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Tittel
AN ELECTROCHEMICAL MODEL FOR ELEMENT DISTRIBUTON AROUND SULPHIDE BODIES

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Bølviken og Logn stiller opp en elektrokjemisk modell for elementstrøm omkring en sulfidforekomst.

Ut fra empiriske data for SP, redox potensial, spesifikk konduktivitet og pH-målinger i grunnvann og overflatevann såvel som innhold av Li, Na, Cu, Zn, Pb, Cl, pH-verdier og spesifikk konduktivitet i jordprøver fra Joma, blir massive kisforekomster vurdert i modellen.

# AN ELECTROCHEMICAL MODEL FOR ELEMENT DISTRIBUTION AROUND SULPHIDE BODIES

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## ABSTRACT

It is suggested that the upper lithosphere can be considered as a primary redox potential field, where the groundwater represents an electrolyte, and the siliceous bedrock a system of membranes in the electrolyte. The redox potentials of this primary field decrease with depth from the surface and hence electrical currents flow — positive (e.g. $H^+$) downwards and negative (e.g. $OH^-$) upwards — in the lithosphere. A body of electrically well-conducting sulphide mineralization can be regarded as a dipole inert electrode in the electrolyte, the lower end constituting the anode and the upper the cathode. Secondary currents in addition to those of the primary field flow between cathode and anode; cations move upwards and anions downwards in the electrolyte, and electrons upwards in the electrode. At some places the direction of the currents are the same for both primary and secondary fields; at other places primary and secondary currents counteract each other. Consequently, patterns of varying current density and ion concentration develop around the electrode. If the environment of the electrode is homogeneous, these patterns will be quite regular; at a vertical electrode current density and ion concentration will be highest in the vertical extensions of the electrode. At a suboutcropping ore body the overburden represents an environmental heterogeneity, because the electrical conductivity of the overburden is higher than that of the country rock and lower than that of the ore.

Thus, when adapted to surface conditions, the model suggests high current density and high ion concentration in the vicinity of the boundaries of the upper part of the ore, and low values for these parameters in the overburden above the ore. Aspects of the possible influence of electrochemical dispersion on element distribution are discussed. Empirical data for self potentials, redox potentials, specific conductivity and pH in ground and surface waters, as well as contents of Li, Na, Cu, Zn, Pb, Cl and values for pH and specific conductivity of soil extracts at the Joma massive pyrite deposit are interpreted in terms of the presented model.

## INTRODUCTION

The existence of natural self potentials (SP) at certain ore deposits has been known for more than a century, and SP measurements are widely used in prospecting (Sato and Mooney, 1960; Society of Exploration Geophysicists, 1966, 1967; Parasnis, 1966, 1967, 1970; Bitterlich and Wöbking, 1972). The origin of these potentials is not completely understood, although largely explained by Sato and Mooney (1960) who state that: "Self potentials associated with a sulphide ore body result from the ohmic potential drop within the country rocks. The electric current is produced by separate but simultaneous reduction of oxidizing agents near the surface and oxidation of reducing agents at depth. The ore does not participate directly in either reaction, but serves as a conductor to transfer the electrons from the reducing agents to the oxidation agents. The possibility for the above reaction to occur depends upon differences in oxidation potential of groundwaters at different depths". This electrochemical mechanism of self potentials is widely accepted in the literature (Becker and Tilford, 1965; Habashi, 1966; Parasnis, 1966, 1967, 1970; Henriet, 1971; Malmqvist and Parasnis, 1972; Govett, 1973).

In another paper (Logn and Bölviken, 1974) the present authors have reported some results of surface and drill hole self potential measurements at the Joma pyrite deposit, Norway, which seem to agree well with the electrochemical theory for SP. Fig.1 shows a typical result from one of these drill holes. The self potential curve indicates two distinct patterns: (1) abruptly alternating potentials with minima down to −800 mV and (2) a generally smooth potential trend, the variation of which is within some tens of millivolts. These two patterns can be recognized in all the drill holes investigated as well as at the surface. The abrupt potential changes occur at boundaries of sulphide horizons and country rock giving low potentials inside the ore. The

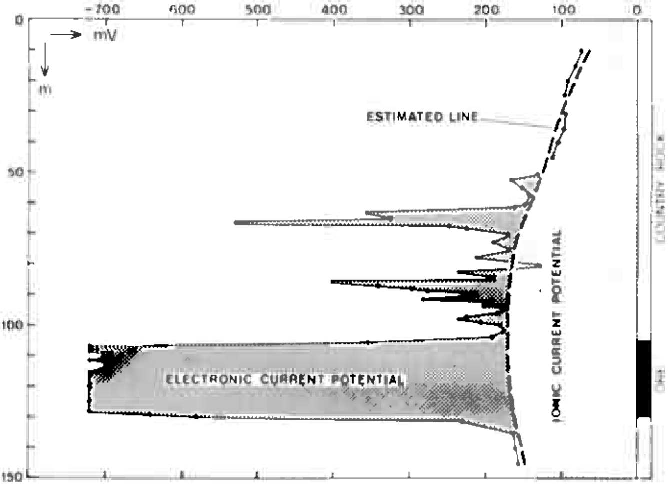

Fig.1. Self potentials in diamond drill hole No.119 Joma pyrite deposit, Norway. Potential pattern can be separated into: (1) electronic current potentials (abruptly changing path), and (2) ionic current potential (smooth trend) by graphical estimation.

potentials of the smooth trend decrease when approaching the upper part of the ore, and increase when approaching the lower part. The two types of potential pattern were interpreted in the following way:

(1) The abruptly alternating potentials are a consequence of the presence of electromotive forces at the country rock/sulphide interfaces. They indicate that electronic currents pass through the ore bodies. These potentials were termed "electronic current potentials".

(2) The smooth potential trend indicates that ionic currents, pass through the pore water of the country rock outside the ore body. These potentials were termed "ionic current potentials".

Electronic and ionic current potentials can be separated graphically as indicated in Fig.1. When this procedure is used on rather complicated drill hole SP data from sections through the ore (Fig.2), more simple patterns of both electronic and ionic current potentials appear; an example of the latter is reproduced in Fig.3. The distribution of ionic current potentials indicates

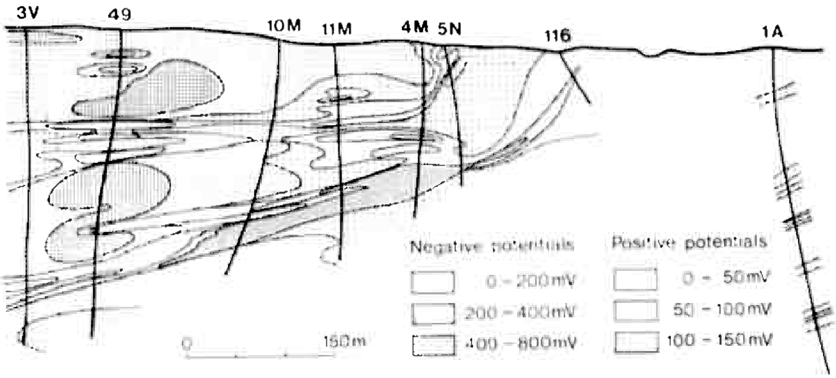

Fig.2. Self potentials in drill holes projected into a vertical section of the Joma pyrite deposit, Norway. (After Logn and Bölviken, 1974.)

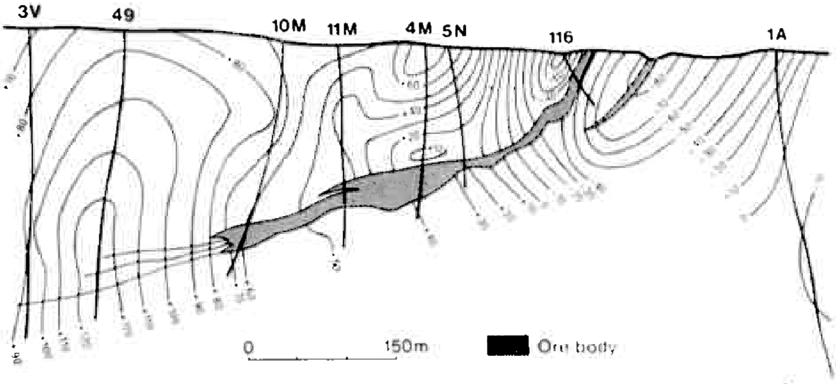

Fig.3. Ionic current potentials in drill holes estimated from data in Fig.2, Joma pyrite deposit, Norway. (After Logn and Bölviken, 1974.)

that the direction of positive electricity is upwards in the country rock. Electronic current potentials are highest at the upper end of the ore and lowest at the lower end, which seem to indicate that the direction of positive electricity is downwards in the ore. In other words, cations migrate upwards and anions downwards in the country rock, and electrons upwards in the ore body. These electrical currents might have geochemical consequences.

To elucidate some possible effects on the distribution of trace elements around an ore body, an electrochemical model of an ore deposit in country-rock groundwater is introduced in this paper. In geochemical prospecting any possibility for tracing electrochemical effects around ore bodies in surface material would be of particular interest. The model is, therefore, adapted to surface conditions. Towards the end of the paper some data from the Joma area, Norway, are discussed in relation to the presented model.

## THE PRIMARY REDOX POTENTIAL FIELD OF THE LITHOSPHERE

All available information indicates that the groundwater near the surface of the earth normally has higher redox potentials and lower pH than the groundwaters at depth (Baas Becking et al., 1960). Consequently, systems of vertical redox potential and pH gradients must exist in the waters of the upper lithosphere. Such systems could be termed primary redox potential fields (Bölviken, in prep.). The primary redox potential field of a homogeneous part of the upper lithosphere could be outlined as follows (Fig.4): terrestrial waters with dissolved ions (e.g. $Na^+$ and $Cl^-$) and redox pairs (e.g. $Fe^{3+}/Fe^{2+}$) constitute an

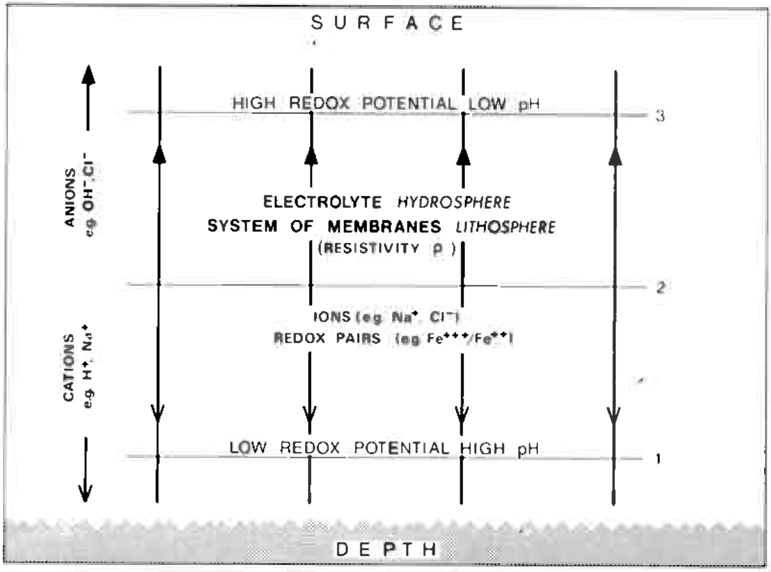

Fig.4. Diagrammatic representation of the primary redox potential field of a vertical section through a homogeneous part of the lithosphere.

indefinite electrolyte and the siliceous bedrock represents a porous medium of membranes in the electrolyte. The redox potential (and consequently the pH) vary regularly through the system, equipotential surfaces being horizontal Redox potentials represented, for example, by the ratio $Fe^{3+}/Fe^{2+}$ increase upwards, whereas pH increases downwards.

Three types of transportation of material may be distinguished in this redox potential field: (1) groundwater movement, (2) diffusion of dissolved species caused by concentration differences, and (3) migration of ions due to electromotive forces.

Groundwater movement and the diffusion is to a great extent controlled by the permeability of the rocks; these types of transport shall not be further discussed here. Migration of ions due to electromotive forces depends on (1) potential differences, (2) electrical resistivity ($\rho$) of the media through which the currents flow, and (3) concentration ($c$) and equivalent conductivity ($\lambda$) of the ions in question. In a homogeneous part of the lithosphere, the main electrical current direction will probably be vertical and current densities uniform. Cations might migrate downwards and anions upwards, $H^+$ and $OH^-$ being the outstanding current carriers with their ubiquity and high equivalent ionic conductance.

## PRIMARY AND SECONDARY REDOX POTENTIAL FIELDS AROUND ORE BODIES

Let us consider a vertical sulphide ore body with negligible electrical resistance ($R_0$) occurring in the primary redox potential field of the earth. If oxidation of the sulphides is slight, the ore body could be considered as an inert electrode in an electrolyte, the composition of which varies between the ends of the electrode (Fig.5). Because of the redox potential differences originally present in the electrolyte (terrestrial waters) and the difference between the type of electrical conductance in electrode (ore) and electrolyte, a secondary redox potential field is developed locally around the electrode. The electrode takes on the character of a dipole, the lower end becoming an anode and the upper a cathode.

Secondary currents in addition to the primary ones will flow between the anode and the cathode. In the electrolyte (country-rock groundwater) near the electrode cations will move upwards from the anode towards the cathode, and anions downwards from the cathode towards the anode. Within the electrode (ore body) electrons will move upwards from the anode to the cathode in order to compensate for the electrons produced by the chemical reactions at the anode, and those consumed by the reactions at the cathode. Potential gradients will build up around cathode and anode and the system will tend to approach a state as schematically indicated in Fig.5.

In nature this state will be reached to a variable extent depending on the effects of groundwater movement, oxidation of ores and other parameters such as potential differences, velocity of redox- and diffusion processes, and electrical resistivity of the various media. Oxygen of the atmosphere and

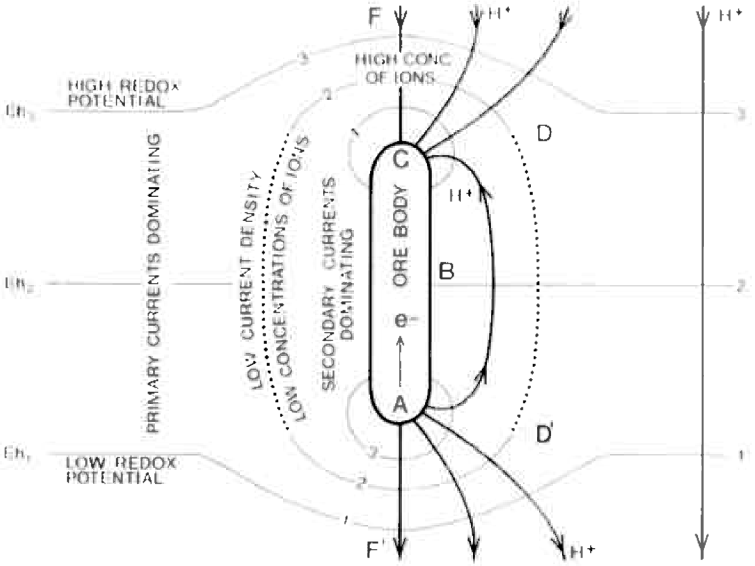

Fig.5. Schematic model of an ore body as electrode in a primary redox potential field. $Eh_1$, $Eh_2$ and $Eh_3$: selected equipotential surfaces. Heavy lines indicate path of primary and secondary currents, arrows indicate direction of positive electricity (cations) in the electrolyte. Arrow inside ore body: direction of electron flow in the ore. A = anode; B = electrical symmetry point at country rock/ore interface; C = cathode; D = limit of zone where secondary currents counteract primary currents; F = extension of the ore.

reducing agents in the inner of the earth would be the ultimate energy source of such natural galvanic cells. The maximum difference in redox potential between the electrolyte at the anode and that at the cathode could be considered as the electromotive force (EMF) of the cell.

At any point in the electrolyte the current densities resulting from the developed potential pattern will be the vectorial sum of the primary and secondary current densities. Far away from the electrode (ore) primary currents will dominate; close to the ore secondary currents are predominant. At a certain distance from the electrode (line D—D', Fig.5) the primary and secondary current densities will be approximately equal, and since they are of opposite direction the total current density approaches zero along line D—D'. Concentration of ions carrying the current will consequently be low in this zone. At the vertical extension of the ore (line F—F', Fig.5) the primary and secondary currents will both have the same vertical direction. Along the line F—F' the total current density is at a maximum, and ion concentration will consequently be high. In the space outside the lines D—D' and F—F' primary and secondary currents will either amplify or counteract to a variable degree, and the ion concentration at different places in the electrolyte would vary accordingly.

Various ions in the electrolyte will behave differently. Generally, cations will move towards the cathode where they will be reduced or kept in solution depending on their local concentration and on their position in the standard potential range. If the reduced form is a gas, it will diffuse away from the cathode; if it is a solid it will precipitate at the cathode. Oxidizing agents of the primary field will be in excess in the environment of the cathode. These agents will counteract the reduction processes at the cathode. They might also, in turn, oxidize the species reduced at the cathode when these diffuse away from the latter.

Protons have the highest equivalent conductance of all ions and will most probably be the main carrier of current in an acid environment. Hydrogen is more noble than those elements normally occurring in the highest concentrations in natural waters, and $H^+$ may be reduced at the cathode according to the equation:

$$2H^+ + 2e^- = H_2$$

Anions will move towards the anode where they will be oxidized or kept in solution according to their concentration and the position in the standard potential range. The oxidized form of the anions, which normally would be a gas, will diffuse away from the anode. The reducing agents of the primary field will be in excess in the environment of the anode. These agents will counteract the oxidation processes at the anode. They might also, in turn, reduce the species oxidized at the anode when these diffuse away from the anode.

Hydroxyl ions have the highest equivalent conductance of all anions and would be the main current carrier in a basic environment. Hydroxyl will probably be oxidized at the anode together with elements, for example $Cl_2$. The reactions at the anode can be represented as:

$$2OH^- \rightleftharpoons H_2O + \tfrac{1}{2}O_2 + 2e^-$$

In Fig.6 the patterns of redox- and self potentials as well as ion concentrations caused by the galvanic cell are diagrammatically illustrated along four selected traverses. On approaching the ore from a distant point, potential patterns will be quite regular, potentials decreasing towards the cathode and increasing towards the anode. Owing to the EMF of the cell, concentration of protons and cations more oxidizing than $H^+$ will tend to decrease towards the cathode (increasing pH), and increase towards the anode (decreasing pH). Similarly, concentrations of hydroxyl and anions more reducing than $OH^-$ will tend to increase towards the cathode and decrease towards the anode.

Cations more reducing than $H^+$ and anions more oxidizing than $OH^-$ will probably show a more complicated picture. At traverses outside the line D—D′ (traverses 1 and 4, Fig.6) concentration of these cations will increase towards the cathode and decrease towards the anode. The anions will conversely decrease towards the cathode and increase towards the anode. At traverses between points D and D′ (traverses 2 and 3, Fig.6) the concentration of these ions will be at minimum along the line D—D′.

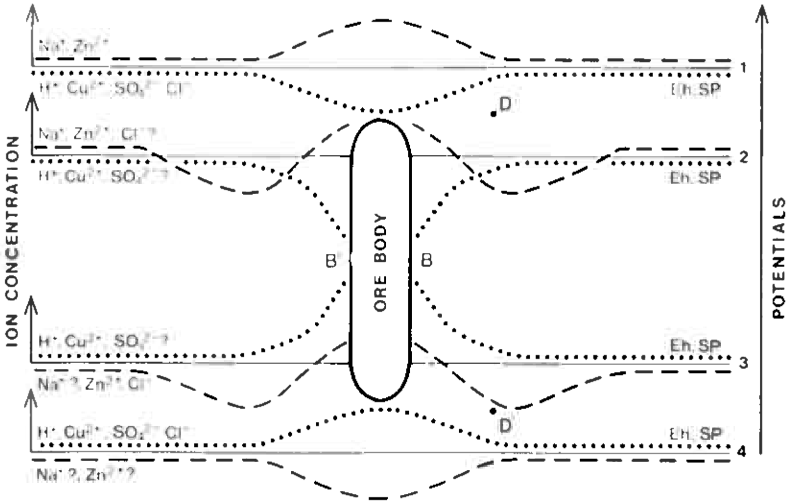

Fig.6. Estimated patterns of redox potential, self potential and concentration of ions along four traverses in the electrolyte (groundwater) around a schematic model of a vertical inert electrode (ore body) in a primary redox potential field (upper lithosphere). Traverses 1 and 4 cross the extension of the electrode, traverses 2 and 3 cross the electrode between points D and D' (see Fig.5). Question mark after symbol indicates particular uncertainty for that element.

For all ions in question the concentration at any point will be a result of the local redox potential, the current density and the necessity for electroneutrality between cations and anions. The relative importance of the different effects cannot be estimated quantitatively at the present stage. Some of the indicated trends are therefore uncertain; the most questionable are indicated with a question mark in Fig.6.

## ADAPTION OF THE ELECTROCHEMICAL MODEL TO SURFACE CONDITIONS

The processes described above presuppose homogeneous and isotropic conditions in the electrolyte, a situation which could never be fulfilled in nature. Of the many possible heterogeneities we shall here briefly discuss the nature and effect of the overburden, since this is of particular interest in geochemical prospecting. Fig.7 shows a model of the upper part of an ore body outcropping in the bedrock beneath glacial till. Ice movement is assumed to have taken place from right to left, and glacial debris from the ore is contained in the till. Post-glacial oxidation of this debris has occurred as well as post-glacial oxidation of the ore and country rock.

Owing to great differences in electrical resistivity ($\rho$) current directions will decline abruptly at the boundaries of bedrock (high $\rho$) and overburden (low $\rho$). In the overburden the resulting current density will be high in the vicinity of the outer edges of the ore, and low above the ore. The concentra-

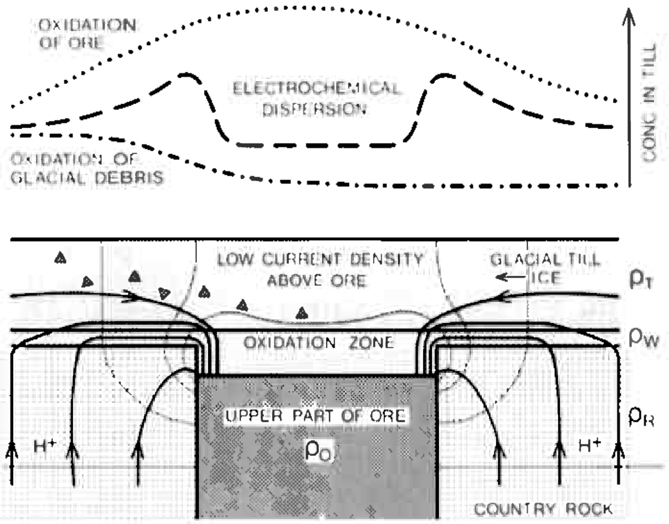

Fig.7. Schematic model of the upper part of a sulphide ore body outcropping under glacial till. Thin lines: equipotential surfaces. Heavy lines with arrows: current direction of positive electricity ($H^+$) in the electrolyte: $\rho_R$, $\rho_W$, $\rho_T$, $\rho_O$, : electrical resistivity in country rock, oxidized zone, glacial till and ore, respectively. Upper curves indicate paths to be expected from various dispersion mechanisms in the groundwater of the overburden sampled close to the bedrock.

tion of ions taking part in the electrochemical processes are supposed to be high where the current densities are high. Resulting concentration patterns in the electrolyte of the overburden are shown in the upper part of Fig.7.

Electrochemical dispersion will cause characteristic maxima at the edge of the ore and a minimum above the ore. For elements with an originally lower concentration in the ore than in the country rock this minimum would be more pronounced than for elements with similar concentrations in ore and country rock. For elements enriched in the ore the electrochemical dispersion pattern in the groundwater may be modified by dispersion caused by oxidation of ore minerals in situ or in the glacial debris. Clearly, the development of these distribution patterns would also be modified by groundwater movement in bedrock and overburden.

## INTERPRETATION OF EMPIRICAL DATA FROM THE JOMA AREA FOLLOWING THE ELECTROCHEMICAL MODEL

The Joma deposit is situated in inner North Trøndelag, central Norway, in an area of cold climate approximately 600 m above sea level (a.s.l.). The economic mineralization consists of about 17 million tons of massive pyrite with varying amounts of chalcopyrite, sphalerite and galena, in a country rock of highly metamorphosed greenstones rich in carbonates (Fig.8). A

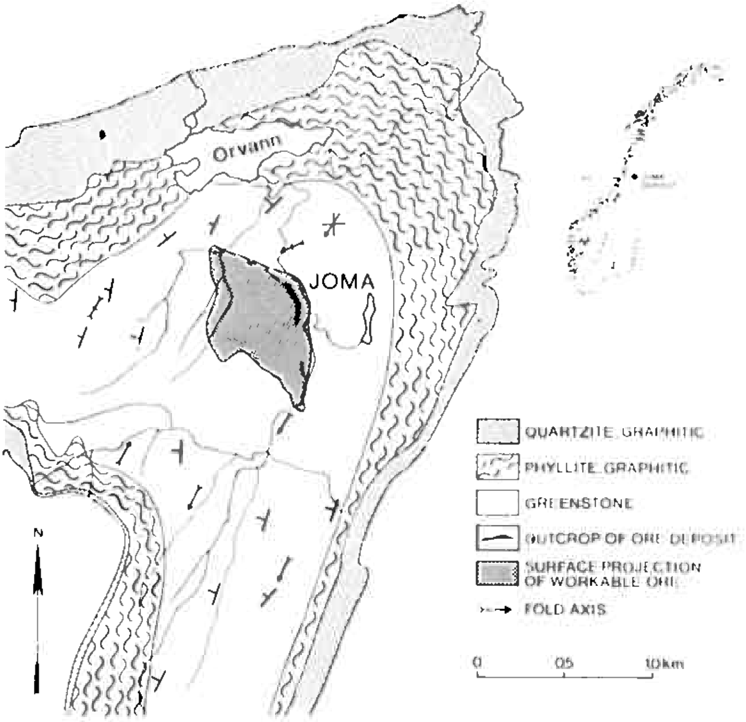

Fig.8. Geological map of the area surrounding the Joma pyrite deposit, central Norway. (After R. Kvien, personal communication, 1974.)

graphitic phyllite dipping under the greenstones is observed in the lower half of drill hole 1A and in the lowermost 2—3 m of drill hole 3V (Figs.2 and 3). The overburden, mostly 0.5—1.2 m thick above the deposit, consists of glacial till and also partly bog and weathered rock. A more detailed account of the deposit and its surroundings has been given earlier (Logn and Bölviken, 1974). Unless otherwise stated, the methods referred to in the following account have been described in an earlier paper about in-situ measurements of pH, Eh and SP in drill holes (Bölviken et al., 1973).

### *Drill hole data*

Looking back to Fig.3 it is seen that the self potential trends from the drill holes at Joma and those outlined from the model agree quite well, taking into account the dip and complex geometry of the sulphide mineralization. Simultaneous in-situ measurements of pH, redox potentials (Eh) and self potentials (SP) have been carried out in drill hole 117, which intersects the thickest part of the ore near the outcrop. In this hole (Fig.9) pH decreases regularly with depth from 6.7 near the surface to a minimum of 6.0 in the middle of the ore at a depth of 50 m. From 50 m, pH increases with depth

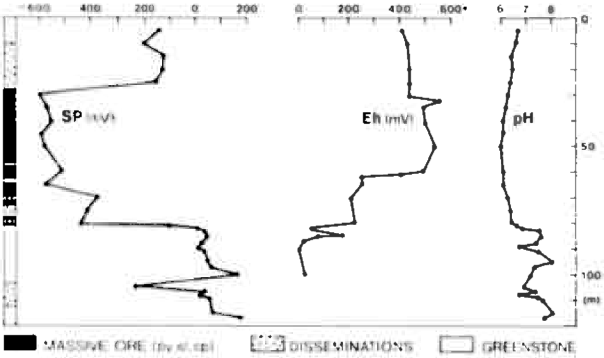

Fig.9. Self potentials (SP), redox potentials (Eh) and pH in drill hole No.117, Joma pyrite deposit, Norway. All parameters are measured in situ (Bölviken et al., 1973).

to 6.5 at the footwall boundary of the ore. In the footwall country rock the pH values are quite irregular, generally they increase with depth. Eh increases with depth in the upper part of the hole, from approximately 400 mV near the surface to a maximum of about 570 mV at a depth of 50 m where the pH is at minimum. Further down Eh decreases abruptly with depth reaching approximately 50 mV at a depth of 100 m. Local Eh maxima appear close to the ore boundaries both in the hanging- and footwall. Electronic current SP are constantly about −450 mV through the ore, while ionic current SP increase with depth from approximately −150 mV near the surface to +150 mV at a depth of 110—120 m.

The authors are not able to explain all these results at the present stage. The pH and Eh values seem to be greatly influenced by oxidation of sulphides. It is uncertain whether or not the local Eh maxima and other features of the Eh curve could be effects of a secondary redox potential field.

Judging from the results in another drill hole (Fig.1), the self potentials in hole 117 appear to be influenced by the geometry of the sulphide mineralization. The ore body dips approximately 30°, a reason why the potential pattern above its upper part must be deformed. When this is taken into account, the results obtained for ionic current self potentials appear to agree fairly well with what would be expected from the model in Fig.5.

pH values in waters from a section through the deposit and country rock are shown in Fig.10. The data are all from in situ measurements. In all the drill holes intersecting ore, pH seems to have a bimodal distribution in the country rock with an acid and a basic trend. In a drill hole located in the footwall (1A) such bimodality is less pronounced and has only been observed in the upper half of the hole. When the pH data are compared with the geological description of the drill cores (R. Kvien, personal communication, 1974) and the SP data (Fig.2), it seems quite clear that practically all the acid peaks on the pH curves coincide with occurrences of massive or disseminated sulphides. The sulphides appear to have been somewhat oxidized since the

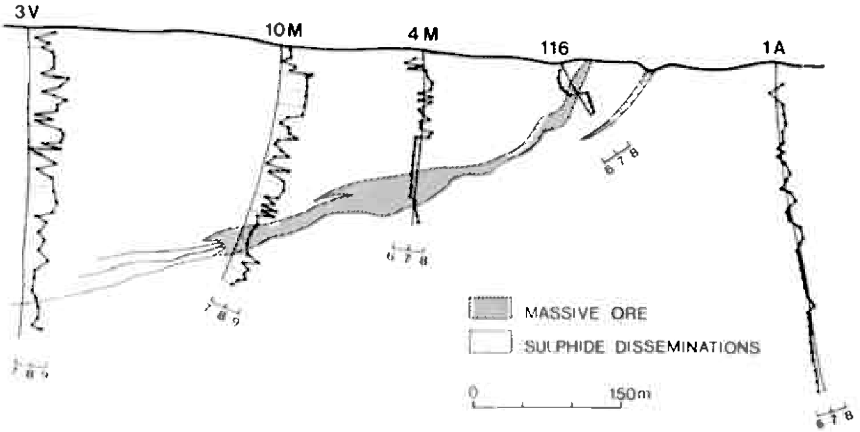

Fig.10. pH in drill-hole waters, from a vertical section through the Joma pyrite deposit, Norway. In-situ measurements with glass electrode.

pH in the massive ore decreases regularly from approximately 8.0 at depth to 6.0—6.5 near the surface.

The most basic trend probably reflects the pH in porewater within the country rock (greenstones rich in carbonates). pH values of this trend seem to decrease with depth in the deepest drill holes through the ore. Drill hole 1A in the footwall intersects greenstones in the upper half and more or less bituminous phyllites in the lower half (R. Kvien, personal communication, 1974). The change in pH pattern occurs halfway down the hole at the border between the two formations. The pH of the basic peaks in the upper half of hole 1A (greenstone) is nearly constant with depth (approximately 7.5), while the pH in the lower half (phyllites) decreases slightly with depth (from 6.9 to 6.5). It is also interesting to note that even though the low pH produced by the sulphides should be expected to lower the pH in the country rock in the vicinity of the sulphide mineralization, the pH in the country rock is higher nearer the ore body (3V, 10M, 4M, 117) than away from it (1A), although the greenstone in hole 1A does not seem to differ substantially petrographically from that in the other holes (R. Kvien, personal communication, 1974). The total picture of the distribution pattern of pH appears to be in agreement with what should be expected in a secondary redox potential field around the Joma deposit.

The authors believe that the pH patterns described above reflect conditions in the bedrock; we find it unlikely that the results are significantly influenced by the original composition of the water used during the diamond drilling because:

(1) The holes had been drilled at least 5 years before the pH measurements were made (1971).

(2) The water that had been used during the drilling must have been taken from nearby streams. These all have pH values between 6.5 and 7.5 and low

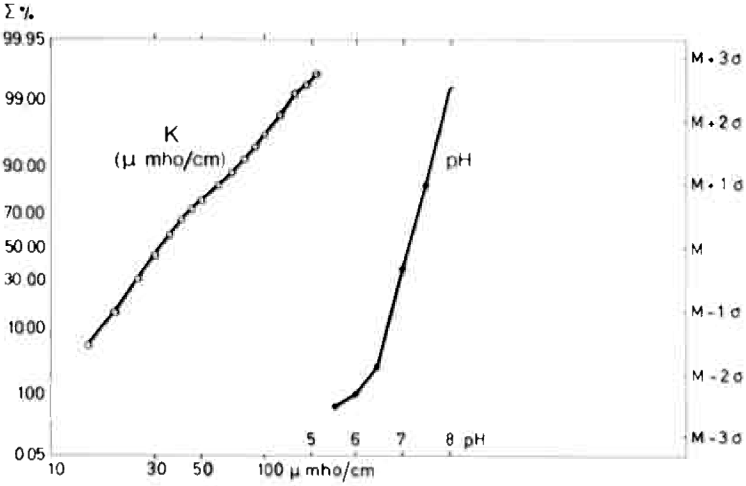

Fig.11. Frequency distributions of specific conductivity ($K$) and pH in 936 samples of stream waters from an area surrounding the Joma pyrite deposit, Norway.

contents of dissolved salts (Fig.11), which indicate low buffer capacity.

(3) The details indicated on the pH curves were reproducible, and results appeared to be very little influenced by stirring the drill-hole waters on moving the probe up and down (Bölviken et al., 1971).

Specific conductivity of the water in drill holes was measured (1971) in samples brought to the surface. Fig.12 shows the results from the drill holes sampled. The specific conductivity is rather uniform within the holes; in-situ measurements, like those of pH, would probably have given more diverse results. There are, however, clear differences between the holes. The conduc-

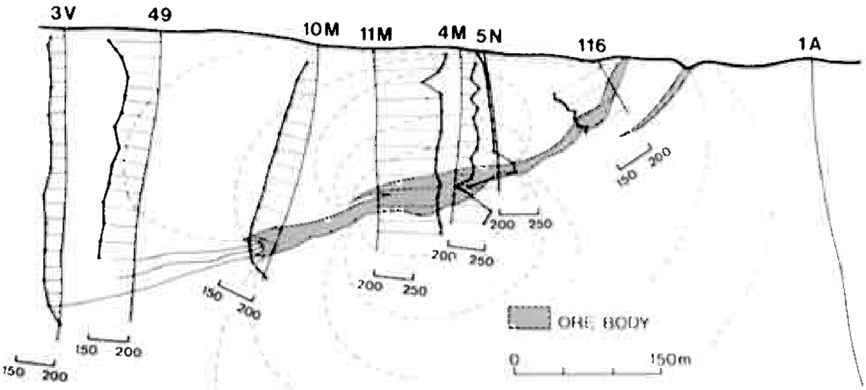

Fig.12. Specific conductivity in drill-hole waters from a vertical section through the Joma pyrite deposit, Norway. The conductivity was measured after ca. 1 hour in samples brought to the surface. Unit on curves: μmho/cm. Dashed lines indicate estimated paths of current flow in the country rock.

tivity is highest in the drill holes passing through the central part of the ore (11M, 4M), and lowest in those intersecting the ore near the surface (116) or at depth (3V). This must be due to a relatively low salt concentration in these last-mentioned holes. It cannot be an effect of pH variations since the water of drill hole 116 is acid and that of 3V basic; both these should produce better specific conductivities than the more neutral water of holes 11M and 4M, other things being equal. This pattern of specific conductivity can, however, be explained by reference to the electrochemical model. Drill holes 11M and 4M intersect the thickest part of the ore body. The ore is almost flat dipping in this part, the main direction of the secondary currents consequently being nearly horizontal and little influenced by primary currents. Due to the geometry of the ore body the current densities are probably high and rather uniform in the country rock above the central part of the ore (Fig.12). Local high current density imposed on the electrolyte in the rock would attract ions from the environment and promote local high specific conductivity.

### *Surface data*

Samples of glacial till were taken as close as possible to the bedrock (maximum depth = auger length = 1.4 m) along a profile across the central part of the ore (north of the profiles shown in Figs.2 and 3). After drying and sieving to minus 180 micron, the lithium, sodium, copper, lead and zinc contents of these samples were determined (atomic absorption) after hot nitric acid digestion. The $Cl^-$ (ion-selective electrode), pH (glass electrode) and specific conductivity (as introduced by Govett, 1973, 1975) were determined in water extracts of the soil. Results are shown in Fig.13.

The conductivity of soil slurries as well as copper, lead and zinc contents of the soil show similar patterns (Fig.13a): all are markedly high just above both massive and disseminated sulphides indicating that oxidation processes in this case are the dominant factor behind these distribution patterns.

pH, lithium, sodium and $Cl^-$ (Fig.13b) show distribution patterns different from those of conductivity and heavy metals. Lithium has low concentrations just above the main ore, above the hanging wall sulphide disseminations and above the footwall massive mineralization. Local maxima are obtained at both sides of the main ore. Both sodium and $Cl^-$ depict a somewhat similar path, but the trends are more diffuse than that for lithium. Lithium distribution seems to agree quite well with the pattern outlined from electrochemical dispersion (Fig.7). Even though the lithium content is known to be higher in the country rock than in the sulphides this should not significantly influence its content above the disseminations in the hanging wall, since the sulphide mineralization here is rather poor. Clearly, there is a possibility that the distribution pattern obtained for lithium in the till merely reflects primary distribution in the bedrock or syngenetic secondary distribution in the overburden. On the other hand, $Li^+$ is one of the cations with high ionic equivalent conductance which according to the electrochemical model should be one of the principal current carriers beside $H^+$.

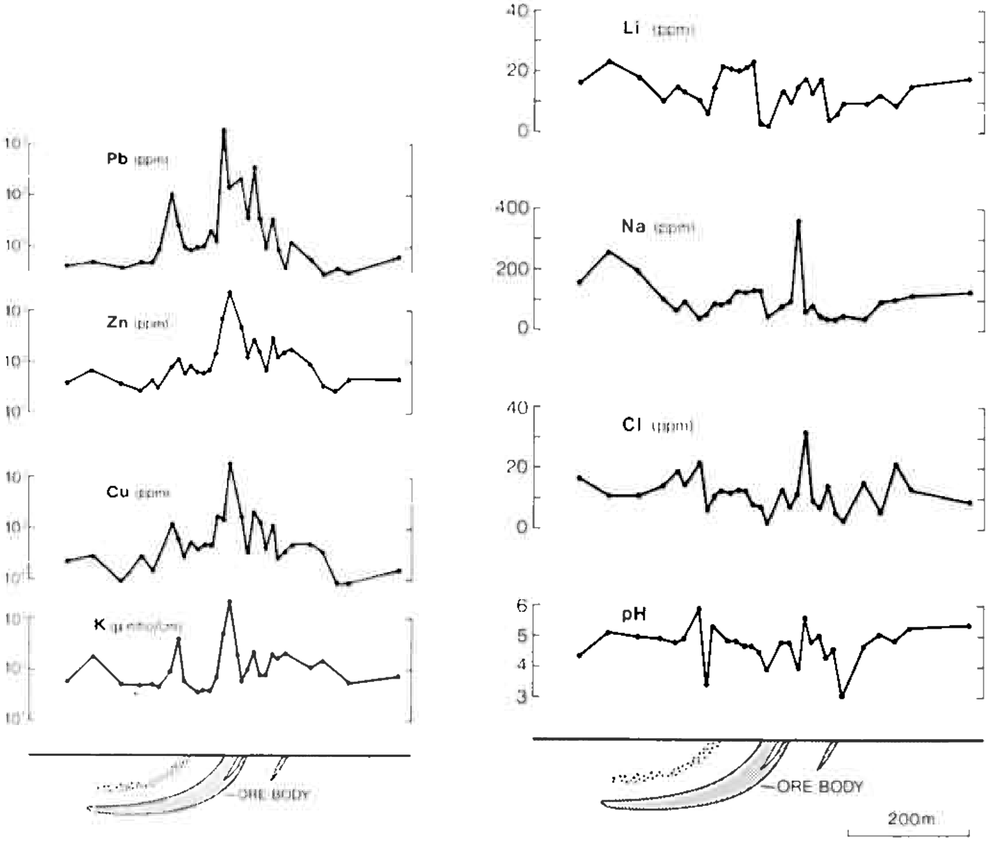

Fig.13. Specific conductivity, pH and chloride in water extracts and copper, zinc, lead, lithium and sodium in nitric acid extracts of glacial till from a profile crossing the Joma pyrite deposit, Norway.

pH is rather randomly distributed although some similarities with the lithium distribution might be recognized. Owing to oxidation of the ore indicated by the pH pattern in the ore and the heavy-metal distribution in the overburden, pH would be expected to be low above the ore which is the case only to a certain extent, indicating that one or more mechanisms counteract a drastic pH decrease near the ore. From the present data no conclusions can be drawn regarding the possibility that electrochemical processes may represent one of these mechanisms.

In an orientation survey around the Joma deposit (1964) surface waters were sampled at 200—500 m intervals along all streams in the area. Specific conductivity and pH were determined in these samples approximately 1 month after sampling. Frequency distributions of the results are shown in Fig.11, and

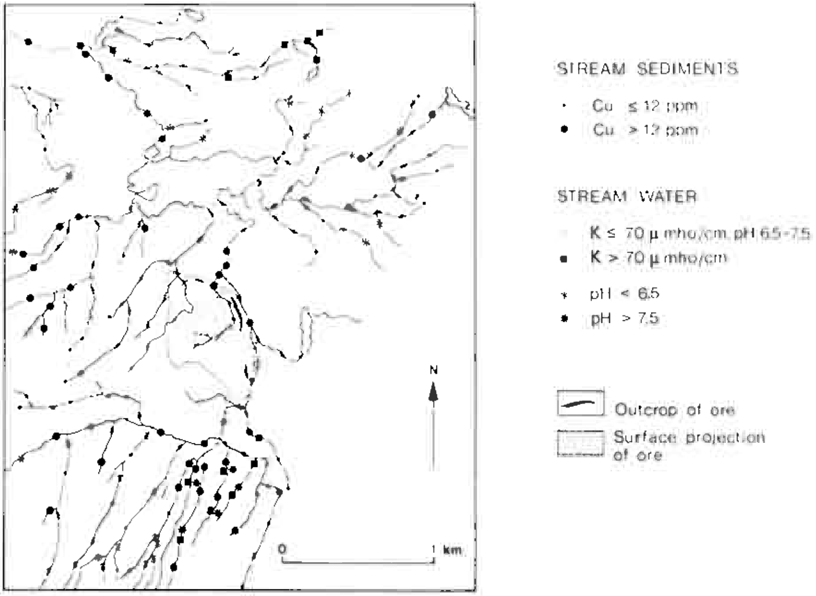

Fig.14. Anomalies (> 90 percentile) of cxCu in stream sediments and specific conductivity and pH in stream water of an area surrounding the Joma pyrite deposit, Norway.

anomalies in Fig.14 together with results for cxCu in stream sediments. A zone of low pH probably caused by phyllites of the same type as in drill hole 1A (Figs.8 and 10) was found approximately 1 km north of the deposit. The Joma ore body does not give clear pH or conductivity anomalies.

Two main conductivity anomalies including all samples with results higher than the 90 percentile were found outside the deposit. One is in a drainage system 1.5 km north of the Joma deposit, the other in several small streams at the southern extension of the main ore. The southern conductivity anomaly coincides with areas of high pH (> 8) stream waters and high metal contents in stream sediments. This stream sediment anomaly has been related to disseminated sulphides which are known to occur in this zone. Since the pH values are high, the high conductivity in these stream waters cannot be caused by oxidizing sulphides alone. Oxidizing sulphides in host rocks especially rich in carbonates could probably produce the combination of high conductivity and high pH. Coinciding high conductivity and high pH in stream water could, however, be caused by electrochemical processes and reflect high current densities due to natural galvanic cells in the drainage area. This last interpretation offers interesting possibilities for regional exploration through pH and conductivity measurements in stream waters and stream sediment slurries.

## CONCLUSIONS

The electrochemical model presented in this paper is a tentative and highly simplified image of natural features and processes. In nature many factors influence the complex system of an ore deposit in its environment. More research is needed in order to prove whether or not electrochemical ion transport might really be one of the dominating factors contributing to the element distribution around an ore deposit. The natural current densities at Joma were estimated to be of the order of 5 $mA/m^2$ within the ore body and 0.1 $\mu A/m^2$ in the country rock (Logn and Bölviken, 1974). The authors consider that natural current densities of this magnitude may probably have some geochemical consequences beyond those of interest solely to pure academic discussions. Electrochemical and other mechanisms might in some instances interact. This seems to be the case when considering the effects on specific conductivity of natural interstitial waters. Since glacial overburden could be considered chemically as a more or less neutral blanket positioned over the bedrock ready to receive any pattern imposed upon it, the search for electrochemical dispersion at shallow depths in glacial till appears to be a favourable alternative to deep overburden sampling. Interesting too is the possibility that electrochemical mechanisms might influence the mineralogical compositions of ore and country rock, as earlier pointed out by Govett (1973), Govett and Whitehead (1974), and others.

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