevant electrode, and so on.

Concluding remarks

From the foregoing it will be evident that the geoelectrical work at Boliden Aktiebolag is variegated. The characteristics of every exploration problem, every indication and every ore must be considered individually and the appropriate technique, modification of electrode configurations, coil separations, etc., for investigating the indication or the ore must be selected in an intelligent manner.

We do not believe that a single method, be it IP or EM, is the cure for every prospecting malady. A judicious combination of several prospecting methods (including geology and geochemistry) is ultimately the most effective method of directing an exploration campaign.

Thanks are due to Boliden Aktiebolag, Sweden for making possible the presentation of this contribution at the Canadian Centennial Conference.

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Contents

The use of induced polarization measurements to locate massive sulphide mineralization in environments in which EM methods fail

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Abstract. For many years the Electromagnetic Method has been used throughout the world in the search for massive sulphide mineralization. It has been particularly useful in environments in which the mineralization is at a shallow depth; many orebodies have been found using EM techniques.

However, experience in recent years has shown that some zones of "massive" sulphide mineralization are not EM conductors. In some cases this is due to the type and/or concentration of mineralization in the zone, or because of the depth to the top of the source. In other situations the geologic environment is such that the EM anomalies from sulphide mineralization cannot be distinguished from those due to ionic conductors.

The induced polarization method has been found to be more useful than EM techniques in these situations. Results are available from areas where the source is at considerable depth, as well as areas of ultrabasic rocks and semiarid and tropic weathering in which numerous ionic conductors are present.

Résumé. On a utilisé pendant de nombreuses années à travers le monde la méthode électro-magnétique pour découvrir les minéralisations sulfides massives. La méthode a été surtout utile là où les minéralisations se trouvaient à faible profondeur. De nombreux amas ont ainsi été trouvés.

Cependant l'expérience des dernières années a démontré que certaines zones de minéralisation massive de sulfides ne sont pas des conducteurs électro-magnétiques. Dans certains cas c'est dû soit au genre et/ou à la concentration de la minéralisation dans la zone, soit à la profondeur à laquelle elle se trouve. Dans d'autres cas le milieu géologique ne permet pas de distinguer entre les anomalies électro-magnétiques causées par la minéralisation sulfurée et celles qui sont dues aux conducteurs ioniques.

Dans ces cas la méthode de polarisation induite s'est montrée plus utile que les procédés électro-magnétiques. On peut obtenir des résultats dans des régions où la source se trouve à une grande profondeur aussi bien que dans des régions à roches ultrabasiques, semi-arides et soumises aux intempérismes tropicaux où existent de nombreux conducteurs ioniques.

The induced polarization method was initially developed for, and widely used in, the search for disseminated sulphide mineralization. The method has been found to be of great use in this type of exploration. Recently, it has been used in all of the mining areas of the world in which disseminated mineralization is of economic interest. Many zones of mineralization, some of which were 'ore', have been located.

As geophysicists gained more experience with the IP method, their understanding of the method and its applicability increased. It became clear that the method could be used to locate and outline zones of massive (concentrated) sulphide mineralization. A great deal of controversy still exists concerning this point. In massive sulphide zones the conductivity is very high; under these conditions it is difficult to maintain polarization (store energy).

However, even the most massive sulphide mineralization is not a single crystal. There are many crystal faces; polarization takes place at an infinity of surfaces. Almost all sources contain disseminated, as well as massive, portions. It has been our experience that all zones of massive mineralization give rise to recognizable IP anomalies.

In many situations in which the massive mineralization is very conductive, and at a shallow depth, the various electromagnetic techniques have been successfully applied. The line-mile cost of EM is usually less than that of IP; therefore it is frequently preferable. However, recently we have found that in certain cases the IP method can be used to outline zones of massive mineralization that cannot be detected using EM techniques.

The induced polarization measurement

The electrochemical phenomena giving rise to the induced polarization effects used in exploration have been previously described (Hallof, 1957; Marshall and Madden, 1959). There are two well known and widely applied measurement techniques used in exploration (Seigel, 1962; Wait, 1959; Hallof, 1960, 1964). The chargeability parameter M_a used in the pulse-transient type survey has been shown to be mathematically equivalent to the frequency effect parameter Fe_a usually recorded in the variable frequency type survey (Hallof, 1964; Seigel, 1959).

Our field experience has confirmed that the chargeability and the frequency effect are exactly equivalent. Any differences that exist between the two measurement techniques concern the necessary instrumentation and the electrode configurations that are possible. In either measurement technique, one or more derived parameters may be used.

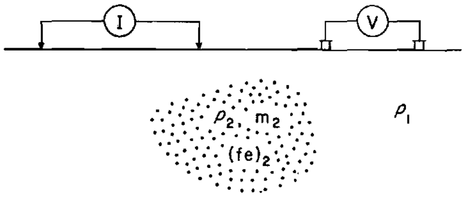
One such parameter is the metal factor, or metallic conduction factor MF; the definition of this parameter is shown in Figure 1. It is very useful in the interpretation of induced polarization results (Hallof, 1964, 1967). It is this parameter, the apparent metal factor MF_a, and the apparent resistivity $\rho/2\pi_a$ that we use in our exploration work.

Plotting the results

Numerous techniques can be used to plot induced polarization and resistivity results. Many geophysicists plot profiles along the measurement line; others construct two-dimensional, contoured plan maps using data measured along survey lines.

In our field work, we usually use the dipole-dipole electrode configuration shown in Figure 2. We find that this configuration has definite advantages because of its great flexibility; the relatively short wire lengths required in the field also speed the work.

The results are plotted in the two-dimensional, 'pseudo-section' manner shown in Figure 2. In this field procedure, measurements on the surface are made in a way that allows the



$$ma \simeq m_2 \rho_2 \times \frac{1}{\rho_a} \frac{\partial \rho_a}{\partial \rho_2} \qquad (fe)_a = (fe)_2 \rho_2 \times \frac{1}{\rho_a} \frac{\partial \rho_a}{\partial \rho_2}$$

$$mf \equiv \frac{(fe) \times 100}{\rho_{dc}/2\pi} \times 1000 = \frac{\left[\rho_{dc}/\rho_{ac} - 1\right] \times 100}{\rho_{dc}/2\pi} \times 1000$$

$$= \left[\frac{1}{\rho_{ac}} - \frac{1}{\rho_{dc}}\right] \times 2\pi \times 10^5 = \left[\sigma_{ac} - \sigma_{dc}\right] \times 2\pi \times 10^5$$

Figure 1. Definition of metal factor *MF* parameter used in induced polarization measurement.

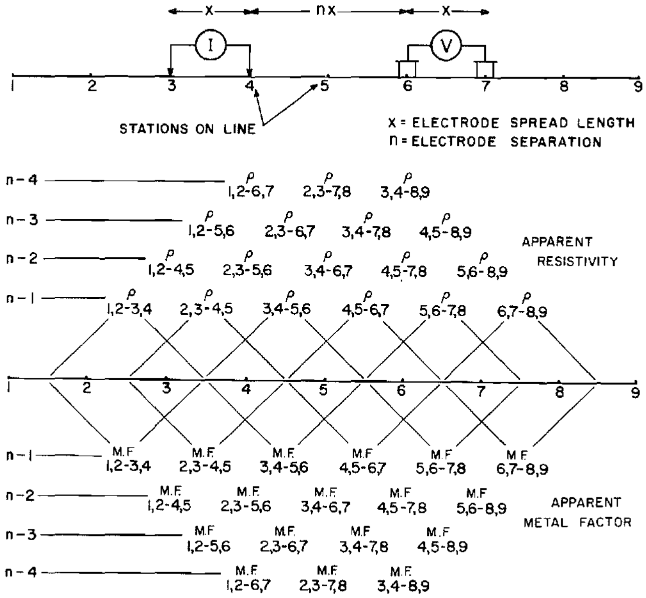


Figure 2. Method used in plotting dipole-dipole induced polarization and resistivity results.

effects of lateral changes in the properties of the ground to be separated from the effects of vertical changes in the properties. Current is applied to the ground at two points a distance X feet apart. The potentials are measured at two other points X feet apart, in line with the current electrodes. The distance between the nearest current and potential electrodes is an integral number n times the basic distance X.

The measurements are made along a surveyed line, with a constant distance nX between the nearest current and potential electrodes. In most surveys, several traverses are made with various values of n; i.e., $n = 1, 2, 3, 4$, etc. The kind of survey required (detailed or reconnaissance) decides the number of values of n used.

In plotting the results, the values of the apparent resistivity and the apparent metal factor measured for each set of electrode positions are plotted at the intersection of grid lines, one from the centre point of the current electrodes and the other from the centre point of the potential electrodes. The resistivity values are plotted above the line and the metal factor values below. The lateral displacement of a given value is determined by the location along the survey line of the centre point between the current and potential electrodes. The distance of the value from the line is determined by the distance nX between the current and potential electrodes when the measurement was made.

The separation between sender and receiver electrodes is only one factor which determines the depth to which the ground is being sampled in any particular measurement. These plots then, when contoured, are not section maps of the electrical properties of the ground under the survey line. They are merely convenient plots of all of the data. The interpretation of the results from any given survey must be carried out using the combined experience gained from field, model and theoretical investigations. The position of the electrodes when anomalous values are measured must be used in the interpretation.

Massive sulphide zones that do not give EM anomalies

The various electromagnetic systems used throughout the world were designed for the detection of zones of massive mineralization. Most massive sulphide mineralization is a good conductor; these zones give rise to definite EM anomalies. EM techniques have been applied in many mining areas and a great many orebodies have been located.

However, our recent experience has shown that in some areas there are massive sulphide zones that cannot be detected by EM. In some cases this is very difficult to explain. It may be that, although massive, the sulphide particles are separated by insulating material and are not interconnected to form a conductor. In these situations, the induced polarization method has been found to be very useful.

In other cases, while the mineralization may not be considered to be massive, the percentage of sulphide present is substantial and would be expected to be sufficient to form a good conductor. In the strata bound lead-zinc deposits common in the limestone rocks of the mid-continent U.S.A., the Pine Point region of Canada and in Ireland, there is associated pyrite or marcasite. There is always 10 to 15% metallic mineralization; there is often as much as 25 to 35%. Numerous attempts have been made to detect these zones using EM methods. None of them have been successful.

The results shown in Figure 3 are typical for this type of mineralization. The ore zone shown was located by a reconnaissance IP survey in the Upper Mississippi Valley zinc-lead district. The ore mineralization is concentrated pyrite-marcasite, with sphalerite. The zone is almost 2000 feet long. As suggested by the IP results (maximum IP effect measured for $n = 1$), the source is relatively shallow.

When the ore zone had been outlined by drilling, a test EM survey was carried out using the vertical loop EM method. The results are plotted in the upper portion of Figure 3; the transmitter was 600 feet from the receiver and the frequencies were 1000 cps and 5000 cps. No significant EM anomaly was located.

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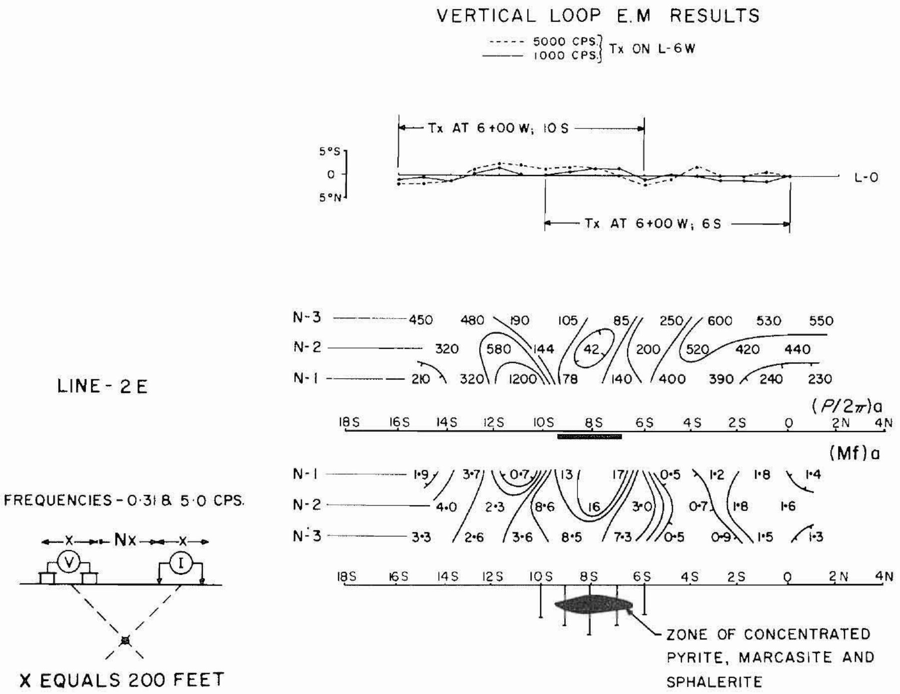

Figure 3. Comparison of EM methods and IP results from Linden area, Wisconsin, U.S.A.

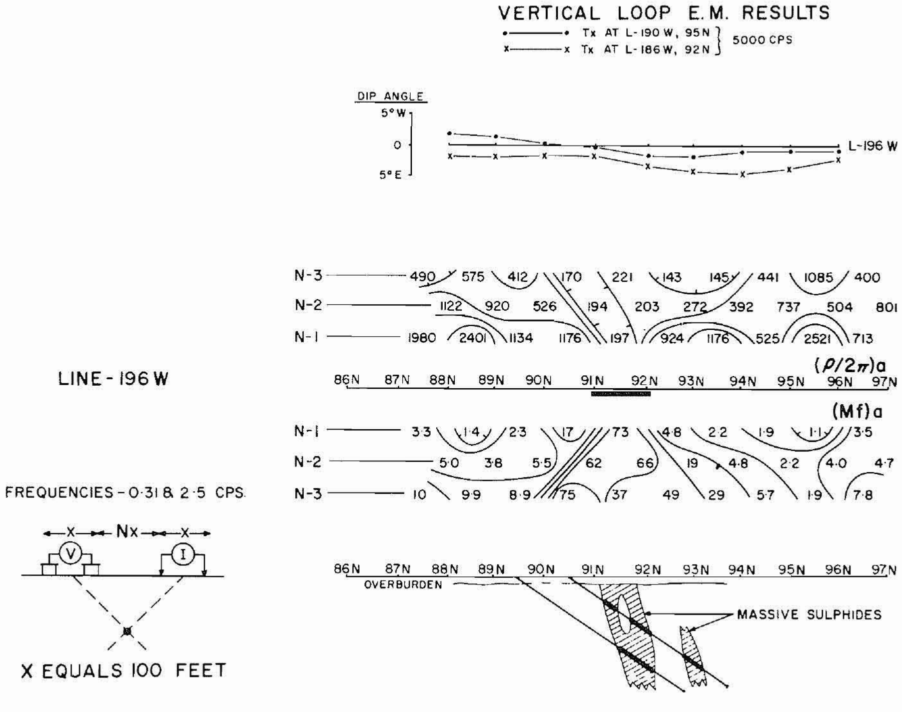

Figure 4. Comparison of EM methods and IP results from Newcastle area, New Brunswick, Canada.

In other mining areas, we have found that some ore zones can be detected using EM methods, while others cannot. This has been particularly true in the New Brunswick area of eastern Canada. It was in this area that the EM methods were first used successfully in Canada in the mid-fifties. Many sulphide zones, some of which were ore, were located.

In recent years, we have found more than a dozen zones of massive mineralization, using IP, that were not detected by previous EM surveys. In some of these cases, the new zones of mineralization are less than 1000 feet from apparently similar massive mineralization located in the period 1954 to 1958 using EM. As is usual in New Brunswick, there is less than 30 feet of overburden in each of these areas.

The IP results shown in Figure 4 and Figure 5 located two of these zones; the EM results are shown on the upper portion of the drawings. The geological situation is the same in both cases. The mineralization is located at the contact between high resistivity, massive-pyroclastic rocks and lower-resistivity argillites. The IP results indicate a shallow (anomalous for $n = 1$) source in Figure 4 and a source at depth (maximum IP effect for $n = 3$) in Figure 5.

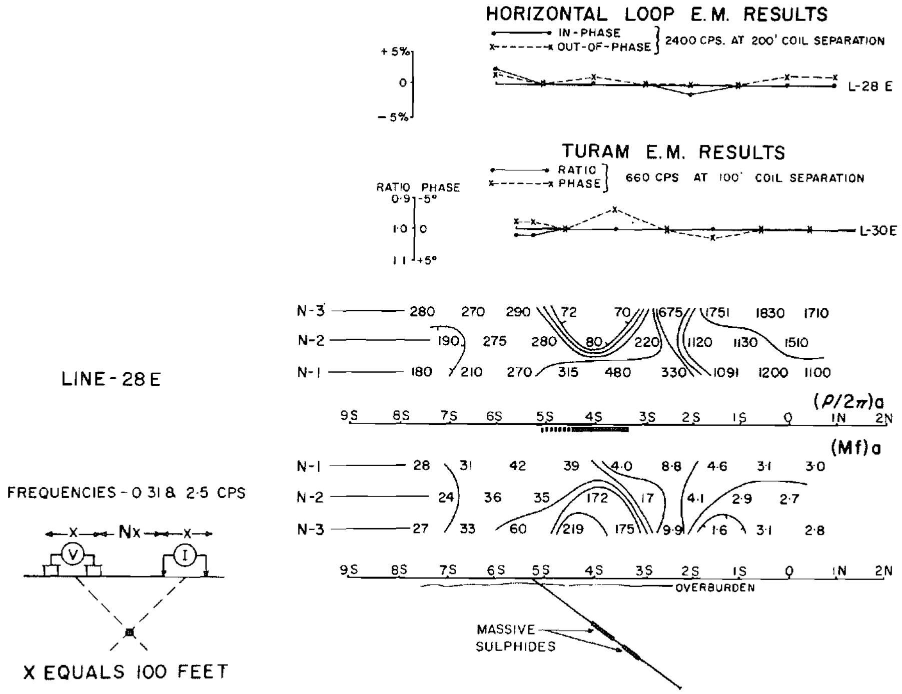

Figure 5. Comparison of EM methods and IP results from Bathurst area, New Brunswick, Canada.

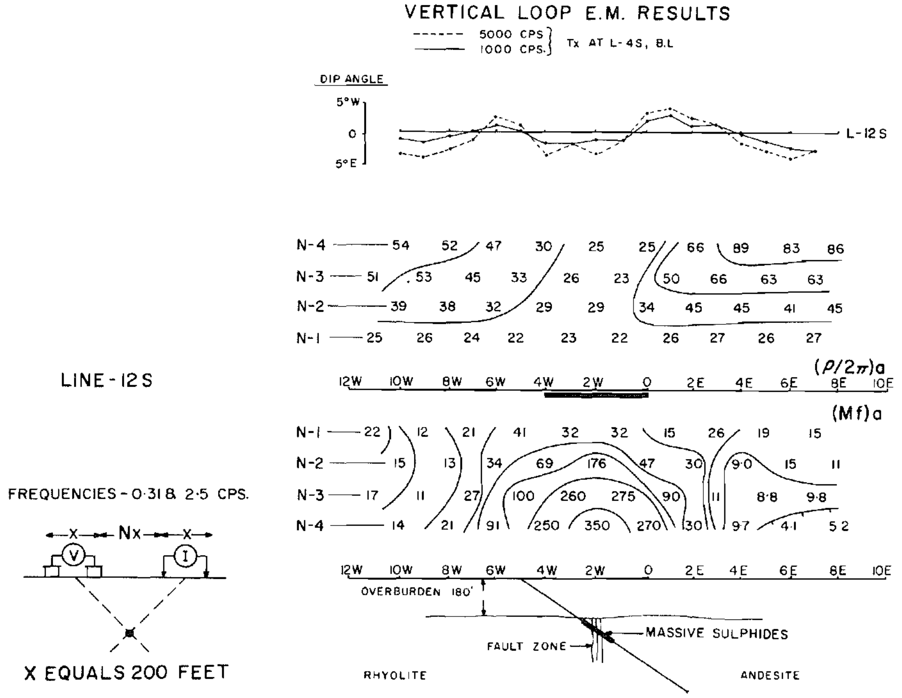

Figure 6. Comparison of EM methods and IP results from Timmins area, Ontario, Canada.

In Figure 4, the 5000 cps vertical loop EM profiles show a weak conductor axis at the geological contact. This feature has been traced for several miles across the property. The sulphide zone causing the IP anomaly is massive and it is 2200 feet long; there is no recognizable EM anomaly from the mineralization.

The results shown in Figure 5 are from two vertical field EM techniques. The sulphide zone is massive, but there is no conductor indicated by either the horizontal loop or Turam EM data. Here the IP results indicate some depth to the top of the source (perhaps 75 feet) and the zone is 1100 feet long.

Sulphide zones too deep to be detected by EM

As a sulphide zone is moved to greater and greater depth, the magnitude of the EM anomaly measured is reduced in magnitude. At some depth for the conductor, the anomalous effects cannot be distinguished from the normal background variations. This is the maximum depth of detection for the EM method and the particular conductor concerned. Our experience has shown that because of its greater discrimination, the IP method has a greater depth of detection than EM methods for all but vertical, thin, sheet-like conductors.

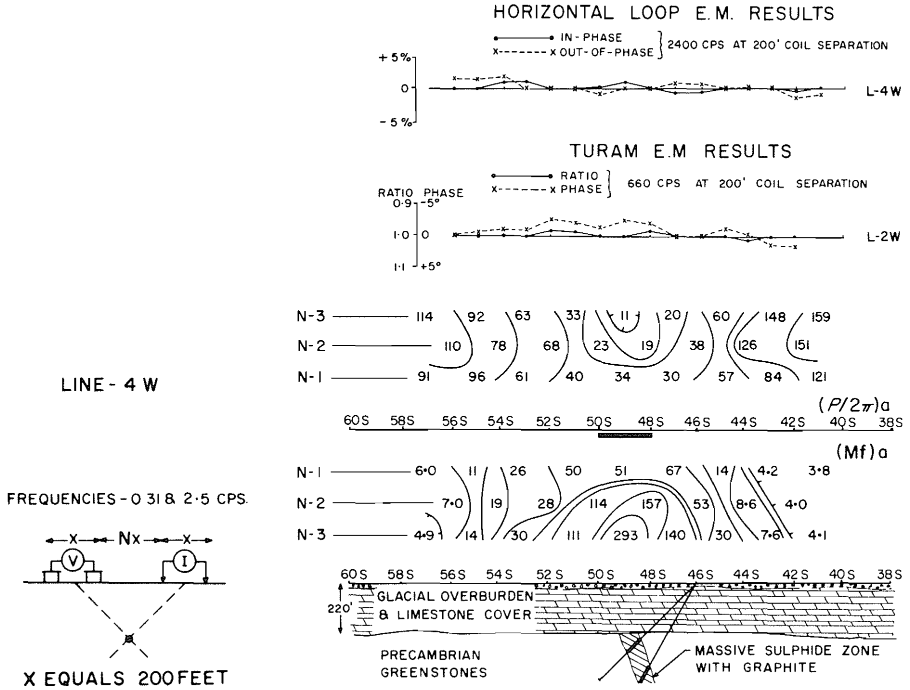

Figure 7. Comparison of EM methods and IP results from Flin Flon area, Manitoba, Canada.

In Figure 6, there is a thickness of 180 feet of glacial overburden over the sulphide zone. The IP data were measured with an electrode interval of 200 feet, so that the depth to the top of the source is about one unit. To the east and west, the resistivity results show the presence of the porous, conductive overburden; the apparent resistivities increase, for the larger values of *n*. At the conductor, the apparent resistivities do not increase with depth.

The IP anomaly is large and very definite. The depth to the top of the source is indicated by the fact that the maximum IP effects were measured for $n = 4$. The angle drill hole shown on the geologic section was spotted to test the source of the definite IP anomaly.

The hole intersected a zone of massive sulphide mineralization within a fault zone. The increase in the basement resistivity ($n = 4$) east of the IP anomaly is explained by the change in rock type.

The IP anomaly was almost 2000 feet long; after the first hole was drilled an attempt was made to better evaluate the source using EM. The vertical loop EM method was employed, using 1000 and 5000 cps. Separations of 800 and 1200 feet between the transmitter and receiver were used; there were no interpretable EM anomalies.

In the example of the IP anomaly shown in Figure 7, the depth indicated to the top of the source is due to 220 feet of overlying overburden and Paleozoic limestone. The resistivity results show that there is no difference between the resistivity of the limestone and that of the basement greenstones.

As in the previous example, the IP anomaly is large in magnitude and definite. The drill holes intersected massive mineralization, with graphite; the zone is probably controlled by shearing. It is approximately 800 feet long.

The Turam EM and horizontal loop EM results shown on Figure 7 were measured as part of previous reconnaissance surveys. The variations shown must be considered to be normal background; there is no EM anomaly that can be interpreted.

Geologic environments that cause extraneous EM anomalies

Most of the postwar successes and widespread use of the EM methods were in Canada and some in Sweden. In these temperate to arctic areas, there is little or no surface weathering. Zones of massive sulphide mineralization may be covered by glacial overburden, but they will extend to bedrock surface.

The rock types encountered in these areas, with a few exceptions, are poor conductors of electricity. EM anomalies can be expected from massive mineralization, but there are almost no other geological features that can be expected to be good conductors. This situation is a definite advantage to the geophysicist interpreting EM data.

With the successes of the method in Canada, its use was expanded into other areas. It was soon discovered that in other geological environments and with other types of weathering, there were frequently other types of conductors that confused the EM results.

These extraneous anomalies are due to ionic conductors. Zones of porosity within the rocks are filled with ion-charged solutions. These zones of porosity may be due to oxidation and weathering, hydrothermal alteration, shearing and fracturing, etc. The high-salinity solutions are created by the deep-weathering chemical reactions. Our experience has shown that these conditions occur in all arid and tropical areas.

There is one type of ionic conductor that is common even in temperature climates. Alteration and shearing in basic and ultrabasic rocks frequently create talc and serpentine minerals. The platey structure of these minerals gives rise to many unbonded charges; very conductive layers of adsorbed ions form in the shears. These zones become excellent conductors that create EM anomalies.

The IP and EM results shown in Figure 8 are from a typical area of ultrabasic rocks in northern Manitoba. The 1000 cps vertical loop EM results show two conductors, depending upon

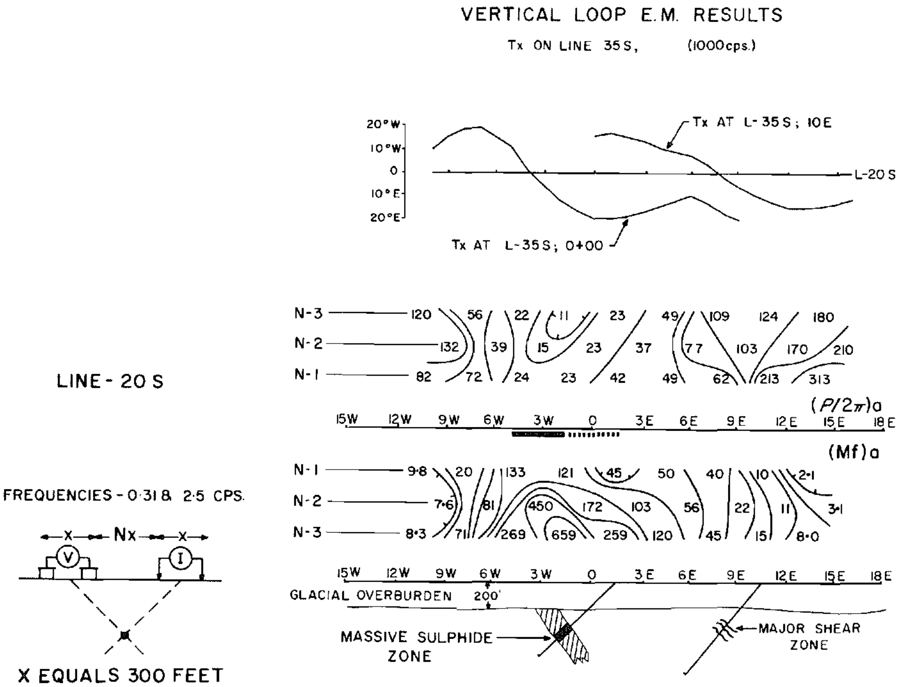

Figure 8. Comparison of EM methods and IP results from Lynn Lake area, Manitoba, Canada.

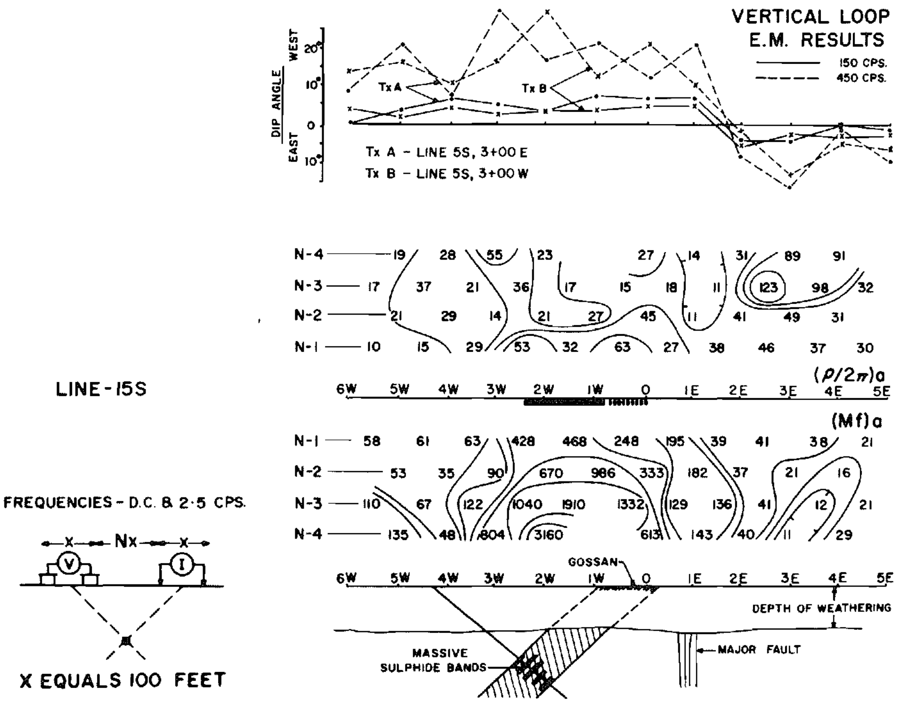

Figure 9. Comparison of EM methods and IP results from Mutooroo area, S. Australia, Australia.

the position of the transmitter. The two EM conductors correlate approximately with the edges of a broad, low-resistivity zone within the ultrabasic rocks.

Both of the EM conductors were tested by drilling before the IP survey was done. The western conductor is associated with a massive sulphide zone, at depth. The eastern conductor is due to a broad zone of intense shearing in the ultrabasic rocks.

The IP results show a strong, definite IP anomaly centred at 3+00W. The depth of overburden is indicated by the fact that the maximum apparent IP effects are measured for $n = 3$. There are no anomalous IP effects correlating with the EM conductor at 8+00E. As in most other ultrabasic areas, the background IP effects are high due to metallic magnetite.

The geologic evidence suggests that the zone of low resistivity is because of a broad zone of weak shearing. The major fault is located at the eastern edge; the replacement sulphide zone is at the western edge of the zone of porosity.

The EM responses from the two geological features are exactly similar; they both apparently were important enough to warrant drill holes. The IP measurements clearly indicate the

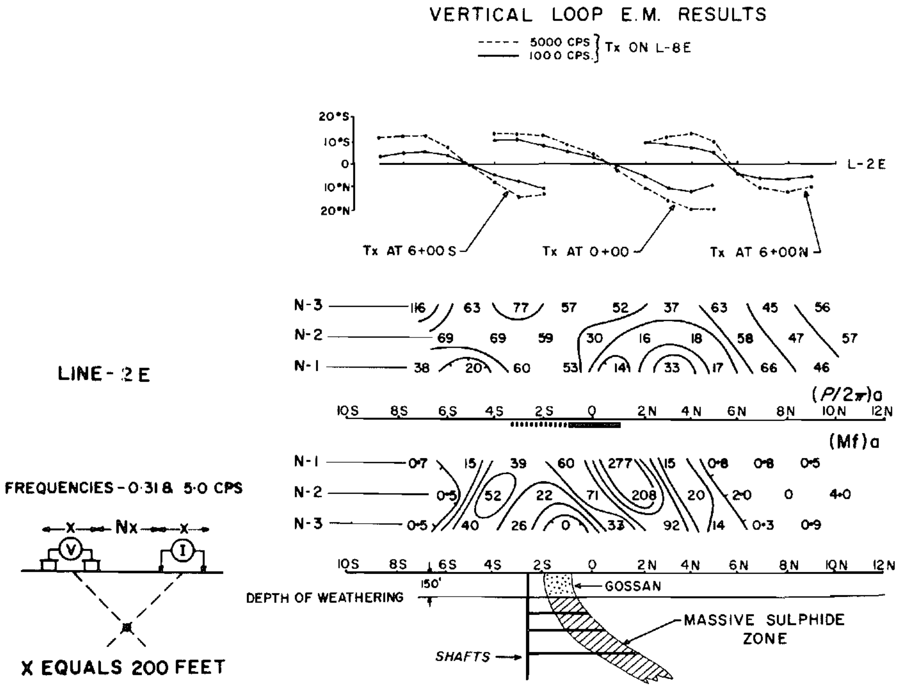

Figure 10. Comparison of EM methods and IP results from Mono area, Pinar del Rio Province, Cuba.

locations and importance of the zone of massive sulphide mineralization.

Many ionic conductors are located in carrying out EM surveys in arid and semiarid areas such as Australia. Each shear zone and fault gives a response.

The IP results shown in Figure 9 were detailed to evaluate a definite anomaly located during a reconnaissance survey in South Australia. A very strong anomaly is indicated; it is centred, at depth, at 2W to 1W. Later drilling confirmed the presence of an extensive zone of massive mineralization. The zone is several thousand feet long. The depth to the top of the source of the IP anomaly is caused by the complete weathering (oxidation) of the mineralization to a depth of approximately 100 feet.

The lowest resistivity zone in the area is indicated to be at 1+00E, at least 250 feet east of the centre of the IP anomaly. A major fault zone, that can be observed to the north, is extrapolated to pass through this location. Our experience elsewhere in this type of environment indicates that most fault zones are saturated with saline solutions; they usually give resistivity lows and cause EM anomalies.

This is confirmed by the 150 and 450 cps EM results shown in the upper portion of Figure 9. The data shown were measured as a test after the drilling was completed. With the transmitter in two positions, the low-frequency EM results show a conductor at 1+50E.

There are several sharp variations in the EM results to the west of the fault. These variations are probably due to changes in the salinity, or porosity, of the weathered layer. Some of them may be due to the massive mineralization at depth, but they cannot be distinguished. The EM response from the fault saturated with saline solutions is greater than that from the massive sulphide zone.

The same geologic situation encountered in semiarid Australia usually occurs in areas of tropic weathering such as Cuba. The deep weathering conditions create zones of porosity and ion-charged groundwater. The interpretation of EM results from tropic areas is usually confused by anomalies from ionic conductors.

The IP and EM results shown in Figure 10 are from a test survey carried out over a known zone of massive pyrite in Pinar del Rio Province, Cuba.

The weathering is very deep in this area. The rock types are quartzites and slates; this difference in rock type results in an extremely uneven depth of weathering. The apparent resistivity results show that the surface ($n = 1$) values are low and variable.

The vertical loop EM results (1000 and 5000 cps) show a conductor at each slate band. The deep weathering creates porous zones that are saturated during the rainy season. These ionic conductors give EM anomalies that are just as definite as that from the sulphide zone at depth.

The IP results show a strong anomaly that correlates with the pyrite zone. The ionic conductors give resistivity lows, but no IP effects. The IP data are much more discriminating than the EM results.

Conclusions

The electromagnetic method has been very successful in the exploration for massive sulphide deposits. Most zones of massive sulphide mineralization are good conductors of electricity; they give EM anomalies with any technique used.

However, experience in the last few years has shown that there are some zones of massive sulphide mineralization that do not give rise to EM anomalies. Even when these zones are known, when the sources are shallow, they do not give recognizable EM anomalies. This type of massive mineralization can be detected using induced polarization measurements.

As with all geophysical methods, EM techniques have a limited depth of detection. The anomalies have lower magnitude as the source is deeper; at some depth the anomalous effects are too weak to be distinguished from the background effects. We have numerous examples of field results that show the appreciably greater depth of detection of the induced polarization method. Zones of massive sulphide mineralization have been located using IP, that were too deep to give EM anomalies.

In some geological environments, the presence of ionic conductors that give EM anomalies will badly confuse EM results. Typical examples of ionic conductors are shears in ultrabasic rocks and in areas of deep weathering (tropic and arid). In these areas, there will be EM anomalies from massive sulphide zones, if the depth of oxidation is not too great; the interpretational difficulties arise in the separation of the two types of anomalies.

The IP effects used in field exploration are due to electrochemical phenomena at ionic conduction – electron conduction interfaces. There are no IP effects unless metallic minerals are present. IP surveys in tropic and arid areas are not confused by the presence of ionic conductors; anomalies are obtained only from metallic conductors.

In many areas, the search for massive sulphide mineralization can be effectively carried out using EM methods; the cost will be somewhat less than if IP is used. However, the geophysicist should always remember that there are situations in which IP is much more effective than EM in exploration for massive mineralization.

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Geophysical exploration methods for nickel

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Abstract. Nickel-bearing sulphide deposits are currently the major source of the world's nickel. These sulphide deposits are commonly more conductive, more magnetic, and heavier than their environment and thus are detectable by geophysical means. The most widely used methods in the Canadian Precambrian Shield are the electromagnetic and magnetic methods. Induced polarization, self potential, and gravity surveys are useful in exploration for small bodies under shallow overburden. Induced polarization surveys are also useful in the search for weakly disseminated sulphide bodies. In some tropical and sub-tropical areas electromagnetic techniques are not effective as salt laden moisture in the overburden and weathered rock makes these formations very conductive. Where these conditions prevail, induced polarization, magnetic and geochemical methods are the most effective.

Résumé. Les gisements sulfides nickélifères représentent la principale source mondiale de nickel. Ces gisements sulfides sont habituellement plus conducteurs, plus magnétiques et plus lourds que le milieu encaissant, de sort qu'ils peuvent être détectés par des procédés géophysiques. L'auteur présente les méthodes géophysiques utilisées au Canada pour l'exploration du nickel et examine de façon spéciale les relevés électromagnétiques et magnétiques. Il présente brèvement d'autres méthodes appliquées à des problèmes particuliers qui se posent lors de la recherche des sulfures de nickel et des latérites nickélifères dans les régions tropicales et sous-tropicales. Il fait la revue des travaux d'exploration avec des exemples tirés de cas précis.

In the last twenty years geophysics has been used extensively in the search for nickel with considerable success. Nickel orebodies in the Thompson area of northern Manitoba, in the Sudbury area of Ontario, in northwestern Quebec and in Finland have been found through the use of geophysics.

This paper discusses the common geophysical methods that may be used in the search for nickel with emphasis on conditions such as exist in the Canadian Precambrian Shield. Some aspects of geochemistry, and the special problems associated with exploration for nickel in tropical and subtropical regions will also be touched on.

Physical properties

Nickel-bearing sulphide deposits are currently the major source of the world's nickel. Many of these deposits are tabular or pseudotabular in shape and the metallic sulphide content is rarely less than 10 percent.

These sulphide bodies can be located geophysically as the major sulphide constituent is pyrrhotite, which is a good electrical conductor, is normally magnetic and has a relatively high specific gravity. Nickel sulphide bodies often conduct electricity as much as a thousand times as well as their environment (Seigel, 1966). They are usually magnetic and have a density around 15 to 80 percent higher than the surrounding rocks.

Geophysics can also be used as an indirect aid in locating nickel orebodies. All known nickel deposits of commercial consequence occur in or near basic or ultrabasic rocks, which are usually sufficiently magnetic to alter the earth's magnetic field in their vicinity. Thus, both airborne and ground magnetic surveys are useful in locating rocks of these types and thus delineating favourable areas to be explored for nickel.

Methods

Table I shows the geophysical and geochemical methods in use today that are applicable to the search for nickeliferous sulphide deposits with the above mentioned properties.

All of the methods shown in Table I have their place in a comprehensive exploration program for nickel. However, most exploration programs in Canada only make use of *electromagnetic and magnetic methods.* There are several fundamental reasons for this, the most important of which are:

1. The physical property contrasts to which these two methods respond are high for nickeliferous sulphide deposits under Canadian conditions.
2. Both methods can be carried out from an aircraft, thus making it possible to cover large areas quickly.
3. Surveys on the ground with these two methods are relatively rapid and inexpensive.
4. These two methods should be sufficient to locate most nickeliferous sulphide bodies of economic size and grade within 250 feet of the surface under Canadian conditions.

Table I. Geophysical and geochemical methods for searching for nickeliferous sulphide deposits.

Physical Property or Phenomenon	Airborne Methods	Ground Methods
Electrical conductivity	Electromagnetic	Electromagnetic
Magnetic susceptibility	Magnetic	Magnetic
Electrical polarization at surface of sulphide particles		Induced polarization
Conductivity and electrochemical activity		Self potential
Density		Gravity
Ion migration or soil transportation		Geochemical

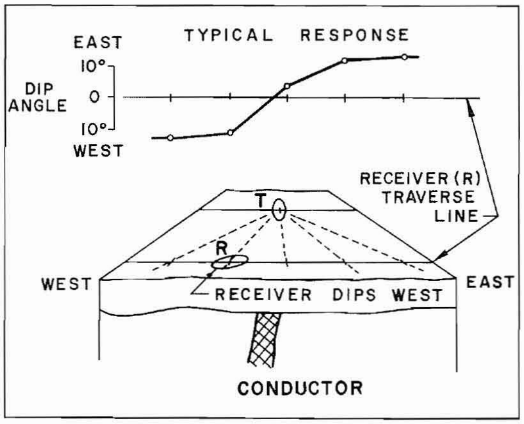

Figure 1. Vertical coil, or dip-angle electromagnetic method, with fixed transmitter position.

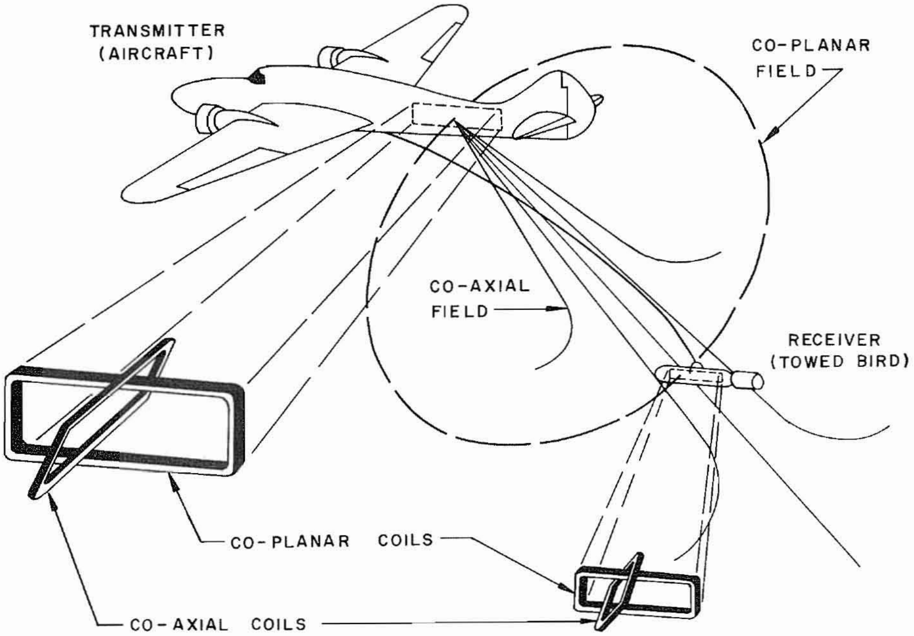

Figure 2. The International Nickel airborne electromagnetic instrument.

Induced polarization techniques can be used for the same purposes as ground electromagnetic techniques since both methods respond to most sulphide bodies with a metallic sulphide content of 10 percent or more. However, induced polarization methods are slower and more expensive than electromagnetic methods and thus are only used where there is a distinct advantage to be gained, such as in the search for small sulphide bodies under shallow overburden, in the search for bodies with an abnormally low sulphide content, or in the search for sulphides in areas such as some tropical regions where overburden or rock conductivities are abnormally high. A limitation of the induced polarization method is that it responds to many ultrabasic bodies whether sulphides are associated with them or not. This response to ultrabasic bodies may, in part, be caused by the constituent magnetite content of these rock types.

Self potential surveys are rapid and inexpensive and as such are useful in locating and outlining sulphide bodies under shallow uniform overburden. However, self potential surveys should be used with discretion as the method responds to lateral variations in surface conditions and may not respond to sulphide bodies located under lakes or swamps.

Gravity methods can be of use in the direct detection of sulphides in areas where the overburden is shallow and reasonably uniform in thickness. However, these methods are not widely used as variations in overburden thickness can produce anomalies similar in shape and magnitude to anomalies caused by sulphide bodies. In addition, gravity surveys are relatively slow and expensive.

Geochemical surveys are of limited use in the Canadian Precambrian Shield as much of the shield is covered by transported glacial material. This glacial material usually includes impervious layers restricting the percolation of groundwater and thus restricting migration of nickel ions. However, there may be small isolated areas where thin permeable overburden allows ion migration and the formation of geochemical anomalies. There may also be cases where glaciers moving across nickel deposits have picked up fragments of the deposit and redistributed them in the form of a glacial train that can be followed geochemically.

Instruments

Several electromagnetic instruments, both airborne and ground, are used in Canada in the search for economic sulphide deposits (Pemberton, 1962; Hood, 1967). The comments and case histories in this paper deal with results obtained with the vertical coil ground electromagnetic unit and the International Nickel airborne electromagnetic unit, the operation and use of which are well known to the author. Similarly, several magnetometers, induced polarization units, self potential units and gravity meters are on the market today (Hood, 1967), most of which are suitable for exploration for nickel where the respective methods are applicable.

To put the following comments and case histories in their proper perspective, the vertical coil ground electromagnetic instrument and the International Nickel (INCO) airborne electromagnetic instrument will be briefly described.

The *vertical coil ground electromagnetic instrument,* sometimes referred to as a dip-angle instrument (Grant and West, 1965), consists of a transmitter coil held in a vertical plane (axis horizontal) and a receiver coil capable of measuring the dip of the resultant electromagnetic field.

The plane of the transmitter coil is oriented so as to contain the receiver coil, as shown in Figure 1. An alternating current is passed through the transmitter coil and the electromagnetic field so generated induces eddy currents to flow in any conductive material in the vicinity. These eddy currents, in themselves, generate a second electromagnetic field which distorts the shape of the electromagnetic field generated by the transmitter. This distortion is recorded by measuring the dip of the resultant electromagnetic field at the receiver position.

The instrument can be used with the transmitter in one fixed position, moving only the receiver from station to station, or with the transmitter and receiver both moving along parallel lines.

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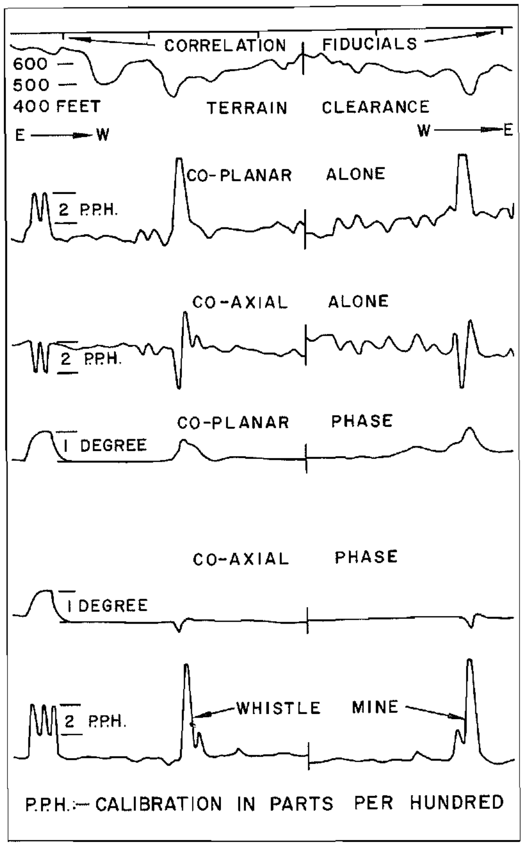

Figure 3. Airborne electromagnetic anomalies over Whistle mine, Sudbury area.

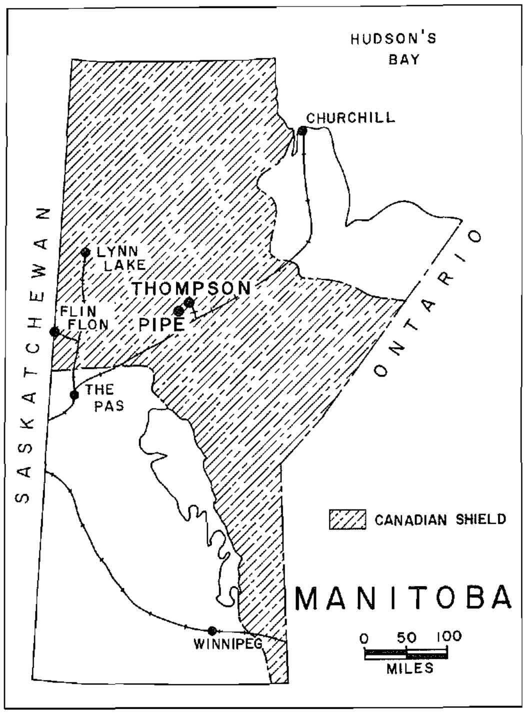

Figure 4. Location of the Thompson and Pipe mines.

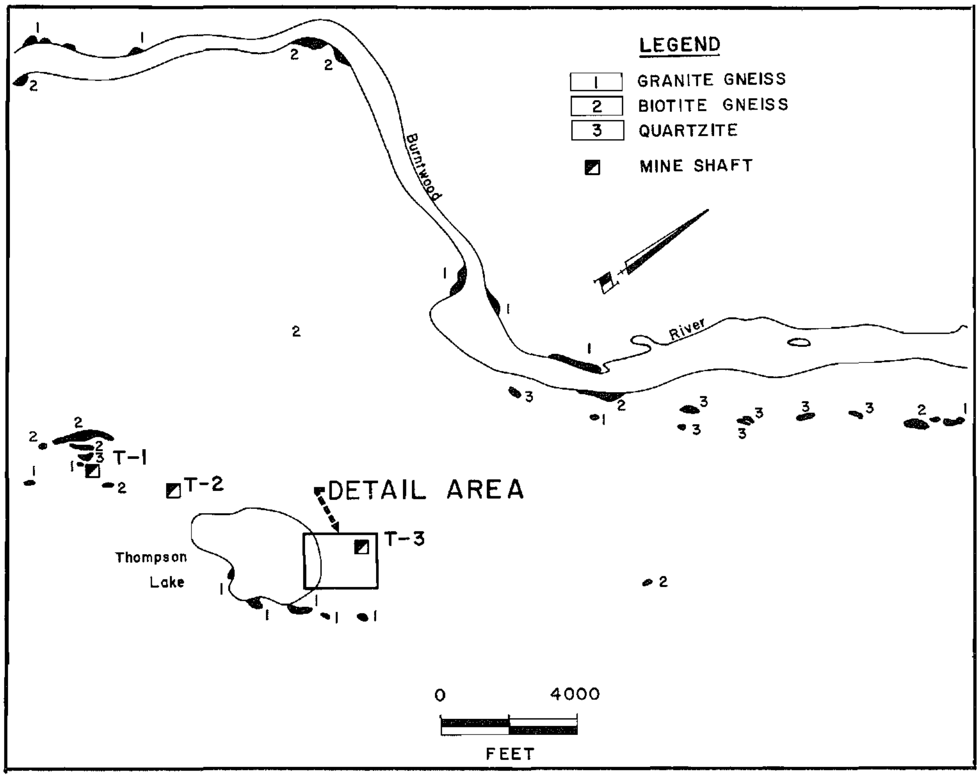

Figure 5. Outcrop map, Thompson area, after Zurbrigg, 1963. (Permission to use data granted by the Canadian Institute of Mining and Metallurgy.)

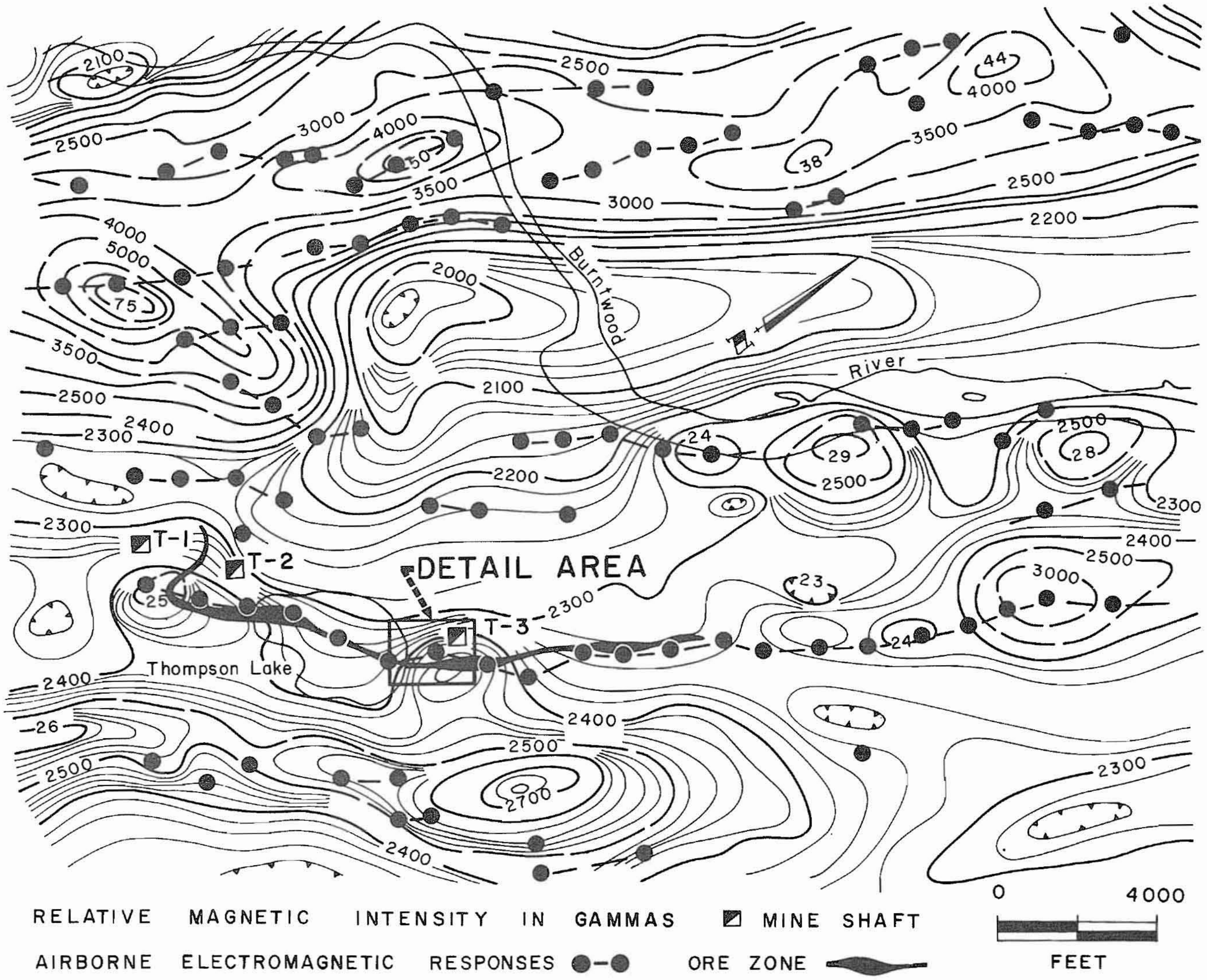

Figure 6. Airborne electromagnetic and magnetic survey, Thompson area, after Zurbrigg, 1963. (Permission to use data granted by the Canadian Institute of Mining and Metallurgy.)

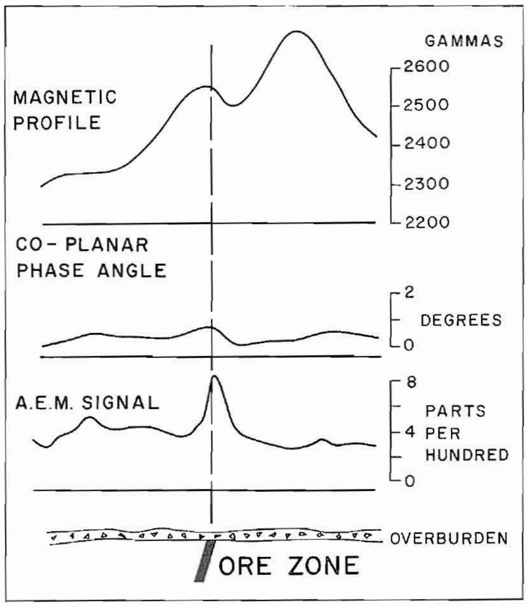

Figure 7. Airborne electromagnetic and magnetic profiles, Thompson mine.

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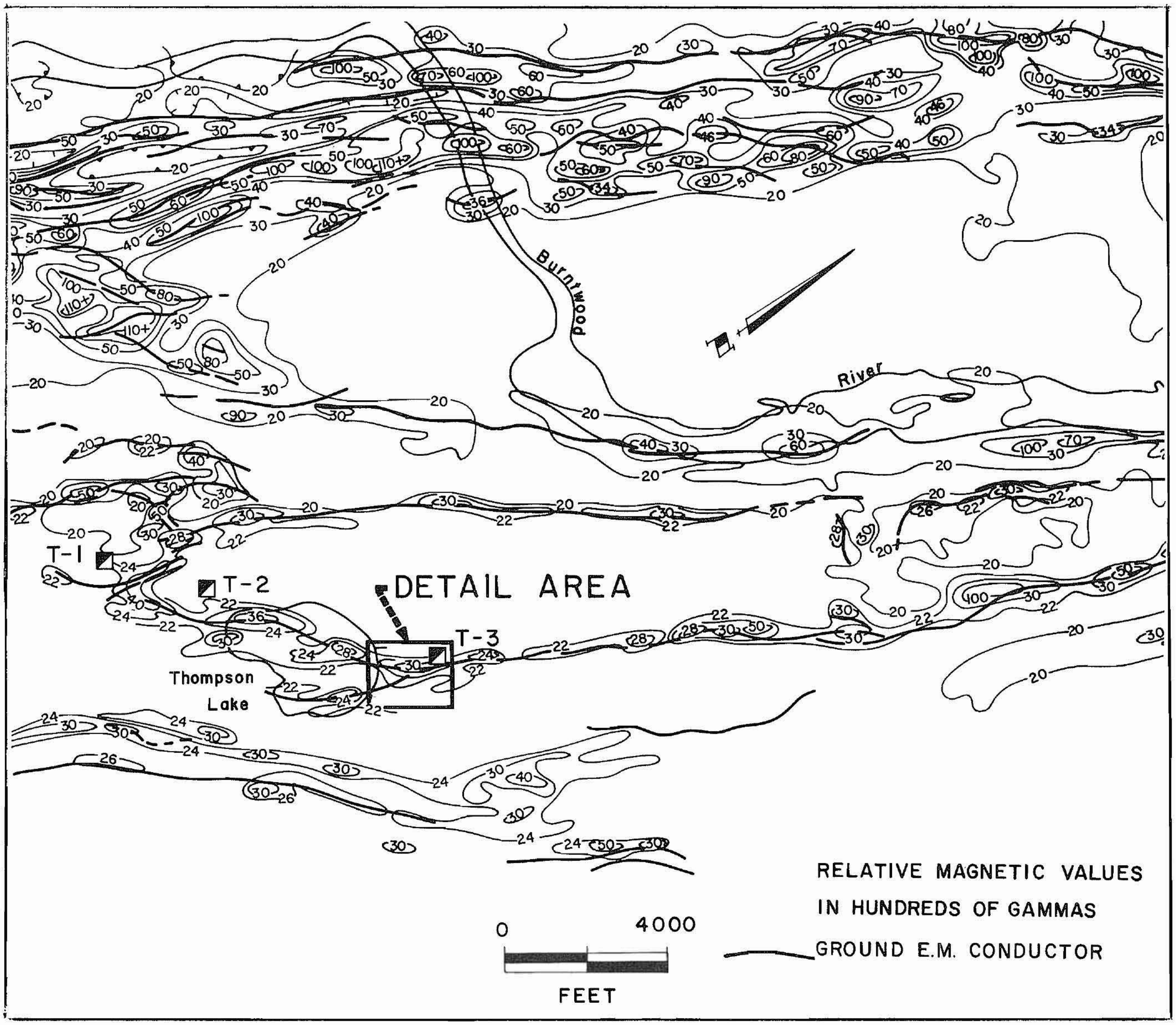


Figure 8. Ground electromagnetic and magnetic surveys, Thompson area, after Zurbrigg, 1963. (Permission to use data granted by the Canadian Institute of Mining and Metallurgy.)

This description is, of necessity, very brief and simplified. Readers desiring more information are referred to Grant and West, 1965.

The *INCO airborne electromagnetic instrument* consists of two, frequency distinguished, maximum coupled, transmitter-receiver systems. The two transmitter coils are mounted in a fixed wing aircraft in mutually orthogonal positions. The two receiver coils are mounted in corresponding positions in a bomb-shaped vehicle commonly referred to as a 'bird'. The bird is towed behind the aircraft on the end of a 500 foot cable. The transmitter and receiver coils in one system (coplanar) lie in a common plane. The transmitter and receiver coils in the second system (coaxial) have a common axis. Figure 2 shows the basic system in pictorial form.

The information that is recorded is the algebraic difference between the amplitudes of the signals picked up in the two receiver coils. This procedure is followed in preference to recording the individual signals because spurious responses resulting from changes in coupling as the bird wanders are greatly reduced, without hindering the ability to detect conductive material in the ground. Information concerning the effect of bird movements may be obtained by separately recording the amplitude of the signals picked up in the two receiver coils.

Additional information on the conductivity-width product is obtained by recording the phase relationship between the transmitted and received signals.

The survey is usually carried out by flying the aircraft at a mean terrain clearance of 500 feet along lines spaced one quarter of a mile apart.

Examples of the results obtained with the International Nickel airborne electromagnetic unit are shown in Figure 3. These anomalies were obtained on two flights over the sulphide deposit known as Whistle mine in the Sudbury area.

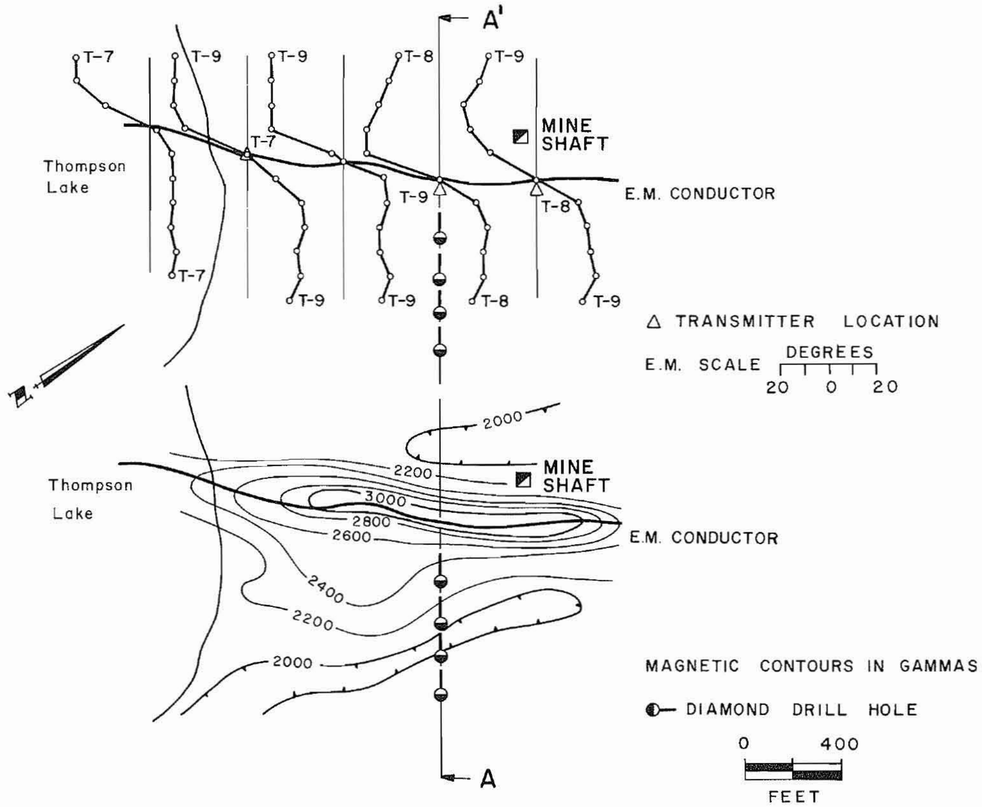
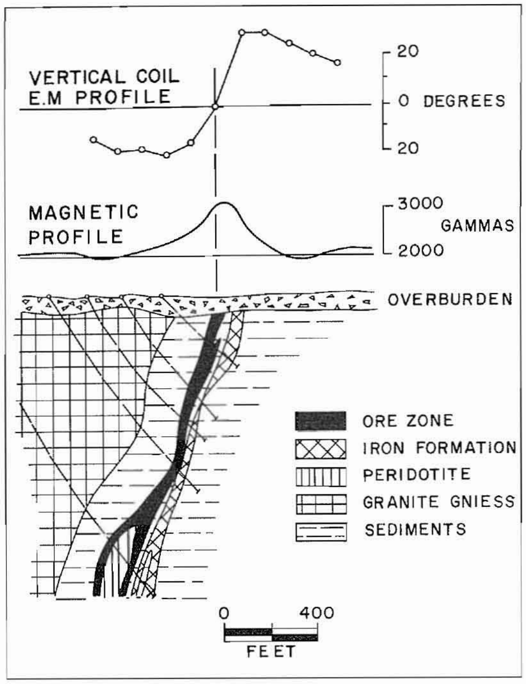


Figure 9. Ground electromagnetic and magnetic surveys in detail area, Thompson mine.

Figure 10. Section *A-A*[1], Thompson mine.



Case histories

Electromagnetic and magnetic methods. To illustrate the use of electromagnetic and magnetic methods, and the sequence of exploration using these methods, two case histories from northern Manitoba have been selected—the Thompson mine and the Pipe mine. Figure 4 shows the location of these mines.

The area in the vicinity of the Thompson mine is largely covered with overburden, as can be seen in Figure 5. Consequently, the small and widely scattered outcrops reveal very little of the geology of the area.

The first geophysical surveys that were conducted in the area were airborne electromagnetic and magnetic surveys. Numerous airborne electromagnetic responses associated with magnetic anomalies were found. Figure 6 shows the results of a portion of this survey. The black dots represent airborne electromagnetic responses, all of which are caused by sulphides, with or without graphite. Figure 6 also shows the location of the Thompson orebody. Figure 7 shows airborne geophysical results in profile form for a flight across the orebody.

The airborne surveys were followed up with detailed ground electromagnetic and magnetic surveys, the results of which are shown in Figure 8. The solid lines are vertical coil electromagnetic anomalies (commonly referred to as conductors). Many such conductors were drilled before the Thompson orebody was found.

The ground electromagnetic conductor over the Thompson orebody is long and strong. This conductor coincides with the axis of a long string of magnetic anomalies. Figure 9 shows the ground electromagnetic results in profile form and magnetic contours for the small detail area indicated on Figures 5, 6 and 8.

Figure 10 shows a section through the Thompson orebody with corresponding ground geophysical profiles. The electromagnetic conductor coincides with the position of the ore zone and is caused by the conductive sulphides of the ore. Pyrrhotite, which is the major constituent of the ore, is both conductive and magnetic, and is also the major cause of the magnetic anomaly.

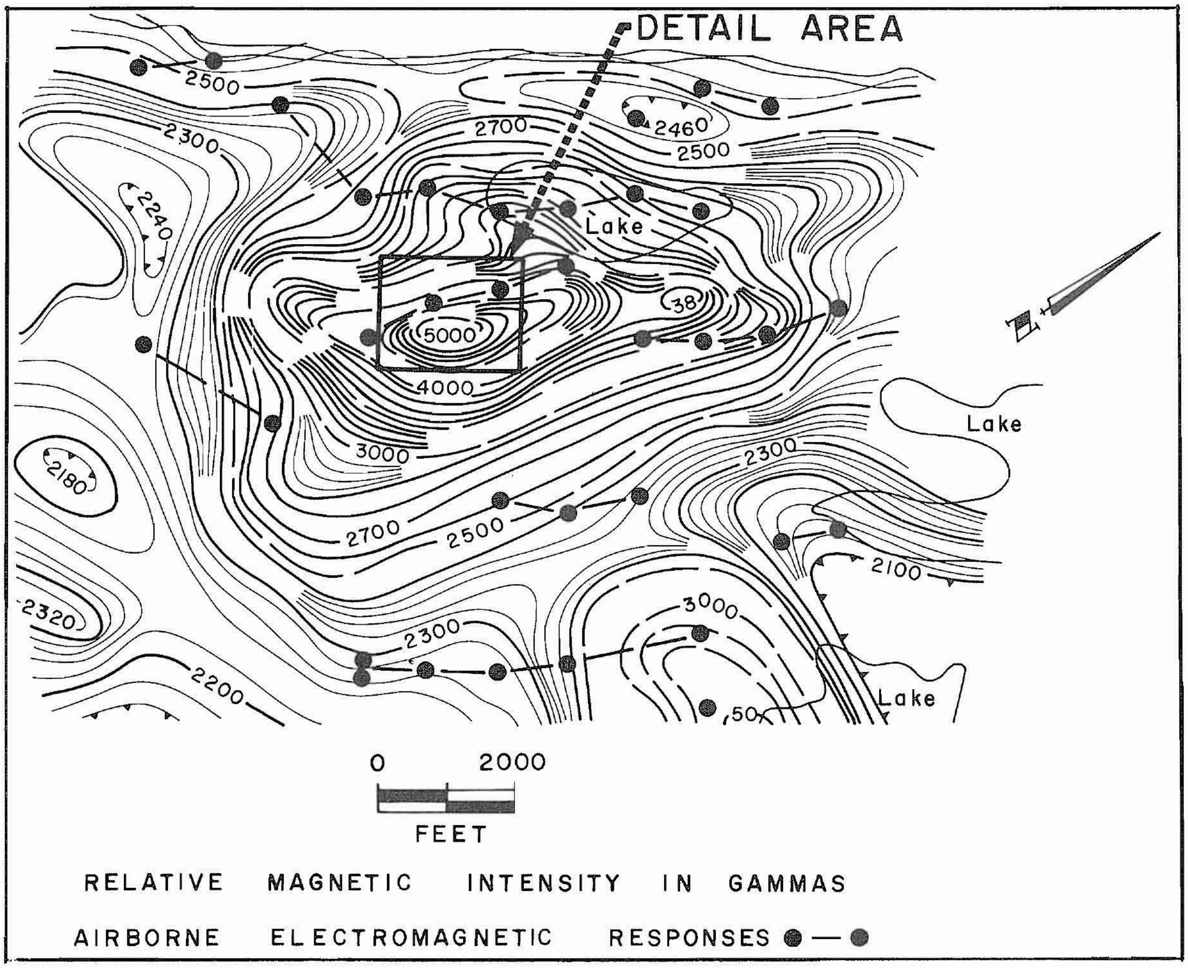


Figure 11. Airborne electromagnetic and magnetic survey, Pipe area.

The 'iron formation' adjacent to the orebody also contributes, to a minor extent, to the magnetic anomaly, as it carries a small amount of pyrrhotite and minor magnetite. The top of the peridotite body is quite deep at this point and consequently contributes very little to the magnetic anomaly.

The ratio of the number of orebodies to the number of electromagnetic conductors in Figure 6 clearly demonstrates that all conductors that are associated with magnetic anomalies are not orebodies. Graphite or barren sulphides associated with iron formation can give a similar geophysical picture. The ratio of the number of conductors associated with magnetic anomalies to the number of sulphide bodies capable of sustaining a mining operation in the Canadian Precambrian Shield is difficult to estimate; however, this ratio may be greater than a thousand to one.

The exploration program at Pipe was similar to that at Thompson. Airborne electromagnetic and magnetic surveys were flown first. These surveys were followed up with ground electromagnetic and magnetic surveys and the interesting results were investigated by drilling. Figure 11 shows a portion of the airborne geophysical results and Figure 12 shows ground geophysical results obtained in the small detail area indicated in Figure 11. A section through the orebody with corresponding geophysical profiles is shown in Figure 13.

In this case, as at Thompson, the electromagnetic conductors are caused by conductive sulphides in the ore. The presence of two sulphide-rich zones is revealed in the ground electromagnetic results shown in Figure 13. The magnetic anomaly over the central part of the Pipe ore zone (Figures 12 and 13) is much stronger and wider than at Thompson. In the Pipe case the peridotite mass is close to surface and constituent magnetite in the peridotite, magnetite inclusions in the ore and pyrrhotite of the ore itself, all contribute to the magnetic anomaly.

Other methods. Vertical coil electromagnetic surveys do not always respond well to sulphide bodies with very short strike length. In these cases induced polarization or self potential methods can be of value if the overburden is shallow.

The upper part of the main Maclennan orebody in the Sudbury district, now mined out, was a small body of roughly equidimensional shape in horizontal section which fitted the conditions mentioned in the previous paragraph. Figure 14 shows a section through this orebody with corresponding magnetic, vertical coil electromagnetic, self potential, and induced polarization profiles. The vertical coil electromagnetic results were extremely weak over this ore body, but distinct anomalies were obtained with the other methods. In this case a detailed magnetic survey was of great help in outlining the sulphide body. Figure 15

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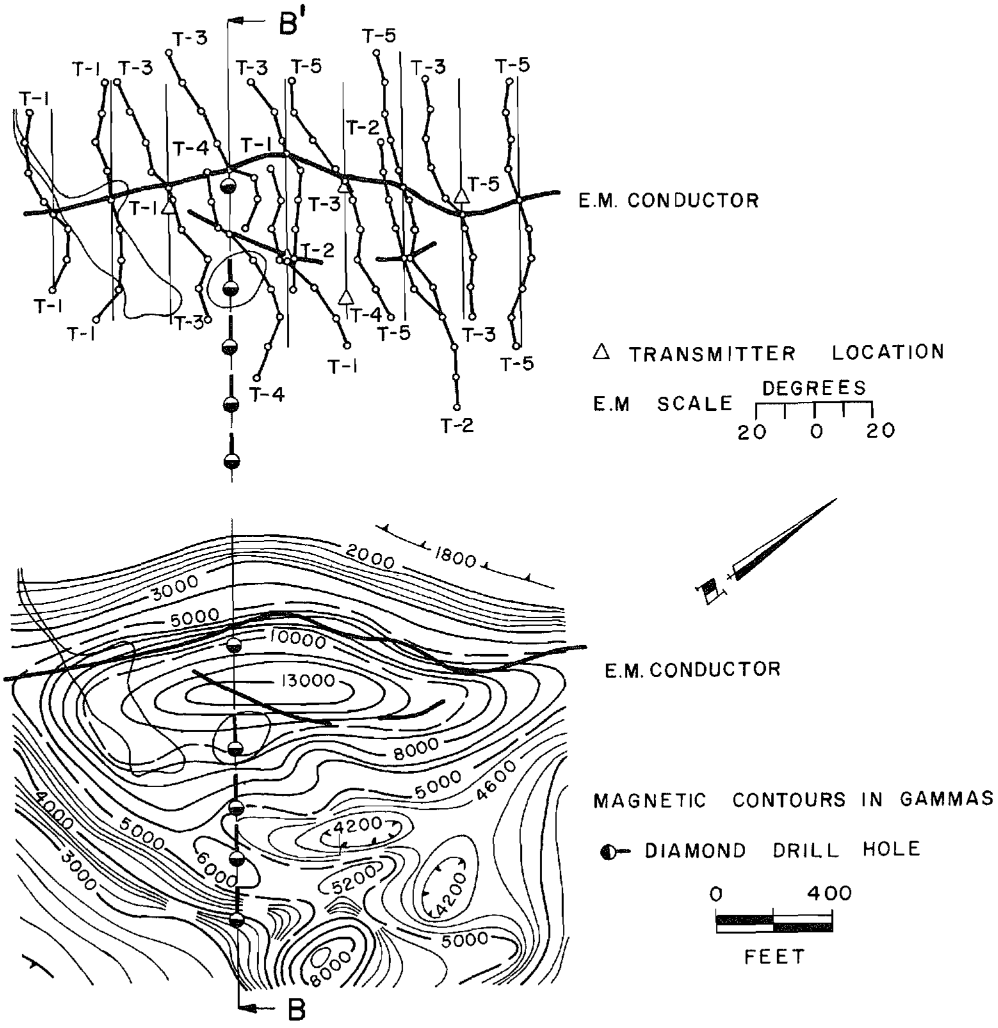

Figure 12. Ground electromagnetic and magnetic surveys in detail area, Pipe mine.

is a plan of the area showing the sulphide body superimposed on ground magnetic information.

If the overburden is shallow and uniform in thickness, a gravity survey can also reveal diagnostic results. The Garson offset sulphide body in the Sudbury district is a pseudo-tabular body occurring under approximately 35 feet of overburden. Figure 16 shows a section through the deposit with corresponding gravity profiles, both before and after removal of the regional trend. This deposit was originally discovered by magnetic methods, and a magnetic profile is also included in Figure 16.

Tropical and subtropical areas

Nickel in economic quantities and concentrations can occur in two forms in tropical and subtropical areas. These two forms are nickeliferous sulphide deposits and nickeliferous laterites.

Sulphides. The fundamental approach to exploration for nickeliferous sulphides based largely on electromagnetic methods such as is used in Canada is not always applicable in tropical and subtropical areas. In many of these areas topographic and climatic conditions have produced deep weathering and overburden heavily laden with salt. Moisture, even in minute quantities, in the overburden and weathered rock takes salt into solution and thus becomes an electrolytic conductor. This condition makes the overburden and partially weathered rock very conductive. For example, in the Kalgoorlie area of Western Australia overburden conductivities of 0.1 mho per meter are common and of 1 mho per meter not uncommon. Under these conditions, minor shears carrying aqueous salt solutions or moisture filled depressions in the bedrock surface will cause anomalies with electromagnetic techniques.

In these areas the most effective method for the detection of sulphide bodies is the induced polarization technique. This method responds to the electrical polarization created at the interface between sulphide particles and their environment by passing current through this interface (Seigel, 1962; Hallof, 1960), rather than to the conductivity of the sulphides themselves, and thus does not produce spurious anomalies over electrolytic conductors. Unfortunately, induced polarization methods are similar to electromagnetic methods since they also respond to barren sulphides and graphite.

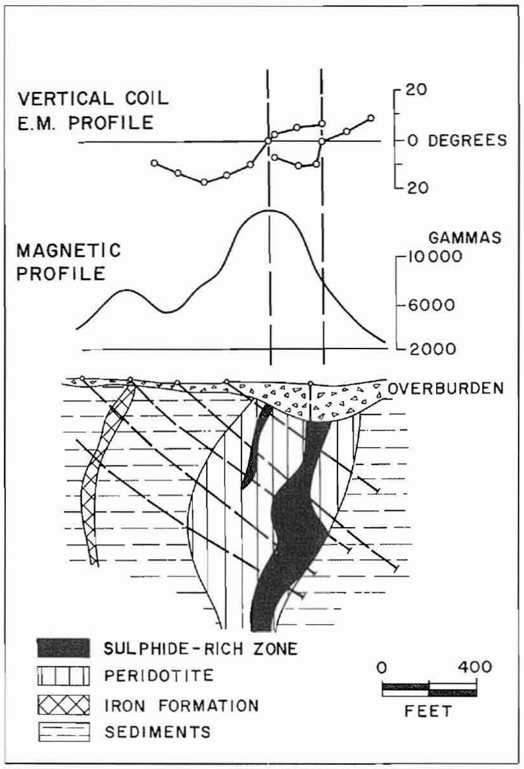

Figure 13. Section *B-B*¹, Pipe mine.

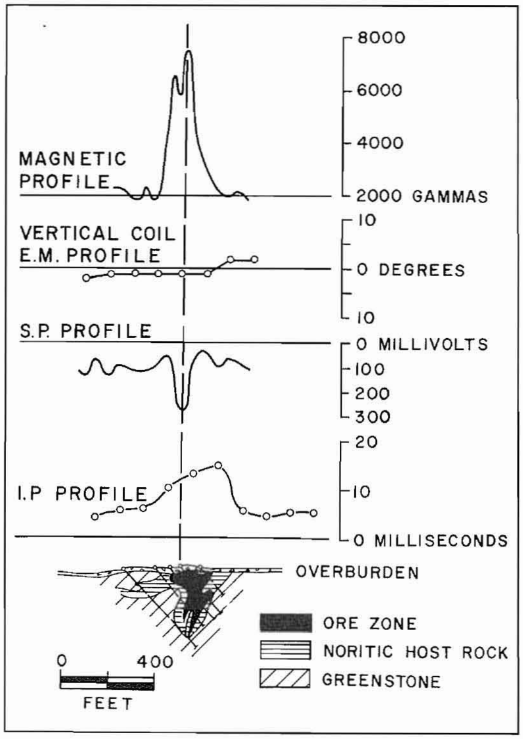

Figure 14. Section *C-C*¹, Maclennan mine.

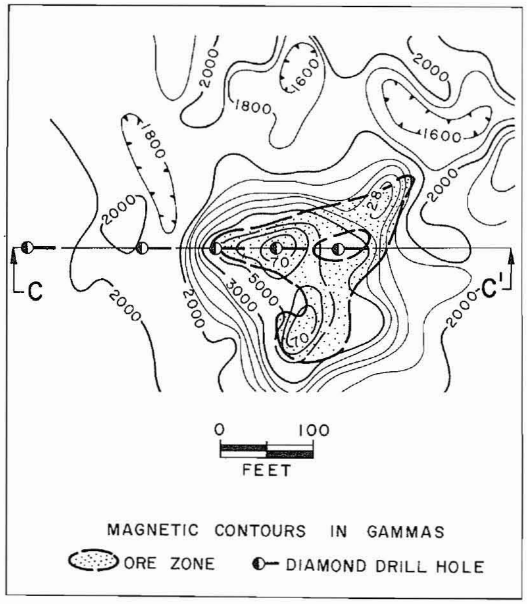

Figure 15. Detail ground magnetic survey, Maclennan mine.

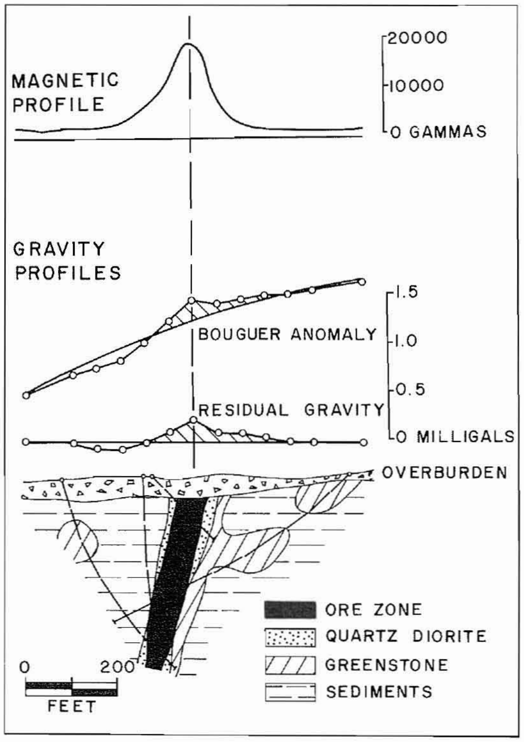

Figure 16. Gravity and magnetic profiles, Garson offset sulphide deposit.

Table II. Geophysical and geochemical techniques used in the search for nickel in Canada and the tropics and subtropics.

Survey	Purpose
Canadian Conditions	
Airborne magnetometer	To locate basic and ultrabasic rocks and to locate sulphides
Airborne electromagnetic	To locate sulphides
Ground magnetometer	To delineate basic and ultrabasic rocks and to locate sulphides
Ground electromagnetic	To locate sulphides
Induced polarization	To locate small or weakly disseminated sulphide bodies
Self potential	To delineate sulphide bodies under shallow uniform overburden
Gravity	To delineate sulphide bodies under shallow uniform overburden
Tropical and Subtropical Conditions	
Airborne magnetometer	To locate basic and ultrabasic rocks and to locate sulphides
Induced polarization	To locate sulphides
Ground magnetometer	To delineate basic and ultrabasic rocks and to locate sulphides
Geochemical	To locate basic and ultrabasic rocks and to locate sulphides
Resistivity	To delineate conductive laterites

In the tropics, as in Canada, magnetic methods are useful for locating and delineating basic and ultrabasic rocks and for directly locating nickeliferous sulphide bodies.

Geochemical techniques can be useful adjuncts to geophysical exploration programs for nickel in tropical and subtropical areas, if samples can be taken below the transported soil and duricrust or calcrete horizons. Geochemical methods can be useful in locating ultrabasic rocks, as well as directly locating nickel bodies, as these rocks normally have a constituent nickel content of 0.1 to 0.2 percent.

Laterites. In tropical and subtropical areas nickel can occur in economic quantities and concentrations in laterites. Here again geophysics can play a role in finding and delineating these bodies.

Nickel-bearing laterites result mainly from weathering and erosion of basic or ultrabasic rocks. As these rocks are commonly magnetic they can often be located and delineated with magnetic methods.

The nickel-bearing horizon is a soil which is generally clay-like in appearance with a very low resistivity. Preliminary work indicates that in some cases this clay-like horizon can be delineated with a resistivity survey.

Summary

In conclusion, Table II summarizes in tabular form the geophysical and geochemical techniques in use today that are applicable to the search for nickel under the two sets of environmental conditions discussed, namely the Canadian Precambrian Shield, and areas of the tropics characterized by highly conductive overburden. There are, of course, exceptions to all rules, and special situations may require an unusual approach; however, the methods discussed are the currently favoured methods and barring unforeseen developments are expected to prevail for some time.

Acknowledgments

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Discussion on Geophysical Exploration Methods for Nickel, by J.S. Dowsett.

Edwin Gaucher, Soquem, Canada. What have your experiences been in using gravity to separate graphitic conductors from sulphide conductors?

J.S. Dowsett, International Nickel Company, Canada. We have been very unfortunate except in areas where the overburden is thin. We found that changes in overburden thickness often produce anomalies that have the same general magnitude as do those expected from a nickel sulphide body. That is why gravity techniques are not very useful unless you can demonstrate, through experience, that the area you are working in has reasonably light overburden. In some areas, such as the Chibougamau area in northwestern Quebec, we have been quite successful with gravity techniques in separating graphite conductors from sulphide conductors. But it is not a universally applicable tool.

Alex Becker, Geological Survey of Canada. Did you find that in your airborne EM work you came across areas, say in northwestern Quebec, where you had a steady background level over which you would then be detecting your conductors? What I'm driving at is: Did you find any one area as compared with another area that gave a higher ground effect to your system?

Dowsett. Perhaps the problem you are trying to describe is whether widely spread horizontal conductors, such as conductive overburden, give a response with the airborne technique. Is that what you mean?

Becker. Yes, but I am particularly interested, because you have done rather extensive work, in whether you have found that in some areas it is worse than in others. Could you tell us which areas are the worst.

Dowsett. We would have to refer to a map to describe exactly where the bad areas are, but there are bad areas, this is quite true. In the early days we had a lot of trouble with overburden problems. We have largely eliminated them now in Canada by the reduction of frequencies to those which, in general, do not respond to overburden conductivities such as exists in the Canadian Precambrian Shield, although there are some areas, just northwest of Timmins for instance, in which the overburden seems to be extremely conductive and we do have trouble in such areas to a minor extent. I don't think there is any place in Canada, in the Canadian Precambrian Shield, where overburden problems are so serious that we are not successful with our airborne electromagnetic techniques. Does this answer your question?

Becker. Perhaps the question itself was a bit misleading. I didn't really want to know which areas give your system the most trouble. The fact is we are interested in the electrical properties of overburden and I was just curious to know where there might be a good place to go to study these effects.

Dowsett. You're looking for an area where there is no conductivity in overburden, is that it?

Becker. Difficulty with the overburden.

Dowsett. Such as high conductivity?

Becker. Yes. You've answered the question. Thank you very much.

Norman Paterson, Huntec Ltd., Canada. I have a comment here. Most of us are looking for sulphide bodies, and the overburden is the geologic noise that we are trying to remove. The people in the Geological Survey are trying to solve the inverse problem; to measure overburden thickness and overburden conductivity and this becomes the signal then, rather than the noise. For many years we have been coping with this background noise – filtering it, interpreting it out and doing practically everything we can to get rid of it and now you are trying to get it back in again.

William Dolan, Newmont Mining, Canada. Have you had an occasion to make any exact conductivity measurements at the Thompson orebody?

Dowsett. No we haven't. We've drawn some inferences from interpretation from airborne curves but haven't made a direct measurement. We have made very crude estimates of conductivity-thickness product and this is in a low order of magnitude. I haven't looked up the figures to be 100 per cent sure that the figures I gave are correct, but even then, it would be a crude figure.

Dolan. Like ten maybe?

Dowsett. In that order of magnitude. I was thinking of even less than that, in the region of one – perhaps between one and ten.

Paterson. International Nickel is known for doing ground follow-up work with vertical-loop methods and perhaps drilling more conductors than many companies do. Other companies may prefer to conserve drilling funds in order to explore different areas, doing their skimming, so to speak, by interpretation, using probably more sophisticated ground EM techniques such as in and out of phase measurements and especially more gravity. I would like to know if you would care to comment on this and whether you have any definite philosophy.

Dowsett. Well the philosophy that we follow is much as you have described. I think you are quite right that we do drill more conductors than other people. The use of horizontal-loop techniques over an individual conductor does give some indication of the range of the conductivity-thickness product, quite true; but if we came up with a figure of say 30 for the conductivity-thickness product, we couldn't really be sure that the correct answer wouldn't be half that, or twice that, while the positive results will come from the drilling. To be 100 per cent sure that you are not walking away from an orebody, if there is a reasonable conductor indicated, the only conclusive way to solve the problem is to drill. I know this can be very expensive in some areas. There are areas where we have had good geologic environment and we've drilled quite a number of conductors, perhaps more than was justified. Nonetheless, it is a procedure which might prevent you from walking away from an orebody because the situation was a little different from what you had predicted.

Paterson. I still feel that, as exploration people, we have to be very probability conscious and accept the fact that we could walk away from orebodies. After all, we are only looking down 200 feet, and we are going to be walking away from thousands of orebodies that are deeper than that, so we are always going to be walking away from orebodies. Our problem is to maximize the gain we get from an exploration program: for every dollar spent we are to make sure that we get maximum dollar return. That is my feeling about what our job is as exploration people. This is why I wonder whether this philosophy (which I don't argue with) of drilling the conductor as a conductor is, in your mind, a better one than trying to interpret, or to carry interpretation one step further and drill fewer anomalies with the possibility of walking away from some orebodies.

Dowsett. Just let me enlarge on it a little bit. We don't, by policy, drill everything. We are essentially looking for nickel and the philosophy we follow generally dictates that there be a magnetic anomaly associated with the conductive bodies. If we find a conductor with no magnetic association, we may drill it if the geology is extremely favourable and the conductor is quite strong, but generally speaking in our broad exploration policy, this type of conductor would not be considered as a prime target. We also filter out conductors that don't appear to be too strong. Where the cut-off is, varies from area to area, depending on the geological conditions. Other facts are taken into consideration too including transportation facilities and the closeness to Sudbury. Our policy isn't just blanket drilling of everything, by any stretch of the imagination.

This is the type of question a geologist might ask. We have dealt with the probability of finding an orebody with different procedures and my experience is different from his experience. I was wondering if somebody else would care to give his experience on the general probabilities of airborne EM developing an economic orebody.

D.W. Wagg, Geoterrex Ltd., Canada. I am not going to speak as an authority, but I would like to make one comment. Someone made the remark (true or otherwise) that International Nickel spends about a quarter of the total amount of exploration money spent in Canada, but they don't have a quarter of the orebodies. One could draw the conclusion, perhaps, that theirs is not the optimum way of doing it. However, we may be neglecting the fact that a very large number of companies who optimize all the factors, in their opinion at least, have a good deal less return than INCO. It's not all an open-and-shut case I would feel, and each person would have his ideas of percentage returns, depending on the practice that was used.

Contents

Geophysical aspects of porphyry copper deposits

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Abstract. Porphyry copper deposits are an increasingly important source of the world's copper and molybdenum. 'Porphyries' are often defined from an economic and engineering standpoint rather than from specific geophysical and geologic characteristics. However, these deposits have a general range of physical properties which guides exploration procedures.

There are several pertinent facts concerning distribution, age and geochemistry of porphyry deposits, as they are known in southwestern North America. Regional geophysical studies can locate broad linear structures and favorable ore environments. In a global sense, the world's porphyry copper occurrences appear to be related to structures of the type associated with midoceanic ridges.

Most geophysical methods are indirect in their application to discovery of porphyries, but these techniques supply important information about related structure and lithology. Induced polarization (IP) surveying often directly indicates the presence of even weak sulfide mineralization, and thus it is a popular geophysical means of exploring for these deposits. An integrated program of several geophysical methods with strong geological and mining assistance appears to be the search procedure in most common use today.

The application of such methods is illustrated by examples of geophysical results and interpretation of data from southwestern North America.

Résumé. Les gisements de cuivre porphyritique représentent une source de plus en plus importante de cuivre et de molybdène dans le monde. Les porphyres sont souvent définis en termes d'économie et de technique plutôt qui suivant leurs caractéristiques géophysiques et géologiques. Ces gisements ont, cependant, un ensemble général de propriétés physiques qui servent de guide au choix des procédés d'exploration. Certaines données intéressantes se rapportant à la répartition, l'âge, et la géochimie des gîtes de porphyre du sud-ouest de l'Amérique du Nord sont connues. Il est possible, par des études géophysiques régionales, de localiser de larges structures linéaires ainsi que des milieux propices à l'existence de minerais. Les gisements de cuivre porphyritique dans le monde sont en général liés à l'existence de structures associées aux rives mi-océaniques.

La plupart des méthodes géophysiques s'applique d'une manière indirecte à la découverte des porphyres, mais ces techniques fournissent des renseignements importants sur les problèmes de structure et de lithologie qui s'y rattachent. Les mesures de polarisation provoquée (PP) révèlent souvent d'une manière directe la présence de minéralisations sulfureuses même faibles; cette méthode se révèle donc un moyen géophysique populaire de recherche de ces gisements. La mise au point d'un programme comprenant l'intégration de plusieurs méthodes géophysiques s'appuyant sur des activités géologiques et minières semble donc se présenter comme le processus classique suivi dans la plupart des cas aujourd'hui.

Although an impressive and ever-increasing percentage of the world's copper production (Figure 1) comes from porphyry-type deposits, geophysical methods have not been exploited for their discovery to the same extent as for other ore types over the earth. Reasons for this are that even though porphyries are a relatively new source of metals, most of these bodies have been known for some time since they are commonly associated with smaller, higher-grade orebodies. Also they have a large areal expression and are usually found in unforested desert areas, so that less expensive geologic exploration methods have been sufficient. Finally, the contrasts in physical properties between ore and wall rock are seldom very distinctive, so that some geophysical surveys have not been very diagnostic.

As existing, more obvious copper resources are exhausted and as geophysical prospecting methods are perfected, we can expect fewer direct exploration ideas to come into vogue. Where geophysics heretofore has been usually restricted to use as a direct ore-finding tool, there is an increasing trend toward integration of techniques, with more dependence on a variety of exploration viewpoints. Often in the past geophysics has been oversold to exploration managers, so that there is the task of our putting these methods in their proper economic perspective. There is also the ever-present problem of properly educating responsible exploration personnel in the capabilities and limitations of new concepts in the continually changing fields of scientific prospecting.

Several good articles on the application of geophysics to porphyry copper deposits are included in the Society of

WORLD COPPER PRODUCTION, 1962
THOUSANDS OF TONS

	TOTAL	PORPHYRY	
USA	1,228	921	
CANADA	465	—	
MEXICO	52	43	
CHILE	646	581	
PERU	183	165	
EUROPE	219	—	
USSR	700	?	
ASIA	362	—	
AFRICA	1,059	—	
AUSTRALIA	118	—	
WORLD	5,050	1,710(?)	34 % (?) PORPHYRY
WESTERN HEMISPHERE	2,584	1,710	66 % PORPHYRY

Figure 1. Information on world copper production, by the U.S. Bureau of Mines, after McMahon (1965).

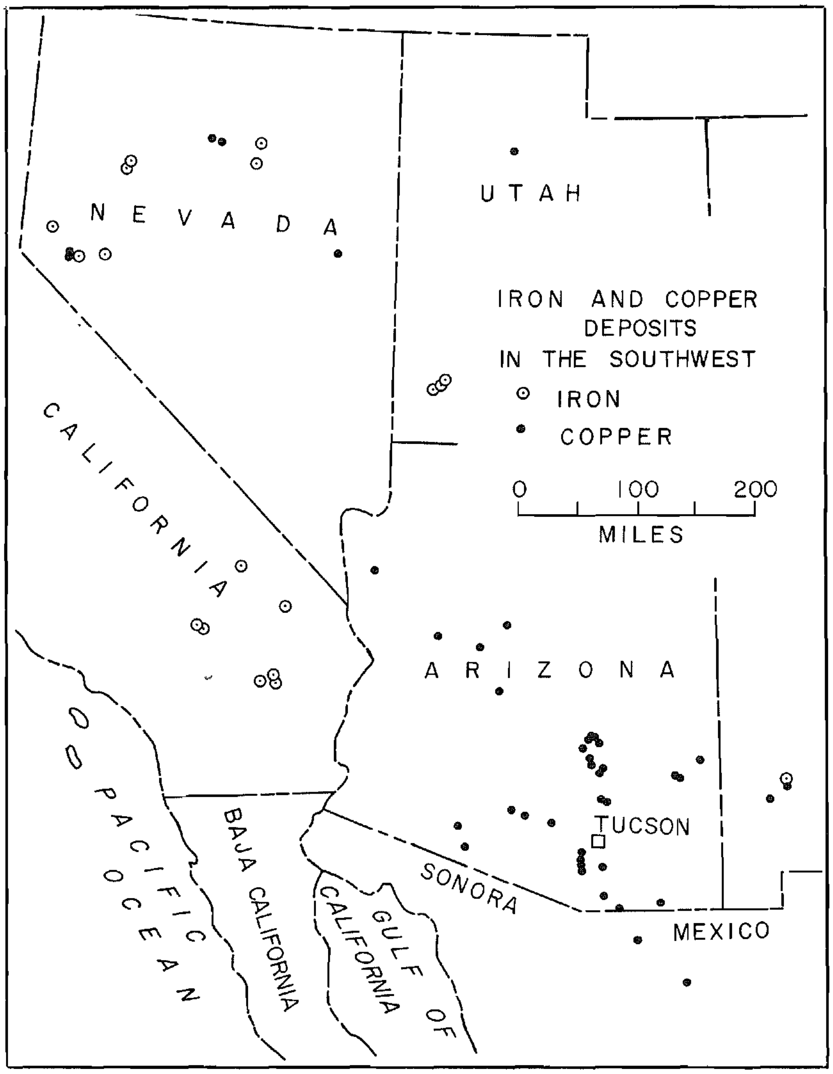


Figure 2. Iron and copper deposits in southwestern North America, implying regional zoning.

Exploration Geophysicists' volumes of *Mining Geophysics* (1966). Brant (1966) has nicely summarized the direct use of physical methods in his recent review. Good papers by Seigel (1959) and Baldwin (1959) have appeared in the pioneering volume edited by J.R. Wait (1959) entitled *Overvoltage Research and Geophysical Applications.* Heinrichs and Thurmond (1956) have described the discovery of the Pima Mine near Tucson, Arizona, which triggered a very sizable mining boom in the Twin Buttes district.

The purpose of this paper is to present and emphasize the regional geophysical environment of porphyry deposits rather than review specific local details. Some discussion of induced electrical polarization, is, of course, needed because of the unique potential this method portends to porphyry copper exploration. If mention of the South American deposits seems neglected, it is because they are less well known and space does not permit their inclusion.

Porphyry copper deposits

Definition. There are different definitions of what is meant by the term 'porphyry copper deposit', according to various local and engineering, geological, or perhaps geophysical prejudices. In the limited parts of the world where they are found, almost any large, low-grade copper occurrence would automatically qualify in the engineering definition of a porphyry copper, whether or not the texture of the orebody is porphyritic, or even if it is not an intrusive igneous rock. Bulk-handling mining methods are usually necessary. By common convention, a porphyry copper deposit can be defined for the exploration man by the criteria listed in Table I.

Table I. Distinguishing features of porphyry copper deposits.

1. Associated with intrusive, porphyritic igneous bodies.
2. Consisting of disseminated sulfide mineralization in large part.
3. Containing large tonnage of low-grade ore; bulk mining methods apply.
4. Often secondarily enriched and extensively altered.
5. Usually carrying molybdenum and minor gold and silver.

Porphyries of the southwestern United States. The best recent geological reviews of the several deposits in southwestern North America are compiled in a volume edited by Titley and Hicks (1966), which also contains the Brant (1966) article mentioned previously. References included in this book would make up a

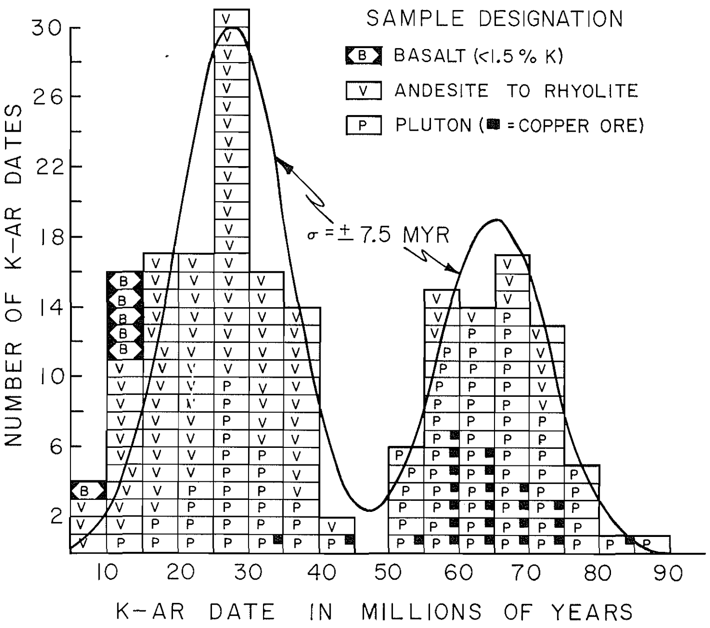


Figure 3. Histogram of potassium-argon dates of rocks in the Basin and Range province, after Damon and Mauger (1966).

rather comprehensive geological bibliography on the subject.

Figure 2 is a map showing the locations of porphyry deposits in the Southwest. These deposits constitute part of a large metallogenic province which is regionally zoned by certain important geochemical characteristics. The geophysical prospector must make observation of the mineral assemblages and their relationships which determine the physical properties of these bodies. The magnetic minerals magnetite and pyrrhotite are usually rare in most of the deposits in the interior of the province, and one gets the distinct impression that there must have been an excess of sulfur here during the process of copper mineralization. Brant (1966) invites attention to the fact that most Laramide intrusive rocks in this region have a low magnetic susceptibility. Magnetite is also destroyed during weathering of related sulfide bodies and is commonly altered by hydrothermal alteration processes which accompanied sulfide mineralization. All these factors combine to make the magnetic method only an indirect exploration technique in the region. Magnetite becomes more prevalent with mineralization in deposits in surrounding areas in Nevada, Utah, and New Mexico. It is interesting that the large, central, oval-shaped porphyry zone is thus bordered by copper-iron porphyry occurrences and finally by magnetic iron replacement deposits. The source of copper and sulfur must have been deep in the earth's mantle, if it is related to the width of this broad metallogenic province.

Age of deposits. Evidence that porphyry deposits of the Southwest are genetically and temporally related is given in Figure 3 (after Damon and Mauger, 1966). The median age of intrusive rocks associated with copper mineralization here is 65 million years, effectively that of the Laramide revolution of early Tertiary time. Damon presents a convincing picture of pulselike periods of datable thermal events related to mineralization in the Southwest. There are also older copper deposits in this region such as the Mesozoic, pre-Cretaceous Bisbee orebody (Bryant and Metz, 1966) and the Precambrian United Verde massive sulfide deposit at Jerome, Arizona. The mid-Tertiary Bingham Canyon, Utah, and Railroad Valley, Nevada, deposits are the youngest. There is little doubt that geochronology is a useful guide to mineralization and can be a prospecting method in its own right.

Regional structural environment. The tectonic history of the Southwest is important to the study of the porphyry deposits. Regional geophysical mapping is useful for this purpose. The present mechanisms of movements in the deep crust and upper mantle as applied to the past are meaningful.

The Texas zone. Mayo (1958) and Schmitt (1966) have found a major regional structural control of the Southwest copper deposits and have called attention to the west-northwesterly

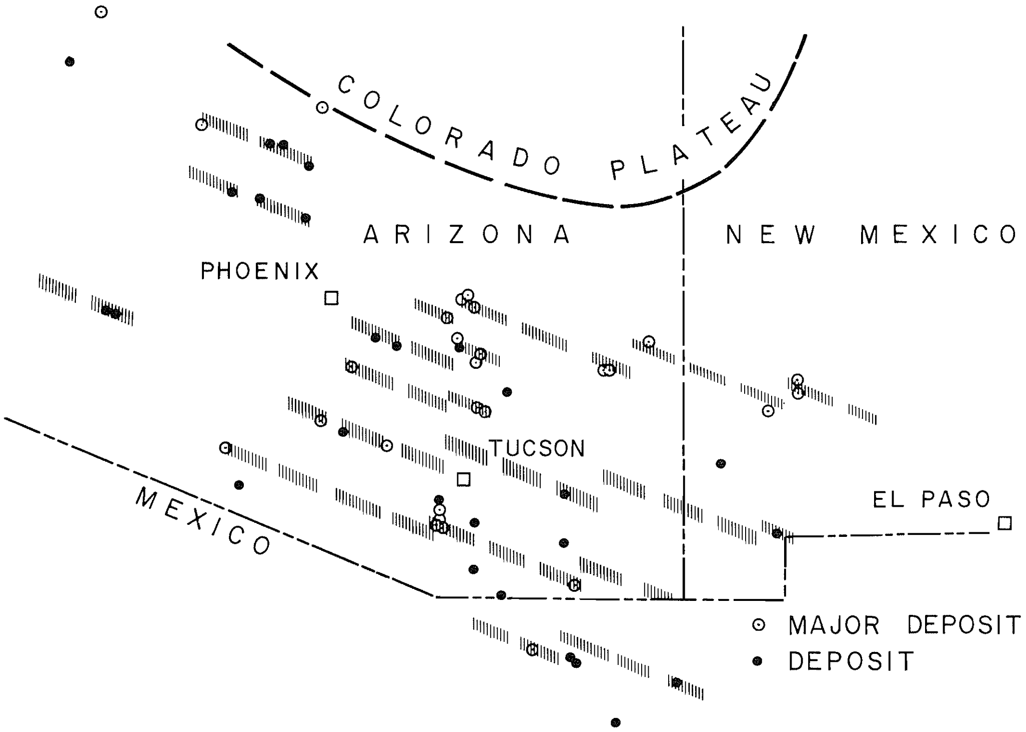


Figure 4. The Texas lineament zone in the Southwest.

Contents

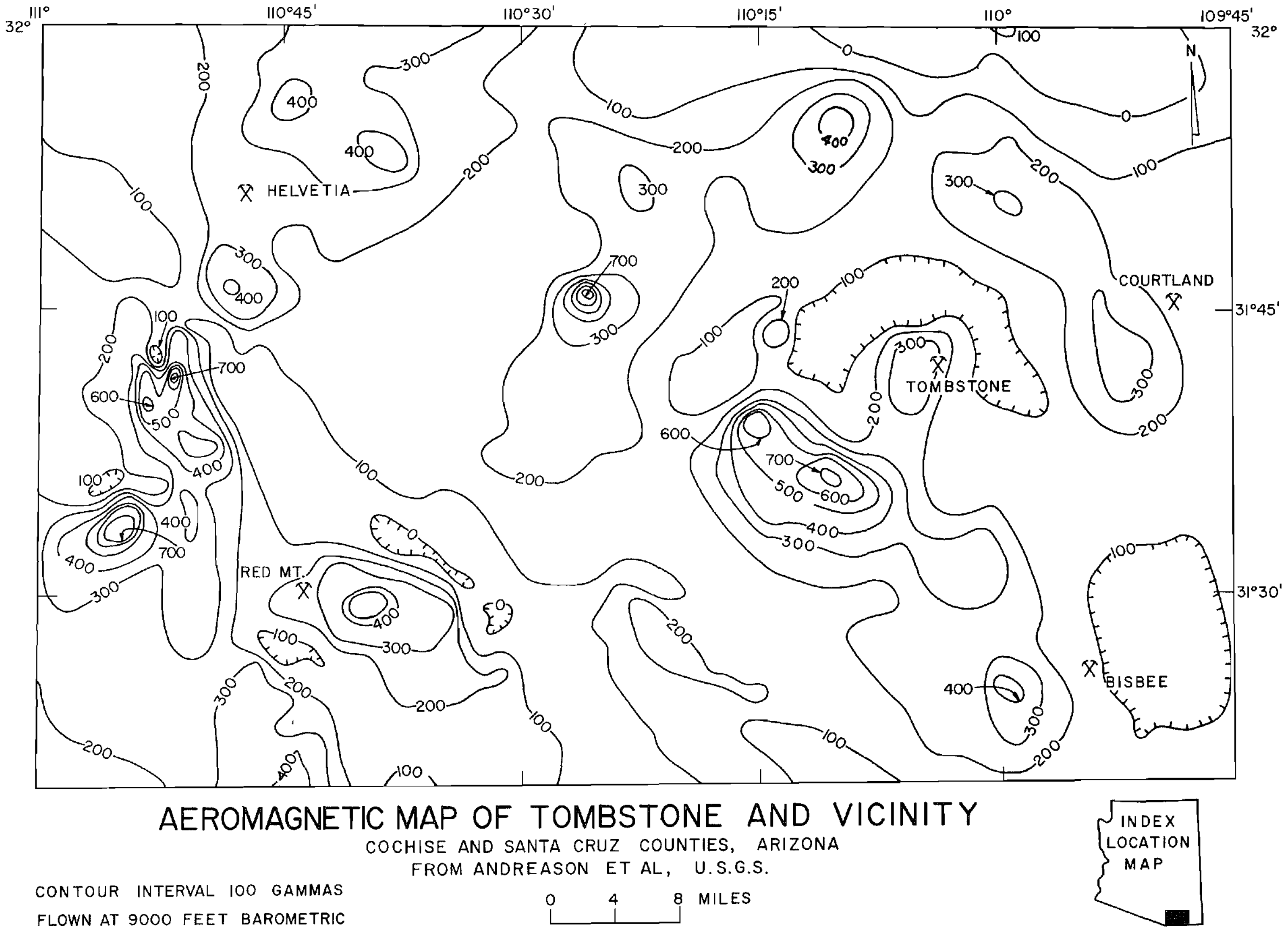


Figure 5. Aeromagnetic map, with regional gradient removed, of part of southern Arizona, after Andreasen, *et al.* (1965).

trending Texas lineament. Figure 4, this writer's version of the Texas zone, is mainly a compilation of experience with deposits in the region.

The Texas zone is not necessarily prominent in all of its many characteristics, but it is the principal, most consistent, linear crustal feature that is associated with mineralization. It is almost parallel to the southern edge of Arizona in the western part of the state. Early travelers and later border surveyors found the boundary trail to be the easiest topographic route to the Colorado River.

Some persistent north-northeast trending offsets in the Texas zone are to be seen (Figure 4) which seem to be more recent in age. These offsets may, however, be related to an older, underlying Precambrian 'grain' in the Southwest. There is also an alignment of deposits in a north-south direction through Tucson, Arizona, which Schmitt (1966) related to the Jerome-Wasatch zone.

The Texas zone and the north-northeasterly trends are sometimes observed in regional geophysical surveys, as seen in the aeromagnetic map of Figure 5. A regional gradient of 10.85 gammas per mile increasing to the north-northeast has been removed. The porphyry copper deposits of Bisbee, Courtland, and elsewhere lie on the convex side of regional, broad, arcuate positive magnetic anomalies that are probably related to the edges of deep, intersecting lineament structures. Some of the mines shown here (e.g., Tombstone) are not porphyry deposits.

West Coast fault zones. While investigating the regional structure of the Texas zone one must also inquire into the present complex fault relationship given on Figure 6. Movement along the San Andreas fault zone apparently has been taking place since Cretaceous time (Hamilton and Myers, 1966), so during porphyry emplacement the Texas lineament may have been physically related to this system.

Presently active, *en echelon* faults in the Gulf of California are subparallel to the Texas zone. There is recent copper

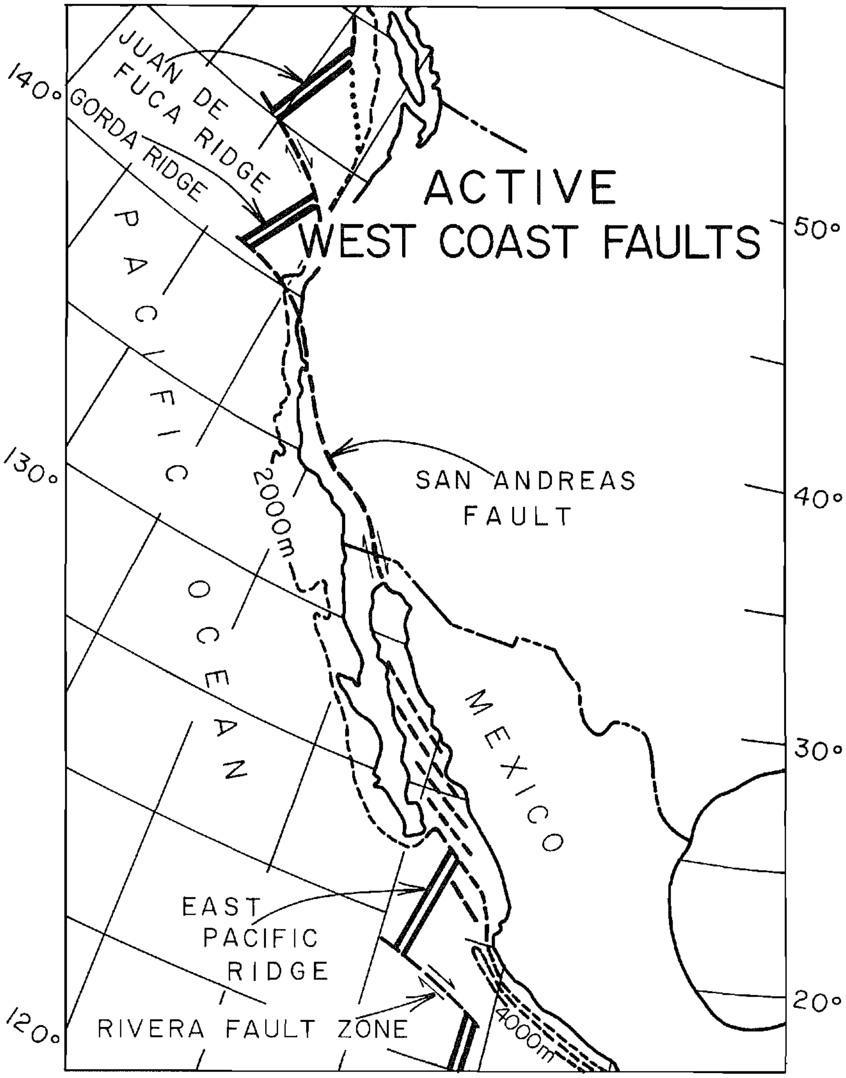


Figure 6. Major faults on the west coast of North America.

mineralization in Baja California at Santa Rosalia, which may be the product of a modern porphyry-type intrusive at depth. Copper geochemical anomalies have also been found along the East Pacific Ridge (Bostrom and Peterson, 1966), and this ridge may even now underlie the western United States as it probably did in Tertiary time.

The *en echelon* faults in the Gulf of California are conspicuous on the bathymetric map (Figure 7) compiled by Rusnak, *et al.* (1964). Even with a 200-fathom contour interval the underwater scarps are quite prominent, being somewhat better preserved from erosional and depositional processes than subaerial features. The earth's crust is thin (averaging 7.3 km) in the deeper southern Gulf of California, which allows tectonic structures originating from the mantle to be more clearly revealed. Santa Rosalia and Volcan Las Tres Virgenes are located at a major structural intersection. Geophysical surveys in the Gulf of California by Harrison and Mathur (1964) and others substantiate this general structural situation.

The fault mechanism of the San Andreas zone is apparently related to transform faulting on the Gorda and East Pacific Ridges, as was pointed out by Wilson (1965). A transform fault has been defined as one in which spreading segments of ocean floor move past one another, as shown on Figure 8. Purely transcurrent faults move in the opposite sense from the standpoint of direction of ridge offset. Judging from studies of symmetrical magnetic anomalies found parallel to ocean floor ridges (Vine, 1966) and from earthquake mechanism interpretation (Sykes, 1967), the concept of transform faulting is valid. An example of a transform fault is seen in the Rivera fracture system which offsets the East Pacific Ridge shown on the lower part of Figure 5. Such structures surely must have existed in the past as they do in the present, and the Texas lineament strongly resembles presently known transform faults. This idea is not altogether new. Schmitt (1966) has correlated the Texas system with the east-west trending scarps (fracture zones) which extend offshore from coastal California. It now seems evident that these zones represent formerly active transform faults. They probably are old extensions of the Texas zone, even in view of the apparent offsetting effect of the related, continent-bordering San Andreas fault.

The north-south alignment of tensional structures and normal faulting which is so common in the Basin and Range province are probably best explained by the concept of crustal spreading brought about by past activity of an underlying East Pacific Ridge.

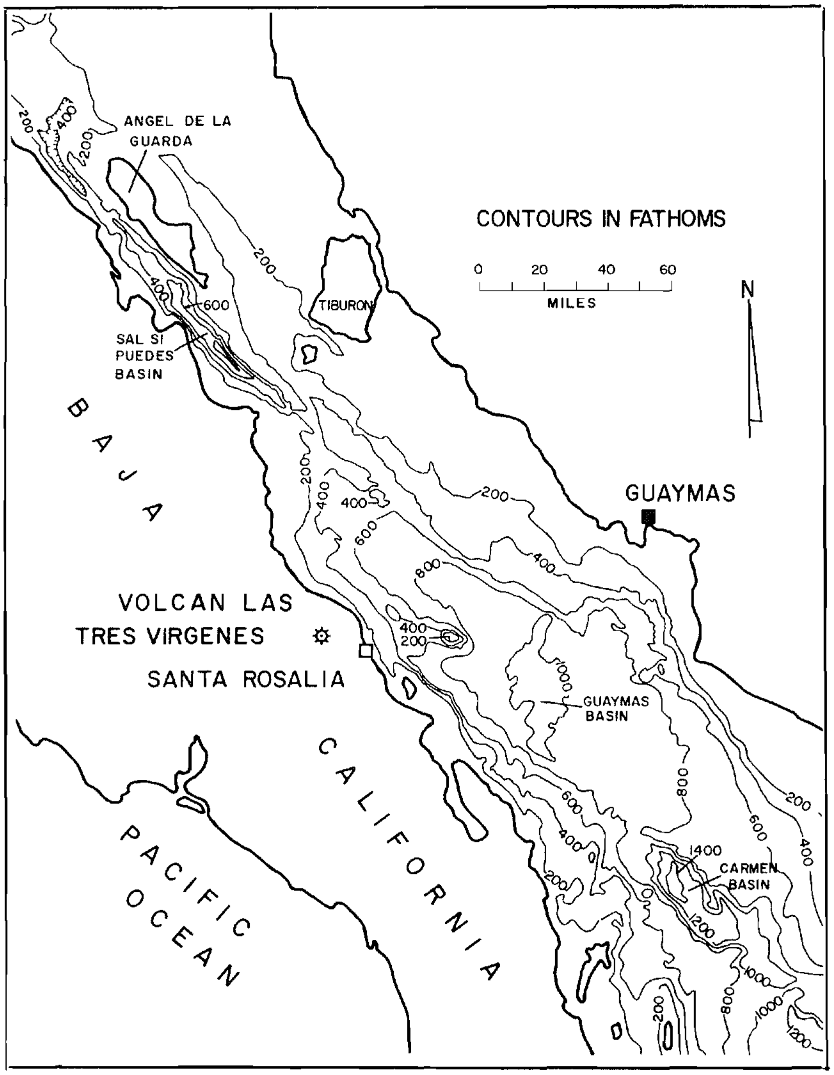
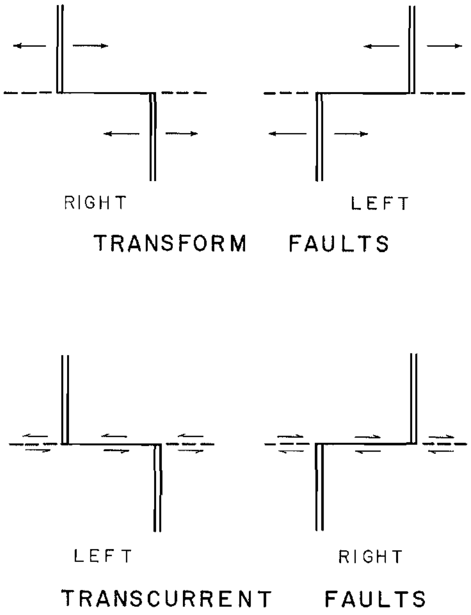


Figure 7. Bathymetric map of part of the Gulf of California, after Rusnak, *et al.* (1964).

Figure 8. Types of major displacement strike-slip faults.



Regional geophysical mapping

Heat flow. Heat flow measurements in the Southwest (Figure 9) show that the Basin and Range province has anomalously high values; the average background for continents is 1.4 microcalories per square centimeter per second. Roy (1967) interprets this to be residual deep heat from the Laramide and later orogenies.

Refraction seismic and magnetotelluric measurements. From refraction seismic determinations by the U.S. Geological Survey (Pakiser, 1963), the Mohorovicic discontinuity is interpreted to be relatively shallow in the Basin and Range region, and underlying seismic velocities and densities are anomalously low as shown on Figure 10. Magnetotelluric surveys in this region (Swift and Madden, 1967) reveal much higher electrical conductivities in the upper mantle than are found elsewhere, and these are attributed to higher temperatures. Shallow-focus earthquakes in the Southwest occur along north-south linear zones in western Arizona and southeastern California. Since most of the conditions described above are also found in data from midocean ridges, the correlation of tectonics appears strong.

Gravity. Proper station spacing in regional gravity surveys in the Southwest is important in bringing out structural detail because

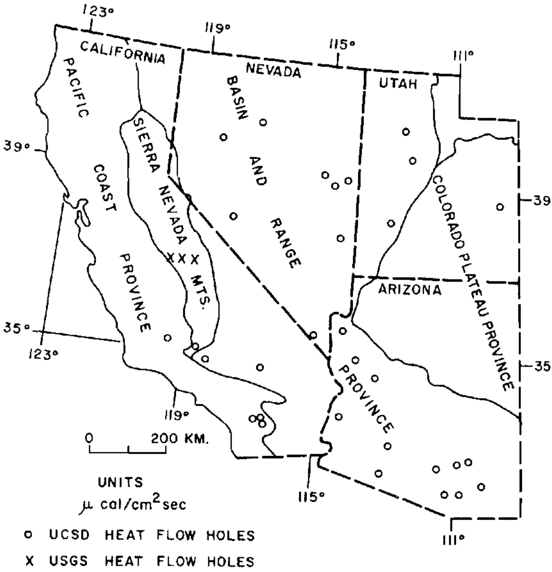


Figure 9. Preliminary heat flow data from the Southwest, after Roy (1967).

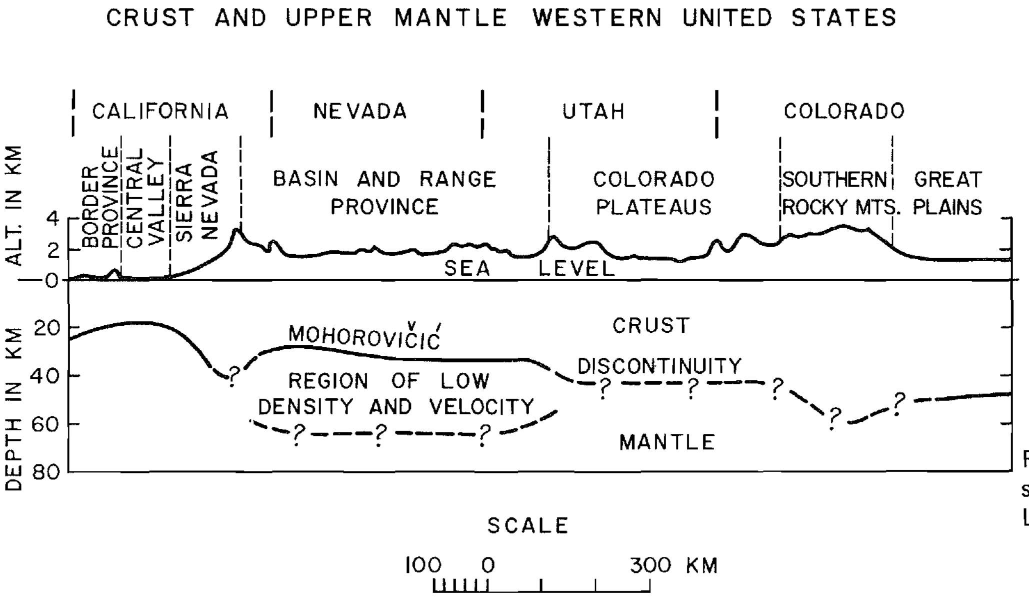


Figure 10. Interpreted refraction seismic section from San Francisco, California, to Lamar, Colorado, after Pakiser (1963).

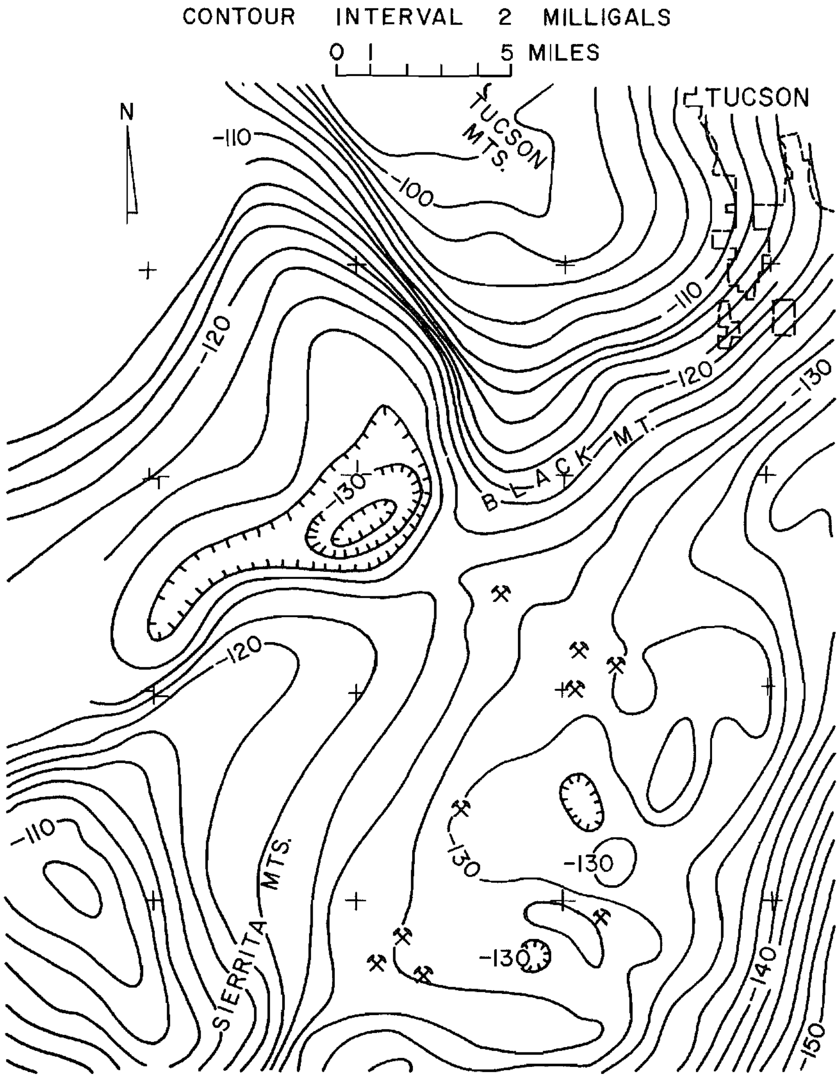


Figure 11. Gravity map of the Twin Buttes mining district, Arizona, after the U.S. Geological Survey (Plouff, 1962) and the University of Arizona (Davis and Sumner, in press).

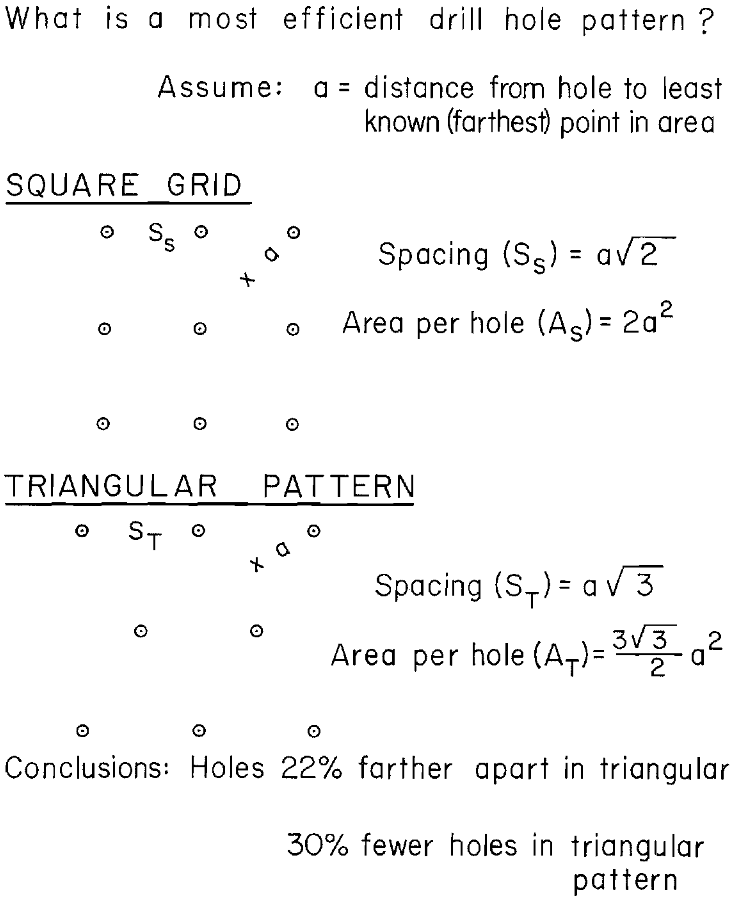


Figure 12. Optimum search and sampling pattern, using drilling sites as an example. *X* is the distance from near drill holes to the least known (farthest) point.

widely scattered stations will not outline shorter wavelength anomalies. Elevation influence on Bouguer gravity anomalies amounts to an areal average of about 32 milligals decrease per 1000-foot increase, giving pronounced regional gravity effects caused by regional isostatic compensation. Figure 11 is a fairly typical gravity map showing regional structure in the Tucson, Arizona area including the Twin Buttes mining district. The average density of gravity readings here is about one station per square mile. The prominent east-northeasterly trending Black Mountain fault separates the volcanic Tucson Mountains to the north from the granitic Sierrita Mountains which rise west of the open pit mines. No obviously important structures directly related to known mineralization are on this particular map, but the presence of concealed scarps certainly limits selection of likely exploration areas. Gravity surveys are useful in disclosing pediments which are not too deep for exploration.

The search problem

Principles of operations research apply to an optimum search and sampling problem, as posed by exploration for ore deposits. Operations research is a scientific method of attacking problems to provide data which can be used as the basis for decisions. Target size, relative dimensions, distribution, and physical properties and their contrasts must be related to the limits and capabilities of the measuring system. Slichter (1960) has pointed out that the size-range of deposits in the Basin and Range province is approximately log-normal, i.e., there are fewer of the larger deposits. Slichter also shows that deposits in Southwest mining districts are not randomly scattered in areal distribution but are strongly clustered. This information is not new to the professional exploration man, who stands by the axiom that a good place to look for new mines is near old ones.

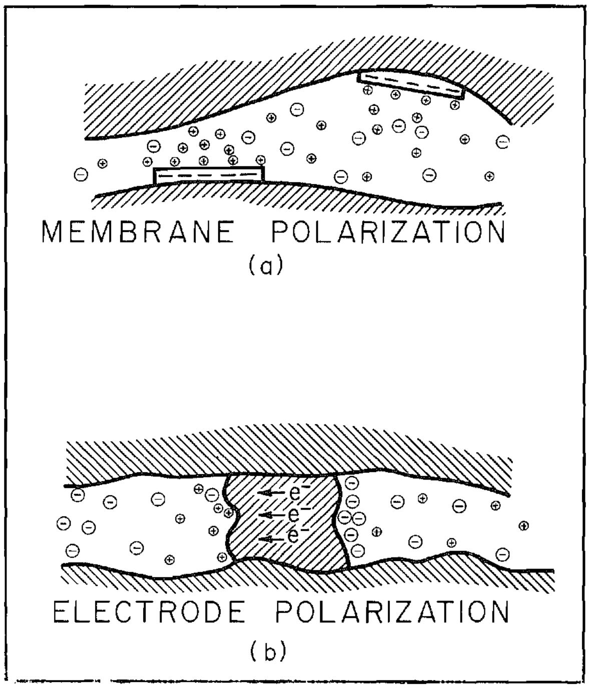


Figure 13. Induced polarization mechanisms in rocks, on a microscopic scale, showing ions in pore fluids.

A simple example of an optimum search procedure, based on a regular drill pattern for sampling the subsurface, is seen in Figure 12. From the initial condition that the distance from holes to the least known (farthest) point on triangular and rectangular grids is the same, one can show that an equilateral triangular drilling pattern is 30 percent more efficient than a square grid. Assumptions are that the subsurface distribution of mineral values is unknown or is apparently homogeneous and isotropic, which can first be verified by geophysical and geological surveying.

Induced electrical polarization

The IP phenomenon. Most of the physical property contrasts between mineralized porphyry bodies and enclosing rock are not distinctive, except for the induced polarization effect. Even here there are definite exceptions, so that one must use this more expensive geophysical technique with some discretion. Thus, though it can be classed as a direct exploration method for sulfide mineralization, IP is not necessarily a primary means of search.

Unlike most physical properties of materials, we do not completely understand the causes of IP phenomena in rocks. Continued research progress is being made, and we can recognize several electrochemical mechanisms which are important. Ion

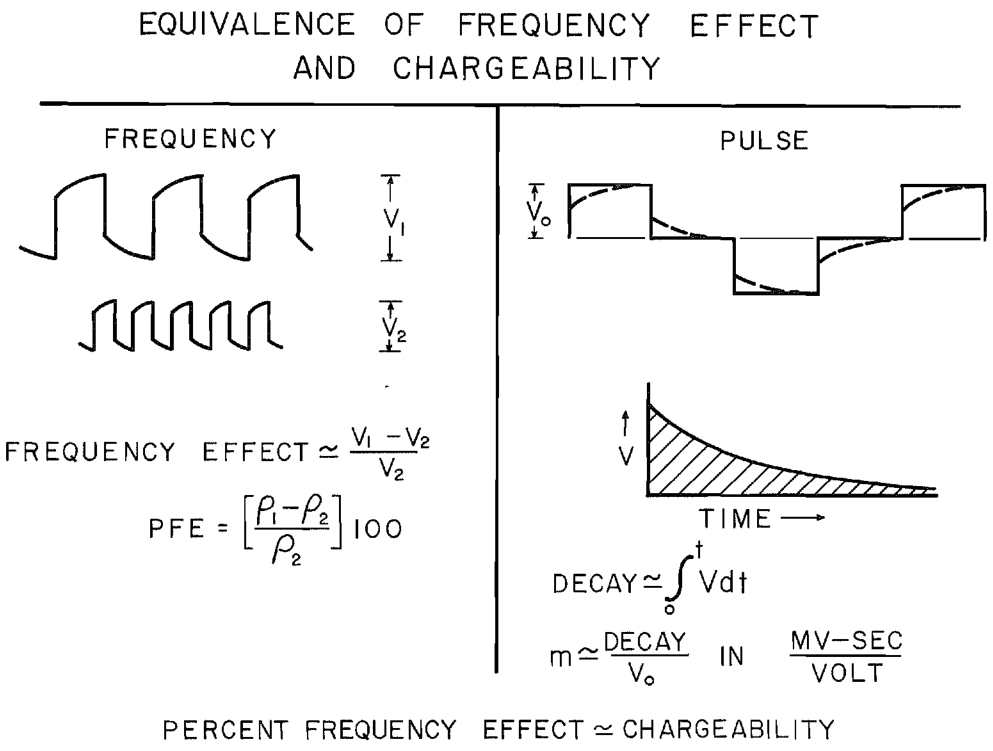


Figure 14. IP response waveforms due to a pulsed, constant-current source.

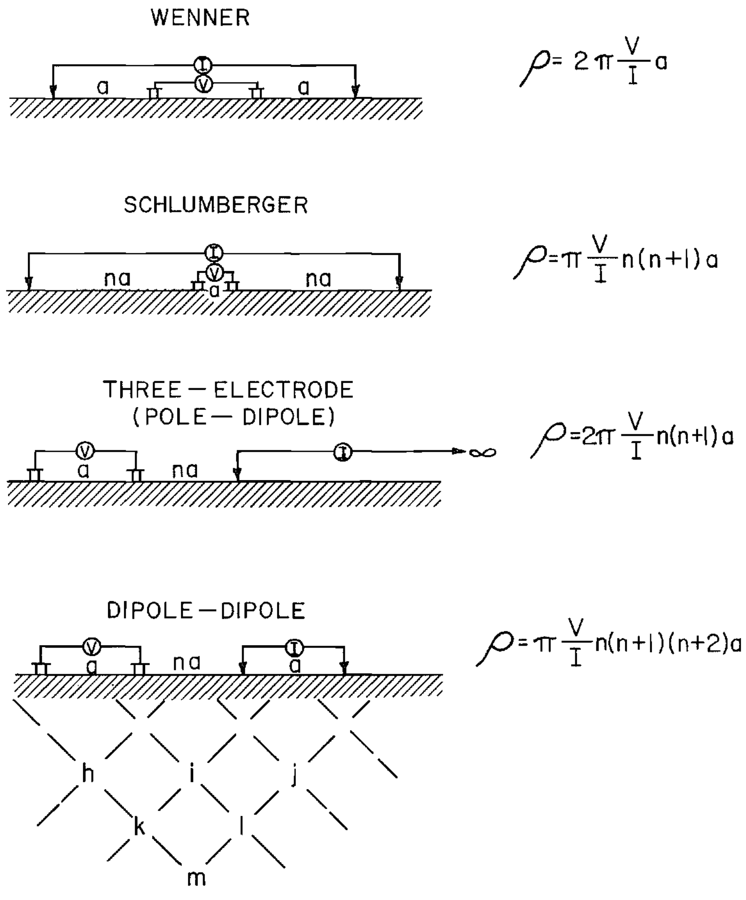
movement in pore fluids in the influence of a weak electric field plays the dominant role in each. Membrane polarization basically is due to restriction of ion mobility by nearly ion-sized pore or 'ion-cloud' constrictions. The term membrane polarization is also applied to induced polarization in any nonmetallic rock, such as is illustrated microscopically in Figure 13a. Here, if an ionic double layer which adjoins a charged particle is disturbed by an electric field, a weak IP voltage occurs as equilibrium is reestablished.

Electrode polarization refers to the voltage developed across the interfaces adjoining a metallic particle in an electrolyte, as depicted in Figure 13b. Surface area of metallic conductive particles in contact with the pore fluid electrolyte largely governs the relative magnitude of IP response. In nature, electrode polarization is much more pronounced than membrane polarization. Membrane effects in the Southwest are usually found to be associated with fibrous and layered minerals in older conglomerates, recent tuffs and volcanic rocks, and impure tremolitic limestones. Graphite is rare here, but when present it gives rise to polarization because of quasi metallic-type bonding in the basal planar lattice of its crystal structure.

Electrical properties of porphyries in the Southwest. Mineralized porphyries usually contain finer-grained sulfides and relatively large amounts of associated pore fluids, so their IP response is generally strong. As little as 1/2 of 1 percent sulfides by volume (about 1 percent by weight) gives an effect which is two or three times the normal background. In the Southwest, earlier formed syngenetic magnetite in intrusive rocks does not seem to contribute much IP response, probably because it is not in as intimate contact with pore fluids as later formed, epigenetic sulfides.

In contrast with many other continental provinces, near-surface indurated alluvium and volcanic rocks have very low

Figure 15. Commonly used IP and resistivity electrode configurations, with geometric factors.



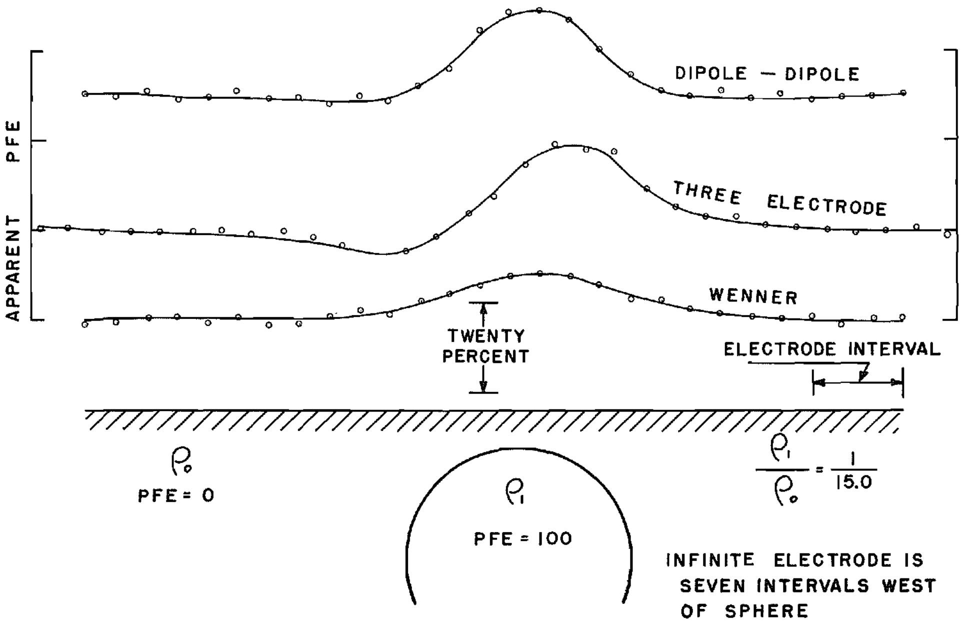


Figure 16. A comparison of profile IP results, using different electrode arrays, over a spherical body.

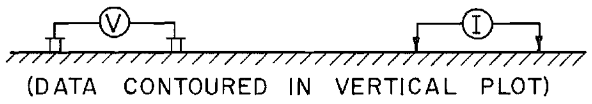


Figure 17. Advantages and disadvantages of the dipole-dipole electrode array.

ADVANTAGES	DISADVANTAGES
1. INCREASED RESOLUTION a. IN RESISTIVITY b. IN I.P.	1. NOISE FROM: a. MAGNETOTELLURICS b. TOPOGRAPHY
2. LESS SURVEY WIRE USED	2. MORE CURRENT IS NECESSARY
3. SIMULTANEOUS PROFILING AND SOUNDING	3. INVOLVED INTERPRETATION
4. SYMMETRICAL ARRAY	4. MORE ANOMALIES

resistivities in Arizona, New Mexico and Nevada. These low values are probably due to the high concentration of residual salts from chemical weathering in the semiarid desert climate. The resistivities of porphyry deposits are thus about the same as their surrounding environment.

Resistivities in brecciated porphyries are quite variable, ranging from nearly that of massive sulfides in loose and altered material to very high values in zones that have been impregnated with later invading silica. IP effects in breccias are difficult to predict. Although porphyries are often homogeneous and isotropic on a gross scale, sulfides may be disseminated, massive, or in veinlet form. The IP effects of these modes, which also involve their resistivity and membrane phenomena, apparently show variations in conductivity spectra (Fraser, *et al.*, 1964).

IP surveys in the field. Most field IP measurements in the Southwest are presently being made in the frequency domain using the dipole-dipole array. Time domain equipment was historically the first instrument system in the area, having been originally developed in Jerome, Arizona, by Newmont Exploration Limited. If the entire IP decay curve is measured, the pulse scheme has a definite theoretical advantage over the dual frequency method. Figure 14 shows response waveforms due to a pulsed, constant current source. Electronic filtering and integration usually modify this response for an appropriate readout device. The frequency and time domains are, of course, theoretically equivalent, as was reviewed by Hallof (1964).

One must specify the frequencies or pulse duration in field results, if they are to be compared to surveys elsewhere. Frequency effect is usually given as resistivity difference divided by the higher-frequency resistivity, although it would be more correct to divide by the lower-frequency resistivity.

Common IP and resistivity electrode arrays with their

Contents

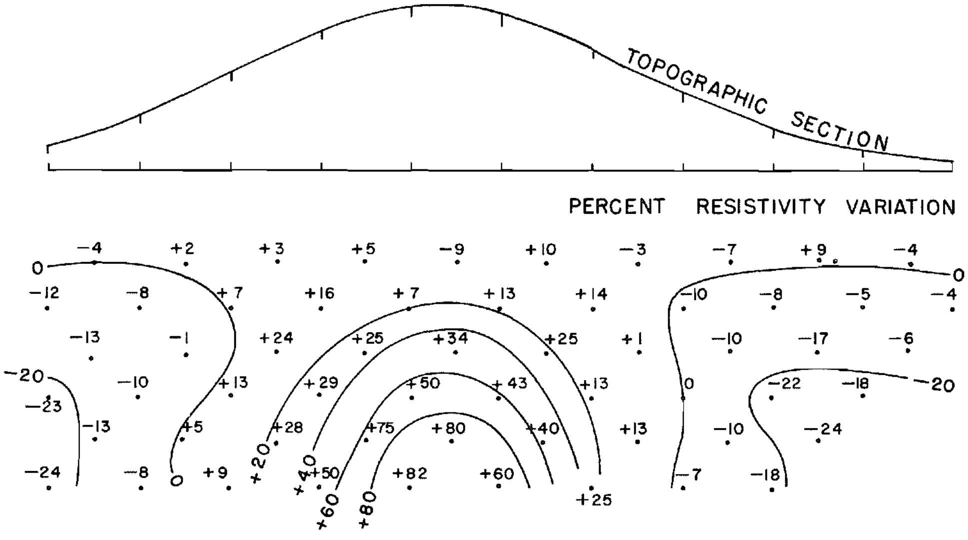


Figure 18. Percent apparent resistivity variations due to topography, using the dipole-dipole array.

geometric factors are given in Figure 15. The Wenner, Schlumberger, and Brant (gradient) arrays which are popular elsewhere are not much used in the Southwest because of greater amounts of wire required, more lengthy field procedures and noise problems. Data from the three electrode (pole-dipole) and dipole-dipole arrays can be plotted in the convention shown at the bottom of Figure 15 where *h, i, j,* etc., are the apparent resistivities or PFEs at the appropriate value of *n*. One must be careful not to view this plotting method as a section representation of resistivity or IP effect.

Deep oxidation of many porphyry deposits and thickness of postmineral cover require a greater depth of exploration with large intervals between electrodes. The larger size of porphyry bodies permits their resolution to greater depths. The pole-dipole configuration is most often used with time domain equipment, and although it is unsymmetrical it otherwise gives good response. The dipole-dipole configuration measures a higher order field, and it has better resolution. One can observe that the geometry of the electric field which is measured to determine apparent resistivity can be a basis of classification of different electrode arrays. By this token, from Figure 15 the dipole-dipole geometric factor approaching n^3a (where na is the distance between dipoles) is the expression of a higher order field. A comparison of modeled, profile IP data from arrays over a spherical body is given on Figure 16.

Advantages and disadvantages of the dipole-dipole survey arrangement are tabulated in Figure 17. Although capacitive coupling is usually nil, electromagnetic inductive coupling (which gives rise to false IP effects) still can be seriously large over low-resistivity areas if the frequencies used are too high. Also linear, grounded artificial conductors such as fences can cause false IP anomalies because of electromagnetic coupling. Magnetotelluric noise sometimes is a distinct problem at lower frequencies and must be overcome by numerical or electronic filtering, surveying in another azimuthal direction, or by surveying at another time of day. The 'brute force' solution to the noise problem is to use a higher-powered transmitter, while the more sophisticated approach is by synchronous detection and perhaps autocorrelation methods.

While variations of topography in a survey area do not cause IP anomalies, magnitudes and locations can be distorted, especially when using the dipole-dipole array. This is diagrammed by the percent apparent resistivity variations over modeled topography plotted on Figure 18. Valleys give apparent negative percentage variation in resistivity values, and hills are seemingly positive. The true resistivity variation over this modeled material is constant and repeatable to less than 2 percent before and after the experiment. Thus, in mountainous areas one must be aware that there can be strong topographic effects on resistivity measurements.

IP interpretation. Interpretation of IP results over porphyry copper bodies is usually not complicated if data are of good quality and if the survey was properly laid out. Curve-matching techniques are commonly employed to estimate depths and electrical property contrasts of horizontal and vertical contacts. Many simple, typical solutions can be derived analytically, but more complex situations require numerical or modeled approaches. Even for experienced interpreters, it is dangerous to use intuition alone to solve field problems. If they are documented in detail, case history examples are helpful experiences to all those who are involved in porphyry copper exploration.

Groups using the frequency domain have advanced the idea of using a metallic conduction factor, or metal factor (MF), in interpreting data, defining this quantity as

$$\text{Metal factor} = \frac{\text{percent frequency effect}}{\text{resistivity (in ohm-meters)}} \quad (2 \times 10^3)$$

which has equivalent parameters (Keller, 1959) in the time domain. Many people working in the time domain feel that the metal factor is frequently an unnecessary and confusing parameter and that chargeability or frequency effect is sufficient to define IP in the field. It is true that the metal factor concept can be easily abused if MF is used alone by causing unduly magnified background. Figure 19 is a brief summary of arguments for and against the metal factor. This writer feels that the metal factor can be of definite aid in interpreting porphyry conditions, but not to the exclusion of an initial thorough review of frequency effect (chargeability) and resistivity.

METAL FACTOR ARGUMENT

FOR	AGAINST
1. INCREASES RESOLUTION	1. UNNECESSARY FOR INTERPRETATION
2. GIVES CONDUCTIVITY DIFFERENCE, DUE TO MINERALIZATION	2. NO PHYSICAL MEANING
3. COMPENSATES FOR "SATURATION EFFECT"	3. MISLEADING IN LOW RESISTIVITY AREAS a. ERROR HIGH d. EM COUPLING ERRORS EMPHASIZED c. GIVES ONLY INVERSE OF RESISTIVITY
4. CORRELATES RESISTIVITY AND POLARIZATION ANOMALIES	
5. NORMALIZES POLARIZATION a. USEFUL FOR MINERALIZATION ESTIMATE	

Figure 19. Arguments for and against the metal factor.

Figure 20 is an interesting example of IP mapping over a known deposit and a recently discovered faulted segment. This survey was originally run by H.O. Seigel in 1948 near the San Manuel Mine, about 45 miles north of Tucson, Arizona. Known ore-grade mineralization near the shafts was indicated, and known pyritic mineralization west of the San Manuel fault in Section 3 was shown. Drill holes seen on the figure verified the presence of pyrite but did not go deep enough to encounter ore. Recent (1965) careful analysis of this area by J. David Lowell on behalf of Quintana Minerals Corporation revealed that the pyrite halo in the southwest part of Section 3 surrounds a downfaulted mineralized block of the San Manuel orebody. IP data did not directly contribute to this particular discovery, but they provide a realistic field example from the literature (Brant, 1966). One must conclude that the IP method alone is not enough to find porphyry orebodies.

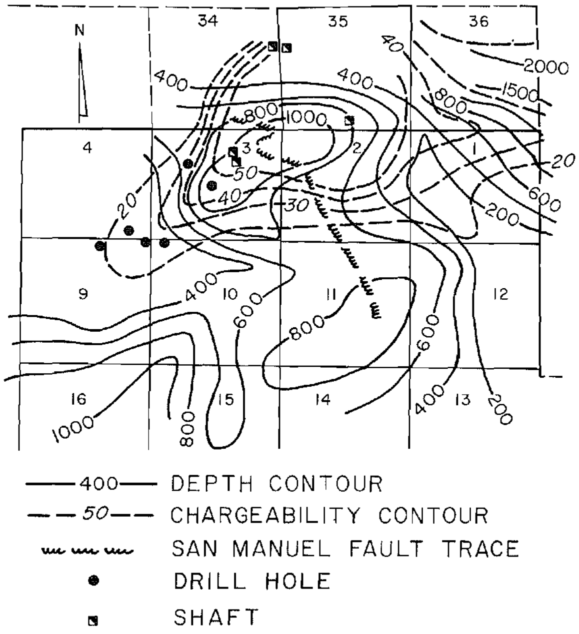


Figure 20. IP test survey near San Manuel, Arizona, by Newmont Exploration Limited, after Brant (1966).

Another example of geophysical surveying in the Southwest can be cited from past work by Huntec for Stebbins Mineral Surveys on the Papago Indian Reservation in the Vekol Hills, located about 65 miles northwest of Tucson. A reconnaissance IP program by Canadian Aero Minerals Surveys laid out near an aeromagnetic anomaly and old prospect pits brought out the weak anomaly seen in Figure 21. Of the several mining companies who viewed this data, Newmont Mining Company and New Jersey Zinc Company analyzed the situation as being worth additional exploration. This is one of the first examples of a successful porphyry discovery by induced polarization methods. It is rumored that after necessary detailing by further geophysical and geological work, sulfide mineralization was found which may eventually be mined.

Conclusions

Future exploitation of large, ever lower grade copper deposits seems inevitable as the world's need for metal accelerates and as higher-grade bodies are depleted. Brant (1967) points out that even over the past decade base metal production has increased by 30 percent to keep pace with consumption, while grade has decreased 25 percent. This accelerating trend is particularly evident in porphyry copper production statistics.

Exploration for porphyry copper orebodies probably will be assisted by regional geophysical information, as we understand more about the dynamic mechanisms of the earth. Data from regional surveys concerned with the deep structure of the Southwest porphyry copper province compare closely with data from midocean ridges.

Directional trends for future geophysical exploration research will involve oceanographic geophysics and regional studies, as well as investigations of improvements in interpretation and instrumentation.

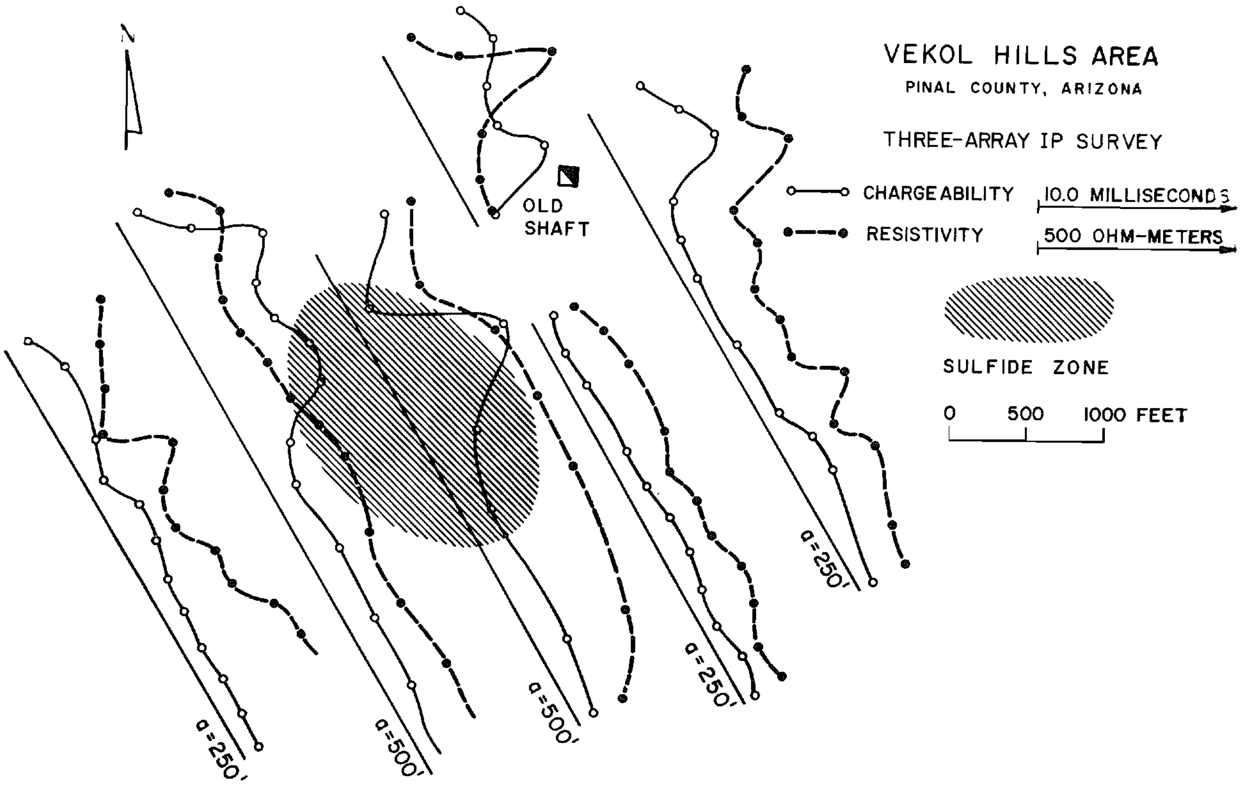


Figure 21. Results of an IP survey in the Vekol Hills by Canadian Aero Mineral Surveys Ltd. for Stebbins Mineral Surveys.

Acknowledgments

The writer is indebted to John M. Guilbert and Quentin Whishaw for stimulating discussions on some of the topics covered in this paper. The Anaconda Company and Phelps Dodge Corporation have provided research funds to the Geophysics Laboratory at the University of Arizona, which have made possible some of these results.

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Geophysical detection of deeply buried sulfide bodies in weathered regions

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Abstract. In many areas of the world where deeply weathered overburden prevails, e.g., the southwest U.S.A., geophysical detection of sulfide ore occurrences has major economic significance.

Induced polarization (IP) methods have been effective in deeply weathered areas, particularly for detection of disseminated sulfides. However, there is a type of sulfide occurrence that rarely lends itself to detection by IP. That is the stringered or massive discrete sulfide occurrence of relatively small volume. When such occur at depths greater than their effective radii, detection becomes very difficult. Yet they can have considerable value.

The application of electromagnetic (EM) methods to the problem is discussed. The applicability of time-domain EM methods to partially solving the problem is indicated. Depth penetration of as much as four times the radius of the target is considered feasible under certain circumstances.

Résumé. Dans plusieurs régions du monde où l'on rencontre des morts-terrains attaqués en profondeur par les intempérismes, comme par exemple dans le sud-ouest des États-Unis, la détection géophysique des venues de minerai sulfuré est d'une grande importance économique.

Les méthodes de polarisation provoquée (PP) ont été efficaces dans ces régions, en particulier pour la détection des sulfures disséminés. Toutefois, il existe un type de venue qui se prête rarement à la détection par polarisation provoquée: il s'agit de la venue qui se présente en filet ou en masse individuelle de volume relativement faible. Quand ces venues reposent à des profondeurs supérieures à leurs rayons réels, la détection devient très difficile. Cependant elles peuvent être d'une grande valeur économique.

On étudie les possibilités que présentent les méthodes électromagnétiques pour les fins susmentionnées. On mentionne aussi les possibilités d'application des méthodes électromagnétiques par impulsion pour résoudre en partie le problème. Une pénétration en profondeur qui peut atteindre quatre fois le rayon de la cible est possible dans certaines conditions.

The purpose of this paper is to briefly review the problems in geophysical prospecting for base metals in deeply weathered areas and to indicate the more fruitful areas to seek solutions to these problems.

To the geologist, deep weathering may mean tropical weathering, the resultant silica depletion yielding laterites with the possibility of lateritic ores. On the other hand, it may mean temperate weathering, with the consequent deep oxidation and gossans as the indicators for ore deposits.

To the geophysicist, deep weathering inevitably brings to mind low-resistivity overburdens that frequently extend to depths of more than 100 meters.

The scope of this discussion will be limited to direct detection of sulfides, excluding sphalerite, in deeply weathered environments which are neither conducting nor magnetic.

The gravimeter and the magnetometer both play an important role in prospecting for base metals in deeply weathered areas, but generally an indirect role. The Pima orebody (Arizona) had abundant magnetite in an associated skarn; Bagdad (also Arizona) had as a signature a magnetic low; Phelps Dodge uses underground gravity extensively at Bisbee (Arizona) to find new massive sulfide ore shoots. However, most known sulfide occurrences in deeply weathered areas do not tend to exhibit characteristic magnetic or gravimetric effects.

The geophysical methods offering the highest probability (but not certainty) of yielding a characteristic anomaly over sulfide zones are electromagnetics and induced polarization. To date, those reported discoveries in deeply weathered areas where geophysics has played either a primary or secondary role have involved IP or EM. Important examples are Pima, where an EM anomaly coincident with a magnetic anomaly was the *signature,* and Cuajone in Peru, discovered after drilling an IP anomaly. In the latter case the IP revealed a large area of sulfides, whereas the copper was confined to a small portion of the sulfide zone.

It would be redundant in view of other presentations at this meeting to elaborate on the effectiveness of IP in prospecting for the large porphyry copper-type deposits. What seems appropriate is to consider the relative applicability of EM and IP in searching for base-metal deposits in deeply weathered areas.

IP versus EM

Strictly speaking, IP exploits the phenomenon of overvoltage. EM exploits the phenomenon of electromagnetic induction.

In another sense, IP exploits the pseudocapacitance of the ground arising from numerous discrete metallic particles, whereas EM exploits the inductance of the ground arising from abundant current paths, such as result from massive or stringered sulfides.

A form of generalization is provided by the chart in Figure 1. Keller and Frischknecht (1966) have presented evidence that is compatible with this chart, and this is shown in Figures 2 and 3. Figure 2 illustrates the profound influence a few percent sulfides have on the resistivity of a gabbro in Maine, while Figure 3 shows a case in Arizona where the sulfides had negligible effect on resistivity, a condition explained by lack of sulfide interconnection possibly associated with weathering.

To mention some extremes, Newmont Exploration Limited has recently encountered a granodiorite exhibiting 3 to 4% sulfides by volume that are so well interconnected as to yield a resistivity about 1/150 that of the barren granodiorite, in fact less than 2 ohm meters. Newmont also encountered a case in New Brunswick some years ago where 30% sulfides (by volume) occurred as discrete particles, exhibiting relatively high resistivity.

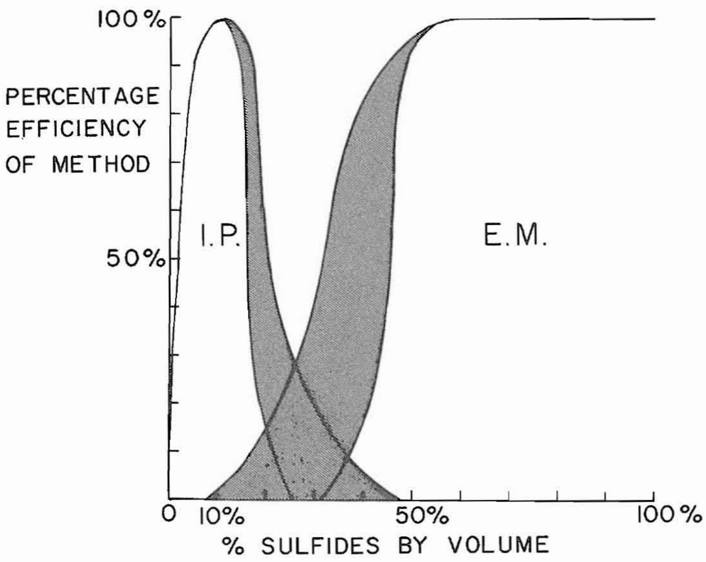

Figure 1. Generalization of efficiency of IP and EM methods.

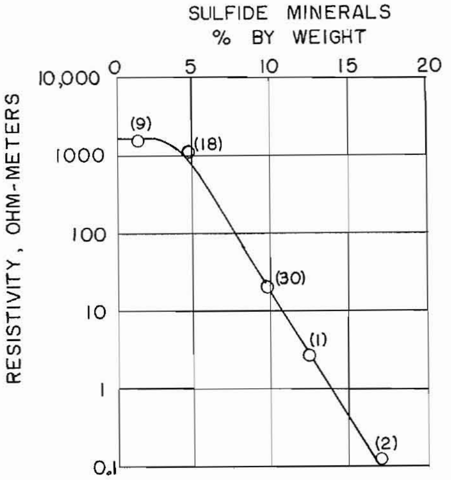

Figure 2. Observed relationship between resistivity and the amount of pyrrhotite and pentlandite present in gabbro. Samples were taken from an orebody in southern Maine. The numbers in parentheses indicate the number of measurements averaged and plotted as a single point.

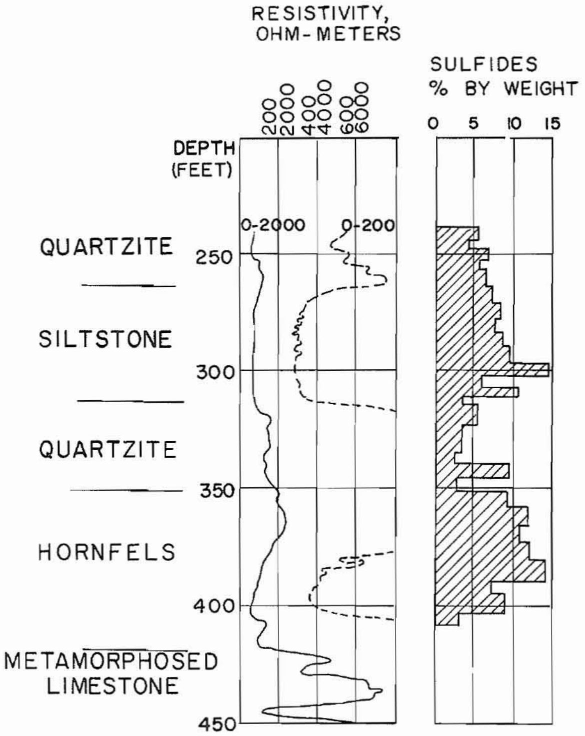

Figure 3. Borehole resistivity measurements made in a porphyry ore deposit in southern Arizona. The rock resistivity is high despite the presence of conducting sulfide minerals (after Keller and Frischknecht, 1967).

Accordingly, on an absolute physical property basis, there is a 'grey zone' from 10 to 30% sulfides (by volume) where neither IP nor EM has clearcut preference and must be determined by local conditions.

However, massive sulfide occurrences commonly grade into disseminated sulfides in one or more directions. Hence, it is rare that a massive occurrence does not provide some sort of an IP target, even though it may develop largely from a disseminated zone somewhat removed from the main ore zone.

Measurement considerations may also enter into the decision of whether to apply EM or IP. There are many areas of temperate weathering, e.g., parts of Arizona, where it is difficult to make adequate electrical contact with the ground, or where high surface conductivities create the necessity for large current levels to obtain a usable signal at the potential stakes. Frequently it is difficult to establish a good enough current loop to achieve this. These are problems not encountered with EM since galvanic connection with the earth is not normally required.

On the other hand, conventional airborne and ground EM is greatly handicapped by the conducting surface layers in deeply weathered areas, frequently of the order of 0.05 to 0.2 mhos/meter. Most conventional EM systems give large positive responses to the variations at the surface and yield little information from the fresh bedrock underneath. For example, with a system operating at a typical 400 Hz, a conductivity of 0.2 mhos/meter yields a skin depth of about 56 meters. In other words, the transmitted energy is largely dissipated within 150 meters of the surface.

For two-dimensional bodies (i.e., effectively infinite strike length) either dominantly massive or dominantly disseminated, as long as they are truly two-dimensional and no more than one cross-section dimension from the surface, IP usually suffices as a prospecting tool that provides a characteristic signature in deeply weathered areas. Of course, this assumes a properly conducted survey and a sophisticated job of interpretation.

But what about discretely bounded spheroidal massive sulfide bodies of modest dimension? Suppose these occur at depths of several radii beneath deeply weathered overburden. Few have

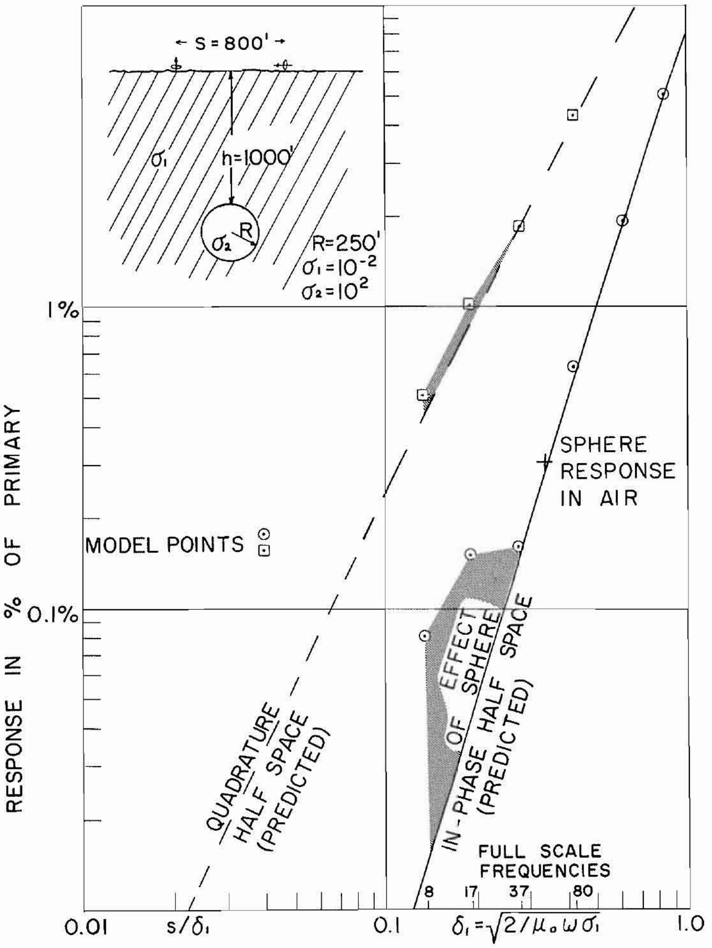

Figure 4. Results of an EM scale model study.

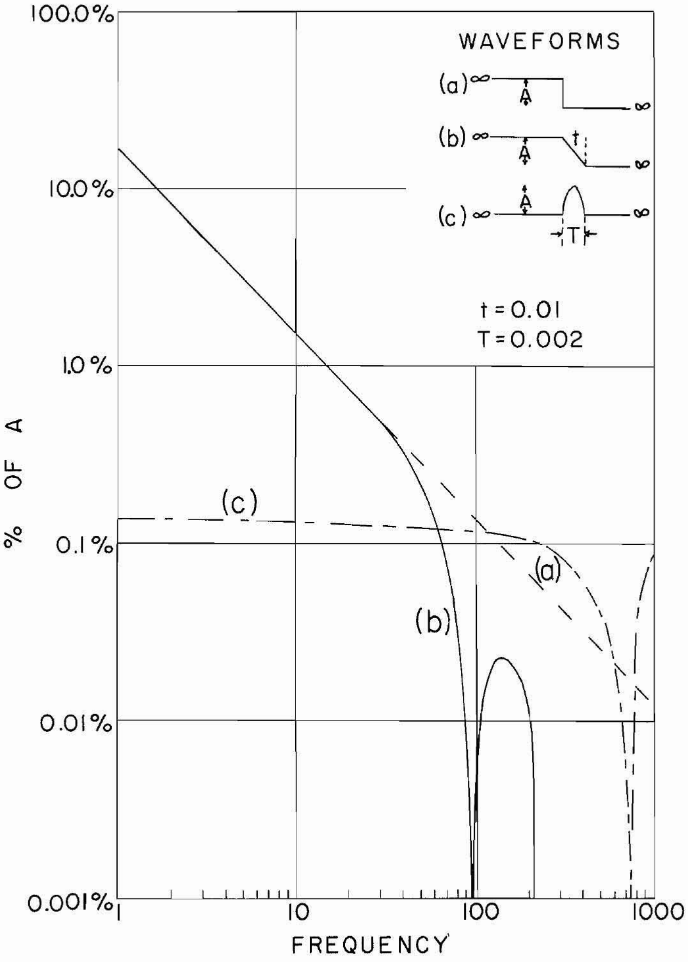

Figure 5. Frequency contents of various transmitted wave forms.

been found that fit this condition, yet the laws of probability infer the existence of many.

This type of ore occurrence can have enormous economic potential. Take the case of Cyprus Mines Corporation's Mavrovouni orebody in Cyprus, now mined out. That amounted to 15 million tons of contiguous massive sulfides bearing 41/2% copper. There were minimal associated disseminated sulfides. It had the general shape of a potato with its major axis horizontal. The host rock was a sequence of relatively fresh intermediate pillow lavas.

Mavrovouni was found by pursuit of a surface showing, but nevertheless its main bulk is in excess of 130 meters deep. Had Mavrovouni been under 60 or more meters of later sediments, it would likely have remained undiscovered.

At present-day copper prices a new Mavrovouni will gross in excess of 750 million dollars.

It is difficult to believe that other Mavrovounis do not exist, even under a few meters of cover. A noteworthy consideration is that even with a showing plus evidence of ancient mining, eight holes were drilled before the Mavrovouni orebody was actually discovered (Lavender, 1962).

Many readers probably know of at least one instance where a prospect with an attractive surface showing was abandoned after one discouraging drill hole.

The question is: How would Mavrovouni have been detected with geophysics had geophysics been handy at the time of examination? Gravity was likely the best method because the volume-density product was sufficient versus the depth; but had the center of the orebody been 30 meters deeper, it wouldn't have sufficed. A later EM survey at 50 Hz succeeded in doing little more than indicating some faults associated with the subsidence. There is no magnetic signature.

IP has since been popularized, but the Mavrovouni ore is mostly gone. Albeit, we can estimate the response from IP, neglecting the possible effects of alteration-derived clay facies that might well have expanded the apparent target.

Employing Seigel's approximate formulation for the IP over a buried sphere (Seigel, 1959), which is

$$\frac{M_a - M_1}{M_2 - M_1} = F \frac{6r^3}{d^3} \frac{\rho_1 \rho_2}{(\rho_1 + \rho_2)^2}$$

we can reach an estimate of the IP response. Some realistic figures for the various parameters are: Radius = r = 300 feet ≈ 90 meters; M_2 = body chargeability = 40; M_1 = background chargeability = 10; ρ_2 = body resistivity = 0.05 ohm meters; ρ_1 = background resistivity = 5 ohm meters; d = depth to center ≈600 feet ≈180 meters; and F is a form factor depending on the array employed =

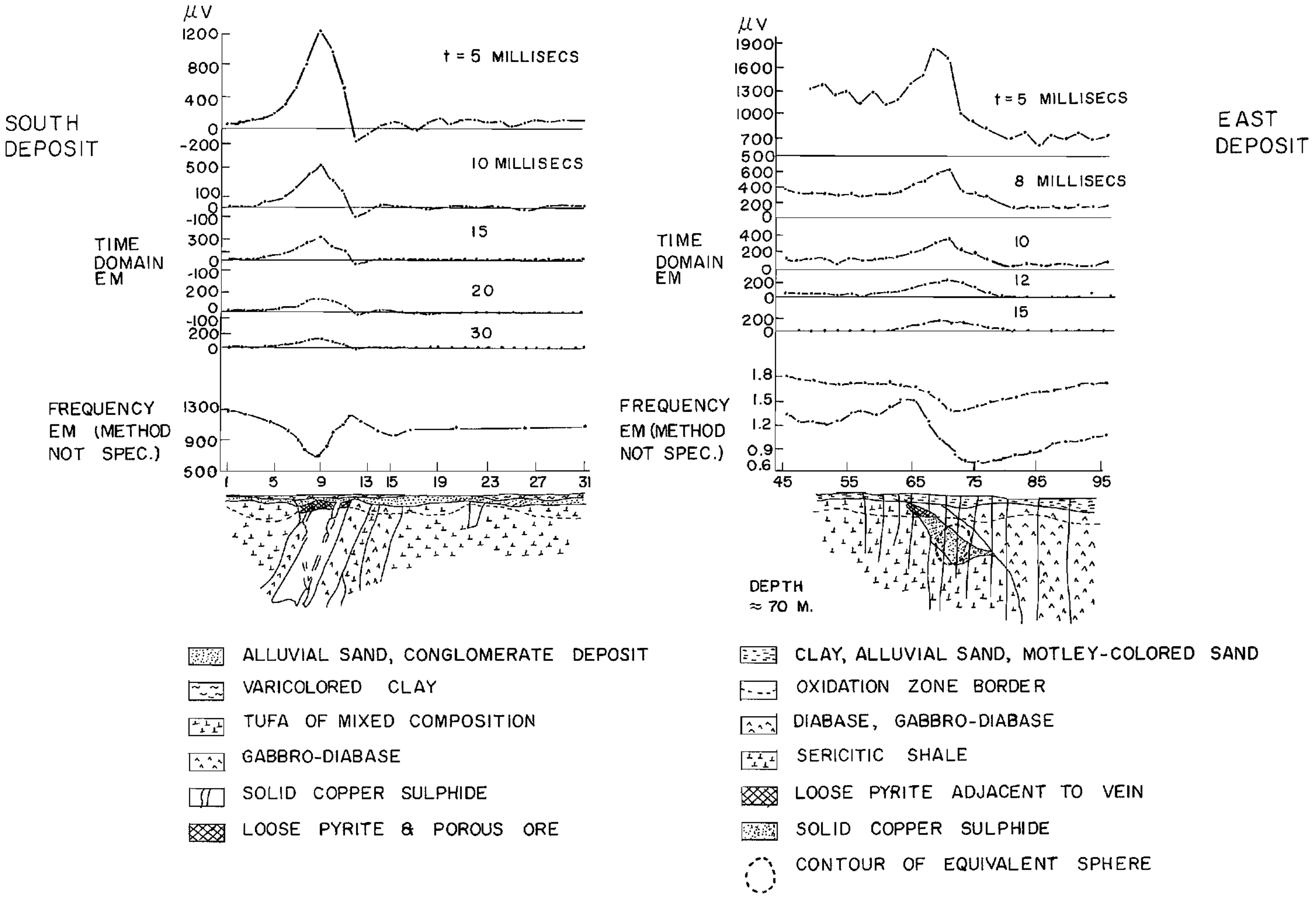

Figure 6. Results of tracing by transitional process recordings (after Kovalenko, 1961).

0.7 for this case. This yields, for an optimum three-array response, i.e., separation ≅ depth:

$$\frac{M_a - M_1}{M_2 - M_1} = 5.25 \times 10^{-3}$$

Or, in better perspective, response directly over the body would have been about 1.6% above background.

Even allowing much more favorable parameters, which is unlikely, the background heterogeneities in a volcanic sequence would demand an IP response at least 30% above background to result in a positive anomaly.

The prospecting problem that we are dwelling on is that of detecting massive or heavily stringered sulfide bodies in the range of 5 to 20 million tons under deeply weathered overburden, be it weathered outcrop or later sediments.

These occurrences could be either the well known massive sulfides of Cyprus, Turkey and Spain in volcanic settings, replacements in dolomites and limestones of the general Mississippi Valley type, or several other types.

For perspective, consider a 7-million ton massive sulfide orebody averaging 2% copper. The diameter would be about 500 feet (150 meters). The gross value would be more than 100 million dollars at present prices. It would be difficult not to realize a profit.

That IP is not necessarily the best prospecting solution I have endeavored to document. Nonetheless, it is appreciated that IP may well contribute to the discovery of other Mavrovounis.

However, it is believed that there is an alternate approach.

Figure 4, showing the results of an EM scale model study, helps to define the problem. Here all is idealized. The conducting earth (actually sulfuric acid) is uniform. The EM system has optimum sensitivity, and the 'orebody' is four orders of magnitude better conducting than the background.

Nevertheless, the body is a sphere two diameters deep, and it is seen that detection is only feasible at very low frequencies.

To summarize:

1. We should have a means of detecting spheroidal massive sulfide bodies under unusually conducting overburden to depths of at least 3 radii.
2. IP does not normally provide a means.
3. Conventional EM is masked by the overburden.
4. EM would need precise coil separations of as much as 1000 feet (300 meters) and frequencies in the range of 3 to 20 Hz. Such an EM system would be too cumbersome and costly to be practical in any extensive application.

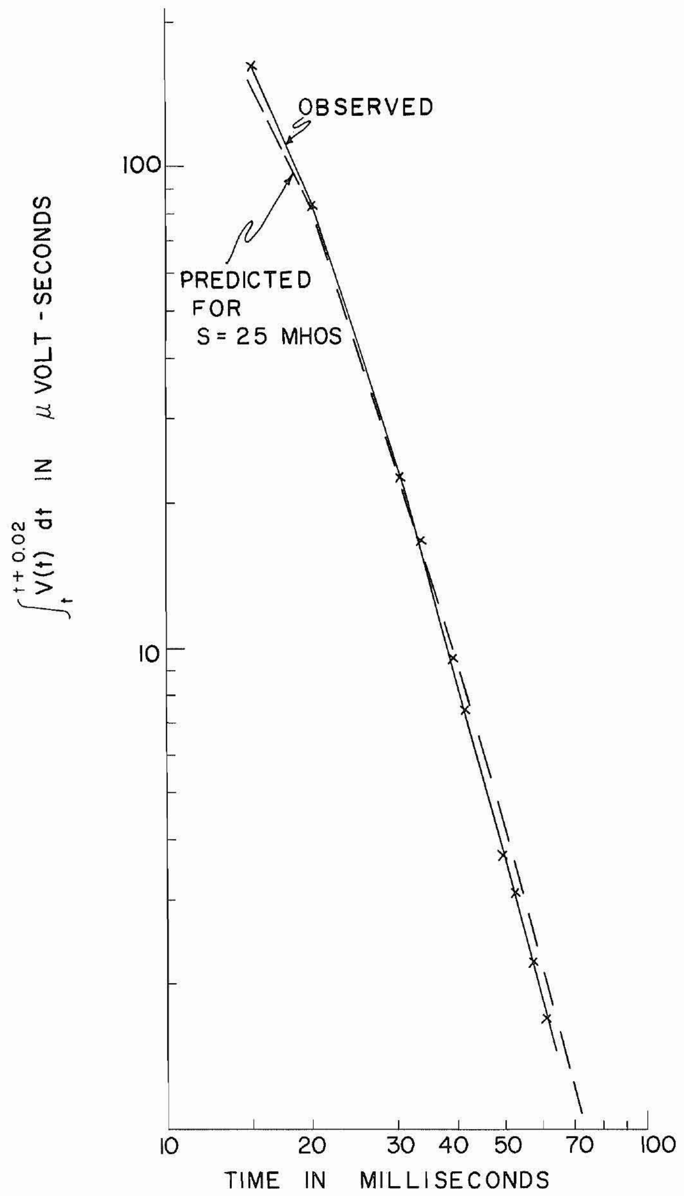

Figure 7. Plot of a typical integrated decay curve with the predicted curve for an overburden of 25 mhos.

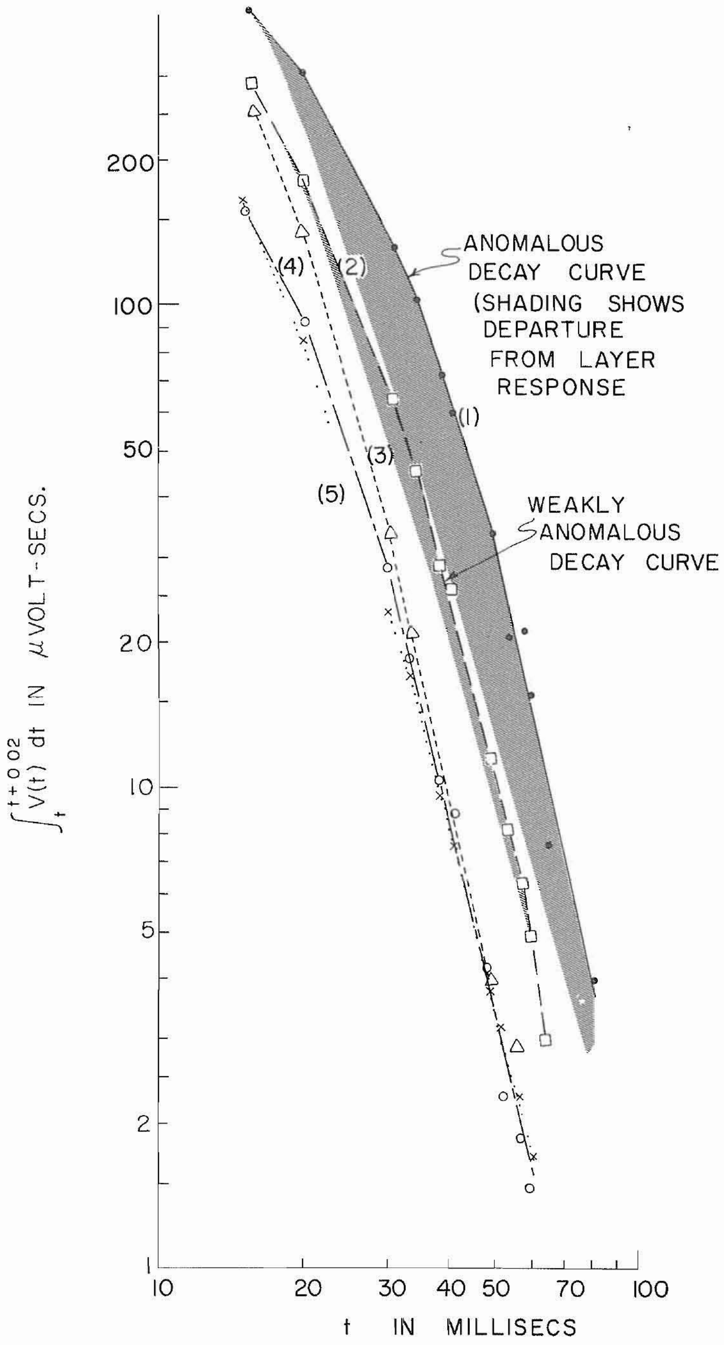

Figure 8. Time curves from stations at the middle of adjacent contiguous loops.

The above gross considerations led to examining the possible application of time-domain EM.

In Figure 5 we have illustrated the frequency content of various transmitted wave forms. The step and ramp wave forms result in a dominant concentration of the transmitted energy in the very range of frequencies that have a chance of penetrating highly conducting overburden.

At first glance the time domain approach offers several major advantages:

1. As in conventional EM, galvanic contact is not necessary.
2. The measurement is made after the transmitted field is removed, obviating the necessity of precise spatial relationships between transmitter and receiver.
3. To a first approximation, a few milliseconds after transmitter cut-off elementary superposition maintains. In other words, as in IP, magnetics, and gravity, the combined effects of all responsive bodies are reflected additively.
4. Since the secondary field is measured absolutely rather than relative to the transmitted field as in conventional frequency EM, a means of discrimination obtains from the fact that overburden response varies as coil separation, whereas the response of a deep-seated body is little modified by coil separation. However, this advantage is difficult to exploit in practice.

The disadvantages of time-domain EM are manifold. The formidable efforts of Barringer Research's engineers in bringing

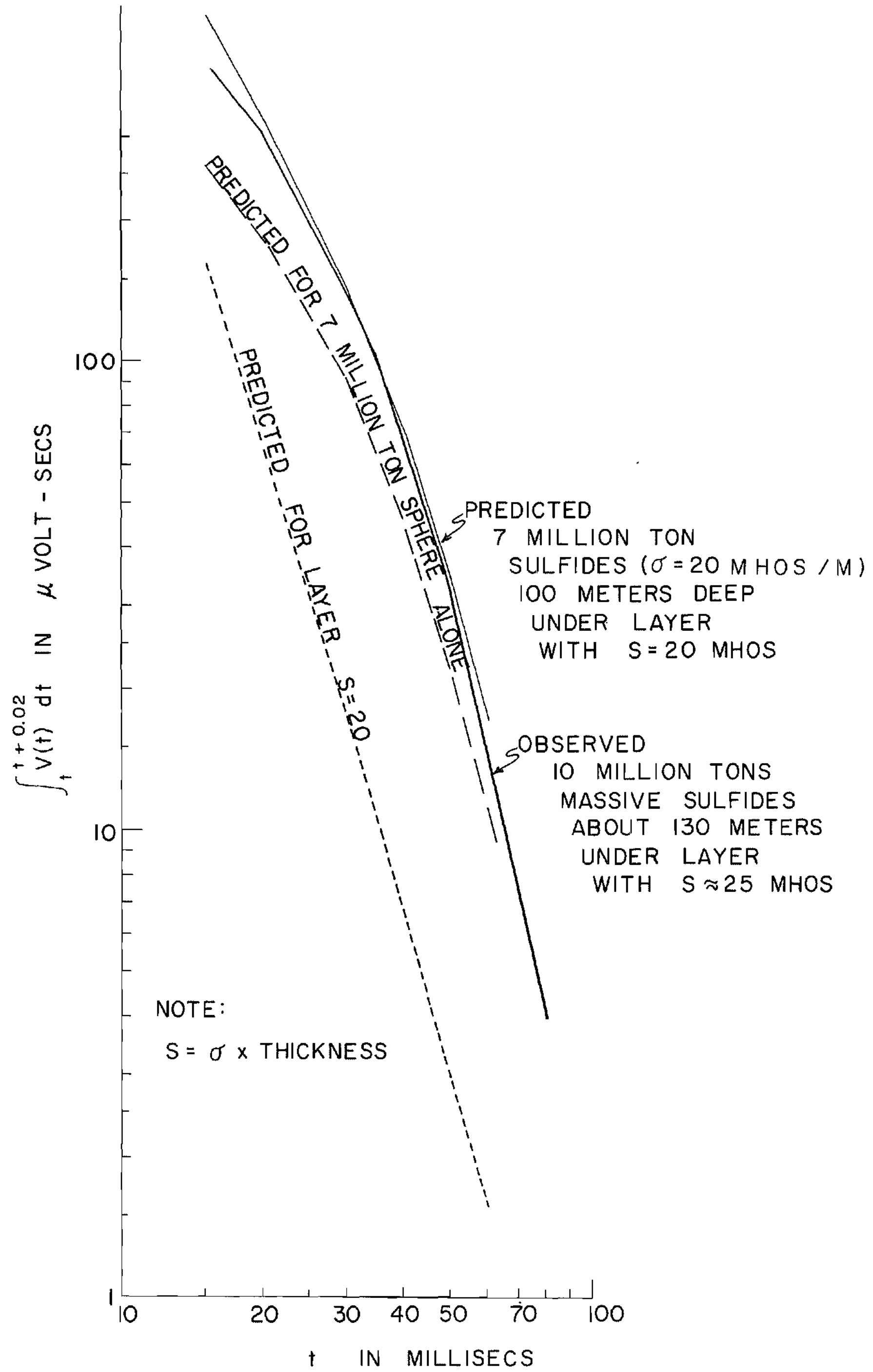

Figure 9. The strongly anomalous curve from Figure 8 shown in juxtaposition with the calculated response for a 7-million ton orebody.

the INPUT, a time-domain airborne EM system, to perfection attest to this. To list them briefly:

1. The receiver must be essentially wide-band to receive the desired transient signal. Accordingly, filtration that is so helpful in frequency EM is not possible.

2. Consequently, exceptional primary field strength is required to provide sufficient signal to noise ratio.

3. This in turn creates the problem of storing tremendous amounts of energy in a coil by introducing large currents, then terminating the current with resultant manifestation of the stored energy as an extremely high voltage on the transmitter coil. The insulation problems are frightening.

4. In like manner, a highly sensitive receiver coil is required, but with high self-resonance. These are conflicting objectives. (N.B.: The high self-resonance necessary is a consequence of the transmitted signal ringing the coil.) Critical damping, in conjunction with maximum self-resonance, results in minimal transmitter-induced energy out of the receiver coil.

5. The extremely sensitive receiver coil required is also inordinately sensitive to minor vibrations caused by wind,

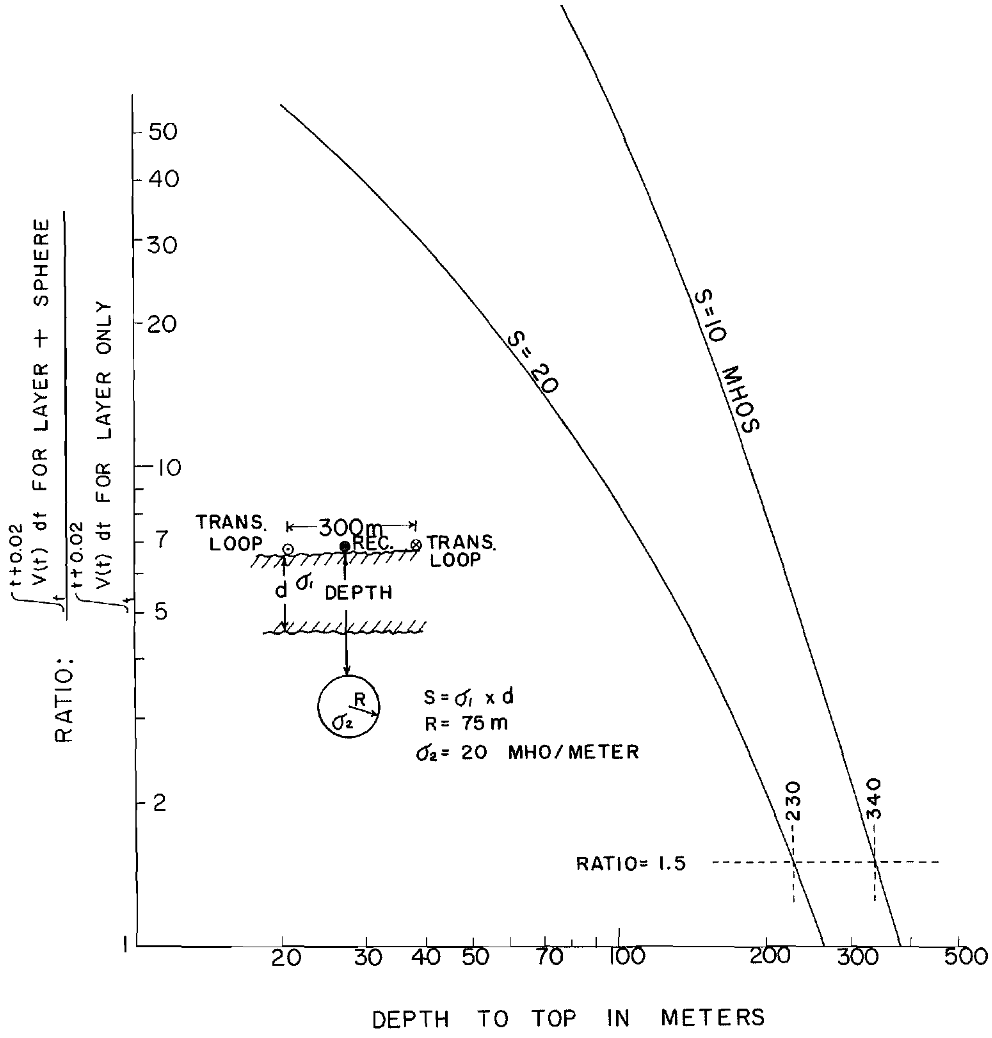

Figure 10. Partial summary of the depth capability of the Newmont time-domain equipment.

vehicles, etc. That is, its motion in the earth's field serves to generate a signal.

That these problems can be surmounted is well known. Barringer Research, as mentioned earlier, has developed a highly effective time-domain airborne EM system, although unsuitable for the type of problem we are discussing here. For some years Russian workers have employed a time-domain ground EM system employing a flat-lying transmitter loop as much as several thousand feet on a side and measuring the vertical secondary field within (Kovalenko, 1961). This system was developed by the exploratory geophysics faculty of the Sergei Ordzhonikidza Institute in Moscow. Some examples of the application of Russian equipment are shown in Figure 6.

It is evident that the orebodies exhibit a response to this equipment long after the background response has subsided. Note the response of conventional frequency EM shown below the time-domain response. Evidently in this instance frequency EM would have sufficed, though it lacks the clear powers of discrimination exhibited by the time-domain data.

At the site of the Russian test work, it is unlikely that the overburden was more than 5 mhos, i.e., thickness times conductivity, e.g., $\sigma = 0.1$ mhos/meter times 50 meters.

In 1962 Newmont Exploration Limited devised a time-domain EM system somewhat similar to that reported by the Russians. However, the depth of penetration desired was approximately four radii of a spheroidal target beneath an overburden of 10 mhos.

The overburden condition that Newmont actually encountered while working in Cyprus on behalf of Cyprus Mines Corporation was between 20 and 35 mhos rather than 10. A frequently encountered lithologic section was 100 meters of highly conducting marls overlying a thick section of weathered and saline pillow lavas.

The equipment employed deserves description.

The transmitter consists of a square single turn loop of No. 4 wire 300 meters on a side. The loop resistance is 1 ohm with an inductance of 300 millihenries. The loop is driven with a 700 amp pulse of about 100 milliseconds duration. The pulse, while essentially a step because of its duration, must be terminated as a ramp over about 3 milliseconds. This is accomplished by an arcless interrupt circuit devised by General Electric.

The current source is composed of ninety 12-volt automobile batteries in series. After considering the several alternatives, batteries were found to be the most efficient and least expensive source. The batteries are mounted on a 4-wheel drive vehicle. Transmission recurrence is about four per minute to provide the batteries with a relatively nonabusive duty cycle. Charging is effected at night by a trailer-mounted 3 kw gasoline-driven generator.

Reception of the vertical transient field is effected at nine uniformly distributed stations within the loop. Two receiver parties are employed simultaneously for efficiency. One station is common to both parties for equipment comparison.

Contiguous loops are read for saturation coverage. Loops are laid in advance of the one being read so that the receiver parties work continuously. A rate of coverage of 3 square miles a month is possible with 15 men working 10 hours a day.

The receiver equipment consists of a coil and a receiver-programmer. The coil has an effective NA of 20,000 turns meters squared. Self-resonance is about 400 Hz. Critical damping results in negligible ringing signal by 15 milliseconds after cut-off. The coil is housed in a small tent during readings to minimize wind vibration.

Following 50 db of DC preamplification, the transient signal out of the coil is selectively gated to a series of integrating amplifiers. In other words, the transient curve is integrated in a series of sequential slices. The integration intervals while variable are about 20 milliseconds for maximum 50 Hz power frequency rejection. The integrators are monitored by meter. After recording the readings, the integrators are cleared and the preamplifier rebalanced in anticipation of the next transmission. Depending on noise conditions, as many as 20 transmissions are employed to get a good average.

The signal gating is effected by reed relays driven by a programmer. The programmer can be varied for a range of 10 to 30 milliseconds integration interval or its initial delay can be varied from 10 to 50 milliseconds depending on requirements. The programmer is remotely triggered by the transmitter shut-off event. The integration intervals are overlapped via the delay to provide sufficient points to plot the resultant time curve.

A satisfactory signal to noise ratio derives from three things: (1) averaging repeated readings, (2) the inherent filtration provided by integration, and (3) overwhelming power from the transmitter. Usable readings have been obtained where the absolute signal to noise ratio was less than one one-hundredth.

Figure 7 shows the plot of a typical integrated decay curve matched with the predicted curve for an overburden of 25 mhos.

Figure 8 depicts time curves from stations at the middle of adjacent contiguous loops. No. 1, which is strongly anomalous, was situated over about 10 million tons of nearly massive sulfides at a depth of about 130 meters. No. 2 also reflects some additional mineralization, but not so strongly. No. 3 is over a zone of weak mineralization and affects the curve earlier. Nos. 4 and 5 show strictly overburden response.

In Figure 9 we show in juxtaposition the strongly anomalous curve from Figure 8 and the calculated response for a 7-million ton orebody at a depth of 100 meters under a layer of 20 mhos. Also shown are the calculated response curves for the layer and sphere alone to illustrate the effect of superposition.

Figure 10 in part summarizes the depth capability of the Newmont time-domain equipment. The calculated ratio of the response for a 7-million ton orebody to the response for overburdens of 10 and 20 mhos, respectively, is displayed. In practice, a ratio of 1.5 should be recognizable yielding a penetration of 230 meters with an overburden of 20 mhos, and 340 meters with an overburden of 10 mhos.

One other gratifying aspect of this method is the utility of plan presentation. By plotting a selected parameter such as the 30 millisecond intercept, a meaningful contour map can be obtained. There are certain geometric pitfalls to be avoided in using a plan presentation, such as the effect on response if a conductor is under the corner of the loop, but these can be dealt with. Other phenomena to be watched for are heterogeneities in the overburden and aberrations in the receiver operators.

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Discussion on Geophysical Detection of Deeply Buried Sulfide Bodies in Weathered Regions, by William Dolan.

Question. It seemed to me the significance of the paper was in applying INPUT on the ground and it would seem strange that nobody has ever asked the question, "Why don't we use the method more often?" My question would be, if it's not a trade secret, "Are you continuing in this direction?"

William Dolan, Newmont Mining, Canada. Yes, as fast as we can convince technical talent, which is always a problem. Since the work I have reported on, we have done a variation of this down a drillhole and we anticipate applying virtually the same system, although somewhat more sophisticated and with some modifications, in areas such as Western Australia. I would like to submit a comment here that I've heard regarding this question on fissile properties. There is a great deal of uncertainty in my mind about just why some of these things respond out of all proportions to their actual measured *in situ* conductivity. There are two or three things that one might take into account in this regard and one I have speculated upon is that in several places, there is definite anisotropy in terms of conductivity: for example, over one sulfide body (of about 5 million tons) with roughly spherical dimensions that outcropped in Cyprus. There was a very modest and uncertain IP anomaly over this body, which was exposed by stripping. On the other hand when this equipment was run over it, it went absolutely crazy, as I thought it should (and I was delighted when it did). It didn't go crazy in the way I would have predicted, but it did go crazy.

Edwin Gaucher, Soquem, Canada. In what way do you mean the equipment went crazy?

Dolan. I saw when we put this equipment over this particular orebody for a test (it wasn't an orebody in question but massive sulfides), the effect was many orders of magnitude above the background but it wasn't what I would have expected at the time. In fact it was a negative effect but this was a matter of geometry which I have subsequently sorted out.

Gaucher. How did you first locate the zone?

Dolan. On IP.

Gaucher. What method was used?

Dolan. Pole-dipole and dipole-dipole using DC and a measuring time of 53 seconds.

Gaucher. Do you mean the IP effect and the time-domain effect were the same?

Dolan. I said it gave an IP effect, but it was not discernible from numerous background effects nearby. In other words it was in no way unique, whereas the response to the time-domain EM was roughly three orders of magnitude above any comparable background effect. I am sorry, this is the sort of thing I would like to divulge at this meeting if it weren't for certain restrictions.

Alex Becker, Geological Survey of Canada. Have you ever observed any negative effects with that EM?

Dolan. This was a negative effect. But it was a geometric effect deriving from its position relative to the loop. In other words we had it in the corner of the loop, partly determined by local culture and other matters.

Becker. Would you say that you have had an experience where you've had the anomaly at the corner of the loop and it produced a negative anomaly?

Dolan. That's right. Of course any lateral variation in the overburden gives associated magnitudes which are quite interpretable if you have any exposed geology. One other thing I might add, which I should have included in the paper: I'm sure many of you are aware that the essential response factor on something like this is, in a sense, quite anologous to the thickness-conductivity product, that is the conductivity times the effective radius squared. A small percentage increase in radius has quite a dramatic effect, in view of the fact that it is a squared term in the response factor. Regarding physical properties there have been many comments at this meeting about lack of liaison between geophysicists and geologists; in other words, in terms of geophysicists translating geophysical measurements into proper geological terms so they're really useable. It is important that we try to be more exact in our assessment of the physical properties of the zone we are investigating.

Contents

Base metal exploration in the Cordillera

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Abstract. In the Cordilleran region, geophysical methods have been employed in the following varieties of massive sulphide exploration: thick tabular deposits, veins, and pyrometasomatic deposits. Of the thick tabular type, geophysics has played an important role in exploration in the Anvil-Vangorda area of the Yukon Territory, where helicopter magnetic and electromagnetic surveys have been used for preliminary reconnaissance followed up on the ground with magnetic, electromagnetic, self-potential and gravity surveys. In the search for vein deposits, the electromagnetic method has been used extensively. For pyrometasomatic deposits, the magnetic and electromagnetic surveys have been used for preliminary reconnaissance followed up on the ground with magnetic, electromagnetic, self-potential and gravity surveys. In the search for vein deposits, the electromagnetic method has been used extensively. For pyrometosomatic deposits, the magnetic and electromagnetic methods have been important, as at Pima, Arizona. In the latter case, more extensive disseminated mineralization was subsequently discovered. Detection of vein-type mineralization has also led to the discovery of extensive disseminated mineralization.

Résumé. Dans la région de la Cordillère, on a utilisé les méthodes géophysiques pour explorer les massifs sulfures suivants: les gisements tabulaires épais, les gisements filoniens et les gisements pyrométasomatiques. Les méthodes géophysiques ont joué un grand role dans l'exploration des gisements du genre tabulaire épais dans la région d'anvil-Vangorda au Yukon. On a utilisé, pour les travaux de reconnaissance, des relevés magnétiques et électromagnétiques effectués à l'aide d'hélicoptères, suivis au sol de relevés magnétiques, électromagnétiques gravimétriques et de polarisation spontanée. On utilise généreusement les méthodes électromagnétiques dans la recherche des gisements filoniens. Elles sont aussi assez souvent utilisées dans la recherche des gisements pyrométasomatiques comme on l'a fait à Pima en Arizona. Dans ce dernier cas on a découvert par la suite des minéralisations disséminées plus étendues. La détection de minéralisation filonienne a conduit aussi à celle de minéralisation disseminée.

This paper discusses base metal exploration in the Cordillera of western North America. It is concerned with the search for massive sulphide deposits of the thick tabular, vein, and pyrometasomatic types and with disseminated deposits. The emphasis is on aspects that have not received wide attention in the literature.

The exploration for massive sulphide deposits has been carried on using techniques similar to those employed with such success in the Precambrian and Appalachian regions. The main difference has been the complexity introduced by the rugged terrain that frequently occurs.

Thick tabular deposits

The thick tabular deposits are conformable to sedimentary horizons and some outstanding examples occur, such as the Sullivan Mine at Kimberley, British Columbia. Of current interest

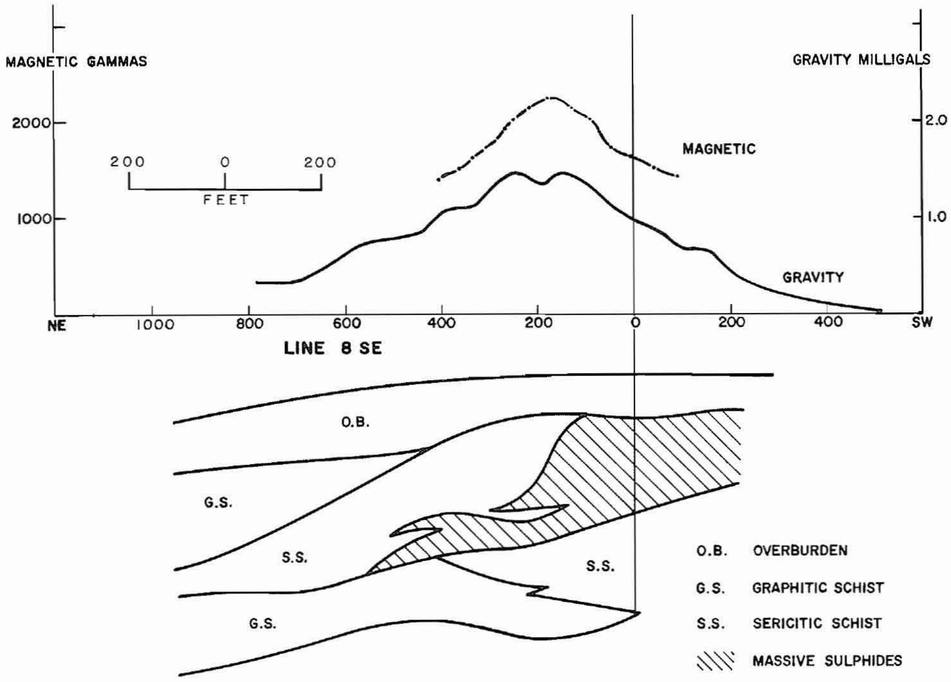

Figure 1. Ground geophysical profiles, Vangorda deposit, Y.T.

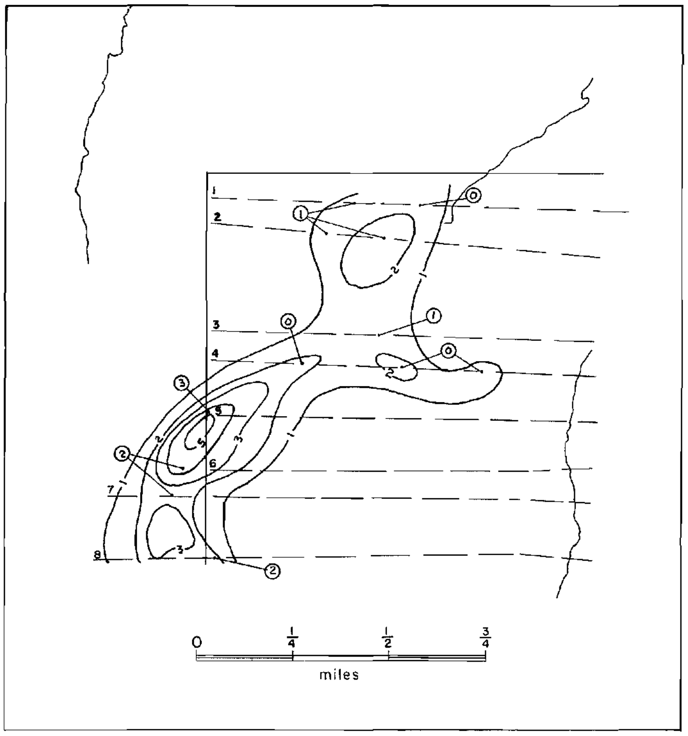

Figure 2. Helicopter electromagnetic survey, Adams Plateau, B.C.

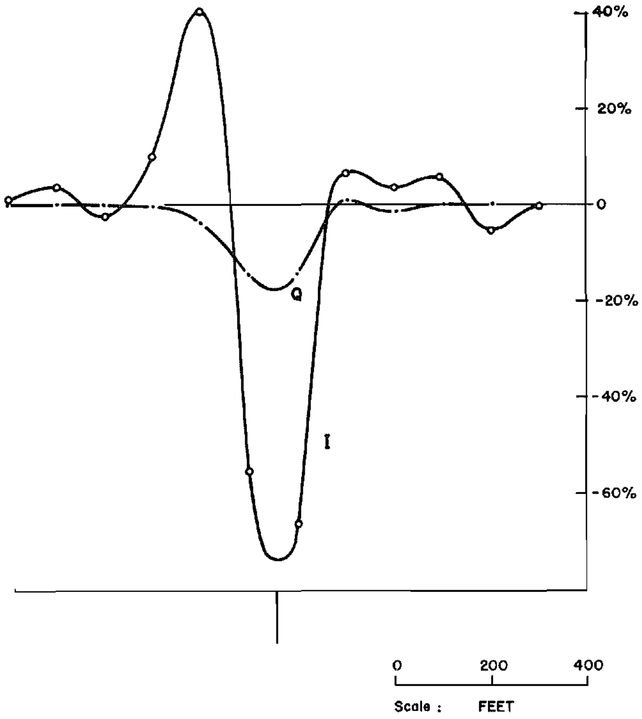

Figure 3. Ronka ground electromagnetic profile, Neglected Prize, Tracy Arm, Alaska.

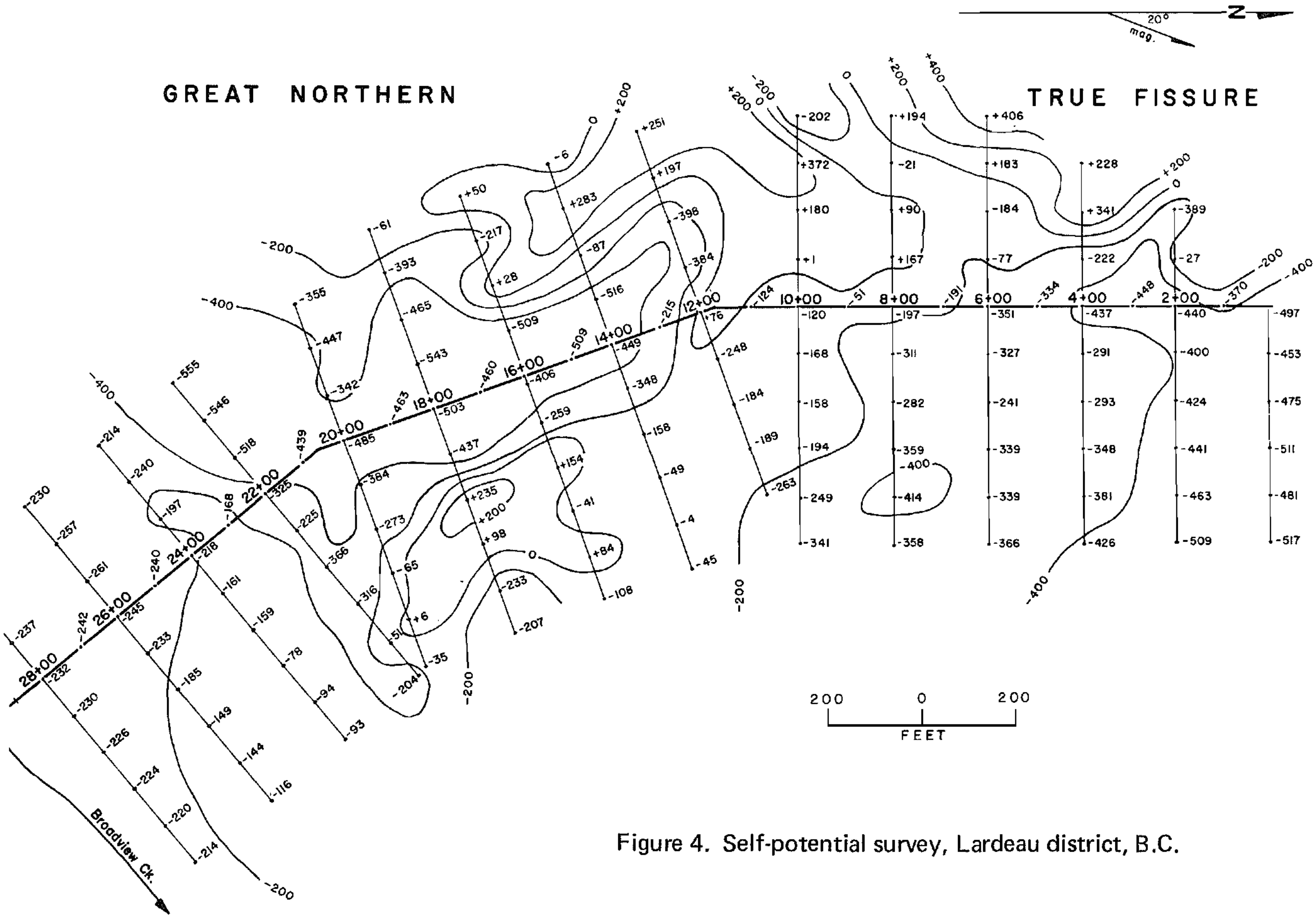

Figure 4. Self-potential survey, Lardeau district, B.C.

Figure 5. Aeromagnetic map, Highland Valley area, B.C.

is the important role played by geophysics in exploration in the Anvil-Vangorda area of the Yukon Territory. The geophysical approach used on the Vangorda deposit was described by Chisholm (1957). This involved magnetic, self-potential and gravity ground methods. Geophysical profiles with the corresponding geologic section are shown in Figure 1. The self-potential response of the deposit was negligible and not shown. Anomalous SP values were due to graphitic schist.

During the past two years, active exploration has been carried out in the district using a more modern approach. Initial reconnaissance is carried out with helicopter-borne magnetic and electromagnetic gear. Anomalous areas screened from the airborne data are subjected to ground magnetic, electromagnetic and sometimes gravity work. The current nature of the work precludes the showing of examples, but some of the interpretational problems will be mentioned. In magnetic surveys, the presence of intrusive plugs yields anomalies that are of approximately the same amplitude and dimensions as those from the orebodies being sought. Electromagnetic surveys yield a complex anomalous pattern over graphitic schist horizons. Gravity surveys show strong regional variations due to lithologic contrasts. Some broad highs occur over denser rock units that

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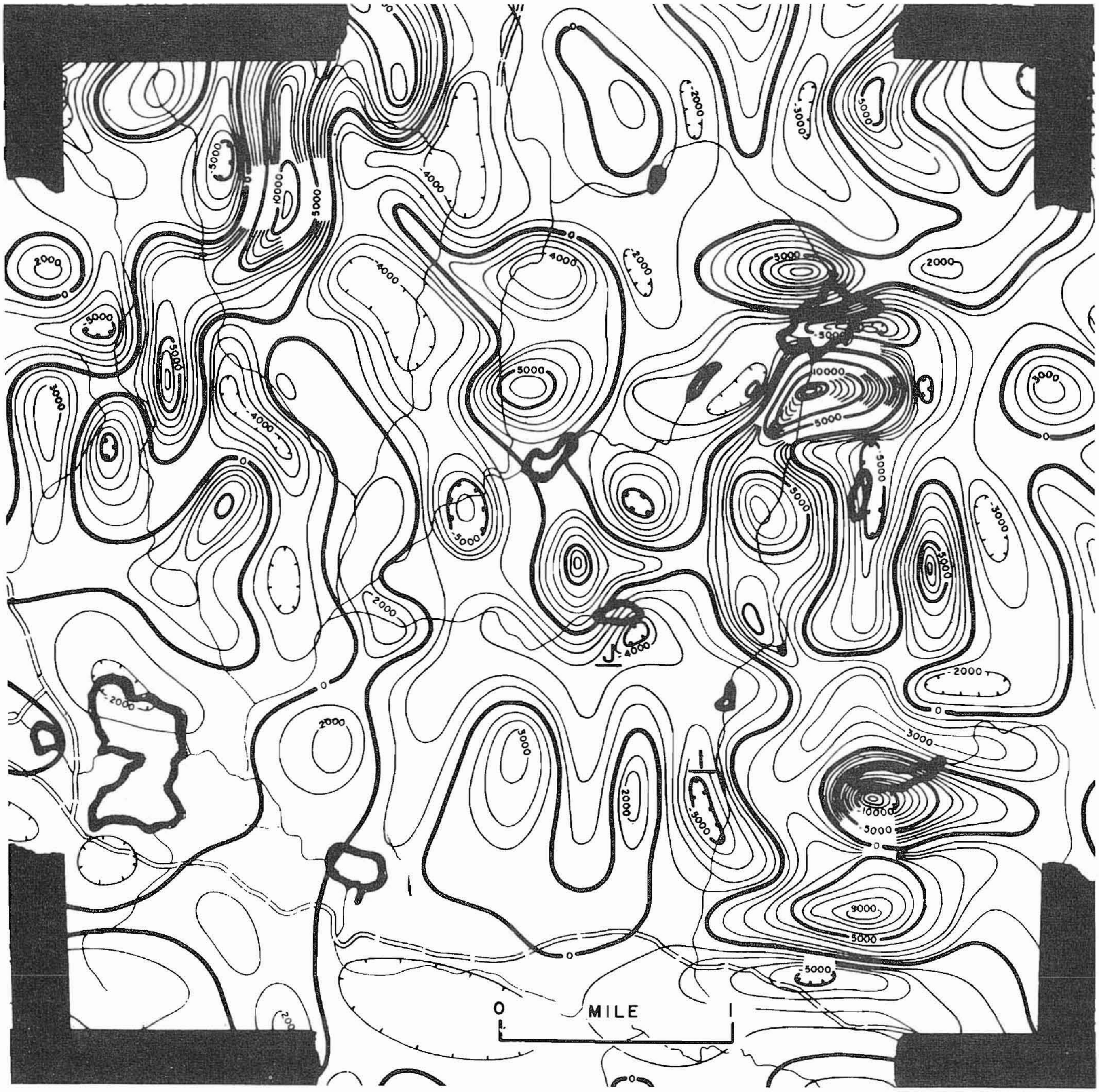

Figure 6. Second derivative of total magnetic intensity, Highland Valley area, B.C.

may incorrectly be assumed to be due to large tabular massive sulphide deposits. In spite of these problems, orebodies have been discovered using geophysics in conjunction with geological and geochemical methods. The outstanding examples are the Faro orebodies of Dynasty Explorations Limited.

Vein deposits

Narrow veins are often a lucrative exploration target in the Cordillera, Many of these consist of massive galena with variable amounts of sphalerite and silver. Unfortunately, these vein occurrences are generally in rugged terrain, and often graphitic shears occur in the same environment. The electromagnetic method has been employed both from the air and on the ground. One of the early helicopter surveys is shown in Figure 2; this is part of an electromagnetic survey on the Adams Plateau in south-central British Columbia. The Hunting system was employed, with coaxial coils mounted in a 'bird' at 20-foot spacing. In-phase and quadrature components of the secondary field were recorded. Contours of in-phase amplitude are shown in Figure 2, with spot values of the in-phase to quadrature ratio. The anomaly at lower left correlates with the Lucky Coon zone, a narrow vein dipping at 45° to the northwest.

Figure 3 shows a Ronka ground electromagnetic traverse over the Neglected Prize, a vertical copper-zinc vein at Tracy Arm in southeast Alaska (Gault and Fellows, 1953). The excellent quality of the conductor is shown by the high in-phase to quadrature ratio. The steep slopes at this prospect necessitated slope chaining of picket lines so that the coil spacing could be maintained at the required 200 feet.

In the Lardeau district of B.C., the veins contain much massive pyrite. Here, the self-potential method was used successfully and has obvious operational advantages in rugged terrain. The existence of a dip slope meant that the relatively narrow vein suboutcropped over a considerable width. This is reflected in the rather broad negative shown in the Great Northern area in Figure 4.

Pyrometasomatic deposits

The outstanding case history of a pyrometasomatic deposit is that of the Pima mine in Arizona (Heinrichs and Thurmond, 1956). This deposit gave clear magnetic and electromagnetic responses. Much more extensive disseminated mineralization was subsequently discovered.

A somewhat different situation occurred immediately to the east of Pima, at Mission. Lacy and Morrison (1966) have described electromagnetic work that detected vein systems. These were found to occur within a large body of disseminated mineralization.

Disseminated sulphide deposits

In the Cordillera, the so-called porphyry copper and molybdenum deposits are the most important exploration target. For preliminary reconnaissance, the magnetic method has been effective. Unfortunately, the magnetic pattern over porphyry deposits varies considerably. In some instances, there is an association with magnetic lows that mark zones of alteration. In other cases, mineralization may be associated with relatively magnetic skarn or relatively nonmagnetic acid intrusive rocks.

Figure 5 shows a portion of an aeromagnetic survey flown in the Highland Valley area of B.C. in 1957. The general increase in magnetic intensity from southwest to northeast is due to lithologic changes, this being the intermediate transition zone between the coarse porphyritic granite of the center of the batholith and the basic margin. Magnetic lows associated with the Jersey and Iona ore zones appear as nosings on the magnetic contours (marked *J* and *I*). To show these lows more clearly against the background variations due to lithologic changes, a second derivative calculation was carried out. On the resulting map, Figure 6, lows associated with the Jersey and Iona zones are much more clearly defined.

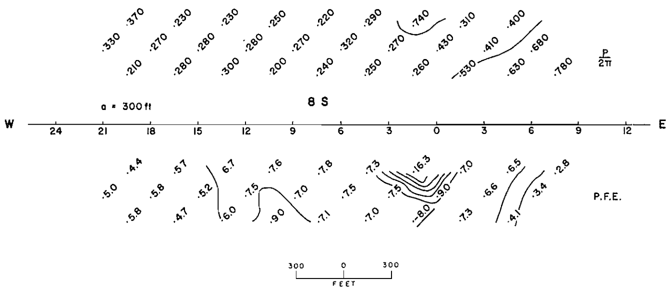

Figure 7. Induced polarization traverse, Brenda deposit, B.C.

For the direct detection of disseminated mineralization, the induced polarization method has been by far the most effective. It is quite sensitive to disseminated pyrite, and the IP anomaly commonly outlines the pyritic zone if pyrite is present. This may be more extensive than the zone of economic mineralization, or the zone of maximum pyrite may be displaced laterally from the zone of maximum economic values. An exception to this is the Brenda deposit in south-central B.C. This is a very large deposit with negligible pyrite and average values of 0.19 per cent Cu and 0.06 per cent Mo. Overburden is shallow, so that in spite of the low sulphide content, the corresponding anomaly shows clearly and accurately marks the limits of the orebody. A typical traverse using frequency-domain equipment is shown in Figure 7.

The self-potential method has been used with some success in B.C. when disseminated mineralization occurs at a shallow depth. It has proved quite pyrite-sensitive, and does not always show discernible anomalies over other sulphide minerals.

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Geophysical exploration of Mississippi Valley–Appalachian type strata-bound zinc-lead deposits

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Abstract. It has been the experience of The New Jersey Zinc Company that surface and airborne geophysical methods have not been productive in the detection of anomalies which could be related to the subject type ore deposit and are of limited use in indicating the regional environment favorable for their occurrence in the United States. Down-the-hole applied potential methods have been helpful in a few cases in indicating trends of environments and of ore and the connection or absence thereof between mineralized holes. Because primary screening of potential areas is commonly done today on a pattern of widely spaced drill holes to delineate environments and to discover ore, the development of down-the-hole geophysical methods seems to offer the most promise for aid in the search for the subject types of deposits.

Résumé. La société New Jersey Zinc Company a constaté, par expérience, le peu de résultats obtenus aux moyens de méthodes géophysiques tant terrestres qu'aériennes dans la détection d'anomalies susceptibles d'être liées au type de gisement considéré, et leur emploi limité pour l'indication du milieu local favorable à leur présence aux Etats-Unis. Les méthodes de tension appliquées au fond de trous de sonde ont permis dans quelques cas de distinguer les caractéristiques des milieux et des gisements ainsi que les relations ou l'absence de relations entre les minéraux rencontrés dans les forages. Le passage au crible de régions intéressantes se pratiquant couramment aujourd'hui suivant un réseau de forages espacés, dans le but de délimiter les milieux favorables et de détecter les gisements, les méthodes de mesures géophysiques pratiquées au fond des trous de sonde semblent offrir l'aide la plus précieuse à la recherche des types de gisements considérés.

In a paper by the senior author presented originally at a CENTO Symposium (1964) in Ankara, Turkey and subsequently at an AIME section meeting at Reno, Nevada (1965), brief evaluations were made regarding the applicability of geophysical methods to exploration for the Mississippi Valley - Appalachian type orebodies. This paper is devoted to a documentation of these evaluations.

This record of effort in geophysics extends over 32 years, 1928 - 1960. During this time concepts regarding the genesis of these deposits have evolved from the early 20th century classical one of stratigraphic-structural control of localization of deposition of ore minerals from the solutions originating in intrusives at depth, what may be designated as the *Z* or vertical source concept, to the currently controversial one of paleophysiographic-sedimentary control of localization of ore minerals from solutions originating in extrusives in a submarine environment, or from some other source essentially within the stratigraphic section, the *X-Y* or horizontal source concept. It will be helpful if the history of geophysical effort from early attempts at detection of anomalies which could be related to ore, to current efforts to delineate environments favorable for ore occurrence be considered in the above context of evolution of concepts of genesis.

Also, most of this effort was devoted to calibration of methods over known, drilled-out orebodies and little of it applied to prospecting because the calibration results were not generally encouraging. The results are classified on a relative basis as productive, indeterminate or nonproductive rather than in such absolute terms as success or failure. The latter terms are not time-sensitive and thus ignore the fact that geophysical measurements made by competent people remain as a continuing challenge for reinterpretation in the light of advances in geological knowledge and new insights regarding the significance of the data.

For the benefit of those not having access to the publications noted above, the characteristics of the subject deposits which constitute the parameters to be dealt with in their search, geophysical and otherwise, are set forth below, to define the nature of the targets.

Targets, Environments and Characteristics

Geologic. Mississippi Valley - Appalachian type zinc-lead deposits are strata-bound and in the United States occur in Paleozoic carbonate rocks of age Cambrian, Lower Ordovician, Middle Ordovician and Mississippian. Mississippi Valley type occurs in nearly horizontal beds whereas the Appalachian type occurs in folded beds. The features controlling their localization are derivatives of paleophysiography:

A. Specific sedimentary environments such as pinchouts, talus or landslide breccias, reefs, mud banks and compaction or drape structures related to the topographic relief on an unconformity below. Southeast Missouri (Ohle and Brown, 1954) and perhaps the deposits in Ireland (Derry, *et al.*, 1965) are in such environment. The rocks below the unconformity are commonly not carbonates.

B. Solution collapse breccias under a karst topography or subsidence structure above a subsurface drainage system, all of which are related to an unconformity above. Examples of the former type are the tri-state district of Missouri, Kansas, Oklahoma (Fowler, 1932); east Tennessee (Crawford and Hoagland, 1968); Friedensville, Pennsylvania (Callahan, 1968); and Ymir, British Columbia (Fyles and Hewlett, 1959). Examples of the latter type are southwest Wisconsin (Heyl, *et al.*, 1959) and some aspects of the East Tennessee deposits. The type of rocks above the unconformity appears to be irrelevant. In the cases cited, they may be dolomite, limestone or shale.

C. Facies changes within a formation, but not clearly related to an old shoreline, that is unconformity below, or between basins of dissimilar source and type of sediments. Austinville, Virginia exemplifies both (Brown and Weinberg, 1968) and Pine Point, Northwest Territories, Canada the latter (Campbell, 1957).

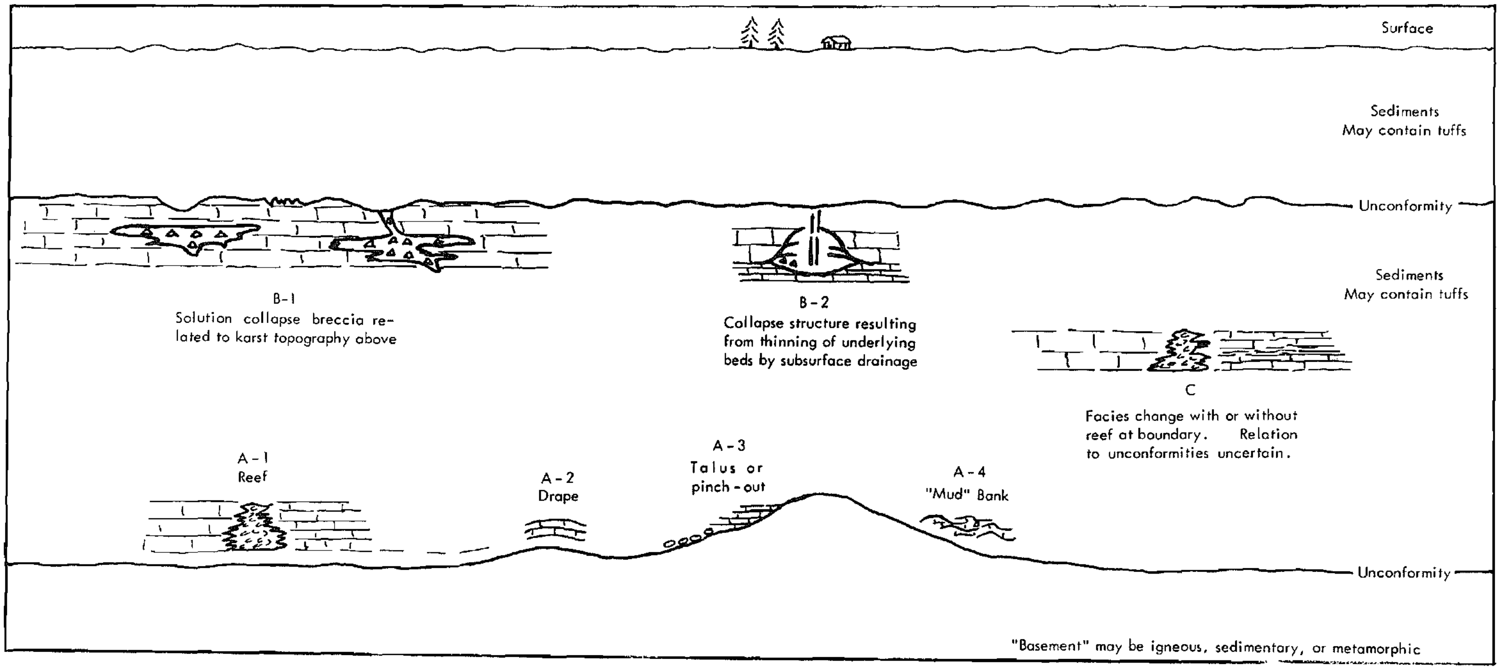


Figure 1. Mississippi Valley type mineral deposits.

Table I. Description of environments responsible for localization of Mississippi Valley type mineral deposits.

District	Type of Localization	Age of Ore Host	Age of Rock Below the Unconformity
Type A Cases			
S.E. Missouri, U.S.A.	A-1, A-2, A-3	Upper Cambrian	Precambrian
Pine Point, N.W.T., Canada	A-1	Devonian	Precambrian
Tynagh, Ireland	A-4	Lower Carboniferous	Devonian
Type B Cases			
East Tennessee, U.S.A.	B-1, B-2	Lower Ordovician	Middle Ordovician
Tri-State District, U.S.A.	B-1	Mississippian	Pennsylvanian
S.W. Wisconsin, U.S.A.	B-2	Middle Ordovician	Upper Ordovician
Friedensville, Pa., U.S.A.	B-1	Lower Ordovician	Middle Ordovician
Ymir District, B.C., Canada	B-1 and C?	Middle Cambrian	Ordovician
Type C Cases			
Austinville, Va., U.S.A.		Lower Cambrian	
Pine Point, N.W.T., Canada		Devonian	

Appalachian type ore deposits are merely folded Mississippi Valley type as evidenced by their indifference to structural setting, deformation of ore minerals and parallelism of regional bedding with the bedding of detrital sphalerite and carbonate in the matrix of some solution collapse breccias.

Geometric and scalar. The environments noted above as responsible for the localization of the subject type ore deposits are illustrated in Figure 1 as they appear in vertical section. The table, by letter and number, identifies the environments of the districts so localized, the age of the host rock and that of the rocks above or below the unconformity. In a plan view, not illustrated, the shape of the environments, and consequently of the ore deposits, are characterized by linear elements, in a pattern appropriate to its paleophysiographic derivation, that is simple linear, curved or straight, reticulate or en echelon.

The mineralization is truly strata-bound. Consequently the overlying beds contain no direct expression of the mineralization below although they may contain features detectable by geophysics which are distractions rather than determinants.

The favorable environments above unconformities may be many miles long and several miles wide. However, the individual orebodies therein may be only a few thousand feet long, 75 to 800 feet wide and up to 100 feet thick, although the thickness of most of them is around 20 feet or less.

The favorable environments below unconformities may cover thousands of square miles. However, the dimensions of the elements of the deposits therein are of about the same order of magnitude as for those occurring above an unconformity.

The point to be remembered here is that for the detection of anomalies associated with such deposits at depth of 800 to 1200 feet in horizontal sediments, the depth at which much prospecting is being done, the deposits must appear as very narrow and thin targets to any remote sensing equipment on surface even though the entire deposit, rather than an uneroded remanent thereof, is available for discovery. Hence the importance of developing down-the-hole geophysical methods to reduce the remoteness factor.

Topographic. In the limestone terrains usually encountered in this search problem, the surface is commonly characterized by a karst topography. As a consequence, the overburden, residual or otherwise, varies in thickness abruptly and significantly. Such variation controls to some extent the distribution of electric current in the ground. Also this superposition of a present karst topography on the derivatives of a fossil one, which controlled the localization of ore, may be responsible for the hydrologic problems encountered in some deposits in solution collapse breccias and contribute additional complication to the situation from a geophysical standpoint.

Cultural. The areas where these deposits have been found in the United States and are likely to be found in the future, are characterized by few outcrops except in river valleys and road cuts. The soil cover, residual or loess, such as in Wisconsin, glacial-residual such as in Pennsylvania, or residual-alluvial such as in the southern Appalachians, varies in thickness from 10 to 60 feet. The areas are well settled and generally farmed. They contain a network of wire fences, communication and power lines, local pipelines and organic-rich barnyards, any or all of which can be distractions to some types of geophysical surveys.

Mineralogical - chemical. Although the host rock is commonly dolomite, some of the ore deposits, such as those in east Tennessee, occur in dolomite bodies in a limestone formation. Also, there is usually little if anything to distinguish unmineralized formations in the section from the unmineralized portions of the ore host.

While the mineralogy varies from district to district, sphalerite is the dominant ore mineral in all of these deposits except those in southeast Missouri where galena is the dominant and sometimes the only ore mineral.

The next most common mineral is iron sulfide, generally pyrite although marcasite is a prominent constituent in southwest Wisconsin ores. In the east Tennessee district, iron sulfides are virtually absent in the Mascot - Jefferson City portion thereof.

Galena is an important but subordinate accessory mineral in the tri-state southwest Wisconsin, Austinville, Virginia and Copper Ridge, Tennessee districts, but it is absent in the Mascot - Jefferson City, Tennessee and Friedensville, Pennsylvania deposits.

Among the gangue minerals, dolomite and calcite occur commonly as vug linings and veinlets. Chert and quartz are well represented locally in some deposits whereas fluorite, barite and anhydrite occur less commonly.

The metal content of these ores grade from 3 to 6% Zn and 0.5 to 1% lead as an accessory, except in southeast Missouri where usually only lead is present of grade 4 to 6% Pb. Pyrite-marcasite content where present ranges from 3 to 10%. In the zinc-lead deposits, the galena and pyrite commonly occur most concentrated on the hanging wall side of the ore. With respect to grade, the chances for detection of the subject type of deposit at shallow depth by geophysical methods are improved enormously if the sulfide mineral content, particularly pyrite and galena, is greater by a factor of two or more than is the case in the deposits in the United States. The near-surface relatively high-grade deposits at Pine Point, N.W.T. Canada and in Ireland were detectable by geophysical methods.

Those bodies which outcropped were oxidized with the development of minerals appropriate to the sulfide mineralogy thereof. In general, calamine is the common product of the oxidation of sphalerite in the Appalachians and smithsonite in southwest Wisconsin. Where iron sulfides are present, limonite gossans are prominent and were guides to early exploration. In many cases sufficient oxidized ore was formed to justify a mining operation solely thereon; for example, Bertha and Austinville district, Virginia and Mascot - Jefferson City district, Tennessee. Following the exhaustion of the oxidized ore, the sulfide source was exploited. Where such oxidation is present, self-potential measurements are appropriate. However, where oxidation is deep, up to 150 or 200 feet, the sulfide source thereof may not be detectable by sulfide-sensitive geophysical methods of shallow range.

Physical. *Magnetic.* Topographic relief on an unconformity may be mapped by magnetic methods and environments in younger beds related to such relief thereby indicated. The deposits themselves have no readily detectable magnetic contrast with their environment.

Electrical. Sphalerite is a nonconductor, as are the gangue minerals. Only galena and pyrite are available to contribute to the electrical characteristics of the ore relative to its environment. In some districts enough of the latter two minerals may be present to permit detection by IP surveys but not enough for EM methods. A resistivity contrast may exist between the ore and its environment because of the vuggy character of the ore, its galena and pyrite content or to a combination of these features. Water-bearing vuggy ground that is barren of sulfides may be responsible for distracting resistivity contrasts.

Gravimetric. Except perhaps for the high-grade Pine Point, N.W.T., Canada deposits, there is insufficient density contrast between the ore and its environment to be detectable by conventional gravity measurements. This comes about because the sulfide mineral content of the deposits is relatively low, thus contributing little increase in density whereas the deposits are commonly vuggy and porous thus decreasing the density thereof. The net effect relative to the environment is about zero.

Seismic. Topographic relief on an unconformity and the favorable ore loci related to it may be delineated provided a sufficient contrast in the speed of sound exists between the rocks bracketing the unconformity and the relief thereon is not rugged and is relatively large-scale. While to the eye it appears that a velocity contrast should be present between the ore and its host formation, the dimensions of the ore may be too small to be detectable by conventional reflection or refraction seismic methods. Time of arrival measurements in a pattern of holes with seismometers and shot point in the host bed may be informative.

Radioactive. This experiment was premised on the possibility that the process responsible for ore emplacement might have changed the distribution of radioactivity in the ore host or in the regional environment and that such change would survive removal of the ore. Rather conclusive tests on the ground, underground, and from the air over unmined and mined-out deposits failed to disclose any consistent radioactive contrast between the ore and its environment or any significant characteristics of environments favorable for ore occurrence.

Geophysics

History of geophysical programs. The first systematic effort to investigate the application of geophysics to the search for the subject type deposit was conducted in 1928 under the direction

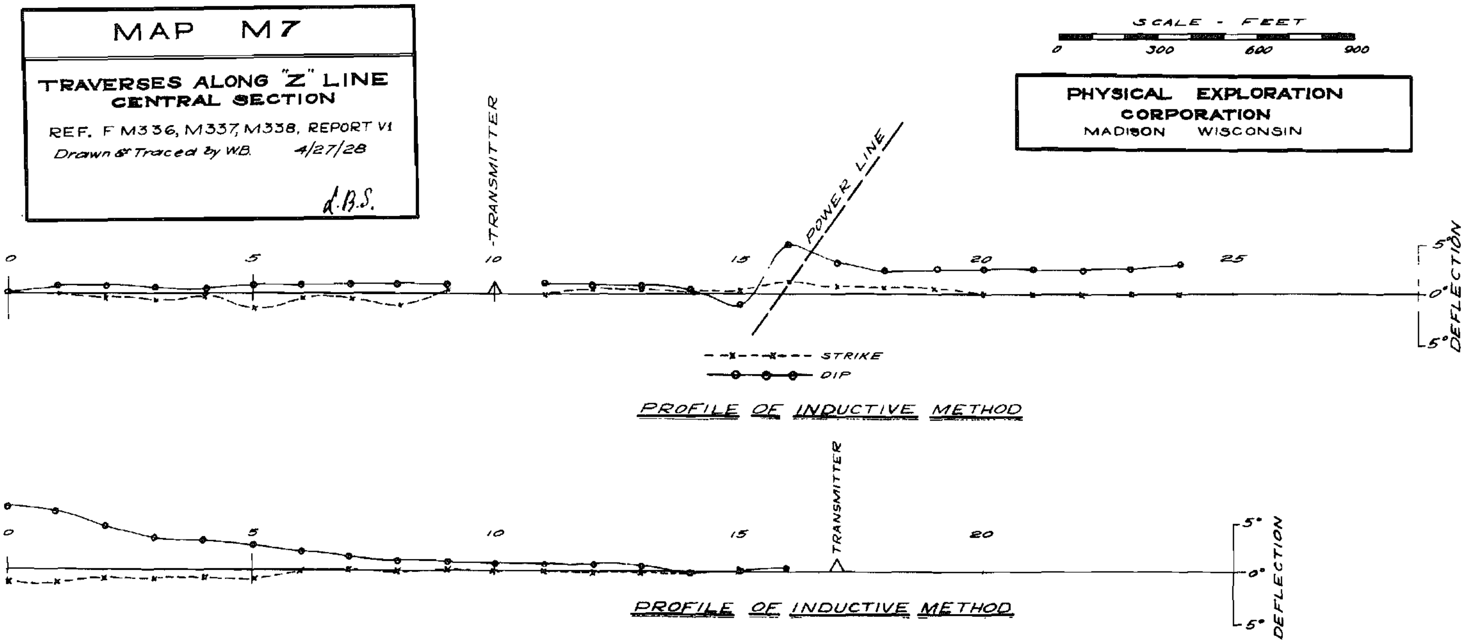


Figure 2. Vertical loop electromagnetic data, Austinville, Va. 1928.

of Louis B. Slichter of The Physical Exploration Company, a contractor. The investigation was directed to calibrate methods over a partially drilled out deposit with the hope that the findings could be utilized in the vicinity for the direct detection of anomalies which might be associated with ore. The methods employed were magnetic, electromagnetic, self-potential and applied potential on surface and in drill holes. The senior author participated in this survey.

Subsequent history was as follows:

1937-38	Ratiograph surveys by Hans Lundberg at Friedensville, Pennsylvania and Austinville, Virginia.
1946-49	Applied potential surveys in drill holes at Austinville - Ivanhoe, Virginia and Friedensville area, Pennsylvania.
1949	Applied potential surveys in surface and drill holes, Ymir district, British Columbia, Canada.
1951	Radiowave survey (Carl A. Bays & Associates), Austinville, Virginia.
1952-53	Radiometric surveys in Virginia, Pennsylvania, Tennessee, Missouri, Oklahoma and Kansas. Self-potential survey, Wisconsin.
1952-54	Seismic experiments in southwest Wisconsin with the University of Wisconsin.
1954	Applied potential survey in Wisconsin.
1960	Induced polarization survey in Grant and Lafayette counties, Wisconsin with McPhar equipment and personnel.

This was our last effort in experimenting with the application of geophysics to our search for the subject type deposits.

A description of the equipment and procedures used and some of the resulting data will be summarized with respect to the method employed rather than on a strict time or space basis. For the locales involved, the southeast Missouri, tri-state and Wisconsin districts are Mississippi Valley type, occurring in practically horizontal sediments, whereas the Friedensville, Austinville - Ivanhoe and east Tennessee districts in the United States and the Ymir district, British Columbia are Appalachian type occurring in folded beds.

The electromagnetic method. In 1928, L.B. Slichter tested the applicability of the electromagnetic method for discovery of Appalachian type lead-zinc orebodies. The tests were carried out at Austinville, Virginia, using a large vertical source coil excited by a gasoline-driven 900-cycle alternator. The inductive reactance of the coil was neutralized by a bank of condensers, providing excellent frequency stability and high power efficiency. The source loop in this arrangement was part of a resonant circuit.

The electromagnetic signal was detected by a tripod-mounted search coil designed to permit rotation of the coil about vertical and horizontal axes. Observations were made at 100-foot intervals on either side of the source loop, the traverse being confined to the plane of the source coil. Traverse lengths of up to 2000 feet on either side of the source could be achieved. Measurements were made of the inclination of the source field and of its azimuth relative to the azimuth of the traverse. In the absence of anomalous conditions, the field of the source is aligned normal to the plane of the source and hence would be horizontal and perpendicular to the traverse direction. This electromagnetic procedure is identical in principle with vertical coil methods used today; only the instrumentation and field tactics have changed.

Mason (1929) includes pictures of this early type of apparatus.

No anomalous conditions resulted from Slichter's tests other than from effects caused by recognized cultural features. In general, the electromagnetic field was within two degrees of its nonanomalous direction. Typical results of the field data are shown in Figure 2 which was taken directly from Slichter's 1928 report. The only striking effect seen here is caused by a shallow pipe line.

Slichter emphasized that relatively high resistivity materials such as the deposits of the Austinville type are not suited to

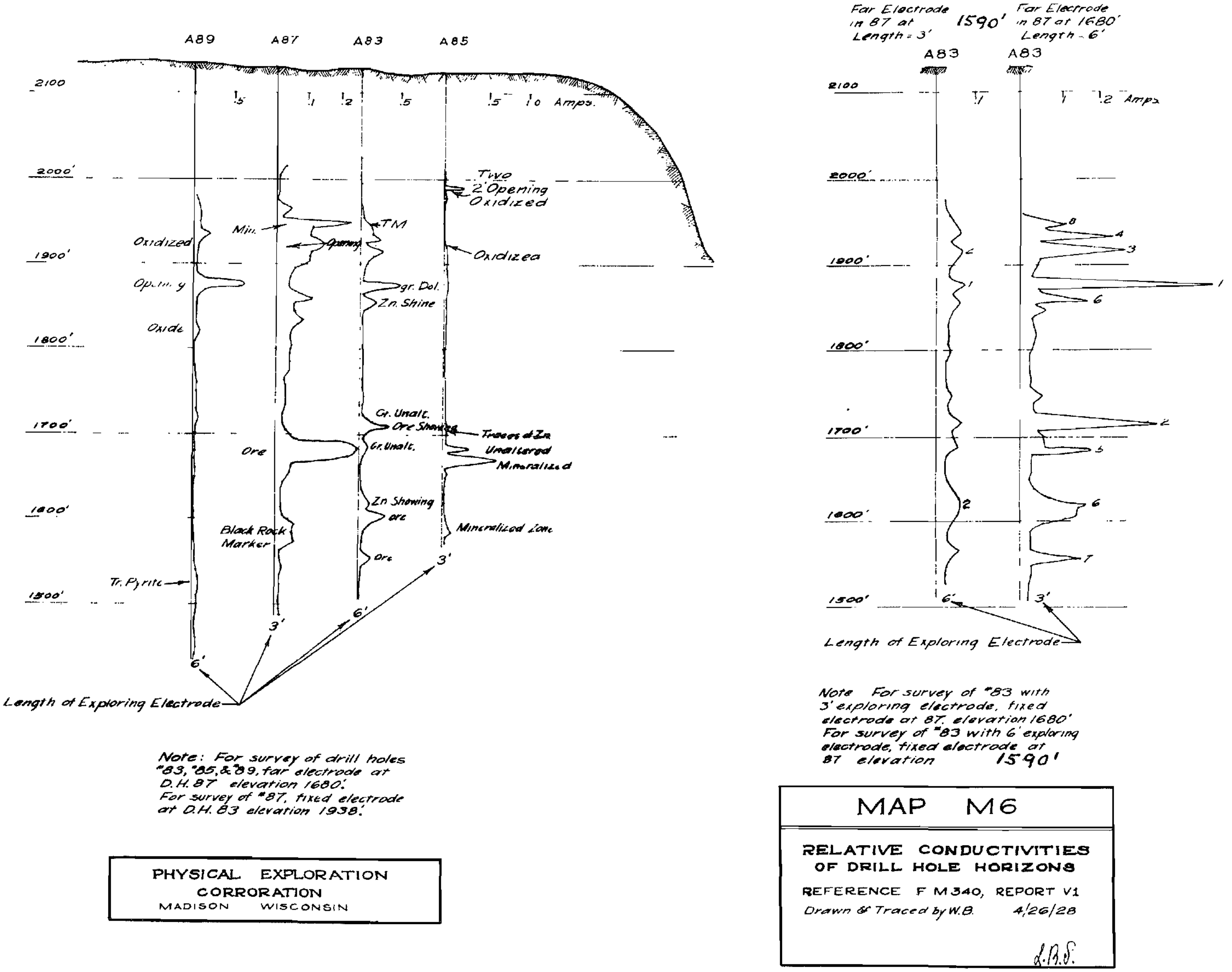


Figure 3. Single electrode drill hole logs, Austinville, Va. 1928.

detection by the electromagnetic method. The work was carried out in the hope that a shallow massive galena-rich stockwork might be found. This was recognized as a remote possibility.

The applied potential method. In 1928, L.B. Slichter carried out electrical surveys at Austinville, Virginia, which made use of available drill holes – particularly those which penetrated known ore. One of his ideas was that the surface potential distribution above an electrified elongated orebody might disclose the direction in which the orebody extended. He also hoped to be able to determine whether or not conductors present in adjacent drill holes were connected.

To be sure that applied potential procedures were applicable to the Austinville situation, it was necessary to find out what sort of resistivity contrast existed between the country rock and the ore. This was difficult with the equipment available and Slichter was not successful in measuring the resistivity of the ore in place. He did, however, demonstrate that the resistivity contrast between the ore and its surroundings was great – greater than 1:15 by his estimates. This was done as illustrated in the left-hand group of drill-hole profiles shown in Figure 3 taken from Slichter's 1928 report. This is the section of holes A-89, A-87, A-83 and A-85. An electric log is shown in this section for each of the four holes.

The logging of drill holes was new to both mining and petroleum geophysics when this work was done; the logs presented here were among the first produced for the mining industry or as a matter of fact for any exploration group. The logs presented in the section at the left of Figure 3 show the current variations which resulted when a constant voltage was applied between the casing of hole A-83 and a metal electrode which was lowered into the hole being logged. Observations were usually made at 5- or 10-foot intervals with detail data being obtained over zones of particular interest. The current scale was made logarithmic to facilitate plotting of a wide range of current values.

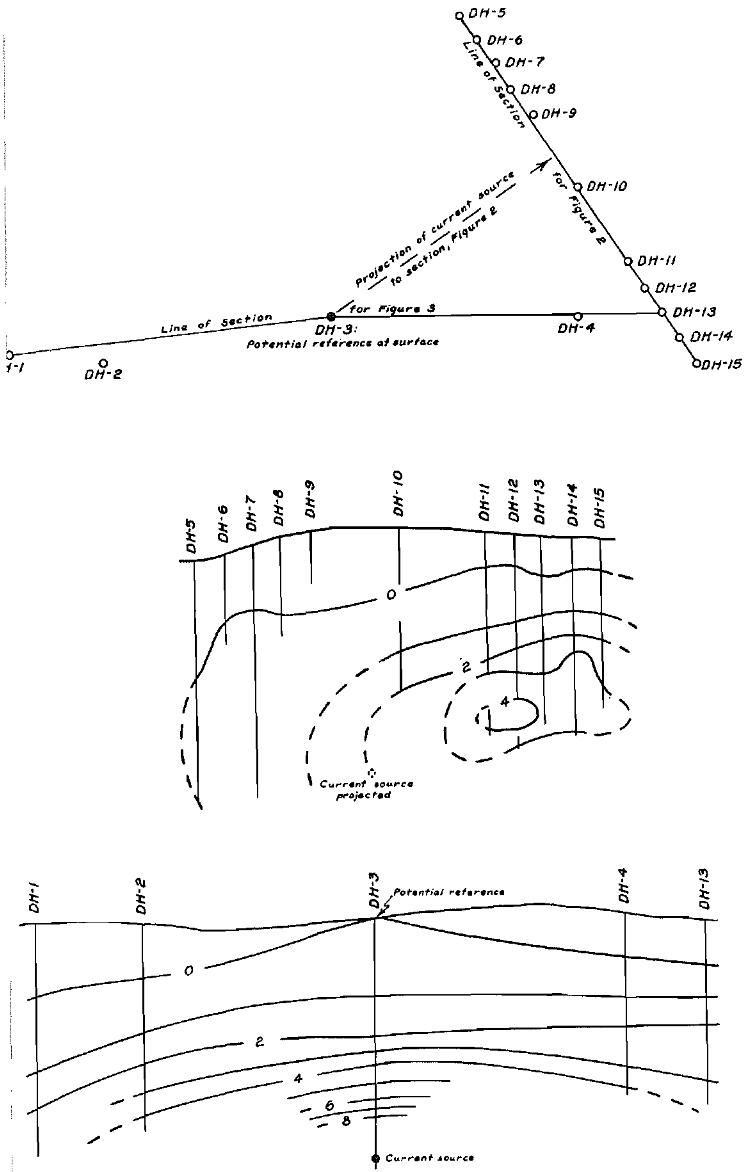


Figure 4. Example of applied potential data using drill holes from Ivanhoe, Va.

Having established that conditions were suited to the use of his applied potential technique, Slichter proceeded to obtain surface potential data above a current electrode suspended in a conductive orebody at a depth of about 500 feet. The return current electrode was at the surface 4500 feet away. It was found that the maximum of the surface potential distribution did not occur directly above the current source as it would in a uniform medium but was displaced 300 feet from this location. This led to the forecast that the ore penetrated by the drill hole extended in the direction of the surface potential high. The reasoning was that current was leaking out of the electrified conductor over its entire surface and hence it behaved as a large electrode. The maximum potential over the surface might therefore be expected to occur or at least be displaced toward the midpoint of the body if the point of electrification happened to be at distance from its midpoint. It was subsequently found by drilling that in this case the orebody had the shape of a pencil which extended in the direction of the offset surface potential high.

We now return to Figure 3. The two logs of hole A-83 shown at the right of this figure were specially devised in the hope of emphasizing the existence or lack thereof of an electrical connection between certain conductors in holes A-87 and A-83. One of the two logs, the one on the right, was obtained with a fixed current electrode in hole A-87 in conductive ore at an elevation of 1680 feet. The second log, the one to the left, was obtained with the fixed electrode in a mediocre conductor at 1590 feet in A-87. Slichter felt that there was some evidence in these data that the ore at 1680 feet in A-87 was connected to the conductor at 1710 feet in A-83. His reasoning involved study of the relative changes in amplitudes of the peaks of the two logs in A-83 obtained for the two locations of the fixed electrodes in A-87. However, he emphasized that this was a tentative conclusion and that further work was necessary to substantiate the result. He had in mind several check procedures which were not feasible at the time because of equipment problems.

It was not until 1945 that the possibilities for use of the applied potential method were further tested. Experiments were then undertaken by a newly organized Geophysical Research group of The New Jersey Zinc Company who worked on the problem in consultation with Professor Slichter.

The tests carried out by The New Jersey Zinc Company group made much more use of drill-hole access than had ever been done before. Efforts were made, for example, to map the potential distributions about electrified orebodies in three dimensions rather than solely over the earth's surface. The goals of the tests can be summarized as follows:

1. To further investigate the promising possibilities developed by Slichter for determining the axial direction of an electrified pencil-type orebody by means of surface potential data.
2. To continue the study of to what extent the continuity or lack of continuity of conductors between ore intersections could be established.
3. To study the possibility for finding blind orebodies located near barren drill holes.

Extensive field data were obtained from a number of districts including Austinville - Ivanhoe, southwest Wisconsin, Friedensville, Pennsylvania and Ymir, British Columbia. This work was supplemented by model studies and by a considerable amount of theoretical work.

A detailed account of applied potential work at Ivanhoe, Virginia is presented in a paper by McMurry and Hoagland (1956) in which extensive data from that area are presented and interpreted. Subsequent research has led to some modification of a few ideas stated in this paper but no radical changes in viewpoint have emerged. A summary of conclusions regarding the merit of the applied potential method is given below after which examples of field data are presented.

1. The ability to define the direction of extent of elongated pencil-shaped orebodies by electrifying the bodies and measuring the surface potential distributions above them is poor. Model data and carefully planned field tests show that resistivity variations near the surface exert primary control over the surface potential distribution.
2. Little encouragement resulted for detection of blind orebodies narrowly missed by drill holes. This circumstance

obtains because strong background effects associated with resistivity variations in the host rock are common. It has not been possible to recognize electrical effects caused by hidden orebodies because of these distractions. In particular, the use of drill hole resistance logs to determine continuity in the manner tried by Slichter did not prove effective.

3. It is often possible to prove conclusively that two conductors are not connected. The inverse has not been possible; that is, one cannot prove beyond doubt from applied potential data that two conductors encountered in separate drill holes are indeed connected. However, the situation is not entirely bleak. For example, it is often possible to conclude that the chances that two conductors are connected are good even though a dogmatic statement on the point is not possible. Furthermore one can often make good judgments where there is a problem of determining which of several conductors penetrated in two or more holes are likely to be connected.

The result of all this effort is the feeling that applied potential techniques can provide limited but worth-while assistance in reducing the number of drill holes required to trace out orebodies, which are conductive relative to their environments.

Examples of applied potential data. Figure 4, taken from the paper by McMurry and Hoagland, illustrates the results obtained for an applied potential survey which made use of 15 drill holes at Ivanhoe, Virginia. The upper illustration of this three-part figure gives the locations of the drill holes; the intermediate and lower illustrations show the potential distributions which resulted in two vertical sections of drill holes, one longitudinal and one oblique, when the current source was suspended in an excellent conductor in hole No. 3 of the longitudinal section. The potential reference for this survey was at the top of hole No. 3; the return current electrode was far away and hence had little influence on the potential data.

The equipotential contours in both sections are extremely elongated with the effect being more pronounced for the longitudinal than the oblique section. This sort of potential distribution cannot be explained as due to the effects of elongated pencil-type orebodies. It is believed that the country rock as a whole is triaxially anisotropic as regards its resistivity. Many aspects of the potential data illustrated in Figure 4 can be explained by assuming that the resistivity is a maximum along axes normal to the bedding, is a minimum in the bedding along axes parallel to the direction of maximum elongation of the equipotential surfaces, and has an intermediate value along bedding plane axes normal to the axes of minimum and maximum resistivities. The estimated magnitudes of the minimum, intermediate, and maximum resistivities are about 500, 1000 and 2000 ohm-meters. Thus the minimum resistivity is actually high in an absolute sense – much higher than is the resistivity of the conductor in which the current source was suspended, which was in the neighborhood of 50 ohm-meters.

The orebodies at Ivanhoe are pencil-type features. Drilling data have shown that the axes of the Ivanhoe ore pencils tend to be parallel to the direction of minimum resistivity. The results from the longitudinal section of Figure 4 are of interest in this connection for they were interpreted as indicating that the channel in which the electrified ore in hole 3 was located might extend under holes 1 and 2. On the basis of this forecast, holes 1 and 2 were deepened and ore was found where it was predicted that it might occur.

The maximum voltage in the oblique section coincides approximately with ore zones in holes 11 and 12. Actually hole 13 contained more ore than did holes 11 and 12. Nevertheless the result conforms reasonably well with experience at Ivanhoe that mineral deposits tend to coincide with channels defined by the direction of maximum elongation of potential surfaces which form about electrified conductors associated with these channels.

The volumes of earth occupied by conductors present in the region being investigated by an applied potential survey carry a larger fraction of the current flow than they would if the conductors did not exist. In other words, current is diverted into a given conductor over that portion of its surface nearest the current source and, of course, flows out over portions of its surface more remote from the source. Since current flow is always from regions of relatively high to regions of relatively low potential, those volumes where current is flowing into a conductor are lower in potential than normal while the region through which current leaves a conductor appears to be at above-normal potential. This means that low potentials will be observed in drill holes which pass through or near a conductor in a region where current is being diverted into the conductor and that high potentials will be detected in a hole which cuts or passes near conductor in a region through which current is flowing out of the body. Therefore one can often determine whether a conductor cut by a drill hole extends toward or away from a current source in a second hole. If it extends away from the current source, that is if current from the source is being diverted into the conductor, there is clearly no possibility that the conductor is connected with the current source. On the other hand, if a potential peak coincides with the conductor, it can be concluded that the conductor extends in the direction of the current source. It may or may not extend as far as the current source.

The above discussion shows why applied potential data can often prove that two conductors encountered in different drill holes are not connected but they cannot prove the converse; that is, they can only show in many cases that it is possible that two conductors are connected.

With this in mind, consider again the results of Figure 4. We conclude that it is possible but not certain that ore found by deepening holes 1 and 2 is necessarily continuous with the ore zone penetrated by hole 3. Likewise is it not possible to say that the ore in hole 3 extends continuously to the region marked by the potential high in the oblique section, that is, to join the conductors in holes 11, 12 and 13.

The self-potential method. Self-potential surveys were carried out at Austinville, Virginia by Slichter in 1928 and at Ivanhoe, Virginia by New Jersey Zinc personnel in 1947. No effects directly or indirectly associated with ore were recognized. The anomalies which did occur often correlated with cultural features, chiefly such things as pipelines and fence lines. Some anomalies were mapped which were due to near-surface features such as swamps.

A 5 1/2 square mile area was surveyed in southwestern Wisconsin in 1953. The area chosen for this test included a number of shallow mineral deposits and areas which had been drilled and found to be barren. The self-potential survey yielded anomalies over some, but by no means all, of the known mineral deposits which were investigated. Moreover distinct anomalies occurred in some areas which had been drilled and found to be barren. For these reasons self-potential data have not been useful in guiding exploration for shallow targets in southwest Wisconsin.

The ratiograph or racom method. In 1938, Hans Lundberg covered 31 miles of ratiograph traverse at Friedensville, Pennsylvania, which was followed by 23 miles of similar profiling at Austinville, Virginia. The procedure is described in a paper by Lundberg and Zuschlagg (1932). The hydrological environments at the two locales were quite different. At the time the Friedensville deposit was undeveloped and undrained whereas the Austinville deposit was in production and a large area tributary thereto at least partially drained.

The ratiograph surveys involved profiles using what would now be called a pole-dipole electrode array with the added feature of a potential reference electrode positioned halfway between the potential electrodes. It was the ratio of the voltages between this reference and the two potential electrodes which was measured.

Details regarding the survey are not recorded in the reports. For example, information concerning electrode interval used, whether direct or alternating power supply was employed, and the nature of the receiving equipment is lacking. Furthermore the data presented do not show what magnitudes of potential ratios were obtained nor is there a discussion of the accuracy of the measurements.

The objects of the survey were as follows:

At Friedensville. To investigate the structural control of ore deposition; to indicate and trace water-bearing channels; and to locate and investigate the gneiss limestone contact on South Mountain.

At Austinville. To outline the fault pattern in the Austinville dolomite beyond the mine workings.

For structure and fault patterns in both areas, the ratiograph surveys did not contribute information any more definite than was already known.

With respect to guides to exploration, the surveys are considered to be nonproductive. This is not so much the fault of the survey as of the then current concept for conducting them; to wit that structure is responsible for ore localization. Today the structures involved are considered to be postmineral and responsible only for rearranging the original pattern of mineralization.

In tracing water-bearing channels at Friedensville, this objective was partly achieved in the sense that the survey indicated local areas of porosity or permeability. However, in the meantime mining has demonstrated that the original concept of major channels of inflow is in error because in fact the water enters the mine by percolation and infiltration on an intricate small-scale three-dimensional pattern of joints.

The gneiss limestone contact at Friedensville was located satisfactorily by both the ratiograph and magnetic survey and the data correctly interpreted that the contact was a steeply dipping fault. However, the forecast regarding displacement was much less than demonstrated later by drilling.

It is regrettable that factual data concerning the ratiograph method were not submitted with the reports so that a more rigorous analysis could be made than is now possible.

Radiowave propagation characteristics. Measurements of the strength of radio signals from commercial radio stations were carried out in the Austinville, Virginia area in 1951 by Carl A. Bays & Associates of Urbana, Illinois. The work was premised on the fact that reports of similar surveys carried out in Illinois under the auspices of the Illinois Geological Survey noted the existence of interesting correlations between geological features and variations in field intensities of commercial radio transmitters. The correlations which were described in the Illinois reports were empirical, there being no good theoretical basis to explain them.

Most of the radiowave measurements utilized a continuously recording radio field intensity meter which was transported in a station wagon. However, an important phase of the effort involved use of a portable detector which measured variations in the inclinations of the radio fields from commercial transmitters and from a portable 300-watt transmitter which could be positioned wherever desired.

The results of about one month's test of this technique in and around Austinville were discouraging. The vehicle-mounted equipment yielded field intensity data which were dominated by cultural factors, chiefly power lines. Effects due to geological features could not be recognized.

To obtain data free of cultural effects, tests were run in remote areas using the portable apparatus including the portable transmitter. It soon became evident that the inclinations were greatly affected by topography – even minor topographic features produced significant responses. The conclusion was reached that effects caused by geological features could not be recognized in the face of distractions due to things like powerlines, pipelines, bridges and hills. This circumstance, coupled with the fact that there was no theoretical reason to think that the method might be useful, led to termination of experiments with radiowave intensity measurements.

The induced polarization method. This method was tried in southwest Wisconsin where many of the known deposits are shallow and hence offer hope that others might exist amenable to detection by appropriate surface surveys. Over 100 miles of pole-dipole profiles were carried out with an equispaced array of electrodes 330 feet apart. Observations were made at 330 feet along each profile. In addition to this reconnaissance effort, detail data were obtained in the vicinity of a known orebody. The frequency effect technique was employed using frequencies of 10 and 0.5 cycles per second.

Little success was achieved. The reconnaissance profiles crossed at least nine known orebodies, none of which yielded a response which could be considered unique. The detail data failed to exhibit effects which could be correlated with the known ore.

One of the limitations of the IP technique in southwest Wisconsin is the relatively high background noise level which was encountered. This may not have been due to the numerous fence lines present in the area. Care was taken not to have any electrode, current or potential, within several tens of feet of a fence. Furthermore all fences were crossed at 90 degrees. No obvious distinction was observed for data obtained with an array in the middle of a field as compared to results obtained when the array was situated within a few tens of feet of a fence. Many of the fence lines were insulated from the earth to permit electrification for purposes of controlling stock. This probably was helpful in minimizing their influence on the induced polarization data. No explanation for the high noise level has been found. It is possible that improvement in signal-to-noise

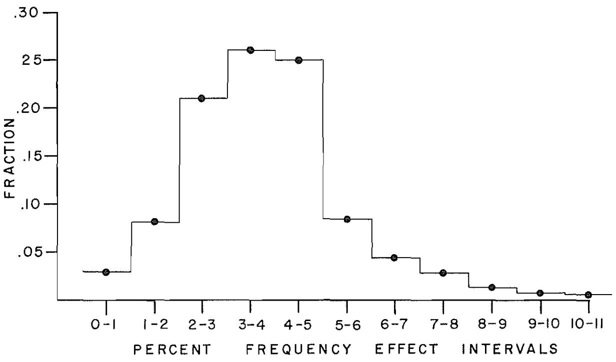


Figure 5. Distribution of frequency effects for induced polarization survey in southwest Wisconsin. The fraction of the total of frequency effects falling within the specified frequency effect intervals is plotted.

$$\text{PFE} = 100 \times \left[\frac{\rho_{dc}}{\rho_{ac}} - 1\right]$$

ρ_{ac} = resistivity measured at 10 cps, and ρ_{dc} = resistivity measured at 0.5 cps.

level might have been obtained had the higher frequency been 5 cycles per second or less rather than 10 cycles per second.

The curve of Figure 5 shows how the abundance of observed frequency effects is distributed as a function of the percent frequency effect interval. Study of this curve shows that effects between 2 and 5% are common; they cover almost 90% of the 1473 cases involved. Clearly an anomaly would have to have a frequency effect a good deal higher than 5 or 6% to be considered unique.

The nine targets which were crossed by the reconnaissance survey were known from drilling. None of them was accessible for direct testing of their IP responses.

Magnetic method. In most cases magnetic surveys have been of little help in the search for strata-bound orebodies such as those being considered here. This is because both the orebodies and their calcareous host rocks are relatively nonmagnetic. In many districts, such as in the Appalachians and in southwest Wisconsin, the features responsible for the localization of orebodies are related to an unconformity above or to facies change, neither of which has magnetic expression. However, it was thought that the southeast Missouri area might be a possible exception. In this area orebodies are often associated with features related to an unconformity below, such as pinchout structures formed on the flanks of Precambrian knobs. This subject is considered by W.H. Callahan (1964, 1968). Extensive magnetic data have been scrutinized with the object of locating such favorable structures. It was reasoned that the Precambrian basement should be more magnetic than the overlying sediments and hence that knobs might produce diagnostic magnetic effects. The results of these studies were disappointing. In some cases known knobs were found to be essentially without magnetic expression; in other cases they produced distinct magnetic effects. Finally it was found that some magnetic anomalies were associated with variations in the magnetic susceptibility of the basement rocks and that such variations had little to do with the presence or absence of knobs. The result was that the existence of a magnetic anomaly offered but weak evidence of the presence of a buried knob and the absence of magnetic anomalies in a given area did not by any means rule out the presence of knobs in the area.

Since it was realized that some knobs do cause magnetic anomalies, magnetic data were studied to see if anomalies caused by knobs in a uniformly magnetic basement could be recognized. The results were again disappointing. It was found that distinct isolated magnetic anomalies seldom occur. The peaks are often well defined but the flanks become entangled with the flanks of other nearby magnetic features. The nature of the flanks of an anomaly is important when the object is to find out whether the magnetic body responsible for the anomaly has a limited depth range, as would be true for a knob, or whether it extends to great depth as was usually the case of magnetic effects caused by variations in the magnetization of the basement rock.

An example of an area in southeast Missouri which was explored for buried knobs is afforded by the results presented in Figure 6. Total intensity aeromagnetic data are shown together with the locations of drill holes and Precambrian outcrops. Two sections in the lower half of the figure illustrate two pinchout zones of the Lamotte formation which were defined by drilling.

Section *A-A′* in the lower left-hand corner of the figure illustrates a pinchout which occurs at the south flank of a nonmagnetic rhyolite knob which outcrops at the north end of the section. The outcrop is in a magnetic low area. The magnetic data would not have pointed to the presence of the knob had it been covered. Drill hole 4 at the south end of the section lies close to a magnetic high; this high is judged to be due to a local increase in the magnetization of the basement rock and to have no association with a bedrock topographic feature.

Section *B-B′* is illustrated in the lower right of Figure 6. This is a case in which a basement knob appears to be associated with an aeromagnetic high. Drill hole 6 of this section located a pinchout zone on the south flank of this knob.

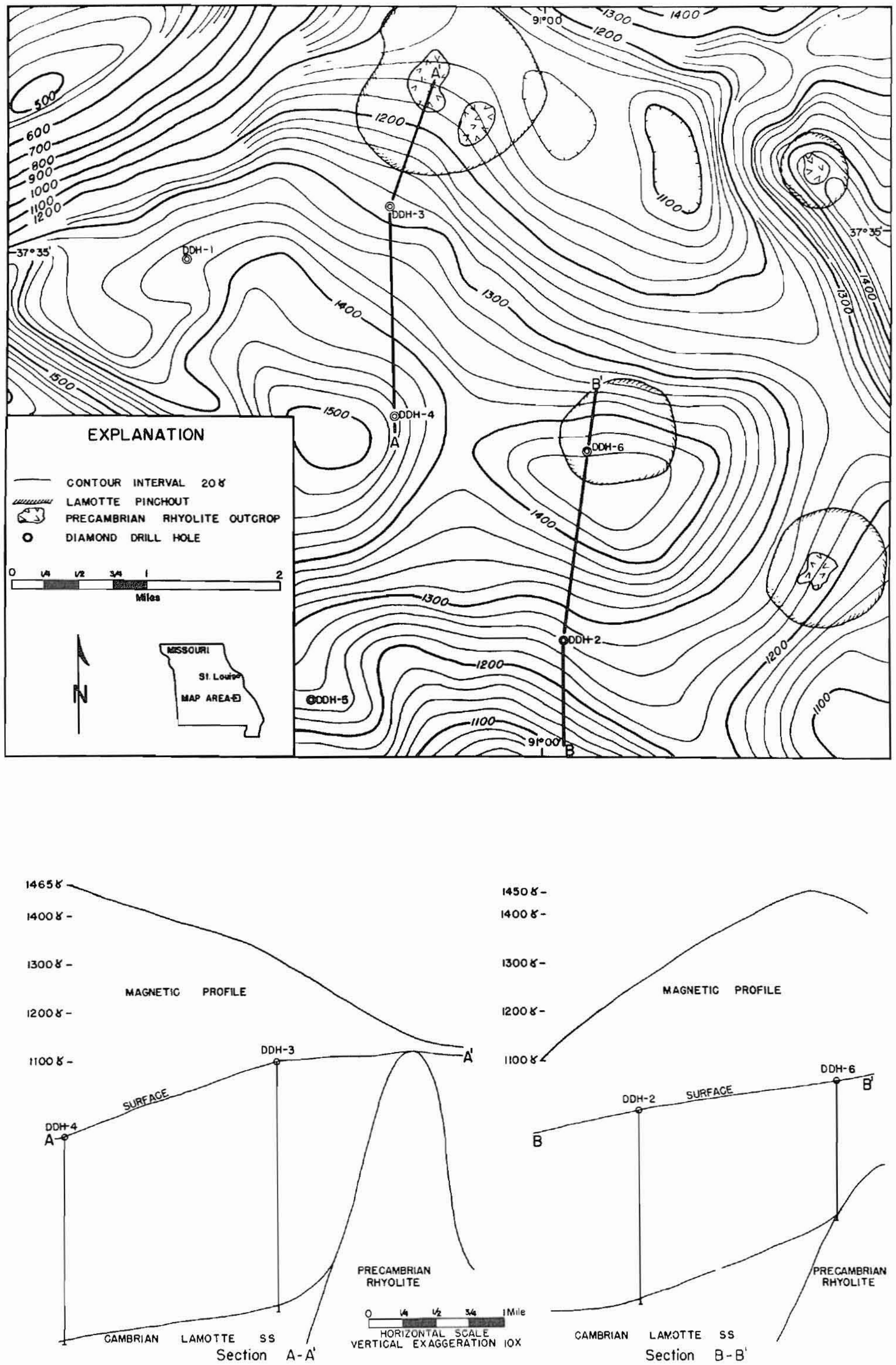
The nature of the magnetic data is such as would be caused by an isolated magnetic feature within the basement which extends to great depth. It is not the sort of anomaly which would result from a local knob in a uniformly magnetic basement. The magnetic feature therefore did not provide clearcut evidence that a knob was present.

The knob which outcrops not quite 2 miles east of section *B-B′* does not produce a recognizable magnetic effect. Therefore this knob is in the same category as the nonmagnetic knob at the northern end of section *A-A′*.

A Precambrian outcrop shown in the northeast corner of the map of Figure 6 occurs at the northwest end of an elongated magnetic feature. The magnetic data suggest that the anomaly is due to a magnetic contrast in the basement rocks, not to a topographic high in the uniformly magnetic basement.

Experiences such as those just described have led to the conclusion that the contribution that magnetics can make as a guide to exploration in southeast Missouri is ambiguous.

The radiometric method. Extensive radiometric surveys were carried out between 1952 and 1954 to determine whether or not recognizable radiation patterns could be correlated with the subject type zinc-lead deposits. It was realized that gamma rays are rapidly absorbed by any matter and that the method would



Section A-A'

Section B-B'

Figure 6. Aeromagnetic and geological data in an area of southeast Missouri.

not detect radioactive elements buried more than a few feet below the earth's surface. In a sense the radiometric method was considered a special kind of geochemical procedure.

Tests were carried out on the ground in southwest Wisconsin and in four widely separated areas in the Appalachians; Friedensville, Pennsylvania; Austinville, Virginia; Jefferson City and Flat Gap, Tennessee; underground at Austinville; and with helicopter-borne equipment in the tri-state district. The results were nonproductive. Reproducible anomalies were discovered during the surveys but no distinct correlation between anomalous radioactivity and known mineral deposits or with geological features related to these deposits was recognized.

The seismic method. In 1954, attempts were made to obtain seismic reflections from shallow, flat-lying beds in southwest Wisconsin. It was hoped that such data could be used in mapping shallow, minor structures in the flat-lying beds of southwest Wisconsin. The work was sponsored by the University of

Wisconsin but was supervised by geophysicists of the Houston Technical Laboratories, a subsidiary of the Texas Instrument Company. The New Jersey Zinc Company provided detailed geological data from the test areas.

High-resolution seismic equipment designed and built by the Houston Technical Laboratories was used. This equipment differed in a few details from conventional seismic apparatus. For example, frequencies of over 100 cycles per second were favored in the high-resolution equipment as compared to frequencies of 25 to 40 cycles per second in conventional equipment. This was necessary because early reflections tend to have higher frequencies than do later reflections. Also the camera speed, interval between timing lines and automatic gain control were adapted to facilitate study of reflections received within about 0.3 second of firing time.

The speed of seismic energy in the limestone of the area was found to be about 15,000 feet per second. The speed in the near-surface overburden was only 1100 feet per second. This meant that the energy reflected from shallow markers of particular interest, usually at depths of 200 to 300 feet, would return to the surface so quickly as to be swallowed up by the still active ground unrest caused by the shot. Thus reflected energy from contacts 200 or 300 feet below the surface could have been present but not recognized.

The conditions just described would also have created problems in the treatment of deep reflections had such been observed. This is because the time variations caused by significant variations in the elevation of a reflection marker would tend to be obscured by time variations associated with relatively small changes in thickness of the cover where sound transmission was slow. This problem would have been dealt with had good reflections been obtained but it would have been a trying one.

Conclusions

The New Jersey Zinc Company has been involved with testing of geophysical procedures for locating strata-bound orebodies since 1928. All of the geophysical procedures commonly used in mining exploration, save gravity, have been used. In addition to these, a few unconventional surveys were carried out. Only applied potential procedures involving the use of drill holes have been at all productive.

The applied potential method has had limited but worthwhile use in tracing out conductive orebodies which have been penetrated by one or more drill holes. The achievements of the method have involved reducing the number of holes required to trace out elongated conductive ore pencils and to provide a basis for judging whether or not conductors present in two or more drill holes are likely to be connected.

The fact that geophysical procedures other than applied potential surveys have been ineffective is an expected though disappointing result. Two of them, the electromagnetic and radiowave procedures, were unpromising from a strictly theoretical viewpoint. Several others, such as the seismic and radiometric methods, could not be evaluated without extensive, careful field trials and there were no *a priori* reasons for great expectations from them.

The induced polarization method has been used widely and successfully by others in the search for strata-bound orebodies. The results of induced polarization work in southwest Wisconsin which are described here should not be considered typical.

The gravity method was not used simply because there was no sound reason for doing so in any of the areas considered. This is not a method which needs to be field tested.

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