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PRESENT GEOTHERMAL ACTIVITY IN ICELAND

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Geothermal activity is a sensitive indicator of deep geothermal and geochemical conditions. The variety of geoenergy of volcanic and hydrothermal activity, and the zonal character of the chemical composition of the discharged fluids, observed in Iceland, are quite consistent with the geological and structural features of the various parts of the island. The Median Zone of Iceland, regarded as a special land expression of the oceanic rift, is characterized by large hydrothermal systems with a high content of H_2. The salt composition of the hydrothermal springs sets Iceland apart from volcanic regions of the Circum-Pacific belt. The isotope composition of He and S in thermal fluids indicates a participation of mantle emanations in their development as well as the similarity of Icelandic crust with the oceanic type.

A gentle maximum, >2.2 mcal/cm^2/sec, has been observed in the distribution of the background heat flux; it generally corresponds to the position of the Median Zone. The intensity of heat of hydrothermal and volcanic activity in Iceland fluctuates regularly over the area of the island and reaches a maximum, about 10 mcal/cm^2/sec, in the southern branch of the Median Zone. Current data can be used in more accurate models explaining thermal conditions in the oceanic rifts.

thermal activity is understood as a sum of all the
manifestations of deep-seated heat: conduction
onvection removal of heat by deep-seated gaseous
fluids and magmatic melts, i.e., hydro-
al and volcanic activity. Hydrothermal activity is
st conspicuous expression of the dynamics of deep
sses. Readily available for a quantitative evalua-
hydrothermal activity allows an objective compari-
the intensity of the geoenergy process in different
of the tectonosphere, thereby providing an ap-
to tectonic motive forces.

convection form of geothermal activity, a geo-
l expression of mass heat transfer, entails geo-
and geochemical consequences. For that reason,
f geothermal activity provides means for relating
tonic concepts to petrological and geochemical
s and, more specifically, to the discovery of in-
juvenile (mantle) substance at, or near, the sur-
the earth. Geochemical investigations of hydro-
al activity give an idea of the character of combust-
aseous and aqueous fluids as well as of deep thermo-
ic conditions. As shown by experience, it also re-
the corresponding specific structural and tectonic
tions.

geothermal activity of Iceland, its most spec-
r geologic feature, is interesting first of all be-
of the position of the island on the axis of the Mid-
ic Ridge. The structure and type of the Icelandic
and its relationship with the structure of the ridge,
n to discussion. Therefore a study of hydro-
al activity in Iceland, and its comparison with other
cally and volcanically active regions of the world,
clear up some of the obscure points. Should the
pal factors of hydrothermal activity in Iceland be
ified, they would provide a standard for determining
atures of this process in the global system of mid-
ic rifts.

The present article is based on material obtained mainly during our work in Iceland, in 1970, as members of the group of the Geological Institute, USSR Academy of Sciences, and the 1971-1973 Joint Geological and Geophysical Expedition, USSR Academy of Sciences. In addition, we took advantage of references published by the Icelandic specialists—primarily by the geochemists G. Sigvaldason and S. Arnorsson; geophysicists G. Palmason, T. Einarsson, and G. Bödvarsson; volcanologist S. Thorarinsson; and the composite monograph by Barth (1950).

In the interpretation of material so obtained, it should be kept in mind that volcanic activity, whose products cover the entire area of Iceland and make up almost all of its visible section, were concentrated in the Quaternary in the transverse Median Zone and in the Snaefellsnes Peninsula. The major role in the structure of the Median Zone, regarded by many investigators as an unusual land expression of a rift valley of the Mid-Atlantic Ridge (Muratov, 1961; Thorarinsson, 1970), belongs to deep linear faults. Therefore, the abundance of fissure eruptions is distinctive feature of Icelandic volcanism, although the central type of volcanic structures also are present here. It is the latter that are responsible for the acidic and intermediate volcanics whose volume accounts for a mere one tenth of the volume of basalts (Thorarinsson, 1967_1). In the Holocene, volcanic activity concentrated in the north of the Median Zone and in its axial part; in the south, it was concentrated in two separate branches at its margins. In the southwestern branch (Reykjavik-Langjökull), modern volcanism is confined to the southern segment. K. Saemundsson (Palmason and Saemundsson, 1974) believes that this south-western branch has (or had) an independent extension to the north, in the area of Skag Island and reflects a former projection of the "hot spot" in the rift valley.

The energy effect of volcanism is quite strong. We have made an attempt at its evaluation for the period of

Iceland settlement, i.e., the last 1,100 years. This evaluation is based on historically recorded observations of volcanic phenomena and on data obtained in special studies. As a result, it was possible to calculate the volume of ejecta in various parts of the country (Thorarinsson, 1967_2). Hence, a rough approximation of the geoenergy effect of volcanism is readily calculated, keeping in mind that liberation of heat accumulated in the cooling melts is at a maximum here (Polyak, 1966). It turns out that the average effect of historic volcanism in Iceland, over the area of its manifestation, is about 4.5 μcal/cm^2/sec; and that it is particularly high, 6.4 μcal/cm^2/sec, in the southern active branch of the Median Zone (Fig. 1). The majority of volcanic eruptions are associated with this branch, among them the major 1783 Lakagigar eruption responsible for about 10% of the entire volume of lava poured out over the surface of the earth for the last 500 years. The best known Icelandic volcanoes, Hekla and Katla, also are located here. The famed Surtsey volcanic island originated in 1963-1967, in the Vestmannaeyjar Archipelago, on the trend of this branch beyond the land. An eruption occurred on the Heimaey, in 1973. Manifestations of historic volcanism are distributed fairly evenly over this branch, while they are known in the southwestern branch only between Tingvedlir and Cape Reykjanes. Calculations show that the specific energy effect of historic volcanism is about one-third here of the volcanism of the southern branch; it is only one quarter of that in the northern branch (Fig. 1). The volcanism of the southern branch accounts for about 75% of the total effect of historic volcanism in Iceland; that of the northern branch, 8%; and the active segment of the southwestern branch, 7.5%. The balance is accounted for by the Snaefellsnes zone and the galciated area of the Erajvaiskudl Volcano.

The order of magnitude so established for the average effect of volcanism is typical not only for the historic but also for the longer stages of the geological evolution of Iceland. This conclusion is based on a detailed study of productivity of Holocene volcanic activity (Jakobsson, 1972) and on an estimate of the volume of the seismic layer "0", identified with the Quaternary volcanics (Palmason, 1971). On the assumption that the period of accumulation of the latter corresponded to the Brunhes paleomagnetic epoch, as reflected on the latest Icelandic maps (Palmason et Saemundsson, 1974). The average specific energy effects of Icelandic volcanism over the areas of its manifestation, in the last 0.7 m.y., turns out to be 3.5 μcal/cm^2/sec; the Holocene figure is 5.4 μcal/cm^2/sec. The second figure is exactly the same as obtained earlier by Bödvarsson (1954). Lastly, according to Walker (1963), "the belt of active volcanism in Iceland remained almost unchanged during the Tertiary and Quaternary. The width of the belt did not exceed tens of kilometers, while the intensity of volcanism within it remained constant" (Thorarinsson, 1970, p. 123). It was therefore possible to compare the estimates of the geoenergy effect of volcanism and the more inert forms of geothermal activity—the background conduction heat flux and discharge of the thermal springs.

The background heat flux in Iceland, as in other regions of modern volcanism, is significantly higher than the average for the planet. A feature of the geothermal field in all such regions is its extreme diversity, i.e., an abundance of strong local positive and negative anomalies caused by the movement of underground waters. Therefore only a few tests drilled for that purpose have discovered an undisturbed regional geothermal field.

The heat conductivity of Icelandic rocks was estimated by mass measurements on specimens selected from a collection of cores at the Department of Natural Heat and from outcrops, and characterizing the principal petrochemical varieties of rocks with a degree of "freshness". The reliable value of heat flux so obtained turned out to be about 20% lower than accepted for Iceland on the basis of earlier and isolated estimates. The attendant determinations of the conduction component in each thermometrically studied drillhole were based on the values of the geothermic gradient published by Palmason (1967, 1974).

A comparison of these figures with statistically obtained average values of heat flux in volcanic regions on land (Polyak and Smirnov, 1968) and in zones of the mid-oceanic ridges (Le Pichon and Langseth, 1969) has made it possible to identify and exclude from the regional picture the high anomalies associated with the rise of thermal waters, and to determine the values characteristic of the undisturbed field. The spatial distribution of background conduction heat flux is illustrated, along with other geoenergy characteristics, in Fig. 1. Its principal feature is that the zone with a higher background heat flux (>2.2 μcal/cm^2/sec) is considerably wider than the Median Zone, with a generally the same trend. This broadening of the zone of higher heat flux is consistent also with submarine measurements at the Reykjanes Ridge (Talwani et al., 1971). These measurements indicate that there is no usual decrease in heat flux on the southeastern slope of the ridge. At the same time, the pattern of the field of conduction heat flow over Iceland exhibits trends transverse to the Median Zone—such as the Snaefellsnes—Erayvayskudl axis. The lack of measurements of heat flux in basins off southeastern Iceland, and their scarcity between Iceland and Greenland, make it difficult to judge to what extent, if at all, these trends can be related to volcano-tectonic activity in the Britain-Arctic belt. The available data on the Denmark Strait (Lachenbruch and Marshall, 1968) constitute a fairly reliable evidence of a similarity between hydrothermal conditions in this region and the Northwestern Peninsula of Iceland. This peninsula, the same as the eastern part of the island (likewise made up of Miocene plateau-basalts), is characterized by minimal values of heat flux.

Conspicuous against this regional geothermal background are anomalies associated with hydrothermal activity. The total number of manifestations of this activity in Iceland is close to 500 (Barth, 1950). A comprehensive study of them has enabled us to subdivide all the thermal phenomena into four types differing in chemical composition and heat potential (Kononov and Polyak, 1974; Polyak and Kononov, 1974).

The gas zonation of thermal waters. One of the most important indicators of deep geochemical and geothermal conditions is the composition of gases in underground waters. Thermal and mineral waters are classified by the composition of their gases into genetic types: methane, nitrogen, carbon dioxide, nitrogen-carbon dioxide, and hydrogen sulfide-carbon dioxide. The clear-cut zonation of gas composition in thermal waters of Iceland is consistent with the geological and structural zones of the island (Fig. 2). Nitrogen-bearing thermal waters are present in the area of pre-Quaternary plateau basalts. Carbonate waters are associated with the volcanic zone of the Snaefellsnes Peninsula, now evidently dying down. The nitrogen-carbonate steam-water mixtures are discharged in areas of pre-Holocene volcanic activity of the Median Zone and in some of the adjoining areas. Lastly, thermal waters with the highest temperatures designated here as a new genetic type of hydrogen-bearing waters, are associated with parts of the Median Zone characterized by the most intense volcanic activity.

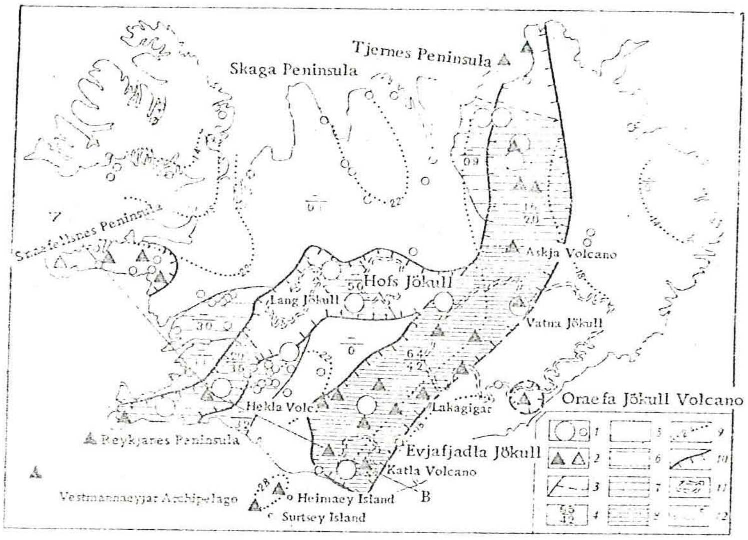

Fig. 1. Energy effect of modern geothermal activity in Iceland.

1) Largest present geothermal systems (a) and springs (b); 2) centers of volcanic activity for the last 1,100 years (a) and the preceding millineum (b); 3) boundaries of regions with a different total effect of volcanic and hydrothermal activity; 4) numerator; energy effect of volcanism, μcal/cm^2/sec; denominator: discharge of thermal springs of the region; 5-8) total effect of volcanic and hydrothermal activities, mccal/cm^2/sec: 5) <0.1, 6) 0.9-3.2, 7) 3.0-6.9, 8) 10.7; 9) isolines of the background conduction thermal flux, in mccal/cm^2/sec (from the data of Palmason, 1967, 1974); 10) boundaries of zones of active volcanism (Thorarinsson, 1970; Palmason and Saemundsson, 1974); 11) boundaries of glaciers; 12) line of profile in Fig. 4.

The nitrogen type of thermal waters, most common in Iceland, is typical of all the tectonically active regions of the world. Springs of this type are present in the USSR in the Pamirs, Tien Shan, and Kamchatka. Their main feature is a great predominance of nitrogen in the gas (95-98% by volume). The temperature of nitrogen waters, at the surface, is below the boiling point, as a rule; their calculated temperature at depth does not exceed 150 C. The amount of liberated heat is relatively low, in some springs: on the order of 10^6 cal/sec. The heat parameters of nitrogen waters are consistent with the model of heating of nitrogen-saturated infiltration waters in the background geotemperature field within the upper 2.0-2.5 km of the geologic section (Ivanov, 1960; ...varsson, 1961). It is commonly believed that they develop outside the zone strongly affected by magmatic and thermal-metamorphic processes. However, some of the deep emanations reach the nitrogen thermal water, in Iceland, as indicated by certain features of isotope composition of their gases.

The carbonate springs of Iceland, hot and cold, containing up to 98% CO_2 in the gas phase, are typical of dying-down volcanic activity. The waters of this type are quite similar to carbonate thermal mineral waters of central and southeastern Europe and Central Asia. Usually the formation of carbonic acid water is associated with thermal metamorphic processes. In Iceland, carbon dioxide may be liberated in thermal metamorphism of basalts that contain a considerable amount of it; or else it may come out directly from the magmatic centers.

The nitrogen-carbonate thermal waters, also known as "geysers", are large modern hydrothermal systems. This type includes the well-known Pauzhetka and Uzon-Geyser systems of Kamchatka; Wayrakey and Cavernau in the Taupo zone, New Zealand; Onikobe and Beppu, Japan; and others. In Iceland, thermal waters of this type likewise are high-temperature. They are discharged at the surface as steam-water mixtures; their calculated temperature at depth might exceed 250°C (Arnorsson, 1970_1). In some of the centers of their discharge, the amount of liberated deep heat attains 10^7 cal/sec, which is equivalent to background conduction heat loss over an area of 1,000 km^2. Considering the geology of these systems that are associated here with comparatively narrow zones of deep linear faults, their heat potential cannot be explained by heating within the background geotemperature field. It is necessary instead to assume some inflow of deep fluids with a high heat content. This assumption is supported also by the presence of CO_2 in gases of these systems, and by the isotope composition of certain components of the thermal waters.

The hydrogen type of thermal fluids is a quite distinctive feature of hydrothermal activity in Iceland. They are rich in free H_2 which at times is the predominant gas. Its concentration in solution gases of some thermal fields is as high as 64% (Sigvaldason, 1966), with H_2 discharge to the atmosphere attaining 1 m^3/min. The other components of gases in these thermal waters are H_2S (up to 25%, by volume) and CO_2 (up to 93%), with small amounts of N_2, inert gases, and CH_4. In contrast to crater fumaroles of many active volcanoes of the world, to which the hydrogen

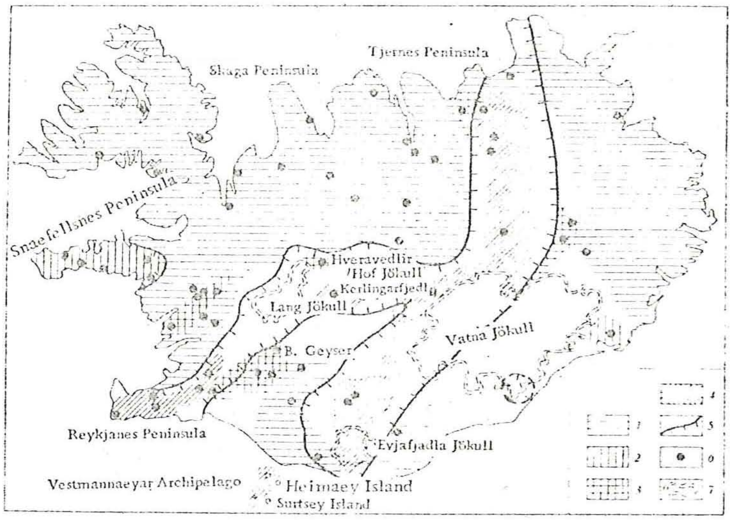

Fig. 2. Gas zoning of thermal waters in Iceland.

1-4) Areas of thermal waters: 1) nitrogen, 2) carbonate, 3) nitrogen-carbonate, 4) hydrogen; 5) boundaries of zones of active volcanism (Thorarinsson, 1970; Palmason and Saemundsson, 1974); 6) testing sites; 8) boundaries of glaciers.

steam-water jets of Iceland are similar in gas composition, thermal waters of this group are typical modern high-temperature hydrothermal systems with the highest heat potential. They are discharged at the surface as steam jets; their temperature at depth approaches 300°C. The heat output in discharge zones of some of the hydrothermal system of this type attains 10^8 cal/sec, and $5 \cdot 10^8$ cal/sec in the largest among them, the Thorfa Jokull system (Bödvarsson, 1961), which places it in the first place in the world. To realize this amount of heat, the background conduction heat flux would have to "strip it off" completely from a fifth of the area of Iceland, which is utterly implausible. Such a high heat potential of hydrogen thermal waters indicates, even better than in the instance of the nitrogen-carbonate, participation of a deep heat-carrier in their development.

There is no concensus of opinion on the origin of hydrogen in thermal waters of this type. It is improbable that hydrogen is formed, as believed by some investigators, under near-surface conditions, in the oxidation of sulfide-ions or decomposition of H_2S, inasmuch as both are common in the volcanic steam-water jets, including those not containing free hydrogen. A deep origin of H_2 is more probable: it can be extracted from basalts, at sufficiently high temperatures; or else it may be the product of certain deep-seated reactions, such as the "fayalite-water" reaction, theoretically possible also under thermodynamic conditions of a magmatic melt (Matsuo, 1965). Finally, the appearance of hydrogen may follow a degassing of the interior of the earth where it is believed to be present in large amounts (Vernadskiy, 1933, cited from 1954-1960; Kropotkin, 1956; Larin, 1971).

Only two analogs of hydrogen thermal waters are known outside of Iceland: the Sonoma Valley geysers in California where H_2 accounts for 15% of the total gas volume (Ellis, 1970); and the Ajuachapan thermal field, Salvador, where its content attains 44%, by volume (Sigvaldason and Cuellar, 1970). The geotectonic position of both these thermal phenomena is similar: they both are located at the junction of the American continent with the East Pacific Rise, or in structures associated with it. The conclusion is that the hydrogen type of thermal fluids is generally characteristic of hydrothermal activity in the system of mid-oceanic ridges.

The boundaries of the gas-chemical zones usually coincide fairly well with the geologic boundaries, as illustrated, in part, in Fig. 2. However, there are discrepancies; the most important of these occur in the northern part of the Median Zone, in the area of the Tjernes Peninsula. The presence of nitrogen thermal waters in this part of the zone indicates the presence of a boundary cutting the zone and separating its northern part, the less active with respect to geoenergy.

Judging from the gas composition of thermal waters, a similar weakening of activity takes place in southern Iceland where the boundaries of the zone of hydrogen thermal waters coincide with those of the southern volcanically active branch. The presence of nitrogen waters in the coastal belt enhances a separation of this branch of the Median Zone from the line of the Vestmannaejar Archipelago to the south, where hydrogen again becomes dominant in gases of the Surtsey and Eldfegl (Heimaey Island) volcanoes.

Finally, mention should be made of the absence of hydrogen thermal waters—and of all others, for that ter—in the southwestern branch, north of Lake Tingvadlavatn and east of the Hofs Jökull. This casts doubt on the current combining of geothermally active regions of Reykjanes-Hangidl and Kerlingarfjodl-Hveravedlir into a single belt related to other active branches of the Median Zone, to the east.

With reference to salt composition, hydrothermal waters of Iceland differ from those in other volcanic regions of the world by a lower mineralization. The content of substances in solution usually fluctuates from 150 to 1,200 mg/liter. An exception is the coastal thermal waters of the Reykjanes Peninsula with a 52 mg/lit ization. However, their composition is determined by sea water coming in through the faults that cut the coastal zone and the oceanic floor, and by the subsequent concentration of these waters as the result of evaporation.

The distribution of the principal anions (HCO_3^-, CO_3^{2-}, Cl^-) of underground waters, too, exhibits a clear-cut zonation. As a rule, SO_4^{2-} is predominant over the other anions in condensates of steam-water jets in the Median Zone; together with HCO_3^- and CO_3^{2-} it determines the composition of their deep liquid phase. The chloride-sodium thermal waters of the nitrogen-carbonate type, typical of volcanic regions of the world, are rare in Iceland where HCO_3^- and CO_3^{2-} are predominant in anion composition of thermal water with such composition. This casts doubt on the existence of the so-called deep hydrochlorosphere postulated by some investigators (Derpgol'tz, 1963).

Other anions in thermal waters are represented at most by fluorine, an indicator of the presence of acidic magmatic bodies.

No zonation has been observed in cation composition of thermal waters. The predominant cation usually is Na^+. The content of K^+ and Mg^{++} is higher in condensates of steam-gas jets of the hydrogen type, in areas of discharge of highest-temperature fluids.

An important distinctive feature of Icelandic thermal waters is their high alkalinity (pH as high as 10) and a high content of silica, up to 1,300 mg/liter of SiO_2. The silica concentration, observed in thermal waters and wet steam from drillholes, constitutes the basis for determining the temperatures at depths—from thermodynamic conditions of certain geochemical equilibria in these fluids. The "silica-temperatures" so determined for thermal waters with different gas composition appreciably differ among themselves: 40-120°C in nitrogen thermal waters of Iceland; 153°C for warm carbonate waters (single determination); and 137-274°C in the nitrogen-carbonate and hydrogen (Arnorsson, 1970). This is another evidence of the close relationship between the geochemical and geothermal parameters that characterize different aspects of development of various thermal waters.

Among the microelements, microgram amounts of Li, Ge, Mg, Ti, and V are widespread in Icelandic thermal waters. Some of the samples of acid waters contain Cu, Co, Ni, and Zn (Arnorsson, 1970_2). However, even the thermal waters of the Median Zone have not yielded, as yet, any exotic components in anomalously large amounts. On the whole, the composition of macro- and micro-elements in underground waters indicates that it is determined, in the majority of all thermal regions, mainly by the process of leaching.

The low content of dissolved substances in Icelandic thermal waters, as compared with other volcanic regions (Kamchatka, Japan, New Zealand), evidently reflects differences in the composition of water-bearing sequences, i.e., in the composition and structure of the crust in these regions.

The isotopic composition of the components of thermal waters. Many aspects of the origin and evolution of hydrothermal fluids (depth of origin, rate of movement, composition of the enclosing rocks) are clarified by the study of the isotope composition of some of their components. With this in mind, we have analyzed the ratios of helium and sulfur isotopes in thermal phenomena of Iceland.

With respect to the isotopic composition of helium, we know that the ratio $^3He/^4He$ in various natural objects varies substantially from $n \cdot 10^{-2}$ in certain meteorites to $n \cdot 10^{-10}$ in uranites. It has been established that this ratio is as high as 10^{-7}-10^{-8} in the stable continental segments of the crust (Kamenskiy et al., 1971), while its range in the eastern volcanically active zone of Kamchatka is $(0.5$-$1.4) \cdot 10^{-5}$ (Mamyrin et al., 1969). The variations in the $^3He/^4He$ ratio in terrestrial gases is explained by a mixing of helium flows from three sources: mantle helium ($^3He/^4He = n \cdot 10^{-5}$); crustal helium, generated in radioactive decay within the "granite" layer ($^3He/^4He = n \cdot 10^{-8}$); and atmospheric helium ($^3He/^4He = 1.4 \cdot 10^{-6}$).

In the course of our study, we tested 58 thermal phenomena scattered over the entire island. As a result, it has been established that the $^3He/^4He$ ratio lies within the $(0.7$-$3.3) \cdot 10^{-5}$ range, i.e., it is higher than in the continental segments of the crust and approaches that in the mantle (Kononov et al., 1974). At the same time, this ratio drops off significantly, to $0.6 \cdot 10^{-6}$, in Kamchatka going westward from the areas of present volcanic and hydrothermal activity (Tolstukhin et al., 1972). This difference between two regions of present volcanism can be explained by the absence of any substantial granite layer in the Icelandic crust, while it is a significant component of the subcontinental (Markov et al., 1967) crust of Kamchatka. The fact that helium with a high $^3He/^4He$ ratio rises to the surface over the entire area of Iceland, rather than being confined to the zone of present flows of magmatic melts, is consistent with the high $^3He/^4He$ ratio in basalts of the ocean floor (Krylov et al., 1974), and with the data on the excess of ^3He in bottom waters of the ocean (Clarke et al., 1969). These data are interpreted as reflecting an upward flow of mantle helium through the oceanic crust—where this process is not camouflaged by the generation of radiogenic ^4He, to the same extent as it is in the continents; it also is consistent with the view of Icelandic structures being similar to those of the ocean floor.

The general background of high (mantle-associated) $^3He/^4He$ over the area of Iceland exhibits distinct variations of the second order. These are not quite consistent with the established geochemical and energy zonation of the present geothermal activity, evidently because of different depths of generation of the corresponding fluids. At the same time, a zone of higher $^3He/^4He$ ratios ($>2.0 \cdot 10^{-5}$) extends across Iceland in the general direction of the system of the mid-oceanic ridge, and coincides with the Median Zone, in the southern part of the island. It coincides on the northwest with a probable continuation of the Reykjanes-Lang Jökull branch toward Skaga Island and farther on, to a junction with the Kolbeynsey submarine range. In addition, some of the areas of the island exhibit a direct correlation of $^3He/^4He$ ratios with the configuration of layer "3" of the Icelandic crust, as determined by the seismological investigations (Palmason, 1971). Thus, the values of $^3He/^4He$ in thermal gases, and their spatial distribution, reflect important features of deep geologic structure.

In contrast to helium, the isotopic composition of sulfur in underground waters and gases clearly exhibits a clear-cut zonation consistent with the over-all structure of the island and with zonation of the chemical composition of thermal waters (Vinogradov et al., 1974). As illustrated in Fig. 3, the composition of sulfur in thermal phenomena associated with volcanically active branches of the Median Zone corresponds to that in the meteoric troilite believed to be typical of deep, undifferentiated reaches of the earth and accepted as a standard of comparison ($\delta^{34}S = 0$‰). In the majority of thermal phenomena outside of the regions of active volcanism, the values

Fig. 3. Isotopic composition of sulfur in thermal phenomena of Iceland.

1-3) Zones of $\delta^{34}S$ value in ‰: 1) <3, 2) 3-8, 3) >8; 4) tested thermal phenomena; 5) boundaries of zones of active volcanism (Thorarinsson, 1970; Palmason and Saemundsson, 1974); 6) boundaries of glaciers.

of $\delta^{34}S$ vary from +2.3 to +7.3‰; and from +8.7 to +15.1‰ near the shoreline.

Such a zonation is explained by a mixing of fluids with different original isotopic composition of sulfur. On the one hand, we have here condensates of steam-gas jets of the Median Zone, where sulfur originates in volcanic H_2S with a "zero" (meteoric) value of $\delta^{34}S$. The source of sulfur with a different isotopic composition is the oceanic salt complex with up to $\delta^{34}S = +20$‰ sulfate sulfur rendered heavier in isotopic fractionation during the course of geological evolution.

The similarity of isotopic composition of both the sulfate and sulfide sulfur in thermal phenomena of the Median Zone of Iceland and the meteoric sulfur, in conjunction with the general geotectonic position of the island and with its other geochemical and geothermal features, suggests a juvenile origin for sulfur in areas with a high present geothermal activity in this zone. This clearly sets Iceland apart from volcanically active Kamchatka and New Zealand where the juvenile components have not been identified (Vinogradov, 1970; Wilson, 1966). It is believed that this is due to a contamination of volcanic and hydrothermal emanations by a "heavy" sulfur of oceanic sulfate assimilated by the continental and subcontinental crust of these regeions, during the course of its development. Thus, isotopic composition of sulfur in thermal phenomena of the Middle Zone of Iceland, too, suggests a different structure of its crust.

The heavier isotopic composition of sulfur in the coastal thermal phenomena is the result of drawing of ocean waters into the present hydrothermal systems. This is particularly well expressed in the Reykjanes Peninsula where isotopic composition of sulfur indicates that linear faults in the ocean floor continue for 20 km over the peninsula. At the same time, isotopic composition of sulfur is close to the meteoric, at the southern extremity of the nonvolcanic zone in the area of the Evfjadla Jökull, in a thermal locality 5 km from the shore. This thermal phenomenon lies on the line of the Vestmannaejar volcanic archipelago—evidently a deep fault, although the isotopic composition of sulfur indicates that the surface expression of this fault is not present everywhere.

The study of changes in isotopic composition of sulfur along the trend of the Median Zone reveals important geological facts. It has been established, for example, that the values of $\delta^{34}S$ increase in the southwestern branch of the Median Zone, north of Tingvedlir. That suggests the absence of juvenile H_2S inflow, and may be interpreted as the result of the division of this part of the branch into segments, as already pointed out in the analysis of distribution of the hydrogen thermal waters.

The energy effect of thermal water discharge. As repeatedly mentioned before, heat parameters of thermal waters, closely related to the geochemical and reflecting, as the latter do, the conditions of their development, are quite similar within the same hydrothermal zones whose lateral distribution enhances the principal geological features of Iceland. This is particularly well expressed in the variations of specific energy effect of discharge of thermal waters (Polyak and Kononov, 1974). This effect has been estimated from the calculated total heat liberated by thermal waters of this or that region belonging, as demonstrated, to one and the same geochemical type; and from the reduction of the value to the area of the region under study. A definite zonation is determined as a result; its elements, together with other geoenergy characteristics, are illustrated in Fig. 1. Particularly conspicuous here are the volcanically active branches of the Median Zone and some areas contiguous to them. A fact particularly important in that connection is the hydrogen type of thermal fluids in the Median Zone—considering that hydrogen is the most active natural heat carrier, with a specific heat capacity four times higher than for water and 20 times higher than for basalt. In addition, it migrates readily, and its generation—when determined, for example, by serpentinization—may be accompanied by a high yield of heat. However, the total effect of this process may be reduced by a cooling of the rising gas in its adiabatic expansion.

the same time, the zonation so determined ex- certain features of hydrogeothermal conditions in parts of the same structural zones. First of all, there is a significal inhomogeneity in geoenergy along the trend of volcanically active branches of the Median Zone—inhomogeneity suggesting the existence of some "geoenergy barriers" transverse to the trend. This is best expressed in a sharp drop in heat by the thermal waters in the near-ocean extremity of the northern active zone; and in the separation of the area of intense hydrothermal activity in the northern part of the southwestern branch. Another significant fact is the difference between the northern and southern branches—despite the arbitrary character of their subdivision. The stretch between the southwestern and southern branches (Hreppar zone) appears to be "colder" than expected on the basis of values characteristic of the other regions. There seems to be a certain general difference between northwestern and southeastern Iceland: an impression is created of a geoenergy asymmetry of the entire region, along its sublatitudinal direction.

An average of 2.6 μcal/cm²/sec from the entire zone of active volcanism, is liberated in the discharge of thermal waters, i.e., about the same amount as for the background conduction heat flow. This figure for Iceland, as a whole, is 1 μcal/cm²/sec, or almost the average for the planetary loss of heat by conduction.

The total effect of geothermal activity. Our analysis makes it possible to characterize the effect of present geothermal activity in Iceland—both quantitatively, in a geoenergy expression, and qualitatively and genetically. A graphic representation of this effect is Fig. 4 which illustrates the expenditure of deep heat as a result of the three phenomena considered. This geoenergy profile shows, against the fairly even distribution of background conduction heat flow, two conspicuous maxima of the expenditure of intra-terrestrial energy, corresponding to the southwestern and southern branches of the Median Zone, and reflecting a great loss of deep heat in the present volcanic and hydrothermal activity. The western peak is flanked by the less conspicuous but also quite expressive maxima corresponding to segments of development of the nitrogen-carbonate thermal waters along the periphery of the southwestern zone. It is with these peripheral maxima that some of the values of conduction heat flow, regarded as anomalous, are associated. Their secondary origin is obvious: they coincide with the total heat loss in the measured zones, with consideration given to discharge of thermal waters.

The profile gives a clear idea of the general intensity of the losses of intra-terrestrial energy in all forms of geothermal activity, and of the relative role of each form in this process. Considering the tectonic position of Iceland, it is of interest to compare these data with the distribution of heat flux over the mid-oceanic ridges.

Up to now, measurements of conduction heat flow were the only basis for judging the geoenergy regime of these ridges. Although nobody disputed the important role of heat removal by volcanic and hydrothermal activity, in addition to conduction, no direct evaluation of it has been obtained in submarine segments of the ridges. Consequently, a reduction of conduction heat flow, down to zero, usually is registered over the axial parts—rift valleys—of the median ridges. This reduction is readily explained by a lowering of the vertical temperature gradient in centers of discharge of deep fluids, on the ocean floor.

Figure 4 shows that the integral curve of heat loss in Iceland (10) differs from profiles of conduction heat flow for the mid-oceanic ridges (curves 6 and 7) solely in their axial parts. The profiles differ in the same way from the

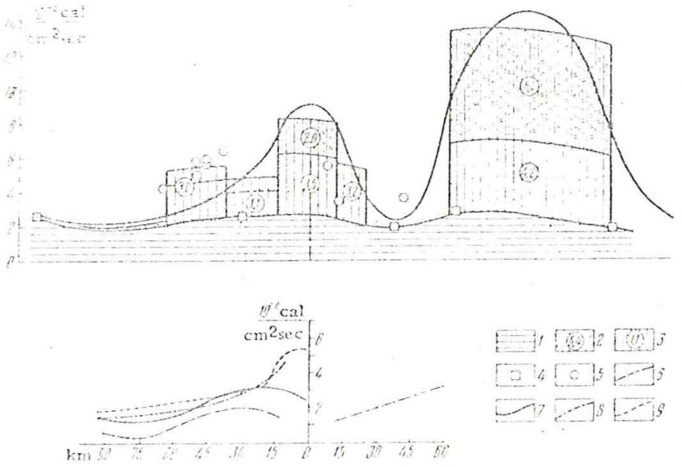

Fig. 4. Geoenergy profile across Iceland (see Fig. 1).

1-3) Output of deep heat, in mcal/cm²/sec: 1) by conduction; 2) by hydrothermal waters, 3) by volcanism; 4-5) values of conduction heat flow: 4) background, 5) anomalous; 6-9) distribution tion of conduction heat flow: 6) observed over Reykjanes Ridge (Talwani et al., 1974), 7) averaged normalized over the Indo-Atlantic Ridge (Op cit.), 8) Mackenzie model (Mackenzie, 1967), 9) Le Pichon-Langseth model (Le Pichon and Langseth, 1969); 10) smoothed-over integral curve of the energy effect of present geothermal activity in Iceland.

theoretical distribution curves 8 and 9 derived from various heat models of spreading. At the same time, curve 10 is closer to the theoretical, although it—in contrast to the modeled and statistical—illustrates the actual distribution rather than that normalized for distances and the effect of spreading. The greatest similarity to the Icelandic integral curve of heat loss is exhibited by the curve of distribution of conduction heat loss, derived from the Le Pichon-Langseth model for the Indo-Atlantic ridge (Le Pichon and Langseth, 1969). However, this similarity should not be overestimated, because the authors of this model, themselves, note its limitations due to omission of convection heat loss. They state that a better correspondence of this model with reality requires an answer to the question, "how significant are heat losses in discharge of crustal waters to the oceanic bottom waters?" In our opinion, the study of geothermal activity in Iceland provides that answer by determining both the energy effect of the process and its relationship with subcrustal reaches.

Thus, a determination of the geochemical and geoenergy features of present geothermal activity is helpful in attacking geological and tectonic problems, by shedding light on details of the structure and evolution of various segments of the crust.

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