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Recent Hydrothermal Systems of Kamchatka

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ABSTRACT

Study of the largest manifestations of the recent hydrothermal activity in Uzon-Semyachik, Pauzhetka-Kambalny and other regions in Kamchatka enable us to conclude:

in the area of recent volcanism characterized by a general increase of conductive heat flow, some regions can be distinguished with an especially intense geothermal regime specified by an additional supply of heat by deep fluids. Within such anomalies the formation of hydrothermal systems can be observed.

Recent hydrothermal systems of Kamchatka are natural hydrodynamic systems belonging to the type of small artesian basins and artesian slopes having porous-bedded, fissure-bedded and more seldom fissure-veined permeability and containing high-temperature underground waters. They are associated with volcano-tectonic grabens and circular depressions filled with a series of tufaceous material of mainly acid composition and two-membered structure. Localization of certain thermal manifestations within the systems is determined by disjunctive tectonics and outflows of thermal waters to the surface. The same factors are responsible for the position of the recharge areas of the systems with infiltration waters forming the main mass of their water reserves. Usual hydrodynamic methods can be used for a quantitative estimation of these reserves.

Heat recharge of the systems is realized by the supply of an over-critical fluid. This is confirmed by hydrogeothermal data, similarity of the chemical composition of high temperature hydrothermal water and their thermo-physical parametres.

Manifestations of hydrothermal activity do not reveal any connection with recent andesite-basaltic volcanism of Kamchatka; on the contrary, they are associated with the acid volcanism of the Middle and Upper Pleistocene stage of its geological history, testifying to their genetic similarity.

Hydrothermal activity is one of the manifestations of the general geothermal activity of the interior. It is closely related, in time and space, to a certain stage of the volcano-plutonic process and tectonic evolution of mobile belts.

The perspectives of obtaining heat and electric energy from hydrothermal systems are considered.

Introduction

In the last few decades, geothermal research has greatly increased both in the USSR and the world over. One of the trends of the research — the study of recent hydrothermal systems of active volcanic regions — is directly related to the problem of utilising terrestrial heat.

Recent hydrothermal systems are understood by the authors of this paper as specific hydrodynamic systems arising in the Earth's crust when a plutonic heat-carrier, such as magma or a water fluid above critical temperature, intrudes into water-bearing strata. Such a definition of the term « recent hydrothermal systems » is based on the following premises:

— the water circulation within these systems is governed by the classical laws of hydrodynamics even though it does have some specific features associated with the high temperature in the depths of the Earth (such phenomena as *thermoartesian head, steam-lift*, etc.);

— the specific discharge of terrestrial heat in such areas by far exceeds the world's average value and cannot be maintained by the flow of heat from the depths by conductivity.

This viewpoint is now widely shared by Soviet experts owing to the work of V. V. AVERIEV (1957-1968) who proposed that geothermal activity be considered in terms of: *geothermal regions* (those with a strong geothermal background), each of them including several hydrothermal systems having at depth a common source of heat; *recent hydrothermal systems* existing apart within separate geological structures of the same geothermal region; *geothermal deposits* as such, i.e. those areas of recent geothermal systems which are suitable for the extraction and exploitation of heat power, areas which owe their existence to specific local features in the geology of individual structures (fractured zones, horst traps occurring under truncated, water-impermeable mantles, etc.). In view of the fact that (1) in Kamchatka, geothermal deposits vary within several square kilometres, hydrothermal systems — within a few tens of square kilometres, while geothermal regions — from tens to hundreds of square kilometres in area and that (2) the beginning of the modern phase of local hydrothermal activity coincided in Kamchatka with the beginning of the Quaternary Period (and in some cases, possibly, with the termination of the Tertiary Period), V. V. AVERIEV stressed the similarity in scope and duration between the manifestations of recent and old hydrothermal activities and summed it up as follows:

Manifestations of hydrothermal activity

recent	old
geothermal region	ore region
hydrothermal system	ore field
geothermal deposit	ore deposit

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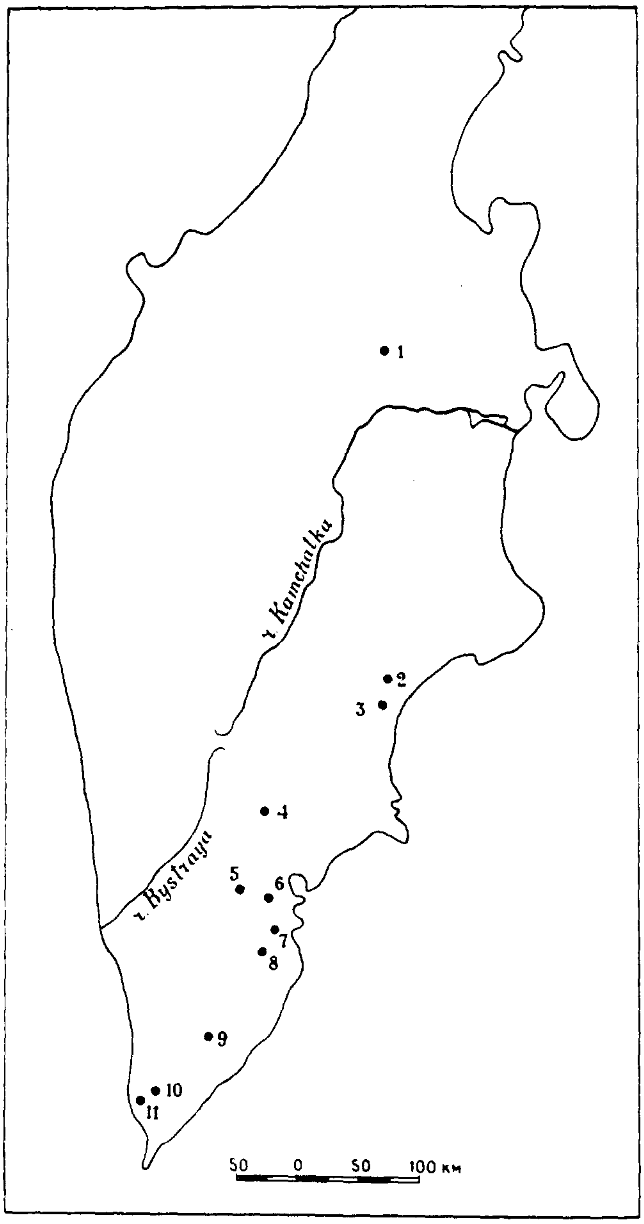

FIG. 1. — *Distribution of hydrothermal systems.* 1 - *Kireunsky*; 2 - *Uzon-Geyserny*; 3 - *Semyachinsky*; 4 - *Nalychevsky*; 5 - *Bolshe-Banny*; 6 - *Paratunka*; 7 - *Zhirovshy*; 8 - *Severo, Mutnovsky*; 9 - *Khodutkinsky*; 10 - *Pauzhetka*; 11 - *Koshelevsky.*

According to the classification adopted for ore deposits, the hydrothermal systems of Kamchatka are subdivided into epithermal (with a temperature up to 150°; e.g. the Paratunka system) and mesothermal (with a temperature over 150° but under 300°; e.g. the Pauzhetka system). These temperatures were recorded in the upper layers of hydrothermal systems by drilling test wells 800 ÷ 1200 m deep. There is every reason to believe that the deeper strata of the systems, as it were, their roots, must have still higher temperatures.

At a depth of several hundred metres where pressure is high, thermal waters occur in the liquid phase despite high temperature. Often they occur as hydraulically uniform flows roughly coinciding in size with the systems. Phase transitions (the boiling of water followed by the condensation of steam) take place, due to a decrease in pressure in the focuses of discharge of these systems. These phase transitions are the causes of sharp non-uniformity in the chemical composition of surface water manifestations, even though the compositions of thermal waters remains fairly uniform at depth.

This paper is concerned with the main features of hydrothermal systems of Kamchatka, the study of which was initiated by B. I. PIYP, V. V. IVANOV, S. I. NABOKO, V. V. AVERIEV. Owing to the works of these and many other researchers, a vast body of evidence is now available on the hydrogeology, geochemistry and thermal regime of such systems. These data agree well with those on analogous systems published abroad by K. BANWELL, G. BODVARSSON, J. MCNITT, A. MAZZONI, G. MARINELLI, F. TONANI, D. WHITE, G. FACCA, J. HEALY, F. STUDT, J. ELDER and others.

Kamchatka's various hydrothermal systems have not been understood to the same degree. Within the Pauzhetka, Paratunka and Bolshe-Banny systems, a wide variety of tests have been performed including test drilling with a view to exploitation; geological, hydrogeothermal and hydrochemical maps have been compiled on the basis of detailed field tests for the Uzon-Geyzerny, Semyachinsky, Koshelevsky and Severo-Mutnovsky systems; other systems have so far been subjected only to reconnaissance studies (Zhirovsky, Khodutkinsky, Karymchinsky, Kireunsky systems) and still others to short-hole test drilling in places (Nalycheovsky). The geographical position of already-known systems is illustrated in Figure 1. By comparing Figure 1 with Figure 2, it should be possible to clarify their geostructural positions. Some of the systems occur so closely to each other as to suggest some sort of association between them. Thus, V. V. AVERIEV put forward an idea that the Uzon-Geyzerny and Semyachinsky systems as well as the Pauzhetka and Koshelevsky ones must derive heat from the same source and therefore must be grouped in Semyachinsky and Pauzhetka geothermal regions respectively. Yet, the plutonic structure of the systems has not so far been sufficiently elucidated to fix the delimitation of their boundaries.

Geological structure

Kamchatka's most powerful hydrothermal systems are concentrated in its eastern volcanic zone. The formation of the zone is associated with the development of graben-synclinal big troughs of a north-eastern trend the limits of which are on the side either regional breaks with a considerable displacement amplitude (1000 ÷ 1500 m) or a series of step-like faults of small amplitude disturbing the normal plunge of the Quaternary volcanic and volcanic-sedimentary rocks filling

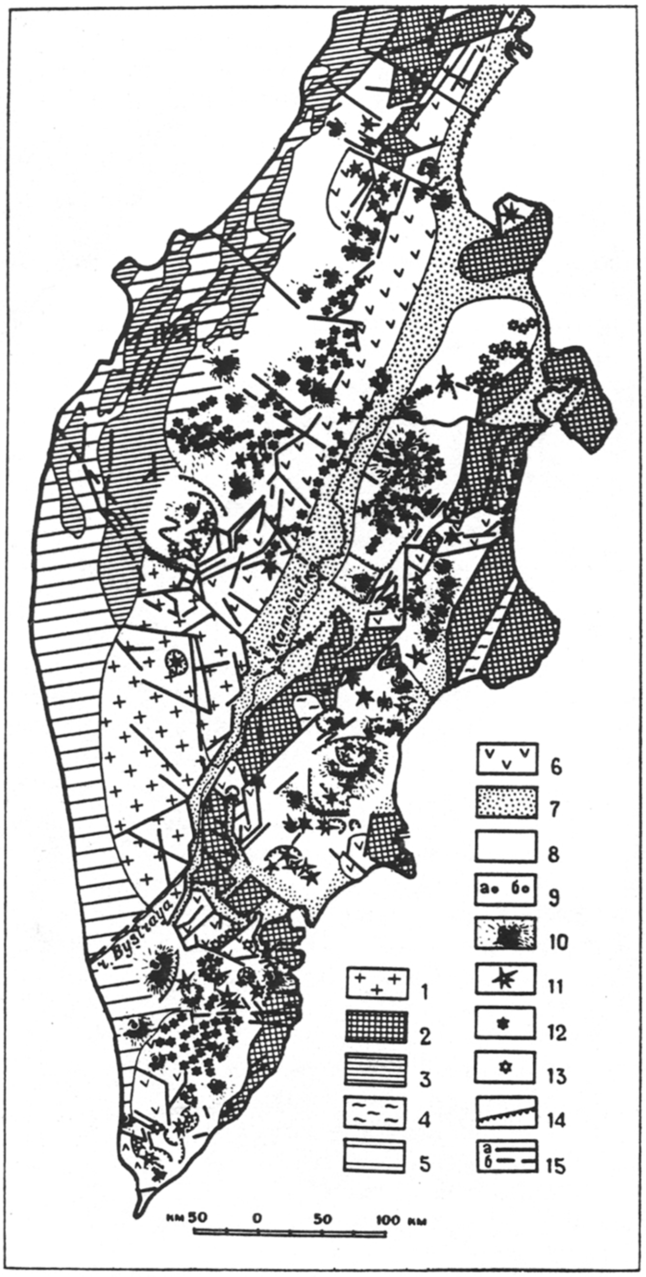

FIG. 2. — *Diagram of modern tectonics of Kamchatka (according to* E. N. ERLIKH*).* 1 - *Malkinsky Arch formed in the Paleogene on the territory of the Sredinny Mountain Range and parts of geosynclinal trough* (Cr_2+Pg)*;* 2 - *horst-anticlinal uplifts inheriting the position of geosyncline of outer arc which have been active since the Miocene;* 3 - *Tigilsky-Palansky system of uplifts formed in the Pliocene in the axial portion of Kamchatka's rear trough*; 4 - *areas of Pliocenic troughs involved in active uplift in the Quaternary Period;* 5 - *monocline of western Kamchatka-recent platform*; 6 - *accumulative-tectonic zones of uplifts of Quaternary age inheriting the position of former geoanticline of inner arc of Neogenic times*; 7 - *zones of active continental sedimentation in the Quaternary*; 8 - *graben-synclines*; 9 - (a) *dead volcanoes of central type.* (b) *active volcanoes of central type*; 10 - *shield and big lava volcanoes;* 11 - *stratal and composite volcanoes*; 12 - *slag cones and lava volcanoes associated with areal volcanism*; 13 - *extrusive domes of regional type*; 14 - *volcano-tectonic dislocations;* 15 - *Breaks*: (a) *active*, (b) *passive zones of basement.*

these troughs in the direction of the axial parts of structures (see Figure 2). Typically graben-synclines have a telescopic structure, which involves the development of a certain type of structures of an ever higher order within their limits, a development finally yielding narrow depressions immediately adjacent to sporadic volcanic series also occurring within their limits. The thickness of volcanic formations filling the graben-synclines is on the average 1500 m. Usually graben-synclines are superimposed on earlier-formed troughs, composed of Miocenic-Pliocenic rocks which reveal their inherited nature. The graben-synclines are bordered by block-folded edifices of a horst-anticline type which are composed of pre-Quaternary formations and in places complicated by narrow superimposed grabens. Many areas on graben-synclines are also superimposed by structures of a still higher order such as circular volcano-tectonic depressions of the caldera type which resulted from the development of pre-surface magmatic chambers. Geothermal systems are confined to the structures of this type — superimposed grabens and circular depressions — while individual geothermal deposits are associated with local features of these structures (local horst uplifts, fractured zones, etc).

Kamchatka's recent hydrothermal systems with the highest temperature (mesothermal) are confined to the big circular volcano-tectonic depressions and calderas superimposing graben-synclines. The formation of such structures is associated with powerful manifestations of acid volcanism including both the intrusion of extrusive bodies of dacite-liparite composition and the ejectamenta of acid pyroclastic material such as pumices and ignimbrites. The more recent (Quaternary) strata of relatively friable pyroclasts-filling depressions may exceed 1 kilometre in thickness and are rather good collectors which prepare the way for the formation waters. The Uzon-Geyserny, Semyachinsky and Pauzhetka systems are of such a structure (Figures 3, 4, 5). The main emissions of thermal waters within these structures are determined either by the faults along their borders (hydrothermal manifestations in the Valley of Geysers and Bolshe-Banny Springs) or by superimposed fissured zones intersecting the structure (waters of the Uzon Caldera, Bolshoy Semyachik mountain range). Probably, the same break-like dislocations also serve as focus of recharge for hydrothermal systems with a plutonic heat carrier.

Another type of structure enclosing hydrothermal systems (usually epithermal) is represented by narrow linear graben, both those superimposing the horst-anticlinoria of the border of the eastern volcanic zone (e.g. Paratunka graben; Figures 6, 7) and the similar graben developed in the axial parts of graben-synclines (Nalychevsky graben). Manifestations of volcanism are practically absent within the limits of such structures, yet they are broadly developed in the areas adjacent to them, being represented there by the fields of extrusive

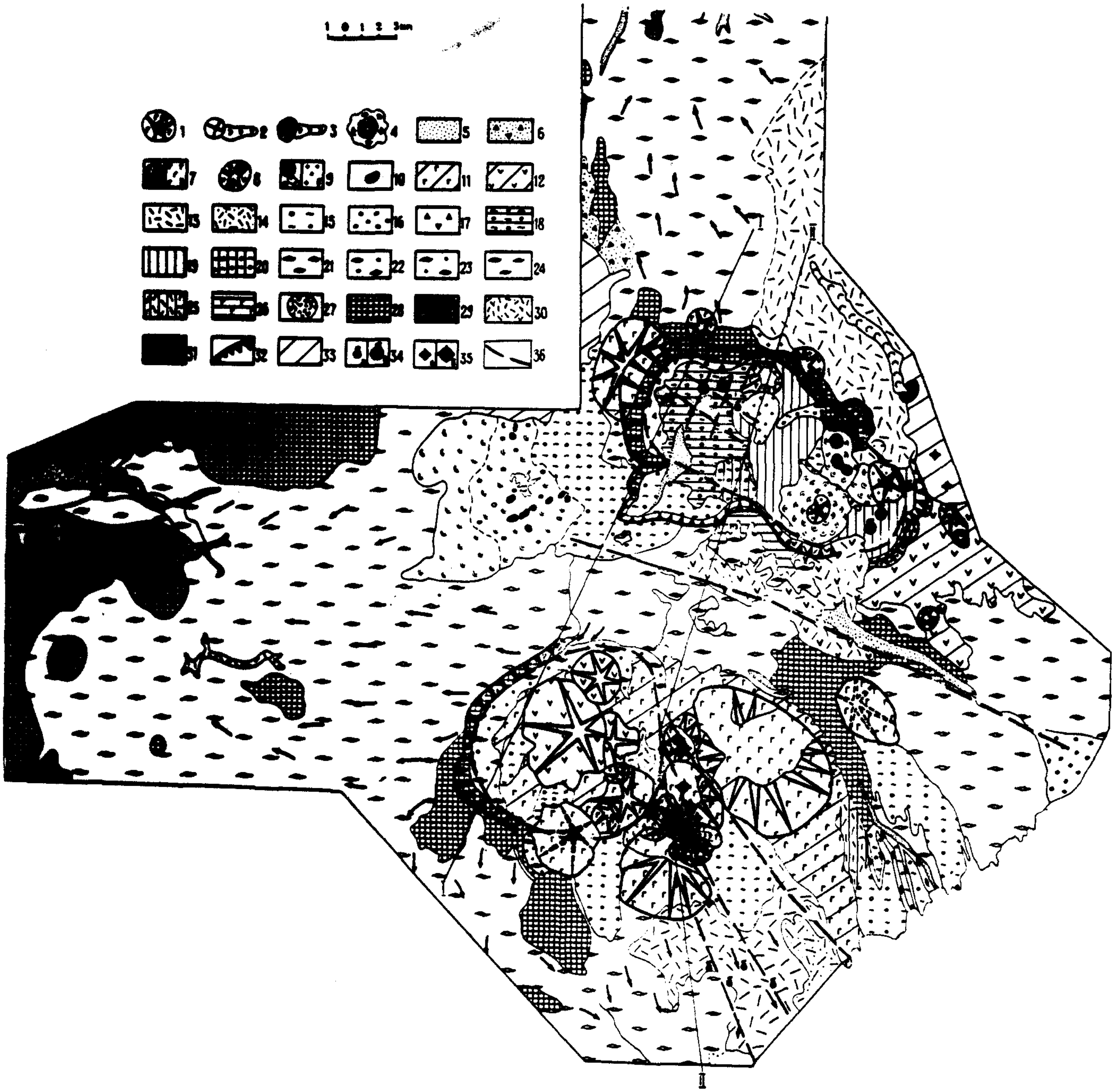

Fig. 3. — *Reconnaissance geological map of Uzon-Semyachinsky region* (V. V. AVERIEV, G. E. BOGOYAVLENSKAYA, O. A. BRAYISEVA *1968).* 1 - *Holocenic basalt and andesite-basalt stratal volcanoes*; 2 - *Holocenic basalt slag cones and their lava sheets*: 3 - *Holocenic andesite-basalt extrusive domes and their lava sheets*; 4 - *Holocenic and Upper-Pleistocenic-Holocenic dacite-liparite volcanoes, extrusion and their lava sheets*; 5 - *Holocenic alluvial deposits of flood plain and low terraces above the flood plain*; 6 - *Holocenic volcanic-proluvial deposits*; 7 - *Upper-Pleistocenic basalt and andesite-basalt stratal volcanoes*: (a) *preserved parts of edifices*, (b) *destroyed parts*; 8 - *Upper-Pleistocenic andesite and dacite volcanoes and extrusive domes*; 9 - *Upper-and Middle-Pleistocenic dacite extrusive domes and their lava sheets*: (a) *preserved part*, (b) *destroyed parts*; 10 - *Upper-Pleistocenic basalt, slag lava cones*; 11 - *Upper-Pleistocenic basalt sheets*; 12 - *Upper-Pleistocenic andesite lava sheets;* 13 - *Upper-Pleistocenic pumice sheets;* 14 - *Upper-Pleistocenic ignimbrites*; 15 - *moraines of the second phase of Upper-Pleistocenic glaciation*; 16 - *fluvio-glacial deposits of the second phase of Upper-Pleistocenic glaciation*; 17 - *Upper-Pleistocenic-Holocenic deluvial-proluvial talus deposits*; 18 - *Upper-Pleistocenic lacustrine-alluvial deposits of Lake Vtoroy Uzonsky overlain by moraine of the first phase of Upper-Pleistocenic glaciation*; 19 - *Upper-Pleistocenic lacustrine-alluvial deposits of Lake Pervy Uzonsky;* 20 - *ditto, but covered with moraine*; 21 - *Middle-Upper-Pleistocenic ignimbrites associated with the Uzonsky depression;* 22 - *ditto, but covered with a thin mantle of glacial deposits;* 23 - *Middle-Upper-Pleistocenic ignimbrites of Semyachic River Valley;* 24 - *Middle-Pleistocenic ignimbrites associated with Semyachinsky depression;* 25 - *Middle-Pleistocenic ignimbrites of Volcano Taunshits;* 26 - *Middle-Pleistocenic covers;* 27 - *Middle-Upper-Pleistocenic basalt stratal volcanoes;* 28 - *Upper-Pliocenic-Lower-Pleistocenic tuffs and lavas of basalt composition;* 29 - *the same deposits but covered with a thin pumice mantle;* 30 - *Upper-Pliocenic Middle-Pleistocenic lavas and tuffs of predominantly acid composition;* 31 - *Miocenic rocks of folded base;* 32 - *modern position of benches of circular structures;* 33 - *lava fields of Taunshits and Kikhpinych;* 34 - (a) *thermal springs,* (b) *powerful groups of boiling springs and geysers;* 35 - *areas of manifestations of* (a) *relatively weak and* (b) *intensive solfataric activity;* 36 - *zones of dislocation with break in continuity.*

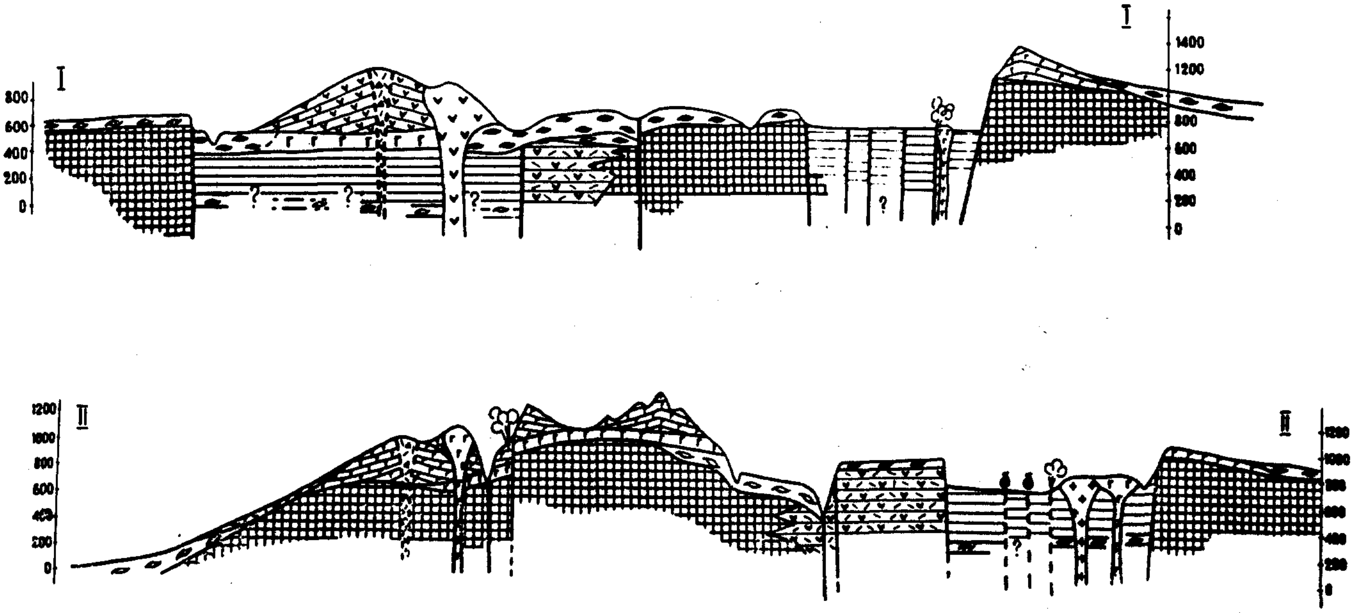

FIG. 4. — *Cross-section for the Uzon-Semyachinsky region* (V. V. AVERIEV, G. E. BOGOYAVLENSKAYA, O. A. BRAYTSEVA, E. A. VAKIN *1968*).

domes of dacite-liparite composition (extrusives of Goryachaya Sopka, Baby Kamen and domes of the Topolovy Spring in the basin of the Paratunka river) or by large bodies associated with central-type volcanoes which have the same composition of dacites or acid andesites (the area of the Severo-Mutnovsky system). The principal water-bearing strata in the structures of this type are pre-Quaternary complexes of rocks underlying grabens which are represented by lithified, often slightly metamorphic, dislocated volcanogenic-sedimentary formations. They have a more heterogeneous petrochemical and lithological composition than the depression-filling strata and occur as various tuffs and tuff-breccias and also as argillites, aleurolites, sandstones and conglomerates. The open porosity of these strata is very low and therefore the conditions for localising subterranean waters are restricted there to the fissured zones intersecting the grabens. The fields of hydrothermally-altered rocks occur in the extension of such zones at edges of grabens, which favours the conclusion that the thermal waters occurring within grabens have come in from the areas of adjacent uplifts.

It follows from the above that, in the structures of both types, hydrothermal activity is associated with the manifestations of acid volcanism, a pointer to the volcano-plutonic stage in the development of the given area. These manifestations indicate the final phases of the first Quaternary volcanic cycle during which the forms of volcanic activity were evolving from shield basalt volcanoes and also regional basalt volcanism to andesite stratal-volcanoes and mass manifestations of acid magmas. The age of the main outburst of acid volcanism in the Quaternary period is dated to the end of the Middle and the beginning of the Upper Pleistocene. At the recent stages of geological history, the andesite-basalt volcanism of the second Quaternary volcanic cycle is in evidence in the areas of hydrothermal activity: sporadic slag cones with lava flows of basalt such as the Barkhatnaya Sopka (coniform hill) in the basin of the Paratunka river, stratal-volcanoes and extrusions such as the Bolshoy Semyachcik volcanic range.

The extremely important feature in the geological structure of most areas in which hydrothermal systems develop is the presence of lithological and tectonic screens promoting the formation, accumulation and retention of thermal waters. Such screens are represented by the horizons of poorly permeable rocks overlying and underlying more permeable strata (as for example in the area of Pauzhetka) or by the bodies of slightly fissured magmatic rocks (such as grano-dioritic intrusions in the Paratunka basin) blocking the lateral migration of thermal waters. Distribution of surface thermal manifestations is controlled by the position of water-bearing horizons or water-enclosing fissured zones in relation to the base levels of drainage and hydrodynamic conditions in the given system.

Hydrogeothermal description

The water-bearing systems in which hydrothermal activity takes place are small in size because the geological structures they are associated with are rather strictly limited to calderas, superimposed and inherited grabens and some such formations, or because the water-enclosing lithological complexes occur only locally. The presence of relatively impermeable deposits in the upper strata of these geological structures imparts to them a geologically closed character. This is especially true of volcano-tectonic depressions. The water-bearing sys-

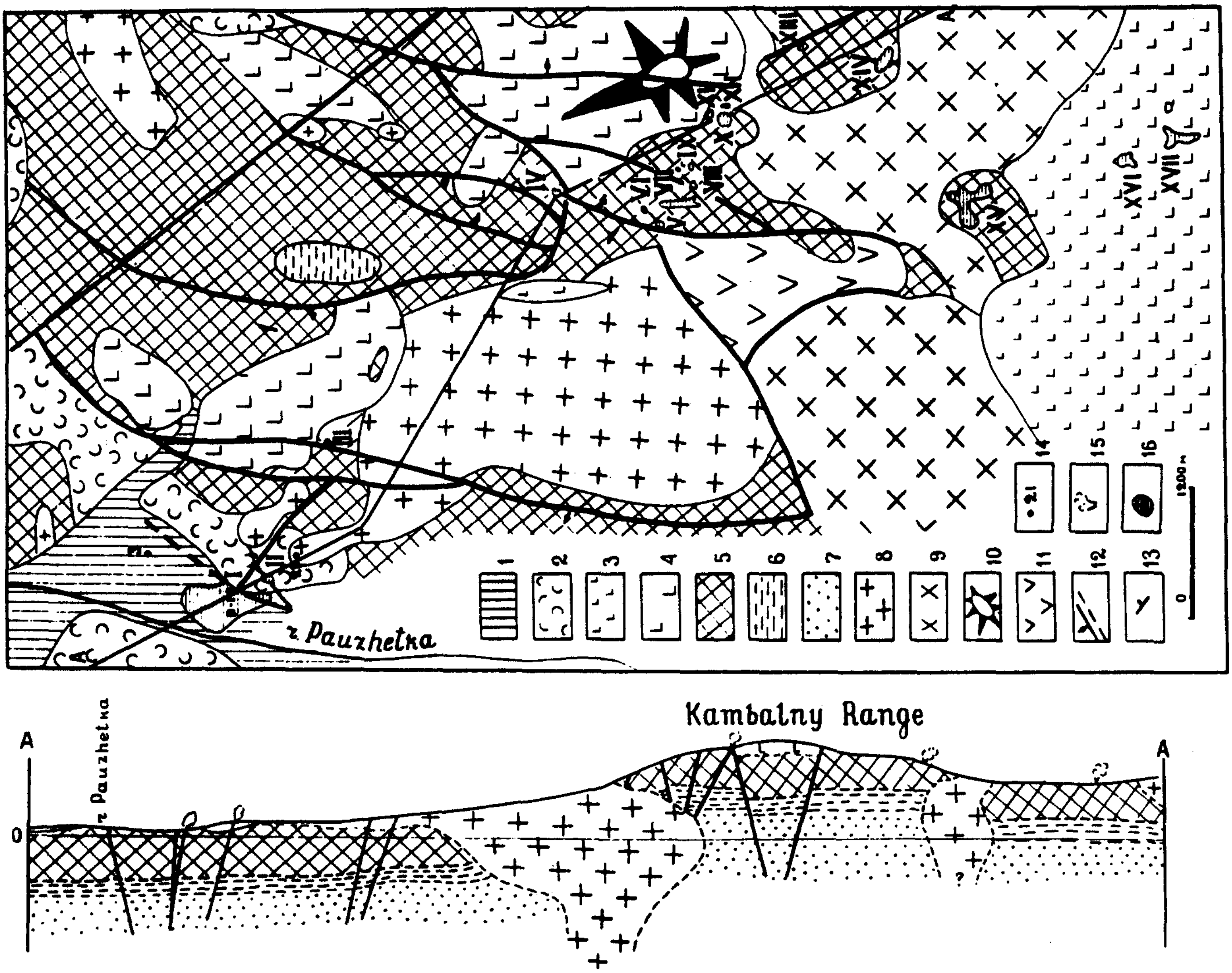

FIG. 5. — *Geological map of Kambalny mountain range* (V. I. BELOUSOV *with* V. M. SUGROBOV's *assistance 1968).* 1 - *Upper Holocene, alluvial deposits;* 2 - *Lower Holocene, pumice deposits;* 3 - *Holocene, andesite and basalt lavas of volcano Kambalny;* 4 - *Holocene, andesite and basalt lavas of volcano Chornye Skay;* 5 - *Pleistocene, Pauzhetka series (psephitic, aleuropelitic, ash tuffs of rhyodacites composition);* 6 - *Pleistocene, caked tuffs of dacites;* 7 - *Pliocene, volcano-mictic sandstone;* 8 - *Holocene, rhyodacites of Ploskaya extrusion;* 9 - *Holocene, rhyolites and dacites of extrusion of Kambalny range;* 10 - *Chornye Skaly (volcano of central type);* 11 - *Holocene, Krivaya (andesite-basalt extrusion);* 12 - *breaks;* 13 - *elements of occurrence;* 14 - *wells;* 15 - *steam jets;* 16 - *thermal fields (I - Pauzhetka, II - Verkhne-Pauzhetka, III - east-Pauzhetka. IV - first group of north-Kambalny steam jets, V-IX - second group of north-Kambalny steam jets, X-XIV - third group of north-Kambalny steam jets, XIII-XIV - east-Kambalny, XV - third group of south-Kambalny steam jets, XVI - second group of south-Kambalny steam jets, XVII - first group of south-Kambalny steam jets).*

tems associated with such depressions, as far as hydrodynamics goes, correspond to the small-size artesian basins and slopes which are formed due to the seepage of atmospheric precipitations. According to the nature of circulation, the waters of these systems belong to the fissure and stratal-fissure type of head (artesian) waters, since their flooded strata possess fissure and porous permeability, while their overlying and underlying strata are only slightly permeable and therefore hamper the passage of water.

The flooded strata is 200 ÷ 500 m in thickness, as revealed by test drillings in the Pauzhetka and Bolshe-Banny deposits, while the thickness of their watertight enclosing strata is 50 ÷ 150 m. The permeability of the water-enclosing tuff-generating complex of rocks composing closed-type hydrogeological structures is not high and is according to laboratory studies and random water samples from test wells $1\times10^{-2} \div (5 \div 6)\times10^{-4}$ darcy.

The effective permeability of water-bearing strata — determined by prolonged water sampling from test wells — usually exceeds the figures obtained in the laboratory because here we are probably dealing with a sum-total of porous and fissure (both micro- and macro-) permeability. Thus, the permeability of water-bearing psephitic tuffs (data collected during the test exploitation of the Pauzhetka deposit) varies from 0.26 to 0.44 darcy.

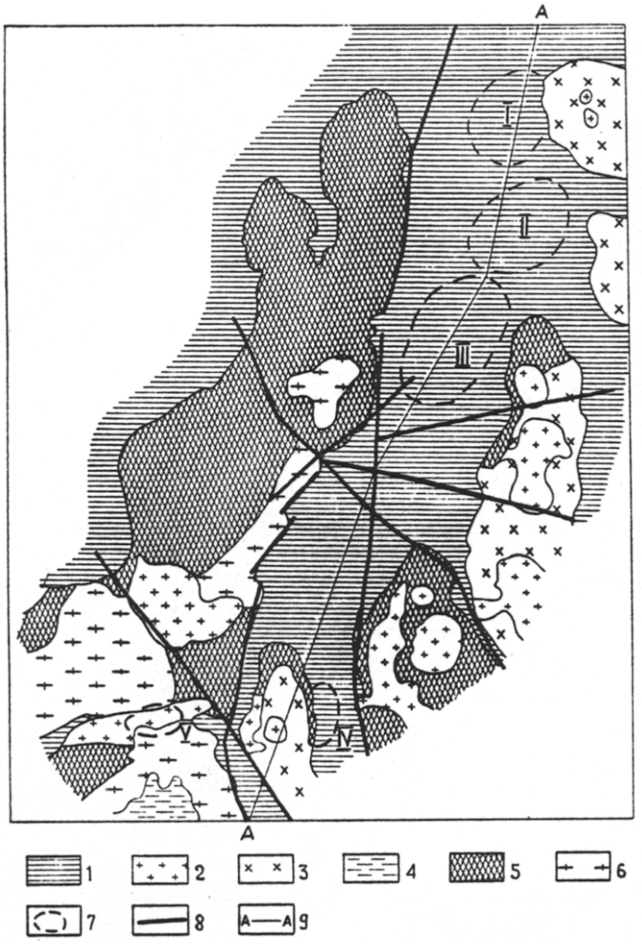

FIG. 6. — *Reconnaissance geological map of Paratunka deposit* (V. I. VOROBYOV, S. I. FEDORENKO, YU. F. MANUKHIN, *Kamchatka Geological Board* 1969). 1 - *Holocene, friable deposits (sand, pebbles, cobble round-stone)*; 2 - *Quaternary and Neogene: extrusions of rhyodacites andesite-basalt volcanic edifices;* 3 - *Neogene: basalts, andesite tuffs and liparites, ignimbrites;* 4 - *Middle Miocene (Beryozovsky series): liparite tuffs, liparites;* 5 - *Miocene (Paratunka series): andesite tuffs, sheets of andesite-basalts, andesites and andesite-dacites;* 6 - *Miocene: intrusions of granodiorites, diorites. quartz-diorites;* 7 - *explored areas of Paratunka hydrothermal system (I - Severny, II - Nizhne-Paratunka, III - Sredne-Paratunka, IV - Verkhne-Paratunka, V - Karymshinsky);* 8 - *breaks;* 9 - *lines of profile.*

In hydrothermal systems associated with the areas of horst anticlinoria, the porous permeability of compact rocks is negligible, while water or steam circulates through a system of breaks and fissures. The permeability of strata in the water-influx zone of such systems can be imagined by the example of the Bolshe-Banny deposit. According to laboratory studies, the permeability of silificated psammitic tuff (locally occurring) is equal to $(3 \div 14) \times 10^{-4}$ darcy and that of andesite with hairline cracks $(7 \div 9) \times 10^{-4}$ darcy. But the effective permeability of flooded strata of the same area comes close to the permeability of flooded strata of the Pauzhetka deposit (just as high discharges of wells: $15 \div 25$ kg per second). The design and depth of wells of the Pauzhetka and Bolshe-Banny deposits are roughly the same.

Plutonic temperature measurements were taken in the hydrothermal systems of Kamchataka (Pauzhetka and Paratunka deposits). According to the thermographs presented in Figure 8, temperature measurements were taken to a depth of 1200 m. A maximum temperature of 200 °C was recorded in this range of depths in Pauzhetka. All the thermographs are convex in relation to the axis of depths, indicating an intensive rise in temperature in the upper zone which is usually a water-impermeable strata. The temperature gradient in these strata grows to $50 \div 70$ °C per 100 m. In flooded strata, the temperature gradient sharply drops. The distribution of temperatures over the area depends on the nature of flooding and the geological structure of each particular part of the area, and is associated with the migration of water under the influence of the pressure-head gradient (induced convection) and free convection. In the flooded strata, temperature is distributed rather uniformly, gradually decreasing towards the limits of the hydrothermal flow as seen from the example of the Pauzhetka deposit presented in Figure 9. In the upper water-tight overlying strata, temperature is distributed according to the conditions of conductive heat transmission, while the seepness of the curves is determined by the thermo-physical constants of the rocks composing the strata. The temperature curve sometimes differs from the theoretical one, due to convection in the test wells. Temperature anomalies in water-tight horizons are observed only near breaks and fissures through which water and steam are passing. The anomalies are commonly traced also on the surface, providing a clue to the position of water-conducting zones underground.

A comparison of thermographs obtained by drilling test wells in the hydrothermal systems with a theoretical curve, reflecting changes in boiling point according to increases in normal hydrostatic pressure with depth, shows that all the temperature readings are lower than the figures for the saturated-steam curve (Figure 8). The water can boil only in the presurface zone where hydrostatic pressure is the lowest.

In the strata enclosing strongly heated waters and steam, temperature either remains constant or grows very gradually with depth. This tendency fails to be confirmed only in individual parts of hydrothermal systems. Such parts coincide with induced thermal fields resulting from the lateral migration of steam-thermal waters. Such an inversion of temperature is typical of hydrothermal systems in which water cicrculation takes place in a fissure-porous collector (e.g. Pauzhetka system).

The piezometric levels of thermal waters, as shown by test-drilling in Kamchatka's hydrothermal systems, agree with the static levels of cold head waters changing in area with changing geomorphology. The absolute elevations of piezometric levels decrease in a regular

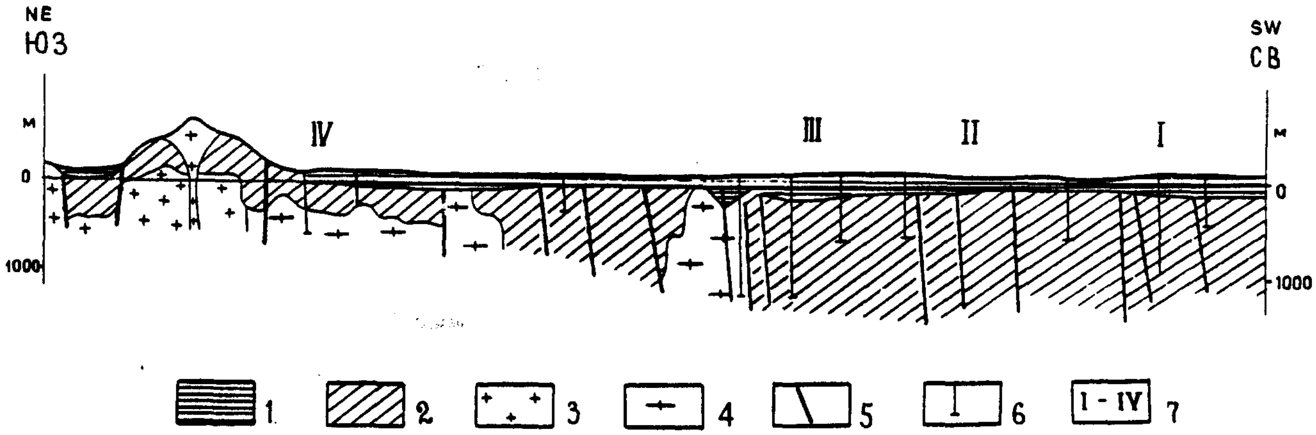

FIG. 7. — *Cross-section of the Paratunka deposit* (V. I. VOROBYOV, S. I. FEDORENKO, YU F. MANUKHIN). 1 - *Holocene, friable deposits (sand, gravel, pebbles, cobble round-stone);* 2 - *Miocene (Paratunka series), andesite tuffs, sheets of andesite-basalts, andesites and andesite-dacites;* 3 - *liparites;* 4 - *intrusive rocks (diorites, quartz-diorites, granodiorites);* 5 - *breaks*; 6 - *wells;* 7 - *explored areas (see Figure 6).*

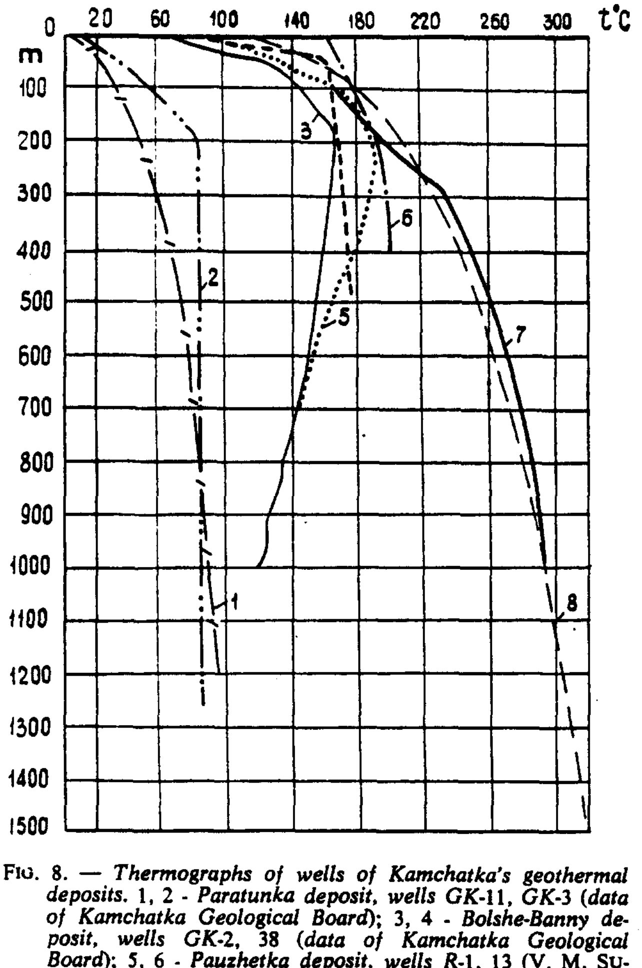

FIG. 8. — *Thermographs of wells of Kamchatka's geothermal deposits.* 1, 2 - *Paratunka deposit, wells GK-*11, *GK-*3 *(data of Kamchatka Geological Board)*; 3, 4 - *Bolshe-Banny deposit, wells GK-*2, 38 *(data of Kamchatka Geological Board)*; 5, 6 - *Pauzhetka deposit, wells R-*1, 13 (V. M. SUGROBOV); 7 - *Waiotapu (New Zealand)*; 8 - *theoretical curve for changes in boiling point with increasing normal hydrostatic pressure.*

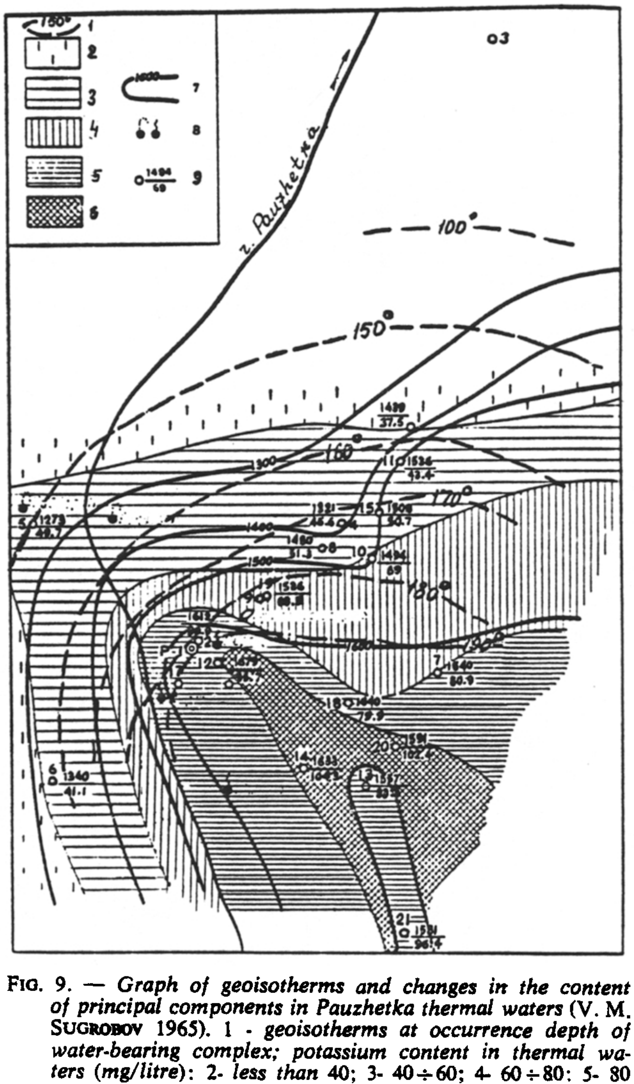

FIG. 9. — *Graph of geoisotherms and changes in the content of principal components in Pauzhetka thermal waters* (V. M. SUGROBOV 1965). 1 - *geoisotherms at occurrence depth of water-bearing complex; potassium content in thermal waters (mg/litre)*: 2- *less than* 40; 3- 40÷60; 4- 60÷80; 5- 80 ÷100; 6- *over* 100; 7- *isohypses of chlorine (mg/litre)*; 8- *springs and geysers;* 9- *wells (numerator shows chlorine concentration, denominator - potassium concentration).*

pattern from the elevated elements of relief towards river valleys, lakes and sea coasts. Powerful focuses of discharge of hydrothermal systems as well as discharge zones of common cold waters are confined to the negative forms of relief. Thus, Pauzhetka hydrothermal waters are discharged in the Pauzhetka River Valley, while Semyachinsky waters are discharged along the ocean coastline.

In natural conditions, hyperthermal as well as cold head and non-head waters are hydraulically associated with one another, while stratal pressure in a hydrothermal system is determined by stratal pressure existing in the hydrogeological structure in which the system arises. This is evident during the exploitation of deposits of hyperthermal waters and steam, when there is an influx of cold water into geothermal wells in the zone of dropping pressure. In a head-pressure system of cold waters, the flow thermal waters (Figure 9) plays the role of a drain, a stream resulting from hot water seeping $5 \div 10$-times faster than cold water owing to the drop in water viscosity with increasing temperature. The stream of thermal waters involves cold infiltration waters and accumulates considerable geothermal reserves in a relatively limited area. Owing to the lower viscosity of thermal waters, the same poorly permeable strata become collectors for them, at the same time hampering the passage of cold waters.

The influence of high temperature on the migration of thermal waters stands out with particular prominence at the points where the systems are discharged. The discharge of thermal waters is intensified as the static level rises because of the *thermo-artesian* head. Whereever piezometric levels occur below the surface, thermal waters are discharged as a result of steam separation. The boiling of water depends on the local geology and hydro-geology in the areas of thermal fields, and above all on the temperature in the strata of hydrothermal systems and the level of hydrostatic pressure. The boiling of water with decreasing hydrostatic pressure in the area of discharge also involves the spontaneous pumping-out of water by steam, while the thermal power of thermal waters is partly converted to the mechanical power of rising steam-water mixture in the channel of a spring, geysers or the well with which they are opened (owing to steam expansion). The hydraulic effect of the pumping out of water by steam (*steam-lift*) was studied by V. V. Averiev (1960).

Surface activity

Those hydrothermal systems in the upper parts of which there is a relatively permeable stratum enclosing overheated waters (in relation to atmospheric pressure), manifest various forms of thermal activity depending on the position of piezometric levels. In the areas where the piezometric level occurs over the earth's surface (usually the area of discharge of a head system), there are predominantly hot or boiling springs and geysers, steam jets and the patches of soil heated by them (Pauzhetka thermal field, the Valley of Geysers, Bolshe-Banny field, etc.) .

Where piezometric levels come to test below the surface, there are only outbursts of steam in the form of separate jets or scattered steaming (patches of steaming ground). The outgoing steam is usually *secondary* and its temperature corresponds to the saturation point under the given atmospheric pressure, because the steam separating from thermal waters passes through ground, or surface waters which occur very widely. Usually the areas where steam bursts out coincide with the elevations of microrelief. If steam, on separation from the surface of subterranean waters, passes into depressions filled with surface waters, boiling or mud pots and pools are formed with a continuously steaming surface. As a rule, they have little or no discharge.

Surface thermal manifestations in hydrothermal systems with compact fissured strata in the upper parts, mostly take the shape of steam jets and hot and boiling pots. The latter often look like springs, though they are formed by the intrusion of steam or gas jets into surface or ground waters. These manifestations are similar to the manifestations of closed-type hydrothermal systems in the areas of low occurrence of piezometric levels. Thus, steam formation is the cause of many and varied forms of surface thermal manifestations such as boiling springs, geysers, steam jets, steaming ground areas and the zones of hydrothermal metamorphism.

The thermal capacity of hydrothermal system or thermal fields is at present determined by the sum-total heat discharge of springs, steam jets or fumaroles, as well as the heat discharged from the surface of rocks in thermal areas. Given in Table 4 are the data on the thermal capacity of thermal fields and hydrothermal systems. When collecting the data, due consideration was given to all its components, including the discharge of high temperature waters and heat loss from the surface of thermal areas. The heat discharge by geothermal wells gives the only idea about the thermal capacity of those thermal fields in which other types of measurements are hard to take.

According to the latest data, the Uzon-Geysernaya and Semyachinsky systems have the highest thermal capacity in Kamchatka, with 1.34×10^5 kcal per second and 0.75×10^5 kcal/sec respectively, approaching in this regard the hydrothermal systems of New Zealand. V. V. Averiev (1966) pointed out that these values were very close (in the order of size) to the values indicating the thermal capacity of fumarole activity for individual volcanoes which have so far been determined within a range 4.5×10^5 kcal per second (for Mutnovsky Volcano) to 0.2×10^5 kcal per second (for Avachinsky Volcano).

The specific discharge of heat (the ratio of thermal capacity of hydrothermal systems to the area of their surface manifestations) makes it possible to compare the intensities of hydrothermal activity in various regions. It is noteworthy that the specific discharge of heat in hydrothermal systems is of the same order and exceeds the world's average conductive heat loss, dozens and even hundreds of times. The variations between values for the specific heat discharge from system to system are explained by different approaches on the part of researchers to the delimitation of areas with generating thermal fluids and by the difficulty of their precise delimitation. Thus, V. V. AVERIEV described the specific discharge of heat in hydrothermal systems as the intensity of thermal recharge, and related it to the area in which the seepage and heating of atmospheric waters took place. This area usually has clearly defined geological boundaries, and corresponds to the area of water-head systems. This parameter makes it possible to elucidate the total thermal effect of a hydrothermal process by giving consideration to the life span of individual systems. Having calculated the life span to be equal to $n \times 10^4$ years according to the data on the evolution of the relief of similar regions, V. V. AVERIEV concluded that the life-long discharge of heat by individual systems should make up 10^{15}-10^{16} kcal. This quantity correlates with the heat effect obtained by discharging on to the surface $10 \div 250$ km^3 of silicate material with a temperature of 1000°C. The quantity thus obtained is also in perfect agreement with the quantity of magmatic products (extrusive bodies and pyroclastic material) which is recorded in hydrothermal regions.

The recorded thermal capacity of individual systems in actual fact indicates the present range of hydrothermal activity. Its changes in time are above all expressed in the evolution of its surface manifestations. No direct data are available on the entire history of particular systems. Only the ratio between modern thermal fields and the zones of hydrothermally altered strata provide grounds for certain conclusions on that score. It is possible to judge with greater certainty about changes in the nature and distribution of hydrothermal activity within definite systems at the time these systems are under study.

Regular observations conducted for many years show that hydrothermal activity in conditions unmodified by exploitation undergoes few or no changes with time. Thus, the discharge and chemical composition of hydrothermal fluids of Paryaschy I, Pauzhetka's biggest boiling spring, were shown to be stable after 5 years of regular and 25 years of sporadic observations.

A different picture is observed in hydrothermal deposits under exploitation, when the intensive consumption of water results in a considerable decrease in the piezometric level and hence hydrostatic pressure. The experience of the Pauzhetka deposit shows that the discharge of boiling springs drops in the course of exploitation. And this is only too natural and indicative of the fact that, just as in natural conditions, the regime of ascending springs is closely connected with that of the given (high-temperature) water-head system. In the course of the experimental exploitation of the Pauzhetka deposit, the sharp decrease in piezometric level was accompanied by the conversion of this permanently functioning boiling spring with a discharge of 10 litres per second into a geyser with a discharge of 0.6 litres per second. Upon termination of its experimental exploitation and restoration of its piezometric level, the spring resumed its former permanent discharge. The directly recorded conversion of a permanently functioning boiling spring into a geyser and vice-versa, upon hydrodynamic changes in the water-bearing horizon containing hyperthermal waters, is an obvious pointer to geysers and boiling springs having the same nature and also to geysers being a special case of boiling springs.

A decrease in hydrostatic pressure in the areas where the piezometric level is low, results in a more intensive steam separation and hence the appearance of more steam outbursts on the surface, and an increase in the discharge of the already existing steam jets. This observation correlates with the fact established at the Pauzhetka deposit that the activisation of surface thermal manifestations is not accompanied by changes in temperature in the water-bearing complex.

Thus, within one and the same hydrothermal field, it is possible to record both the signs of hydrothermal activity getting weaker (a decrease in the discharge of springs) and the signs of activisation (intensive steam separation). These abnormalities may be caused by hydrodynamic changes in the water-head system rather than by changes in the hydrothermal activity as a whole. Thus, in order to solve the problem of evolution of hydrothermal activity, it is necessary to have data on all its basic parameters (temperature in the strata, thermal capacity of the system, the qualitative composition of hydrothermal fluids.

Changes in hydrostatic pressure in a system bring about changes in the position of the steam-formation level, and hence the nature and intensity of hydrothermal alteration of strata. In view of the fact that a decrease in hydrostatic pressure may be associated with a decrease in piezometric pressure, and therefore with a decrease in piezometric level, the old fields of hydrothermally altered strata cannot be produced in evidence of a wider development of hydrothermal activity in the past. In order to solve this problem it is necessary to reconstruct in each particular case the paleohydrogeothermal conditions of manifestations of hydrothermal activity.

Chemical composition of thermal waters

The chemical composition of Kamchatka's thermal waters is typical of waters occurring in the regions of active volcanism. Almost all their principal types described by hydrochemists (V. V. IVANOV, D. WHITE, and others) have been found on the peninsula. In the course of recent studies of the Uzon-Geyserny system, a discovery was even made there of waters close in composition to the acid *fumarole therms of plutonic formation* (under V. V. IVANOV's classification) widely occurring in the Kuril Islands, but hitherto unknown in Kamchatka.

In the focuses of discharge of hydrothermal systems, some of the water manifestations are rather heterogeneous in chemical composition. Table 1 gives an idea of the principal hydrochemical types occurring in each of the systems which have been studied from this particular angle. The first type includes the waters of thermal (commonly boiling) springs, the most descriptive of the plutonic composition of solutions in circulation in the systems. The second type includes the waters of warm springs occurring on the periphery of discharge areas, and arising from the subterranean boiling of ascending superheated waters and from the subsequent condensation of the resultant steam in the pre-surface strata of the profile. The third type includes the natural condensates of steam-gas jets filling dischargeless pots; and finally, the fourth type includes steam which has been filtered by ground waters.

TABLE 1. — *Chemical composition of thermal waters of Kamchatka's major hydrothermal systems.*

M = Total Dissolved Solids (g/l)
b.p. = boiling point
T = temperature in °C
Ionic composition in eq.%

System	Type of water I	II	III	IV
Pauzhetka	M 3.2 - T b.p. - pH 8.2 $\frac{\mathrm{Cl}\ 95 - \mathrm{SO_4}\ 3}{(\mathrm{Na+K})\ 94}$ Paryaschy I Spring	M 0.5 - T 50 - pH 4.8 $\frac{\mathrm{SO_4}\ 86 - \mathrm{HCO_3}\ 7}{\mathrm{Na}\ 71 - \mathrm{Ca}\ 12 - \mathrm{Mg}\ 8}$ Yuzhny Spring	M 1.8 - T 70 - pH 2.5 $\frac{\mathrm{SO_4}\ 100}{\mathrm{Al}\ 40 - \mathrm{NH_4}\ 20 - \mathrm{H}\ 18}$ II Yuzhno-Kambalny field	M 0.09 - T 98 - pH 8.0 $\frac{\mathrm{HCO_3}\ 88}{\mathrm{NH_4}\ 48 - \mathrm{Na}\ 26}$ Verknee thermal field
Uzon-Geyzerny Caldera Uzon	M 2.1 - T 84 - pH 8.0 $\frac{\mathrm{Cl}\ 94}{\mathrm{Na}\ 90 - \mathrm{K}\ 5}$ Geyzeritovy Spring	M 1.2 - T 55 - pH 7.0 $\frac{\mathrm{SO_4}\ 75\ \mathrm{HCO_3}\ 20}{\mathrm{Mg}\ 53 - (\mathrm{NA+K})\ 38}$ Posledny Spring	M. 3.0 - T 96 - pH 2.1 $\frac{(\mathrm{HSO_4+SO_4})\ 100}{\mathrm{Al}\ 39 - \mathrm{H}\ 37 - \mathrm{Fe}\ 22}$ western solfataric field	M 0.05 - T 95 - pH 8.0 $\frac{\mathrm{HCO_3}\ 100}{\mathrm{NH_4}\ 100}$ eastern field
Valley of Geysers	M 1.8 - T b.p. - pH 7.6 $\frac{\mathrm{Cl}\ 85 - \mathrm{SO_4}\ 10}{\mathrm{Na}\ 95}$ Velikan Geyser	M 0.6 - T 68 - pH 7.2 $\frac{\mathrm{SO_4}\ 86 - \mathrm{HCO_3}\ 14}{\mathrm{Na}\ 48 - \mathrm{Ca}\ 43}$ Area of Lower Geysers	M 1.2 - T 98 - pH 3.5 $\frac{\mathrm{SO_4}\ 97}{(\mathrm{Na+K})\ 69 - \mathrm{Mg}\ 12 - \mathrm{H}\ 8}$ Area of Upper Geysers	—
Semyachinsky	M 1.7 - T 55 - pH 7.5 $\frac{\mathrm{Cl}\ 57 - \mathrm{HCO_3}\ 28 - \mathrm{SO_4}\ 13}{\mathrm{Ca}\ 43 - \mathrm{Mg}\ 28 - \mathrm{Na}\ 21}$ Nizhne-Semyachinsky Spring	M 2.1 - T 55 - pH 7.5 $\frac{\mathrm{SO_4}\ 67 - \mathrm{HCO_3}\ 28}{\mathrm{Ca}\ 61 - \mathrm{Mg}\ 31}$ Intermontane basin	M 0.9 - T 95 - pH 2.3 $\frac{\mathrm{SO_4}\ 94}{\mathrm{Na}\ 36 - \mathrm{NH}\ 33 - \mathrm{Al}\ 20}$ Solfataric field of Volcano Burlyaschy	M 0.3 - T 98 - pH 8 $\frac{\mathrm{HCO_3}\ 100}{\mathrm{NH_4}\ 98}$ Volc. Tsentralny Semyachik
Mutnovsko Zhirovsky	M. 0.8 - T b.p. - pH 7.9 $\frac{\mathrm{Cl}\ 43 - \mathrm{SO_4}\ 36 - \mathrm{HCO_3}\ 21}{(\mathrm{Na+K})\ 99}$ Nizhne-Zhirovsky Springs	M 1.0 - T 58 - pH 7.1 $\frac{\mathrm{SO_4}\ 80 - \mathrm{HCO_3}\ 19}{\mathrm{Ca}\ 79 - (\mathrm{Na+K})\ 18}$ Verkhne-Zhirovsky solfataric field	M 0.8 - T 96 - pH 4 $\frac{\mathrm{SO_4}\ 99}{\mathrm{Al}\ 56 - \mathrm{H}\ 14 - \mathrm{C\ a12}}$ Dachny Springs	—

The non-uniformity of surface manifestations of hydrothermal activity in chemical composition is in the first place associated with the differentiation of components of initial jets in the focuses of their discharge owing to the phase transitions below the earth's surface, and in the second place, with the pre-surface changes in the composition of plutonic jets on being mixed with ground waters, their concentration on evaporation in thermal water reservoirs, and their interaction on contacting the enclosing rocks.

The Uzon thermal field is a classical example of surface hydrochemical anomaly associated with the discharge of a thermal system. The locally manifested zonality of waters makes it possible to follow stage-by-stage the chemical differentiation of superheated therms in the focus of their discharge: from slightly alkaline sodium chloride waters in the centre of their discharge area, through the group of mixed waters of heterogeneous chemical composition, over to the slightly acid waters of peripheral areas. The gradual transition of one type of water to another — illustrated by a mixing-process graph (Figure 10) — manifests itself in the concentrical hydrochemical zonality of waters round the principal thermo-effluent channels (Figure 11).

The above general regularity of changes in the content of chlorine and sulfates, as well as the common nature of distribution of potassium, sodium, rare alkalies, boron and arsen acid in the waters of springs and thermal lakes, are indications of the genetic community

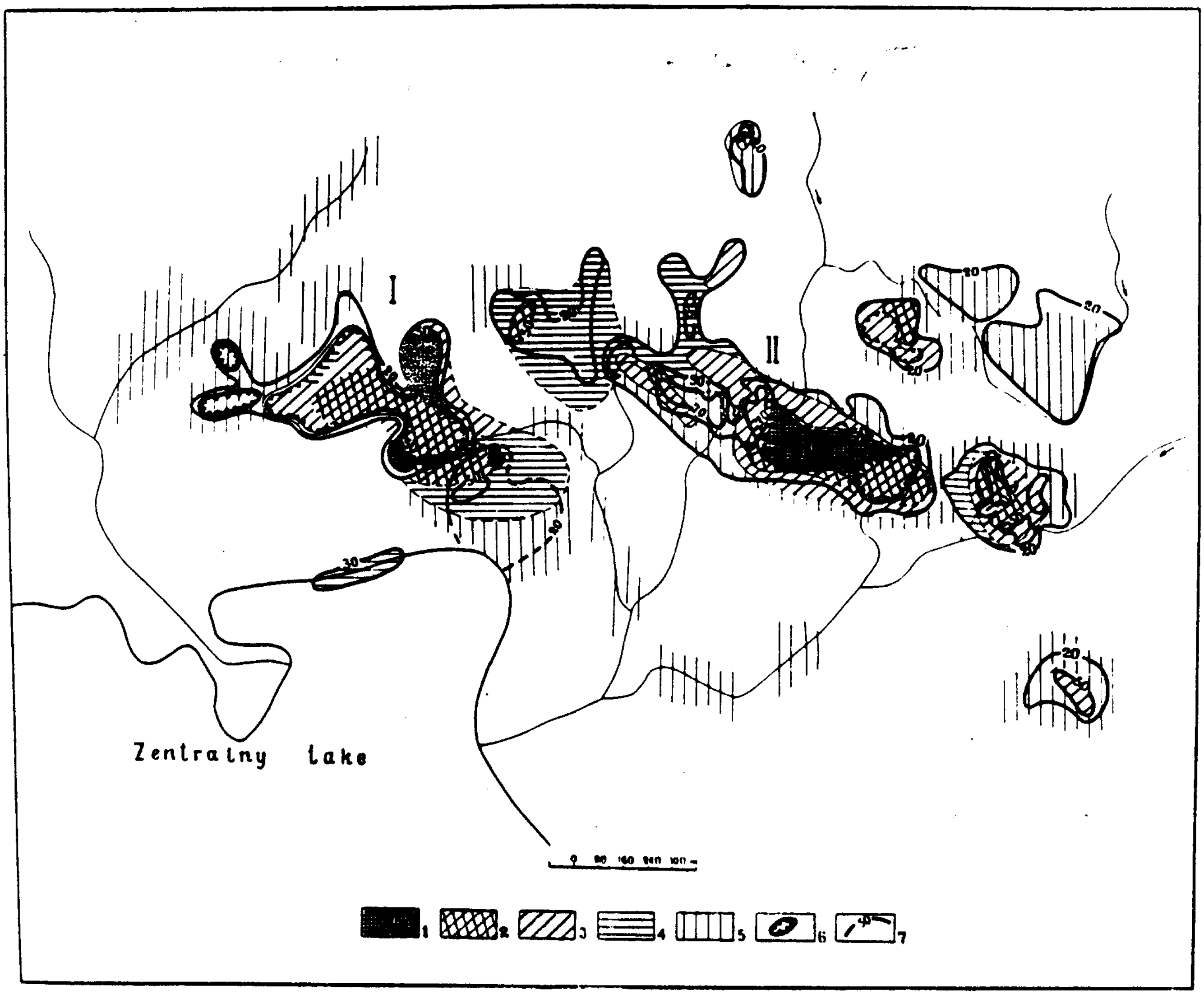

FIG. 10. — *Map of hydrochemical zonality of the discharge area of Uzonsky* (G. F. PILIPENKO 1966-1967). *Types of water*: (1) *chloride sodium*; (2) *sulfate-chloride sodium*; (3) *chloride-sulfate sodium*; (4) *hydrocarbonate-chloride and chloride-hydrocarbonate sodium*; (5) *sulfate-hydrocarbonate and sulfate* (*Na, Ca, Mg*); (6) *acid lakes* (*pH* 2-3); 7 - *isotherms* (*at a depth of* 0.5 *m*).

of all the chemical types of waters occurring in the Uzon caldera. It follows from the above that the principal causes of such zonality are:

(1) the dilution of plutonic hydrothermal fluids on mixing with pre-surface waters involving a regular decrease in mineralisation, temperature and the content of most typical components from the centre of the discharge area to its periphery;

(2) the concentration of hydrothermal solutions owing to evaporation in boiling dischargeless water reservoirs (right-hand upper portion of mixing-process graph).

The appearance of a sulfate-ion in the mixed water of sulfate series is associated with the superimposed process of oxidation of H_2S (and possibly SO_2), being discharged by the steam-gas differentiate at the expense of ground water oxygen. The formation of acid lake waters may be promoted by the oxidation of sulfur to H_2SO_4 by microorganisms (thionic and sulfur bacteria).

The mixing-process graph of Uzon therms correlates well with the data on the composition of superheated chloride waters virtually for all the known high-temperature hydrothermal systems, both occurring in Kamchatka (Kamchatka Geysers, Pauzhetka Springs), and in other countries (Morgan Spring, Wairakei wells and even acid Lake Frying Pan, a source of much controversy among scientists). This testifies to the similarity between the formation processes of hydrothermal-system waters and their pre-surface metamorphism.

The unique completeness of hydrochemical zones in the area of Uzon and their concentricity are associated with the specific conditions of thermal waters

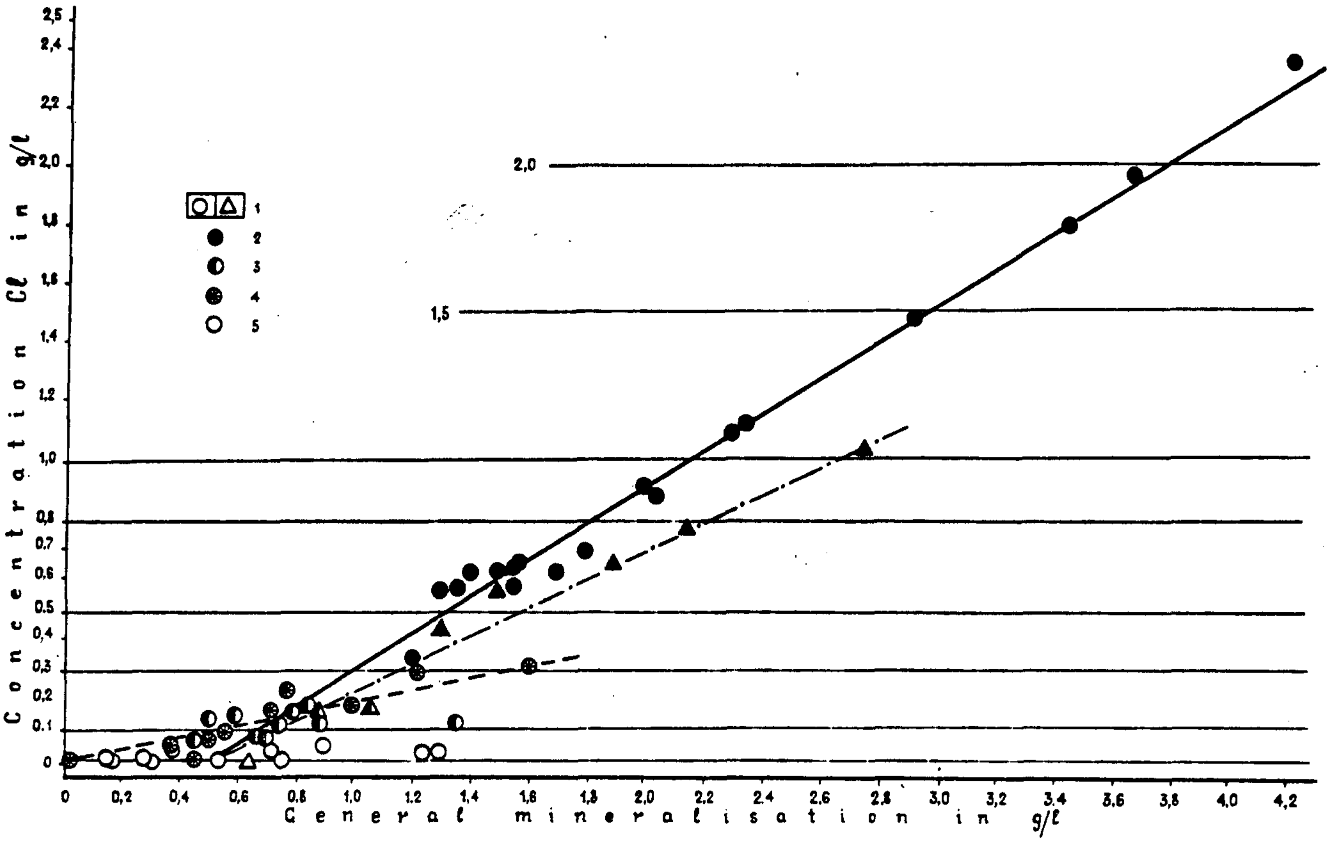

FIG. 11. — *Mixing-process graph for Uzonsky thermal waters* (G. F. Pilipenko 1966-1967). 1 - *nature of thermal manifestations*: (a, *circles*) *springs* (*pH 5-8*), (b, *triangles*) *acid lakes* (*pH 2-3*); *Types of water*: 2 - *chloride and sulfate-chloride sodium*; 3 - *chloride-sulfate sodium*; 4 - *hydrocarbonate-chloride and chloride-hydrocarbonate sodium*; 5 - *sulfate-hydrocarbonate and sulfate* (*Na, Ca, Mg*).

discharge. This discharge takes place in a flat-bottom depression devoid of deep cuts. In other systems, it usually takes place on the slopes and thalwegs of narrow valleys (e.g. valleys of River Geysernaya and Zhirovaya). The powerful ground-water descending streams on the slopes of such valleys are « lubricated » by intermediate hydrochemical zones. The streams also promote the sharp division of discharged hydrotherms into the steam jets of slopes and the springs of thalwegs. In composition, these two forms of surface hydrothermal activity are the extreme hydrochemical types occurring in the Uzon field.

The data available on the Uzon-Geyserny system favour the conclusion that sodium chloride waters with a total mineralisation of 1.5 ÷ 2.0 grams per litre, being least of all metamorphic, are probably the closest in composition to the typical waters of internal recharge. These waters contain gas of which up to 85 ÷ 90% is CO_2, up to 10% H_2S and up to 10% N_2 and rare gases belonging to the nitrogen-carbon-dioxide type according to V. V. Ivanov's classification. The waters of all the high-temperature hydrothermal systems of Kamchatka have such a gaseous composition (Table 2) and so have similar regions throughout the world. The content of acid gases, as well as that of main salt components, decreases towards the periphery of the discharge area, but in contrast to the latter, also decreases in its centre, in the areas of concentration of initial jets. Radon follows a similar pattern of distribution.

The study of salt and gas composition of surface spring waters and steam jets makes it possible to reconstruct the initial composition of hydrothermal solutions with regard to the redistribution of components, resulting from the division of the whole system into separate phases in process of therm discharge. Such balance calculation was performed by V. V. Averiev and V. I. Kononov in order to determine the plutonic composition of hydrotherms occurring in the Uzon-Geyserny system (Table 3). It turned out that at a depth of several hundred metres, where hot waters can exist only in the liquid phase, the role of carbon and sulfur compounds sharply grows and they either become just as important as chlorine or even come to the fore. In order to completely reconstruct the plutonic composition of hydrothermal fluids, it is also necessary to consider their interaction with surrounding rocks in the process of being discharged, including the precipitation of mineral neoformations.

TABLE 2. — *Chemical composition of typical high-temperature waters of Kamchatka.*

System	Pauzhetka		Uzon-Geyzerny			Kireunsky	Zhirovsky	Bolshe-Banny		Paratunka			Nalychevsky
Type of water	Chloride sodium							Chloride-sulfate sodium					Sulfate-chloride sodium
Name of spring	Paryaschy 1 Spring 10.1957	Well 4 03.1961	Velikan Geyser 07.1962	Uzon. Spring Tsentralny 05.1968	Uzon, Spring Geyzeritovy	Spring Sredny Kipyaschy 0.8.1951	Low group 08.1961	Spring No. 4 03.1968	Well No. 35 06.1968	Nizhne-Paratunka Springs 09.1950	Sredne-Paratunka area, well 2 04.1965	Well K-7 07.1965	Spring Novy 10.1951
	1	2	3	4	5	6	7	8	9	10	11	12	13
M (1)	3279	3448	2195	3778	2065	1537	820	1027	1400	1548	935	1173	4435
T°C	T boil. p. (2)	195° max	T boil. p.	T boil. p.	84	T boil. p.	T boil. p.	T boil. p.	—	42.5	90	—	73
pH	8.1	8.2	7.6	6.4	8	7.2	7.9	8.4	8.7	8.1	9.0	8.9	6.45
NH_4^+	0.4	0.6	0.2	6.7	5	3	—	0.15	0.1	n.d.	n.d.	n.d.	0.6
K^+	74	105	60	98	45	12	6.4	25	25	8	10	10	167
Na^+	1010	986	597	1144	511	416	213	305	324	297	206	240	982
Mg^{2+}	8	3.5	3.7	2.2	4	2.8	trace	n.d.	n.d.	3.2	n.d.	n.d.	32
Ca^{2+}	60	52	26	4.8	13.4	33	1.1	15	23	16	71	111	256
Fe^{3+}	—	—	n.d. (3)	0.3	—	0.4	n.d.	—	—	n.d.	n.d.	n.d.	—
Fe^{2+}	—	—	n.d.	n.d.	—	n.d.	n.d.	—	—	n.d.	n.d.	n.d.	1.0
Al^{3+}	—	—	—	0.2	—	—	—	—	—	—	—	—	n.d.
As	—	—	—	2.0	0.25	—	5.0	0.14	0.12	trace	—	—	6
F^-	0.4		—	1.5	—	0.8	—	—		1.2	2.0	2.5	0.8
Cl^-	1667	1633	859	1853	—	578	146	126	127	200	39	62	1594
B_r^-	3	—	2.5	3.5	887	3.7	—	—	—	0.2	—	—	7.8
J^-	—	—	1.2	0.5	—	n.d.	—	—	—	n.d.	—	—	n.d.
SO_4^{2-}	76	78	143	124	39	125	164	511	532	706	556	700	445
HCO_3^-	41	4	81	17	55	74	122	33	42.7	61	n.d.	n.d.	492
CO_3^{2-}	0.9	22	38	—	—	—	—	23.7	37.2	—	19	14.4	—
CO_2	—	—	—	—	—	32	—	—	—	—	—	—	458
H_2SiO_3	216	393	382	268	353	190	121	215	290	81	32	32	191

(1) Total mineralisation, mg/l
(2) Boiling point
(3) Not detected

Research teams: 1, 6, 13 - IVANOV, KRAPIVINA; 2 - AVERIEV, SUGROBOV, RENNE; 3 - AVERIEV, KONOVOV; 4, 5 - AVERIEV, PILIPENKO, VEYNREBE; 7 - VAKIN, KIRSANOVA, KONONOV, POLAK; 8, 9 - EVTUKHOV, KOVALENKO, KRAEVOY; 10 - IVANOV, PROKOFYEVA; 11, 12 - KARPOV, KRAEVOY, MANUKHIN, SHUVALOV.

TABLE 3. — *Plutonic composition of thermal fluids of Uzon-Geyzerny system* (KONONOV 1965).

Location	Phase	Discharge kg/sec	Principal ions, g/kg						Content in steam g/kg		Formula of ionic composition of spring water and jet steam	Content of principal elements in plutonic hydrothermal fluids g/l
			Cl^-		SO_4^{2-}		HCO_3^-					
			surf.	plut.	surf.	plut.	surf.	plut.	CO_2	H_2		
Caldera of Volcano Uzon	steam	14.0	0.004		0.142		0.127		10.0	0.33	$M_{0.4}\frac{SO^4 51\ HCO^3 43}{NH^4 70\ Mg 10}$	$\Sigma\ CO_2$ 2.02
				1.11		0.22		2.80				Cl 1.11
	liquid	56.0	1.394		0.0964		—				$M_{2.8}\frac{Cl 90\ SO^4 5}{Na\ 93}$	Σ S 0.07
Springs of Geyzer Valley	steam	77.7	0.005		0.115		0.048		3.0	1.0	$M_{0.2}\frac{SO^4 72\ HCO^3 24\ Cl 4}{Ca 48\ Na 39\ Mg 13}$	$\Sigma\ CO_2$ 0.88
				0.66		0.78		1.23				Cl 0.66
	liquid	200	0.919		0.460		0.073				$M_{2.3}\frac{Cl 69\ SO^4 46\ CO^3 4}{Na 97\ Ca 3}$	Σ S 0.26

Compounds of sulfur and carbon dioxide in plutonic water are given in terms of ions HCO_3^- and SO_4^{2-}.

Geothermal resources

Hydrothermal systems contain exploitable resources of high-temperature waters and steams. Their parts, the exploitation of which is a commercial proposition and a technical possibility, are regarded as geothermal or terrestrial-heat deposits. These deposits supply heat to geothermal power plants, hothouses and hotbeds and central heating networks.

The resources of geothermal deposits are determined by: (1) the mass of heated waters circulating in the upper zone of high-temperature water-head systems; (2) the amount of energy contained in the heated strata of the given part of the earth's crust; (3) the inflow of a plutonic fluid into the depression zone of stratal pressure, resulting from the intensive exploitation of upper horizons.

In the upper strata of a hydrothermal system, hydrothermal fluids are usually represented by head-pressure waters from the viewpoint of hydrodynamics. In that case, the quantitative evaluation of their resources may be done by conventional methods.

According to generally accepted practice, the resources of subterranean waters are divided into natural and exploitable. As a rule, natural resources are equal in quantity to the discharge of the subterranean stream and determine that renewable quantity of water in a water-bearing complex which can be used for an unlimited period of time. In most cases, it is very difficult to determine the discharge of a head water stream, because its limits are vaguely defined and it is necessary to perform a lot of special-purpose operations. As regards thermal fluids, this vagueness is still greater because it is necessary to determine temperature limits. In view of this, the evaluation of expoitable reserves has lately been carried out. It is believed that exploitable reserves may by far exceed natural reserves if one exploits a deposit for a limited period of time, exhausting its geological reserves to the permissible degree. The exploitable resources of thermal waters are mostly calculated by prolonged test water sampling from wells or by test exploitation coupled with observations of their regime in order to establish changes on the basic parameter of the wells.

In the course of studying the Pauzhetka deposit, it was found possible to use the formulas of unsteady movement (hydrodynamic method and a combination of hydraulic and hydrodynamic methods) for the evaluation of exploitable resources. Such a method of calculation makes it possible to predict changes in the level and discharge of wells for the limited period of exploitation by initially determining the parameter of the producing horizon (the method is explained in more detail in C. M. SUGROBOV's report to this Symposium). The valuation of exploitable resources is done by this method at the stage of detailed exploration.

A short-time exploitation (for several years) of geothermal deposits is probably associated with the utilisation of renewable geothermal reserves since, during this period (as shown by Kamchatka experience), either the regime of hydrothermal systems, or the scope of hydrothermal processes undergoes no appreciable changes.

Today, the problem of utilising the energy contained in the hydrothermal systems, as well as the heat drawn from the depths of the earth into the depression zone of stratal pressure is at the stage of theoretical research. This is because up to now the amount of heat extracted through wells has been of the same order as the natural thermal capacity of the systems. V. V. AVERIEV believed that one of the ways to increase the exploitable resources was by the influx of steam from greater depths in the area of decreasing hydrostatic pressure, the artificial formation of new hydrothermal systems being possible.

The minimum value of natural reserves of hydrothermal systems is determined by the thermal capacity of natural surface activity. The predicted value of exploitable resources (thermal capacity) may be determined even before drilling on the basis of the experience gained in the exploitation of deposits, an experience indicating that the resources valuated by drilling exceed the natural thermal capacity 3-5 times. It is this very value that should lie at the root of prospecting and exploitation drilling. The data on the reserves of Kamchatka's hydrothermal systems are presented in Table 4.

The choice of a method to utilise geothermal resources depends in each particular case on the parameter of the heat carrier, the thermal capacity of the systems and their geographical position. The deposits of high-temperature waters and steams (with an outlet temperature of 100 °C and more) are used in the geothermal power industry and for the supply of central-heating networks. The Pauzhetka deposit supplies heat to an electric station with a capacity of 5 MW which is now being expanded. As seen from Table 4, the hydrothermal resources of Kamchatka can provide enough heat to maintain the operation of geothermal electric stations with an aggregate capacity of 500 MW. Thermal waters with an outlet temperature up to 100 °C are mostly used for local central-heating networks and hothouses. Thus, the Paratunka deposit supplies heat to a hothouse-hotbed complex. It also supplies heat to an experimental freon electric station by using hot water with a temperature of 80 °C as a heatcarrier. There are

TABLE 4. — *Natural and predicted (exploitable) thermal capacity of Kamchatka's hydrothermal systems.*

Hydrothermal systems and deposits	Natural thermal capacity 10^3 kcal/sec	Condition and temperature of heat carrier on the surface	Consumption of heat by wells, 10^3 kcal/sec	Maximum temperature in wells (°C)	Predicted (exploitable) thermal capacity, 10^3 kcal/sec	Notes
Pauzhetka (1) system	25	saturated steam, water (boiling)			80	geothermal electric station in operation, 5 MW
Pauzhetka (1) deposit	15	water (boiling)	33	200		idem
Koshelevsk (2)	75	saturated and superheated steam	—	—	225	
Severo-Mutnovsky (3) system	60	superheated steam	—	—	130	
Zhirovsky (4) system	4	water (boiling)	—	—	20	
Bolshe-Bannv (5) system	5.6	water (boiling)	25	171	75	explored in detail
Uzon-Geyzerny (6) system	134	water (boiling)	—	—		state reservation
Semyachisky (7) system	75	saturated and superheated steam	—	—	150	
Kireunsky (8) system	5.2	water (boiling)	—	—	20	
Paratunka (9) deposit		water 32.5-81.5°C	—	106	37.5	hothouse-hotbed complex in operation
Nalychevsky system		water 38-75°C	—	75	35	

(1) data collected by V. V. Averiev, V. M. Sugrobov; (2) data collected by E. A. Vakin; (3) data collected by E. A. Vakin, B. G. Polak; (4) data collected by V. I. Belousov, T. P. Kirsanova; (5) data collected by B. G. Polak, V. I. Kononov, Yu. A. Kraevoy; (6) data collected by V. V. Averiev, G. N. Kovalyov, G. F. Pilipenko; (7) data collected by V. V. Averiev, E. A. Vakin; (8) data collected by T. P. Kirsanova; (9) data collected by Yu. A. Kraevoy, Yu. F. Manukhin.

possibilities to recover certain chemicals from the hydrothermal waters.

The problem of the origin of hydrothermal systems

The description of Kamchatka's modern hydrothermal systems given above shows that the present-day condition of their upper parts has more or less been elucidated. However, the structure of their « roots », the nature of migration of the plutonic heat carrier, the primary causes of formation of the systems and the regularities of their evolution are much less clear and the fact that there is no universal solution to these problems for every part of the world is a poor consolation for us indeed. In dealing with the problem of the origin of hydrothermal systems, the authors of this paper, like all others in the field, have to limit themselves to more or less substantiated hypotheses. Yet, it seems relevant to call attention in this manner, to what we think are the most important aspects of the problem.

The authors share V. V. Averiev's opinion that a plutonic water fluid above the critical point containing a definite amount of mineral and gaseous components must be the source of heat in hydrothermal systems. However the nature of the fluid is still vague. Is it, as many believe, a derivate of magmatic chambers in the crust or, as V. V. Averiev believed, a product of independent plutonic (sub-crustal) processes?

Hydrothermal systems can be thoroughly heated by the volatiles that are generated from the magmatic melt at the moment of its crystallisation only if the recharging intrusives are very big in size. If the content of volatiles in magma is normal ($1 \div 10\%$ by weight) and the probable enthalpy of the fluid takes place at the moment of separation (800 kcal per kg), in order to maintain the thermal effect of discharge of hydrothermal systems ($10^{15} \div 10^{16}$ kcal for the period of their existence), magmatic chambers are needed with a volume of hundreds of cubic kilometres. The frightening proportions of recharging chambers have long been a major argument of the opponents of this hypothesis. Yet, if the size of Kamchatka calderas and the amount of ignimbrite material they throw out while forming are to be compared with the output of heat from thermal waters, it will be clear that the volume of only acid magmatic chambers in this region (over 5000 cubic km), on separation of $1 \div 2\%$ of volatiles, is sufficient to maintain the activity of local hydrothermal systems. If the possibility of convection in magmatic chambers in this region and the influx of fresh portions of the melt are taken into account, the size of chambers must not have any effect at all on the scope of hydrothermal activity. Certain researchers concerned with ore genesis (D. S. Korzhinsky, G. L. Pospelov) precisely in this manner regard intrusive bodies as fluid-conductors, channels for trough-magmatic solutions, etc.). But the mechanism and degree of separation of volatiles from the melt, as well as the role of convection in magmatic chambers, are still awaiting a special study.

V. V. Averiev's concept that the generation of the heat-carrying fluid does not depend on the intrusive process, is not in need of any of such assumption. Yet it offers no solution to the problem of plutonic processes that may give rise to the appearance of the fluid. Has the fluid of the mantle a juvenile origin (J. Ferhungen's gaseous magma) or does it consist of immobilised restored waters which had been retained till a certain moment by crustal matter? To what extent is it possible to relate the appearance of the fluid to the synthesis of H_2O and other reactions in the association that are accompanied by the evolution of heat? It is these vague aspects that V. V. Averiev had in mind when he called the fluid « endogenic steam » without specifying this definition.

The nature of the plutonic fluid cannot be elucidated without analysing the geochemical peculiarities of modern high temperature thermal fluids. The most important of these peculiarities is the surprising uniformity in their composition which manifests itself in Kamchatka just as vividly as in other volcanic provinces of the world. What are the reasons for this uniformity? Does it reveal the common nature of plutonic recharge or is it the consequence of the same transformations of matter in conditions of geothermal anomalies? Considering that these transformations, which take the shape of various metasomatic reactions, are decidedly exothermic by nature, we, together with some of our foreign colleagues, assume that the appearance of thermal anomalies in the upper horizons of the lithosphere partly at least, should be the consequence of an influx of plutonic matter undergoing the above changes, but not merely the consequence of the addition of heat which accompanies this influx.

The space-time association of surface manifestations of hydrothermal activity and acid volcanism in Kamchatka and similar regions, in our opinion, testifies to the genetic relation between them. There are two different opinions on the nature of this relation. Some believe that acid magmatic chambers result from the local melting of crustal rocks under the influence of a plutonic water fluid above the critical point. This idea is confirmed by the already known role of water in the formation of acid silicate melts. According to geothermal and petrochemical data, there is a possibility of acid magmas fusing in the depths of tectonically and volcanically active belts. Yet, so far there are no convincing reasons to prefer this viewpoint to another, according to which, acid intrusive bodies, being differentiates of mantle basalt magma, are the source of a fluid recharging hydrothermal systems. At any rate, an opinion is now shared by many that the appearance of volcano-tectonic depressions and the mass manifestations of acid volcanism associated with this appearance are brought about by the intrusion of large bodies of medium-acid composition into the upper horizons. Whatever such intrusive bodies may be — chambers recharging hydrothermal systems or merely fluid-conductors — their possible presence in the depths of isometric depressions and the absence of manifestations of acid volcanism within linear grabens correlate well with the earlier mentioned difference in the temperature of hydrotherms, which are confined to the structures of various types. In the light of this, it is possible to regard the volcano-tectonic depressions as the structures of primary accumulation of hydrothermal solutions, ascending from strata immediately underlying the earth's crust, and the grabens — as the structures of secondary concentration of thermal fluids owing to their lateral migration from the surrounding regions of acid volcanism. The interrelation between acid magmatism and hydrothermal activity still awaits further clarification.

There is no visible connection between the hydrothermal activity and the andesite-basalt volcanism of Kamchatka. Yet, similarity (predicted by V. V. Averjev) is observed between the intensity of recharge of typical hydrothermal systems with heat and the average capacity of volcanic process in individual live volcanoes. The coincidence in these parameters — despite the entirely different dynamics of heat discharge by volcanoes and thermal waters — should be regarded as an indication of possible common causes of volcanic and hydrothermal activities. The elucidation of these causes is a very important task for volcanology and geothermal studies.

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