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Thermometric analysis of explosion breccias in Obkoronda deposit

V.I. Sotnikov and A.A. Proskuryakov

Explosion breccias are a distinctive feature of subvolcanic hydrothermal deposits (3), including deposits of the copper-molybdenum association where the process of explosive brecciation is closely tied up with the development of magmatism and of ore formation (4, 5). Thus data on the thermodynamic regime of explosion brecciation are important in reconstructing the whole history of development of the endogene process in deposits of the subvolcanic type. We have obtained some thermodynamic parameters in association with thermometric analysis of the explosion breccias in the Obkoronda molybdenum deposit (Northeast Transbaykal).

The central breccia body of the deposit was investigated; it is composed mainly of angular fragments of the leucocratic granite country rock. In areas where the brecciation affects the quartz-feldspar bodies (metasomatic deposits of the early endogene stage of areal "steaming") fragments of quartz which usually has acquired a smoky color clearly predominate. In some parts of the breccia bodies are found fragments of biotite granites and diorites that apparently represent biotite-bearing rocks at deeper levels.

The breccia body was formed as a result of the repeated occurrence of explosive outbursts which are reflected in particular in the varied character of the cementing material. At present we can very definitely speak of two stages of brecciation in the central body at Obkoronda.

In the first stage, possibly preceding ore mineralization, the cement is represented to a significant degree by fine-clastic material that has been metamorphosed (to a distinctive metamorphogenic rock with "ocelli" of quartz). In the breccias of the second stage, which are superposed on the older ones but which were formed after the main molybdenum mineralization, the cementing material also is a fine-clastic mass of the country rock (including that formed in the early stage of brecciation) that has been intensely impregnated by magnetite, giving the late cement a distinctive black color.

In the quartzose part of the groundmass of the "metamorphogenic" cement the primary inclusions contain about 40% gas and are homogenized into a liquid phase at 350-380 and 220-325°. Inclusions that are homogenized into a gas phase at 275-475° are numerous. They are characterized by clearly different phase relationships even within narrowly local areas. The gas-phase content ranges from 40 to 90%, with a predominance of the essentially gaseous components (2). Critical phenomena are noted in inclusions with a homogenization temperature of 355°.

The primary inclusions in the quartz ocelli in the "metamorphogenic" cement are especially common. Among them a group of high-temperature faceted, subfaceted, and round inclusions (50-65% gas phase) with homogenization into a gas at 365-480° is recognized. Syngenetic with them are inclusions that are homogenized into a liquid phase at 340-365°, often with critical phenomena. We must also take note of the primary inclusions with mainly irregular amoeboid forms that homogenize into a liquid phase at temperatures of up to 300°. Such inclusions burst with only slight heating.

One can estimate the temperatures of the later brecciation from the results of the study of the secondary inclusions in the fragmented quartz within the cement as well as from the early secondary inclusions in the quartz ocelli in the "metamorphogenic" cement; their homogenization temperature is 260-315°. Homogenization takes place into a liquid phase.

In the quartz from the quartz-feldspar bodies that have not been affected by brecciation inclusions are rather numerous. Faceted (rectangular and rhomboid), subfaceted, and rounded inclusions predominate, with 50-70% gas phase, that are homogenized both into a gas and into a liquid at 320-365°, along with inclusions with 40% gas that are homogenized into a liquid at 250-320°. Many are three-phase inclusions with liquid and gaseous CO_2.

In the quartz of the coarser quartz-feldspar bodies inclusions also are noted with homogenization into a gas at 280-440°. In this case

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Translated form Termometricheskiy analiz eksplozivnykh brekchiy obkorondinskogo mestorozhdeniya, Vyssh. Ucheb. Zaved. Izv., Geologiya i Razvedka, 1973, no. 10, p. 65-68. The authors are with Novosibirsk State University.

Composition of gas phase (in volume percent) in individual inclusions.

Inclusions	H_2S, SO_2, SO_4 NH_3 HCl, HF	CO_2	O_2	CO	H_2	N_2 + RG*
From quartz-feldspar bodies homogenized into a liquid at 280° C	6	73	Not observed	Not observed	Not observed	16
	4	74	Not observed	Not observed	Not observed	22
Related to late explosive brecciation (homogenized into a liquid at 280° C)	Not observed	52.2	Not observed	Not observed	5.5	42.3
	Not observed	71.2	Not observed	Not observed	3.2	25.6

Analysts: Z.K. Mazurova and N.A. Shugurova, Institute Geology and Geophysics, Siberian Division, USSR Academy of Sciences.

*Rare gases.

they often are syngenetic with inclusions homogenized into a liquid phase. Nonequilibrium and "unlaced" inclusions and inclusions with large amounts of CO_2 occur in a number of associations. All these inclusions probably characterize periods of heterogenization of solutions (perhaps their local boiling) in the general evolution of the hydrothermal system.

Similar inclusions are found in the coarse fragments of quartz in the breccia body. In the small fragments the number of such inclusions decreases significantly; this is especially clearly marked in the decrease in the number of three-phase inclusions with CO_2. Moreover, the total number of inclusions in the quartz fragments from the breccia is significantly greater than in the quartz of the quartz-feldspar bodies.

Secondary inclusions in the quartz fragments are numerous and are localized along systems of variously oriented healed fractures. Their dimensions and morphologic characteristics to a significant degree are determined by the character of the fractures.

Faceted (mainly rectangular and rhomboid) inclusions with 40% gas and homogenization to a liquid at 260-330° are the most typical group of inclusions. Isolated assemblages of syngenetic inclusions are found in which the gas-phase content ranges from 5 to 90%. An unusually great role for CO_2 is displayed in the inclusions. The presence of sets of inclusions with a varied role for CO_2 in the individual syngenetic members is characteristic; this probably reflects the heterogeneous composition of the solutions in association with the presence of free CO_2.

Along some weakly healed fissures completely or partly "unlaced" inclusions with various phase relations are found rather commonly. The solutions that fill them clearly had a weak reaction capability and did not bring about a reworking of the walls of the vacuoles into an equilibrium form. Thus the temperature intervals for the phenomenon of explosive brecciation in the early and late stages are, respectively, 220-480° (or possibly even somewhat higher) and 260-330°. Within these limits occurred a steplike change in the thermodynamic parameters of the system that clearly is depicted by the characteristic groups of inclusions.

A sharp change in the thermodynamic regime in the process of explosive brecciation depended on changes in the aggregate state of the solutions, their boiling and heterogenization in discrete regions. Characteristic here is the formation within narrowly local tracts of syngenetic groups of inclusions with diverse gas-liquid phase relationships, with critical phenomena, and with varied CO_2 contents. The heterogenization of the solutions is represented with special clarity in the early brecciation. Much in common is noted (in relation to the temperature regime and the aggregate state of the solutions) between the process of early explosive brecciation and the formation of the quartz-feldspar bodies.

The period of instability also was reflected in the formation of inclusions of complex nonequilibrium morphology, of palmate, isometric, and subfaceted form, completely or partly "unlaced"; in the presence of essentially gaseous inclusions, and so on. Given an unstable thermodynamic regime the pressure in the system clearly dropped very significantly. Thus, judging from the presence of critical inclusions with homogenization temperatures of 355° (1) and of groups of two-phase gas-liquid inclusions homogenized into a gas phase at 275-280°, these pressures lay in the range 100-200 atm (or even somewhat less).

At the same time inclusions are commonly found with a liquid CO_2 content of up to 80% (or more) of the total volume of the inclusions and with temperatures of complete homogenization of about 300°. The pressure in such

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inclusions, which usually burst even with slight heating, should increase to 700-800 atm at the moment of homogenization. A pressure of up to 580 atm is developed during homogenization of the three-phase inclusions with liquid CO_2 that are homogenized into a liquid or a gas phase at 300-320° (2).

The concentration of the solutions in the process of explosive brecciation was relatively low; this is confirmed by the absence of inclusions with a solid phase, the critical temperatures, the similarity in their critical point to that of pure water, and the common weak manifestation of mineralization related to brecciation.

The composition of the gas phase according to several analyses of individual inclusions is presented in the table, from which it can be seen that, for inclusions related to the explosive brecciation as compared with the inclusions in the quartz-feldspar bodies, H_2 and N_2 + rare gases in association with the absence of sulfur gases and a somewhat reduced role for CO_2 are more characteristic. For inclusions that are syngenetic with brecciation but which are developed on the margins of the explosion breccia body, the role of CO_2 is markedly increased relative to that in inclusions in the central part of the body; this apparently is related to the considerable migrational ability of the CO_2 that is released from the solution during its boiling.

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Terrestrial Heat Flow on Pre-Cambrian Shields in the USSR

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ABSTRACT

Geothermal gradients, thermal conductivity of rocks and heat flow data are given for the Pechenga area, the Monchegorsk pluton, the Ricolatva area, the Koashva and the Khibini mountains in the Kola peninsula, on the Pre-Cambrian Baltic shield. Heat flow values are low, being respectively 0.85 ± 0.00 HFU; 0.95 ± 0.08; 0.69 ± 0.01; 1.22 ± 0.01; 0.85 ± 0.03 HFU. Comparison of geothermal data with seismological data for the Ukrainian Pre-Cambrian shield is given.

Introduction

At the first stage of the Upper Mantle Project, great importance was attached to the problem of studying heat flow on Pre-Cambrian crystalline shields. These relatively stable zones of the earth's crust are convenient for studying contributions of heat flow from the earth's crust and upper mantle.

Because of relatively little drilling on shields and the necessity of long-term preservation of boreholes and wells measurement, fruitful articles were published only at the third stage of the Upper Mantle Project, and these generalized and summarized the whole complex of geothermal and associated geological and petrochemical investigations on shields.

Of great interest were articles by Australian, Canadian and Indian geophysicists, who independently gave basic data concerning low heat flows on Pre-Cambrian shields and correlation of these data with the generation of heat (BECK 1965, JESSOP 1970, LAMBERT, HEIER ET AL. 1968, HYNDMAN ET AL. 1968).

Though crystalline Pre-Cambrian shields can be egarded as the most steady, most consolidated and relaively stable formations of the earth's crust, on the whole lmost all of them have undergone considerable uplift the course of their evolution. As a result of this lift the upper strata of the crust underwent considerle erosion and thus the Pre-Cambrian basement outipped. In this way the upper strata of the crust which been the richest in radioactive elements underwent siderable deterioration. This may account for low ocontent of uranium, thorium, and potassium and consequence, low heat flow in the region of ancient ds (CLARK and RINGWOOD 1964). Another explan of low heat flows on the territory of shields made RASKOVSKY in 1961, was based on the relatively high heat conductivity of ancient consolidated rocks composing shield masses.

Australian investigators, in connection with the beginning of the National Upper Mantle Project, carried out special prospecting drilling at rather shallow depths (200-500 m). Everywhere heat flow for the Australian shield is equal to 41.0 mW/m² (0.98 HFU). Much attention was also attracted by the correlation of the contents of uranium, thorium and potassium, radioactive elements, with geothermal parameters according to depths (HYNDMAN ET AL. 1968, LAMBERT and HEIER 1968). It became possible to draw the conclusion that heat flow from the continental mantle in the region of the Australian shield is 18.8 mW/m² (0.45). (HYNDMAN ET AL. 1968).

The investigations of heat flow on the Canadian shield, which had been carried out for many years (BECK 1965, JESSOP ET AL. 1970) showed that the heat flow field is more stable here and, on the average, is a little lower than on the Australian shield being 29.3-35.6 mW/m² (0.70-0.85 HFU). There exist also very low values 20.9-25.1 mW/m² (0.5-0.6 HFU). At the same time on the Indian shield, GUPTA ET AL. (1970 a, 1970 b) showed that the lower heat flow field on the whole is less stable than on all other shields of the world and anomalies are located, where heat flow value is as much as 60.7 mW/m² (1.45 HFU), on three widely separated regions of the Indian shield.

Geology of the areas under investigation

Our investigations in connection with the tasks of the Upper Mantle Project were carried out on the Kola peninsula of the Baltic shield. According to the programme of the Upper Mantle Project, special drilling was carried out on the Kola peninsula to a much greater depth than on the Australian shield. Of special interest is the Pechenga structure. Here, in wells down to the depth of 1000-2000 m, complex investigations of geothermal, petrochemical and geochemical parameters were carried out. Thickness of the earth's crust in the north-eastern part of the Baltic shield is about 35 km, the top 7 km of which consists mainly of greenstones (LITVINENKO 1960).

The Baltic shield is one of the Pre-Cambrian massifs which may be classed amongst those raised highest

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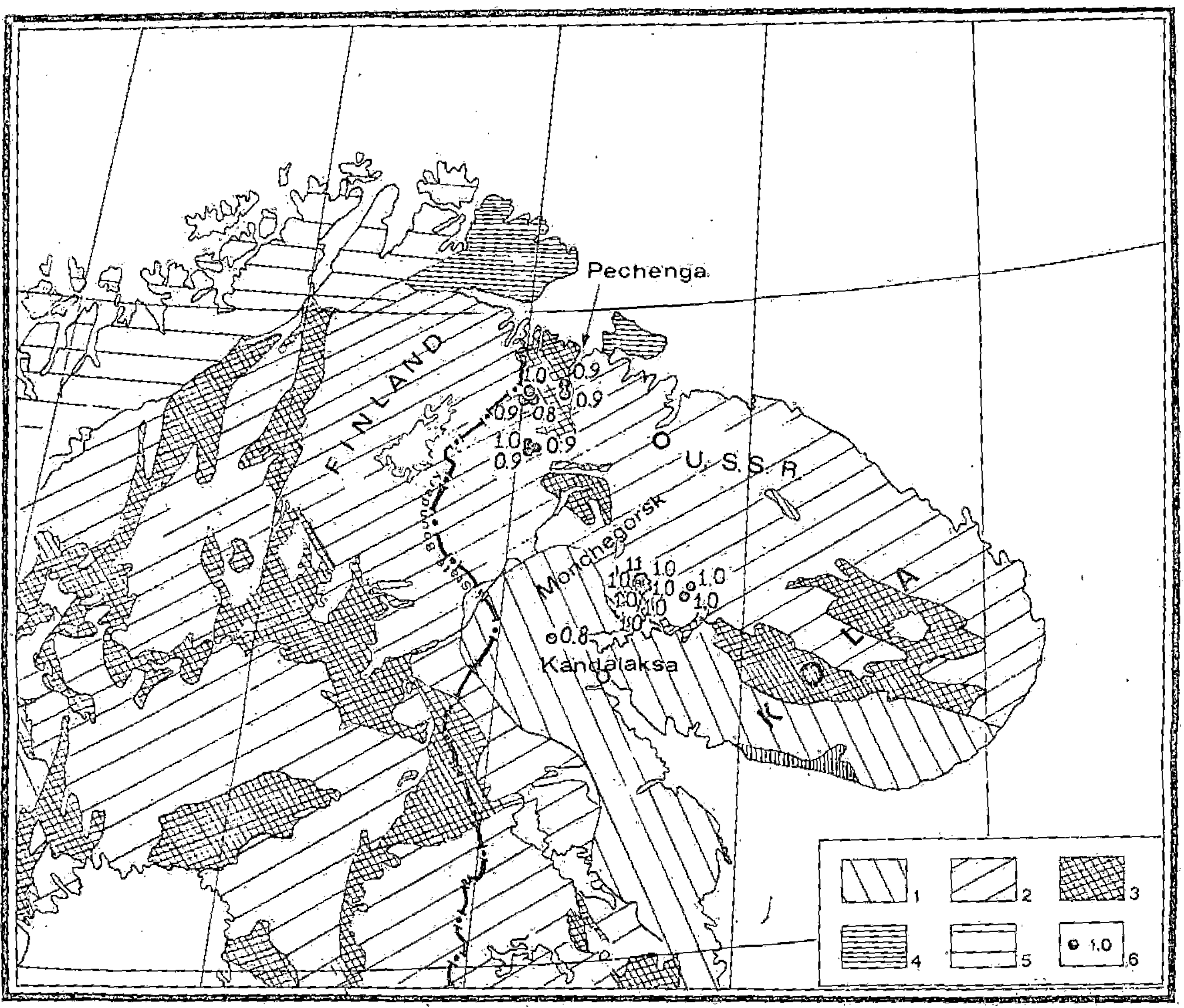

FIG. 1. — *Heat flow map of the Kola peninsula: 1) region of Archean folding; 2) anticlines of Pre-Cambrian foldings; 3) synclines of Pre-Cambrian foldings; 4) Ripheus folding; 5) Caledonian folding; 6) heat flow values, in HFU.*

in the earth, and thanks to this fact and also as a result f continuous denudation of the massif over a great period of time, from the end of the Proterozoic era till the resent day, extremely deep parts of this massif have utcropped.

The Baltic shield consists of Archean formations; aleozoic rocks are known only on the shield margins. esozoic deposits are absent. In the region of the Baltic ield it is possible to distinguish not less than five oronic periods and three Wisconsin phases of glaciations: e first orogenic period occured during the middle of Archean, the second, on the boundary of the Arean and the Proterozoic, the third is called Lapparelian, the fourth Caledonian and the fifth Hercynic.

The most ancient folds are Saamic, they are accomied by huge intrusions of three rock complexes (gab-amphibolite, diorite, granite) and by metallization cesses on the Kola peninsula.

Caledonian folding touched the Kola peninsula only at the edge. At that time different fractures appeared, along which gabbro-diabase and norite intrusions have penetrated and in the central part of the Kola peninsula basic rocks have intruded (Moncha-Tundra). The Khibini Mountains on the Kola peninsula are associated with Hercynian folding. This is one of the largest alkaline rock provinces on the earth.

The Baltic shield underwent large-scale movements only in the Quaternary when it was covered three times entirely by ice and before the beginning of glaciation a strong uplift had taken place, which was stopped by glaciation. Large-scale splits and sinkings are associated with the end of the Quaternary.

Like the Baltic shield, the Ukrainian shield is also a Pre-Cambrian prominence of the Russian platform. Unlike the Baltic shield, the Ukrainian massif is a tec-

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To the south-east the Ukrainian massif joins the Dnieper-Donetsk depression, a geosyncline region. Using data of heat flow obtained by profile measurements along the Ukrainian shield and the Donetsk depression it is possible to calculate the field of deep isotherms and correlate it with temperature gradients according to the results of velocity measurements of seismic waves. Pre-Cambrian shields are convenient areas for evaluating undisturbed heat flow from the mantle.

The study of the heat flow was carried out in 42 wells on the Kola peninsula, in the areas of the Pechenga structure on Archean gneiss outcrops, in the areas of Monchegorsk pluton in Proterozoic pyroxenites and in the Khibini mountains. The locations of these regions are shown in Figure 1.

A geological cross-section of the structure, drawn according to geological and seismic data, is available up to the depth of 5.5 km of the whole column of Pechenga series, which includes diabases and intrusions of gabbro-diabases and ultrabasic rocks. At the depth of 5.5-7.0 km a formation of Archean gneisses occurs and at the depth of 7 km can be found a layer of basaltic rocks.

According to this cross section, the « A » and « B » wells and « Ricolatva » well were chosen. In the « A » and « B » wells gabbric rocks and sedimentary rocks were found, and in the well « Ricolatva » Archean gneisses were found. Cores from these wells were tudied by complex physico-chemical methods which nclude the determination of thermal properties, density, etrographical and chemical analyses of the rocks, as ell as the evaluation of the concentration and distribuon of uranium and potassium in gabbroes and gneisses. hese measurements were carried out by the track-meth, that is by registration of U^{238} fission tracks. Below give data only for the most important regions where, m our point of view, very deep drilling was carried . For the purpose of interpretation we also use vious data from the Kola peninsula which have ady been published (LUBIMOVA 1969).

ults of geothermal investigations

In Figure 1, all the previous and recent heat flow es of the Kola peninsula are shown. In the process easuring temperatures, thermistor elements were . Reading accuracy was ± 0.01°C. Before carrying emperature measurements, a stabilization of wells ome months was provided for. Core samples were undisturbed as cylinders 10-20 cm high and 3-6 diameter.

NGA STRUCTURE AREA

eothermal measurements in the « A » well were out to the depth of 1002 m (reading along the vertical line). The well had been out of work for about one year. In the upper part the well crosses a sequence of alternating phyllites, sandstones and diabases; in the middle part basic rocks of gabbroic type are found; in the lower part periodites and pyroxenites were observed.

Temperature profile, lithology and temperature gradient for the well « A » are shown in Figure 2. Geothermal gradient is 12.6°C/km in the interval of 158-605 m, and then it becomes 12.4°C/km.

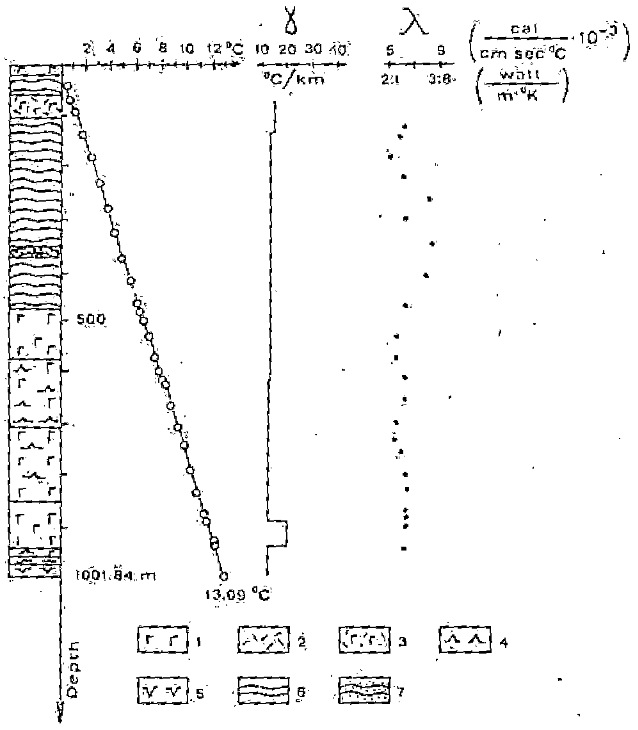

FIG. 2. — *Geological and geothermal logs of well A. 1) gabbro; 2) diabase; 3) gabbro-diabase; 4) pyroxenite; 5) peridotite; 6) phyllite; 7) sandstone.*

Thermal conductivity (λ) was measured in 8 phyllite and 14 gabbro core samples, of 15-20 cm length. In phyllites, λ varied in the range of 2.13-3.50 W/m°K (5.08-8.35 × 10^{-3} cal/cm sec °C). The arithmetic mean gave 2.85 (6.80). In gabbro samples, λ varied in the range of 2.28-2.75 W/m°K (5.45-6.58); mean $\bar{\lambda}$ is 2.58 (6.16). Heat flow in the phyllite formation comes out to be 36.0 mW/m^2 (0.86 HFU), and in the gabbro formation is 3.14 mW/m^2 (0.75). Mean weighted heat flow for the well « A » is 33.5 ± 2.1 mW/m^2 (0.80 ± 0.5 HFU).

In the « B » well (Figure 3) phyllites and sandstones alternate with gabbro-diabases up to the depth of 1023 m. Below diabases, gabbro-diabases and pyroxenites occur. The well had been out of work for 5 months. Geothermal gradient in the phyllite is 11.5°C/km and in gabbroes it increases to 13.8°C/km.

Thermal conductivity of 37 undisturbed core samples, each 15-20 cm in length, was measured. In phyllites it varies in the range of 2.43-3.84 W/m°K (5.81-9.18);

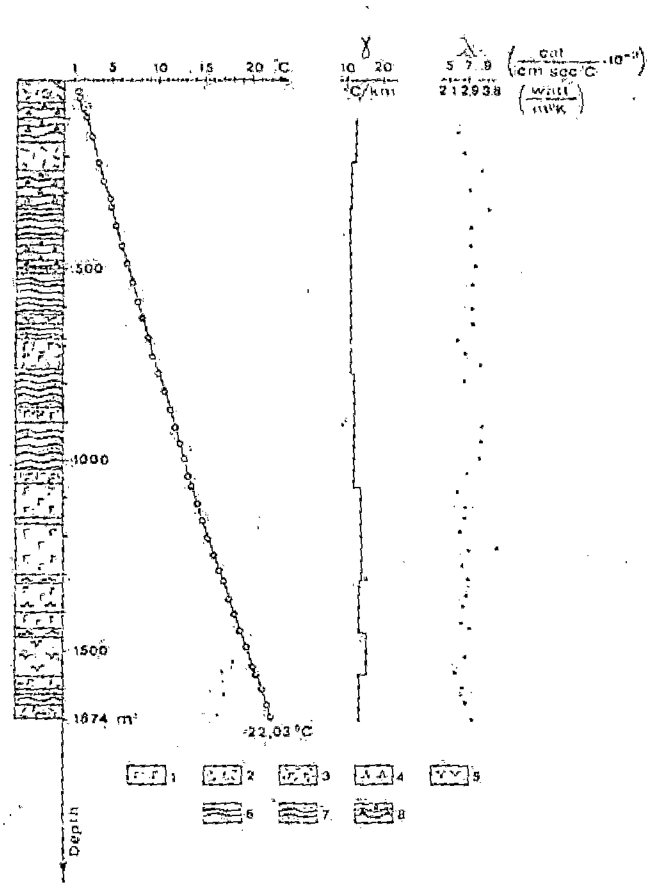

FIG. 3. — *Geological and geothermal logs of well B. Same legend of Fig. 2. Symbol 8 sandstones.*

in gabbroes in the range of 2.29-2.93 (5.46-6.99). The mean $\bar{\lambda}$ (arithmetic) for phyllites is 3.04 W/m°K (7.27) and for baggroes 2.62 W/m°K (6.27). The heat flow for the well « B » in phyllites is 35.2 mW/m² (0.84), in gabbroes 36.0 (0.86) with a mean value of 35.6 ± 3.3 (8.5 ± 0.08 HFU). Combined with the previously reported values in this region, the average heat flow for the Pechenga region comes out to be 33.9 mW/m² (0.81±8%) and with the correction for the glaciation 38.1 mW/m² (0.91 ± 8%).

MONCHEGORSK PLUTON

In the region of Monchegorsk (Figure 1) 6 wells were studied earlier to the depth of 1000 m (LUBIMOVA 1969). They all were situated in the region of Monchegorsk pluton. This is an intrusive body of basic and ultrabasic rocks which are underlain by Archean gneisses. Wells which were studied earlier crossed pyroxenites, peridotites and partly gabbro-norites. In one of the new wells about 20 rock samples were studied for measuring the heat conductivity. The well had been out of work for about 4 months. It crosses diorites and biotites which alternate with biotite gneisses; below 1129 m there appear silicified gabbro-norites, milonite replacement in gabbro-norite rocks, which alternate with gneisses.

Temperature measurements were carried out to the depth of 1425 m (along a vertical line); at the maximum depth the temperature was 18.45°C. In the upper part of the well the temperature increases with increasing depth. The gradient increases gradually from 3.0 to 10.0 °C/km (however in the interval of 397.3-417.0 m it increases sharply to as much as 23.6°C/km). The real causes for such a sudden increase are not well understood. In Table 1 geothermal gradients, are given.

TABLE 1. — *Geothermal gradient, heat conductivity and heat flow measured in a well in the Monchegorsk pluton area.*

Depth, m	Gradient °C/km	Mean heat conductivity (W/m°K) (mcal/cm sec°C)	Heat flow (mW/m²) (μcal/cm²sec)
595.7- 770.3	11.1	2.19 (5.24)	24.3 (0.58)
770.3-1129.8	13.0	2.51 (6.00)	32.7 (0.78)
1129.0-1259.2	12.4	2.65 (6.32)	33.1 (0.79)
1259.2-1359.4	14.4	2.65 (6.32)	38.1 (0.91)
1395.4-1422.2	11.6	3.22 (7.69)	37.3 (0.89)

The correction for temperature and pressure amounts to not more than 1.5%. Maximum correction for the relief in the area of the wells on the Monchegorsk pluton is 3-4%. The most considerable correction refers to the glaciation effect. It amounts to 10%.

After corrections and consideration of the previously published data, the average value of the flow in the Monchegorsk pluton area is 39.8 ± 3.3 mW/m² (0.95 ± 0.08 HFU).

RICOLATVA AREA

Ricolatva muscovite rocks outcrop in the northern part of the Ensk region, in the zone of Archean gneisses of the Belomorsk complex, which occupies the south-western part of the Kola peninsula. The Ricolatva well had been out of work for 4 months and then temperature measurements were carried out.

The maximum depth of measurements is 1128 m. The temperature at this depth is + 14.90°C. In Figure 4 a geological cross-section of the well and a temperature curve are shown. The geothermal gradient in the upper part of the well is 12.8-12.3°C/km, in the lower part it gradually decreases to 10.5-10.3°C/km. Gradient and heat flow values for various linear intervals are given in Table 2.

35 core samples, 10 cm in length, were taken from the well for studying their thermal properties. The rocks are varieties of gneiss and pegmatite.

The heat flow is calculated for the whole well and the mean weighted value is 28.9 ± 2.5 (0.69 ± 0.06 HFU). After making corrections for the glaciation effects the mean heat flow for the Ricolatva well is 31.40±2.50 (0.75 ± 0.06).

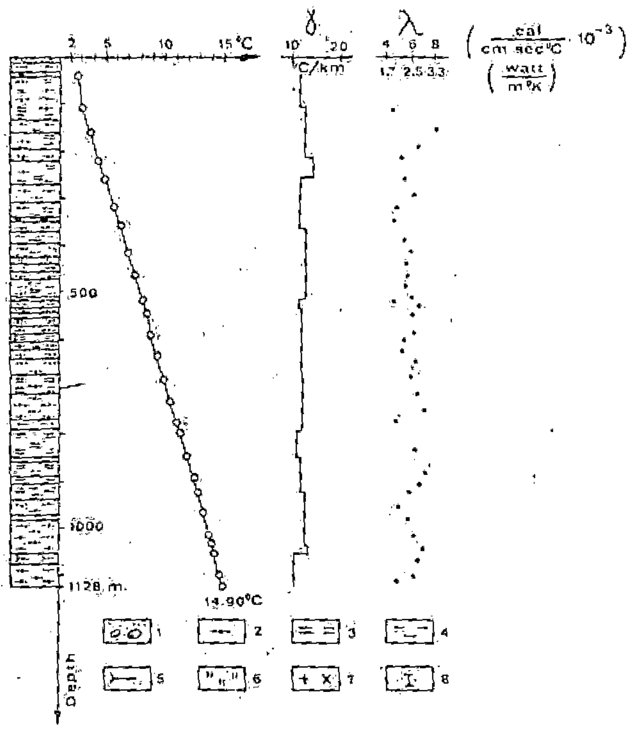

FIG. 4. — *Geological and geothermal logs of a well in the Ricolatva region. 1) moraine; 2) garnet-biotite gneiss; 3) two-mica gneiss; 4) biotite gneiss; 5) gneissic orthoamphibolite; 6) muscovite; 7) plagioclase pegmatite; 8) plagioclase-microline pegmatite.*

TABLE 2. — *Geothermal gradient, heat conductivity and heat flow measured in a well in the Ricolatva area.*

Depth, m	Gradient °C/km	Mean heat conductivity (W/m°K) (mcal/cm sec°C)	Heat flow (mW/m²) (μcal/cm²sec)
100-170	11.7	2.64 (6.30)	31.0 (0.74)
170-289	12.8	2.50 (5.97)	31.8 (0.76)
513.5- 561.0	11.1	2.38 (5.69)	26.4 (0.63)
561.0- 646.6	11.3	2.38 (5.68)	26.8 (0.64)
646.6- 777.7	11.7	2.51 (6.00)	29.3 (0.70)
777.7- 897.0	11.3	2.64 (6.30)	29.7 (0.71)
897.0-1070.1	10.2	2.52 (6.01)	25.5 (0.61)
1070.1-1128.0	10.5	2.40 (5.74)	25.1 (0.60)

KOASHVA, KHIBINI MOUNTAINS

The Khibini massif is the largest polyphase alkaline intrusion in the world. According to the radiometric measurements the age of the massif is Post-Devonian (290 ± 10 My). The massif is situated in the zone of contact of Proterozoic rocks with Archean gneisses. The massif bottom is found at the depth of 8-9 km. Increased seismicity, combustible gas shows and tapping of underground thermal waters testify a magmatic activity which may have continued up to recent times.

From the hydrogeological point of view, the region is characterized by strongly pronounced water divides and outcrops of crystalline rocks.

In all prospecting wells in the alkaline rocks, which are covered by glacial Quaternary deposits, fracture circulating waters have been found to the depth of 400-600 m and in some wells to the depth of 800 m. In some wells artesian waters were found. The Koashva well crosses juvites, ijolites and from the depth af 600 m, urtites. Heat flow measurements could be carried out only at the depth below the underground water disturbance level.

TABLE 3. — *Geothermal gradients, heat conductivity and heat flow measured in a well in the Koushva area.*

Depth, m	Gradient °C/km	Mean heat conductivity (W/m°K) (mcal/cm sec°C)	Heat flow (mW/m²) (μcal/cm²sec)
840.9- 997.3	25.2	2.14 (5.12)	54.0 (1.29)
997.3-1168.4	26.6	1.82 (4.35)	48.6 (1.16)

In Table 3 heat flow values are given as mean weighted according to intervals. For the whole depth range (840.9-1168.4 m), the measured heat flow is 51.1 ± 3.6 mW/m² (1.22 ± 0.01 HFU). The intrusive body effect gives a negative correction of about 8.4-16.7 mW/m² (0.2-0.4 HFU).

KHIBINI MOUNTAINS

Urtites, ijolites and juvites were found in the well. Temperature measurements were carried out to the depth of 1219.1 m. Temperature at this depth was 20.33°C (Figure 5).

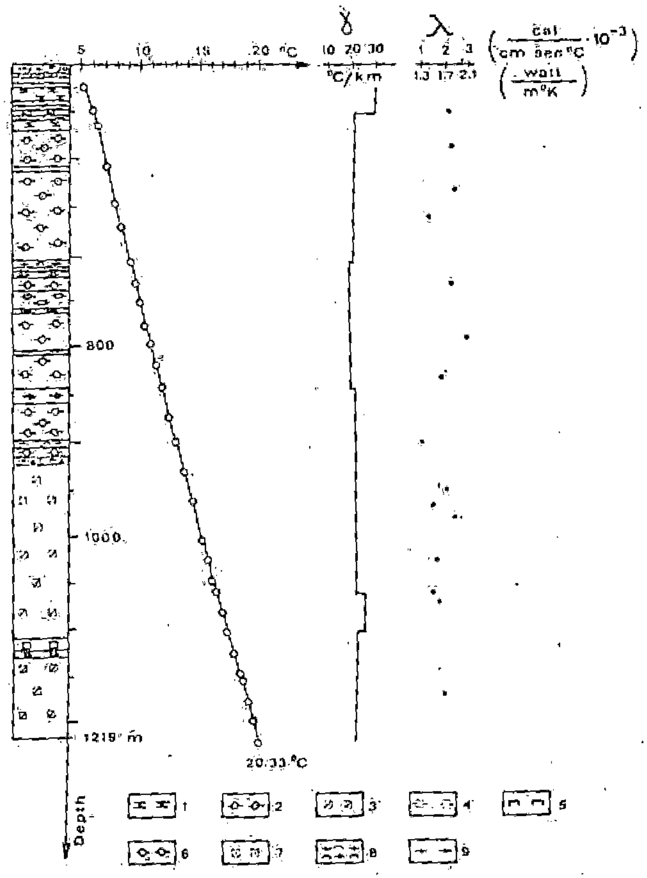

FIG. 5. — *Geological and geothermal logs of a well in the Khibini area. 1) trachytoid malignite; 2) malignite; 3) juvite; 4) trachytoid urtite; 5) pegmatite; 6) trachytoid ijolite; 7) urtite; 8) mica-melteigite; 9) melteigite.*

At the depth of 494 m the gradient sharply increases. At the depth of 550 m the temperature gradually increases, the gradient smoothes out to 2°C/100 m. To calculate the heat flow it is possible to use the lower part of the temperature curve beginning with the depth of 552 m. 15 core samples were taken and studied from this part of the well. The rocks are juvite, ijolite, urtite. Heat conductivity values of these rocks are very low and in the range of (3.01-4.97) × 10^{-3} cal/cm sec °C. In Table 4 the geothermal gradient, heat conductivity and heat flow are given.

TABLE 4. — *Geothermal gradient, heat conductivity and heat flow measured in a well in the Khibini mountains.*

Depth, m	Gradient °C/km	Mean heat conductivity (W/m°K) (mcal/cm sec°C)	Heat flow (mW/m²) (μcal/cm²sec)
552.0- 925.0 ijolites, urtites	20.7	1.70 (4.05)	35.2 (0.84)
925.0-1219.0 juvites	22.9	1.66 (3.96)	38.1 (0.91)

The heat flow is calculated for the whole well, from the depth of 552 m. The geothermal gradient is 21.7°C/km. The heat flow is 36.4 mW/m² (0.87). In a second well in the Khibini mountains, data were used only from its lower part. Here the gradient is 22.3 °C/km. In this interval 4 core samples each 15 cm long were taken and studied. The mean value for λ is 1.59 W/m°K (3.80). The heat flow is 35.6 ± 3.3 mW/m² (0.85 ± 0.08).

Analysis of geothermal parameters

For the territory of the Kola peninsula about 400 undestroyed core samples were studied. These are gneisses, gabbroes, pyroxenites, phyllites, peridotites, etc.. Hystograms of heat conductivity are shown in Figure 6.

Statistical analysis shows that the mean values of heat conductivity coefficient λ, their standard deviation σ and correlation coefficient $\varrho_{\lambda\varrho}$ of heat conductivity λ and density ρ are the following:

1) Archean-gneisses
$\bar{\lambda} = 2.49$ W/m°K (5.94) $\sigma = \pm 0.64$ $\varrho_{\lambda\varrho} = 0.014$
2) phyllites
$\bar{\lambda} = 2.95$ (7.05) $\sigma = \pm 1.10$
3) gabbroes, diabases
$\bar{\lambda} = 2.61$ (6.24) $\sigma = \pm 0.37$ $\varrho_{\lambda\varrho} = 0.38$

HEAT FLOW FROM THE CRUST AND THE UPPER MANTLE IN THE REGIONS OF THE PECHENGA STRUCTURE OF THE KOLA PENINSULA

According to our new determinations the measured heat flow in the region of the Kola peninsula is less than 41.9 mW/m² (1.0 HFU), even with the corrections for the cooling effect of a three-phase glaciation. An exception is the area of alkaline intrusions of Koashva, where the measured heat flow is 51.1 mW/m² (1.22 HFU), and the expected heating effect of an intrusive body determines negative correction of the order of 8.4-16.7 (0.2-0.4). The measured and corrected values of the heat flow are shown in Table 5. Correction to heat conductivity for temperature and pressure effects does not exceed 1.5%, since the temperature changes take place along the well in a narrow range from 1 to 20 °C. Table 5 shows that the heat flow values, corrected for glaciation and intrusion effects do not exceed 41.0 mW/m² (0.98 HFU) in the Kola peninsula. This result, obtained according to data from deeper wells, confirms previous data (LUBIMOVA 1966) for the Kola peninsula. Of great interest in Pre-Cambrian shields are data from an area of very deep drilling where an attempt on the complex study of geothermal, petrochemical parameters and heat generation has been made. Results obtained by ARSHAVSKAYA ET AL (1972) on uranium microcontents in gabbroes samples show that the mean uranium content in gabbroes is 0.4 × 10^{-6} g/g (with variation from 0.07 to 2.28 × 10^{-6}). The spatial distribution shows that track accumulation occurs at the border of pyroxene grains or along fine fissures inside pyroxene and plagioclase grains. For the spatial determination of the uranium content in gneisses, track accumulations were obtained, which were confined to apatite grains. Uranium concentrations in gneisses average 0.5 × 10^{-6} g/g, with variation from 0.1 to 1.6 × 10^{-6} g/g and they are near the uranium content in gabbroes. These values are less by an order of the mean uranium content in acid igneous rocks and this fact apparently is associated with metamorphism effects. These, as a rule, reduce radioactive element concentrations in rocks.

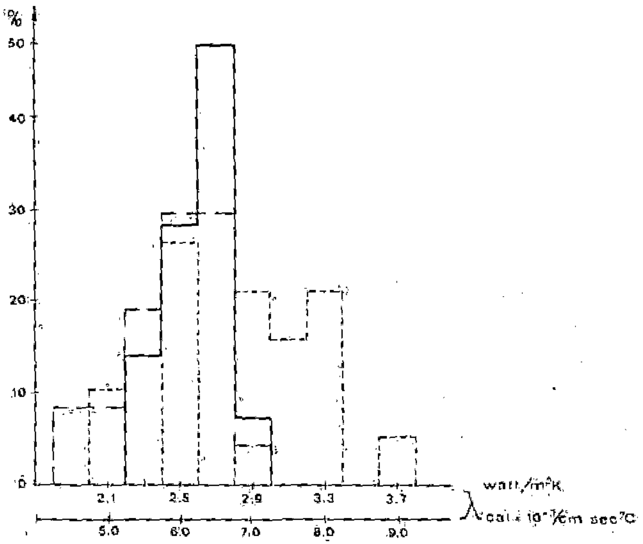

FIG. 6. — *Hystogram of heat conductivity of 94 samples from the wells studied in Zapolyarny and Ricolatva areas. Solid line, gabbroes (28 samples); long-dashed line, gneiss (47 samples); short-dashed line, phyllite, sandstone, tuffs (19 samples).*

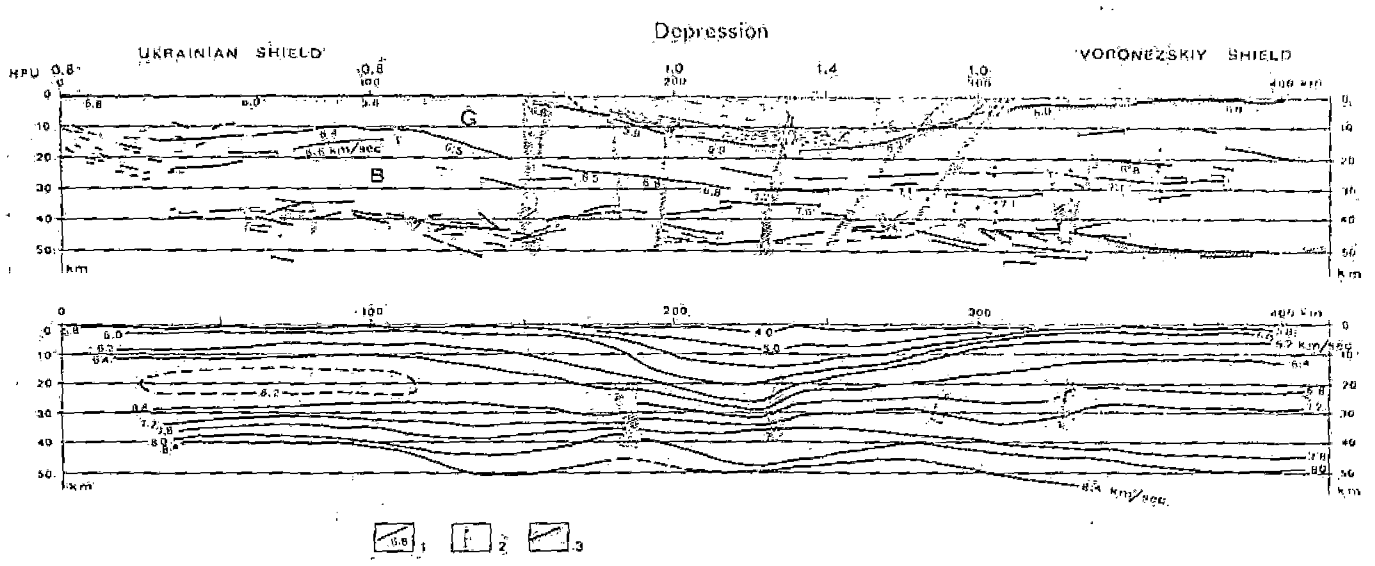

FIG. 7. — *Deep structure and seismic waves velocity in the Ukrainian shield in a north-easterly direction: Krivoi Rog - Dnieper Donetsk depression.* 1, *longitudinal wave velocity values;* 2, *presumed faults;* 3, *Mohorovicic boundary.*

TABLE 5. — *Heat flow in the region of the Kola peninsula.*

	Lat. (N)	Long. (E)	Measured mW/m² (HFU)	Corrected heat flow mW/m²	(HFU)
Pechenga region					
a) well « A »	69°25′	30°50′	33.5±2.1 (¹) (0.80±0.05)	37.3	(0.89) (²)
b) well « B »	69°25′	30°50′	35.6±3.3 (0.85±0.08)	38.5	(0.92) (²)
Monchegorsk pluton	68°06′	32°53′	35.6±3.3 (0.8±0.08)	39.8	(0.95) (³)
Ricolatva	67°30′	31°10′	28.9±2.4 (0.69±0.06)	32.7	(0.78) (²)
Koashva	67°50′	33°50′	51.1±3.6 (1.22±0.09)	41.0	(0.98) (⁴)
Khibini mountains	67°40′	33°40′	35.6±3.3 (0.85±0.08)	40.2	(0.96) (²)

(¹) Probable error.
(²) After glaciation corrections.
(³) After topographic and glaciation corrections.
(⁴) After applying correction for glaciation and intrusive effect.

Because of the predominance of greenstone series in the cross-sections of wells, the heat flow from the crust is very low, 8.4 mW/m² (0.20 HFU). On the basis of this fact it is possible to conclude that the heat flow from the mantle is 25.2-31.4 (0.60-0.75 HFU), if our data of heat flow for the Kola peninsula may be considered as of equilibrium for this relatively stable region of the earth's crust. Possibly this result is an exception because it was obtained in areas where greenstone series outcrop. Strikingly, the low heat flow contribution by the continental crust of the Pre-Cambrian shield, makes us suppose the existence of essential contribution of heat from the underlying mantle. In Figure 9 a summary of heat generation is shown; it is to be attributed to the assumed model of the crust structure in the Pechenga region of the Kola peninsula. For the sake of comparison in this Figure the heat generation in the earth's crust of the Australian Pre-Cambrian shield according to the data of HYNDMAN ET AL. (1968) is also given.

The Australian data are based on gamma-ray spectrometry. Such techniques for determining radio elements concentrations have approximately 10-15 per cent uncertainty. It is probable that for very low microcontents of uranium in greenstone rocks, this uncertainty is higher and, therefore, the uranium content in Australian rocks may have been overestimated. Special techniques, such as the neutron activation method which has been devised by I. G. BERZINA and co-workers (1967) have a very high degree of accuracy for the determination of low uranium microcontents. This method avoids contamination effects.

From the above mentioned facts we conclude that the values for the lower uranium content in the rocks of the Kola peninsula, as determined by BERZINA and co-workers, are the more likely values for the surface rocks in such areas of the Pre-Cambrian shield. This immediately contradicts the most important previously held conclusion, which appeared quite stable, regarding the great contribution to the surface heat flow from the crust of the Pre-Cambrian shields. More data and also determination of the Th contents on the same samples are necessary to substantiate the results obtained and therefore our final conclusion awaits that work in this direction.

Based on the above mentioned data, crustal temperatures have been calculated for the Baltic shield and are shown in Figure 10.

Comparison between geothermal data and seismic waves velocity in the Ukrainian shield

The comparison of the velocity of seismic waves and geothermal data is of great interest. The Ukrainian shield has been studied well with the help of seismic, gravimetric and geothermal methods. One of the peculiarities is a layer of low velocity at the depth of 12-24 km, with a value of 6.2 km/sec (Figure 7). Geothermal data show that the heat flow varies from 0.8 to 1.4 in the direction of the sublatitudinal section across the Ukrainian shield and the Dnieper-Donetsk depression. Isotherms calculated according to the heat conductivity equation and field data are shown in Figure 8. For comparison of the temperature gradient values calculated according to seismic and geothermal data, the following equation was used

$$\frac{dV_p}{dz} = \left(\frac{dV_p}{dp}\right)_T \frac{dp}{dz} + \left(\frac{dV_p}{dT}\right)_p \frac{dT}{dz} \qquad (1)$$

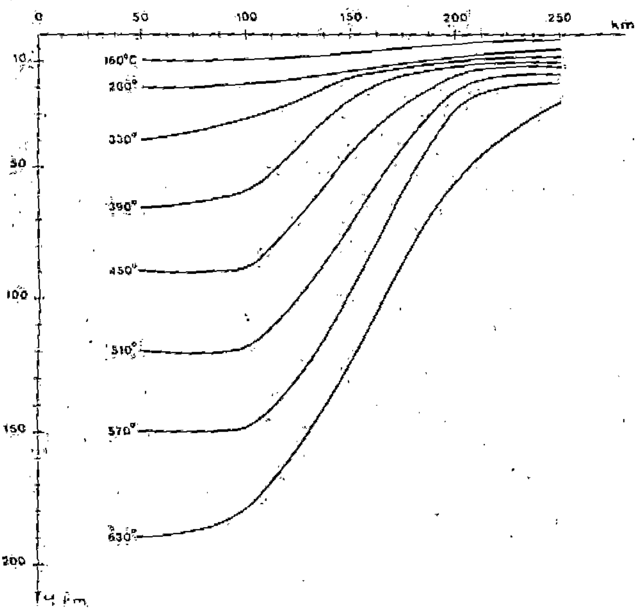

FIG. 8. — *Geoisotherms from heat flow data along the cross-section of Figure 7, based on the solution of the heat conductivity equations (by* V. K. VLASOV *using a computer).*

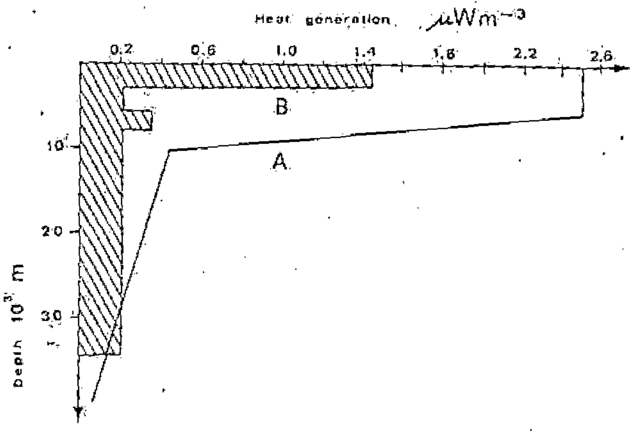

FIG. 9. — *Heat generation from depth data based on the U, Th, K microcontents. A) on the Kola peninsula; B) on the Australian shield.*

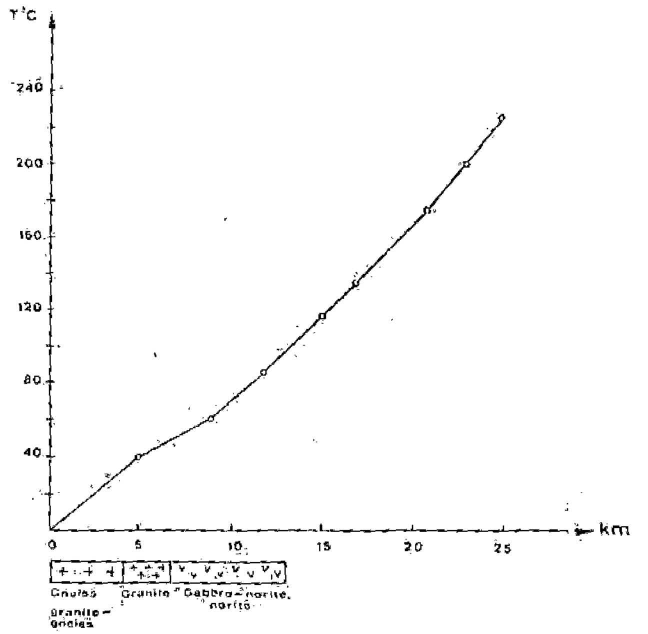

FIG. 10. — *Crustal temperatures calculated for the Baltic shield.*

where V_p is the velocity of the longitudinal seismic waves, p the pressure, T the temperature.

$$\left(\frac{dV_p}{dp}\right)_T = \alpha; \quad \left(\frac{dV_p}{dT}\right)_p = \beta \qquad (2)$$

α and β are experimental constants for « granitic » and « basaltic » layers. In our calculations we used:

$$\left.\begin{aligned} \alpha &= 1.0 \times 10^{-4}\ \text{km/sec bar} \\ \beta &= 2.0 \times 10^{-3}\ \text{km/sec °C} \end{aligned}\right\} \text{for « granitic » layer}$$

$$\left.\begin{aligned} \alpha &= 1.2 \times 10^{-4}\ \text{km/sec bar} \\ \beta &= 2.0 \times 10^{-3}\ \text{km/sec °C} \end{aligned}\right\} \text{for « basaltic » layer}$$

The results of the calculation are given in Table 6. According to equation (3) the critical temperature gradient was calculated and with this gradient a layer of very low velocity might exist

$$\frac{dT}{dz} > \frac{dp}{dz}\left[-\frac{(\partial V/\partial p)_T}{(\partial V/\partial T)_p}\right] = \left(\frac{dT}{dz}\right)_{\text{crit.}} \qquad (3)$$

$\left(\frac{dT}{dz}\right)_{crit.}$ was calculated equal to —13°C/km inside the « granitic » layer and —15.6°C/km inside the « basaltic » layer. Having made a comparison with the corresponding temperature gradients in column 3 of Table 6, it is possible to conclude that there is a discrepancy between the thermal model and the seismic data pertaining to the low velocity layer.

In other words, the existence of a wave conductive layer in the crust of the Ukrainian shield appears doubtful from a thermal point of view.

Conclusion

The results of this work not only once more confirm the low values of the heat flow in the region of the Pre-Cambrian shields according to the data ob-

TABLE 6. — *Low velocity layer. Temperature gradient calculated according to DSS data and comparison of them with temperature gradients obtained by solving a thermal model.*

50 km				100 km				150 km				200 km				250 km			
z depth km	$\partial V/\partial z$ 1/sec	dTe/dz °C/km	dT/dz °C/km	z km	$\partial V/\partial z$ 1/sec	dTe/dz °C/km	dT/dz °C/km	z km	$\partial V/\partial z$ 1/sec	dTe/dz °C/km	dT/dz °C/km	z km	$\partial V/\partial z$ 1/sec	dTe/dz °C/km	dT/dz °C/km	z km	$\partial V/\partial z$ 1/sec	dTe/dz °C/km	dT/dz °C/km
0.63	0.16	49	19	0.5	0.2	56	19	1.25	0.08	27	22								
2.5	0.11	42	17	1.87	0.15	53	18	3.75	0.08	27	21	5.0	0.26	65	36	6.87	0.20	60	33
7.5	0.04	7	15.3	6.25	0.04	7	16	10.60	0.03	2	18	10.0	0.16	53	24	11.9	0.16	53	24
11.25	0.05	13	13	10.0	0.05	13	13	16.25	0.03	2	15	16.8	0.03	2	16	14.4	0.08	27	20
15.0	—0.05	—33	11	15.0	—0.04	—27	13	27.5	0.03	10	4	21.8	0.04	7	12	17.5	0.06	17	16
20.0	—0.05	—33	10	20.0	—0.04	—27	11	33.7	0.06	23	2	25.0	0.06	17	10	21.2	0.05	13	14
22.5	—0.05	—33	8	22.5	—0.04	—27	9	37.5	0.11	47	1.5	28.7	0.11	40	3	25.0	0.11	42	12
27.5	0.12	41	3	26.2	0.16	60	3	43.7	0.06	23	1.1	32.5	0.11	40	2	30.0	0.08	27	8
30.0	0.16	60	2	31.2	0.08	33	2	50.0	0.06	23	2	36.2	0.11	40	1	34.4	0.09	29	2
33.75	0.11	45	1	33.7	0.16	60	2					41.8	0.07	21	1	43.7	0.04	4	1
35.6	0.21	50	0.6	39.5	0.07	28	0.2					48.7	0.06	15	2	46.8	0.12	30	3
38.7	0.13	42	1.2	42.5	0.13	43	2.2												

Te experimental data (from seismic data)

tained from deep wells but also have led to some new interpretations associated with some general problems of the earth's crust structure and evolution. Among them there are: 1) Evaluation of separate contributions to the heat flow from the crust and continental mantle in the region of the Kola peninsula, Baltic shield. 2) Comparison of geothermal gradients inside the earth's crust of the Ukrainian shield foreseen on the basis of the thermal conductivity theory and the observed heat flow.

The results of the most accurate method (in our opinion) of determining uranium microcontents (« track » method) in gabbro samples, taken from great depth, led to recognize a surprisingly low heat flow from the earth's crust of 8.4 mW/m^2 (0.20 HFU) in the greenstone area while the principal contribution comes from the underlying mantle and is equal to about 25.1-31.4 mW/m^2 (0.60-0.75). The latter figure is conditioned by the glaciation effect correction. Not long ago BECK (1965) stimulated an interest in this effect. And really a number of new investigations of glaciation causes makes us revise its essential influence upon variations of heat flow at time intervals. It must be noted that the cause of glaciation in high latitudes can be associated with nutation effect of the earth's rotation, which leads to a redistribution of the sun's energy. Nutation effect prevails at high latitudes and it is insignificant in lower ones (BROEKER, WALLACE 1966).

It is supposed that the principal events in the transition periode from the glacial epoch to the interglacial and again to the glacial, were caused by the biggest insolation peaks. The hypothesis about synchronism of climate variations and astronomic effects permits us to associate variations of heat flow conditioned by glaciation with variations of astronomic parameters of the earth's rotation. The calculation of geothermal gradients foreseen according to the seismic wave velocity in the Ukrainian shield showed that geothermal data do not confirm the supposition regarding the existence of a seismic wave conductor layer with a low longitudinal wave velocity of 6.2 km/sec at the level of the Conrad discontinuity.

Therefore a comparison of the heat flow values and the generation of energy by uranium, thorium and potassium in the Pre-Cambrian areas of the USSR shows that the heat flow from the upper mantle is rather high, about 25-30 mW/m^2 (0.60-0.75 HFU). According to this preliminary data a high geothermal energy potential should exist in those areas.

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