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SELF POTENTIALS AT THE JOMA PYRITE DEPOSIT, NORWAY

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SELF POTENTIALS AT THE JOMA PYRITE DEPOSIT NORWAY

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Abstract.

SP pattern both in drill holes and at the surface are separated into two parts:

(1) A general trend indicating the dipole pattern in the country rock around the deposit with maximum potential variations approximately 200 mV, and

(2) alternating potentials with minima down to -800 mV in the massive sulphides, the steep gradients of which indicate EMF's at the country rock/sulphide interfaces.

Sulphides and country rock are supposed to constitute galvanic cells of which the sulphides represent dipole electrodes and the pore water of the country rock the electrolyte. The redox potential of the pore water decreases with depth.

Separation of the SP potential pattern into two dipole systems offers possibilities for: (1) Locating possible extentions of ore bodies towards depth; (2) rough estimations of tonnage of total ore bodies if the tonnage of upper parts are known; (3) estimations of sulphide contents of ore sections without analysing drill cores or drilling cuts. The concept of galvanic cell indicates that electro-chemical prossesses to some extent control the dispersion of chemical elements around ore deposits.

INTRODUCTION

The existence of natural self potentials (SP) was first reported by Fox (1830). SP-anomalies in connection with ore bodies have later been demonstrated in a great number of cases, after Schlumberger (1922) introduced the use of unpolarizable electrodes. The application of the SP-method is to some extent based on empirical experience; the origin of these natural potentials is not completely understood, although many explanations have been proposed. An exellent survey of the theories are given by Sato and Mooney (1960) in "The electrochemical mechanism of sulphide self potentials", where they relate the SP to natural differences in redox potentials existing in the upper lithosphere. Sato and Mooney do not, however, explain potentials lower than approximately -400 mV in connection with sulphide ores while practical experiences has shown that negative potentials lower than 1000 mV are often encountered in the field. The incomplete knowledge about the nature of the self potentials seems to impede an exhaustive interpretation of SP results. This could be the main reason why SP measurements are not very much used in nowadays mining exploration even though such measurements can be both simple and reliable. More knowledge about the nature of self potentials could be gained through studies of their distribution at known ore deposits. Earlier work of this kind deals mostly with two-dimensional potential distributions at the surface above sulphide ore bodies. In ore prospecting only few reports have been published about measurements of self potentials in drill holes or vertical sections even though the SP drill hole technique is well established in oil exploration (Lynch 1962, Schlumberger 1972).

Recently Parasnis (1970) and Malmquist and Parasnis (1972) have reported interesting results from both surface and drill hole SP measurements. They find that: (1) Both massive and disseminated sulphides may give distinct SP-anomalies; (2) self potentials are stable in time amplitudes of SP variations being within 20 - 30 mV, which would not seriously disturb the much stronger potentials occurring around ore bodies, and (3) SP in drill holes may be as low as -600 mV at a depth of 100 m which Parasnis (1970) considers contradictory to the earlier theory of sulphide oxidation as the main mechanism responsible for sulphide self potentials.

The present paper is a report of the distribution of SP in drill holes and at the surface at the Joma pyrite deposit, Trøndelag Central Norway. Joma was selected for this type of measurements because at the time when the measurements were carried out the deposit (1) was known to produce nice SP-anomalies and (2) was well known through trenching a lot of diamond drill holes and some underground work and (3) was not put into production. Selected SP results from Joma have been published earlier (Bølviken et al. 1973). The investigation seems to corroborate the theory of electrochemical mechanisms as being the origin of self potentials, and indicates that an improved interpretation of SP results may have practical consequences in prospecting.

GENERAL DESCRIPTION

Location and history.

The Joma deposit is situated in North Trøndelag, Norway, near the Swedish border (Fig. 1), 580 m above sea level in a terrain of relatively gentle topography. The maximum height difference within the area of the ore body is about 30 m (Fig. 6). Mean annual temperature is approximately +1°C, average summer temperature is approximately +7°C. The overburden above the deposit is frozen approximately 9 months per year, the frozen ground penetrating 1.5-2 m under the surface.

The ore was found some 70 years ago. From 1910 to 1915 the outcrop of the ore was located by trenching, and some diamond drilling. A second exploration epoch, during the last world war, included different geophysical investigations and diamond drilling. A third epoch which started in 1958 comprised further geophysical prospecting, exploratory underground work and extensive diamond drilling from the surface. These investigations resulted in an evaluation of 17 mill. tons of cuperiferous pyrite ore with 1.3% Cu, 1.7% Zn and 35% S which places Joma among the largest pyrite deposits in Norway.

In 1972 the deposit was opened for mining operation. Planned production is about 250 000 tons of ore per year.

Geology.

The geology of the Joma deposit is described by Foslie (1926), Foslie and Strand (1956) and Oftedahl (1958). During the period 1964 - 68 a detailed geological map was prepared by R. Kvien (personal communication 1972). Fig. 1 is a reproduction of a part of his map. The deposit is situated in a greenstone bed belonging to a series of alternating supracrustal sediments and volcanics. The sedimentary rocks which dip under the greenstone formation consist of phyllitic schists and quartzites with varying content of graphite. The series are strongly folded during the Caledonian orogeny. Different folding phases have been observed, the main fold-axis direction being approximately SW. The deposit lies in a fold where the greenstone bed is thick.

The ore consists of compact pyrite with varying amounts of chalcopyrite and sphalerite, chalcopyrite being abundant in zones both in the hanging- and footwall. Accessory galena occurs locally. In the greenstone of the hanging wall a horizon of disseminated pyrrhotite and pyrite occurs about 50 - 100 m above the massive sulphides.

The ore body is shaped like a saucer gently dipping towards SW in the folding axis direction, being thickest in the central parts (maximum ca. 35 m) and thinning out at the flanks. The country rock and the ore are rich in carbonates, a property which together with the cold climate of the area, prevents any extensive oxidation of the ore.

Overburden and ground water.

The ore body is covered except at the socalled "Elvegang", which is exposed in the river Orvasselv on the eastern side of the deposit. The overburden consists of till partly also of bogs and weathered material. The thickness of the overburden varies from 0.5 m to a few metres, being 0.5 - 1.2 m above the suboutcrop of the ore. The conditions are exellent for surface potential measurements in the summer season. Since the overburden is moist there are small contact resistances at the potential electrodes, and the reproducibility of single measurements was normally within 10 mV.

All diamond drill holes held stagnant ground water, except for one hole (DDH 12 S), which had water flowing out at the top. In holes started on dry ground the water level was found at a depth of 5 - 8 m. The pH of ground water was measured to be 6.0 - 9.5 and the water temperature was 4 - 10°C.

ELECTRIC RESISTIVITY OF GROUND WATER ORE AND COUNTRY ROCKS

Specific resistivity of the drill hole waters measured on samples taken at different depths was as an average 5 000 ohm cm, single values varying between 4 000 and 5 900 ohm cm. This relatively good conductivity yields low contact resistances at the electrode, and the SP measurements in the drill holes were reproducible within 1 - 2 millivolt.

The resistivity of (1) compact ore, (2) sulphide disseminations and (3) country rocks were measured on drill cores, cut by a diamond saw to cylinders with height approximately equal to the diameter (32 mm). The results are indicated in Fig. 2.

The specimens were carefully moistened under pressure to obtain conditions similar to those in situ, before the resistivity was measured by a four point method. In cores with disseminated sulphides the mean angle between pyrrhotite bands and drill core axis was estimated, since the average resistivity would depend on this angle.

Specific gravity of the moist cores was supposed to be a useful parameter indicating content of sulphide minerals. Results of specific gravity measurements are plotted along the ordinate of Fig. 2. For comparison the resistivity (Parasnis 1966) and corresponding specific gravity (Hurlbut 1955) of pure minerals are included in the figure.

The compact pyrite ore has resistivities between 0.25 - 1.5 ohm cm (area A in Fig. 2), central values being 0.75 ohm cm, which agree well with the resistivity of pure pyrite given by Parasnis (op.cit.).

As the Joma ore contains some chalcopyrite, pyrrhotite and sphalerite, the specific gravity of the samples of the ore are lower than that of pure pyrite. The two samples at the left hand side in area A contain pyrrhotite, and those at the right chalcopyrite, sphalerite and some quartz and calcite in addition to pyrite. Chalcopyrite - pyrite ore (F, Fig. 2) is less conducting than the pyrite ore, resistivity being approximately 4 ohm cm, which is in correspondence with the data for pure chalcopyrite given by Parasnis (op.cit.).

The pyrrhorite disseminations from the country rock of the hanging wall cover a larger area of variation (B, Fig. 2) than the compact ore types. The resistivity of the samples of pyrrhotite disseminations is 0.02 - 30 ohm cm, the central value being 0.58 ohm cm. The lower resistivities of the group represent pyrrhotite banding along the core axis.

The greenstone of the hanging wall is represented by the area D in Fig. 2. The resisitivity varies between 10^5 and 10^6 ohm cm, the central values in area D ($3.1 \cdot 10^5$ ohm cm) is supposed to be a fair estimate of the average values in the greenstones surrounding the Joma deposit. The following average resistivity contrasts can be estimated:

ρore/ρ greenstone $\approx$ $\underline{1/430\ 000}$

ρore/ρ drill-hole waters $\approx$ $\underline{1/6700}$

ρgreenstone/ρ drill-hole waters $\approx$ $\underline{60}$

Resistivity of three graphitic phyllites are indicated (area C, Fig. 2), central values being 850 ohm cm. The resistivity of phyllite depends on the content of graphitic material. The graphitefree phyllite (Fig. 2, area E) has the highest resistivity of all rock types investigated, central value being $7.7 \cdot 10^6$ ohm cm. Average resistivity contrast between graphitic phyllite and graphitefree phyllite is 1/9 000.

SP-MEASUREMENTS

SP was measured (1) in diamond drill holes and (2) at the surface. In diamond drill holes the potential differences were recorded at depth intervals of 1 - 10 m between a stationary reference electrode placed at the surface beside the hole and a mobile electrode lowered into the hole. In addition the potential differences between the stationary electrodes of the different drill holes were measured to obtain a common reference for all SP measurements. Altogether SP were measured in 14 holes distributed over the central parts of the deposit. The hole lengths varied between 30 and 360 m. The last drilling operations were finished 3 years before the SP measurements. At the surface the potential differences were recorded every 50 m along 5 selected profiles, in areas of high potential gradients also at intermediate stations along the profiles. The potential of the background field at some distance from the deposit was chosen as a common reference (zero).

The electrodes used consisted of Cu-wire immersed in a saturated solution of $CuSO_4$, separated from the exterior by a wooden plug. The instrument was a potentiometer with 1 M ohm input resistance.

Drill-hole self potentials

SP results of (1) four typical drill holes through ore (3 V, 49, 10 M and 5 N) and (2) one hole through the country rock at about 200 m distance from the ore (1A) are shown in Fig. 3. Results from eight holes projected into section AA are presented in Fig. 4 (see Figs. 9 and 11 for location of profile and ore respectively). Two potential patterns can be distinguished:

(1) An abruptly alternating potential with several minima of varying magnitude.

(2) A general potential trend that seems to constitute some sort of a basis for the abrupt potential variations.

It is possible to separate these two patterns visually by drawing a continuous line through the most positive values of the SP curves as shown in Fig. 3 and Fig. 7.

The steep potential gradients occur at the boundaries of (1) the compact ore and (2) the sulphide disseminations, their SP minima within the mineralization being of the order 400 - 800 mV and 100 - 300 mV respectively regardless of depth (Figs. 3 and 4). The - 400 mV contour follows the boundary of the massive ore closely (Figs. 4 and 11).

The general potential trend, which was reproduced by repeated measurements the next year, is of the order 0 - 50 mV within drill holes and maximum 200 mV along the ore. The sign depends on the position relative to the ore body; in the holes 3 V and 49, which intersect the deeper part of the ore body (Fig. 3), the potentials of the general trend increase with increasing depth, and in the holes 10 M and 5 N, which intersect the upper half of the ore body, the SP potentials decrease with increasing depth. In the "background" hole 1 A, which is drilled through the footwall rocks, the general potential trend is nearly constant through the greenstone in the upper part of the hole, and decreases with increasing depth through the graphitic phyllites in the lower part.

Surface self potentials.

The potential distribution at the earth surface over the central part of the ore is shown in Fig. 5, and that of a profile BB which crosses the greatest thicknesses of the deposit in Fig. 6. The SP-variations along this profile, which should be quite representative for the potential distribution along a geometric symmetry plane of the deposit, is described below. When one approaches the deposit from a reference point on the footwall side, the SP decreases gradually about 100 mV. At Elvegangen which crops out in the river, the potential suddenly drops (the minimum value could not be measured in the profile due to high water level in the stream). Between Elvegangen and the main ore outcrop the potentials again raise to approximately - 100 mV, followed by an abrupt drop to a minimum of - 800 mV above the subcrop of the ore. On the hanging wall side the potential increases to ca. 150 mV above the deeper parts of the body some 200 m from the outcrop. Then a decrease follows until the potential reaches an approximately normal value about 500 m from the outcrop.

On both sides of the strong anomaly caused by the main ore, there are local minima, of which those in the hanging wall rocks, being approximately - 300 m V, are supposed to be caused by pyrrhotite disseminations.

As in the drill holes there seem to be two potential distribution patterns, which can be separated graphically: (1) An abruptly alternating potential occurring in close connection with the sulphide mineralizations and (2) a more smooth general potential trend, in some way connected with currents in the country rock. The positive maximum belong to this trend.

INTERPRETATION OF SP RESULTS

The two types of potential distribution patterns distinguished in the preceeding section are interpreted in the following way:

(1) The abruptly alternating pattern is a concequence of the precense of electromotive forces at the interfaces of country rock and sulphides, and indicates indirectly that electronic currents pass within the sulphides.

(2) The general trend pattern indicates that ionic currents pass through the pore water of the silicious country rock outside the ore body.

In the following these two types of potentials are called "electronic current potential" and "ionic current potential", respectively. As indicated above (Fig. 3) it is in most cases easy to separate the two potential patterns in drill holes by a simple graphical estimation as illustrated in Fig. 7. This procedure can also be used for surface data, see Fig. 6.

Electronic current potential.

The potential distribution within the ore was measured relative to the point of lowest potential found in the ore (hole 10 M, in the central part of the deposit).

Fig. 8 shows a horizontal projection of the distribution of the minimum potentials recorded in each drill hole within the deposit. From both flanks of the ore body the minimum potentials decrease towards the central part, where a low potential channel passes along the ore between the upper and lower ends, indicating the thickest, best conducting parts of the ore body where the electric currents are concentrated.

Fig. 9 shows the distribution of SP within the ore in a vertical section along the low potential channel. The equi-potential lines follow the boundaries of the ore body very closely, except at a few zones of low conductivity within the body. The maximum potential drop along the path of strongest current density in this section is found to be of the order of 20 mV, the lowest potential being at depth and the highest near the surface. The real minimum potential drop along the path may possibly be even smaller, since it is difficult to find the exact best position of the electrodes. This potential drop shows that currents must be running downwards through the ore. The resistivity of the compact ore is approximately 0.75 ohm cm (Fig. 2). Using this value, the maximum current density through the ore is calculated to approximately 5 milliamperes pr m^2. At depth the position of the maximum current density path seems to pass NW of the drill holes 49 and 3 V indicating an interesting possibility for finding depth extensions of the thicker parts of the ore body.

The electric currents within the ore deposit must be distributed according to the laws of Kirchhoff. Pyrite, is the best conductor (see page 5), of the main ore minerals. A close connection between SP and pyrite content of the ore should therefore be expected. In Fig. 10 SP is compared with sulphide content of drill cores, which is a good indication of the pyrite content of this type of ore. It is seen that high S^{2-} generally corresponds to low SP readings. Occasional exception from this rule may apparently be due to the fact that S^{2-} is given an average per metre drill core, while SP is recorded more continously.

Any possible effects from Cu and Zn minerals seem to be overshadowed by the effect of the pyrite.

Ionic current potential.

The distribution pattern of ionic potentials (Fig. 11) can be more easily interpreted than the pattern of the original data (Fig. 4) from which they are estimated. The pattern of ionic current potentials is similar to that caused by a dipole with some modifications which are probably due to the irregular shape of the ore body. The two negative centers which occur at the surface are very likely caused by the two sulphide bodies, the main ore and Elvegangen respectively.
The highest potential observed in the profile in Fig. 11 is about 120 mV, indicating a positive centre situated near the lower end of the ore body. This is in agreement with the results given in Fig. 6 where it is seen that the drill holes 5N, 4M, 10 M and 11 M lie on the NW side of the potential maximum. The position of the centre in relation to the ore cannot be determined exactly due to lack of drill holes, and a maximum exceeding 120 mV migh exist nearer to a possible thicker part of the lower end of the ore somewhere outside section AA. The ionic currents above the ore body can be visualized by the average vertical current density, J_v, along drill hole given by:

$$J_v = \frac{1}{\rho} \cdot \frac{\Delta V}{\Delta z}$$

where ρ is the resistivity of the surrounding country rock and $\frac{\Delta V}{\Delta z}$ is the average vertical ionic potential gradient between the earth surface and the hanging-wall boundary of the ore estimated from SP-logs. The resulting vertical current densities are given in table 1, using $3.1 \cdot 10^5$ ohm cm as resistivity of the country rock.

The horizontal projection of the distribution of the vertical ionic current density, which is shown in Fig. 12, agrees well with the picture in section AA in Fig. 11. The direction of the current is mainly upwards above the ore at depth (around the holes 3 V and 49), downwards above the central parts of the ore body, and upwards above the upper parts of the body.

From the data in Fig. 11 the average horizontal current densities J_h above the ore body have been estimated by computing the potential gradient between drill holes, and multiplying with the average conductivity ρ. The total current densities are estimated as the vector sum of J_v and J_h, see table 2, which shows the ionic current densities vary between 0.1 and 0.3 microampere per m^2 in the country rock above the ore body.

It should be remembered that the vertical current densities calculated above presuppose the same potential in the pore water of the bedrock as in the drill hole water. This will not necessarily be the case since the water filled drill-hole is a much better electric conductor than the country rock (see page 6). The calculated vertical current densities for country rock, therefore, most probably are too low. The calculated horizontal current densities, however, would possibly be closer to the true values.

SP MODEL

Based on the described distribution of SP at Joma a simplified schematic model is shown in Fig. 14. If one approaches the ore from a reference point A the self potential decreases evenly until a point B near the upper end of the ore. At the country rock/ore interface the potential drops abruptly at point C from where it decreases slowly with depth inside the ore. At the ore/country-rock interface between D and E the potential increases suddenly, and from E on through F to A the SP decreases regularily back to the reference zero potential.

The potential pattern seems to fit well into the model of a galvanic cell in which the pore water of the country rock constitutes the electrolyte and the massive ore the electrode, the upper end being the cathode and the lower end being the anode. The electrolyte varies in composition between cathode and anode having higher oxidation potential around the shallower part than around the deep part. The electromotive force of the cell is situated at the interface between ore and country rock, its theoretical magnitude being the Eh difference of the pore water in the country rock at the upper end and that at the lower end. A current will run through the cell driven by a voltage which is equal to the EMF minus potential drops caused by polarization and ohmic resistance of electrolyte and electrode. In the ore body, which represents the outer conductor of the cell, electrones will flow from anode to cathode, i.e. upwards. In the country rock which represents the inner electrolyte of the cell, cations will move upwards and anions downwards, the cations (mainly H^+) being discharged at the surface of the upper end of ore, producing H_2, and the anions (mainly OH^-) being discharged at the lower end of the ore producing O_2 and H_2O. The H_2 produced at the upper end will most probably react with oxidizing species of the atmosphere or waters, and might for example, reduce O_2 to H_2O. The O_2 produced at depth will analogously react with reducing species, and, for example, oxidize Fe^{2+}.

This model is consistent with the mechanism proposed by Sato and Mooney (op. cit.), as far as the distribution of self potentials in the silicious country rock surrounding the ore body is concerned. We have called these potentials ionic current potentials; in the case of Joma they show a maximum variation of approximately 200 mV, which is well within the theoretical maximum limit (400 mV) estimated by Sato and Mooney (op. cit.).
As refered by Sato and Mooney, SP of the order of minus 1 - 1.5 V are frequently found in connection with graphite or sulphides.
This is in agreement with our experiences from Norway. We believe that self potentials of this order can be demonstrated only when one of the electrodes is located in the country rock and the other is in direct electric contact with a sulphide body or other good conducting mineralization. At Joma potential minima of the order of - 800 mV were found under such conditions. These high potential differences should not be confused with the more smooth ionic current potentials within the country rock. Because of the electromotive force

postulated at the sulphide/country rock interface the Laplace continuity equation can not be applied across the ore boundaries. The potentials within and outside sulphide bodies must consequently be treated separately. The potentials within sulphides need some explanation in addition to the theory proposed by Sato and Mooney, a matter which will be dealt with in a forthcoming publication. (Bølviken and Logn, in preparation.)

PRACTICAL CONSEQUENCES

The self potential method has a particular position among the electric ore-prospecting methods, since the energy supply might be interpreted as a dipole with two current electrodes. When regarding the potentials of the country rock <u>outside</u> the ore body the negative pole will be positioned in the upper end and the positive in the lower end of the ore body. When regarding the potentials <u>within</u> the ore body, the positive pole will be positioned at the interface of the country rock and the upper end of the ore body and the negative analogously at the lower end. We do not know of any other geo-electrical method where such a position of current electrodes are possible without knowing the position of the lower and upper end of the ore in beforehand.
With this natural electrode configuration measurements of self potentials in the <u>country rock</u> outside the ore may produce

(1) potential distribution patterns at the earth surface which may be easily interpreted.

(2) potential distribution patterns in drill holes which may give information about extension towards the depth of an ore body, in particular assist in location of the lower positive pole, and provide data for an estimation of volume or tonnage of the lower part of an ore body if the upper part is known through diamond drilling.

The distribution of self potential within the ore body may be used as a corrective guide in a drilling programme by

(1) indicating the direction of the thickest compact part connecting the upper and the lower part of an ore body.

(2) being an alternative to chemical analyses of drill cores or drill cuts.

Beside having these possible practical consequences in geophysics, the concept of sulphide ore and country rock pore water forming a galvanic concentration cell, may also have important implications in geochemical exploration as recently pointed out by Govett (1973). It is not unlikely that the concept might lead to a better understanding of the principles - in particular the electrochemical mechanisms - behind the dispersion of chemical elements around ore deposits.

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REFERENCES

Bølviken, B. and Logn, Ø. A contribution to the understanding of natural self potentials. *In preparation.*

Bølviken, B., Logn, Ø., Breen, A. and Uddu, O., 1973. Instrument for *in situ* measurements of Eh, pH and self potentials in diamond drill holes. In M. J. Jones (Editor) *Geochemical exploration 1972. Proceedings of the fourth International Geochemical Exploration Symposium. London 1972.* Inst. Mining. Metal., pp. 415 - 420.

Foslie, S., 1926. Norges svovelkisforekomster. (in Norwegian with an English abstract). *Norges geol. Unders.*, 127: 1 - 122.

Foslie, S. and Strand, T., 1956. Namsvatnet med endel av Frøyningsfjell. (in Norwegian with an English abstract). *Norges geol. Unders.*, 196: 1 - 82.

Fox, R. W., 1830. On the electromagnetic properties of metalliferous vein in the mines of Cornwall. *Phil. Trans. R. Soc.* 120: 399 - 414.

Govett, G. J. S., 1973. Differential secondary dispersion in transported soils and post-mineralization rocks: an electrochemical interpretation. In: M. J. Jones (Editor) *Geochemical exploration 1972. Proceedings of the fourth International Geochemical Exploration Symposium. London 1972.* Inst. Mining. Metal., pp. 81 - 91.

Hurlbut, C. S. jr., 1955. Dana's Manual of Mineralogy. John Willey, New York, 529 pp.

Lynch, E. J., 1962. *Formation Evaluation.* Harper & Row. New York, 422.

Malmqvist, D. and Parasnis, D. S.. 1972. Aitik: Geophysical documentation of a thirdgeneration copper deposit in North Sweden. *Geoexploration.* 10: 149 - 200.

Oftedahl, C., 1958. Oversikt over Grongfeltets skjerp og malmforekomster. (in Norwegian with an English abstract). *Norges geol. Unders.*, 202: 1 - 75.

Parasnis, D.S., 1966. *Mining Geophysics.* Elsevier, Amsterdam, 356 pp.

Parasnis, D.S., 1970. Some recent geoelectrical measurements in the Swedish sulphide ore fields illustrating scope and limitations of the methods concerned. *Min. Groundwater Geophys./1967 (Ottawa)*, pp. 290 - 301.

Sato, M. and Mooney, H.M., 1960. The electrochemical mechanism of sulfide self potentials. *Geophysics.* 25: 226 - 249.

Schlumberger, 1972. *Log Interpretation. Volume I - Principles.* Schlumberger Limited, New York, 113 pp.

Schlumberger, C. and Schlumberger, M., 1922. Phénomènes électriques produits par les gisements métalliques. *Comptes Rendus.* 174: 477 - 480.

Svinndal, S., 1968. Diamant-boring med hullavviksmåling og geologisk bearbeidelse av kjernematerialet ved Joma-malmen/Røyrvik. *Unpubl. Rep. Norges geol. Unders.* 665. 9 pp.

Table 1 Average vertical current density J_v in the hanging wall country rock (greenstone), Joma pyrite deposit, central Norway. Resistivity of greenstone $3.1 \cdot 10^5$ ohm cm. Positive current is upwards.

Drill hole	J_v ($\mu A/m^2$)	Drill hole	J_v ($\mu A/m^2$)
3 V	+ 0.033	4 M	- 0.233
16 M	+ 0.065	5 N	- 0.151
16 M	- 0.133	119	- 0.366
10 M	- 0.018	117	+ 0.667
11 M	- 0.083	116	+ 0.306
12 S	- 0.167	2 H	+ 0.234
33 N	- 0.0394	1 A	- 0.024

Table 2 Average horizontal, J_h and total, J_t current density between drill holes through the hanging wall country rock (greenstone), Joma pyrite deposit, central Norway. J_v is taken from table 1. Resistivity of greenstone = $3.1 \cdot 10^5$ ohm cm.

Drill holes	depth (m)	J_v ($\mu A/m^2$)	J_h ($\mu A/m^2$)	J_t ($\mu A/m^2$)
3 V - 49	120	+ 0.049	0.104	0.114
49 - 10 M	90	+ 0.024	0.094	0.097
10 M - 11 M	70	- 0.051	0.214	0.220
11 M - 4 M	60	- 0.158	0	0.158
4 M - 5 N	55	- 0.192	0.095	0.214
5 N - 116	40	+ 0.078	0.278	0.298

FIGURES

Fig. 1. Geological map of the area surrounding the Joma pyrite deposit, central Norway. After R. Kvien (personal communication 1972).

Fig. 2. Resistivity of pure minerals (Parasnis 1966) and massive sulphide ore, sulphide disseminations and country rock of drill core samples from Joma pyrite deposit central Norway.

Abscissae: Resistivity, Ordinate: Specific gravity.

M: Magnetite: Py: Pyrite; Po: Pyrrhotite; Cpy: Chalcopyrite.

A: Massive sulphide ore
B: Sulphide disseminations
C: Graphitic phyllite
D: Greenstone
E: Phyllite
F: Chalcopyrite - pyrite ore

Fig. 3. Self potentials and geological observations in diamond drill holes 3 V, 49, 10 M and 1 A at Joma pyrite deposit central Norway. SP variations are separated graphically into two parts (1) an abruptly alternating potential (black) and (2) a general potential trend (bottom inclined line) see Fig. 7.

Fig. 4. Self potential in drill holes projected into section AA Joma pyrite deposit, central Norway. Location of section AA is shown in Fig. 5.

Fig. 5. Surface distribution of self potentials at Joma pyrite deposit, central Norway. Potentials are measured along the indicated profiles.

Fig. 6. Self potentials along profile B-B, Joma pyrite deposit, central Norway. Location of profile is shown in Fig. 5. SP variations are separated graphically into two parts (1) an abruptly alternating potential (black) and (2) a general potential trend (bottom line), see Fig. 7.

Fig. 7. Graphical separation of self potential log into ionic current potentials of country rock and electronic current potentials of sulphides.

Fig. 8. Horizontal projection of distribution of minimum self potentials within the ore body, Joma pyrite deposit, central Norway.

Fig. 9. Distribution of self potentials within massive sulphides at Joma pyrite deposit, central Norway (lower half). The position of the ore is indicated in the upper half of the figure.

Fig. 10. Correspondence between self potentials and percentages of S and Cu + Zn in diamond drill holes 117 and 119 crossing the ore body, Joma pyrite deposit, central Norway. Geological and chemical data after Svinndal (1968).

Fig. 11. Distribution of ionic current potentials in drill holes estimated from data in Fig. 4 projected into section AA, Joma pyrite deposit, central Norway. For location of section AA' see Fig. 5. Principle for separation of self potentials into ionic and electronic current potential is shown in Fig. 7.

Fig. 12. Horizontal projection of vertical ionic current potential in the country rock, Joma pyrite deposit, central Norway. Unit on contours: $10^{-2} \mu A/m^2$.

Fig. 13. Simplified SP model based on the distribution of self potentials in vertical sections through country rock and ore, Joma pyrite deposit, central Norway.

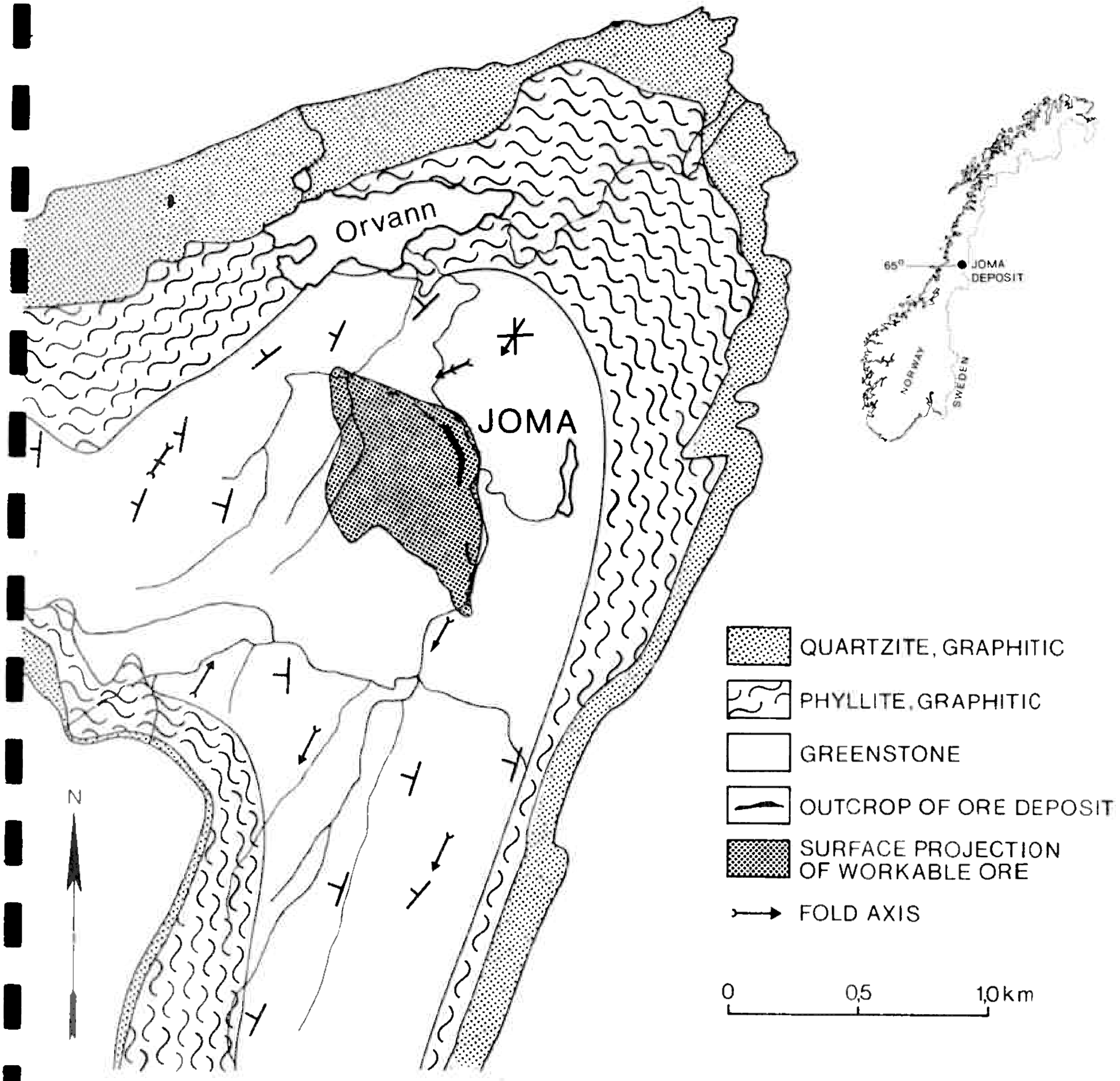

Orvann
JOMA
65°
JOMA DEPOSIT
NORWAY
SWEDEN
N
QUARTZITE, GRAPHITIC
PHYLLITE, GRAPHITIC
GREENSTONE
OUTCROP OF ORE DEPOSIT
SURFACE PROJECTION OF WORKABLE ORE
FOLD AXIS
0
0,5
1,0 km

FIG. 1

FIG.2

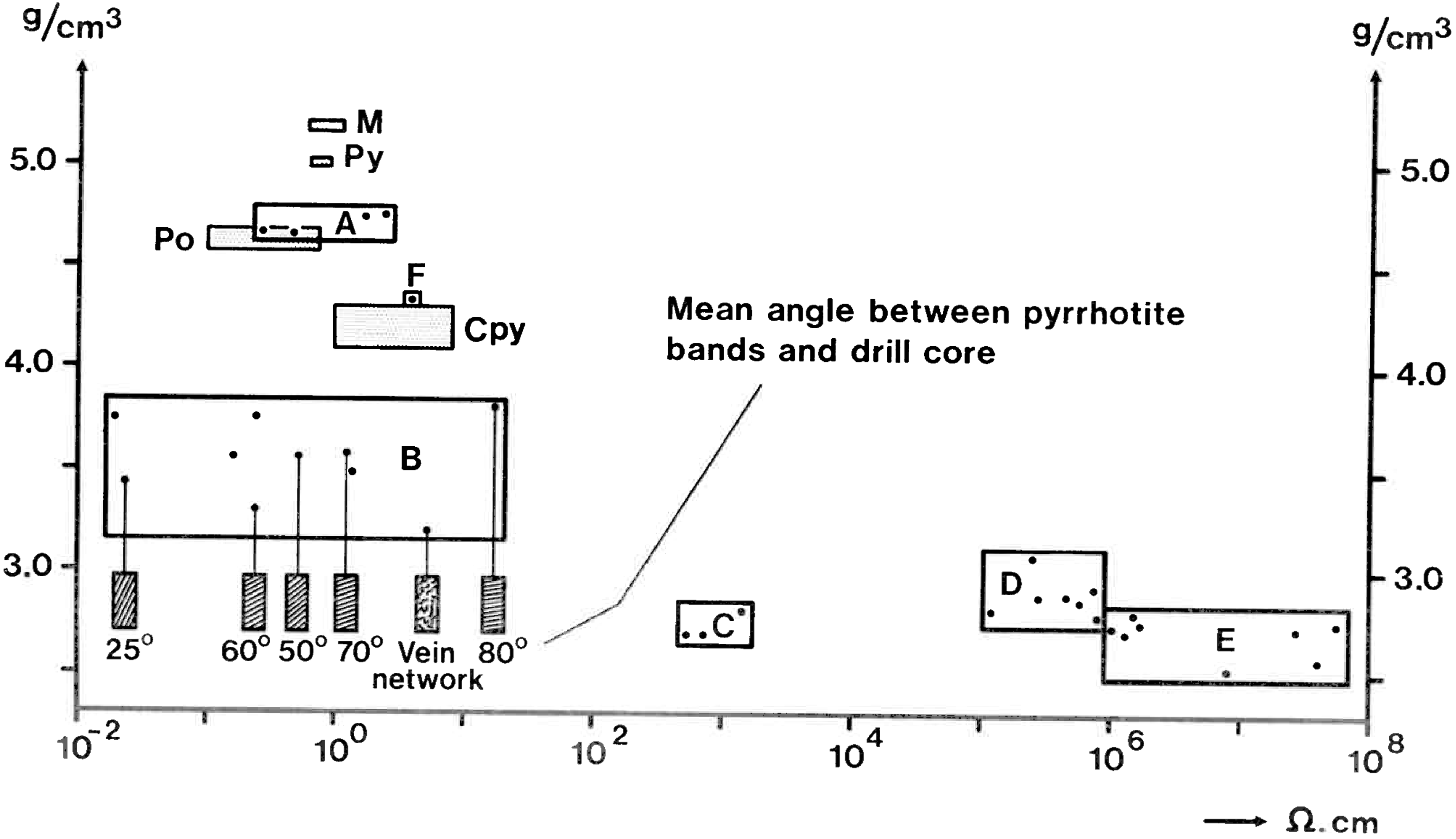
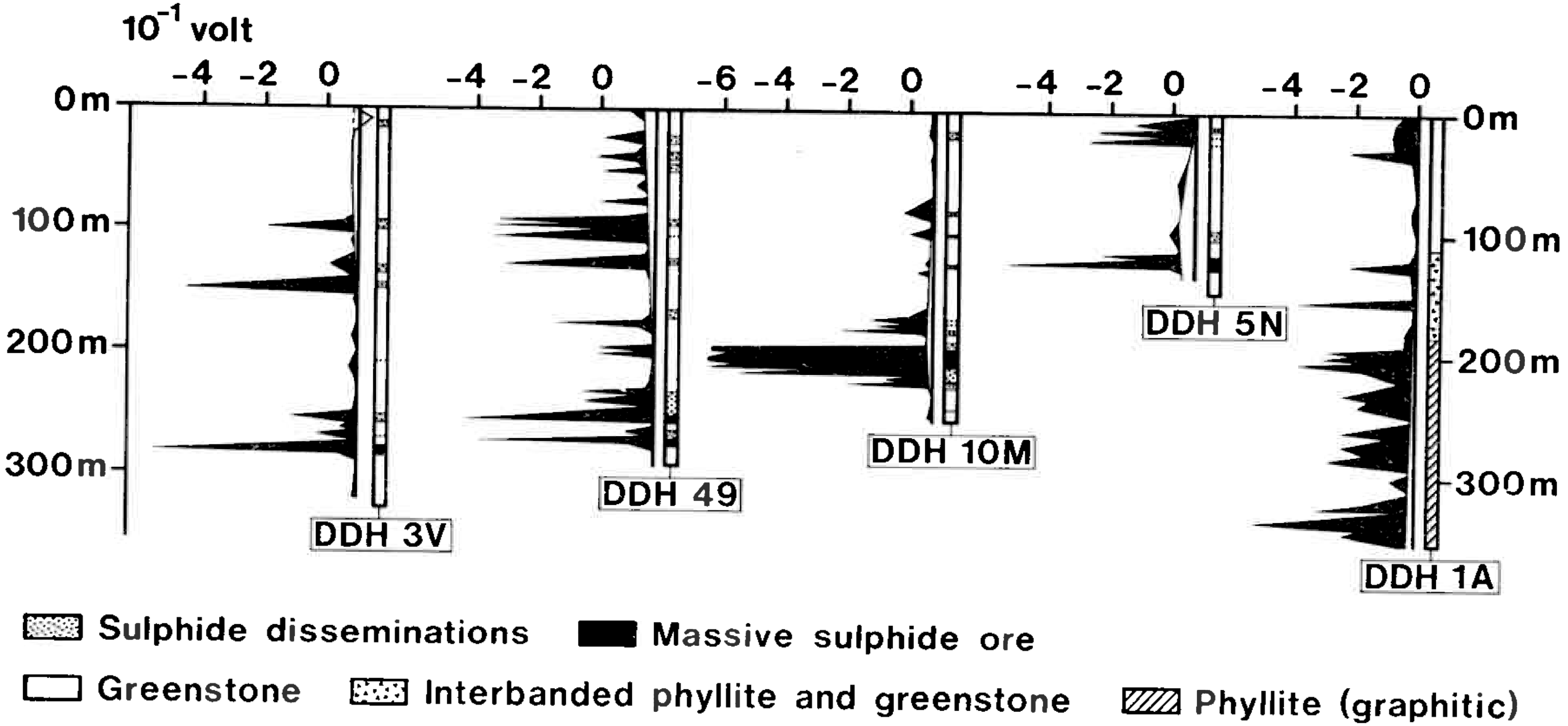

g/cm3
g/cm3
5.0
4.0
3.0
M
Py
Po
A
F
Cpy
B
C
D
E
25°
60°
50°
70°
Vein network
80°
Mean angle between pyrrhotite bands and drill core
10-2
10^0
10^2
10^4
10^6
10^8
Ω.cm

FIG.3


10^-1 volt
-4
-2
0
-4
-2
0
-6
-4
-2
0
-4
-2
0
-4
-2
0
0m
100m
200m
300m
0m
100m
200m
300m
DDH 3V
DDH 49
DDH 10M
DDH 5N
DDH 1A
Sulphide disseminations
Massive sulphide ore
Greenstone
Interbanded phyllite and greenstone
Phyllite (graphitic)

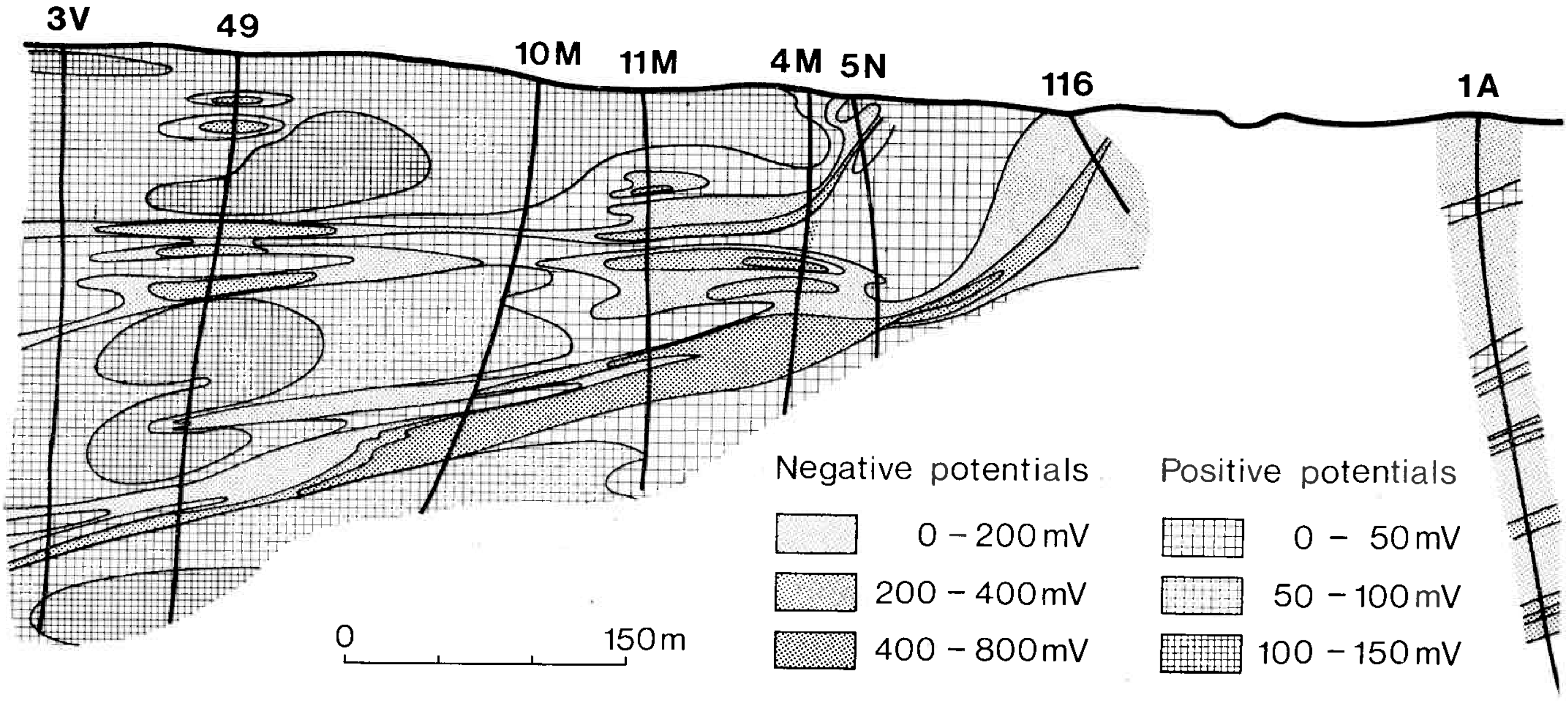

3V
49
10M
11M
4M
5N
116
1A
Negative potentials
0 – 200 mV
200 – 400 mV
400 – 800 mV
Positive potentials
0 – 50 mV
50 – 100 mV
100 – 150 mV
0
150 m

FIG.4

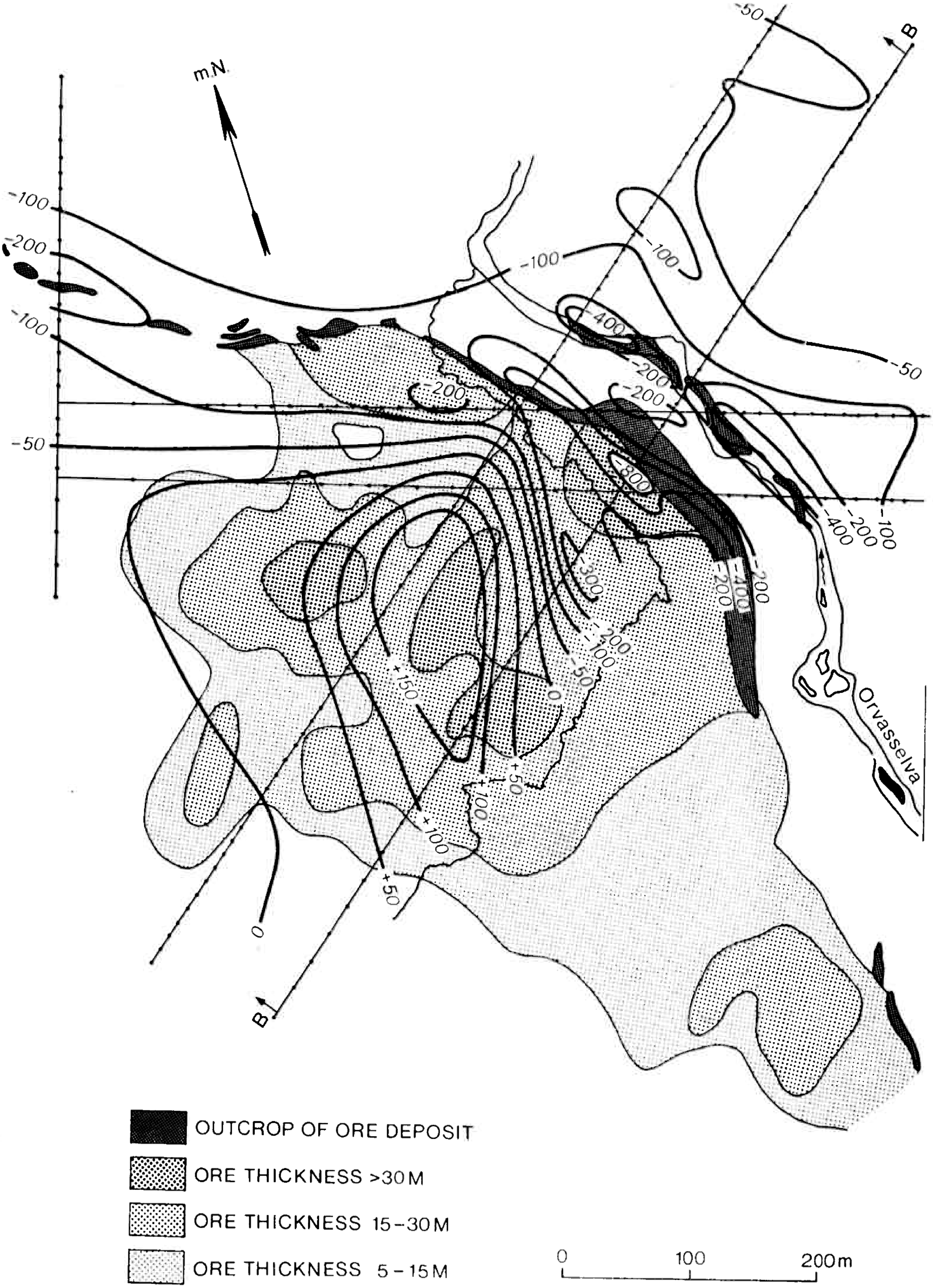
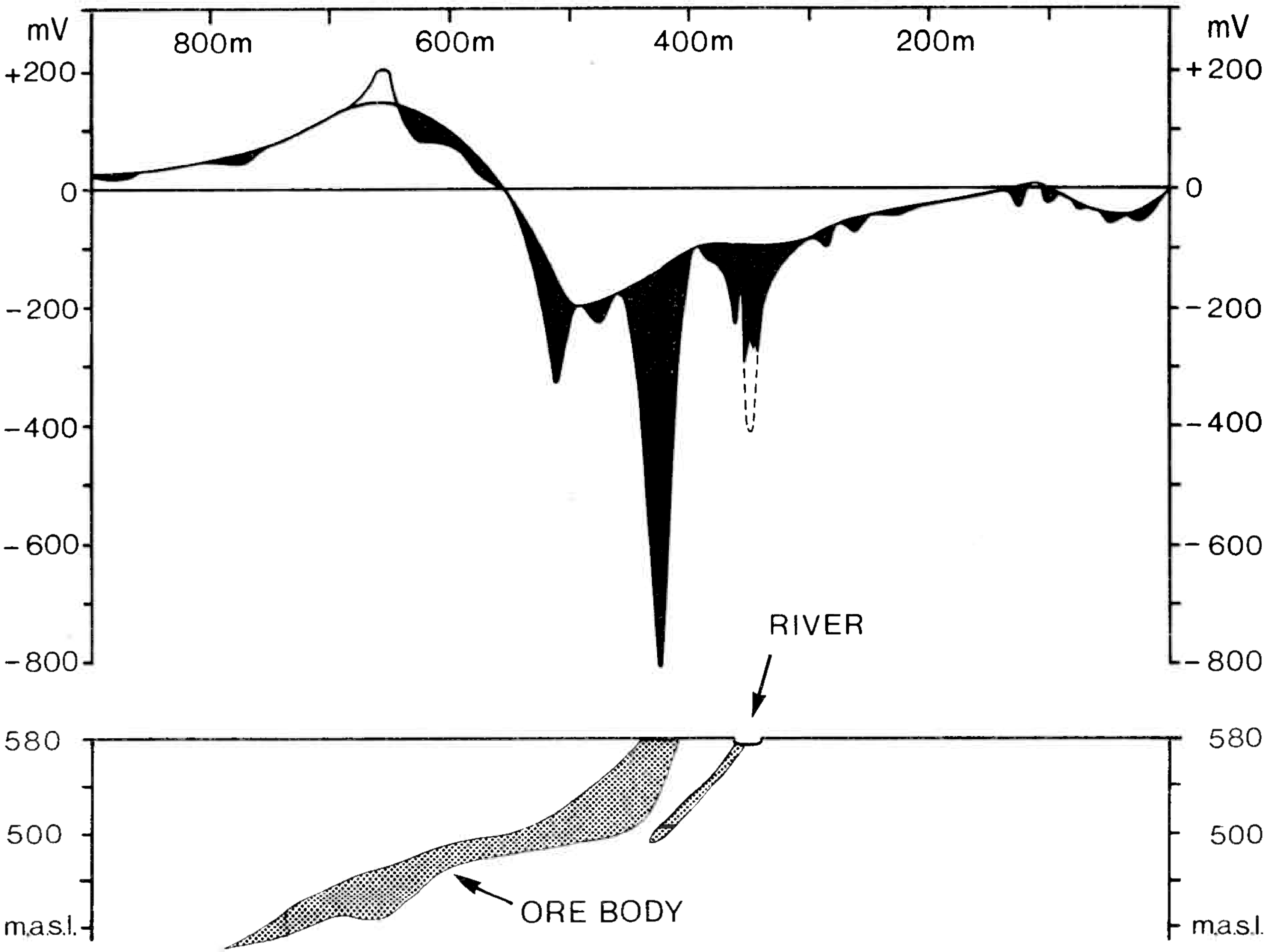

m.N.
-50
B
-100
-200
-100
-100
-50
-100
-400
-200
-200
-200
-800
-50
-400
-200
-100
-300
-200
-400
-200
-200
-100
-50
0
+150
+50
100
+100
+50
0
Orvasselva
B
OUTCROP OF ORE DEPOSIT
ORE THICKNESS >30M
ORE THICKNESS 15-30M
ORE THICKNESS 5-15M
0
100
200m

FIG. 5

FIG. 6


mV
800m
600m
400m
200m
mV
+200
0
-200
-400
-600
-800
+200
0
-200
-400
600
-800
RIVER
580
500
m.a.s.l.
580
500
m.a.s.l.
ORE BODY

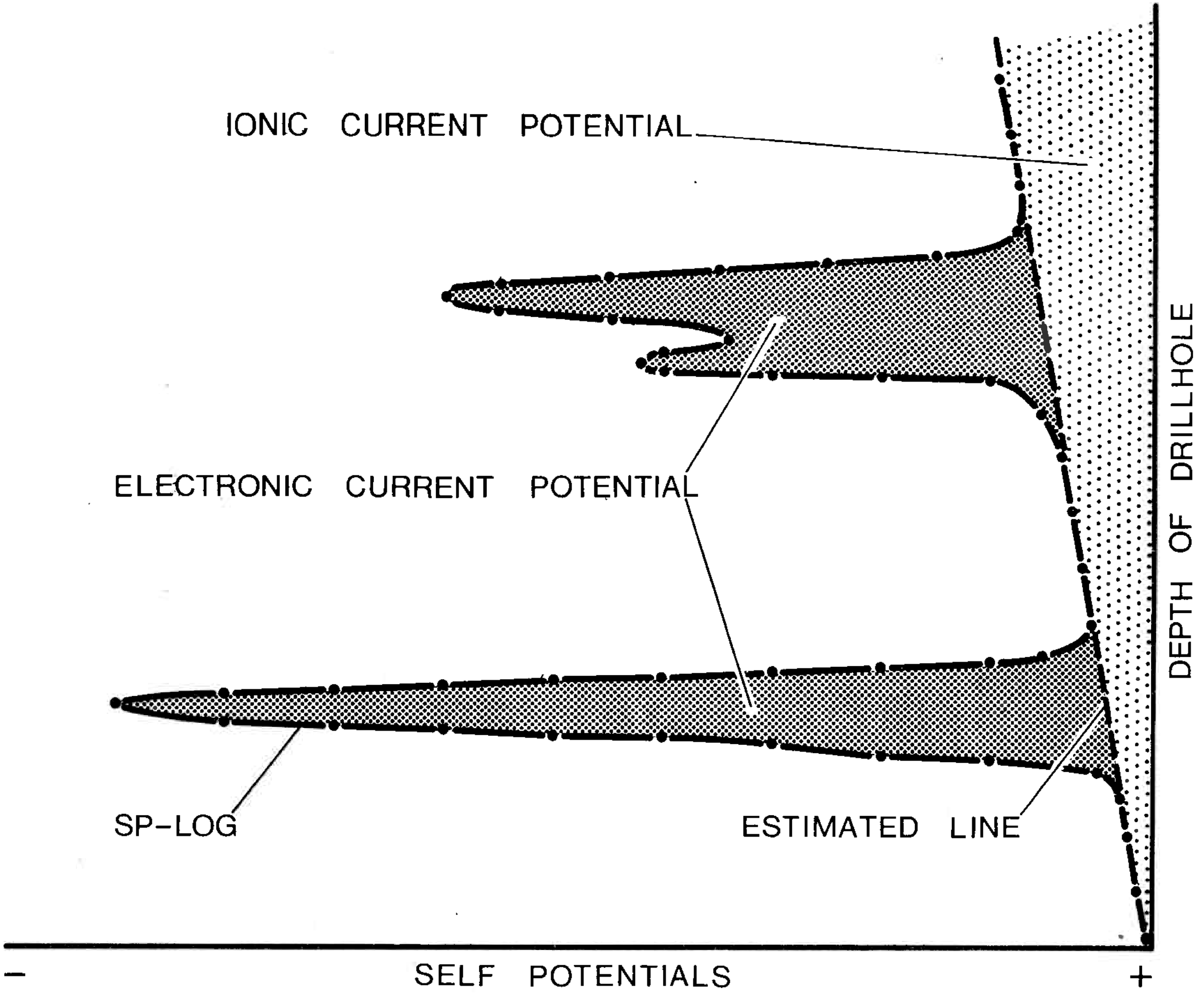

IONIC CURRENT POTENTIAL
ELECTRONIC CURRENT POTENTIAL
SP-LOG
ESTIMATED LINE
DEPTH OF DRILLHOLE
−
SELF POTENTIALS
+

FIG. 7

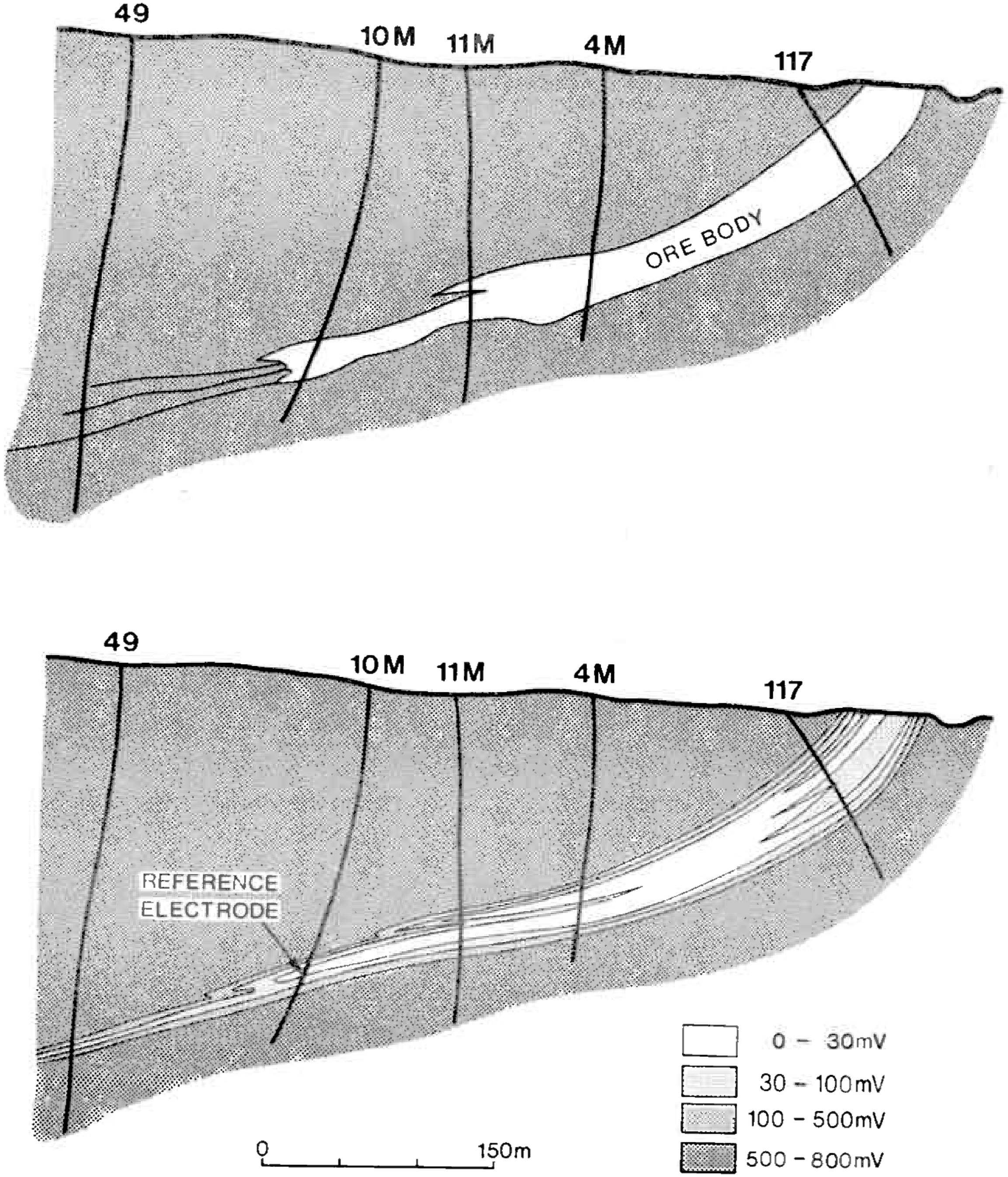

49
10M
11M
4M
117
ORE BODY
49
10M
11M
4M
117
REFERENCE ELECTRODE
0
150m
0 - 30mV
30 - 100mV
100 - 500mV
500 - 800mV

FIG.8

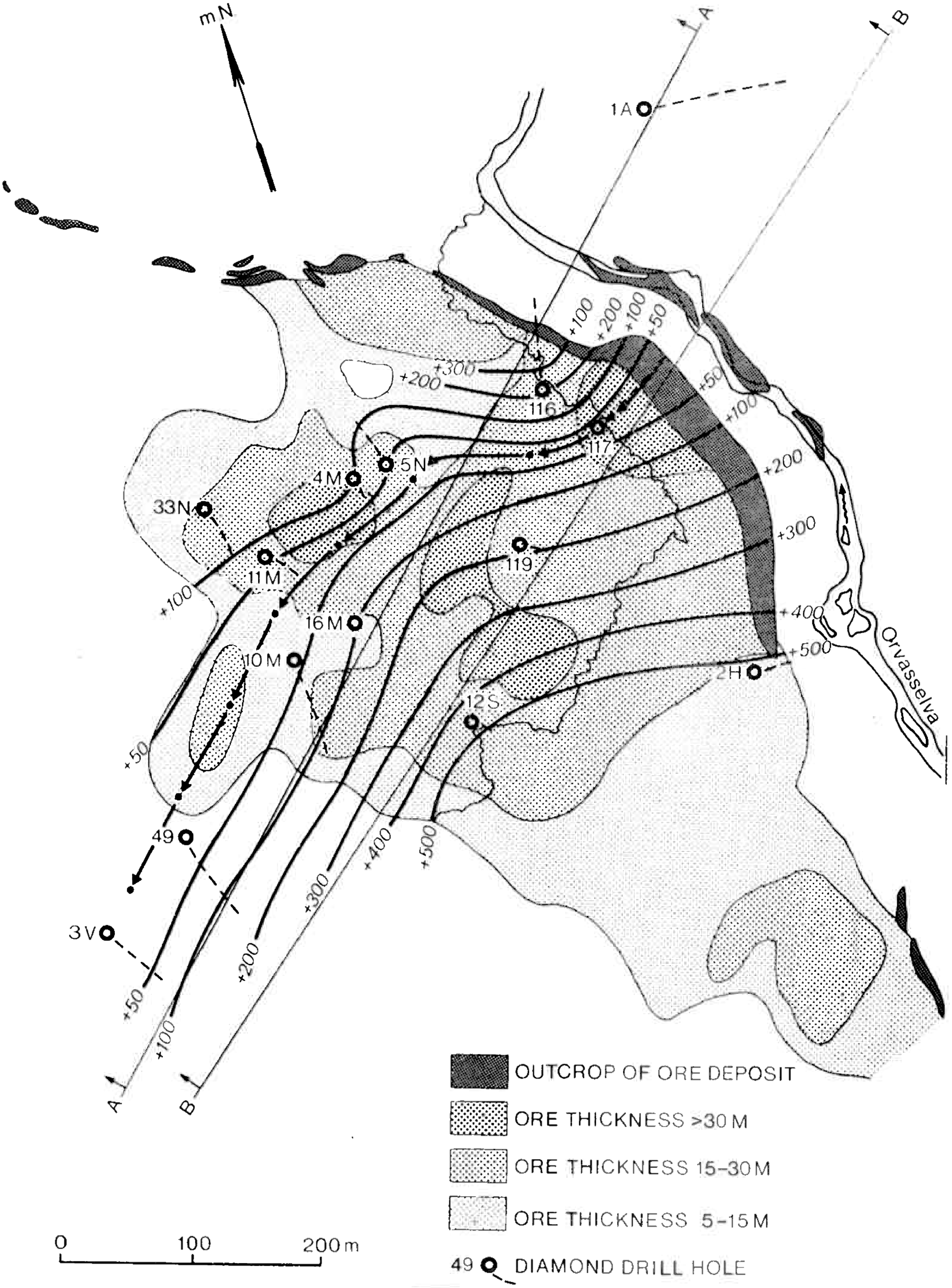

mN
A
B
1A
116
117
5N
4M
33N
11M
16M
10M
119
12S
2H
49
3V
+300
+200
+100
+200
+100
+50
+50
+100
+200
+300
+400
+500
+100
+50
+50
+100
+200
+300
+400
+500
Orvasselva
OUTCROP OF ORE DEPOSIT
ORE THICKNESS >30 M
ORE THICKNESS 15-30 M
ORE THICKNESS 5-15 M
49 DIAMOND DRILL HOLE
0
100
200 m

FIG.9

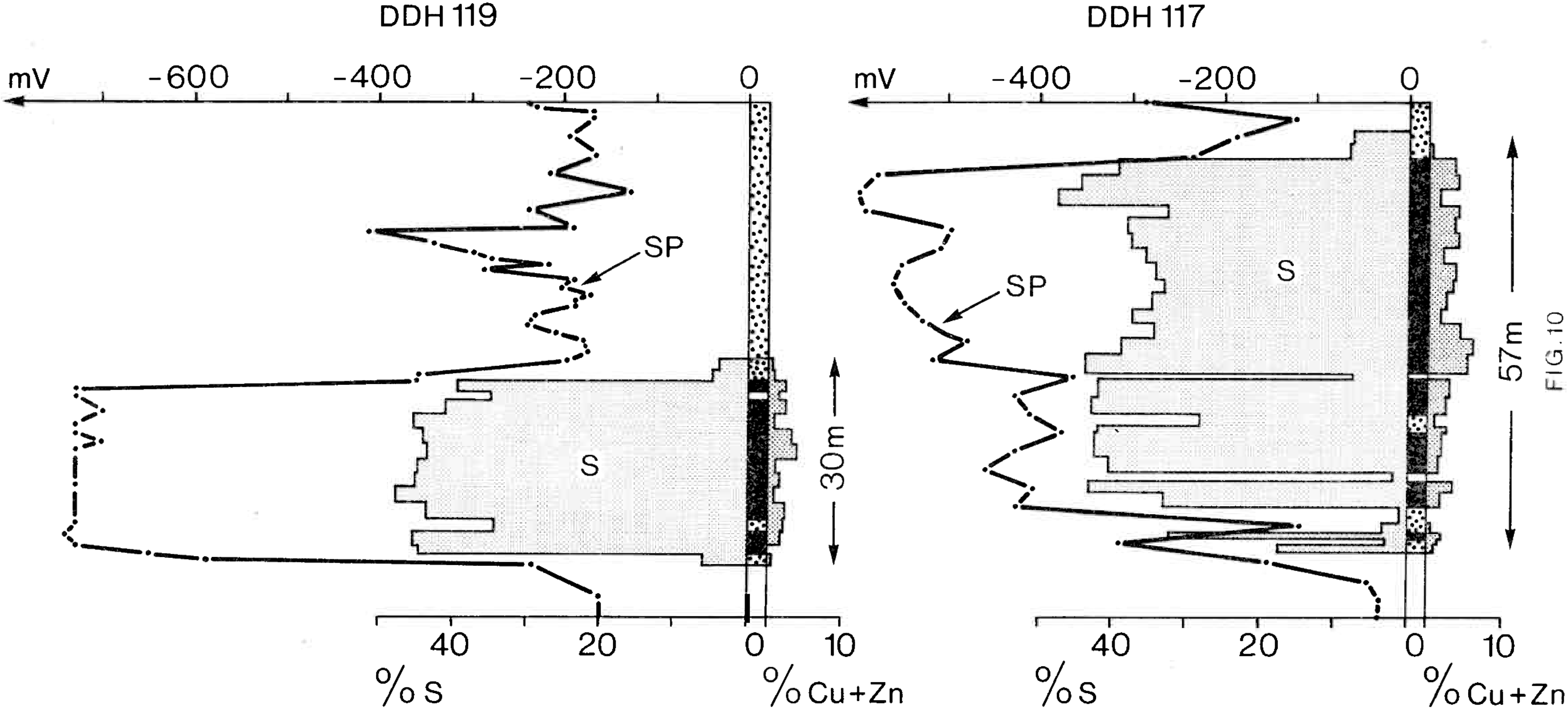
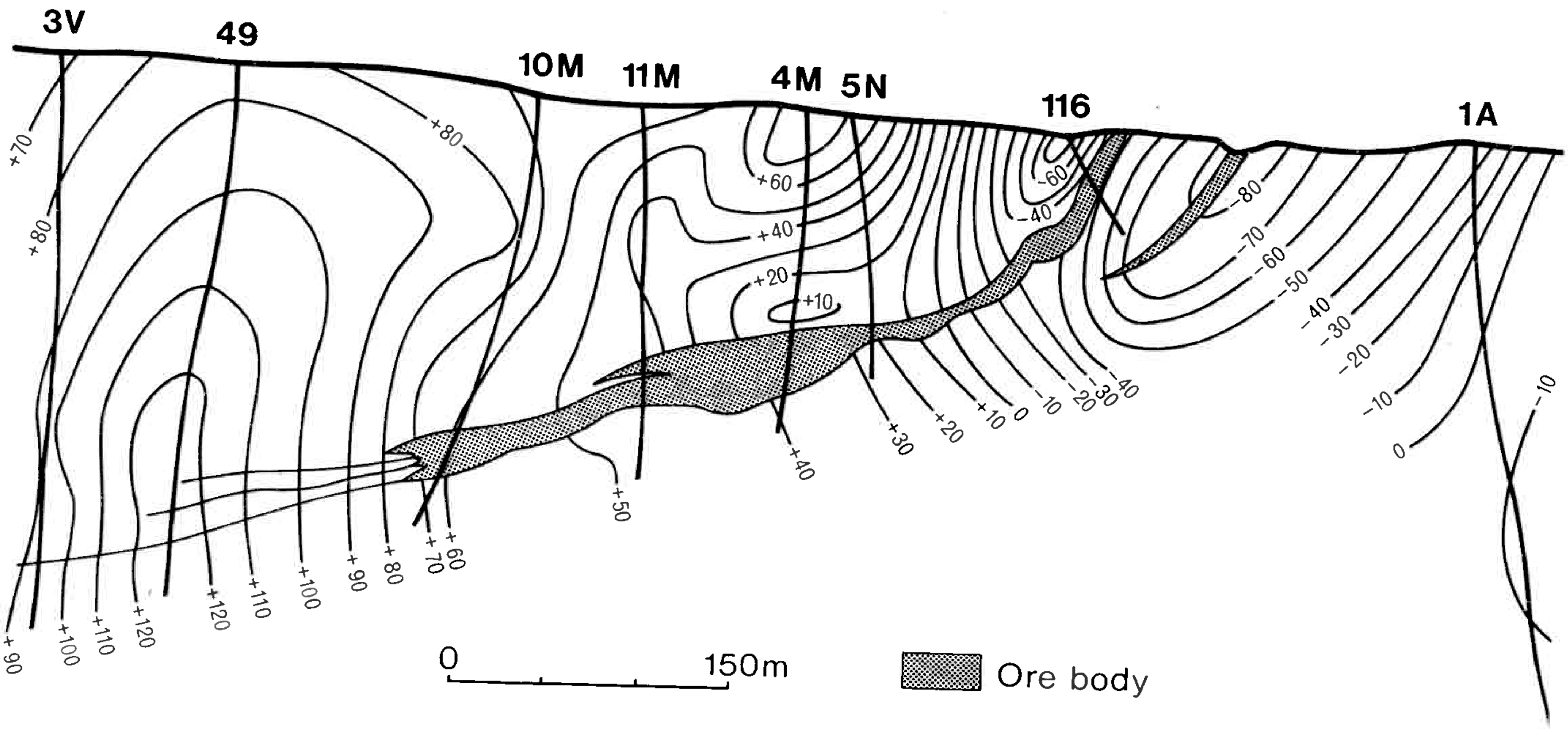
DDH 119
mV
-600
-400
-200
0
SP
S
30m
40
20
0
10
% S
% Cu+Zn
DDH 117
mV
-400
-200
0
SP
S
57m
40
20
0
10
% S
% Cu+Zn

FIG. 10

FIG.11


3V
49
10M
11M
4M
5N
116
1A
+70
+80
+80
+60
+40
+20
+10
-60
-40
-80
-70
-60
-50
-40
-30
-20
-10
0
-10
+90
+100
+110
+120
+120
+110
+100
+90
+80
+70
+60
+50
+40
+30
+20
+10
0
-10
-20
-30
-40
0
150m
Ore body

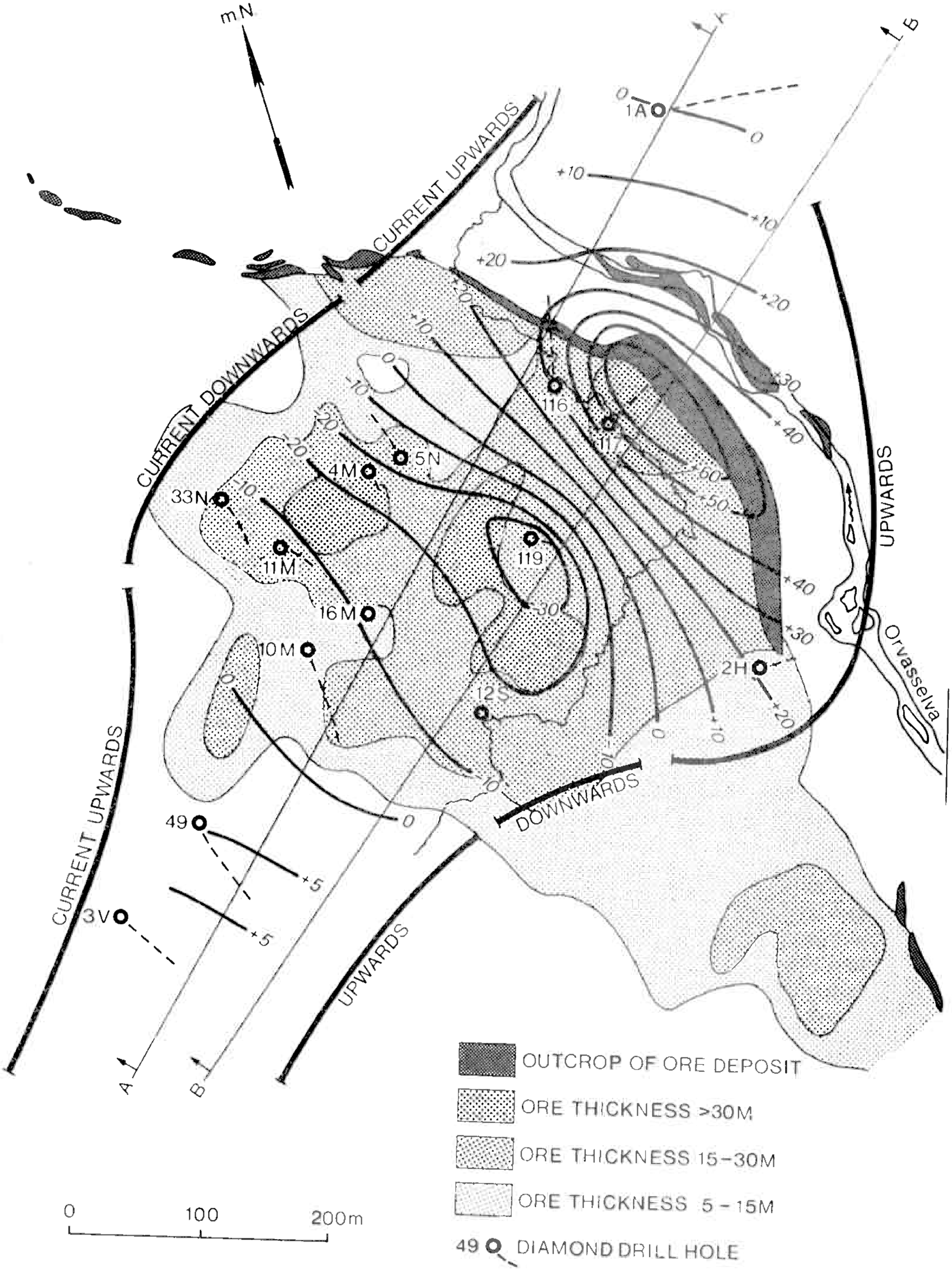

mN
A
B
CURRENT UPWARDS
CURRENT DOWNWARDS
CURRENT UPWARDS
UPWARDS
DOWNWARDS
UPWARDS
Orvasselva
1A
116
117
5N
4M
33N
11M
119
16M
10M
12S
2H
49
3V
0
+10
+20
+30
+40
+50
+60
-10
-20
-30
+5
0
100
200m
OUTCROP OF ORE DEPOSIT
ORE THICKNESS >30M
ORE THICKNESS 15-30M
ORE THICKNESS 5-15M
49 DIAMOND DRILL HOLE

FIG.12

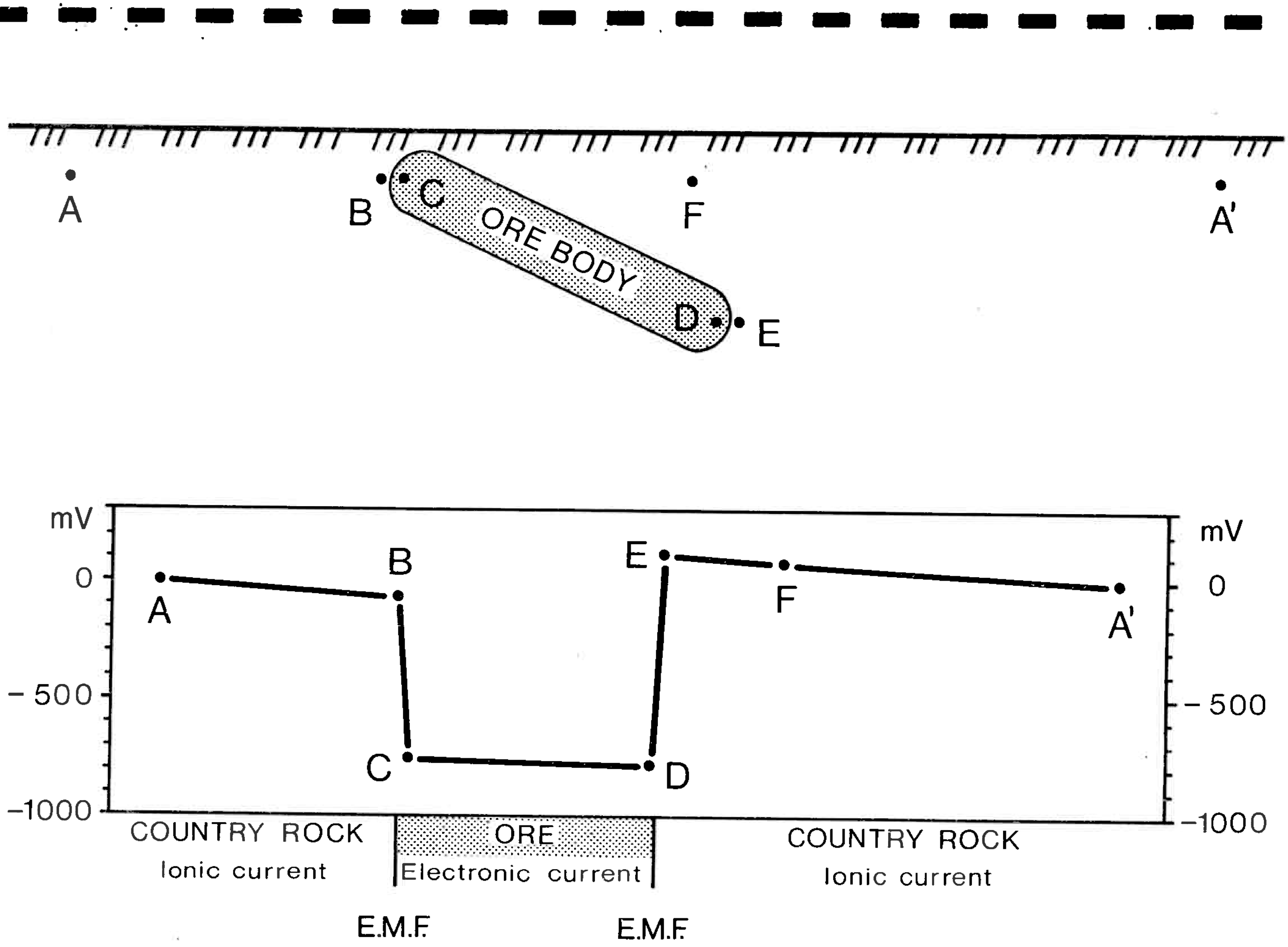

A
B
C
ORE BODY
D
E
F
A'
mV
0
- 500
−1000
mV
0
– 500
−1000
A
B
C
D
E
F
A'
COUNTRY ROCK
Ionic current
ORE
Electronic current
COUNTRY ROCK
Ionic current
E.M.F
E.M.F

FIG. 13