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Temperature Phenomena and Heat Flow Estimates in Two Precambrian Ore-bearing Areas in North Sweden

D. S. Parasnis

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Summary

Temperature measurements in 17 drillholes reaching vertical depths between 365 and 780 m below ground surface in the Skellefte area (lat. 65° 52′ N, long. 20° 20′ E Gr) and Aitik area (lat. 67° 5′ N, long. 21° E Gr) in the Swedish precambrian are reported. The absolute accuracy of the measurements was about 0·03 °C and the relative one about 0·005 °C. A large number of thermal diffusivity measurements were made on rock samples from the two areas in order to estimate the correction to the observed steady geothermal gradients due to climatic amelioration at the end of the Pleistocene. The corrected gradients are between 0·01266 °C m^{-1} and 0·01485 °C m^{-1} (Skellefte) and between 0·01684 °C m^{-1} and 0·02268 °C m^{-1} (Aitik). The diffusivity measurements were supplemented by thermal conductivity determinations on 265 drillcore samples from the different rock formations in the holes.

The undisturbed heat flow in the Skellefte area is found to be 48·7 mW m^{-2} and that in the Aitik area to be 49·8 mW m^{-2}. Distortion of the heat flow due to a sulphide ore in the Skellefte area is demonstrated. The heat flow through the Långsele ore in this area is of the order of 70 mW m^{-2}.

1. Introduction

As part of its research activities, the prospecting department of Boliden Aktiebolag, Sweden, has pursued a programme of temperature measurements in a large number of drillholes in the Skellefte and Aitik orefields in north Sweden, some of which are drilled from the surface and others from deep levels in sulphide mines.

The programme of temperature measurements has been supplemented by laboratory measurements of thermal diffusivity and conductivity on a large number of drillcore samples. Besides pursuing these programmes the Company has also participated in the work of a committee set up by the Swedish Mining Association for a pilot survey of geothermal conditions around sulphide as well as magnetite deposits in Sweden. The data of this survey are being compiled for a separate presentation.

SI units will be used throughout in this paper. Taking 4·18 J as the mechanical equivalent of one calorie the relations with cgs units are as follows:

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* Received in original form 1974 September 25

$$\text{Conductivity } 1\ \text{Wm}^{-1}\,\text{C}^{-1} = 2{\cdot}392\ \text{mcalcm}^{-1}\,\text{s}^{-1}\,\text{C}^{-1}$$

$$\text{Heat flow } 1\ \text{Wm}^{-2} = 0{\cdot}02392\ \mu\text{cal}^{-1}\,\text{cm}^{-2}$$

Dates are also expressed as recommended in SI (year, month, day).

2. The areas and the holes

Temperature measurements in 17 drillholes will be discussed below.

The boreholes fall in two distinct sets, one situated in the Skellefte orefield (65° 52′ N, 20° 20′ E Gr) and the other in the Aitik orefield (67° 5′ N, 21° E Gr) in north Sweden. The geological settings of the holes are shown in Figs 1 and 2. Both areas are peneplanes formed before the onset of the Pleistocene glaciation. The topography of the Skellefte area is, generally speaking, undulating but the topographic relief within the area of measurements is only about 40 m. The mean elevation of the area above sea level (asl) is approximately 220 m. The Aitik area may be characterized as an almost flat plain with a mean elevation of 300 m asl.

From the peneplane morphology of the areas, the rather monotonous geology, the absence of major tectonic disturbances and the fact that the geoisotherms are found to be nearly parallel to each other, it appears that topographic corrections to the temperature measurements are negligible.

The bedrock in both areas is Precambrian and is overlain by a rather uniform glacial drift cover. Less than 2 per cent of the bedrock is exposed.

In the Skellefte area the drift cover varies between 2 and 25 m in thickness at the sites of the 10 boreholes measured, while the cover in the Aitik area is thinner and more uniform (5–12 m).

Petrologically, the bedrock in the Skellefte-field holes consists of either acid volcanics or black shales and greywackes, while that in the Aitik holes consists of skarn-gneiss with occasional pegmatite dikes.

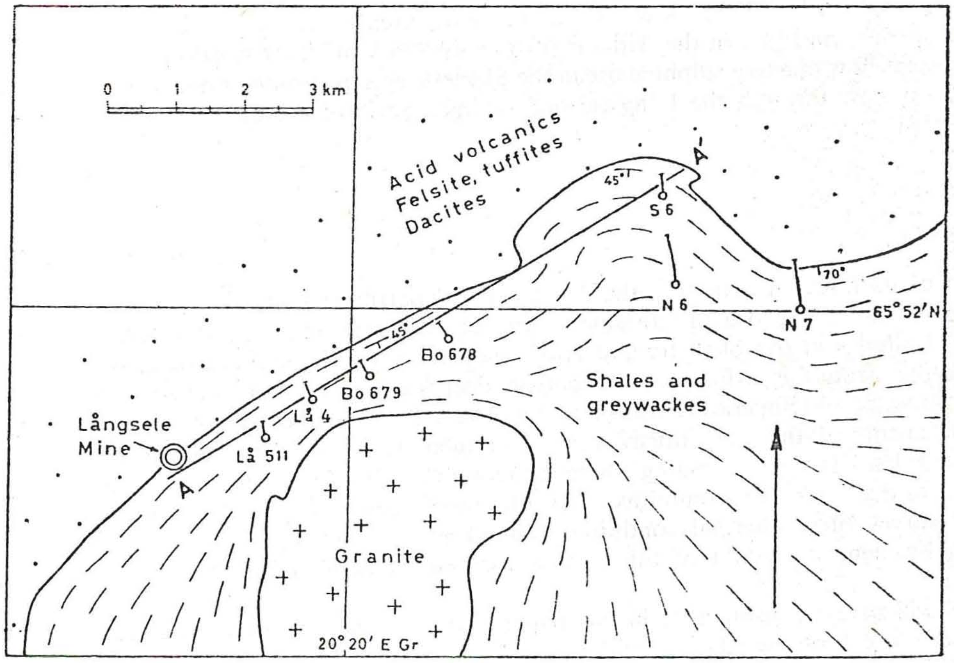
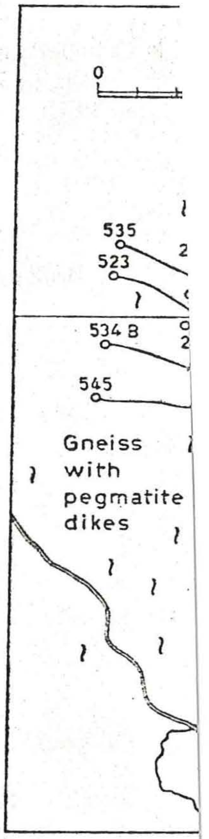


FIG. 1. Geological setting of boreholes in the Skellefte area.



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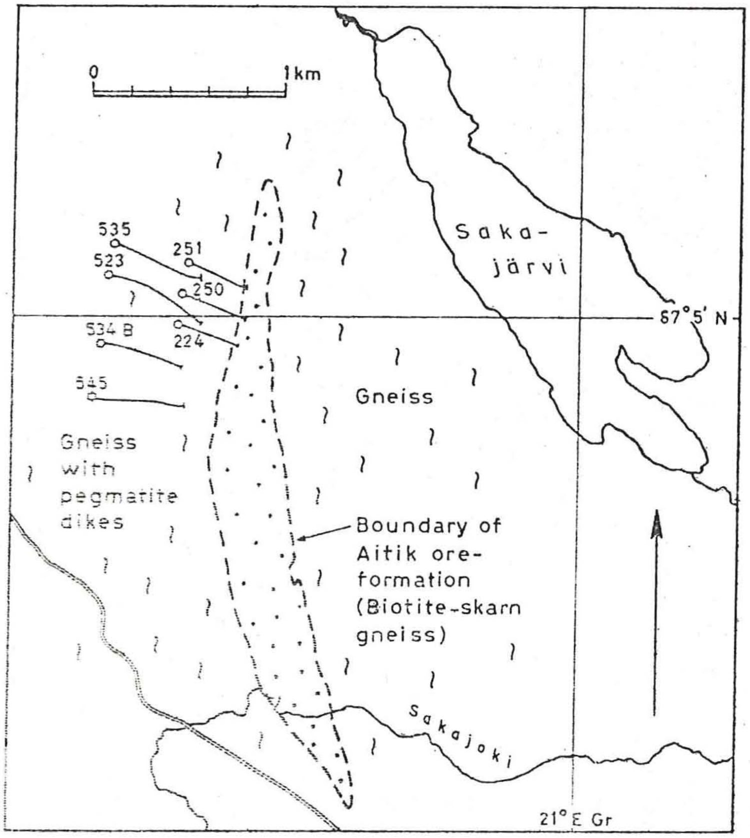

FIG. 2. Geological setting of boreholes in the Aitik area.

The Aitik rock is partly sulphide-impregnated and hosts the Boliden Company's third-generation low-grade Aitik copper orebody which is being worked in open pit since 1968. The sulphide impregnation (mainly chalcopyrite but also some pyrite) that is presently reckoned as workable ore is, however, a very low-grade one having an average sulphur content of 2 per cent (average Cu content 0·4 per cent). The mineralization occurs in what has been called the Aitik formation which dips 45° to the west. The average S content of the formation is probably less than 0·15 per cent. Petrologically the formation does not really differ from the adjoining rocks except for its low-grade sulphide impregnation. The boundary between the impregnated and the unimpregnated Aitik gneisses is quite sharp on the hanging-wall side (Malmqvist & Parasnis 1972).

The 17 holes are diamond drillholes drilled at angles nominally between 63° and 80° with the horizontal. All the holes gradually deviate, however, from the nominal lines of sight in azimuth as well as inclination (*cf.* Figs 1, 2 and 3). Three of the investigated holes have been drilled from the 410-m level of the Långsele mine in the Skellefte field (Fig. 1).

The boreholes have a diameter of 52 mm in the glacial moraine—and 33 mm or less in the bedrock. The holes are not cased in the bedrock. The strength of the Swedish Precambrian bedrock is such that holes in it very often remain open for several years, or even decades, without casing.

All the holes contain water from the groundwater level, which is only a few metres below the surface, down to the bottom of each hole.

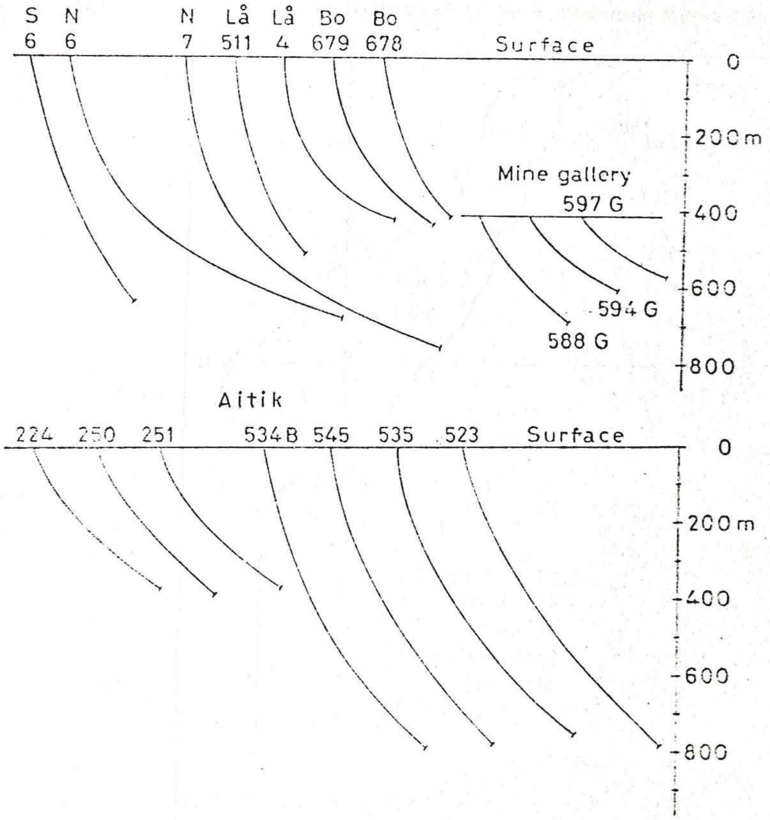

FIG. 3. Profiles of boreholes showing curvatures.

3. Technique of measurements

Temperatures have been measured either by a Hewlett–Packard oceanographic quartz-probe thermometer (model 2800A) or by a thermistor-Wheatstone bridge arrangement. The HP thermometer is a direct digital readout one and works on the principle that the piezoelectric frequency of a suitably cut quartz crystal is temperature-dependent. The thermometer has been calibrated by the manufacturers against a platinum thermometer and is thus an absolute one. Temperatures can be read with an accuracy of 0·001 °C.

The heat capacity of the quartz probe is, however, rather large and the readings drift with time after the probe is in place. The drift is, fortunately, accurately exponential (Parasnis 1971) and extrapolation to infinite time, from readings taken at suitable intervals (e.g. 2, 4, 6 and 8 min) after the probe is in place, is straightforward.

The thermistor-Wheatstone bridge arrangement, in which the thermistor (FS23B) is the unknown resistance in one arm of the bridge, was assembled at the Boliden Company's laboratory. The thermistor was placed and sealed by means of O-ring fittings in an axially drilled hole in a brass rod, about 25 cm long and 10 mm in overall diameter, at the end of a 4-conductor cable. A cable with phosphor-bronze conductors was selected since such a cable has greater tensile strength than a purely copper-conductor cable. The thermistor was smeared with silicone grease before sealing, to secure intimate thermal contact with the brass rod.

The heat capacity of the thermistor probe is sufficiently small for the final resistance reading to be obtained in less than half a minute after the probe is in place.

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All temperature measurements reported in this paper have been made 2·5 years or more after the completion of a hole. There has therefore been adequate time for the borehole to come into thermal equilibrium after drilling.

Although the accuracy of a single temperature measurement is between 0·001 and 0·003 °C the repeatability of a temperature determination at a point in a hole, as shown by separate repeat lowerings of the probes, cannot be quite as good. This is due to inevitable errors in depth—assignment (arising, for example, from indeterminable elastic stretch of cables, unnoticed slip of pulleywheels, backlash etc) and also due to another rather subtle effect, namely, the very slight but nevertheless often noticeable warming-up of the water in the holes due to the cable itself. The repeatability of temperature determination was tested in a number of holes and was generally found to be between 0·004 and 0·01 °C, except when the temperature was affected by flow of fissure water or the annual temperature variation. In the worst case (Nyholm 6) it was about 0·02 °C probably due to the warming-up effect.

The absolute accuracy of a temperature determination in this work is about 0·03 °C.

Generally, all measurements have been made at 10-m intervals as measured by the paid out cable, that is, at 10-m intervals along the hole. As the curvature of all holes is concave upward (Fig. 3) the vertical distance between points of measurement is less than $10 \sin \theta$ if θ is the nominal starting angle of the hole. In the shallower parts of the holes (down to depths of 20–30 m) and in some parts where sudden variations of temperature were encountered, measurements were made at 1-, 2- or 5-m intervals. In the deeper reaches of the Aitik holes measurements were taken at 20-m intervals.

4. Discussion of temperature–depth ($T-z$) curves

Before embarking upon a study of the geothermal aspects of the present measurements, it will be appropriate to discuss the various temperature–depth curves in some detail, as some of the phenomena observed are probably of wide interest in measurements in glaciated Precambrian shield areas. General data concerning the various holes are collected in Table 1.

Table 1

General data on measured boreholes

Hole	Collar elevation (masl)	Start angle deg.	Length (m)	Depth of bottom below ground surface (m)
Skellefte field				
Strömfors 6	195	80	406	386
Nyholm 6	233	80	1079	673
Nyholm 7	167	80	1107	753
Långsele 511	205·1	80	553	508
Långheden 4	218	80	515	407
Boliden 679	214	80	530	432
Boliden 678	227·5	80	559	488
Långsele 588G	−191·01	65	472	724
Långsele 594G	−191·06	63	294	597
Långsele 597G	−191·07	50	283	565
Aitik area				
No. 224	317·71	70	506	365
No. 250	323·87	70	500	383
No. 251	308·77	70	499	369
No. 534B	333·9	80	933	795
No. 545	332·68	80	905	772
No. 535	313·37	80	813	690
No. 523	315·5	80	954	780

It will appear later that, in the two regions studied, the normal horizontal variation of temperature on any level is less than 0·001 °C m^{-1}. Hence, no error of any consequence is involved in horizontally projecting the temperatures measured in a curving hole onto one and the same vertical line in the immediate vicinity of the hole, say the line through the starting point of the hole.

(1) *Skellefte group* (*Figs* 4, 5 *and* 6)

The $T-z$ curve in the hole Strömfors 6 is in many ways typical of the curves obtained in the Precambrian areas of Sweden. It consists of three principal parts.

There is an initial part, from 0 to about 20–50 m depth, where repeated temperature measurements usually yield seemingly discrepant results but where the measured curve can, in fact, be accurately calculated by taking account of the annual temperature variation on the ground surface (Parasnis 1974).

The intermediate part of the curve, starting from about 20 to 50 m and continuing to depths of the order of, say, 300 m is characterized by a smooth increase in the temperature as well as its gradient.

Finally, if the hole is sufficiently deep there is a third part consisting of a straight line whose slope is the observed steady geothermal gradient C' (uncorrected for the effect of post-Pleistocene climatic amelioration). Such a straight part is seen in Fig. 4 for the hole Strömfors 6 from 450 m depth downwards.

Extrapolating the intermediate part of the $T-z$ curve to zero depth we get the present mean surface temperature (S_2) on which the annual variations are superimposed. The straight line of the third part, when produced, intersects the temperature axis at the intercept temperature S_1, the significance of which is discussed later.

For the hole Strömfors 6 $C' = 0{\cdot}01249 \pm 0{\cdot}00016\,°\mathrm{C\,m^{-1}}$, $S_2 = 4{\cdot}055\,°\mathrm{C}$; $S_1 = 2{\cdot}906\,°\mathrm{C}$.

Between about 310 m and 400 m depth in this hole the $T-z$ curve in Fig. 4 shows a slight bulge (about 0·06 °C), which was observed in the repeat measurements as well. This is probably due to a local thermal conductivity change caused by the considerable pyrrhotite impregnation observed in this part of the hole.

In the hole Nyholm 6 the thermal gradient is still increasing at 570 m depth and it seems that the hole is not sufficiently deep to yield the steady geothermal gradient.

In borehole Nyholm 7 the effect of the annual temperature variation seems to extend to a considerable depth but the 31 temperature observations in the deeper interval 300 m to 545 m depth fall on a straight line of slope $C' = 0{\cdot}01235 \pm 0{\cdot}00025\,°\mathrm{C\,m^{-1}}$.

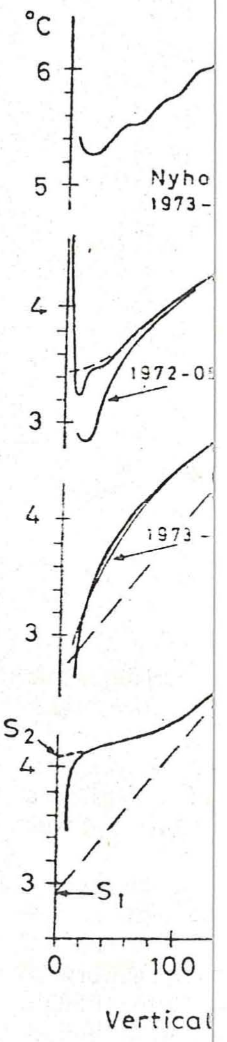
The temperature curve in the hole Långsele 511 is very irregular and is indicative of a tectonically disturbed locality as is witnessed by the corelog. Also water is issuing from this hole under artesian pressure. Some of the irregularities (e.g. at 105 and 230 m) are accounted for by the shear zones observed in the hole while the peculiar notch in the curve at 470 m depth appears to be due to the occurrence here of an amphibolite dike.

No reliable estimate of the steady geothermal gradient can be obtained from hole Långsele 511.

In the hole Långheden 4 a somewhat intense shearing at 330 m depth (with 1 m core loss) seems to cause a distinct temperature anomaly. If the temperature observations in this disturbed zone (325–390 m) are neglected, the $T-z$ curve from 265 m downwards is a straight line of slope $0{\cdot}01255 \pm 0{\cdot}00016\,°\mathrm{C\,m^{-1}}$ (13 observations).

The measurements in the hole Boliden 679 between the depths 220 and 430 m fall on a line of slope $0{\cdot}01022 \pm 0{\cdot}00044\,°\mathrm{C\,m^{-1}}$.

In borehole Boliden 678 the $T-z$ curve from approximately 20 m depth downwards, when smoothed, is concave upwards and approaches asymptotically the dashed straight line in Fig. 11 representing a steady thermal gradient of $0{\cdot}0111\,°\mathrm{C\,m^{-1}}$ (not least squares). Superimposed on the smooth trend are three conspicuous



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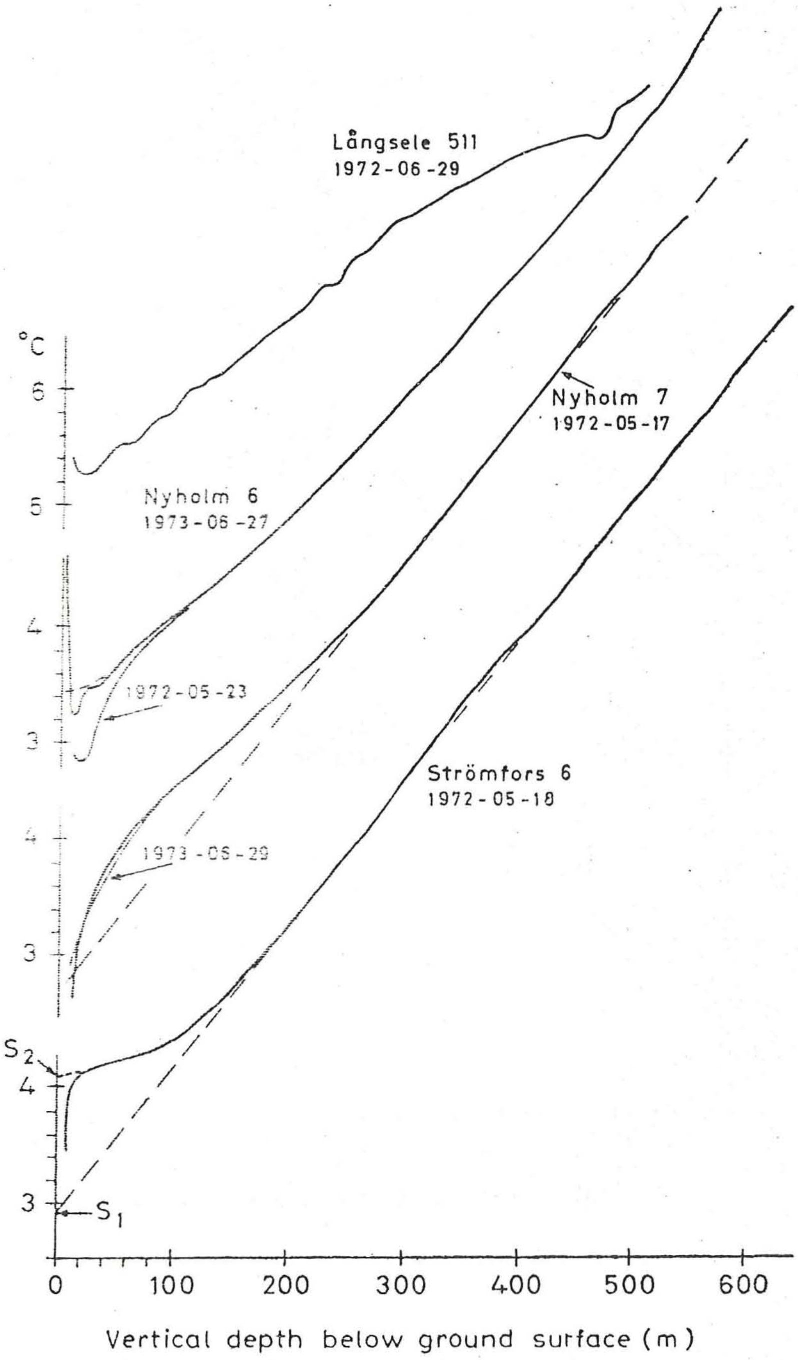

FIG. 4. *T*—*z* curves in some boreholes in the Skellefte group.

deviations in the sections 95–140 m, 320–400 m and 440–470 m. All these appear to correlate with the occurrence of quartz-rich rocks in these sections in an otherwise greywacke or tuffite milieu poor in quartz.

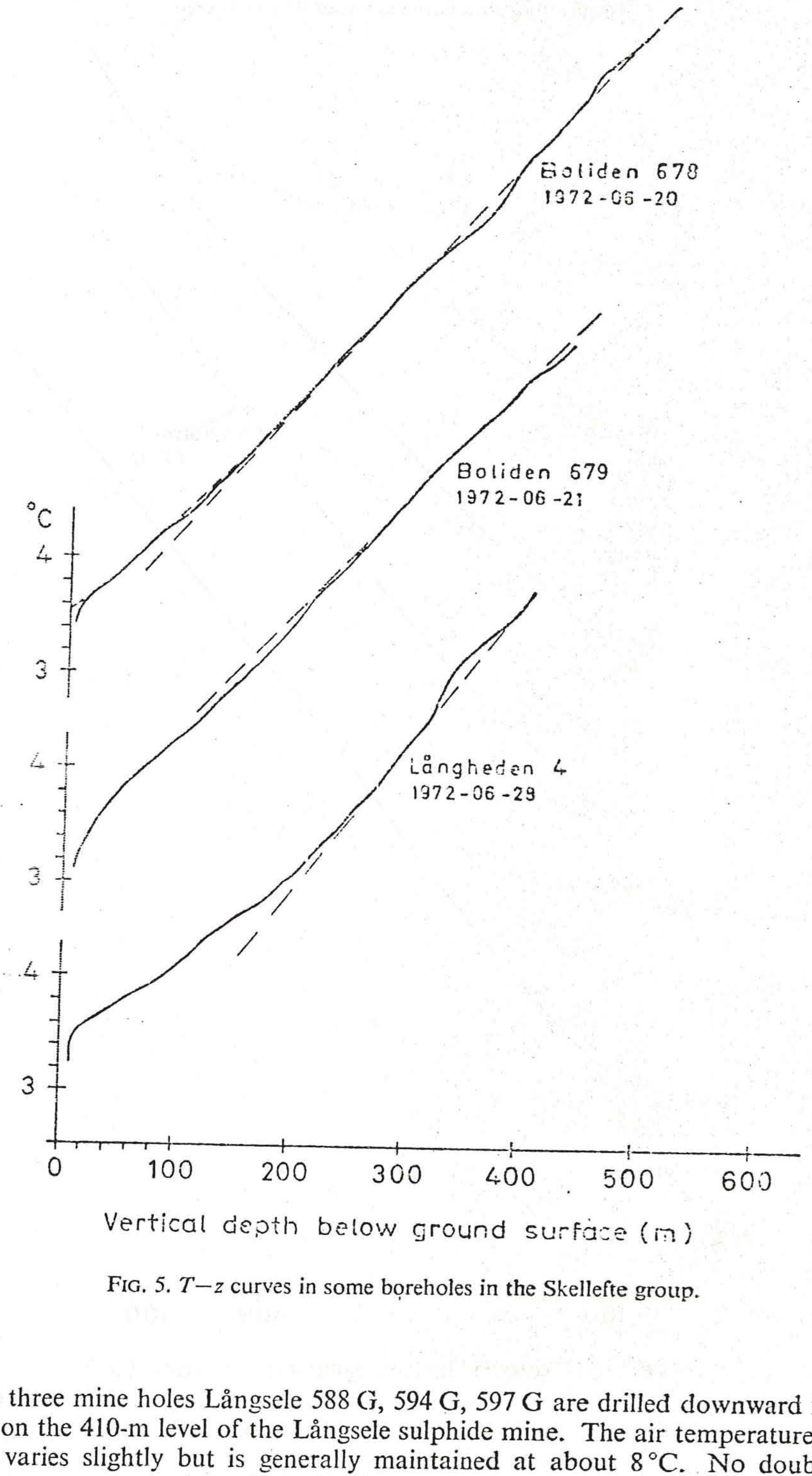

FIG. 5. $T-z$ curves in some boreholes in the Skellefte group.

The three mine holes Långsele 588 G, 594 G, 597 G are drilled downward from a gallery on the 410-m level of the Långsele sulphide mine. The air temperature in the gallery varies slightly but is generally maintained at about 8 °C. No doubt, this temperature penetrates into the bedrock and disturbs the natural temperatures.

It seems that the natural temperatures in 588 G are disturbed down to a depth of about 510 m after which the $T-z$ curve indicates a steady geothermal gradient of $0{\cdot}00797 \pm 0{\cdot}00025\ °\mathrm{C\ m}^{-1}$. The measurements in 594 G from 430 m onwards indicate

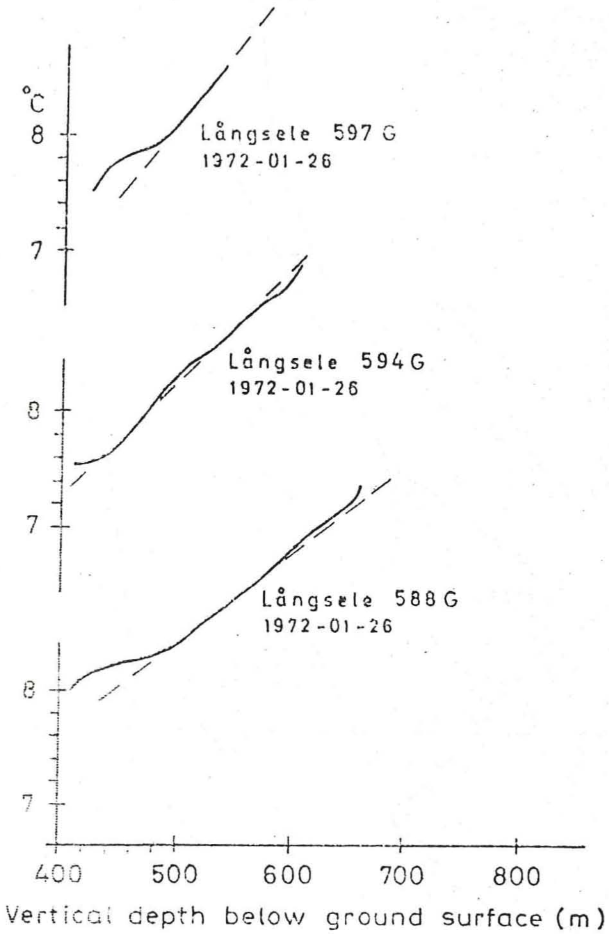

FIG. 6. $T-z$ curve in three boreholes in the Långsele mine.

a gradient of 0·0100 °C m^{-1} (dashed line in Fig. 6, eyedrawn). The slight bulge in the curve at about 510 m has no explanation in the log of the hole.

In hole 597 G the five measurements between 490 m and 540 m depth indicate a gradient of $0{\cdot}01248 \pm 0{\cdot}00035$ °C m^{-1}.

(2) *Aitik group* (*Figs* 7 *and* 8)

The measurements in hole 224 are very irregular. In particular, towards the bottom of the hole there is a very abrupt increase of temperature. Comparing this hole with the other holes in the Aitik area it appears that the temperatures in it down to 360 m depth are lower than normal for the area. Apparently, cold water from the upper regions of the bedrock enters the hole through narrow fissures between 60 and 120 m depth and leaves it through a fissure at 360 m depth. The observed temperatures are therefore not the local steady temperatures of the bedrock. The hole Aitik 224 cannot be used to determine the steady geothermal gradient.

It is convenient to consider the holes Aitik 250 and 251 together. Firstly we notice that at points where the 1970 and 1973 measurements differ, the former always show higher temperatures. This observation can be explained as follows.

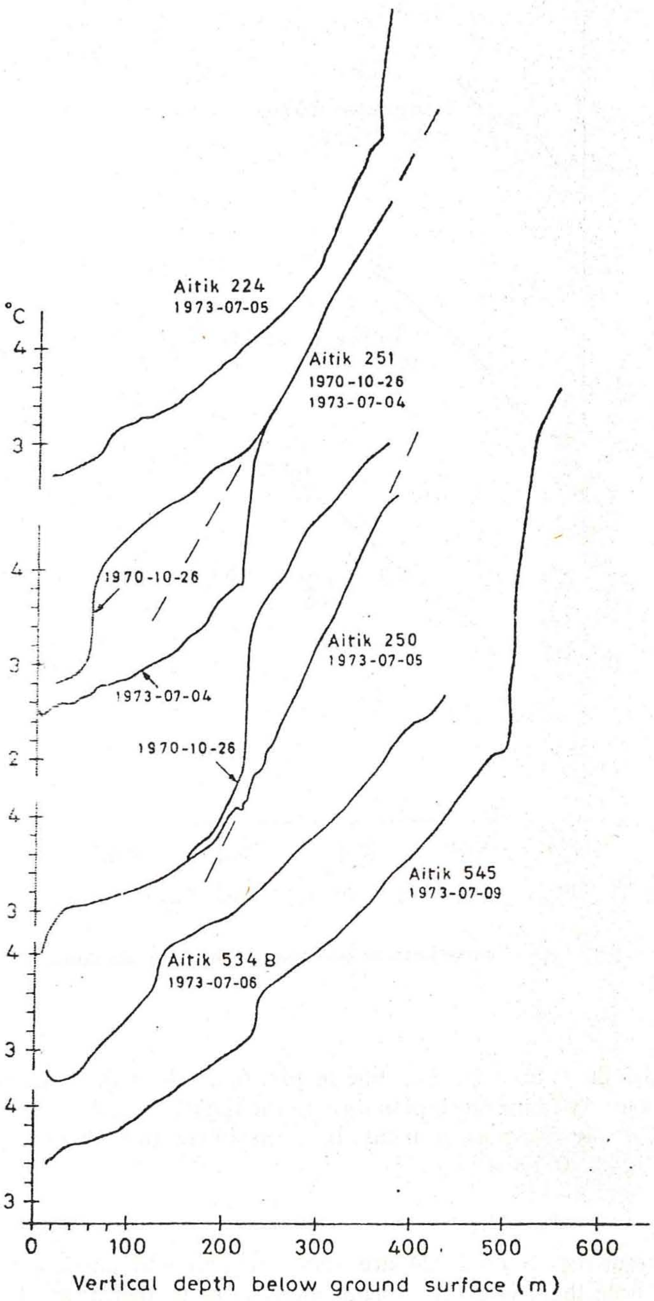

FIG. 7. T—z curves in boreholes in the Aitik group.

The groundwater from the surface regions of the bedrock percolates downwards in both holes through a system of microfissures and leaves the holes at about 200 m depth through a fissure. The presence of a fissure allowing water flow is suggested by the driller's report according to which a loss of drilling water occurring at 192 m depth while drilling hole 250 (in 1965). Now, the 1973 measurements are made at the beginning of July, that is, in the late spring of north Sweden whereas the 1970 measure-

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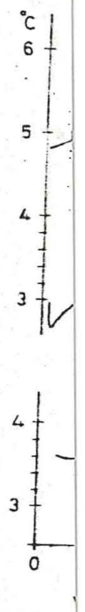

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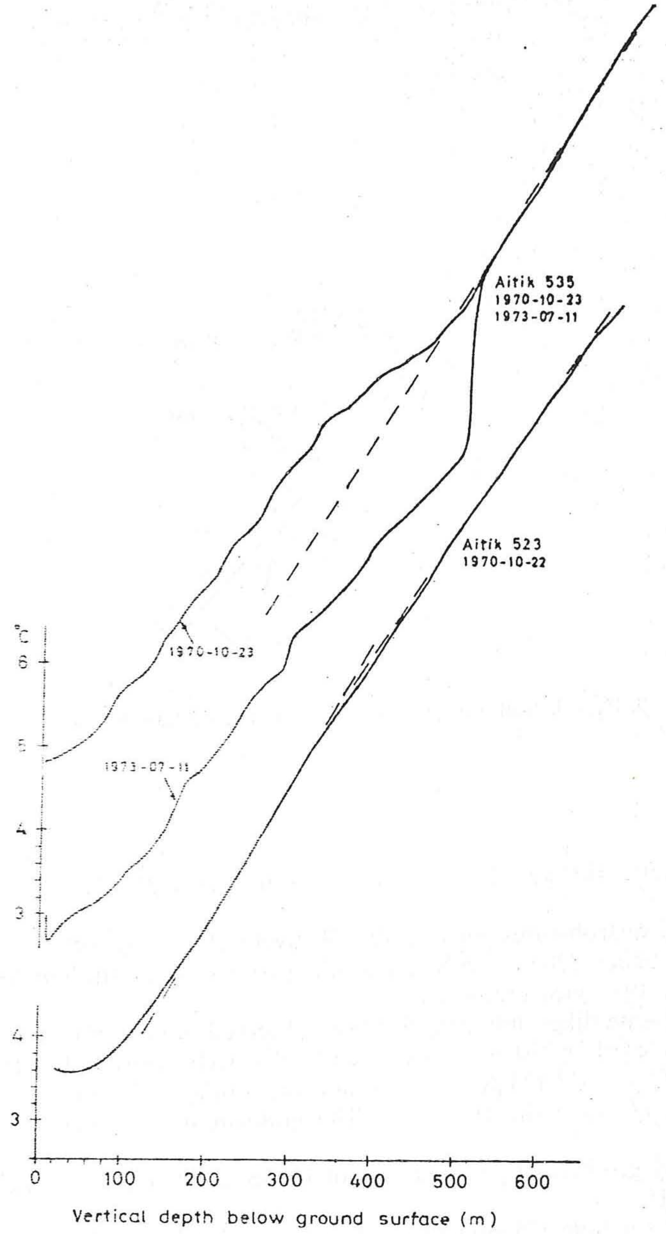

FIG. 8. $T-z$ curves in boreholes in the Aitik group.

ments are made in early autumn and since the groundwater entering the holes at the upper levels is warmer in the autumn we should expect the temperatures measured in the autumn to be higher in that part of a hole where the water is not steady but is percolating continuously according to the mechanism suggested above (*cf.* Fig. 9).

The gradient discrepancy between the 1970 and 1973 measurements in hole 250 below 230 m depth can be explained by assuming that in 1970 the water in the hole was not steady below this depth but was leaving the hole through some then-present microfissures. The existence of a system of microfissures is suggested by the unusually

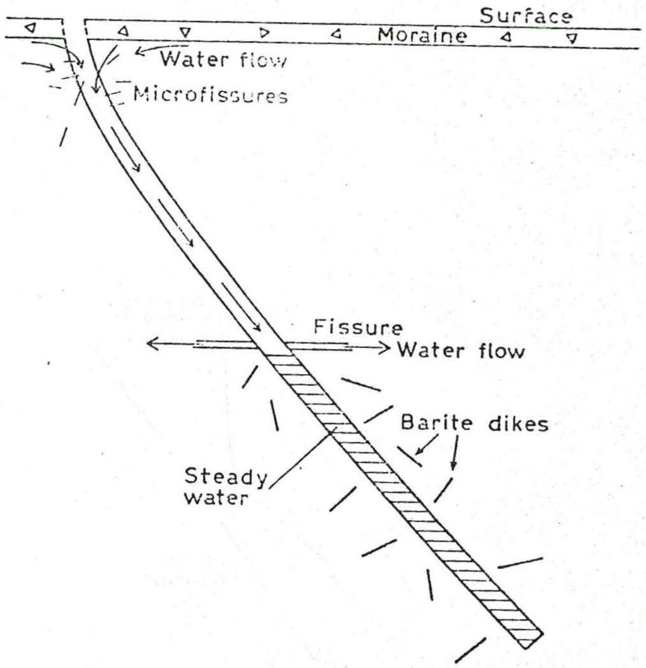

FIG. 9. Hypothetical water flow mechanism in some Aitik holes.

large number of barite dikes that have been observed in hole 250 from 210 m to the bottom.

The system of microfissures must have effectively closed by 1973 making the water in the hole below 230 m steady and leading to a smooth straight line as the $T-z$ curve in the 1973 measurements.

No system of barite dikes, however, has been observed in hole 251. It seems that the water in this hole below 230 m was steady in 1970 as well as 1973. The 1973 figure of $0{\cdot}02072 \pm 0{\cdot}00108\,^{\circ}\mathrm{C\,m^{-1}}$ (23 points) for the steady geothermal gradient in hole 250 appears more reliable than the 1970 one. The gradient in hole 251 is $0{\cdot}01808 \pm 0{\cdot}00096\,^{\circ}\mathrm{C\,m^{-1}}$.

An undisturbed geothermal gradient cannot be obtained from measurements in holes 534 B and 545.

The $T-z$ curves in hole 535 are very similar to those in bh 251. The abrupt jump in the temperature at 510 m depth in 1973 is probably due to a fractured-rock zone recorded between 449 m and 469 m in the log.

The 13 measurements between 550 and 720 m fall almost exactly on a straight line of slope $0{\cdot}01640 \pm 0{\cdot}00034\,^{\circ}\mathrm{C\,m^{-1}}$.

The $T-z$ curve below 180 m in the hole Aitik 523 is found on fine analysis to consist of two straight line segments of differing slopes, one from 180 to 330 m ($0{\cdot}01727 \pm 0{\cdot}00043\,^{\circ}\mathrm{C\,m^{-1}}$) and the other extending from 330 to 660 m ($0{\cdot}01495 \pm 0{\cdot}00019\,^{\circ}\mathrm{C\,m^{-1}}$). The difference in slope can be attributed to a difference in the mean thermal conductivity over the relevant sections (see later).

At 660 m a fourth straight segment of slope $0{\cdot}011\,^{\circ}\mathrm{C\,m^{-1}}$ seems to start but there are too few observations to establish its existence.

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5. Corrections for post-Pleistocene climatic amelioration

The observed steady geothermal gradients must be corrected for the post-Pleistocene climatic amelioration.

The last stage of the Pleistocene is known to have ended in northern Sweden approximately 8900 years ago (Lundqvist 1961; Bergström 1968), Figures for the Pleistocene deglaciation ages in various parts of Sweden are estimated to be accurate to within a few hundred years (Fromm 1973). We may suppose the last stage of the Ice age to have lasted sufficiently long for a constant thermal gradient C to have established itself from the surface downwards with the ground surface (base of ice) at 0 °C. The original $T-z$ curve would therefore have been a straight line of slope C through the origin of the $T-z$ plot ($T = 0, z = 0$). If after a rapid melting of the ice sheet, t_1 years ago, the average surface temperature rose to S_1 C above the freezing point of water, it is well known (see, for example, Ingersoll, Zobell & Ingersoll 1948, chapter 8) that the present $T-z$ curve will be given by

$$T = Cz+S_1(1-\phi(\beta_1)) \qquad (1)$$

where $\phi(\beta_1)$ is the error function with $\beta_1 = z(4\alpha t_1)^{-\frac{1}{2}}$, α being the thermal diffusivity (assumed constant).

For z between 150 and 600 m (the overall depth range for constant gradient in the various holes in the present work) and with $\alpha = 1{\cdot}5\times 10^{-6}\,\mathrm{m^2\,s^{-1}}$ (see below) and $t_1 = 9000$ years, we find that β_1 lies roughly between 0·1 and 0·4. For such small values of β_1 we can use the approximation $\phi(\beta_1) = 2\pi^{-\frac{1}{2}}\beta_1$, the error being only about 0·5 per cent at the lower limit of β_1 and less than 6 per cent at the upper. From (1) we then get (for the range of z of interest) a curve that is effectively the straight line

$$T = (C-S_1(\alpha t_1)^{-\frac{1}{2}})z+S_1. \qquad (2)$$

The slope C' of the straight portion of the present $T-z$ curve is thus $C-S_1(\pi\alpha t_1)^{-\frac{1}{2}}$ and therefore smaller than the equilibrium slope C. The intercept of the present-day straight line represented by equation (2) on the T-axis gives S_1 but it is obvious that even with this knowledge and a knowledge α it is not possible to estimate the correction $S_1(\pi\alpha t_1)^{-\frac{1}{2}}$ from temperature measurements as such.

The correction term in equation (2) can therefore be found, in most instances of this type, only by making plausible estimates of α and t_1. We can determine α either directly (in the laboratory as well as *in situ*) or indirectly from the relation $\alpha = k/(c\rho)$ where k is the heat conductivity, c the specific heat and ρ the density. The latter course was followed in the present work.

Measurements of the specific heat were made on 16 samples of volcanic rocks and 50 samples of shales and greywackes from the Skellefte-field holes and on 36 gneiss samples from the Aitik holes. The mean specific heats for the different groups fall in the narrow range of 706 $\mathrm{J\,kg^{-1}\,K^{-1}}$ (Aitik gneiss) and 723 $\mathrm{J\,kg^{-1}\,K^{-1}}$ (shales and greywackes).

The diffusivities calculated from the relation $\alpha = k/(c\rho)$ gave mean values of $(1{\cdot}57\pm 0{\cdot}05)\times 10^{-6}\,\mathrm{m^2\,s^{-1}}$ for the volcanics, $(1{\cdot}52\pm 0{\cdot}05)\times 10^{-6}\,\mathrm{m^2\,s^{-1}}$ for the shales-greywackes group and $(1{\cdot}20\pm 0{\cdot}04)\times 10^{-6}\,\mathrm{m^2\,s^{-1}}$ for the Aitik gneiss samples. The standard errors stated are for the mean.

Mean values of S_1 determined from the intercept of the straight portions of the $T-z$ curves on the T-axis are 2·79 °C for the Skellefte field and 1·96 °C for the Aitik area (excluding the apparently anomalous negative S_1 for hole 250). The corrections to be added to the observed gradient for the rise in surface temperature at the end of the Pleistocene can be calculated now. They amount to 10–25 per cent of the observed steady gradients and are therefore significant:

0·00236 $°\mathrm{C\,m^{-1}}$ Skellefte field (volcanics)

$0{\cdot}00240\,^{\circ}\mathrm{C\,m^{-1}}$ Skellefte field (shales and greywackes)

$0{\cdot}00196\,^{\circ}\mathrm{C\,m^{-1}}$ Aitik area (gneiss).

As to the reliability of these corrections it should be noted that an uncertainty of 500 years in the age assumed for the Pleistocene climatic amelioration (9000 years) will alter the estimates by approximately 3 per cent or between 6 or 7 units in the last decimal place quoted.

The equilibrium gradient C obtained by applying the above corrections is given in Table 4.

It has already appeared in the measurements reported here that the temperature gradient often becomes on an average less steep as the surface is approached. On the other hand, at depths shallower than about 100 m the gradient may start to increase and is, in some cases, considerably steeper than the steady gradient at large depths. That these gradient variations at shallow depths cannot be due to variations in the thermal conductivity is evident already from the uniform lithology in the holes but has also been verified by conductivity measurements on core samples from the relevant sections, which yield mean conductivities that do not differ significantly from the values in Table 3.

Generally speaking, the observations within the first 20–50 m from the surface (where the gradient can even be negative) are satisfactorily explained by the penetration of the annual temperature wave (*cf.* Parasnis 1974) but it is quite possible that the influence of seasonal variations extends in some localities to depths as great as 100 m. This appears to be the case, for example in hole Nyholm 6 in which the temperatures measured at different times of the year differ appreciably from each other above 100 m but are reproducible within the experimental uncertainty (0·005–0·01 °C) below this depth.

However, even when the gradient variations at depths less than 120 m in the Skellefte holes are disregarded we find that there is almost always a continuous increase in the slope of the $T-z$ curve between this depth and the depth at which the regime of equation (2) starts. Such trends are also present in the measurements of Puranen *et al.* (1968) in Finland.

The present average surface temperatures (4 °C in the Skellefte area and 3 °C in the Aitik area) indicated by the trend of the $T-z$ curves towards zero depth are higher than the temperatures S_1 obtained from the intercept of the measured gradient-line on the T-axis (*cf.* equation (2)). This is suggestive of an additional climatic amelioration besides the one that marked the end of the Pleistocene. Modern researches (Denton & Karlén 1973) show that the holocene climatic history of north Sweden (and the Northern Hemisphere in general) has been very complex. It is too much to expect that geothermal measurements, with all their uncertainties, will be able at present to shed much light on the fine-structure of this complex history or even on the gross temperature changes that took place more than perhaps a century or two ago. Nevertheless it is worthwhile to examine the consequences of a hypothesis which attributes the curvature of the $T-z$ curves to a single step-change in surface temperature, t_2 years ago, from S_1 at the end of the Pleistocene to S_2, the present temperature.

If we adopt this model, then by an obvious extension of equation (1) the present $T-z$ curve will be given by

$$T = Cz+S_1(1-\phi(\beta_1))+(S_2-S_1)(1-\phi(\beta_2)) \tag{3}$$

where $\beta_2 = z(4\alpha t_2)^{-\frac{1}{2}}$ which, on taking cognizance of equation (2) gives

$$T = C'z+S_1+(S_2-S_1)(1-\phi(\beta_2)) \tag{4}$$

where C' is the observed constant slope of the $T-z$ curve at large depths. From equation (4) we obtain

$$\frac{dT}{dz} = C' - (\alpha t_2)^{-\frac{1}{2}}(S_2 - S_1)\exp(-\beta_2{}^2)$$

since $\phi'(x) = 2\pi^{-\frac{1}{2}}\exp(-x^2)$ and hence

$$\ln(C' - dT/dz) = \ln\frac{S_2 - S_1}{(\alpha t_2)^{\frac{1}{2}}} - \frac{z^2}{4\alpha t_2}. \tag{5}$$

This equation shows that the graph of $\ln(C' - dT/dz)$ against z^2 should be a straight line from whose slope and intercept we can calculate αt_2 as well as $(S_2 - S_1)$. The equation is, of course, valid only down to the depth at which the regime of equation (2) starts.

Fig. 10 shows the plots of $\ln(C' - dT/dz)$ against z^2 in holes Strömfors 6, Nyholm 6, Långheden 4 and Boliden 678. For reasons already discussed, the observations above 100 m depth have been disregarded in constructing these plots. Also, since the quantity $\ln(C' - dT/dz)$ is very sensitive to irregularities in the $T - z$ curve, the observed values of dT/dz have been averaged over three consecutive determinations (an interval of 30 m).

All the plots indicate straight lines in accordance with equation (5). Whatever the details of the climatic history may be, we should expect the magnitudes of αt_2 and $(S_2 - S_1)$ obtained from these plots to be approximately the same for all boreholes, since the climatic history at the sites of all the four holes must have been identical.

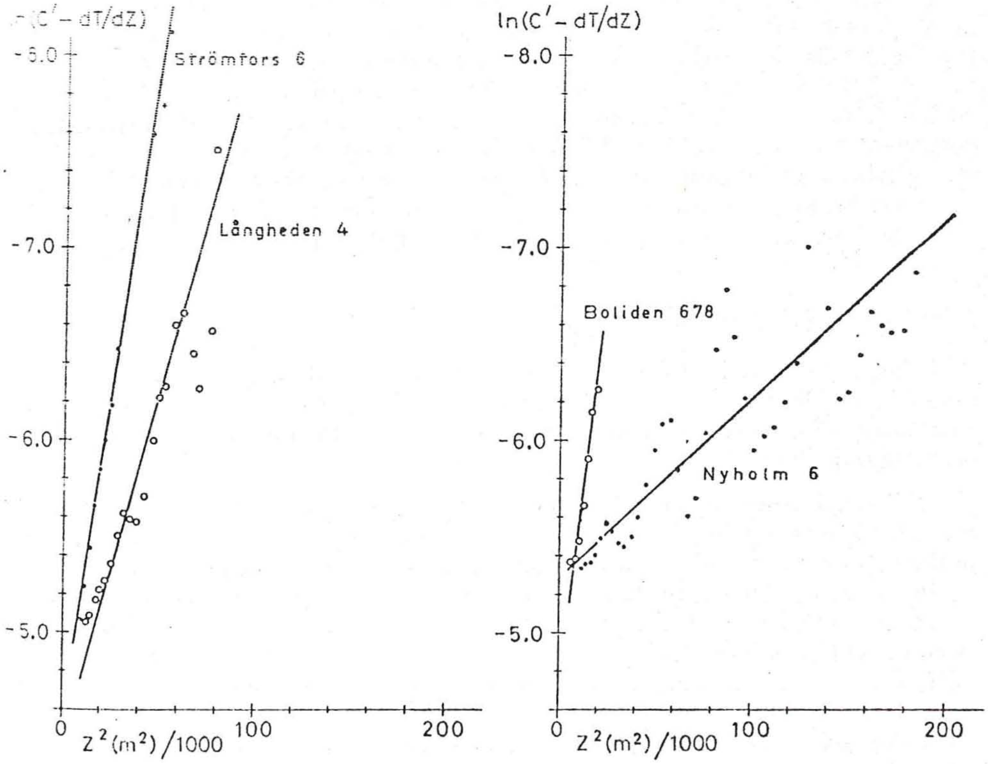

FIG. 10. Plots of $\ln(C' - dT/dz)$ against z^2.

Table 2

Estimates of αt_2 and S_2-S_1

Hole	Intercept	Slope	αt_2 m^2	S_2-S_1 °C	t_2 yr ($\alpha = 1{\cdot}5\times10^{-6}$)
Strömfors 6	$-4{\cdot}598$	$(-6{\cdot}711\pm0{\cdot}916)\times10^{-2}$	3726	1·09	80
Nyholm 6	$-5{\cdot}294$	$(-9{\cdot}201\pm3{\cdot}992)\times10^{-3}$	27171	1·47	580
Långheden 4	$-4{\cdot}408$	$(-3{\cdot}707\pm1{\cdot}866)\times10^{-2}$	6744	1·77	160
Boliden 678	$-4{\cdot}636$	$(-8{\cdot}888\pm1{\cdot}244)\times10^{-2}$	2813	0·91	60

$(9{\cdot}7 \leqslant z^2/1000 \leqslant 20)$

In Table 2 are given αt_2 and (S_2-S_1) obtained from the least-squares adjusted straight lines in Fig. 10. While (S_2-S_1) is of the same order of magnitude for all the holes, the values of αt_2 vary considerably, the most conspicuous deviation being that for hole Nyholm 6. However, it should be recalled that a steady thermal gradient has not been obtained in this hole so that the αt_2 value for this hole cannot be considered to be definitive. The calculations for this hole have been made by assuming $C' = 0{\cdot}013\,°\mathrm{C\,m^{-1}}$.

Using the mean S_1 (2·79 °C) mentioned earlier we find $S_2 = 4{\cdot}1$ °C, which is consistent with the surface temperatures estimated by extrapolating the $T-z$ curves to zero depth.

Table 2 shows that if the curvature of the $T-z$ curves in the Skellefte-field holes is attributed to a single (virtual) step-rise of surface temperature in the holocene, the estimates of the age of the rise vary between 60 years and 580 years, that is by a factor of nearly 10. This variation is probably representative of the precision (or rather the lack of it) with which the climatic history of the non-immediate past can in general be deduced from geothermal measurements alone.

At best we can say that the geothermal measurements reported here are not inconsistent with the following general surface temperature history for the Skellefte area: A step-like increase by 2·8 °C at the end of the Pleistocene 9000 years ago (this age being known from other evidence than geothermal measurements while the magnitude of the rise is estimated from geothermal measurements) and a subsequent (virtual) step-increase by about 1·3 °C for which amelioration, temperature measurements indicate an age in the range 60–600 years. Whatever the actual climatic history may have been this is probably as far as we can reasonably go in the present case in attributing the curvature of the $T-z$ curve to climatic changes.

6. Thermal conductivity measurements

In order to make heat flow estimates we must know the thermal conductivity of the rocks besides the equilibrium temperature gradient. Conductivity measurements were made on a much larger number of samples than the number used for specific heat determinations.

(1) Technique of measurements: Drillcore samples were picked out, to avoid bias towards ‘ interesting ’ bits, at strictly regular intervals (10 or 20 m) over those ranges in the various holes where a steady geothermal gradient was obtained.

In the case of the Aitik holes (Nos 250, 251, 523 and 535) and the two holes Långsele 588 C, 597 G the samples were semicylindrical or sometimes a little smaller since the core has been split longitudinally and one half has been used in chemical analysis for ore estimation purposes. In all the other cases the samples were whole cylinders. All samples were approximately 30 mm in length. The end faces, and for semicylindrical samples also the face parallel to the axis of the cylinder, were ground flat.

In measuring the conductivity, the 'missing' part of the sample was substituted by a half cylinder of a cellular special plastic (type Frigolit). As the conductivity of this plastic is only one hundredth that of a typical rock sample, the correction to the calculated sample conductivity due to the heat flow through the plastic in parallel with the sample is only about 1 per cent.

Very often in geothermal work discs of 2–10 mm thickness are used for conductivity measurements (Beck 1965) but such a small thickness was considered unsatisfactory in the present case in view of the crystalline nature of the rocks, the inhomogeneities in which are sometimes several millimetres across. A core bit of 30 mm in length is believed to be more representative of the rock in bulk than a thin disc, for conductivity measurements.

The thermal conductivity was measured by comparing the temperature drops across the sample and a standard. Perhaps the only novel feature in the apparatus that was constructed for the purpose is that the required constant temperature at the cold end is generated by means of thermopile plates (type Siemens PKE 36A001) using the Peltier effect. Provision must be made in this case for cooling the outward side of the thermoelement plate. The warm-end temperature was generated by means of an ordinary electric heating element. The cold end was kept at about 0 °C and the warm end at about 43 °C. By suitable current-control circuits the temperature at either end could be maintained constant within about 0·02 °C. Temperatures at the ends were measured by means of thermistors embedded in the copper discs in contact with the respective elements, and at the sample-standard interface by means of a thermistor embedded in a wafer consisting of two thin silver discs inserted at the interface.

The end faces of sample and standard were smeared with a mixture of silicone grease and beryllium oxide for obtaining good thermal contact. The assembly was firmly pressed together by spring pressure. To prevent lateral heat loss the sample-standard 'bar' was covered with snugly fitting thick Frigolit packing.

All measurements were made with the sample on the cool side to obtain conditions as near those in drillholes as possible. Depending upon the conductivity of the ore sample, its average temperature in the steady state was between about 10 °C and 20 °C, that of the standard between about 32 °C and 42 °C.

The standard selected is a cylinder (diam. 32 mm, length 31·15 mm) of rather pure natural isotropic, polycrystalline quartz sawn from a quartz-dike in a drillhole in the Skellefte field. Its conductivity, $k_Q(T)$ at temperature T, as determined by comparison with an equal cylinder of 99·99 per cent pure bismuth is found to be

$$k_Q(T) = 7{\cdot}69 - 0{\cdot}019\,T\ \mathrm{Wm^{-1}\,{}^\circ C^{-1}}$$

$k_Q(T)$ given by this relation is estimated to be accurate to within about 2 per cent.

The variation of the conductivity of the quartz standard with temperature has been taken into account in obtaining the estimates of rock conductivities given below. The porosity of the rock samples investigated is very low (about 2 per cent) and as trial measurements on some 20 samples showed no consistent difference between wet and dry samples only dry samples were used for subsequent measurements.

(2) Estimates of average conductivities: As will be seen from Fig. 1 the rocks in the Skellefte-field holes fall into two principal lithological categories, namely, the metamorphosed shales and greywackes belonging to the sedimentary series on the one hand and the felsites, tuffites, dacites, keratophyres and quartz-porphyries of the underlying formation on the other hand.

The only hole in which an undisturbed gradient has been obtained in the volcanic formation is Strömfors 6 while there are four holes (Nyholm 7, Boliden 678, Boliden 679 and Långheden 4) in which an undisturbed gradient has been obtained in the shale formation.

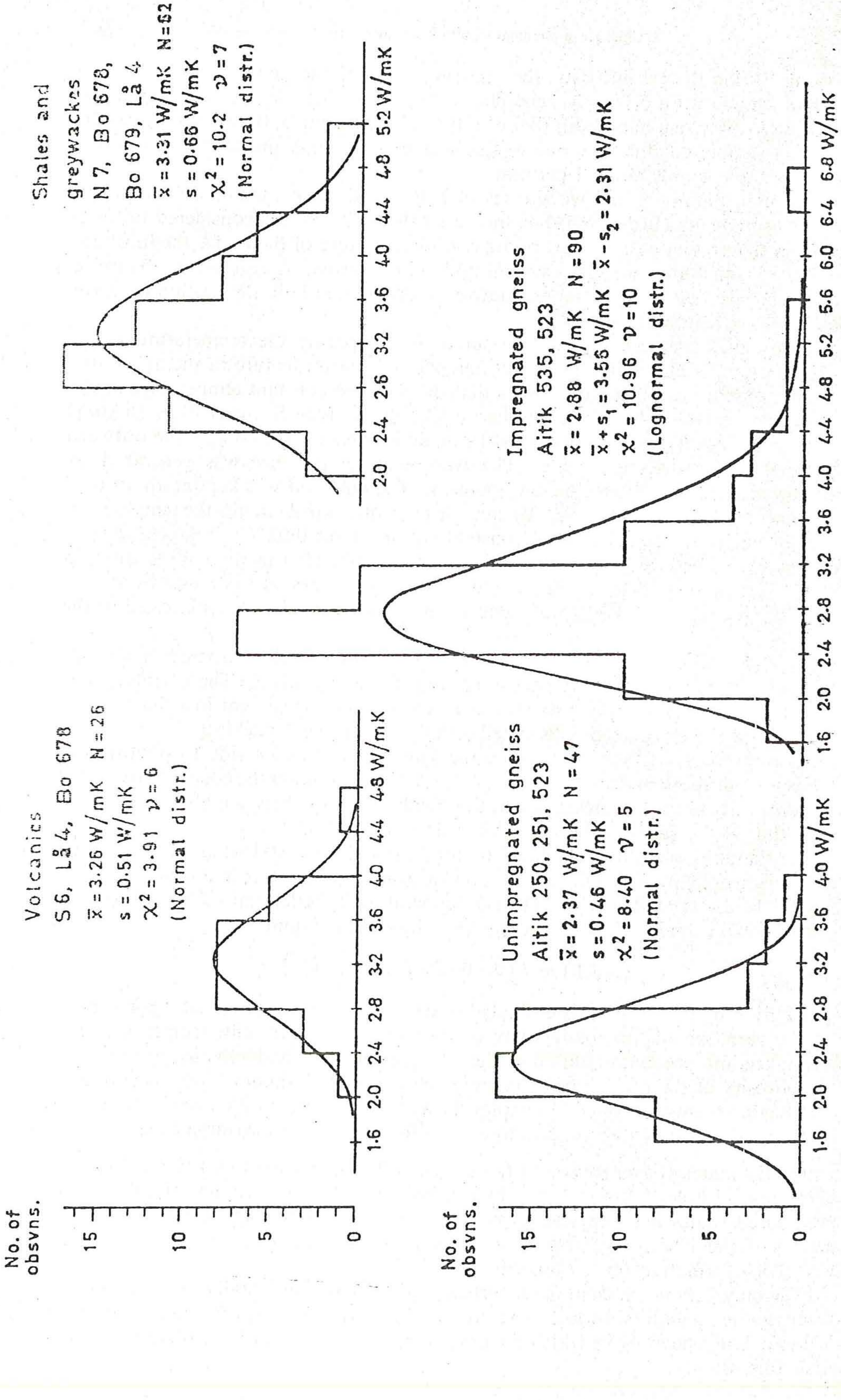

Fig. 11. Histograms of thermal conductivity measurements.

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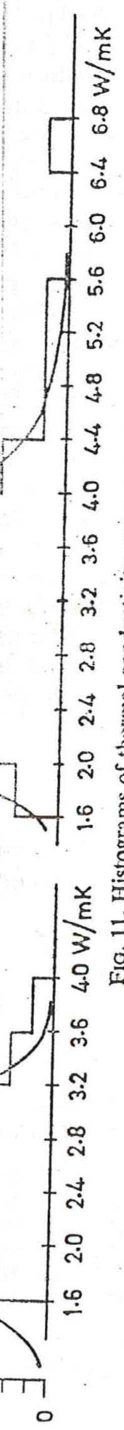

FIG. 11. Histograms of thermal conductivity measurements.

Table 3

Thermal conductivities

Hole	Formation	No. of samples	Mean conductivity and std error of mean (Wm^{-1}°C^{-1})
Strömfors 6	Volcanics	16	3·14±0·07
Långheden 4	Volcanics	5	3·53±0·38
Boliden 678	Volcanics	5	3·36±0·11
Total, Grand Mean and SE of GM		26	3·26±0·10
Nyholm 7	Shales and greywackes	23	3·31±0·11
Boliden 678	Shales and greywackes	16	3·45±0·19
Boliden 679	Shales and greywackes	16	3·16±0·21
Långheden 4	Shales and greywackes	7	3·36±0·22
Total, GM and SE of GM		62	3·31±0·08
Aitik 250	Gneiss without sulphides	20	2·32±0·11
Aitik 251	Gneiss without sulphides	20	2·44±0·11
Aitik 523	Gneiss without sulphides	7	2·33±0·10
Total, GM and SE of GM		47	2·37±0·06
Aitik 535	Gneiss with sulphide imp.	62	2·98±0·12
Aitik 523	Gneiss with sulphide imp.	28	2·81±0·12
Total, GM and SE of GM		90	2·92±0·12

In the Aitik holes also the rocks fall into two principal categories, namely, the unimpregnated gneiss on the hanging-wall side and the sulphide-impregnated gneiss. As has been mentioned previously the boundary between these two is quite sharp on the hanging-wall side.

Standard statistical F- and t-tests show that the variation of thermal conductivity in the volcanic as well as in the sedimentary group of the Skellefte field is completely accounted for by within-sample variation in the respective group and sets of samples taken from different holes do not differ significantly in mean conductivity. A grand mean has therefore been calculated for all the volcanic samples and another one for the sedimentary samples.

Similarly two grand means have been calculated for the two groups of unimpregnated and impregnated Aitik gneiss samples. Nor surprisingly, the difference in mean thermal conductivity between these two sets was found to be statistically significant on the relevant degrees of freedom (risk of null hypothesis being wrong = 96 per cent).

Histograms of the measurements on the above-mentioned rocks are shown in Fig. 11. Distributions not significantly different from Gaussian are obtained in all the cases except for the impregnated samples from Aitik 523 and 535 for which a log-normal distribution is obtained.

In Table 3 are given the mean conductivity figures and the standard errors of the means for the volcanics, shales and the gneiss groups.

It is much more difficult to obtain a representative value of thermal conductivity for the holes Långsele 588C and 597C in both of which a reliable steady geothermal gradient has been observed. This is because the holes intersect not only sulphide-ore sections of varying grades but also the low-grade, sericitized aureole surrounding the

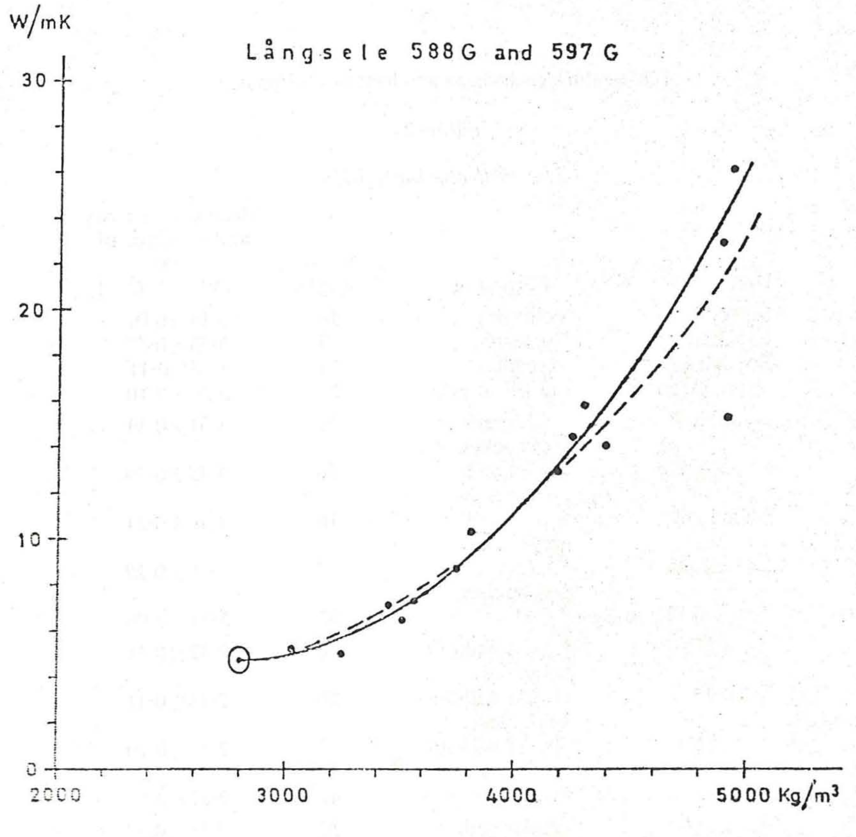

Fig. 12. Dependence of thermal conductivity (k) on density (ρ). The curve shown represents the least-squares equation. $k = 42{\cdot}26-0{\cdot}02611\rho+4{\cdot}5803\times10^{-6}\rho^{2}$ (std error of estimate of $k = 0{\cdot}962$ Wm^{-1} °C^{-1}). The dashed curve is the least-squares curve obtained by neglecting the point (4920, 15·3).

sections. The thermal conductivities of samples from the ore sections do not form a homogeneous population because the conductivity is correlated with sulphide content (and hence density, Fig. 12).

In the section 430–745 m in hole 588G, showing a steady geothermal gradient (Fig. 6), 12 samples ranging from 4·53 to 12·95 Wm^{-1} °C^{-1} gave a mean of 6·45 Wm^{-1} °C^{-1} (standard error of single observation 2·66 Wm^{-1} °C^{-1}, the median being 5·34 Wm^{-1} °C^{-1}. The large variability in the conductivity is due to the fact that the section comprises aureole as well as compact ore. A 'round' figure of 6 Wm^{-1} °C^{-1} is adopted as representative of the thermal conductivity of this section.

In hole 597G the section of steady geothermal gradient (430–610 m) intersects only the aureole. It is evident from Fig. 12 that the dependence of k on density practically disappears when the density falls below 3000 kg m^{-3} (corresponding approximately to a sulphide content of 18 per cent). Samples of density less than this value may therefore be taken to belong to the aureole region. They form a relatively homogeneous group of small variability in thermal conductivity. Fifteen aureole samples form holes 588G and 597G yielded a mean of 4·65 Wm^{-1} °C^{-1} with standard errors of 0·46 Wm^{-1} °C^{-1} (single observation) and 0·12 Wm^{-1} °C^{-1} (mean). The ellipse in Fig. 12 represents the ellipse of dispersion for these 16 aureole samples.

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7. Heat f

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Långsele 594
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Aitik 251
Aitik 535
Aitik 523

7. Heat flow estimates

Table 4 lists the observed and corrected gradients, the mean conductivities and the heat flow values obtained in the present work. Since the heat flow is the product of the corrected gradient and the conductivity, its standard error is calculated from the rms deviations of these two quantities expressed as percentages.

The uncorrected gradients found here are of the same order of magnitude (0·011–0·024 °C m^{-1}) as those reported by Puranen *et al.* (1968) in the Finnish part of the Baltic shield.

Turning first to the Skellefte-field holes we see that the heat flow in the Långsele mine holes is distinctly greater than that in the other holes in the area. Evidently the Långsele sulphide ore is diverting the normal geothermal flow because of its high thermal conductivity. We should therefore expect the isotherms to be systematically distorted in the neighbourhood of the ore. This is clearly seen in Fig. 13 which represents a vertical section of the region, along the line AA′ in Fig. 1. The vertical scale in Fig. 13 is exaggerated 10 times so that the topography and the shape of the ore are considerably distorted.

Further, to keep Fig. 13 simple, only selected temperatures are plotted on it. These are: (a) Temperatures at points 100, 0, −100, −200, −300 and −400 m above sea level, and (b) Temperatures 5, 6, 7, 8, 9 and 10 °C at the appropriate depths read off the $T-z$ curves. In drawing the isotherms the temperatures in hole Lå511 have been disregarded as these are clearly abnormal due to other causes (see above).

It will be seen that the horizontal gradients at any particular level are only of the order of 10^{-4} °C m^{-1}. Even the gradient between the abnormal hole Lå511 and the hole Lå4 is at most 0·002 °C m^{-1}. Thus, as pointed out at the beginning of this paper, no error of any consequence is involved in projecting the measured temperatures in a curving hole, onto one and the same vertical line in the immediate vicinity of the hole, even if a hole curves as much as N6 (Fig. 3).

The heat flow values in the two holes farthest from the Långsele mine, namely S6 and N7, agree closely with each other. Their mean 48·6 mW m^{-2} probably represents the undisturbed heat flow in the area.

Table 4

Geothermal gradients and heat flow estimates (H). v = volcanics, s = shales and greywackes, a = aureole of ore, o = ore and aureole, g = gneiss, gs = gneiss with weak sulphide impregnation

Hole	Depth section (m below ground surface)	Formation	Gradient ($^\circ\mathrm{C\,m}^{-1}$) observed	corrected	K ($\mathrm{Wm}^{-1}\,^\circ\mathrm{C}^{-1}$)	H ($\mathrm{mW\,m}^{-2}$) uncorrected	correct
Strömfors 6	450–632	v	0·01249	0·01485	3·26	40·7	48·4 ± 1·6
Nyholm 7	300–545	s	0·01235	0·01475	3·31	40·9	48·8 ± 1·4
Långheden 4	265–406 (excl. 325–390)	s	0·01255	0·01295	3·31	41·5	42·9 ± 1·2
Boliden 679	220–430	s	0·01022	0·01262	3·31	33·8	41·8 ± 1·8
Boliden 678	160–408	s	0·0111	0·01350	3·31	36·7	44·7
Långsele 597G	490–565	a	0·01248	0·01484	4·65	58·0	69·0
Långsele 588G	510–680	o	0·00797	0·01033	(6)	47·8	62·0
Långsele 594G	440–600	o	0·0100	0·01236	(6)	60·0	74·2
Aitik 250	230–385	g	0·02072	0·02268	2·37	49·1	53·8 ± 2·8
Aitik 251	247–365	g	0·01808	0·02004	2·37	42·8	47·5 ± 2·7
Aitik 535	550–721	gs	0·01640	0·01836	2·92	47·9	53·6 ± 1·8
Aitik 523	185–330	g	0·01727	0·01923	2·37	40·9	45·6 ± 1·5
	340–660	gs	0·01495	0·01691	2·92	43·6	49·4 ± 1·5

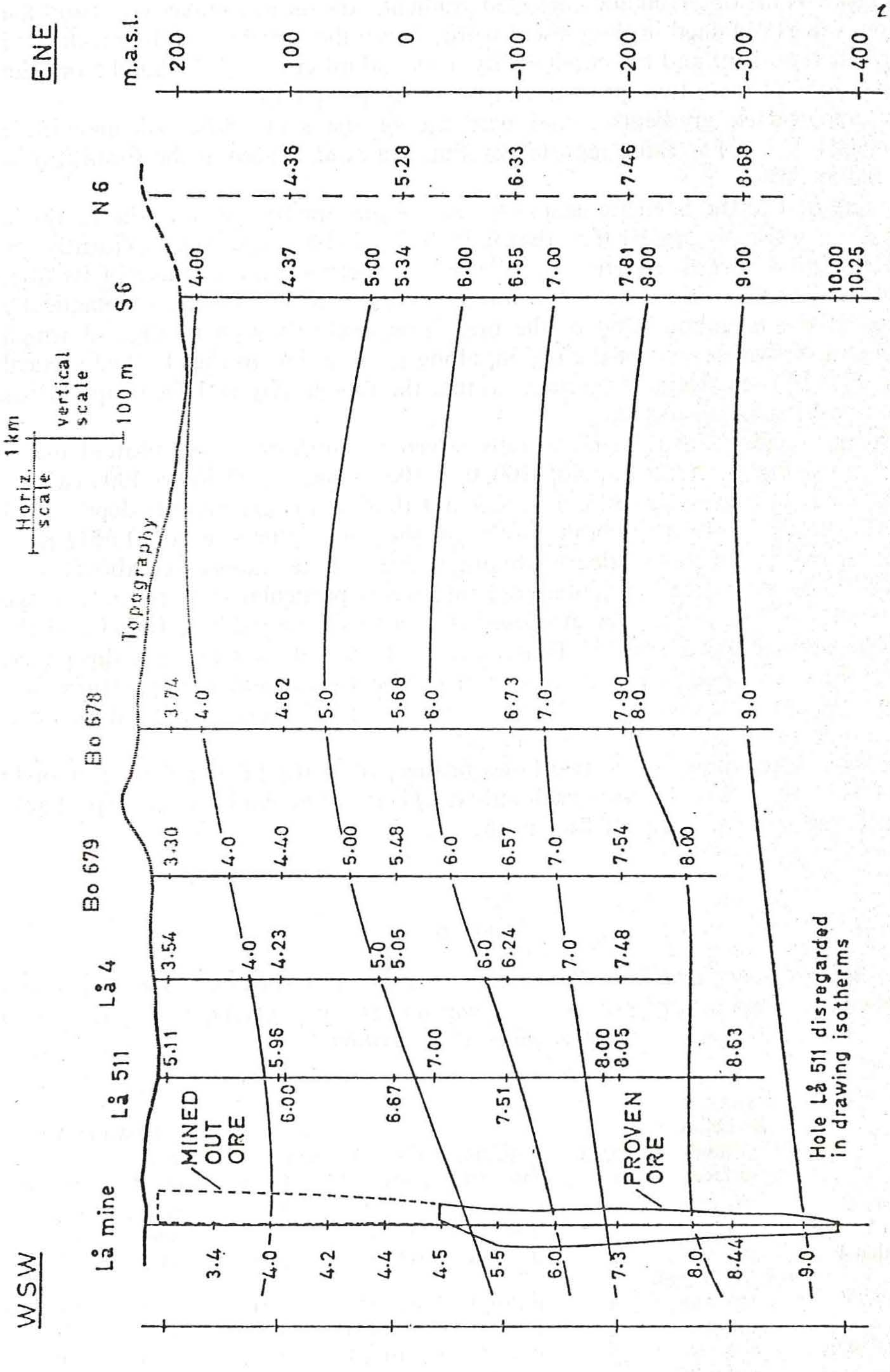

Fig. 13. Vertical section through the line between Långsele mine and borehole Strömfors 6 in Fig. 1.

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Australia
Canada
Kolar, India
South Africa
Ukraine
Finland

Sweden

Skellefte field
Holes S6, N7, Lå
Bo679, Bo678
Holes S6, N7
Aitik field
Holes 250, 251,
535, 523
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Heat flows in Precambrian shields

Shield	Source	Heat flow ($mW\,m^{-2}$)	Std dev. ($mW\,m^{-2}$)	Std error ($mW\,m^{-2}$)	No. of localities
Australia	Lee (1965)	42·6	6·3	2·4	7
Canada	Lee (1965)	36·8	5·4	1·7	10
Kolar, India	Lee (1965)	27·6	—	—	1
South Africa	Lee (1965)	43·0	5·4	2·4	5
Ukraine	Lee (1965)	28·8	2·9	1·7	3
Finland	Puranen *et al.* (1968)	37·6	8·7	3·9	5
Sweden	Parasnis (present work; with climatic correction)				
Skellefte field					
Holes S6, N7, Lå4, Bo679, Bo678		45·3	3·2	1·2	1
Holes S6, N7		48·6	2·1	2·1	1
Aitik field					
Holes 250, 251, 535, 523		50·0	3·6	1·6	1
Skellefte+Aitik		47·6	4·1	1·3	2

In the Aitik area the four holes from which the heat flow can be estimated lie within 500 m of each other, yet the five heat flow estimates range from 45·6 $mW\,m^{-2}$ to 53·8 $mW\,m^{-2}$. The variation is a reflection of the fact that the temperatures in the Aitik area are often somewhat irregular due to the presence of microscopic fissure systems, the effect of which has already been discussed in detail. It is worth noticing in this connection that the standard errors of the Aitik gradient estimates are generally a little greater than in the Skellefte area.

The mean of the Aitik heat flow values is 50·0 $mW\,m^{-2}$. Whether the Aitik formation as such affects the heat flow in the Aitik area significantly is difficult to say because sufficiently deep holes have not so far been drilled outside this formation. Two circumstances, namely the very poor grade of the ore and the fact that the measured conductivities of the Aitik rocks do not differ from the conductivities of micaceous gneissic rocks in general to any significant extent (Clark 1966), suggest that the above mean may represent the undisturbed flow in this part of Sweden.

If the mean of the holes S6 and N7 is adopted as the undisturbed heat flow in the Skellefte area, the Aitik and Skellefte flows do not differ significantly from each other. If, however, the Skellefte-field flows (excepting the clearly anomalous flow in the Långsele sulphide ore) are lumped together, the mean flow in the Skellefte area turns out to be significantly smaller than the Aitik heat flow.

Heat flows reported by Puranen *et al.* for the Finnish shield range from 27·2 to 43·9 $mW\,m^{-2}$ (mean 37·6) but being uncorrected for the effect of deglaciation they are probably considerably lower than the equilibrium heat flow.

Table 5 shows a comparison of the heat flow values in the different Precambrian shields of the world. Various alternative estimates of the mean heat flow in the northern Swedish shield made from the data in Table 5 are shown.

No heat flow values for Sweden have been published up to now, and as the present work involves only two localities in Sweden no firm conclusion can be drawn from the comparison in Table 5.

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FIG. 13. Vertical section through the line between Långsele mine and borehole Strömfors 6 in Fig. 1.

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