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THE GEOLOGICAL SETTING OF THE HYDROTHERMAL SYSTEMS IN THE GEYSERS VALLEY AND UZON CALDERA

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This paper presents new data on the geology, tectonics, and magmatism of the area of the hydrothermal systems in the Geysers Valley and Uzon Caldera in Kamchatka, obtained by the authors after many years of studies there. The conclusion has been made that the geological setting of these hydrothermal systems is regionally controlled by their localization in the intersection of two major faults cutting across Eastern Kamchatka and extending beyond its limits. The hydrothermal systems are related to the area of a magma chamber in the crust whose surficial expression is a volcano-tectonic depression. The age of the systems has been estimated. Isolated at the surface, they appear to have a single water and heat source at depth.

INTRODUCTION

The hydrothermal system of the Geysers Valley and Uzon Caldera are in the Semyachik geothermal region, which structurally belongs to the central part of the Eastern Kamchatka graben-syncline (Figure 1). Detailed integrated investigations of these objects were started in the 1960s under V. V. Aver'ev. The resulting large body of factual information [1, 3, 5, 13], as well as further extensive studies, led to the conclusion that the above hydrothermal systems are localized in a single volcano-tectonic depression. A basis was formed for considering these widely spaced objects to be part of a genetically homogeneous hydrothermal system [2,9,24].

However, many aspects of the geological setting remained unsolved and necessitated special integrated investigations. Between 1971 and 1981, the Laboratory of Hydrogeology, Geothermy, and Geology of Geothermal Areas of the Institute of Volcanology, Far East Scientific Center, USSR Academy of Sciences, undertook extensive studies in many directions under the guidance of V. M. Sugrobov.

Below the authors briefly present new findings on the stratigraphy, tectonics, and volcanism of the region.

STRATIGRAPHY OF THE UZON-GEYSERS REGION

The region is underlain by volcanic and volcanic-sedimentary rocks of Pliocene and Pleistocene age (Figure 2). We describe the rocks in a stratigraphic succession, dividing them into Pliocene and Pleistocene in age and distinguishing separate members.

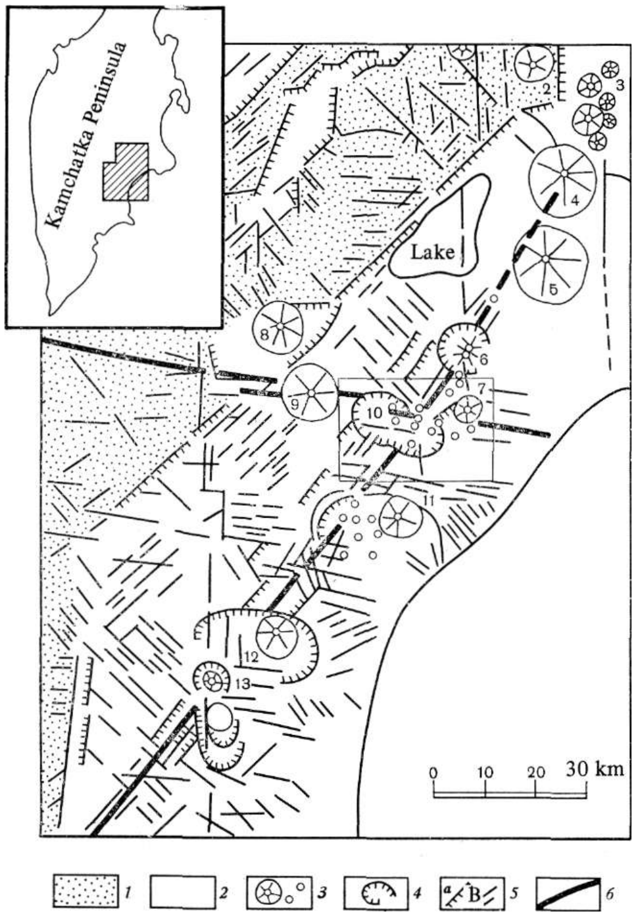

FIGURE 1 Structural schematic of Eastern Kamchatka (compiled from 1 : 1 000 000 interpreted space images).
1 - Horst-anticline of Eastern Range in Kamchatka; 2 - graben-syncline of Eastern Kamchatka; 3 - volcanoes (1 - Kizimen; 2 - Konradi; 3 - Gamchenskii ryad; 4 - Shmidt's; 5 - Kronotskii; 6 - Krasheninnikov's; 7 Kikhpinych; 8 - Unana; 9 - Taunshits; 10 - Uzon; 11 - Greater Semyachik; 12 - Lesser Semyachik; 13 - Karymskii)); 4 - calderas and volcano-tectonic depressions; 5 - faults: a - normal faults; b - cracks; 6 - axial lines of northeast-trending and sublatitudinal regional fault zones intersecting Uzon-Geysers region. The inset is an index map showing the area of Figure 1.

Pliocene Rocks

The Pliocene has been described earlier [16]; therefore, we here present only its brief characteristics. We have distinguished four members: Old Lavas, Cave Tuff, Sand-Lava, and Tuff-Ignimbrite. They were assigned a Pliocene age because they lie stratigraphically below the Estuary Member, which is of Pleistocene age [16]. Also, a paleomagnetic examination of some samples of the Tuff-Ignimbrite Member has shown it to contain reversely magnetized rocks marking the 690 000-y old boundary between the Brunhes and Matuyama epochs (data obtained by the Paleomagnetism Group of the Institute of Volcanology). In consequence, the Pliocene-Pleistocene boundary can be drawn along the upper limit of the Tuff-Ignimbrite Member.

We have identified the Old Lavas Member in the southern part of the region. It presumably includes the relics of a volcano exposed on the left side of the middle reaches of the Geizernaya River and also lavas on the side of the Uzon-Geysers depression (the area of Mount Otkrytaya). These are the oldest sediments known from the area, consisting of andesitic, dacitic, and liparitic (in the Mount Otkrytaya area) lavas totaling 300 m in thickness.

The Cave Tuff Member is exposed in the southern part of the region, as well as on the northern sides of the Uzon-Geysers depression (Mount Otkrytaya area). It is composed of uniform psephitic, agglomerate-like tuff with numerous caves. The tuff unconformably overlies the lavas described above and is as thick as 200—250 m.

The *Sand-Lava Member* occurs along the south and southwest sides of the Uzon-Geysers depression. It comprises basaltic and andesite-basalt lavas alternating with volcanic tuffstone, tuff-gravelstone, and breccia. In the south of the region, these sediments, which are as thick as 200 m, rest with an unconformity on the Cave Tuff.

The *Tuff-Ignimbrite Member* is exposed in the south and southwest of the region. It is made up of stratified pumice tuff with occasional ignimbrite beds. The tuff lies with a sharp unconformity on the Sand-Lava, filling deep pockets and smoothing the terrain. Tuff breccia occurs at the base of the Tuff-Ignimbrite, which varies in thickness between 300 and 500 m.

Pleistocene Rocks.

We have distinguished the *Flood Basalts Member* in the south of the region. It consists of thin basaltic lava flows overlying the Tuff-Ignimbrite. We believe that the relics of a basalt volcano exposed on the sides of the Uzon Caldera belong to this member. The lavas in the south of the region are 8 to 10 m thick, while they are more than 400 m thick on the sides of the Uzon Caldera [7].

The *Estuary Member* is exposed in the estuary of the Geizernaya River and down the Shumnaya River for about 2 km (for a detailed description see [16]). It is composed of alternating agglomerate-like, psephitic, psammitic, and silt tuffs totaling about 600 m in thickness. The Estuary Member is regarded as lying at the boundary between the lower and middle Pleistocene.

The *lavas and pyroclastic deposits* of Kikhpinych and Uzon volcanoes are made up of alternating tuff, tuff-breccia, and lava flows of basaltic and andesite-basalt composition [9, 21, 27], totaling more than 1000 m in thickness. These volcanoes are nearly coeval; they are middle Pleistocene in age [9].

The *Uzon Ignimbrite* (the Kronotskii Ignimbrite, according to B. I. Piip [23]) and the *lavas of the first cycle* of Quaternary acid volcanism have earlier been classified as sediments laid down at the main caldera-forming phase of volcanism in the region [9]. We have examined the ignimbrite sections in detail near the sides of the Uzon-Geysers depression. At the base lie cinder and thin basalt flows, giving way upward in the section to pumice tuff and ignimbrite. That this sequence of rocks is persistent and they lie conformably suggests their genetic similarity. The cinder on the Shirokoe Plateau was earlier dated back to the beginning of the middle Pleistocene [7]. Hence the age of the ignimbrite is believed to be the same. We will describe the lavas in some detail below.

The *Geyser Member* is exposed in the southeastern Uzon-Geysers depression (see Figure 2). It consists of lacustrine sediments unconformably overlying the Estuary and the lavas of the first cycle Quaternary acid volcanism. The Geyser can approximately be

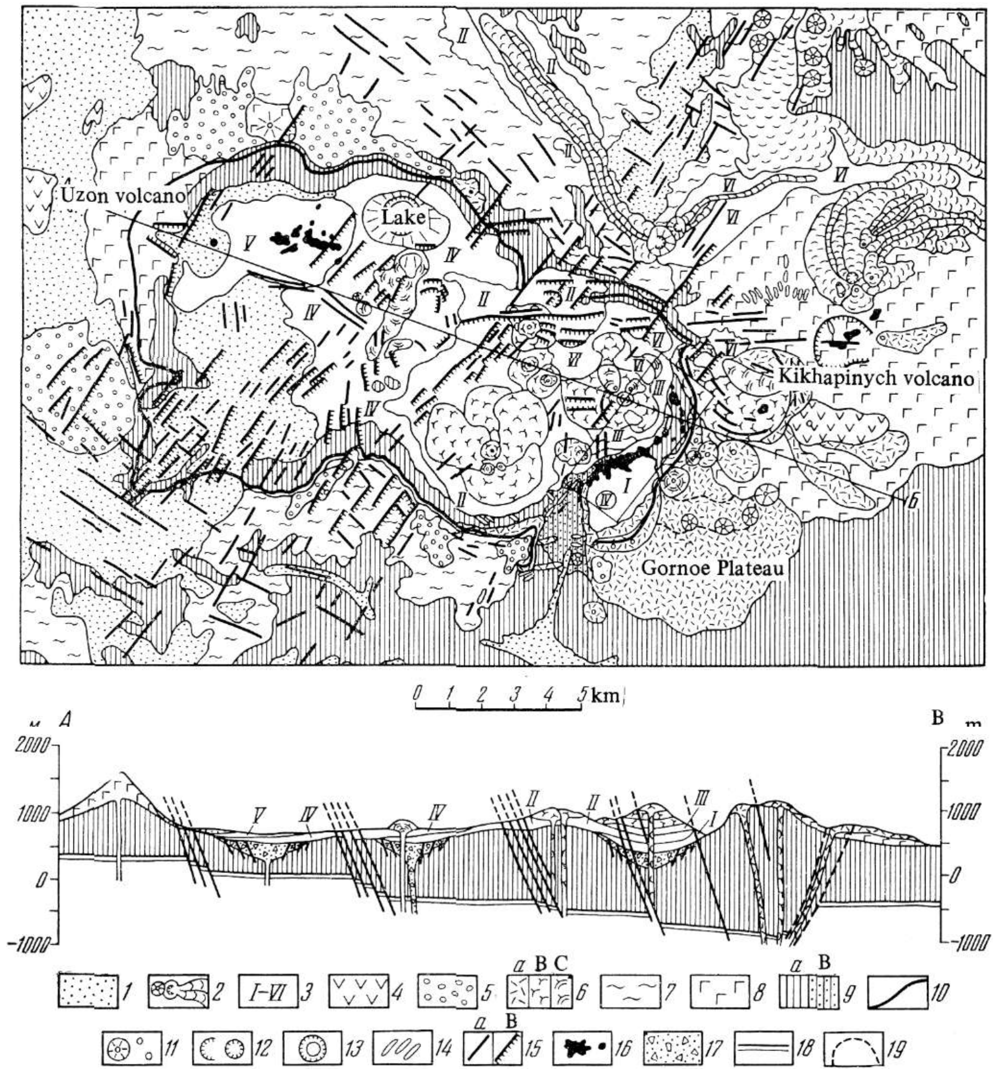

FIGURE 2 Schematic geological map of Uzon-Geysers region (compiled by V. L. Leonov with use of data obtained by O. A. Braĭtseva, G. E. Bogoyavlenskaya, E. N. Erlikh, and A. G. Tsikunov): 1 – alluvial, glacial, and talus-slope deposits and also cliff debris (Q_4); 2 – lavas and cinders of basaltic and andesite-basalt composition (Q_4); 3 – lacustrine sediments (members: I – Geyser; II – Pumice; III – Yellow Crags; IV – Second Lake and Southern Basin; V – Third Lake; VI – Colorado (Q_3^1 – Q_3^4); 4 – andesitic lavas (Q_3); 5 – explosion pumice of Uzon Caldera (Q_3^1); 6 – lavas of first (a), second (b), and third (c) cycles of Quaternary acid volcanism (Q_2^1 – Q_3^1); 7 – ignimbrite (Q_2); 8 – basaltic lavas (Q_2^1); 9 – Pliocene lower Pleistocene deposits members: a – old Lavas; Cave Tuff; Sand-Lava; Tuff-Ignimbrite; Flood Basalts; b – Estuary; 10 – boundaries of erosion scarps bounding Uzon-Geysers depression; 11 – cinder cones and other volcanic centers; 12 – crater funnels; 13 – maar; 14 – dikes; 15 – faults (a – fissures; b – normal faults); 16 – areas of thermal anomalies (approximate outlines of 20°C isotherm at depth of 1 m); 17 – sediments filling inferred calderas (in section); 18 – tentative boundary in Pliocene-lower Pleistocene sediments (in section); 19 – boundaries of separate beds and flows within identified members (markers). Rectangle delineates area shown in Figure 3.

subdivided into four parts (in an ascending order): (1) agglomerate-like tuff and conglomerate (60 m); (2) alternating green psephitic and psammitic tuffs (60 m); (3) white silty and psephitic tuffs (120 m); and (4) alternating white silty, psammitic, and psephitic pumice tuffs (70 m). The total thickness of the Geyser is 310 m.

The *Pumice Member* is extensive in the central part of the depression, and also as erosion remnants along the north side of the Geizernaya River. It is made up of gray pumice tuff, which disconformably lies on the eroded surface of the Geyser. The tuff is of liparite-dacite composition. It usually occurs at a height of 700—750 m above sea level, though it makes up the summit of Mount Otkrytaya at 1180 m above sea level. This mount can be regarded as a peculiar pumice volcano [7]. The tuff is 60—70 m thick.

The *Yellow Crags Member* (Fig. 2) consists of light-pink pumice tuff with lenticular tuff conglomerate and tuff breccia. These sediments, 210 m thick, rest on the eroded surface of the Geyser and Pumice. The Yellow Crags correlates with explosion pumice, occurring on the sides of the Uzon Caldera and on the Shirokoe Plateau [7]. It usually overlies the Uzon Ignimbrite, and hence must be coeval with some sediments of the Uzon-Geysers depression. Because the pumice has not been found on the sediments of Second Lake, it appears to be of the same age as the Yellow Crags, with which it is similar in chemical composition and outward appearance.

The *lavas of the second and third cycles* of Quaternary acid volcanism (they are described in detail under volcanism) outflowed upon the Yellow Crags. Simultaneously new members of lacustrine sediments were accumulating.

At the beginning of the late Pleistocene, the *Second Lake sediments* filled the western part of the Uzon-Geysers depression (see Figure 2). They have been described in detail [7]. Their equivalents are the sediments of the Southern basin, exposed in the southeastern Uzon-Geysers depression. These last consist of stratified tuffstone, gravelstone, and pumice tuff, similar to rocks in the upper part of the Second Lake unit. The sediments of the Southern basin are as thick as 50 m.

The *Third Lake sediments* occur in the lowermost part of the Uzon Caldera. They were laid down in the period from the end of the interglacial to the beginning of the second phase of the late Pleistocene glaciation (Q_3^{3-4}) [7].

The *Colorado Member* has been distinguished in the northeast section of the region (see Figure 2). It is composed of psephitic and psammitic cinder tuffs with a characteristic alternation of layers with normal and cross bedding. These sediments are 20 m thick within the Uzon-Geysers depression and 150 m thick on its north side. As follows from the composition of fragments in the tuffs, the Colorado accumulated early in the period of areal basaltic volcanism in the region, i.e., at the end of the late Pleistocene (O.A. Braitseva, oral communication).

The stratigraphic column for the region is crowned with Holocene cinder and lavas of andesitic and andesite-basalt composition, which make up Savich's Cone, Mount Duga, and the maar of Lake Dal'nee.

PERMEABILITY AND HYDROTHERMAL METAMORPHISM OF WATER-BEARING FORMATIONS

Th bulk of the thermal springs in the Geysers Valley issue from bedrock exposures of poorly lithified, psephitic and agglomerate-like, dacite pumice tuffs in the Geyser and Estuary (Figure 3). The dacite is lithologically equivalent to water-bearing psephitic dacite tuff in the Pauzhetka Suite of southern Kamchatka, which has been studied sufficiently well [4, 12]. Its permeability is known in detail [3, 6, 26]. The averaged

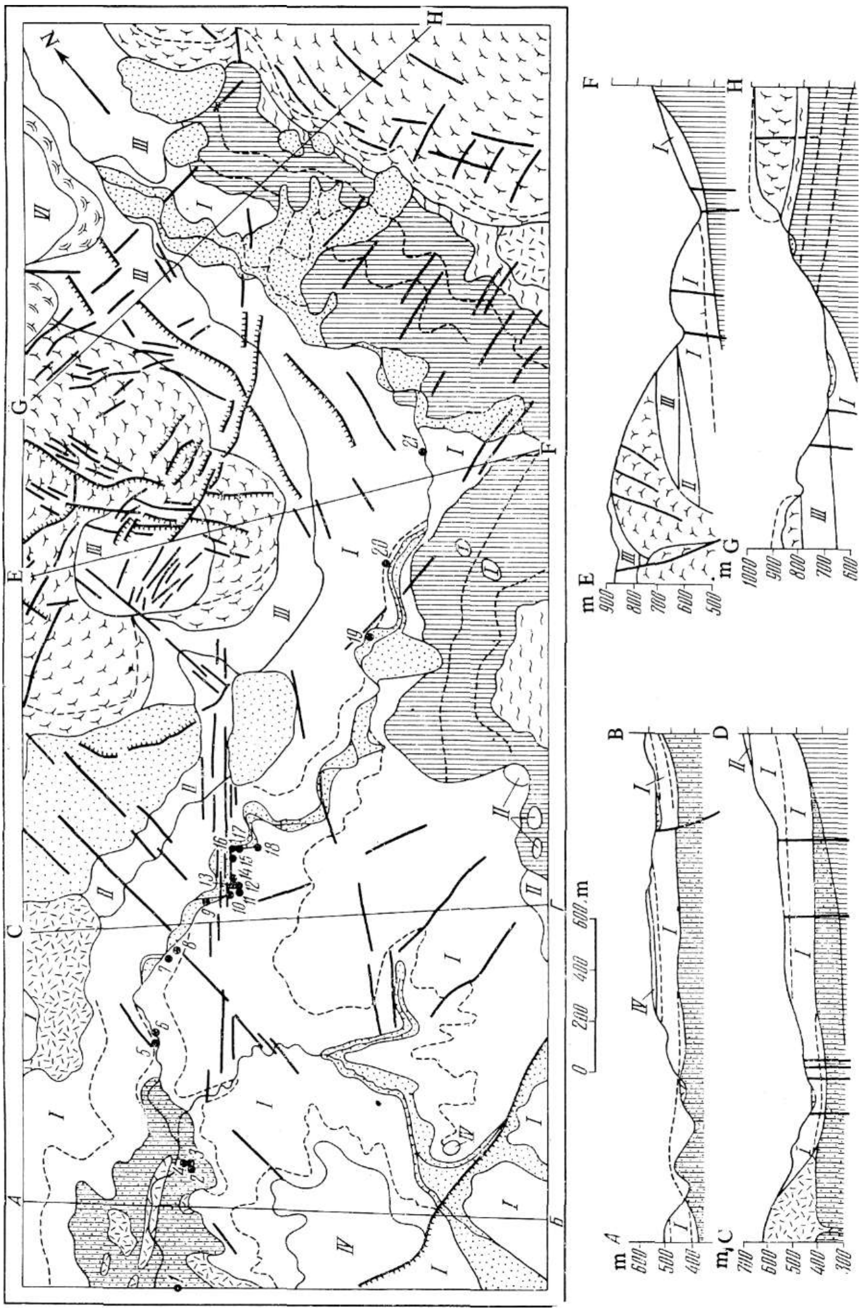

FIGURE 3 Schematic geological map of Geysers Valley. Explanations see in Figure 2. Dark circles depict foloowing geysers: 1 - pervenets; 2 - Troinoi; 3 - Sosed; 4 - Sakharnyi; 5 - Bol'shaya Pechka; 6 - Konus; 7 - Lesser; 8 - Greater; 9 - Shchel'; 10 - Grot; 11 - Novyi Fontan; 12 - Fontan; 13 - Dvoinoi; 14 - NepostoyannyT; 15 - Velikan; 16 - ZhemchuzhnyT; 17 - Gorizontal'nyi; 18 - Rozovy Konus; 19 - Burlyashchiy; 20 - Vos'merka; 21 - Verkhnii.

permeability coefficient for the Pauzhetka psephitic tuff is 0.4 darcy. The pore permeability coefficient is estimated for this rock to be within the first few millidarcies. Comparison of the values suggests that thermal springs percolate in such rock units mainly through fractures, though pore permeability is also possible.

The low-permeable psephitic tuffs in the Geyser and Estuary hinder intensive inflow of cold surficial water. This is an essential structural factor in the formation and activity of the high-temperature hydrothermal system in the Geysers Valley. The upper part of the Geyser and Estuary contains fine-clastic tuff varieties, whose pore permeability coefficients are, as a rule, two orders of magnitude lower than those of the psephitic tuff. They serve as an upper aquiclude, providing better hydroisolation of the water-bearing formations.

These data are in accord with those on the hydrothermal metamorphism in the aquifers and confining beds of the Geysers Valley [3, 22]. Both the Geyser and the Estuary interacted with thermal springs percolating through pores and fractures and have been strongly propilitized. They contain an assemblage of low-, middle-, and high-temperature mineral associations, including clinoptilolite, montmorillonite, analcite, calcite, chlorite, adular, laumontite, quartz, epidote, pehnite, and some other minerals. These minerals crystallized at temperatures from 60 to 200°C or higher.

Zoning of secondary minerals is observed in the sections along Vodopadnyi Spring and the Geizernaya River. Low-temperature mineral associations (montmorillonite, clinoptilolite) occur in the upper part of the sections. Near the discharge areas and faults and fractures serving as conduits for thermal springs, high-temperature associations (adular, quartz, laumontite) predominate. In the mouth of the Geizernaya River, S. F. Glavatskikh has described epidote and prehnite in the Estuary member (they precipitate at 200°C). The mineral zoning near fractures and faults suggests that the hottest thermal springs percolated through them. The overall head drop in the flow of thermal waters, as reconstructed from mineral facies, coincides with that in the modern flow. A sharp temperature drop in the tuff occurring in the upper part of the Geyser (interval 20 to 40 m) supports the suggestion that hydrothermal circulation here is slow.

Therefore, these rocks are not only the upper aquiclude, but also prevent the hydrothermal flow below from large heat losses, which must also favor the onset of high-temperature conditions in this flow.

The hydrogeology of the Uzon Caldera was studied earlier by G. F. Pilipenko [5, 24]. We have examined the water-bearing formation at an exposure, the best in the caldera, on the northwest flanks of the Belaya extrusion which invaded and disturbed the volcanic and other sediments of Second Lake. A large block of lacustrine sediments was raised to a height of 250 m above the floor of the basin. As a result, thin-bedded aleuropelitic and psammitic dacite tuffs are exposed, with an apparent thickness of about 200 m. Consequently, the upper part of the lacustrine sediments filling the Uzon Caldera is a lithological equivalent of the silty and psammitic tuffs in the Geyser of the Geysers Valley and also serves as an upper aquiclude. The buried portions of this section of lacustrine sediments in the Uzon Caldera appear to consist of coarse-clastic tuff, analogous to the psephitic tuff exposed east of the Belaya extrusion, and are as aquifers.

According to S. F. Glavatskikh, aleuropelitic and psammitic tuffs at the exposures of Mount Belaya have undergone strong acid metamorphism responsible for their siliciflcation, kaolinization, and alunitization [10]. The acid metamorphism involved fresh rocks first along a wide band west of the Belaya extrusion, and then the discharge area of thermal springs gradually shifted northward.

The above characteristics of the water-bearing formations of the hydrothermal systems in the Geysers Valley and Uzon Caldera show that the discharge of high-temperature thermal springs in both systems is related to a certain type of lacustrine sediments in which circulation through pores and fractures is possible and which contains relatively perfect aquicludes.

THE STRUCTURE OF THE UZON-GEYSERS REGION

The Uzon-Geysers region lies centrally in the ring-shaped Uzon dome [19]. Below are described faults grouped into three categories according to their trends: the northeast-trending, sublatitudinal, and arcuate, concentric about the center of the Uzon-Geysers depression. We have described them earlier in some detail [17].

The northeast-trending faults are known best [15, 17, 30]. These are normal faults with a southeast block downthrown. In some faults, the northwest block is downthrown. The faults range in length from 100—200 m to 1 km or more. The vertical displacement varies between several meters and 50 m. The faults were active from the beginning of the middle Pleistocene to the Holocene inclusive. They tend to be successively younger from southeast to northwest.

As a whole, the northeast-trending fault pattern reflects a major zone of crustal extension, which is about 20 km wide and stretches far beyond the limits of the region [15, 18, 19]. It is called the Volcanic wide-separation fault [15].

The sublatitudinal faults are the easiest to map in the central part of the region, within a belt 5 to 6 km wide, trending 280°. This trend is parallel with the long axis of the Uzon-Geysers depression. Some faults are as long as 4 km or more. The vertical displacement varies between the first few meters and 50—70 m. The sublatitudinal faults bound the northern side of the Uzon-Geysers depression and appear to have participated in its generation [16]. The total subsidence along the fault system of the interior block in the depression is 200. m. These faults were active at the beginning of late Pleistocene time [17]. The belt of sublatitudinal faults in the region under discussion may mark a regional sublatitudinal fault [29], which was named the Uzon-Valaginskii fault [28].

The arcuate faults, concentric about the center of the Uzon-Geysers depression, are best pronounced on its north and south sides. They usually occur as fissures or low-magnitude faults. Near the southeast boundaries of the depression, we have described a swarm of dikes, most of them ring dikes, which are also concentric about its center and appear to inherit the arcuate fracture system. On the basis of their relationships with the Estuary and Geyser, the dikes have been assigned a middle Pleistocene age. Obviously, some of the arcuate faults are late Pleistocene or younger in age [17].

These characteristics of faults indicate that two main reactivation periods took place in the area.

The first period embraces the middle Pleistocene, when the northeast-trending and arcuate faults were active. There is also a close relationship between faulting and magmatism; magma invaded through both fault systems to form dike swarms. The dike pattern indicates that the northeast faults were initiated somewhat earlier than the arcuate faults. The conculsion can be made that the area was strongly stretched in middle Pleistocene time, with the resulting formation of a system of northeast-trending normal faults and cracks and then of arcuate fractures. Magma intrusion through the arcuate fractures gave rise to a lofty arcuate ridge in the southeastern part of the area and the isolation of an internal-drainage lake basin, the predecessor of the modern Uzon-Geysers depression [16].

The second reactivation period in the region refers to the beginning of late Pleistocene time, when a system of sublatitudinal cracks and normal faults was initiated and the arcuate fault system was partly renewed. The normal faults are the most prominent along the north boundaries of the Uzon-Geysers depression, which has subsided along them to a depth exceeding 200 m [17]. As a whole, this period can be regarded as the second manifestation of tension tectonics in the region, localized along a regional fault trending in an almost east-west direction.

These two basic periods do not rule out similar phenomena in other times, for instance in the Holocene. The evidence for it is, however inadequate.

We do not discuss here in detail the perplexing and disputable problem of the origin of the Uzon-Geysers depression.

QUATERNARY ACID VOLCANISM IN THE UZON-GEYSERS REGION

On summarizing the data on the geothermal areas of the world [1], V. V. Aver'ev suggested that, being crustal processes of the same order, hydrothermal activity and acid volcanism were a response of the Earth's deep interior to mantle magmatism. Therefore, a detailed examination of acid volcanic products is essential in solving the problem of heat supply to hydrothermal systems. In the Uzon-Geysers region, such investigations embraced Quaternary volcanics.

Detailed geological and petrological studies of these volcanics have made it possible to distinguish three cycles of their emplacement in the time interval from the beginning of the middle Pleistocene to the early in the late Pleistocene. The lavas constitute a continuous rock series from andesite to liparite. This succession is retained within each cycle, but the relative percentages of the lavas change.

The first cycle consists of lava flows and extrusions (Gornoe Plateau, the foot of Mount Zheltaya, and Greben', Bortovaya, and Pervaya extrusions), which extend in the form of arcuate ridges along the southeast fringe of the Uzon-Geysers depression (Figure 4). The cycle begins with large outflows (1.2 km^3) of andesitic lavas. They occupy an area of about 20 km^2 and occasionally make up small volcanic edifices. The andesites are highly crystallized and taxitic; their first portions contain 59% silica and the subsequent portions, 62.8% silica. They are followed by liparite-dacite dikes and extrusions (the Greben', Bortovaya, and Pervaya extrusions) invading through concentric fissures. The liparite-dacites are felsitic and contain an insignificant amount of crystals (not more than 7% of rock volume). The cycle is crowned with the outflow of liparites at the foot of Mount Zheltaya and with the formation of its dome. In the northeast side of the Uzon Caldera, this cycle is represented by the Ozernaya extrusion, whose lavas are liparitic in composition. The total volume of the lavas of the first cycle is 1.67 km^3.

The second cycle comprises extrusions and flows inside the Uzon-Geysers depression. (The Ostanets, Tortik, Sestrenka, Geizernaya, and Kruglaya extrusions, and the large flow of the Zheltaya extrusion.) This list of extrusions corresponds to the reconstructed order of their invasion. The lavas range in composition from dacite to liparite. The volume of the liparite is equal to 1.55 km^3, and the total volume of lavas of the second cycle is 1.65 km^3. The extrusions made up of liparitic lavas (Tortik, Geizernaya, Kruglaya) are, rather, acid volcanoes formed by outpouring liquid lava flows ranging in length from 0.5 to 3.0 km. These extrusions are isometric, plateau-like, and their emplacement was unaccompanied by pyroclastics ejection.

The third cycle encompasses the youngest flows on the Geizernaya, Zheltaya, Lepeshka, and Rudich's extrusions (see Figure 4); it is mainly represented by andesites and dacites. This cycle is best manifested on the Geizernaya extrusion. Here, andesitic, andesite-dacite, and dacitic lava flows poured out successively from a sublatitudinal fissure

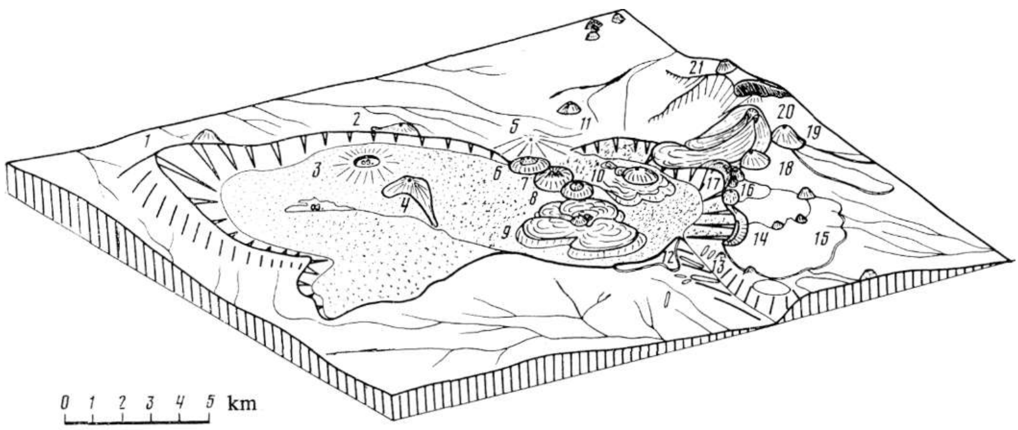

FIGURE 4 Block-diagram of Uzon-Geysers region. Dots indicate lacustrine sediments filling volcano-tectonic Uzon-Geysers depression. 1 – Mount Uzon; 2 – Ozernaya extrusion; 3 – maar of Lake Dal'nee; 4 – Belaya extrusion; 5 – pumice dome of Mount Otkrytaya; extrusions: 6 – Tortik; 7 – Ostanets; 8 – Sestrenka; 9 – Kruglaya; 10 – Geĭzernaya; 11 – Mount Duga; 12 – Shirokoe Plateau; 13 – canyon of Shumnaya River; extrusions; 14 – Greben'; 15 – Gornoe Plateau; 16 – Rudich's; 17 – Bortovaya; 18 – First; 19 – Mount Bezymyannaya; 20 – Zheltaya extrusion; 21 – Savich's Cone.

cutting a liparite dome belonging to the second cycle. The third cycle is completed with a liparitic dike swarm trending east-west. In the Uzon Caldera, the dacitic Belaya extrusion invaded at the brink of the third cycle. The lava volume in the third cycle is 0.26 km^3.

Inclusions of basaltic lavas and their crystalline fragments are widespread in the acid lavas from all the three cycles. They were emplaced at the close of each cycle and increase in amount from the first to third cycle.

The lavas contain similar assemblages of phenocrysts: plagioclase, ortho- and clino-pyroxene, magnetite, and, rarely, olivine. In addition, the liparite of the second cycle contains hornblende. The crystallinity degree of the lavas within the cycle varies between 25-30% in the most basic varieties, and 15-20% in the liparites. At some stage, however, it diminishes to 4—11%. On the whole, the crystallinity degree increases from the first to third cycle at the expense of plagioclase, whose content aries between 2 and 21% of the total amount of crystals. Most of the phenocrysts are zoned, all types of zoning having been found.

The zones frequently have reactional boundaries. Some of the zones contain many molten, crystalline, and gaseous inclusions. The plagioclases range in composition from An_{72-76} to An_{28-30}, some neighboring zones differing by An_{16-20}.

On the basis of molten inclusions in plagioclases, the temperatures of crystallization of the phenocrysts have been found by thermometry techniques. They range widely, from 1385 to 1060°C in the second cycle and from 1320 to 920°C in the third cycle.

An analysis of individual gases from inclusions in plagioclase indicates that the most characteristic gaseous constituents are N_2, CO_2, more seldom CO, H_2, and hydrocarbons. Nitrogen and CO_2 dominate in the second cycle, whereas the third cycle is intermediate in gas composition; the content of CO, H_2, and hydrocarbons being occasionally 30—40% by volume.

The fact that the acid lavas contain plagioclase phenocrysts, which differ greatly in composition, the extensive occurrence of oscillatory and reverse zoning in them, and the development of corrosion-type boundaries between the zones, suggest nonequilibrium crystallization of melt and rapid cooling. Olivine crystals and zoned pyroxenes in the liparite also support the above suggestion. Basaltic inclusions in acid volcanic products, common in the region under discussion, are regarded by many authors as parts of the basic melt not involved in mixing [31, 33]. This leads us to believe that the nonequilibrium mineral associations in acid lavas are caused by mixing of magma melts when high-temperature basalt from the deep interior enters a crustal acid-magma chamber, Additional evidence for the mixing of magma melts is "heterogeneous" pumice [8] we have found at the base of Rudich's extrusion and in the pumice-like dacite of the Belaya extrusion.

DISCUSSION AND CONCLUSIONS

Analysis of the above data makes it possible to consider the geological setting of the hydrothermal systems in the Geysers Valley and Uzon Calders from several viewpoints

The tectonic setting of the region is controlled by its confinement to the intersection of two major faults cutting across Eastern Kamchatka and extending beyond its limits; these are the Volcanic wide-separation fault and the Uzon-Valaginskii fault. The main activity on these faults in the region at the beginning of the middle, and early in the late, Pleistocene appears to have been related to regional causes whose discussion is outside the scope of this paper. In both periods, tectonic movements were responsible for the appearance of extension structures: normal faults, grabens, block sinking, and the reactivation of igneous activity. The Volcanic wide-separation fault is about 20 km wide and asymmetric. Its constituent faults are younger from east to west. These features appear to have played the basic role in the formation and development of the volcano-tectonic Uzon-Geysers depression, whose history comprises two periods. In the first period, at the beginning of the middle Pleistocene, reactivation of the northeast faults gave rise to its southeast boundaries. In the second period, early in late Pleistocene time, the initiation of the east-west fault system was responsible for the formation of its northwest and north boundaries, and the depression became similar in appearance to what it is today.

The geological setting of the hydrothermal system is also determined by the fact that the relevant magma chamber occurs in the crust beneath the study region. The acid rocks of Pliocene age (Old Lavas) in the region indicate that the crustal chamber has existed in the interior since pre-Quaternary time. Its life is an alternation of quiet intervals, with partial crystallization of the chamber, and reactivation periods.

The data now available allow us to assume a mechanism for the crustal chamber to renew its activity, and to consider its history in the Pleistocene. Three cycles of igneous activity can be suggested.

The initiation of the Volcanic wide-separation fault early in middle Pleistocene time was associated with the stretching of the region; as a result, the crustal acid magma chamber, whose temperature was close to the solidus, was entered by a basaltic magma with a temperature of 1340—1300 C. The magma intrusion was accompanied by local melting of granitic material around the feeders [20]. At this time, lavas of mixed composition flowed out on the surface; an example is the andesite of the Gornoe Plateau, emplaced at the beginning of the first cycle. That the last portions of lava are more acid suggests an increasing amount of acid melt. At some stage, the more light-weight granitic melt thus formed began to prevent the rise of basaltic magmas [11], and their heat began to cause phase transformations. This crustal chamber had been melted to the greatest extent by the end of the first cycle, as follows from the insignificant amount of phenocrysts (3-6%) in the liparite of this age. Violent explosions, responsible for the accumulation of the Uzon ignimbrite, appear to have promoted the withdrawal of crystalline phases from the magma chamber to make the melt "dry". On the basis of structural evidence, the top of the chamber occurred at that time at a depth of 7—8 km, and its diameter was about 10 km [17].

During the second cycle, mass liparite removal from the chamber took place early in late Pleistocene time. Judging from the minimum temperature of homogenization of molten inclusions, the temperature of melt in the last flow of the Kruglaya extrusion (t = 1090—1060°C) was at least 1000°C just before the eruption. After the close of volcanism of the second cycle, the magma in the chamber appears to have crystallized with some degree of isolation, the volatiles concentrating in a residual melt.

In the third cycle, a basic magma invaded nearly at the center of the depression (Geizernaya extrusion). This indicates that the chamber, at least its top, was then rather strongly crystallized. A fresh portion of high-temperature basaltic magma intruded along a narrow sublatitudinal band because an east-west fault system was initiated at that time. The composition of the gaseous phase of inclusions (H_2, CO, and hydrocarbons) suggests that the basic melt was formed at great depth.

That the acid volcanic products tend to decrease in volume and the lava crystallinity to increase from the first to third cycle suggests, on the whole, a gradual crystallization of the chamber. It can be assumed, however, that it was reactivated to some extent in the Holocene because of the invasion of a basic magma, which formed the Savich's and Duga cones, and the maar of Lake Dal'nee. The basalt may have supplied additional heat into the upper, then partly crystallized sector of the magmatic system to cause its melting [32].

At present, the crustal chamber in the interior below the region under study may, therefore, be still in a heated state and contain material whose temperature is above the solidus of the granitic system.

The overall structural setting and the presence of the crustal acid magma chamber in the interior below the region determine the pattern of the hydrothermal systems in the Geysers Valley and Uzon Caldera. As shown above, the structure of the region, and also the magmatism and hydrothermal activity on its territory tend to be successively younger from east to west. Comparing the age of the hydrothermal systems with that of acid volcanism, between which a paragenetic association is assumed [1], and also proceeding from the age of structures within which thermal occurrences have been found, we date the hydrothermal system of the Geysers Valley back to the beginning of the middle Pleistocene (250 000 to 300 000 years ago), and the hydrothermal system of the Uzon Caldera, to the beginning of the late Pleistocene (100 000 to 150 000 years ago).

The hydrothermal systems discharge through lacustrine sediments that fill the Uzon-Geysers depression and are also of different ages in the eastern and western parts of the depression.

These data do not enable us to combine the thermal occurrences in the Geysers Valley and Uzon Caldera in a single hydrothermal system as has been done previously [9, 24, 25]. Proceeding from the fact that these thermal occurrences are associated on the surface with different structures and are of different ages, we believe that they should be assigned to two different hydrothermal systems. At depth, however, they are associated with a single crustal magma chamber which is a heat accumulator and provides the heat supply for the hydrothermal systems. Also, their common feature is that they may be related at depth to a single water source (lower water-bearing formation). Analysis of the deep subsurface structure of the region supports this assumption. Figure 5

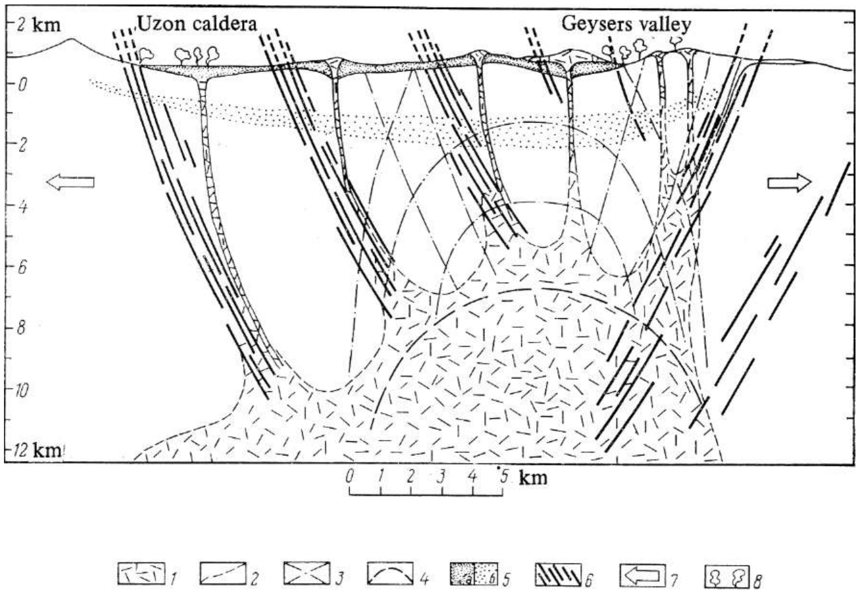

FIGURE 5 Schematic section showing structural localization of hydrothermal system in Geysers Valley and Uzon Caldera (line of section is A-B line in Figure 2): 1 - area of crustal magma chamber and associated extrusions; 2 - inferred boundaries of magma chamber; 3 - system of ring-shaped and conical fractures above chamber, reconstructed from exposed dikes [17]; 4 - speculative upper boundary of chamber in the period of dike invasion (Q_2); 5 - water-bearing formations: a - upper; b - lower; 6 - fault zones (arrows indicate direction of movement on faults); 7 - direction of crustal extension in region; 8 - manifestations of hydrothermal activity.

is a diagrammatic section showing the structural localization of the hydrothermal systems in the Geysers Valley and Uzon Caldera, based on our assumptions.

On the whole, we share the earlier viewpoint that the thermal occurrences of the Geysers Valley and Uzon Caldera are closely interrelated [29]. We believe, however, that this refers to the structure at depth, which in this region is single for both systems, rather than to the conditions at the surface, where two hydrothermal systems of different ages exist. A similar example may be the Bol'shye Bannye and Karymchina hydrothermal systems in Southern Kamchatka, which are presumably linked at depth with a single heat source [14]. The concept of two hydrothermal systems in the Uzon-Geysers region, stemming from its stratigraphy, tectonics, and magmatism, needs further support through new studies into the hydrogeology and geothermy of the region.

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