SVERIGES GEOLOGISKA UNDERSÖKNING

SER C NR 665 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 65 NR 11

LEIF ERIKSSON

EXPERIENCE OF INDUCED POLARISATION DURING SULPHIDE PROSPECTING IN NORTHERN SWEDEN

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C. DAVIDSONS BOKTRYCKERI AB, VÄXJÖ 1971

CONTENTS

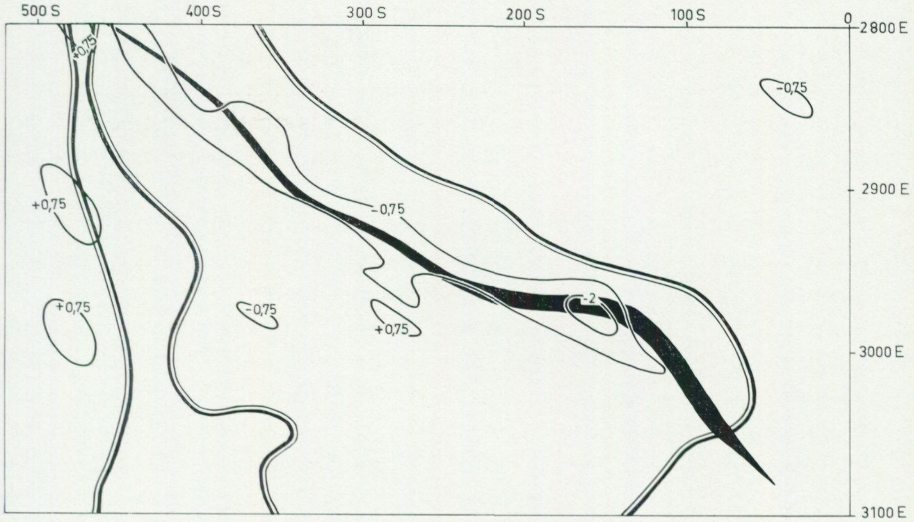
ABSTRACT

The results from a variety of geophysical investigations in northern Sweden over the past five years are selected to illustrate the use of combined potential measurements i. e. induced polarisation, apparent conductivity and spontaneous-potential, in ore prospecting. The measurements, which are in the time-domain using a gradient array, have been carried out with an instrument (with radio reference) developed at the Geological Survey of Sweden. The method has been found to be a useful complement to high frequency electro-magnetic methods in the search for low-grade sulphides. It has also been possible, in some cases, to distinguish between various rock-types. Experiments, e. g. drillhole-measurements, model measurements on ice-covered lakes and measurements over known orebodies and structures, have been made to make it easier to understand and interpret the routine measurements.

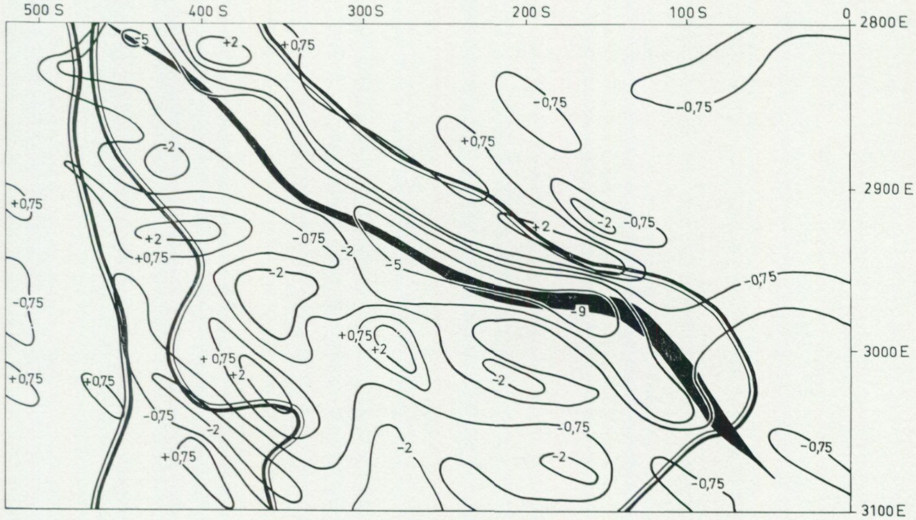
1. Introduction

In the beginning of the 1960s an instrumentation for combined potential measurements, i. e. induced polarisation, conductivity and spontaneous potential, was developed at the Geological Survey of Sweden (SGU). It was thought initially that with this instrument it should be possible to distinguish sulphide orebodies from graphitic schists by analysing their electrical decay curves. This would have been a quite simple solution to a problem that has always been difficult in connection with the Skellefte field and Caledonian sulphide orebodies. However, it transpired that the theoretical basis of the instrument and its application in model experiments, was not confirmed very well in the field. The experience, however, did lead to the development of an instrument that has proved to be very useful, especially under Swedish conditions (Ebell 1965). This instrument, which works in the time-domain with a radio reference, is mainly used for measurements with a gradient array, i. e. with fixed current electrodes located outside the area of investigation, and with a constant separation between the potential electrodes moved along straight lines parallel to the current layout. When the same equipment is employed for drillhole measurements, we also use a gradient array, but it can, of course, also be used in other arrangements. Thus this instrument, was unable to distinguish sulphide ores from graphitic strata, which was one of the intentions for its construction. For the commonest types of sulphide ores with good electrical conductivity this method gives very little more information than the normal electro-magnetic methods (mainly slingram) in combination with magnetic measurements.

In view of this experience, the question naturally arose as to whether there existed relationships between orebodies and country-rocks which could be better elucidated by combined potential measurements than by other techniques. In the south of Norrbotten, SGU has been successful in locating low-grade, disseminated chalcopyrite ores with the aid particularly of our recently developed high frequency slingrams (using 18 kc/s instead of the earlier 3.6 kc/s). The Lulepotten copper ore for instance (Padget 1966), which is a very poor conductor, is indicated much better when using the higher frequency (Fig. 1). In some cases, however, these slingram measurements also have been more or less inconclusive or have been too difficult to interpret because of interference from swamps, water-bearing overburden, fracture zones etc., in spite of good indications of mineralisation in the form of local ore-boulders. We therefore decided to focus the surveying with the new instrumentation on those areas where the ore-boulders indicated that the ores were of a type which the more conventional methods would probably not identify, i. e. low-grade sulphide ores, zinc ores with poor conductivity, disseminated molybdenite ores, etc. Our interest was, of course, stimulated by experience elsewhere in the world.



SLINGRAM 3,6 kc/s ZI %



SLINGRAM 18 kc/s ZI %

Fig. 1. A comparison of "normal" (3.6 kc/s) and "high frequency" (18 kc/s) slingram anomalies over the Lulepotten copper ore.

Many such areas existed where the geological problems had not been solved with the more conventional geophysical methods but where hope for ore remained. During the summers 1965 to 1969 SGU surveyed a number of areas, Vargisträsk being the first of these to show a promising result, (Padget, Ek and

Eriksson, 1969, Eriksson 1969, unpublished report). Here a combination of combined potential measurements, geology and geochemistry enabled zinc copper mineralisation to be located by diamond drilling. Further, Vargisträsk proved to be a nearly ideal object, on which it was possible to make an advanced comparison between induced polarisation and different electro-magnetic methods.

Experience from Vargisträsk has given new hope in the prospecting for ores of very low electrical conductivity. The combination of conventional geophysical measurements with the induced polarisation method, along with geochemical sampling, is an innovation in our prospecting programmes which we have reason to believe will give us new opportunities for finding orebodies. Subsequent to the Vargisträsk project, SGU have surveyed several new areas where ore bodies of the type mentioned above were suspected and in a number of them the results have been positive. However, in many cases drilling has only recently begun, and definite conclusions would be premature here. It is hoped that the following illustrated discussion will give an idea of the method that SGU is using and of the experiences we have of the instrument. The investigations described below illustrate many of the advantages of the combined potential measurements, as well as the difficulties encountered such as the dependence on measuring direction, influence from overburden, disturbance from magnetite etc. Examples are also included of experiments with drill-hole measurements, model measurements on ice-covered lakes, and measurements over known orebodies, showing how these can make understanding and interpretation of the routine field-measurements easier.

I am very greatful to those of my colleagues who have read and commented on this paper. I am specially indebted to David Gee Ph. D. who has corrected the language.

2. Theory and instrumentation

2.1. Metallic and non-metallic IP

Normally the bedrock should be looked upon as a ionic conductor, i. e. the electrical current is led by pore-water ions. Certain minerals, e. g. sulfides, some oxides, graphite etc. act as metallic conductors, and the anomalous phenomena observed are caused by electrochemical processes in the contact between these ionic and metallic conductors i. e. on the mineral grain surfaces.

Fig. 2 A shows a schematic picture of mineralised bedrock and the equivalent electrical circuit where resistors and condensor symbolize the bedrock in which a certain part of the pores are blocked by sulfide grains. When an electrical current is passed through the bedrock, the latter can be regarded as acting simultaneously as an electrical conductor and as a condensor or accumulator.

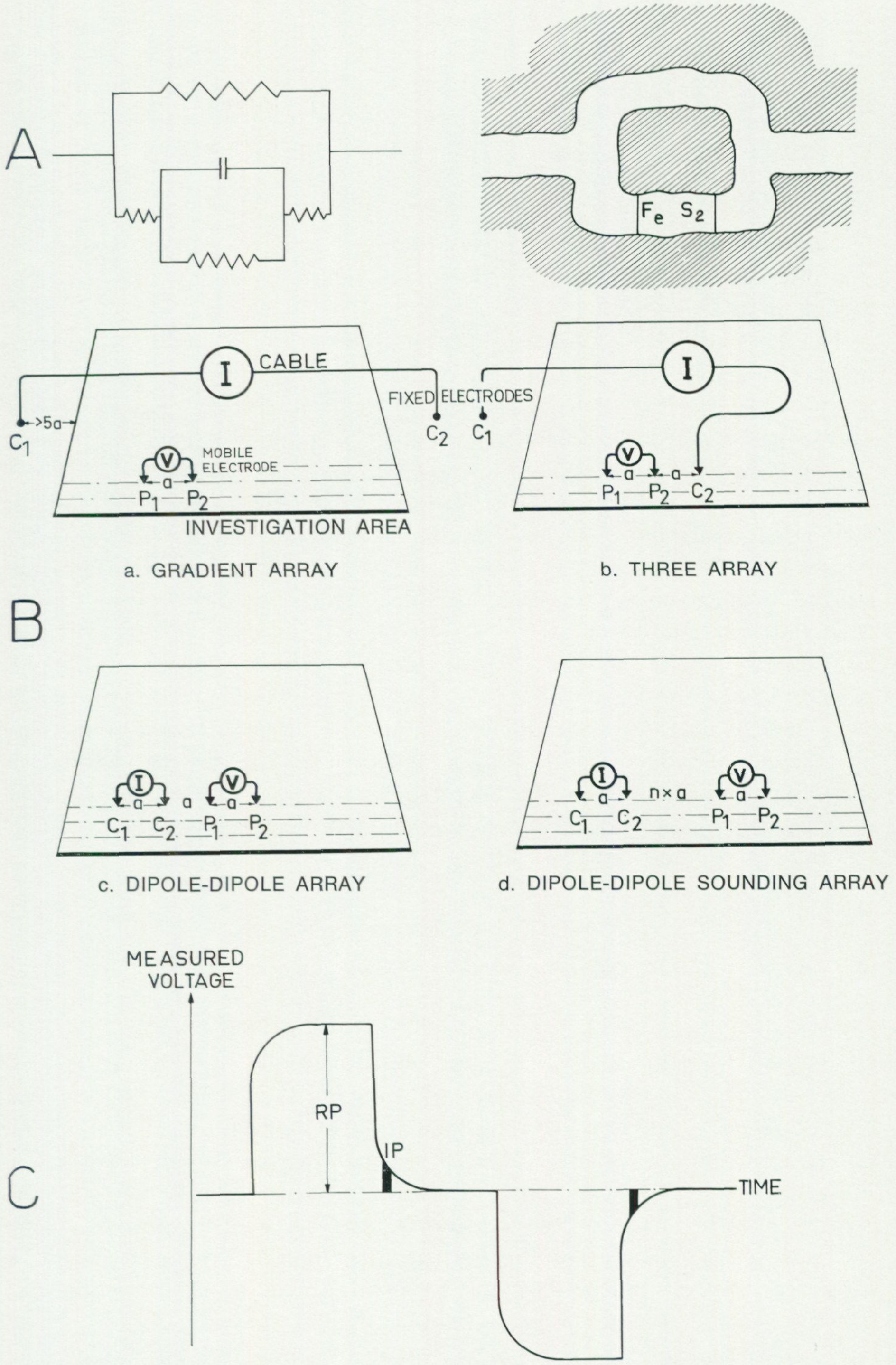


Fig. 2. A. Mineralised bedrock and equivalent electrical circuit, after KELLER and FRISCHKNECHT (1966).
B. Some typical electrode arrays during combined potential measurements.
C. The measured voltage with the time-domain method.

This ”chargeability effect” is registered with IP measurements principally in two ways, by the time-domain or frequency-domain methods. In the case of the former, measuring electrodes are employed to study the potential decay when the current transmitted through the bedrock is interrupted. In the latter, the electrodes measure changes in the apparent resistivity when the frequency of the transmitted alternating or pulsed current is raised (e. g. from 0.1 to 1.0 cps).

The measurements can be carried out in many different ways depending on how the current and measuring electrodes are arranged in relation to the area surveyed.

The most commonly employed measuring arrays with combined potential measurements are illustrated in Fig. 2 B. With the time-domain method, the arrays ”a” and ”b” are most often used (in the measurements described below only array ”a” has been used). In the frequency-domain method, the ”c” and ”d” arrays are more common.

Another type of IP effect, the so-called non-metallic background effect or membrane polarisation, is caused by the accumulation of ion charges in the pore-water when the fine capillaries in which the current is passing are constricted. It can of course be difficult to distinguish an observed metallic effect from a non-metallic effect.

The magnitude of the IP effect is dependant on the time the current is permitted to pass through the bedrock, a long charging time giving a greater IP effect. The latter is also dependant on a number of other factors, e. g. the type of mineral, the number and size of the mineral grains and the extent to which they block the pore passes, the microstructure of these grains, the bedrock porosity, the composition of the pore electrolyte etc.

2.2. The time-domain method

SGU employs the time-domain method, and mainly uses the gradient array shown in Fig. 2 B ”a”. A direct current is passed through the bedrock in positive and negative pulses divided by current-free intervals. Using measuring electrodes placed a suitable distance apart from each other (e. g. 20 m), the potential difference between these electrodes (see Fig. 2 C) caused by the direct current pulses, is measured. During the current pulse, the potential RP is registered, making it possible to calculate the apparent conductivity in the area. In the current-free period, a certain time after the current is switched off the rest-potential IP caused by the induced polarisation is registered. To ensure the greatest possible accuracy, the measured potentials have to be compensated for the spontaneous potential caused by chemical processes in the overburden. The spontaneous potential SP is registered at the same time.

All calculation of measuring data is done by computor, the end-product

Fig. 3. SGU's "IP time-domain 1968".

being anomaly maps showing (i) IP in % of RP as a measure of the induced polarisation, (ii) the apparent conductivity, by comparing the measured potential RP with the calculated normal potential, and (iii) the measured spontaneous potential differences. These maps can then be contoured.

2.3. Transfer of time-reference

As the rest-potential decays with time after the current is switched off, great accuracy of this time recording is necessary to allow comparison of the induced polarisation at the different measuring points. This implies that a reference from the transmitted direct current pulses is required to control the recording of the different potentials at the measuring electrodes.

SGU has chosen to transfer the time reference using a radiolink that automatically controls the potential measuring in a reliable and flexible way.

In general the most important differences between available IP equipment of the time-domain type are the power output and the way the time-reference signal is transferred from the commutator box to the meterbox (i. e. cable, electronic clocks, "self-triggering", radio etc.).

Table 1 illustrates the rapidly increasing interests for IP measurements in SGU. The method is relatively cheap, the measurements usually being carried out by four men divided into two teams. The instrument "SGU IP Time Domain 1968" (Fig. 3, summarised in Table 2) is an improved version of "IP 1964" (Ebell 1965). Among the innovations are integrated circuits and extra stable operation amplifiers.

Table I

YEAR		1965	1966	1967	1968	1969
MEASURED KM^2		3	5	8	20	30
INSTRUMENTS	COMMUTATORS	1	2	2	4	4
	METERBOXES	1	3	3	7	7
AREA COVERED WITH 2 MEN/TEAM		c 1/6 KM^2/DAY (c. 100 points/day)				
COST ABOUT TWICE THAT OF THE SLINGRAM METHOD		SAY 5 000 KR/KM^2				

Table 1. Use of induced potential measurements by SGU during recent years.

Table II

CURRENT SUPPLY:	DC, DRIVEN BY 1 KW MOTOR-GENERATOR.
COMMUTATOR:	250 V, 1 A MAX; 4 SECONDS ON, 4 SECONDS OFF. TRANSFER OF TIME-REFERENCE TO METERBOX BY RADIO-TRANSMITTER 27 Mhz, 0.22 W, RANGE AT LEAST 1 KM. WEIGHT OF COMMUTATOR WITH RADIO 7 KG.
METERBOX:	10 STEPS OF MEASURING 0.025 mV/SCALE–20 mV/SCALE. INPUT IMPEDANCE 10 MOHM. SENSITIVITY 25 μV. IP-MEASURING-TIME 240–480 MILLISECONDS AFTER CURRENT TURN-OFF. WEIGHT 7,5 KG MANUAL SP-COMPENSATION.

Table 2. Technical data for "SGU IP Time Domain 1968".

3. Measurements over orebodies

3.1. The Vargisträsk mineralisation

The Vargisträsk mineralisation Fig. 4 (Padget et al., 1969) containing up to 7 % Zn and c. 0.2 % Cu and Pb, comes out clearly in the IP anomaly, Fig. 4 A. The conductivity anomaly, Fig. 4 B, however, disappears into the background noise caused by water-bearing zones in the overburden, etc.

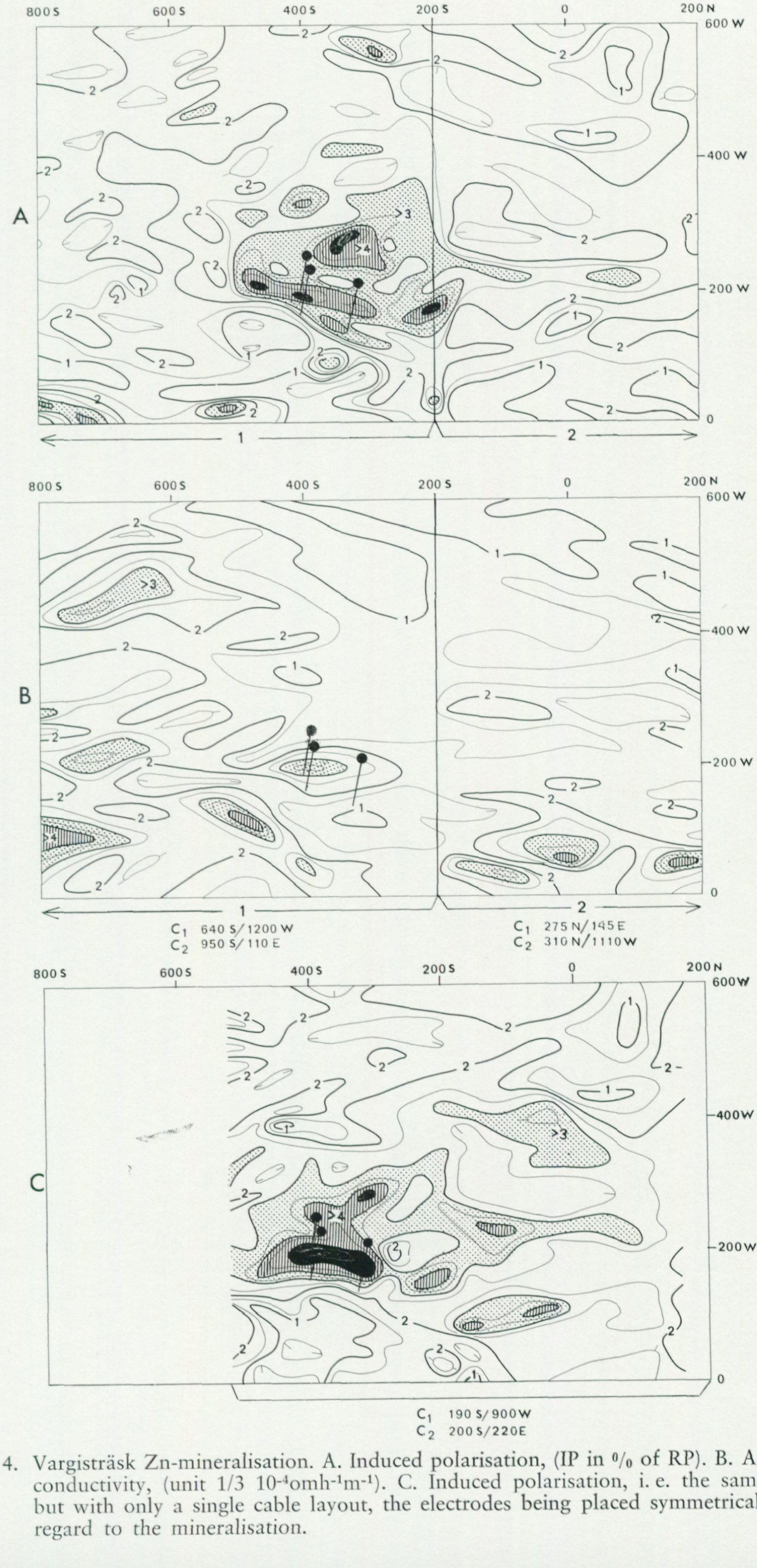


Fig. 4. Vargisträsk Zn-mineralisation. A. Induced polarisation, (IP in ⁰/₀ of RP). B. Apparent conductivity, (unit 1/3 10^{-4}omh^{-1}m^{-1}). C. Induced polarisation, i. e. the same as A, but with only a single cable layout, the electrodes being placed symmetrically with regard to the mineralisation.

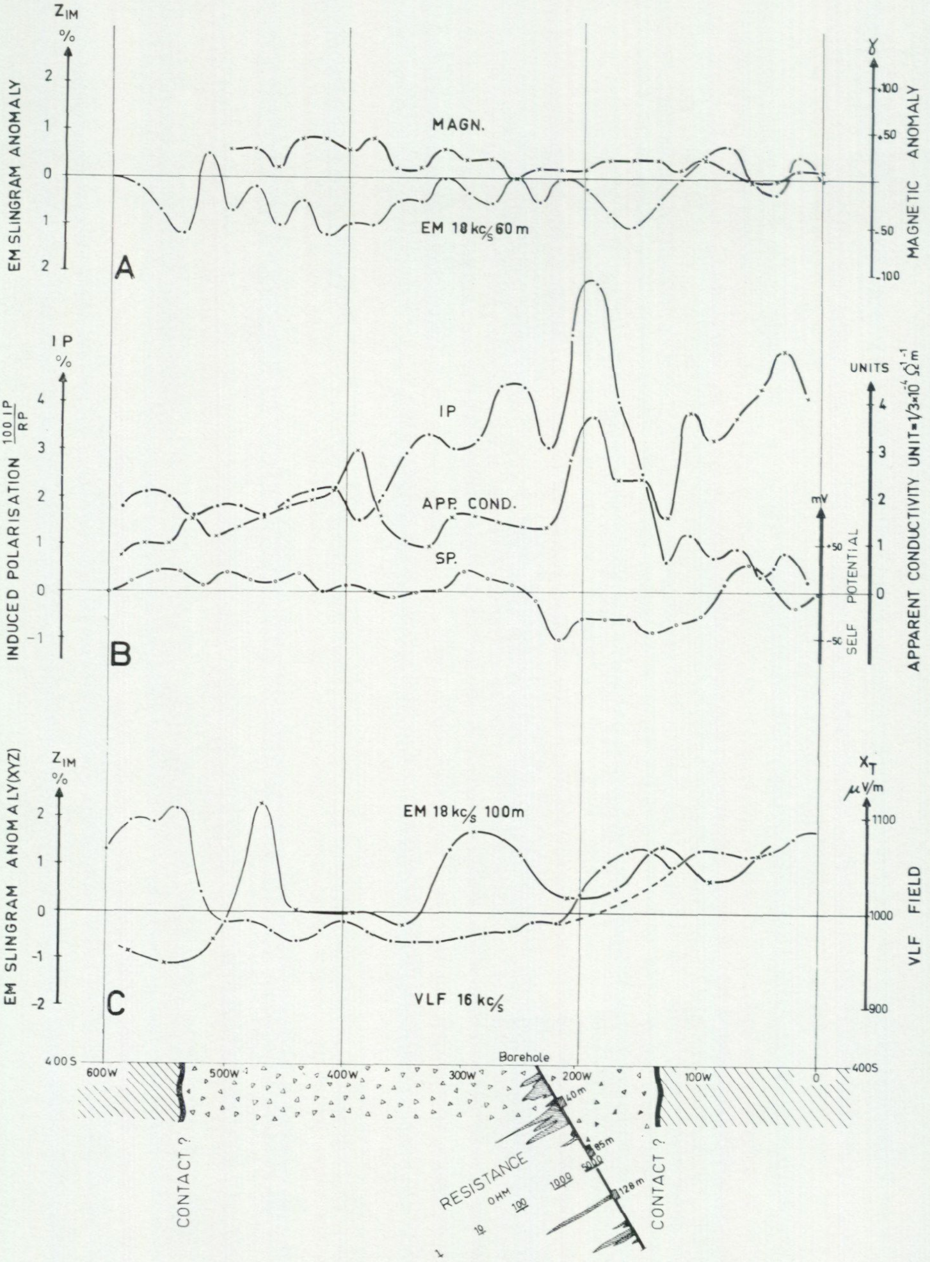


Fig. 5. Geophysical profiles across the Vargisträsk Zn-mineralisation (line 400 S). A. Earlier measurements with high frequency slingram and magnetometer. B. Combined potential measurements (time-domain method), induced polarisation, apparent conductivity and spontaneous potential. C. Follow-up electro-magnetic measurements (VLF, XYZ-slingram).

The area was measured in two parts (E and W, joining along the line 200S) the measuring direction being the same for both. The resulting anomalies, Fig. 4 A, compare well with those of Fig. 4 C, the area in the latter case being measured in one piece, the cable layout traversing the central part of the mineralisation. Thus, limited movements of the cable layout do not seriously influence the resulting anomaly pattern.

It is noteworthy that although the background IP variations within the area are rather small, the differences reflect variation in lithology. These variations primarily concern porosity and bedrock grainsize, these characteristics being (together with the background sulfide content) the most important parametres influencing the magnitude of the background induced polarisation.

The different geophysical methods are compared in Fig. 5, with profiles over the orebody along line 400 S. Note the clear IP anomaly and the difficulty in detecting the Zn-mineralisation 200 W electro-magnetically. It is of interest also to compare the quite good conductivity of the rock-unit between 0 and 140 W with its low IP values.

3.2. The Jårbojoki Mineralisation

Jårbojoki (Fig. 6), a chalcopyrite-pyrite impregnation ore with up to 1–2 % Cu, is consisting of two parallel mineralisation zones. Both IP and slingram give distinct and mainly similar anomalies. Certain parts of the mineralisation come out somewhat better with the IP measurements; others are better defined by the slingram method. The slingram and IP anomalies do not coincide precisely (max. difference 20 m), probably due to the nearness of the two parallel zones, the IP anomalies "attracting" each other whilst the slingram anomalies tend to "repel" each other. The mineralisation comes out as a rather weak conductor on the conductivity map whilst the spontaneous potential anomaly of 50–100 mV only gives a rough idea of the positions of the zones. Here the potential differences have been summarised along the measuring lines to give the total potential.

3.3. The Ainasjärvi Mineralisation

Ainasjärvi (Fig. 7) is a low-grade chalcopyrite-pyrite impregnation ore, containing some magnetite. It is situated in an iron ore district near Svappavaara. The area has long been of prospecting interest because of the existence of many good copper-rich boulders. However, electro-magnetic methods failed to locate the mineralisation, and it was not until the IP-measurements were made in combination with geochemical sampling that the first mineralisation was identified and subsequently drilled. Some difficulties in interpretation of the IP anomaly map, caused by the presence of magnetite, were eliminated by comparison with the magnetic anomaly map. The complicated anomalies on the conductivity and slingram maps are caused partly by swampy overburden

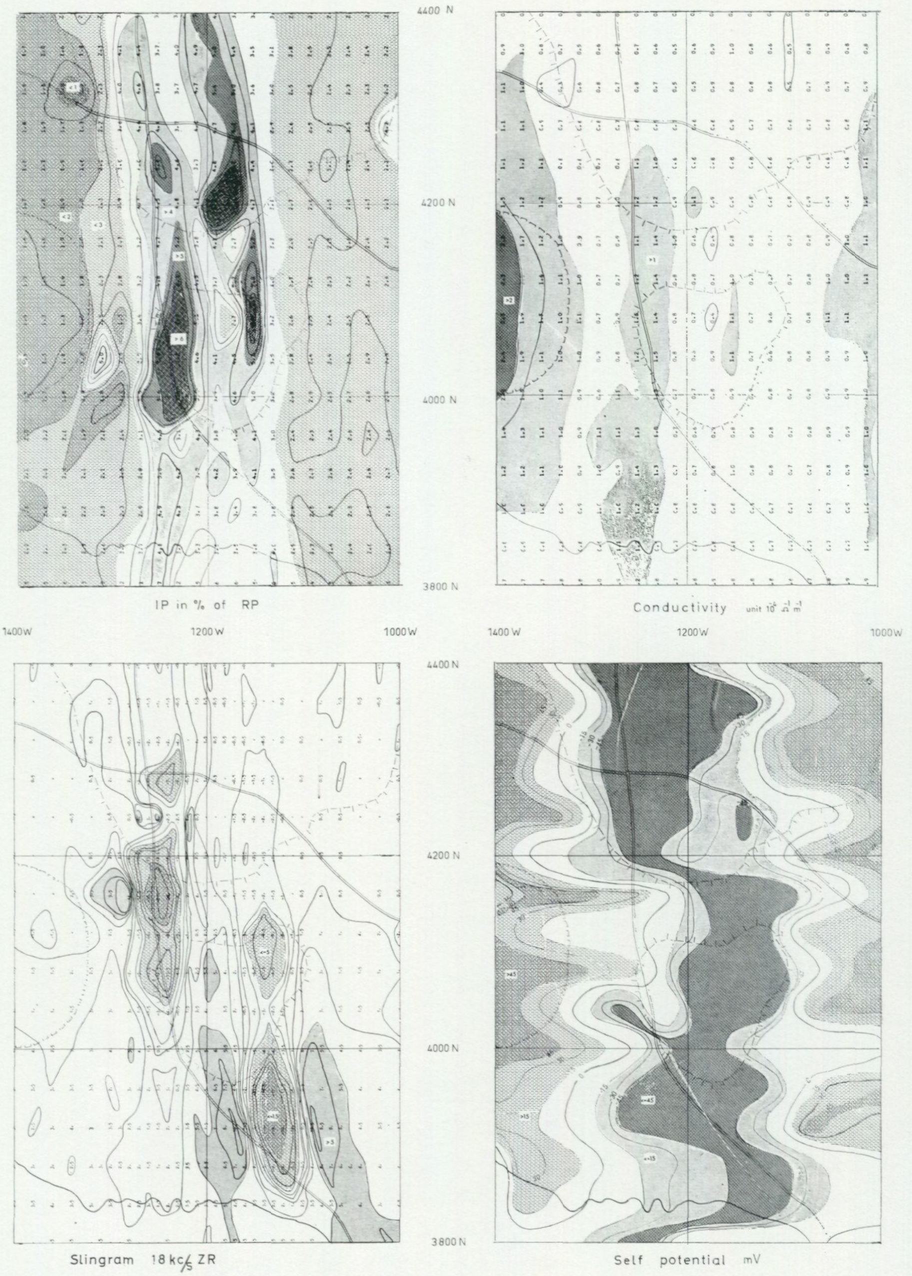
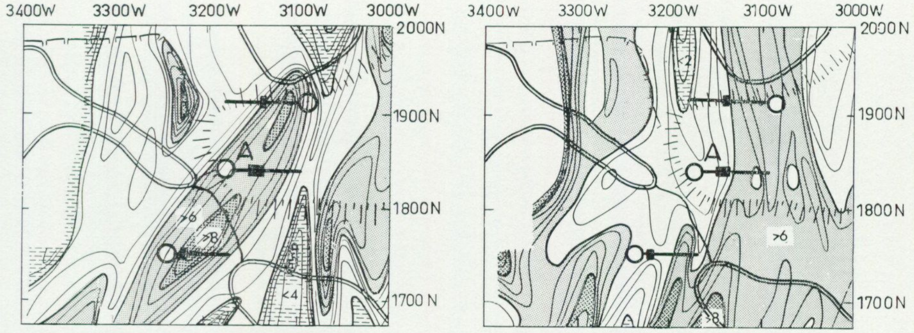
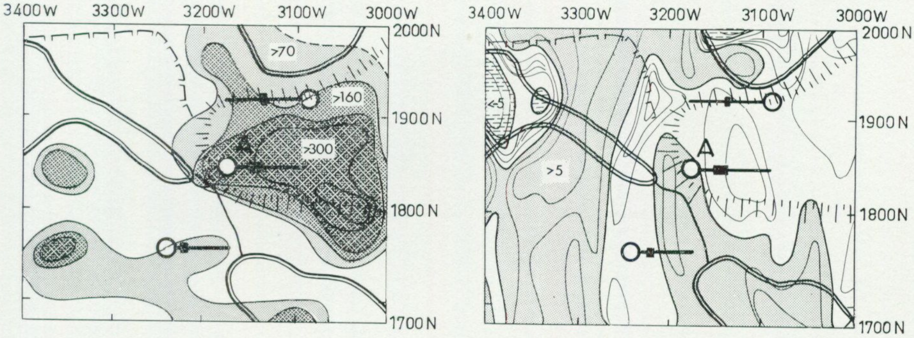


Fig. 6. Jårbojoki chalcopyrite-pyrite impregnation ore.



IP in % of RP

Conductivity unit $10^{-4}\,\Omega^{-1}\,m^{-1}$



Geochemistry Cu ppm

Slingram 18kc/s ZI

Fig. 7. Ainasjärvi low-grade chalcopyrite-pyrite-magnetite impregnation ore.

and partly by wide variations in the bedrock conductivity. The latter can be seen clearly in the drillhole measurements, both for the resistance log and the conductivity log, from hole A shown in Fig. 9.

4. Measurements in drillholes

The principle for IP-measurements in drillholes is illustrated in Fig. 8, the standard equipment being supplemented with a cable drum and special drillhole electrodes. The measuring method is in general the same as that used for ground measurements (i. e. gradient array). Thus drillhole measurements are very suitable as a routine follow-up of the ground anomalies.

The results from the combined potential measurements in Ainasjärvi, hole A, are compared in Fig. 9 with the GEOHM diagram (single electrode resistance log). The mineralisation is clearly indicated with IP and SP but rather faintly with conductivity. Note the changes of levels in IP, COND. and GEOHM along the hole and how these can be related to the ground anomalies in Fig. 7.

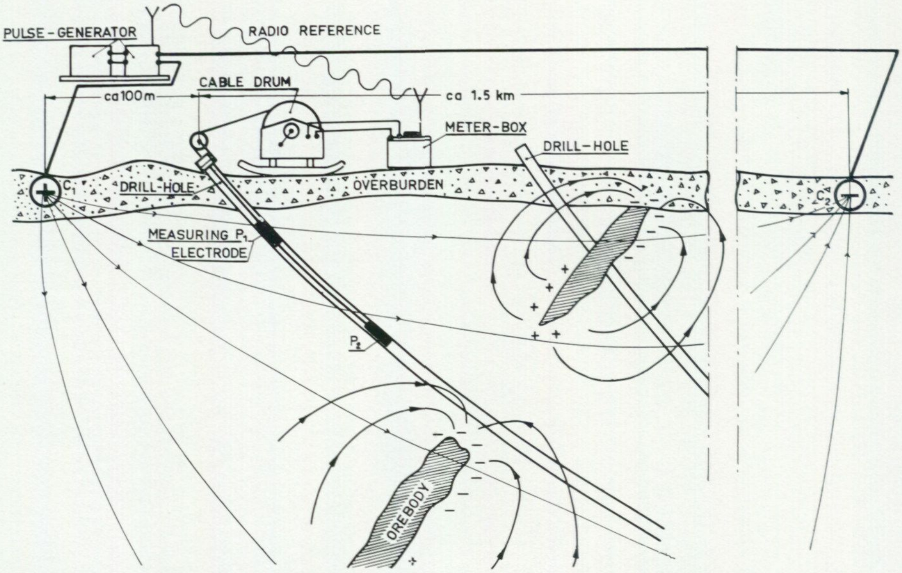


Fig. 8. Principle for combined potential measurements in drillholes (gradient array).

5. Some factors affecting induced polarisation

5.1. Measuring direction in relation to orientation of strata

Fig. 10 and 11 illustrate the dependence of the IP-method on measuring direction over good and poor conductors, respectively.

Fig. 10 is of Brattmyrhögen, a well-tried area for electro-magnetic methods. Good conductors in the area, include graphitic schists and pyrite and pyrrhotite mineralisations, dipping at high angles. Because of the pyrrhotite, we have been able to compare the IP anomalies with the magnetic anomaly picture, the latter being completely independent of the measuring direction. Over good conductors of this type, potential measurements are, of course, more difficult to carry out, the potential differences becoming very small and difficult to read in the vicinity of the conductors (small potential differences – high conductivity).

When the measuring direction is at right angles to the geological strike, the IP anomalies agree very well with the conductors as they are indicated magnetically. On the conductivity map, the anomalies seem to be exaggerated in the areas where the main part of the currents pass by.

When measuring parallel to the strike both IP and conductivity give only the same confusing anomaly picture, which at the best gives a very rough idea of the mineralisations.

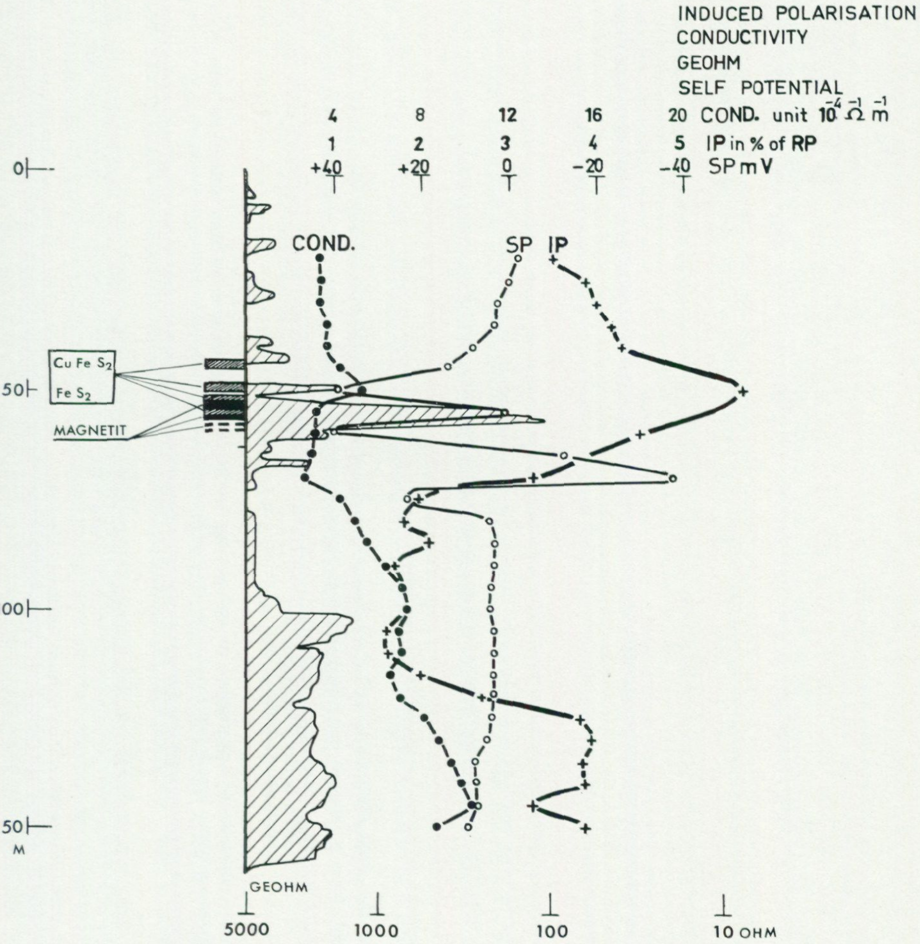


Fig. 9. Drillhole A, Ainasjärvi.

A poor conductor is represented in Fig. 11, Vargisträsk (compare with Fig. 4 and 5). In this case we observe again the same direction dependence. In general it can be said that structures dipping at a high angle and striking perpendicular to the measuring direction tend to be emphasized whilst an unsuitable measuring direction, i. e. parallel or near parallel to the strike, yields anomalies that are difficult to interpret. Electrical digressions in the overburden caused by water-bearing zones, swamps etc. influence the conductivity map to a much greater extent than on the IP map; these disturbances also become more prominent when orientated perpendicular to the measuring direction.

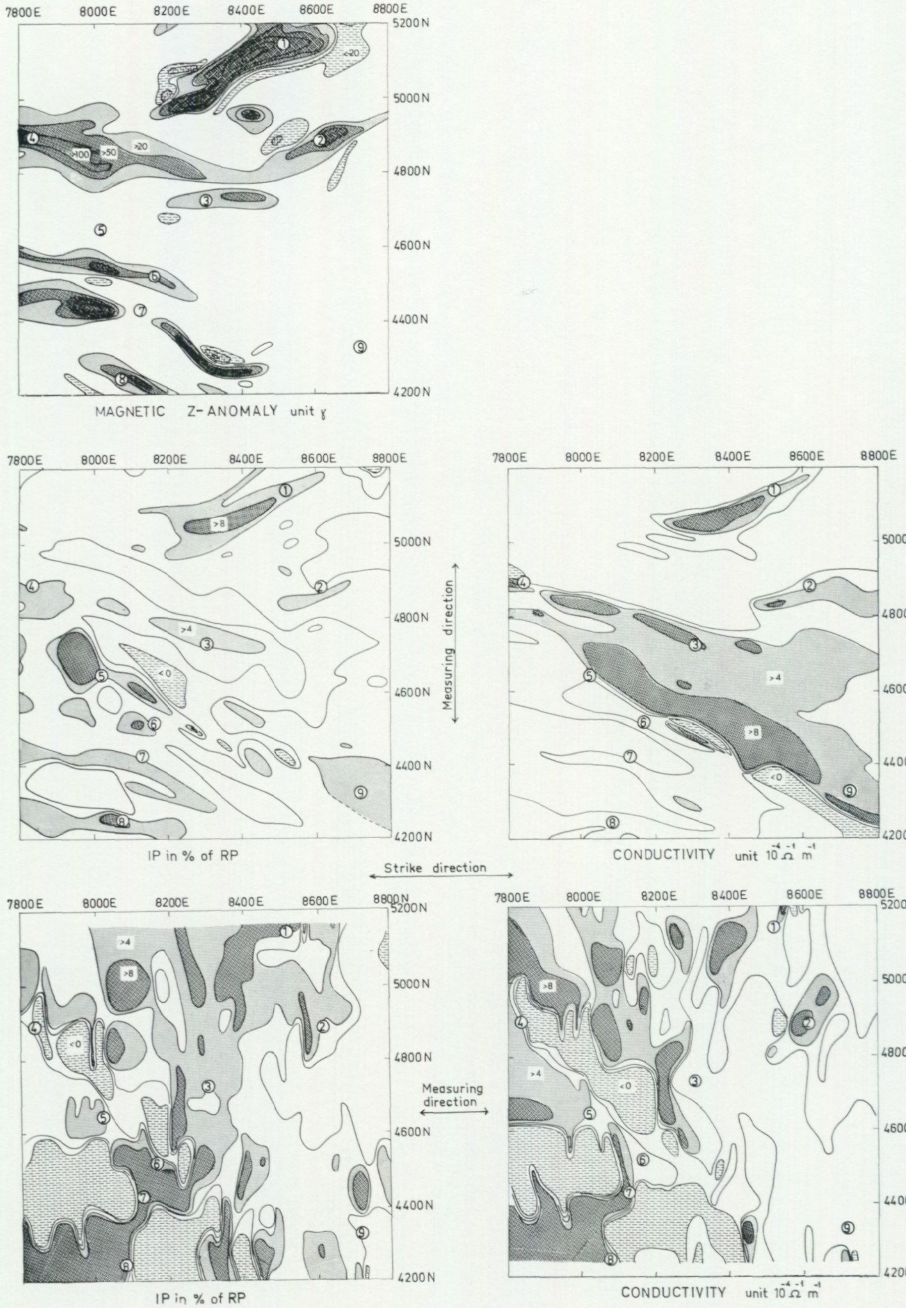


Fig. 10. Brattmyrhögen test-area. Example of direction-dependence of combined potential measurements in an area with good electrical conducturs.

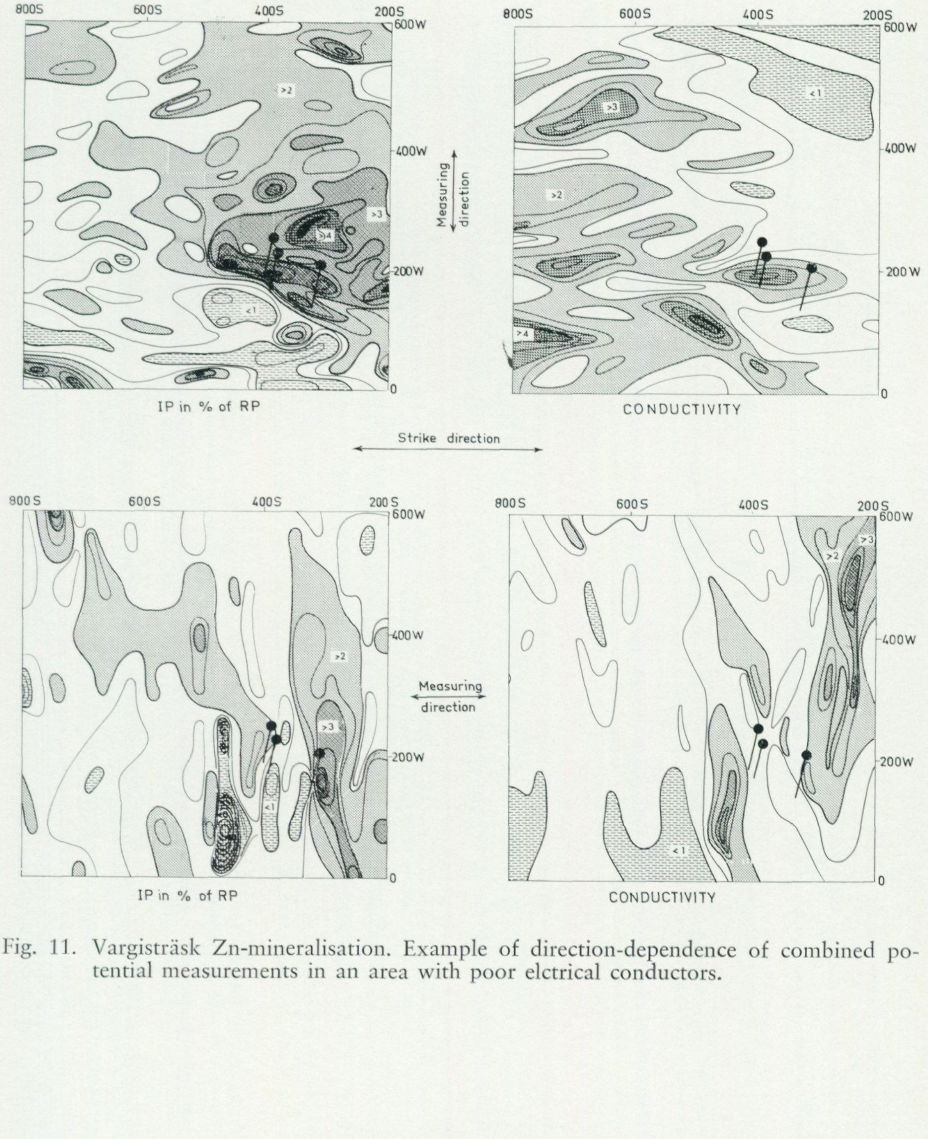


Fig. 11. Vargisträsk Zn-mineralisation. Example of direction-dependence of combined potential measurements in an area with poor elctrical conductors.

5.2. Fracture zones

Fig. 12 is an example taken from Rappen in the Arjeplog area, showing how an inferred broad shear zone influences the combined potential measurements. This zone, where no mineralisation is known, comes out as a minimum on the magnetic map. It is also registered as a clear conductivity anomaly, but does not in this case give any induced polarisation. This can certainly be a great advantage when it comes to separating mineralisations associated with shear zones and similar structures.

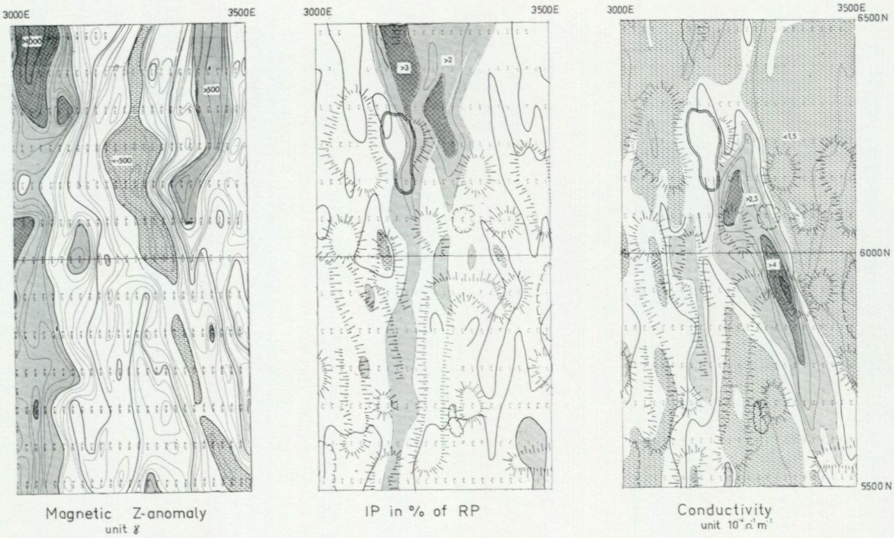


Fig. 12. Broad shear-zone in the Rappen area.

5.3. Magnetite

A magnetite orebody (about 30 % magnetite), also from the Rappen area, comes out clearly (Fig. 13), on both the magnetic anomaly map and on the IP-map. It is interesting, and illustrative from the point of view of interpretation, particularly of dip determinations, to see the good agreement between the anomalies. At the same time the disturbing influence of even small amounts of magnetite during IP prospecting for sulphide orebodies is noteworthy.

The magnetite orebody is situated immediately west of a broad shear zone which, as in the example above, comes out as a magnetic minimum and a conductivity anomaly, but not as an IP anomaly. The rock-type west of the orebody has lower IP values.

6. Model experiments

To make it easier to understand the IP phenomena and to gain experience for interpretation of our routine field measurements we have found it necessary to carry out some form of model measurements, especially adjusted to the kind of measuring arrangement that we use, i. e. gradient array.

Ebell has earlier made some unpublished model experiments in connection with the developing of the instrument. He then used a tank, studying among other things the decay curves from different rock and ore samples on an oscilloscope.

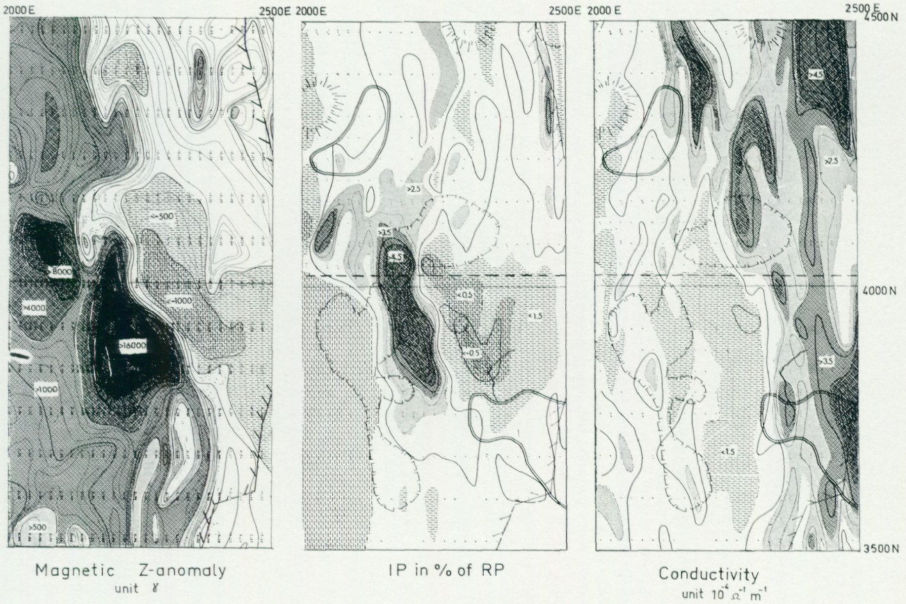


Fig. 13. Magnetite orebody (roughly 30 % magnetite) in the Rappen area.

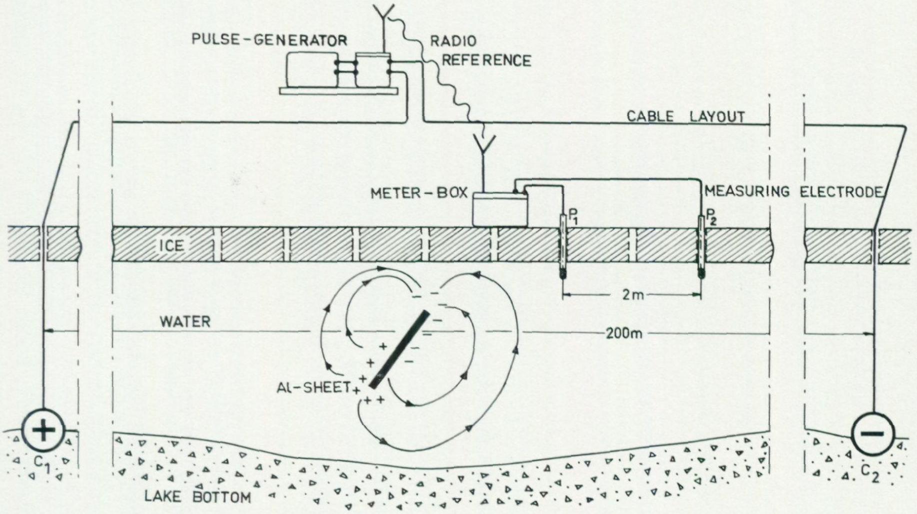


Fig. 14. Principle for IP-model measurements on ice.

To avoid the risk of experimental errors in the laboratory such as electrode polarisation, disturbances from the tank walls etc. and to simulate the field circumstances more closely and on a larger scale, we decided to do experiments on ice. Our previous experiences of routine winter IP-measurements over frozen lakes, required for the completion of areas surveyed during the summer, prompted these experiments.

The basic principles of the model measurements are illustrated in Fig. 14. A gradient array is used with 200 m between the current electrodes, the distance between measuring electrodes being 2 m and 1 m separating the measuring points. Aluminium sheets (200×100×0.1–0.3 cm) were used for the models. Some examples of the results from the measurements can be seen in Fig. 15, where the depth and dip of the model sheet has been varied so that their influence on the IP curves can be studied. IP anomalies provide good opportunities for making depth and dip estimations.

By contrast, the conductivity anomalies are so small, at least when the sheet is vertical, that they are near the noise level. The IP results stimulated us to

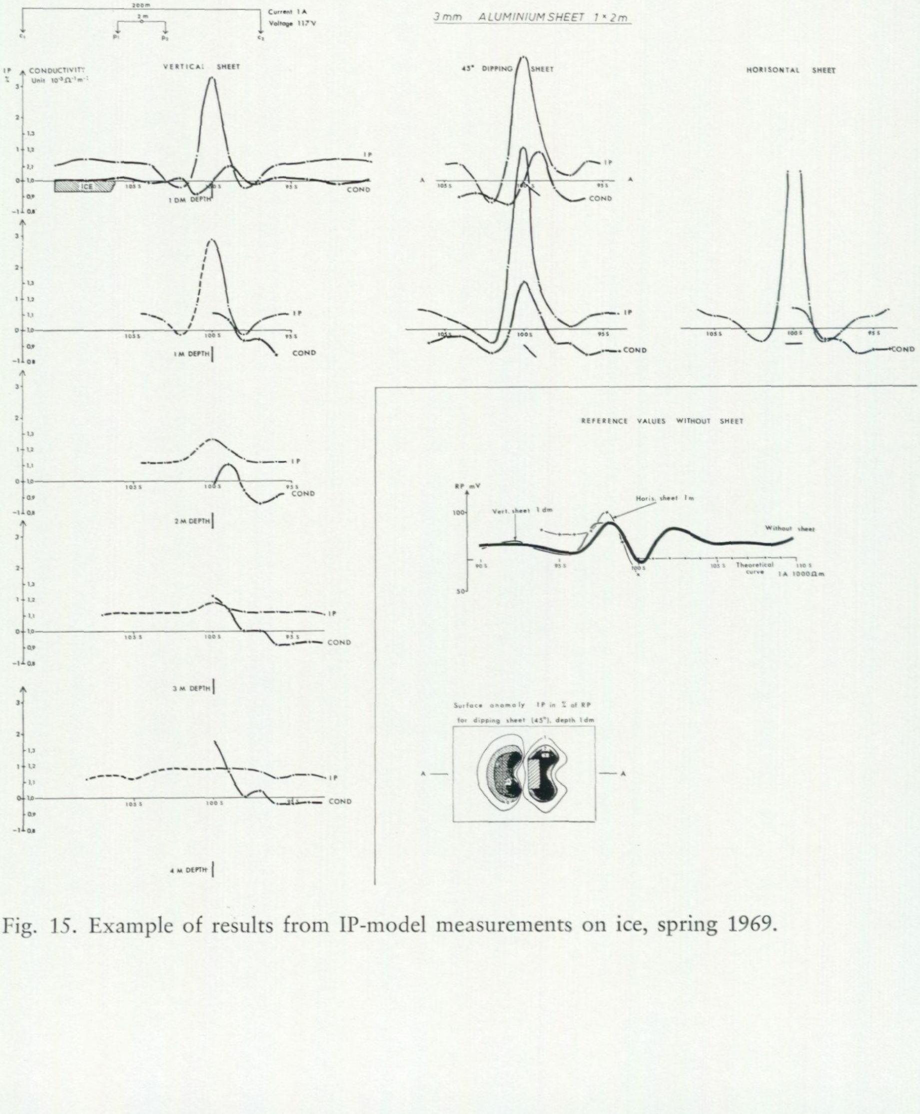


Fig. 15. Example of results from IP-model measurements on ice, spring 1969.

extend the experiments with the aim of examining the concepts of volume polarisation in the same way. We then used an ore-sheet made of pyrite cement. The later trials (Johansson and Eriksson, unpunblished report) were less successful, perhaps due to the very high conductivity of the matrix medium in which the pyrite grains were embedded, the matrix medium conductivity proving to be very important for the size of the IP effect. Another disturbing factor could be the influence from earlier flotation on the pyrite grain-surfaces which apparently are so important for the IP-effect, (mineral, oxide and electrolyte should form the accumulator). However, the experiments will continue, both in the field and in the laboratory, to develop an ”ore-sheet” more suitable for these types of experiments. At the same time we are developing an instrument for measuring the IP parameter dirctly on ore samples and drillcores. (Eriksson and Oldeberg, unpublished report). This instrument, which is now undergoing trials, is also based on the standard equipment.

7. Concluding remarks

Table 3 sums up our experiences with combined potential measurements, and provides a basis for further discussion.

TABLE III

COMBINED POTENTIAL MEASUREMENTS ARE ADVANTAGEOUS

(a) WITH LOW GRADES, WEAK IMPREGNATIONS, DISSEMINATED ORES
(b) WITH NON-CONDUCTING MINERALS i. e. SPHALERITE OR HEMATITE
(c) WHEN LOW GRADES GIVE NEW OPPORTUNITY FOR e. g. MOLYBDENITE ORES
(d) AS INFLUENCE OF TOPOGRAPHIC PHENOMENA IS REDUCED
(e) AS INFLUENCE OF SHEAR ZONES, DYKES etc. IS REDUCED
(f) AS NEW PARAMETERS – POROSITY AND GRAIN-SIZE, GIVE OPPORTUNITY FOR SEPARATION OF DIFFERENT ROCK-TYPES

COMBINED POTENTIAL MEASUREMENTS ARE DISADVANTAGEOUS

(a) AS IT IS DIFFICULT TO MAKE QUANTITATIVE INTERPRETATIONS
(b) AS THE ANOMALIES ARE GREATLY INFLUENCED BY MEASURING DIRECTION
(c) AS EVEN SMALL QUANTITIES OF MAGNETITE GIVE DISTURBING ANOMALIES
(d) AS GRAPHITIC STRATA GIVE DISTURBING ANOMALIES
(e) AS IT IS DIFFICULT TO CARRY OUT MEASUREMENTS OVER ICE AND SNOW
(f) AS EXPERIENCE STILL IS VERY LIMITED

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