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Geoexploration, 12(1974)97—120
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SOME PRESENT-DAY PROBLEMS AND POSSIBILITIES IN MINING GEOPHYSICS

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ABSTRACT

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In answer to the basic question "What is mining geophysics all about?" it is contended that only an a posteriori distribution of ore reserves can be established in the present state of our knowledge and that it is pointless to talk about a priori distributions. The role of mining geophysics in minimizing costs of exploration is emphasized by means of examples drawn from electromagnetic—magnetic, refraction seismic and extra-detailed magnetic surveys. Drilling in mining operations can be successfully directed by using the mise-à-la-masse method as illustrated by a drillhole survey of this type in north Sweden. Drillhole self-potential measurements can be used to estimate the depth extent of orebodies. An example from the U.S.S.R. also shows that well developed SP patterns are present underground even if there is no surface manifestation of an SP anomaly.

The problem of prospecting for orebodies under a highly conductive overburden is discussed and it is pointed out that either a multi-frequency or a transient-field method of electro-magnetic prospecting must be resorted to and that although there are at present technical advantages in the transient-field method, the ultimate advantage probably rests with a multi-frequency technique.

A method, here called the contact polarization curve (CPC) method, that has been developed in the U.S.S.R. is presented in outline. Its principle is to earth a current electrode in an orebody and detect the potential jumps as the electrochemical barriers corresponding to different electronically conducting minerals are exceeded when the current is continuously increased. The method can be used to estimate the total surface area of an orebody or the total surface area of mineralized grains in an impregnation-type ore.

The geothermal method is briefly touched upon and it is pointed out that it may be a potentially useful method in the search for zinc ores.

INTRODUCTION *

I should like to begin my lecture by saying how happy I am to be in Australia, a country where so much outstanding pioneering work in mining

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*This is the text of Dr Parasnis' address as presented at the Conference.

geophysics has been done. I am referring to the work of the Imperial Geophysical Experimental Survey during the years 1928—30. My very first acquaintance with mining geophysics was through the reading of the classic book by Broughton Edge and T.H. Laby describing the results of the IGE survey. Indeed, it was this Australian work which made me take an interest in mining geophysics, and in standing before you today I feel as if a personal circle which began to be drawn more than two decades ago has now closed.

I should like at the outset to also thank the organizing committee for inviting me to deliver a lecture at this conference.

Much water has flowed through the Darling and the Murray since the IGE survey, and it seemed to me appropriate when I was invited to give this lecture that I should highlight some of the present-day problems confronting mining geophysics and the possibilities open to us of coming to grips with them. I intend to build my discussion today almost entirely around concrete practical cases, putting considerable emphasis on drillhole geophysics. I had the opportunity very recently of making a rather extensive tour of the Soviet Union and, in due course, I should like to report a few results of the interesting field work being done there, work that seems to be little known outside the Soviet Union.

BASIC QUESTION

I want to continue now by posing a basic question, namely, what is mining geophysics all about or, in other words, what is our purpose in using mining geophysics? The same question can be asked about geology or geochemistry but let me restrict it today to mining geophysics.

The immediate answer often given to the question is that the purpose is to find new ore deposits. However, this answer is diffuse at worst, and partial at best. It is diffuse because an experienced prospector knows that it is not easy to define an ore. It is a partial answer because whether a mining company is interested in a particular new ore deposit or not depends upon many factors. A promise or even a proven existence of an ore deposit, be it then a rich or poor, large or small one, is not sufficient to make a mining company take an active interest in it. Moreover, as I hope to show you today, the idea of using mining geophysics simply as means of locating hitherto unknown deposits is unnecessarily restrictive.

The prospecting problem before a mining company has two distinct aspects: (a) the company is interested in establishing new or additional reserves in the vicinity of existing mines; (b) the company is interested in prospecting in essentially new areas.

As a rule the immediate or, so to speak, the day-to-day concern of the company is in the problem of type (a) rather than (b). There are several good reasons for this. Most mining companies have milling and ore-dressing plants, some have smelting works and all have customers. The plants and the customers both have to be fed regularly, which can only be done if the

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reserves can be continuously developed. In the vicinity of existing mines there already exists an infrastructure of shafts, workshops, housing, schools etc. so that additional ore in an old mine or in its vicinity requires comparatively very little capital expenditure for its exploitation.

Very often, slightly low-grade ore appears more attractive to a mining company, if it lies within the "catchment area" of the mine, than a very rich ore deposit located far from it. Newcomers in the prospecting game, geologists, geophysicists, geochemists and others are often dismayed to find that the directors of the company show little interest in some of their wonderful geological, geophysical or geochemical indications, except for staking a claim and putting an odd drillhole or two. They will not be so dismayed if they realise that the staking of a claim on a prospecting indication is really only an alibi. The real, and daily headache of a mining company is to establish sufficient new or additional reserves in, or in the vicinity of, existing mines.

Ore deposits are usually quite complicated. In my present context I do not so much mean geologically complicated, as physically and geometrically complicated. Nevertheless, in spite of their complicated shapes ore deposits can be classified into different sizes and it is a matter of empirical observation that the deposits in a district, when they have been developed into reserves often show a certain statistical distribution with respect to size. It does not matter very much whether we employ strike-length, volume, tonnage, value in dollars or something else as the measure of size; some sort of regular or semi-regular distribution is often observed. This seems to be a general tendency in nearly all mining districts of the world, if not exactly a law of nature.

In the beginning when only a few reserves have been developed, virtually nothing can be said about the mathematical function describing the distribution of the reserves. But with each developed reserve in the district, the function, if it exists, will tend to get more defined until, at last, when a fairly large number of reserves have been developed, we may be able to construct a reasonably satisfactory function describing the distribution. This is the a posteriori distribution of ore *reserves*, from which we can estimate the probability that a hitherto undeveloped *deposit* will yield reserves of a particular size. It should be carefully noted that this is not the probability of finding a fresh deposit of that size and still less the a priori occurrence probability of such a deposit.

You will have noticed that we are making a distinction between a deposit and a reserve. As far as I know the first clear statement of this distinction was given by Prof. M.A. Adelman of M.I.T. in a lucid and masterly paper on the economics of mineral exploration read in this very city at the 1st International Conference on the Physics of the Earth and the Oceans in 1970 (Adelman, 1970). A deposit, or ore-in-place as Adelman calls it, can be discovered, reserves are developed. I think we must hold in common with Adelman that this distinction is very important. Failure to recognise it has of late produced pessimistic forecasts of the minerals situation of the world.

An a posteriori distribution tells us nothing about the number of deposits remaining to be discovered, or the a priori probability of their discovery. This feat would be possible only if we had at our disposal a geological law expressing, for instance, the number of ore deposits per some large unit volume of rock in a given geological milieu, a sort of geological Avogadro's law if you like. However, the existence of such a law seems a remote possibility in the present state of our knowledge and I feel in view of this fact that it is rather pointless to talk of a priori probabilities of discovering new ore deposits.

How then are we to answer the question whether it is worthwhile to continue looking for new deposits in an old district? An absolute answer cannot be given but perhaps we could proceed as follows, at least in principle.

We construct first the a posteriori distributions for a large number of geologically similar districts, and then make a note of how many new deposits were discovered in each district after the shape of the reserves distribution curve had reached different stages of stability. Then we will perhaps be able to construct a formula giving us the number (or proportion) of deposits remaining to be discovered, as a function of the stability stage of the reserves distribution curve. If we can now identify the stability stage of the curve in a particular district it may be possible to estimate the proportion of undiscovered deposits.

Now, what has all this got to do with mining geophysics? Two things. Firstly, it is a platitude that no amount of geophysics, geology or geochemistry will discover an ore deposit unless there *is* a deposit to be discovered. Consequently, it is essential to bear in mind the statistical implications of the question: is it worthwhile to continue looking for new deposits in an old area?

Secondly, statistics or no statistics, the optimism of a miner dies hard and as we have already seen most mining companies devote a very large part of their prospecting effort to exploring and re-exploring old, known areas. Quite naturally drilling, shaft-sinking and adit-driving comprise the main activities in this prospecting effort. No mining company can afford to ignore any technique which can direct these expensive operations to the most promising places so as to minimize development costs or any technique that can indicate when or where not to undertake these operations thereby saving money in the exploration stages. Mining geophysics has a very important role to play in minimizing the costs of exploration as well as those of development of reserves and I think it is to the detriment of both geophysicists and the mining companies themselves that this role has not always been fully appreciated.

I shall therefore proceed to give a few examples of the so-called negative case histories of type 1 (cf. Parasnis, 1967), in which drilling could be avoided, or drilling sites modified, on the basis of geophysical work, in either case leading to a considerable saving of costs. All these examples are from old, established areas where additional reserves were urgently needed so that unnecessary drilling would have meant not only extra costs but loss of time.

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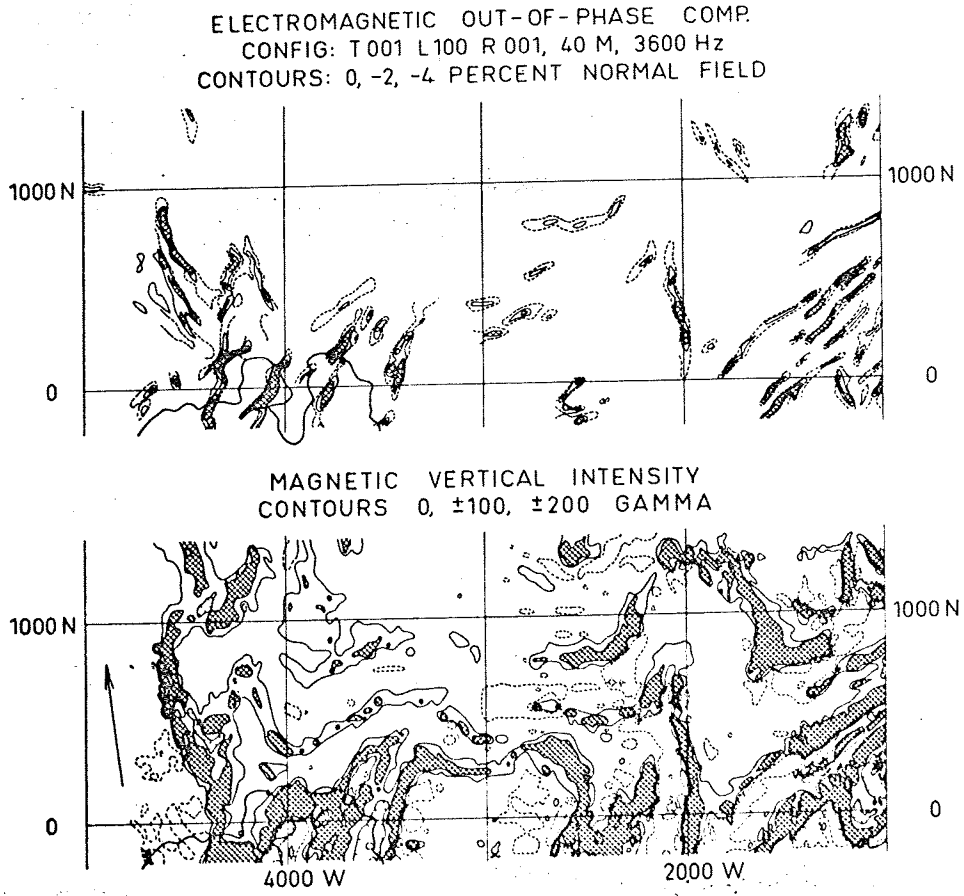
In the upper part of Fig.1 we have the out-of-phase or imaginary component obtained by a horizontal moving source-receiver system.

There are several electromagnetic indications on the map (negative values of the field). Most of them run E—W but some appear to deviate from this trend. In fact, taken as a whole the electromagnetic map gives rather incomplete structural information. One of the lines of thought we had was that the E—W trending indications were due to pyrrhotite-bearing shales, which we know for certain exist in the area, while the N—S trending indications were thought to be due to fracture zones cutting right across the shales. They could therefore be potentially ore-bearing. Before taking any decision about drilling, however, we made a detailed magnetic survey of the area on a 40 X 40 m grid and the result is shown on the bottom map in the picture.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CONTOURS: 0, -2, -4 PERCENT NORMAL FIELD

MAGNETIC VERTICAL INTENSITY
CONTOURS 0, ±100, ±200 GAMMA

Fig.1. EM and magnetic maps of the Bastuliden area, north Sweden.

It now turns out that there are magnetic highs which coincide with the electrical indications but what is of real interest is the fact that each magnetic indication is more or less continuous all along and the indications form a series of zones. The whole magnetic pattern clearly shows that we have here several folded shale horizons separated by non-magnetic beds and the N—S trending electromagnetic indications are simply the limbs of these shale beds. They are not fracture zones or anything of the kind. The magnetic indications are caused by an overall distribution of pyrrhotite in the shales. The electromagnetic indications are not continuous despite the pyrrhotite impregnation but sometimes disappear, even if pyrrhotite is present, because the attitude of the shales is not everywhere favourable for electromagnetic induction by the coil-configuration used.

The sequel to these investigations is interesting too. To check finally that there were no ore bodies hidden within the shales, despite the clearly negative circumstantial evidence from magnetics, we made detailed gravity measurements in the area, also on a grid of 40 × 40 m. The resulting Bouguer anomaly map was quite flat indicating absence of heavy concentrations, and we could definitely discard this area as far as drilling was concerned. It is estimated that in this case the geophysical work (electric, magnetic and gravity) costing about $6,000 saved about $16,000 dollars by making this decision possible.

A problem of an entirely different character was encountered in another area with magnetic and electric indications. Here it was suspected that pockets of preglacially-weathered or crushed bedrock occurred in the area, which is Precambrian with Pleistocene cover. Since such pockets invariably lead to increased drilling costs and in many cases call for modified drilling techniques,

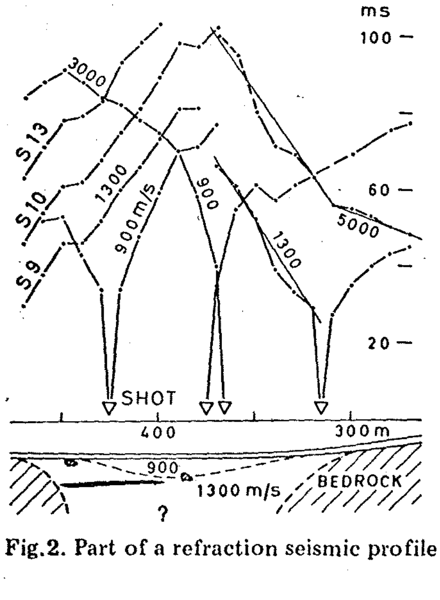

Fig. 2. Part of a refraction seismic profile in central Sweden (interpretation by L. Malmqvist).

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it was considered advantageous to map the weathered pockets and the configuration of the bedrock in some detail, before recommending drilling sites. A seismic survey was therefore undertaken for the purpose and Fig.2 shows the time-distance graphs and the interpretation along part of the profile.

The refraction survey showed that around the coordinate 400 we had a layer of the abnormally low seismic velocity of 1,300 m/sec. This is almost certainly a zone of weathered rock since the seismic velocity in the glacial moraine in the area is 2,200 m/sec. Sandwiched between this layer and a thin low-velocity surface layer of humus and soil, we have a 10 m thick layer with a velocity of 900 m/sec. This, however, is probably moraine but of more porous and loose type than usual.

You will also notice two shaded patches below the coordinates 390 and 450. These are believed to be a couple of large boulders, an inference based on a peculiar but consistent irregularity observed in the time-distance graphs, namely, the parallel displacement of 1,300 m/sec segment at two points indicating that the velocity of the wave travelling through the weathered zone is locally increased.

Another piece of information obtained is represented by the heavy dark line. This is believed to be a stiff clay layer having a characteristic velocity of 3,000 m/sec. It is necessary to postulate the existence of this layer to account for the unexpectedly early first-arrivals on the geophone set-up to the left (not shown). Interface angles do not suffice to explain these in the present case.

The information obtained from this survey is of great help in siting drill-holes in the area, and I would call your attention to the amount of detail that it is possible to obtain by a careful interpretation of refraction surveys.

EXTRA-DETAILED MAGNETIC MEASUREMENTS

However, a seismic refraction survey is relatively expensive and it may be desired in some cases to obtain the required information without a seismic survey. An interesting example of this type occurred recently in sulphide prospecting in north Sweden where ore boulders were discovered in glacial drift overlying a Precambrian basement. Some of these boulders contained accessory magnetite besides chalcopyrite. The large size of the boulders indicated a very short glacial transport, that is, a relatively local origin of the boulders. If loose overburden is less than about 2—3 m thick the easiest approach to locating the mother lode of the ore boulders is to strip the over-burden by a bulldozer rather than drill.

Before taking a bulldozer all the way to this remote area, however, it was necessary to know whether the overburden was sufficiently thin. If not, then a drilling machine would be taken there directly. A refraction survey seemed disproportionately expensive for the problem at hand because all that we wanted to know was whether the thickness of the overburden was less than or more than 3 m.

Now, a detailed magnetic survey on a 20-m grid in the area had indicated some magnetic anomalies and these showed depths to the magnetic masses of a fairly shallow order of magnitude. However, a magnetic survey is inherently incapable of providing depth estimates of masses shallower than half the grid spacing. We were after information from 2—3 m depth and therefore repeated the magnetic measurements along two selected profiles using a distance of 2 m between the observation points.

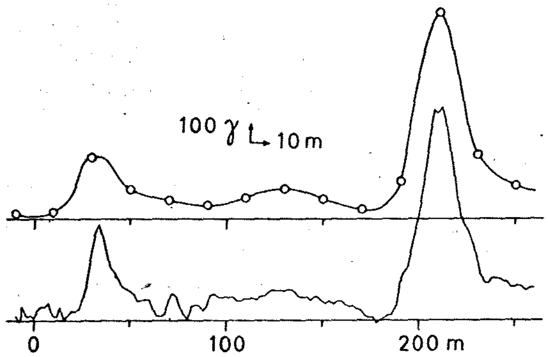

Fig.3. Magnetic measurements profile, detailed and extra-detailed.

Fig.3 shows the results of these detailed and extra-detailed magnetic measurements along one of the profiles. Evidently, the extra-detailed measurements show that the magnetic masses are lying at a considerably shallower depth than the depth estimated from the detailed measurements. The anomaly at the extreme left, for instance, is found to be due to a mass at 5 m depth, and not 13 m as suggested by the upper profile.

However, it was evident from the extra-detailed survey that the depth to the bedrock was not as small as 3 m. Stripping by bulldozer was therefore impractical and as this was all the information we wanted in this connection, a seismic survey could be avoided.

The measurements in Fig.3, despite their simplicity, also illustrate in passing how misleading the filtering technique of magnetic and gravity interpretation can be. We clearly see here how gridding, which is a form of filtering, necessarily leads to too large depths to the causative bodies.

DRILLHOLE MISE-À-LA-MASSE

Short of the actual development of reserves, drilling is the most expensive phase in exploration and in establishing new reserves it is as important to direct drillholes to the right spots as it is to avoid unwarranted drilling. It is hardly necessary to point out in this connection the importance of careful interpretation of geodata and therefore I would instead draw your attention to utilizing measurements in drillholes themselves for siting further drillholes.

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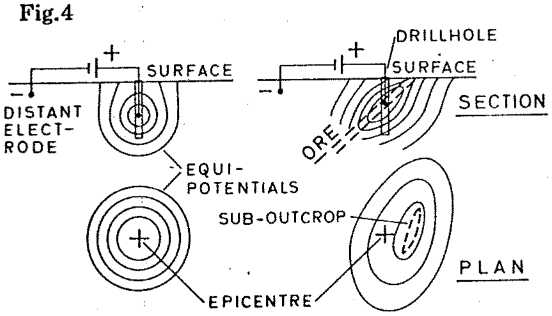
Let us therefore look at a method which can be used with great advantage in directing a drillhole campaign in detail, once a mineralization or ore has been located. This is the mise-à-la-masse method, the principle of which is probably familiar to most of you but I am showing it in Fig.4 for the sake of continuity.

In the left-hand part of Fig.4 are shown the equipotentials that would be observed when a current electrode is placed in a drillhole in a homogeneous isotropic ground. On the surface of the ground the equipotentials are then concentric circles with the epicentre of the current electrode in the hole as the centre of the circles. If the current electrode is placed in an electrically well-conducting ore section in a hole, and if this section is part of a larger orebody, the electric current tends to follow the ore. Consequently, the equipotentials are distorted as shown in the right-hand part of Fig.4, depending upon the geometry of the orebody. Further, the epicentre of the electrode and the centroid of the surface equipotential picture may not coincide.

Fig.4



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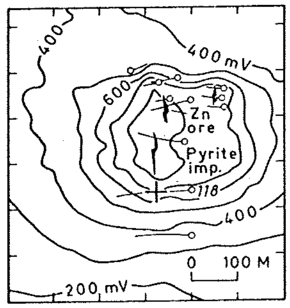

+ Electrode epicentre
Electrode depth 73m (vertical)

Fig.4. Mise-à-la-masse principle.

Fig.5. Mise-à-la-masse survey in north Sweden.

The mise-à-la-masse technique is particularly useful in testing whether an ore section in a drillhole is an isolated occurrence or is part of a larger mass.

Fig.5 is an example of a mise-à-la-masse survey in an area in north Sweden. The figure shows the equipotentials observed on the ground with the current electrode in drillhole 118, at a depth of 73 m. Notice, first of all, that the centroid of the equipotential picture, which is naturally the centroid of the sulphide mass, is displaced 120 m from the epicentre. I need hardly add that this information has been of the greatest significance in planning drillholes.

The shape of the equipotential contours is no doubt conditioned by the shape of the sulphide mass itself. Towards the north we notice a rather sharp gradient in the potentials. As a matter of fact, drilling has shown that the sulphide impregnation ceases abruptly in this direction due to a tectonic disturbance. On the southern side the potentials decrease rather gradually and so does the impregnation.

One would expect on simple physical grounds that if a mass were a very good electrical conductor, the exact point at which the current electrode is placed in it will not matter very much. The equipotential picture should be more or less the same. The mise-à-la-masse measurements in the present area were repeated with the current electrode in the ore section in a drillhole 200 m from No.118. The picture obtained was so similar to the one in Fig.5, even in minute details, that I have not thought it worthwhile to reproduce it for the purpose of this lecture. This experiment proved that the sulphide mass in question is an excellent electric conductor.

A problem that frequently arises during the mining of ore reserves concerns the connection between different ore sections. Such a problem can also be attacked by the mise-à-la-masse technique as Fig.6 illustrates. Here we see a few holes, Nos.6, 9, 1 and 10 drilled from the -275-m level of a mine in north Sweden, and one 530-m long hole, No.2, at the extreme left, drilled from the surface. The underground holes are all in the same vertical plane, while No.2 is slightly off this plane but is projected onto it. Geological dips are very gentle in the mine, but varying.

The ore sections in holes 6 and 9 belong to one and the same stratigraphic horizon, shown by the dashed straight line. The exploratory hole No.2 encountered ore on a surprisingly deep level (530 m) and the question arose whether this ore was connected with the ore in holes 6 and 9. Geologically it seemed not unlikely that this ore belonged to a different stratigraphic horizon, in which case it would mean an entirely new ore lens, but there was no clear geological evidence to this effect.

A mise-à-la-masse survey was undertaken to settle the question and a few of the results are shown in Fig.6. The curves represent the electric potentials

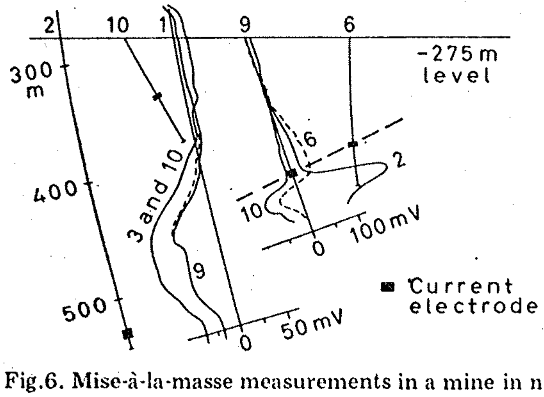

Fig.6. Mise-à-la-masse measurements in a mine in north Sweden.

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measured in the respective holes and the number beside each curve denotes the drillhole in which the positive current electrode was situated while the particular curve was obtained.

Let us first of all look at the dashed curve in hole 9, obtained with the current electrode in hole 6 at the place shown. This curve shows a positive maximum at a point which evidently corresponds to the ore in this hole, that is, No.9. If we look at the curves in drillhole 1 we notice that the potentials are almost exactly the same irrespective of whether the current electrode is in hole 6 or 9. This can only mean that there is a very good electrical connection between the ore sections in holes 6 and 9. This is, of course, to be expected from the geology of the ore but it is nice to have it confirmed geophysically. Similarly, the ore sections in No.10 and No.3 (not shown) must be in direct connection with each other. They belong, incidentally, to a shallower stratigraphic horizon.

It is also evident that the orebody represented by the dashed straight line terminates shortly to the left of hole 9, for if it were to come close to hole 1 we should obtain a positive maximum in the relevant potential curve measured in this hole and this we do not.

Let us now look at the curve marked 2, obtained in No.9 with the current electrode in the ore at the bottom of hole 2. This curve shows a very distinct positive maximum but, mark well, not at the ore in hole 9. Evidently the deep ore in No.2 must be a good electrical conductor and must come quite close to hole 9. That it does not intersect the hole is known as we have no ore at the point where the maximum in the potential is obtained. From the mise-à-la-masse measurements it appears that the ore intersected by hole 2 belongs to a separate stratigraphic horizon, deeper than the horizon represented by the dashed straight line.

I shall leave the mise-à-la-masse method here and continue with another and more conventional drillhole method, namely, the self-potential method.

DRILLHOLE SP

We are all familiar with the negative SP minimum which is often obtained on sulphide, magnetite and graphite bodies. Such a minimum is associated with the negative pole of what is in effect an electrically charged body. If measurements are made at sufficiently great depths we should naturally expect a corresponding positive pole to appear. Somewhere in between we shall obtain the zero equipotential.

Fig.7 shows such a dipole very clearly. If we assume a spherical or a horizontal, cylindrical mass to produce a self-potential anomaly field, it is possible to correlate the distance between the positive and negative centres with the diameter of the mass and the depth to its top. This suggests that some simple empirical rules could be devised for estimating the depth extent of an orebody, from a knowledge of the self-potential field in the upper, usually the more thoroughly investigated, regions of the host rock. Conditions in practice are,

Fig.7

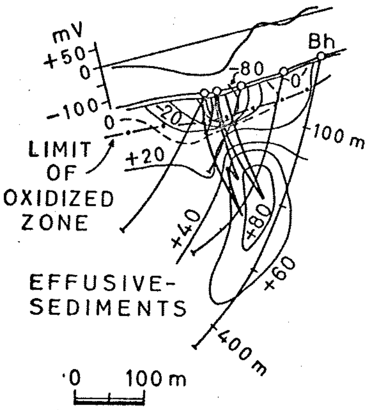


Fig.8

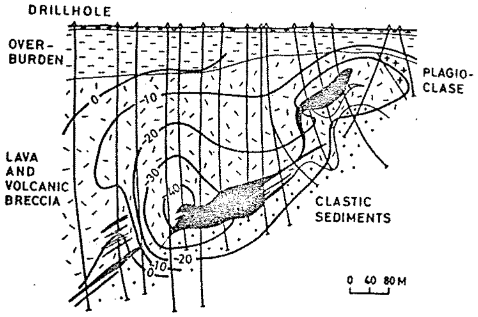


Fig.7. Surface and drillhole SP anomalies. Cu, Pb, Zn ore; Altai, U.S.S.R. (After Yu.S. Riss in Volosyuk and Safranov, 1971, ch.4.)

Fig.8. Drillhole SP anomalies (in mV). Complex sulphide ore, Altai, U.S.S.R. (After Yu.S. Riss in Volosyuk and Safranov, 1971, ch.4.)

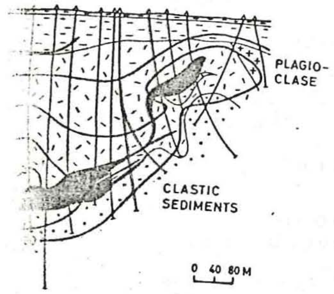
of course, very complicated and we should not hope for more than rough estimates.

It seems from a number of surveys in drillholes that for steeply dipping, tabular bodies the depth extent is about 5—6 times the vertical distance between the negative pole and the contour for the zero potential. If the top is at appreciable depth the depth extent is only 3—4 times this depth or less.

It is also of interest to note that in Fig.7 we have a clear anomaly of about +70 mV in the deep hole to the extreme right, although this hole does not intersect the orebody as such.

Another interesting example of drillhole SP is shown in Fig.8. The ore, shown in black here, occurs at the contact between volcanic rocks and clastic sediments. Measurements in some 15 drillholes in this vertical section have revealed a very well-defined SP pattern but with purely negative values as far as 500 m below the ground surface, suggesting that the depth extent of the ore must be very great. In the orebody itself, the potentials are -25 mV and less. The values in the deepest part of the ore (in this picture) are about -40 mV.

Notice that, in contrast to the previous example, there is no surface manifestation of any self-potential anomaly in Fig.8. Yet the underground pattern is very well developed. The absence of surface anomalies is understandable in view of the fact that the clayey overburden has a resistivity of 3—10 Ω m. The volcanic rocks and the clastic sediments have resistivities of



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the order of 400—500 Ω m. The overburden being a good conductor short-circuits the natural ground currents.

The depth extent of the orebody in Fig.8, estimated on the basis of the SP pattern in the drillholes, turns out to be more than 1,200 m.

I shall leave the topic of drillhole geophysics here to return to it in another context later, and turn now to two electromagnetic methods which have attracted considerable attention in recent years.

THE VLF METHOD

The first one of these is the so-called VLF or the Very Low Frequency method. This measures the variations in the tilt of the electric or the magnetic vector associated with the radio waves transmitted by certain transmitters in the 15—25 kHz band. For the electric case, the amplitude of the secondary field can also be measured but I shall not go into this modification here.

The technique of measuring tilt angles has been used since the very first days of electromagnetic prospecting and the idea is not new in itself. What is new in the VLF method is, in the first place, the elimination of the need to carry mobile transmitters in electromagnetic prospecting. Furthermore, the primary field is everywhere homogeneous at sufficiently large distances from the transmitter antenna.

Fig.9 shows a simple construction and an illustration of VLF anomalies in an area in north Sweden. In the upper portion of the figure we see the horizontal magnetic vectors of the homogeneous primary field and, represented by the circles, the secondary field due to a conductor. The resultant field vector *R* is tilted above the horizontal (positive tilt) on the transmitter side from the conductor and below the horizontal (negative tilt) on the far side.

The lower portion of the figure shows a couple of VLF profiles, 1 km apart, and, for comparison, also the moving source-receiver profiles using horizontal, coplanar coils 60 m apart. Clearly, there are two conductors, actually two several kilometres long and parallel pyrrhotite-bearing shales. The conductors are not continuous along the entire strike length but are, in places, interrupted by gaps some tens of metres long. One such interruption occurs (in both conductors) on the lower profile. We see that while the moving source-receiver anomaly indicates the break, the anomaly in the tilt angle of the VLF field is not diminished to any significant extent. Such an effect can, of course, be both an advantage or a disadvantage.

It is useful to remember that, seen geologically and geophysically, the VLF field possesses some drawbacks. Owing to the high frequency involved (I need hardly point out that the term VLF is a misnomer in geophysical prospecting context) the method is not always well adapted to prospecting for conductors under highly conductive overburden. At 25 kHz and an overburden resistivity of 10 Ω m, the skin depth is only 10 m. However, the small skin depth is not the only, or even the major, problem. Actually, there are physical arguments to support the contention that the significance of skin depth in electromagnetic

Fig.9

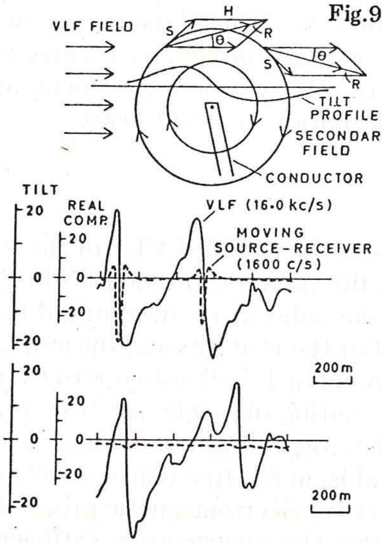


Fig.10

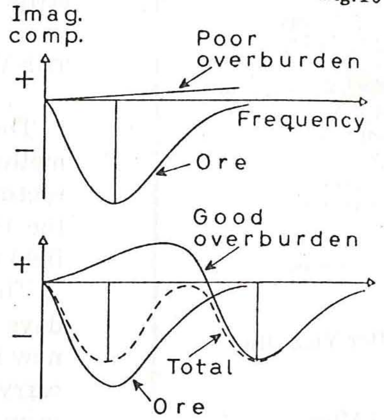


Fig.9. VLF anomalies in the Åmliden area in north Sweden. H' = primary field, S = secondary field, R = resultant field.

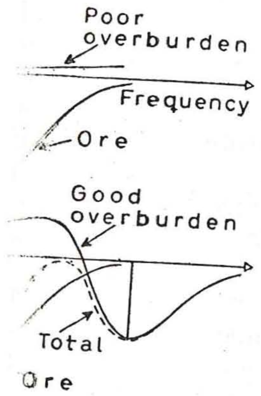
Fig.10. Principle of multifrequency electromagnetic prospecting; effect of conducting overburden.

prospecting is somewhat exaggerated. The important point is that in a highly conductive medium geometric irregularities of second order produce anomalous fields of first order and this effect becomes increasingly aggravating the higher the frequency. As a result, small, local variations in the thickness times conductivity product of a highly conductive overburden are apt to produce a very high geologic noise.

Moreover, as the primary field is everywhere homogeneous, even poor conductors that present an effectively large cross-section to the field may produce unwanted anomalies. For example, we may get strong anomalies when, in fact, the conductor has a break as in Fig.9. This, of course, may happen in all methods exploiting a homogeneous primary field, for example, Afmag, which is a low-frequency method. We should therefore expect a welter of VLF anomalies due to such features as rivers, brooks, faults, long fissures etc. as is, in fact, borne out by field work. The more conductive the overburden or the host rock and the higher the frequency the more serious are these, generally speaking, unwanted effects.

The problem of electromagnetic detection of orebodies beneath a highly conductive overburden is very important in many parts of the world and although I do not think that the VLF method by itself is a solution to it, I should like to dwell a little more here on the capabilities of the continuous wave or C/W methods in this respect.

Fig.10



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From skin-effect considerations as well as more stringent calculations we can deduce that when the frequency of the primary field decreases the total response of a deep conductor increases proportionately more than the response of a shallow conductor. By means of measurements on two frequencies we can to some extent isolate the response of an overburden from that of an underlying conductor.

Now, the basic problem here is one of ascertaining the existence as such of *two* conductors in an overburden-ore system. Whether the poorer one or the better one of the two is ore does not really matter from the miner's point of view. But generally it is very difficult to ascertain the existence of two conductors in the system in question by measurements on two frequencies only.

Let us therefore see if we can come nearer to the solution of the problem by multifrequency measurements, from very low to very high frequencies. In Fig.10 I have shown the sort of results we might expect in the imaginary component of the secondary field. I hasten to add that this is a very schematic picture, drawn on several assumptions, the two basic ones being: (1) that the parameters of the system are such that the principle of superposition holds, at least approximately, and (2) that there is no galvanic coupling between the overburden and the underlying ore. Theoretically the problem is very difficult so we will have to make do with some qualitative considerations.

The imaginary component of the field due to a poorly conducting sheet-like overburden increases very slowly with frequency, as is shown in the upper part of the picture. The response of the ore has a characteristic shape which is familiar. At a particular frequency the imaginary component response of the ore reaches a maximum. If we add together the two curves in the upper part we shall obviously get a curve that attains only one minimum as the frequency is swept from low to high values. Let me interpose here that the terms positive and negative should be understood in the relative sense. The actual signs will depend very much upon the source-receiver geometry.

The frequency response of an overburden that is a very good electrical conductor is more complicated but theory and experiment show that it is qualitatively something like that shown in the lower part. The imaginary component first attains a positive maximum as the frequency is increased and then a negative minimum, usually much larger in magnitude than the positive maximum. The ore response shows as before a negative minimum.

The net response of the overburden-ore system in this case is shown by the broken line. Evidently we should expect two response minima, two resonances so to speak, to appear in this case as the frequency is swept, one corresponding to each of the two conductors. Multifrequency measurements do therefore seem to afford a possibility of resolving the overburden and the ore conductor even when the former has a very good electrical conductivity. The technical difficulties of making measurements on a large number of closely spaced frequencies, from very low to very high, are probably not insurmountable. Such measurements, however, do not appear at present to be economically feasible in routine exploration operations.

TRANSIENT-FIELD EM METHOD

It is then that we are led to consider the method of transients which has recently attracted great attention. If a transient, instead of a sinusoidal, current is sent into a transmitter loop, the primary magnetic flux and likewise the secondary currents induced by it in conductors in the ground are also transient. The currents gradually decay on account of the electrical resistance of the conductors and the voltage induced in a receiver that picks up their field will also decay continuously with time.

It is well known that the signal from the transient current in a single-turn loop will decay exponentially. If we plot the signal strength on a logarithmic scale against time on a linear scale we shall obtain a straight line as shown in Fig.11. The time is measured from the instant that the primary pulse in the transmitter ceases. If the loop is a poor conductor the decay is relatively fast and the straight line is steep. If the loop has a low resistance the induced currents will keep on circulating for a longer time and the slope of the straight line will be flatter. If, then, we have two single-turn loops, and the mutual impedance between them is negligible, we shall get two distinct slopes and

Fig.11

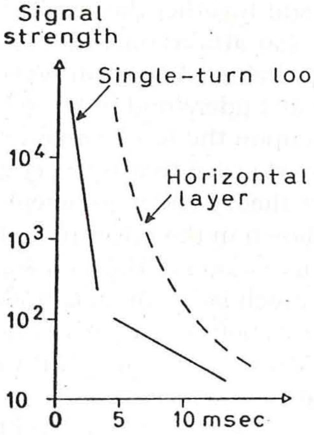

Fig.12

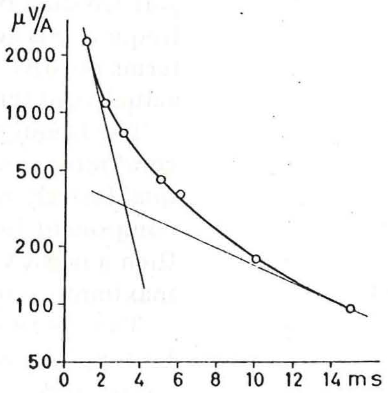

Fig.11. Principle of the transient-field method.

Fig.12. Transient field at a point above an ore body. Decay of maximum secondary field. Cu ore, northern Caucasus, U.S.S.R. Loop 200 × 200 m. (Drawn from data by V.E. Zaitsev in Fokin, 1971, p.164.)

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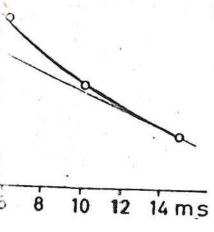

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data by V.E. Zaitsev

this fact will reveal to us the presence of two distinct conductors, which is basically the information we are seeking.

The matter is, however, not quite as simple in practice because the signal against time curve shows a continuously varying slope even though we have a single conductor, but in the form of a horizontal layer instead of a loop. This is shown by the dashed curve in Fig.11, which is based on exact calculations, although qualitative physical considerations also show that the curve must have the form shown. It appears, therefore, that there may be some uncertainty in practice in correctly interpreting the data of transient methods. However, if the slope of the signal-time curve changes abruptly or if the response of the overburden can be estimated it may be possible to distinguish the response of a conductor lying below a highly conducting overburden.

Let us now take a look at a few practical results. Fig.12 shows the decay curve at a point directly above a copper ore lying under a glacial overburden. The experimental set-up was that a current pulse of 20 msec duration was sent through a horizontal rectangular loop of size 200 m and the same loop was used as the receiver antenna after the primary pulse ceased. The signal voltage in the loop is normalized to the primary current.

The expected response if only the overburden layer were present is shown

Fig.13

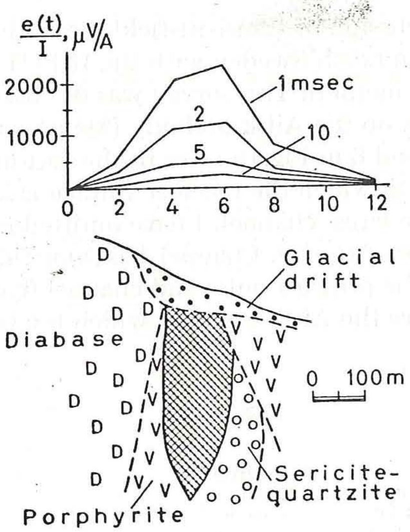

Fig.14

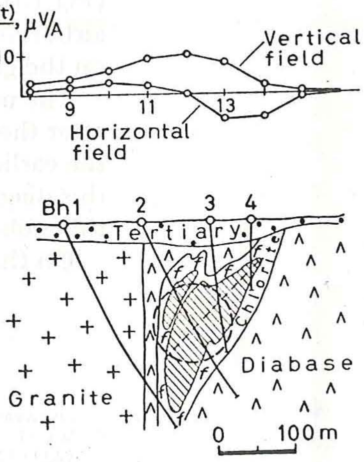

Fig.13. Transient-field profile across an orebody. Cu ore, northern Caucasus, U.S.S.R. Loop 200 × 200 m. (After V.E. Zaitsev in Fokin, 1971, p.164.)

Fig.14. Transient-field profile across an orebody. Cu ore, southern Urals, U.S.S.R. Loop 200 × 200 m, $t = 4$ msec. (After A.D. Skrichin and V.M. Timofeev in Fokin, 1971, p.220.)

by the steep straight line. As this does not explain the decay curve it is concluded that a second conductor is present.

Fig.12 is drawn for the point above the ore at which the secondary field was maximum. The transient-field anomalies along a complete profile across the ore are shown in Fig.13. There is a clear increase in the secondary field as one approaches the ore. The resistivity of the glacial overburden in the present example is reported to be 100 Ωm and it is interesting to note that its thickness above the ore is as much as 40 m. Unfortunately no measurements were made on this ore with a continuous wave method. Personally, I am inclined to believe that an indication with a conventional C/W method will also be obtained in the present case if transmitter and receiver loops of size comparable to the one used in the transient-field experiment are employed.

Fig.14 shows another example of the transient fields measured at various points above a copper ore, 4 msec after the cessation of the primary current pulse in a 200 × 200 m loop. In this case, the overburden consists of Tertiary sediments with an estimated resistivity of less than 10 Ωm. The sediment cover is 25 m thick and together with the thickness of the chloritic alteration zone around the ore, the depth to the top of the ore is 50—75 m.

The circle represents an equivalent conducting sphere of 50 m radius and resistivity 0.04 Ωm, that would give the same field as the observed one. Similarly the inclined dashed line represents a thin, equivalent plate of resistivity 0.0055 Ωm.

To round off my discussion of transient-field methods I shall show a profile (Fig.15) from a survey in north Sweden with the INPUT method, which is an airborne transient-pulse method. This survey was discussed recently in a paper on the geophysical work on the Aitik orebody (Malmqvist and Parasnis, 1972).

The numbers 1, 2, 5 and 6 in Fig.15 refer to the various channels or instants, after the primary pulse, at which the receiver voltage is sampled, No.1 being the earliest and No.6 the latest channel. I have omitted channels 3 and 4 on this diagram for the sake of clarity. Channel 1 is sampled, I believe, at something like 100 μs after the primary pulse and channel 6 at about 2000 μs.

On the far left we have the Aitik orebody which is a poor conductor and

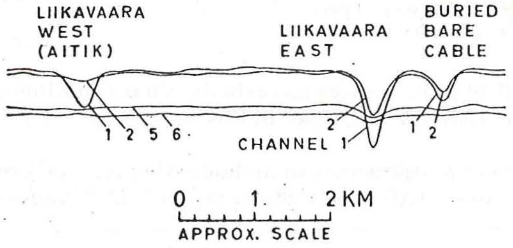

Fig.15. Profile in an INPUT survey in north Sweden.

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the signal is apparent only on the first two channels. The Liikavaara East orebody, on the other hand, is a much better conductor and the INPUT correctly shows measurable signals as late as channel 6.

An interesting anomaly is found on the far right. Here, above a buried cable, there is a strong signal on the first two channels, actually also on the third channel, not shown here, indicating a conductor better than the Aitik orebody. The rate of decay of this signal has nothing to do with the resistivity of the cable which is effectively zero. What is happening is that the primary pulse induces transient currents in the overburden and these are collected by the cable and we get a concentrated linear current. Actually, therefore, the rate of decay depends upon the resistivity of the overburden. In terrain with highly conductive overburden such effects might also be expected at places where the overburden suddenly thickens or where its conductivity becomes significantly better.

A CHALLENGE

We must now ask whether transient-field methods afford any advantage over the continuous wave methods in prospecting for ores under highly conductive overburden.

According to the laws of electromagnetism, an electromagnetic field, no matter what its character, is damped in passing through all conductors, and the higher the conductivity the greater is the damping. A highly conductive overburden will heavily damp transient as well as harmonic fields and act as a more or less effective screen for all that lies below. Theoretically it can be shown that the transient response is a Laplace transform of the frequency response and vice versa. So the information contained in one type of data is not essentially new compared with that in the other type.

My own feeling is that, in principle, the transient methods have no advantage over the harmonic field methods. There are grounds for believing the contrary since we can measure the real as well as the imaginary component in the harmonic method. If the existence of a conductor below a conducting overburden can be established by transient-field methods it must be possible to establish it by properly conducted multifrequency harmonic field measurements and vice versa. We cannot, so to speak, deceive Nature. However, in the present state of technical development, transient methods have an operational and economic advantage in that the equipment is easier to construct than wide-band multifrequency equipment. However, this is probably a transient advantage. Here then, for what it is worth, is a challenge to manufacturers of geophysical equipment: to construct a multifrequency harmonic field apparatus ranging say, from 100 Hz to 100 kHz, that can be used in *an economically feasible manner* in routine exploration programmes.

TWO NASCENT STAGE METHODS

I intend now to devote the last part of my lecture to two auxiliary methods of mining geophysics in the nascent stage. One of them is the Contact Polarization Curve method or, for short, the CPC method and the other is the geothermal method.

The CPC method which, as far as I know, has been used only in the U.S.S.R., is based upon the cathodic and anodic reactions that take place when an electric current passes through an electrolytic cell.

If two metallic or, more generally, electronically conducting electrodes are placed in an electrolyte each assumes a definite potential with respect to the electrolyte. Unless the electrodes are non-polarizable it is necessary to give such electrodes an external electric tension, called electrolytic polarization, to obtain electrochemical equilibrium. An example would be a cell consisting of iron and carbon electrodes in a solution of zinc sulphate.

As the external tension applied to this cell is increased there is first only a very small, almost vanishingly small, flow of current when the tension is low. This is the so-called non-faradic current. Above a certain value of the applied tension, however, a strong flow of current begins. The critical tension at which this so-called faradic current starts to flow depends upon the material of the electrode and also whether the electrode is a cathode or an anode. It can be determined from the intersection of the voltage-current curve with the voltage axis.

Fig.16

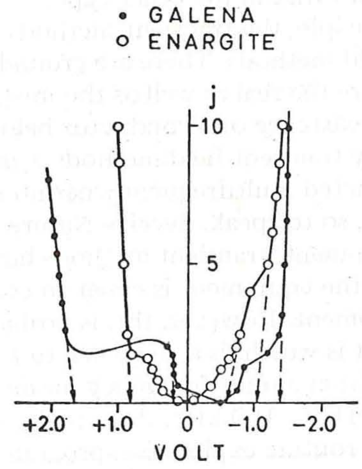

Fig.17

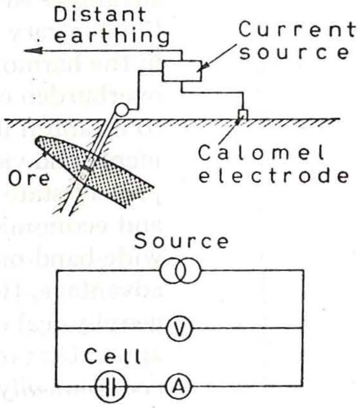

Fig.16. Faradic and non-faradic currents. Current density j against electrode polarization. ●, galena; ○, enargite. (After Yu.S. Riss in Volosyuk and Safvanov, 1971, ch.6.)

Fig.17. Field set-up and equivalent circuit for the CPC method.

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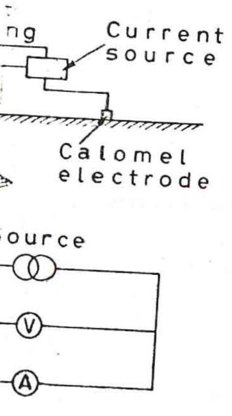

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Many minerals, e.g., pyrite, chalcopyrite, galena etc., are electronic conductors and show the above phenomenon when used as cathodes or anodes in an electrolytic cell. Fig.16 shows the voltage against current-density diagram for galena and enargite (Cu_3AsS_4) electrodes. We see that for cathodic reactions the critical voltage is –1.4 V for a galena electrode and –1.0 V for an enargite electrode. For anodic reactions these voltages are +1.7 for galena and +0.9 for enargite.

Let us now suppose that we have an orebody containing a number of different electronically conducting minerals and that we measure the potential of an electrode placed in such a body as the current through it and the ground is gradually increased. When the current exceeds a certain critical value the electrolytic polarization barrier corresponding to a particular mineral will be exceeded and the electrode potential will show a sudden jump and thereafter increase linearly with the current, until a higher barrier corresponding to some other mineral is broken and so on.

The experimental set-up for such a measurement is shown schematically in the upper part of Fig.17. We have a current source, an electrode in an ore, a distant earthing and a calomel electrode with respect to which the ore-electrode potential is measured. In the lower part of the figure we have the equivalent circuit in which the electrolytic cell represents the ore and ground-electrolyte system.

Fig.18 shows the application of the CPC method to an orebody in Central Kazakhstan in the U.S.S.R. When the ore is a cathode we have electrolytic polarizations of –0.8 V and –1.5 V respectively. In the anodic case we have +0.3 and +1.7 V. The critical voltages –1.5 and +1.7 V correspond to the principal potential barrier of galena. The critical current in this case is 30 mA. There are, however, also subsidiary barriers at –0.8 and +0.3 V.

Now since the current density at which a potential barrier is overcome is a physical constant of a mineral, the critical current through the circuit at this instant turns out to be proportional to the total surface area of the electrode. It does not depend upon the form of this surface, or whether the surface is that of a continuous orebody or the total surface of all the disseminated particles of that mineral. Further, the coefficient of proportionality depends

TABLE I

CPC method: conversion coefficients (electrode area/critical current)

Ore (100%)	Reaction type	Coefficient (m^2/A)
Galena-sphalerite	cathodic	500
Pentlandite	cathodic	400
Chalcopyrite	anodic	95

Source: Yu.S. Riss in Volosyuk and Safronov (1971, ch.6).

upon the material of the electrode only and the type of reaction (cathodic or anodic) taking place at it. This coefficient can be determined by laboratory or full scale experiments. Table I shows the coefficient "electrode area divided by critical current, m^2/A" for a few different ore types.

Knowing the critical current we can therefore estimate the total surface area of the mineral in question in the ore, provided the ore is composed 100% of this mineral. For lower percentages the figure thus obtained must be multiplied by the appropriate factor.

In the example of Fig.18, the critical current was about 30 mA for cathodic reaction at a galena ore and according to the table this gives us a total electrode area of 15 m^2. If the ore grade is 50% galena, the area estimate would be 30 m^2. If now the orebody is a flat lens we can estimate its dimensions as, say, 8 × 2 m. (The lens has two sides.) This, of course, is a very small lens in this case but the point is that an ore section in an exploratory hole can be tested in this manner prior to further drilling to estimate whether it belongs to a small ore find or a large one.

Lastly I will very briefly deal with another nascent stage method, namely, the geothermal method. We know that heat is flowing continuously from the interior of the Earth to the surface at a rate of about 50 mW/m^2, or 50 kW/km^2, a geophysically more vivid manner of expressing the same fact. The flow of heat is normally uniform but is disturbed by inhomogeneities of thermal conductivity in the Earth's crust.

Fig.18

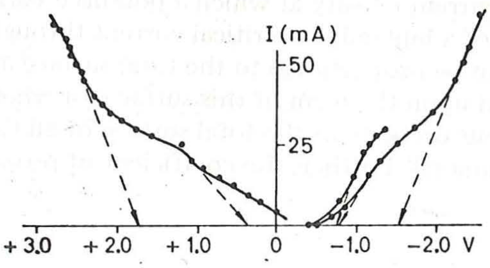

Fig.19

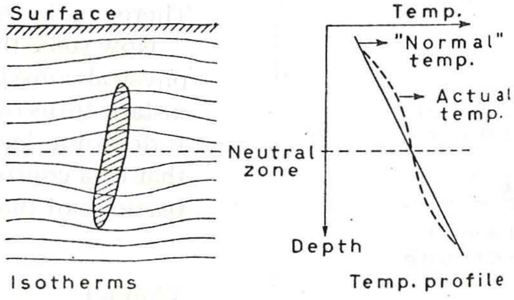

Fig.18. Application of the CPC method; cathodic and anodic polarizations. Galena ore, central Kazakhstan, U.S.S.R. (After Yu.S. Riss in Volosyuk and Safranov, 1971, ch.6.)

Fig.19. Temperature anomaly due to an ore.

If there is an orebody which is a better conductor than the surrounding rock, the heat flow from the Earth tends to be deflected into it. As a result the lower end of the body becomes cooler than the surrounding rock and the upper end becomes a little warmer. Somewhere in between there is a neutral zone as shown in Fig.19 where the temperature within the ore is the same as that outside.

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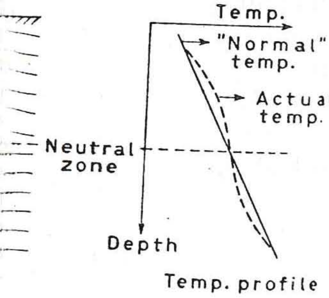

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On the left-hand side in Fig.19 is shown the distortion of the isothermal surfaces due to the orebody. On the right-hand side are shown two depth-temperature profiles. The solid line represents the normal increase of temperature with depth and the dashed one shows the actual temperature in the presence of the better conducting orebody.

If the top surface of a spherical, cylindrical or tabular body is not too shallow the neutral zone is, according to theory, about midway in it as indicated in this figure.

That significant temperature anomalies can be obtained on an ore in some cases and that an estimate of its depth extent is possible is shown in Fig.20 based on measurements in a large number of exploratory holes on an ore deposit in north Sweden. There is no mine here.

On the -40-m level (40 m below a rather level ground surface) we have a maximum anomaly of +0.15°K. We recall that above the neutral zone an ore which is thermally better conducting than the surrounding rock is warmer. On the -50-m level the anomaly decreases to +0.10°K but is still positive and we are therefore above the neutral zone.

On the -80-m level, on the other hand, the anomaly is almost zero or slightly negative. Evidently we have just about passed the neutral zone and by a rule of thumb we may estimate the depth extent of the ore as about twice this depth, that is, as 140–160 m.

The implications of geothermal work in mining geophysics are not yet fully clear and much more basic research in ore provinces is required but I feel that one other avenue is also worth exploring in this respect.

Fig.20

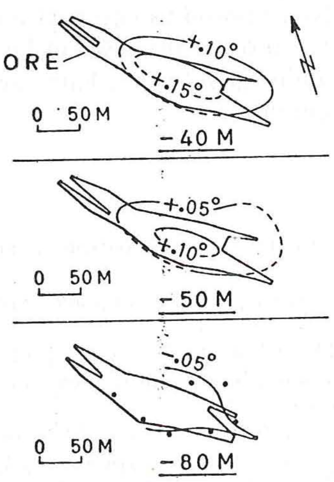

Fig.21

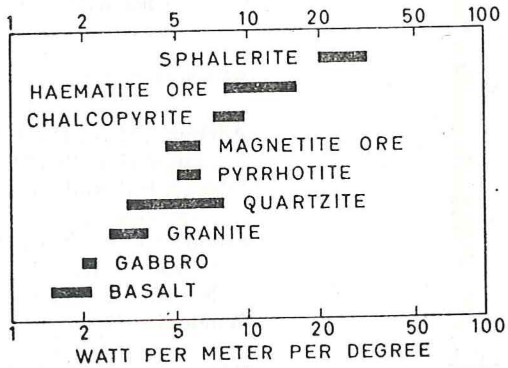

Fig.20. Geothermal measurements on a sulphide ore in north Sweden.

Fig.21. Thermal conductivity chart.

Let us consider the thermal conductivities of a few different rocks and minerals shown in Fig.21. This chart is based upon thermal conductivity values in handbooks supplemented by about 1000 measurements made recently on ore and rock samples in Sweden.

Basic rocks like basalt and gabbro have conductivities around 2 W/m · °K. Acidic rocks like granites and quartzites range from 3 to 9 W/m · °K. Quite surprisingly we find that haematite is more than twice as good a conductor of heat as magnetite. But the most surprising fact of all is that sphalerite tops the list with a conductivity of 20—30 W/m · °K. It is thermally four times as conductive as pyrrhotite!

Now, magnetite, pyrrhotite, pyrite and chalcopyrite ore deposits are very good targets for magnetic and electrical methods of prospecting but there is one ore type, namely, sphalerite-rich ore, which by and large has defied geophysical prospecting methods.

Can we use geothermal methods, perhaps in short auger holes reaching below the depth of annual temperature variations, to prospect for zinc orebodies? I do not know the answer. I am only throwing a speculative suggestion. Perhaps some student of applied geophysics could make a Ph.D. thesis out of it.

On this speculative note I am coming to the end of my lecture. At the break of this year 1973 there is hardly anyone who doubts that geophysical methods can be successfully used for discovering new ore deposits, although we shall be wise to take with a grain of salt the tall claims made in respect of this or that method. However, the application of geophysical work in guiding exploratory drilling in detail and in guiding the development work in mines so as to save time and money is an aspect that has received comparatively little attention. That is why I have chosen to emphasize it in this lecture. We do not have much experience to go on in this respect but the little we have seems to reveal new vistas in mining geophysics. I am sure further work along these lines will reveal still further vistas.

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