Thermal Conductivities of Some Ores and Rocks in Norway

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Thermal conductivities of 61 diamond core samples are given. Most of the samples are from the Joma pyrite deposit and its neighbourings rocks. The measurements from Joma show that there is a very high conductivity in compact pyrite ore, a considerably low conductivity in impregnated ore, a high conductivity in sphaleritic pyrite ore and a low conductivity in the surrounding greenstones and phyllites. Samples from other locations show that quartz and graphitic schists have intermediate conductivities and that magnetite has a relatively low conductivity. The conductivities of all measured specimens fall between 3 and 60 millical/cm.sec. °C.

Comparison of thermal and electrical conductivities reveals the following interesting features: compact pyrite ore, which is usually difficult to separate electrically from impregnated ore and graphitic rocks, has a thermal conductivity distinct from that of the impregnated ore and graphite-bearing rocks. Quartz, which has a poor electrical conductivity, has a relatively high thermal conductivity as compared with that of the ordinary rocks. These features may have direct applications in prospecting for compact ore deposits.

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Introduction

The thermal conductivity measurements described here were undertaken to establish the thermal conductivities of ore types and country rocks in the Joma pyrite ore field to aid in the interpretation of a series of temperature gradient measurements carried out in diamond drill holes through this ore body to evaluate the possibility of using thermal methods in geophysical exploration of pyrite ores of the compact type (Logn, in preparation). Most of the thermal conductivities given in this paper are from specimens from Joma. A few conductivities from other localities in Norway are provided for comparison.

The Joma deposit is one of the largest pyrite deposits in Norway. It is situated at 65°N near the Swedish border (Fig. 1). The history and geology of the deposit are described briefly in a paper on self-potential measurements of this ore body (Logn & Bølviken, in preparation). The ore body is a broadly tabular mass which has been folded into an open synform. The greatest ore intersections are found along the axis (NE/SW) of this fold structure. The ore consists chiefly of compact pyrite with varying amounts of chalcopyrite, pyrrhotite and sphalerite. Galena occurs as a minor mineral. Greenstones occur both above and below the ore body. A phyllitic unit is situated in the footwall.

The greenstone is slightly calcareous with an average of about 2.5% Ca. In the hanging wall greenstone a horizon of mainly pyrrhotite disseminations occurs over a distance of about 50–100 m from the ore body. The phyllite

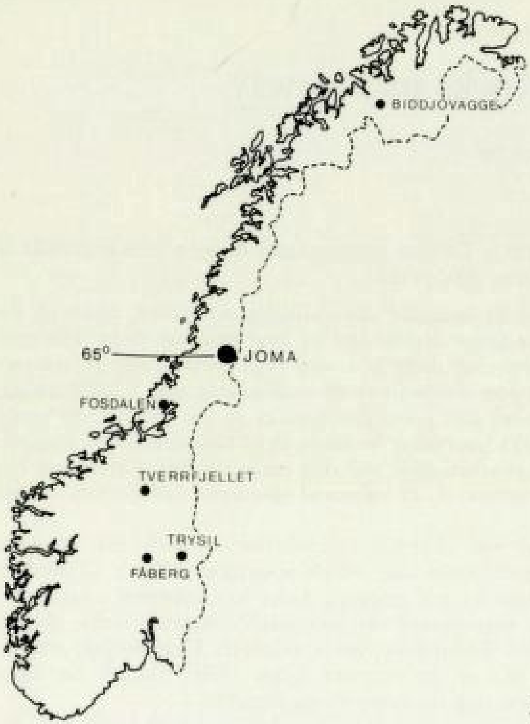

Fig. 1. Location of sample localities.

formation contains a number of graphitic zones which are good electrical conductors and cause strong electro-magnetic and geo-electric anomalies.

Thermal conductivity measurements have also been carried out on compact magnetite ore from the Fosdalen deposit situated at Trondheimsfjord to the south-west of the Joma pyrite deposit (Fig. 1). The ore contains about 45% Fe as magnetite with disseminated pyrites, and traces of chalcopyrite. The country rocks are greenstones and quartz keratophyres. The geology of the mine has been described earlier (Carstens 1955, Logn 1964).

One specimen of a quartz vein from the Tverrfjellet pyrite mine at Dovre, two specimens of sparagmite from Fåberg, one limestone from Trysil (Fig. 1) and three specimens of graphitic schists from Biddjovagge in Northern Norway comprise a supplementary collection on which thermal conductivity measurements were carried out. The complete specimen collection comprises 61 cores.

Methods of measurement

The thermal conductivities were measured by a divided bar method similar to that proposed by Birch (1950). The apparatus is shown in Fig. 2. The specimen, a circular diamond core 32 mm in diameter, was cut by diamond sawing to a disc of about the same thickness with flat parallel faces. The core (A, Fig. 2) is inserted between copper discs 8 mm thick. In the other side of this unit is placed the prototype, to which the specimen can be compared, capped at its outer face by another copper disc. The prototype has the same diameter

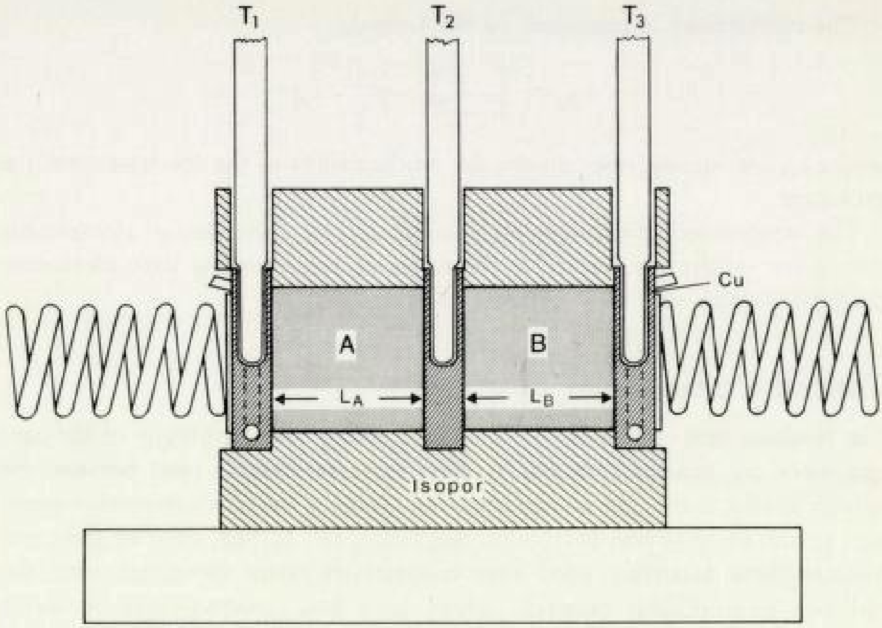

Fig. 2. Diagram of the apparatus used for measuring relative thermal conductivity.

and approximately the same thickness as the specimen. The end faces were covered by a thin film of SiC fine-fraction polish mixed with water in order to reduce the contact resistivity. This 'stack' is assembled in a unit pressed together by springs acting in the direction of the axis of the cylinders. The heating of one end face is supplied by warm water circulating in channels in one of the outer copper discs. A circulation of cold water is provided for the lower temperature side of the systems. The temperature of the water is adjusted so that the warm side of the unit is constantly about 12°C above room temperature and the cold side about 12°C below. The basic assumption in the use of this method is that all heat movement is parallel to the axis of the system. Non-axial heat flow can never be reduced to zero, but can be kept to a minimum by using insulating materials around the unit. For this purpose the unit was shielded by a cap of the 'isopor' insulating material. Three thermometers, scaled in tenths of degrees Celsius and fitting closely in wells drilled in the copper discs, are used to measure the temperature differences across the two poor conductors, i.e. the prototype and the specimen.

Two separate measurements were carried out on each sample by interchanging the specimen and prototype in the 'stack'. The results given in the following section are based on averages of these measurements.

The prototypes used in the measurements were kindly loaned to the authors by Dr. S. Werner, director of the Geophysical Department of the Swedish Geological Survey. The absolute conductivities on these prototypes were:

1) Vismuth: $20.12 - 0.02 \cdot t^\circ$ millical/cm · sec · °C

2) Invar: $22.8 + 0.065 \cdot t^\circ$ millical/cm · sec · °C

t° = room temperature (20°C).

The conductivity is computed by the formula:

$$\lambda_A = \frac{T_2 - T_3}{T_1 - T_2} \cdot \frac{L_A}{L_B} \cdot \lambda_B$$

where λ_A and λ_B are, respectively, the conductivities of the specimen and the prototype.

The conductivity measurements carried out by this sample arrangement have given satisfactory results, as the repeated measurements have given conductivities which vary only within narrow limits.

Thermal conductivities

The resulting heat conductivities vs. corresponding specific gravity of the core specimens are presented in Fig. 3. This representation is used because the specific gravity is thought to give some indication of the heavy mineral content, e.g., pyrite, chalcopyrite, pyrrhotite, magnetite, etc. In fact, most of these ore minerals have relatively good heat conductivity when compared with the ordinary rock-building minerals, which have heat conductivities of about 6–9 millical/cm · sec · °C (Herrin & Clark 1956; Puranen 1968). Impregnations of good-conducting ore minerals in rock-building mineral matrices are well expressed by the specific gravity of the specimen as there is a good correlation between the specific gravity and the heat conductivity of the rocks with impregnated ore minerals.

The specimens are separated into 10 groups (Fig. 3):

A. Rocks:

1) Graphitic schist (Gra, Fig. 3). 3 specimens from Biddjovagge. Average heat conductivity is 17 millical/c · sec · °C. Average specific gravity is 2.55 g/cm^3.
2) Quartz (Q, Fig. 3). 3 specimens, 1 from Tverrfjellet and 2 from Joma. Average heat conductivity is 15.7 millical/c · sec · °C. Average specific gravity is 2.58 g/cm^3.
3) Phyllite (Ph, Fig. 3). 12 specimens from Joma. Some of the specimens are graphitic. Average heat conductivity is 6.9 millical/cm · sec · °C. Average specific gravity is 2.74 g/cm^3.
4) Greenstone (Gr, Fig. 3). 11 specimens from Joma. The greenstone has on average about 2.5%Ca. Average heat conductivity is 7.86 millical/cm · sec · °C. Average specific gravity is 2.87 g/cm^3. Some of the heavier specimens are weakly impregnated with pyrite or pyrrhotite.
5) Miscellaneous. 3 specimens are not grouped. A dark Cambrian schist from Trysil (Cam, Fig. 3) has a heat conductivity 3.0 millical/cm·sec·°C and a specific gravity of 2.72 g/cm^3. This specimen contains minor calcite. The other two specimens (Spa, Fig. 3) are dark-coloured sparagmites from Fåberg, which have heat conductivities of 4.8 and 9.4 millical/cm · sec · °C and specific gravities 2.73 and 2.67 g/cm^3. The specimen with the heat conductivity of 9.4 millical/cm · sec · °C contains traces of graphite.

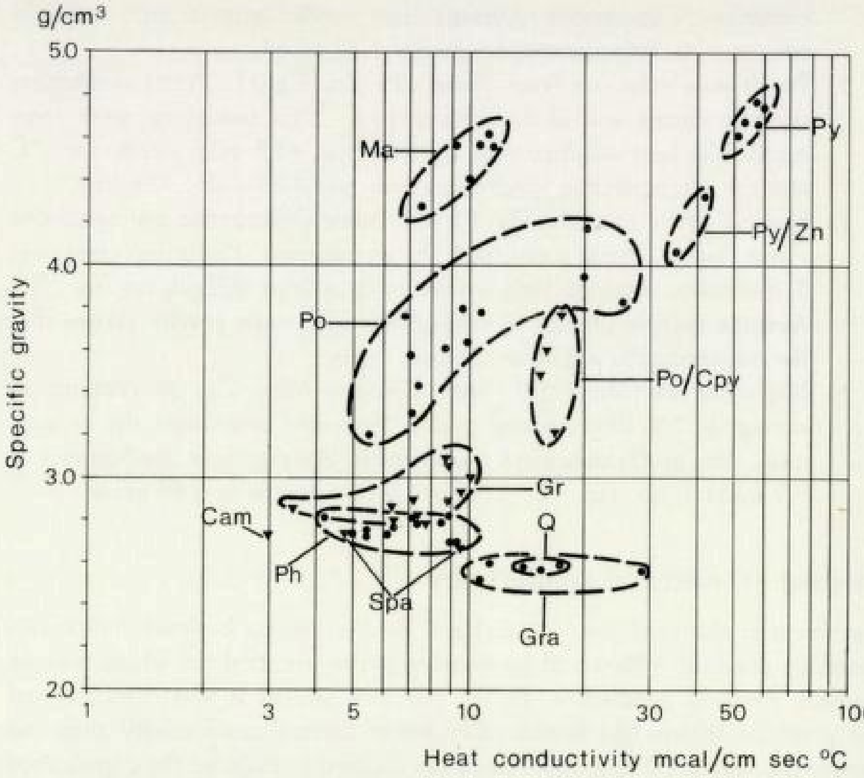

Fig. 3. Heat conductivity vs. specific gravity.

Py	=	Massive pyrite ore from Joma deposit.
Py/Zn	=	Sphalerite-pyrite from Joma.
Po/Cpy	=	Chalcopyrite-pyrrhotite impregnations from Joma.
Po	=	Pyrrhotitic impregnations in greenstone from Joma.
Ma	=	Massive magnetite from Fosdalen deposit.
Gra	=	Graphitic schist from Biddjovagge deposit.
Gr	=	Greenstone from Joma.
Ph	=	Phyllite from Joma.
Q	=	Massive quartz from Joma and Tverrfjellet deposits.
Spa	=	Sparagmite from Fåberg.
Cam	=	Cambrian black schist from Trysil.

B. Ores and disseminated ores:

1) Impregnated pyrrhotite greenstones from Joma (Po, Fig. 3). The impregnations occur chiefly along schistosity bands or in irregular networks, which is probably the reason for the scattering of values obtained. The sample group comprises 12 specimens. Average heat conductivity is 11.6 millical/cm · sec · °C. Average specific gravity is 3.69 g/cm³. Some of the specimens with higher heat conductivity may contain traces of chalcopyrite or pyrite.

2) Impregnated pyrrhotite-chalcopyrite rocks from Joma (Po/Cpy, Fig. 3). The impregnations occur chiefly in bands or in networks. Ordinarily pyrrhotite is more abundant than chalcopyrite. The group

comprises 4 specimens. Average heat conductivity is 16.6 millical/cm · sec · °C. Average specific gravity 3.67 g/cm^3.

3) Pyrite–sphalerite ore from Joma (Py/Zn, Fig. 3). Pyrite constitutes the groundmass and is the main mineral. Two specimens were measured. The heat conductivites are 35.4 and 42.5 millical/cm · sec · °C and the corresponding specific gravities are 4.05 and 4.32 g/cm^3.
4) Massive pyrite ore (Py, Fig. 3) with some chalcopyrite and sphalerite (from Joma). Pyrite constitutes the groundmass. The group comprises 5 specimens. Average heat conductivity is 56.0 millical/cm · sec · °C. Average specific gravity is 4.68 g/cm^3. The mean gravity shows that the ore specimens are quite compact types.
5) Magnetite ore (Ma, Fig. 3) from Fosdalen Mine. The ore contains an average of 5% disseminated pyrite. Magnetite constitutes the groundmass. The group comprises 6 specimens. Average heat conductivity is 9.9 millical/cm · sec · °C. Average specific gravity is 4.50 g/cm^3.

Thermal vs. electrical conductivity

A problem in electrical ore prospecting is to discriminate between indications caused by graphitic schists and by massive pyrite ore, both of which may be excellent electrical conductors. In the previous section it was demonstrated that graphitic schists had considerably lower thermal conductivity than the massive ore samples. The authors therefore decided to examine the correlations between thermal and electrical conductivity. Forty-six drill cores from the sample collection were selected for electrical conductivity measurements. The samples were placed under water pressure to fill dry open pores and were then measured by a four-point-method bridge arrangement. The resulting electrical conductivities vs. the thermal conductivities are presented in Fig. 4.

The most striking feature of the diagram is the great difference in thermal conductivity between two types which have strong electrical conductivity, namely, samples with pyrrhotite impregnations and samples of massive ore. In fact, the strongest electrical conductivities in the diagram are those of two cores with pyrrhotite banding almost parallel to the ore axis. These strong electrically conducting cores have thermal conductivities no higher than those of the ordinary greenstone or phyllite Another interesting feature is the great difference between the heat conductivity of massive magnetite ore and that of massive pyrite ore, which is the reverse of the tendency shown by the electrical conductivities. The highest electrical conductivity in the magnetite ore is about the same as the lowest electrical conductivity in the pyrite ore.

The conductivity values in Table 1 are averages within the respective rectangles of Fig. 4.

The electrical conductivities of the pyrrhotite impregnations (Po, Fig. 4) vary between 0.36 and 52.4 mho/cm. The highest electrical conductivity is found in cores where the pyrrhotite bands pass more or less parallel to the core axis, and the lowest conductivity is found in those cores in which the banding is across the core axis.

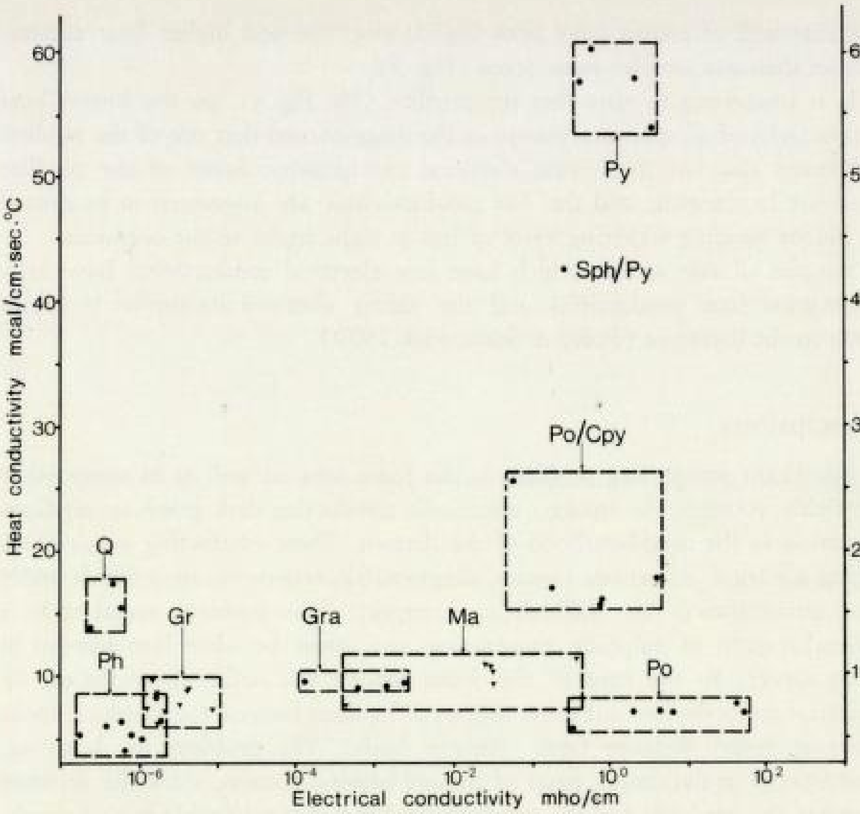

Fig. 4. Heat conductivity vs. electrical conductivity.
Symbols as in Fig. 3.

Table 1. Average thermal and electrical conductivities within the respective rectangles of Fig. 4

	Thermal (20 °C)	Electrical
Massive pyrite ore	57.3 millical/cm · sec · °C	$1.70 \cdot 10^{0}$ mho/cm
Massive magnetite ore	9.9 » »	$8.50 \cdot 10^{-2}$ »
Chalcopyrite–pyrrhotite impregnations (banded)	18.5 » »	$1.20 \cdot 10^{0}$ »
Pyrrhotite impregnations (banded)	6.9 » »	$1.81 \cdot 10^{1}$ »
Graphitic phyllite	9.2 » »	$1.15 \cdot 10^{-3}$ »
Greenstone (calcitic)	8.0 » »	$3.01 \cdot 10^{-6}$ »
Phyllite	6.9 » »	$8.73 \cdot 10^{-7}$ »
Quartz (veins)	15.7 » »	$4.27 \cdot 10^{-7}$ »

Among the samples the highest thermal conductivity is found in the one chalcopyrite–pyrrhotite impregnations (Po/Cpy, Fig. 4), which contains some sphalerite, and this high value may be partly due to the high thermal conductivity of sphalerite.

The low electrical conductivity of the graphitic phyllite indicates that the graphite content in the samples is low. Graphite schists with higher graphite contents will of course have both higher electrical and higher heat conductivities than our samples from Joma (Fig. 3).

It is interesting to note that the phyllite (Ph, Fig. 4) has the lowest heat conductivity of all specimen groups in the diagram, and that one of the phyllite specimens also has the lowest electrical conductivity. Some of the phyllite cores are biotite-rich, and the low conductivities are suggested to be caused by biotite banding occurring more or less at right angles to the core axis.

Samples of vein quartz which have low electrical conductivity, have relatively good heat conductivity and the values obtained are similar to values given in the literature (Poley & Steveninck 1970).

Conclusions

A significant prospecting problem in the Joma area, as well as in many other ore fields, concerns the strongly electrically conducting dark graphitic phyllites occurring in the neighbourhood of the deposit. These conducting zones cause strong electrical indications (turam, slingram, SP, resistivity, etc.) which under most circumstances are difficult to interpret. This problem seems to be a general feature of sulphide prospecting and must be taken into account in every survey. In the case of the Joma deposit the outlining of the ore by electrical methods does not cause serious difficulties because the graphitic rocks occur at some distance from the ore body. The problem is, however, encountered in the deeper parts of the ore-bearing horizon, since the distance between the ore body and the graphitic phyllites is considerably less at depth. The authors therefore believe that the registration of the heat flow through and around the ore body may possibly give valuable supplementary information about the ore extensions at deeper levels, which cannot be supplied by electrical methods. The heat conductivity contrast between ore and the surroundings is the basic physical parameter in this connection. The actual contrasts are apparent from Fig. 4. The compact pyrite ore has a thermal conductivity which is about 7 times stronger than that of the greenstone country-rock, and approximately 6 times stronger than that of the graphitic phyllites. Heat flow measurements thus appear to provide little possibility of discriminating between the graphitic phyllites and the greenstones. More strongly electrical-conducting graphitic schist from Biddjovagge has a slightly stronger thermal conductivity and its contrast with pyrite ore is from 1 : 5 to 1 : 3. These conductivities correspond with the data given by Halck (1958).

The thermal conductivity of magnetite ore from Fosdalen is of the same order of magnitude as the conductivity of most rocks, for instance the greenstones. Compact magnetite ore of the Fosdalen type is therefore not distinguishable by thermal methods. The conductivities are lower than the magnetite values given by Halck (1958). Our results, however, are similar to those of recent measurements carried out in Sweden (Malmquist & Werner, personal communication, 1973).

The relatively high thermal conductivity of sphalerite-rich pyrite ore suggested that sphalerite is also a fairly good heat conductor. Recent results from Sweden support this suggestion (Werner, personal communication, 1973). This conclusion is geophysically interesting, since sphalerite is a poor electrical conductor. The pyrrhotite impregnations have relatively low thermal conductivity, and most of the specimens show little contrast with results obtained from the surrounding greenstone. The higher conductivities of the impregnated pyrrhotite specimens can be attributed to the presence of chalcopyrite. Since the compact pyrite ore seems to be the only first class heat conductor in the Joma field, the possibilities of using thermal methods to outline the extension of this ore body seem promising.

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