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Some Regularities in the Development of Hydrothermal and Volcanic Activity in Kamchatka

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The paper considers the features of the distribution of recent hydrothermal systems and volcanic rocks of Pliocene-Quaternary age in Kamchatka. The specific role of faults with a N-E strike is emphasised. Three regions have been identified in which the regular NE migration of volcanism occurs, as well as the narrowing of the area of occurrence of Pliocene-Quaternary volcanic rocks, the decreasing of the diameter of dome-ring structures and the tapering out of the latest rupture disturbances. In addition, these regions are characterized by the NE growth of the geothermal output of the known hydrothermal systems. The systematic NE migration of volcanic and hydrothermal activity has also been identified within separate volcanic centres confined to these faults. It has been shown that no satisfactory explanation exists for these regularities. The authors assume that they can most probably be explained by the successive migration of magma in a north-easterly direction along the front of the Kurile-Kamchatka arc.

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Research carried out in recent years has shown that the main structures controlling the distribution of high-temperature hydrothermal systems in Kamchatka are large faults with a north-easterly strike which were activated in the Middle Pleistocene [14]. Figure 1 shows the location of the modern hydrothermal systems (according to [23]) and also brings out the main zones of faults with a north-easterly strike (according to [1]). The majority of the hydrothermal systems in Kamchatka are situated along lines parallel to these faults. The following hydrothermal systems stretch in such lines: Essovskaya, Apapel'skaya, Kireunskaya and Dvukh'yurtochnaya in the Sredinnyy range; Nalachevskaya, Akademiya Nauk, Semyachikskaya, Kal'dery Uzon and Doliny Geyzerov in the central area of eastern Kamchatka; and Golyginskaya, Khodutkinskaya, Severo-Mutnovskaya and Zhirovskaya in southern Kamchatka.

The thermal energy accumulated by the rocks of the hydrothermal systems increases along these lines from south-west to north-east and then drops sharply (see

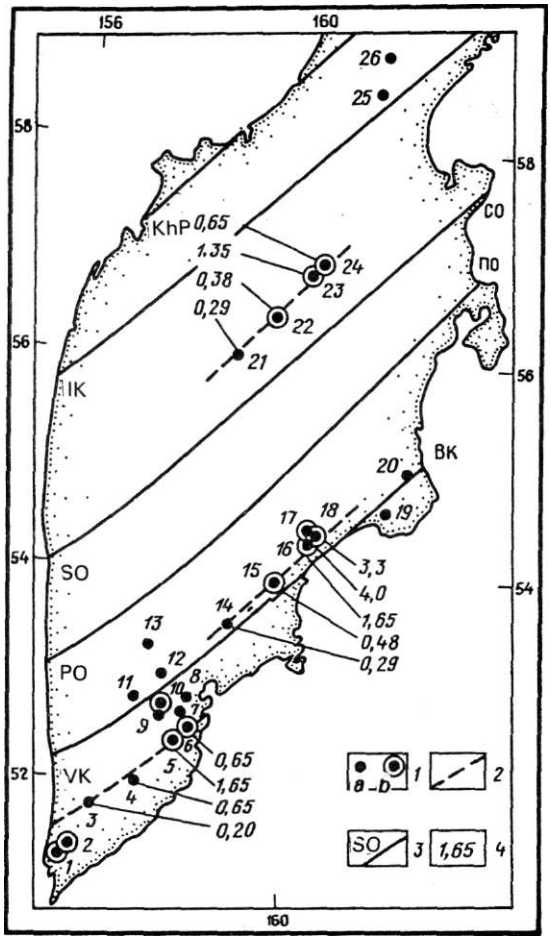


Figure 1 Diagram of the location of hydrothermal systems, thermal lines and the largest faults with a north-easterly strike in Kamchatka. 1—hydrothermal systems, according to [23]: a—low temperature, b—high-temperature (1—Koshelevskaya, 2—Pauzhetskaya, 3—Golyginskaya, 4—Khodutkinskaya, 5—Severo-Mutnovskaya, 6—Zhirovskaya, 7—Verkhneparatunskaya, 8—Paratunskaya, 9—Karymchinskaya, 10—Bol'shebannaya, 11—Apacha, 12—Nachiki, 13—Malki, 14—Nalachevskaya, 15—Akademiya nauk, 16—Semyachikskaya, 17—Kal'dery Uzon, 18—Doliny Geyzerov, 19—Tyushevskaya, 20—Chazhminskaya, 21—Essovskaya, 22—Apapel'skaya, 23—Kireunskaya, 24—Dvukh'yurtochnaya, 25—Rusakovskaya, 26—Palanskaya); 2—main directions along which the hydrothermal systems are grouped, according to [3] with amendments; 3—the largest faults and zones of faults with a north-easterly strike, according to [1]; KhP—Khayryuzovsko-Penzhinskaya, IK—Icha-Koryakskaya, SO—Sobolevsko-Ozernovskaya, PO—Pymtinsko-Ozernovskaya, VK—Vostochno-Kamchatskaya; 4—thermal energy accumulated in the rocks of the hydrothermal systems (10^{18} cal) according to [23]

Figure 1). This is apparently not a chance occurrence, but is associated with the characteristics of the development of tectono-magmatic processes along zones of faults with a north-easterly strike. In this connection, we endeavoured to analyse the way in which the nature of the manifestation of volcanism, the age of the rocks and also the structural characteristics change along these lines.

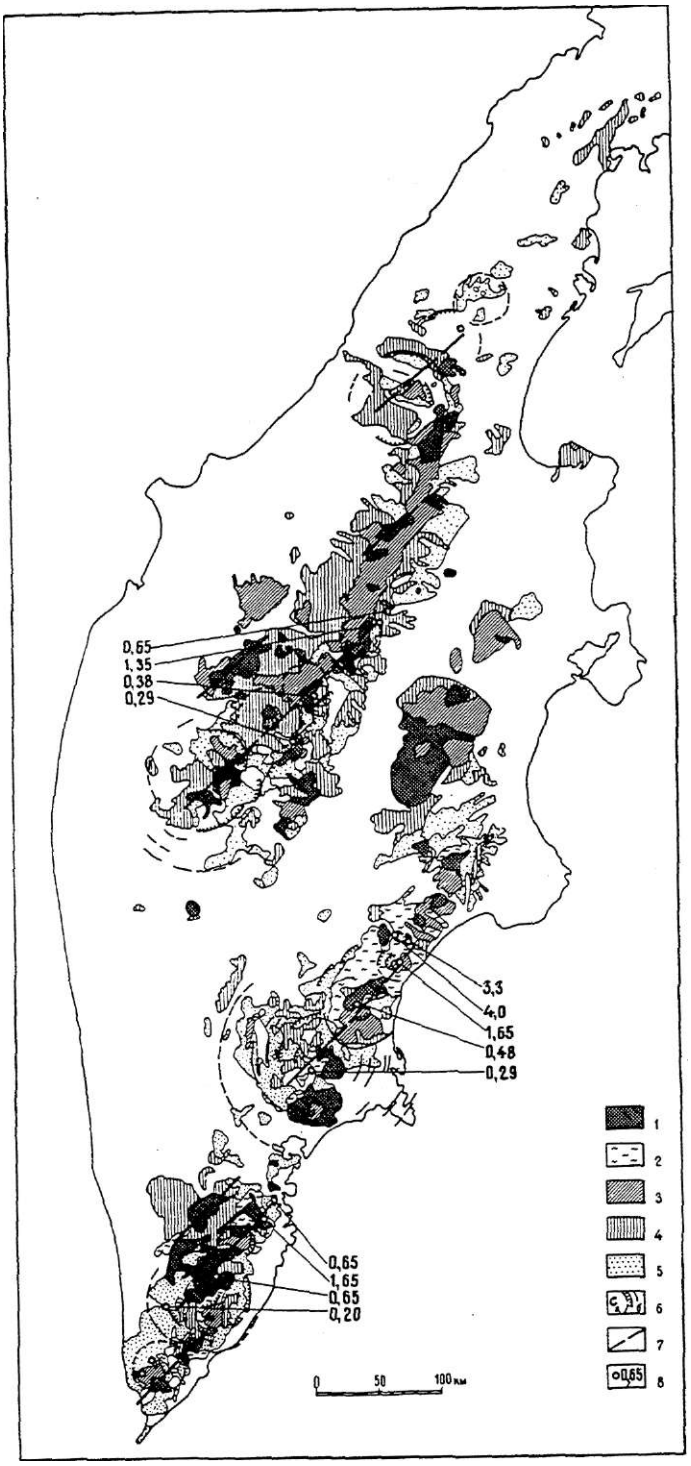
The formation of the modern hydrothermal systems in Kamchatka is closely connected with the latest Pliocene-Quaternary stage of tectono-magmatic activation [20,26]. Figure 2 shows the areas of occurrence of volcanic rocks of Pliocene-Quaternary age. The rocks of Pliocene (in part Upper Miocene), Lower Quaternary and Middle-Upper Quaternary age and the Holocene rocks (modern) are identified separately. These rocks as a whole form two belts with a north-easterly strike, analogous to the Sredinnyy and Vostochnyy Quaternary volcanic belts [4]. Three areas can be identified in the structure of the Vostochnyy belt. They are situated in Southern Kamchatka, in the centre of Eastern Kamchatka and in the Central Kamchatka depression. Let us examine the structure of the regions of Pliocene-Quaternary volcanic rocks in these areas.

THE CENTRAL AREA OF EASTERN KAMCHATKA

The volcanic rocks of Pliocene-Quaternary age here form a single field, stretching for a distance of 250 km (from Avacha bay and the Avacha group of volcanoes in the south to the Kronotskiy volcano in the north). The field extends in a north-easterly direction and is wedge shaped. It is up to 120 km wide in the south-west and 20-30 km wide in the north-east. The line, to which the modern hydrothermal systems are confined, represents the axial line of this field (see Figure 2). An analysis of the occurrence of rocks in the area according to age groups (Pliocene, Lower Quaternary, Middle-Upper Quaternary) shows that rocks of Pliocene age predominate in the south-west, Lower Quaternary rocks occupy the greatest areas in the centre of the area and rocks of Middle-Upper Quaternary age begin to predominate in its north-eastern part. Thus, lavas with a basaltic composition, which predominate in the south-west of the area, are replaced in the north-east by pyroclastic rocks of a mainly dacitic composition.

This is apparent from the example of the Nalachevskiy, Karymskiy and Uzon-Geyzernyy volcanic centres, situated in this region in a chain stretching from south-west to north-east. In the first of these centres vulcanites with an acidic composition make up only a few percent of the Pliocene-Quaternary rocks, reaching a total of 10% in the rocks of Late Pleistocene age [7]. In the Karymsky centre, rocks with an acidic composition, predominated by ignimbrites, make up 44% [5], and in the region of the Uzon-Gezernaya depression the volume of these rocks equals that of rocks with a basic composition [28], i.e. about 50%.

Besides the general 'rejuvenation' of the rocks from south-west to north-east in this area, the spatial and temporal migration of the calderas that appeared in the Middle-Upper Quaternary time is also noted. From the stratigraphical relationships of the pyroclastic deposits surrounding the calderas it has been established that the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calderas in the Karymskiy centre are the oldest and the Semyachikskaya, Uzon-Geyzernaya and Krasheninnikov calderas, situated further to the north-east, become successively younger [28].

Figure 2 also shows the modern rocks of Holocene age. It should be noted that although a Holocene age has been accepted for these rocks [6], they also include, in part, rocks belonging to the Late Pleistocene. At any rate, the last mass escape of basaltic magma on to the surface in Kamchatka is estimated to be of Late Pleistocene-Holocene age [2]. An analysis of the occurrence of these rocks in the area in question shows that they do not conform to the regularity established above for the older rocks. They occur more or less uniformly and in small patches, gravitating towards the axial line of the area. This all makes it possible to agree with O. A. Braytseva *et al.* [2] in regarding the Late Pleistocene-Holocene stage of volcanism in Kamchatka as a separate phenomenon with its own characteristics and regularities.

A definite regularity is also noted in the arrangement of the largest isometric volcanic structures in this area: they successively lessen in diameter from south-west to north-east. Figure 2 shows the main faults and fissure zones associated with these structures. The largest of them is the well-documented Nalachevksiy dome, with a diameter of ~ 100 km [7,16]. The Karymskiy volcanic centre, with a diameter of ~50 km, is situated to the north-east, on its edge. Further to the north-east lie the Bol'shesemyachikskiy, Uzon-Geyzernyy and Krasheninnikov volcanic centres. The diameter of these centres successively lessens from south-west to north-east (Figures 2 and 3). The successive shifting of volcanic activity to the north-east is also traced within individual volcanic centres in this area (see Figure 3). The diagram shows the supposed boundaries of the volcanic centres, and the calderas and fields of volcanic rocks from two phases of post-caldera volcanism. We note that the calderas are slightly displaced to the north-eastern edge of the volcanic centres (this is particularly clear in the older centres, Karymskiy and Bol'shesemyachikskiy). Post-caldera volcanism, which is mainly concentrated within the calderas, with time also shifts to the north-east, covers the boundaries of the calderas and extends onto their north-eastern slopes. The older the centre in this chain, the clearer the manifestation of these regularities.

Let us examine one more feature of the structure of this area, namely the latest major extension zone with a north-easterly strike which passes along its axial line. Rupture disturbances are widespread here and have been described by various

Figure 2 Areas of occurrence of volcanic rocks of Pliocene-Quaternary age in Kamchatka. 1-5—areas of occurrence according to [6]: 1—of modern lavas of a basaltic, andesitobasaltic and andesitic composition and scoriae of them; 2—of Middle-Upper Quaternary pumice, ignimbrites, tuffs, lavas of a rhyolitic, dacitic, andesitodacitic and andesitic composition; 3—of Middle-Upper Quaternary lavas of a basaltic, andesitobasaltic and andesitic composition; 4—of Lower Quaternary lavas of a basaltic and andesitobasaltic composition; 5—of Pliocene, in part, Upper Miocene-Pliocene lavas of a basaltic, andesitobasaltic, andesitic and dacitic composition with tuffs, tuffobreccias and ignimbrites (Alney, Tumrock, Shchapinskaya and Storozhevskaya formations); 6—calderas (a), and arching faults and zones of fissuring (b), bounding large volcanic centres (description of actual centres see text); 7—main magma-supplying faults with a north-easterly strike (identified from [1, 5, 9, 14-16, 25, 26 and others]); 8—hydrothermal systems of Kamchatka and their thermal energy (see Figure 1)

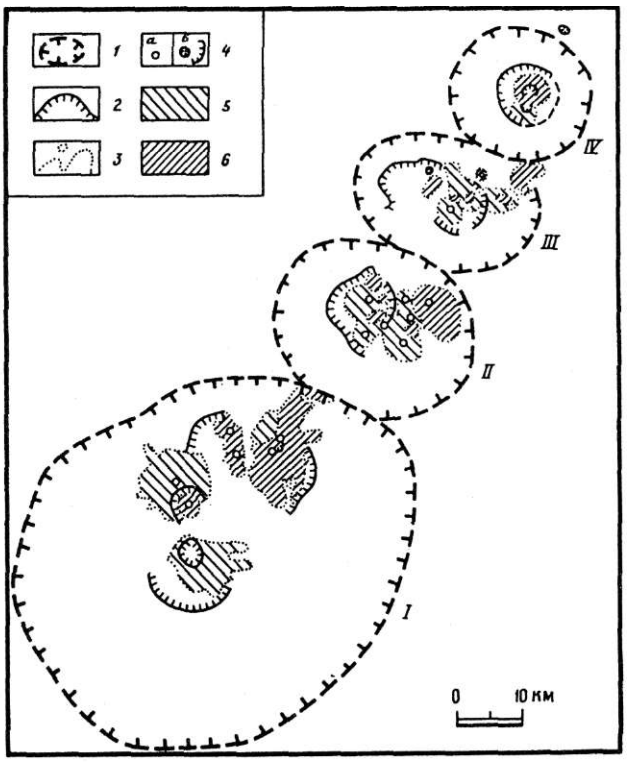
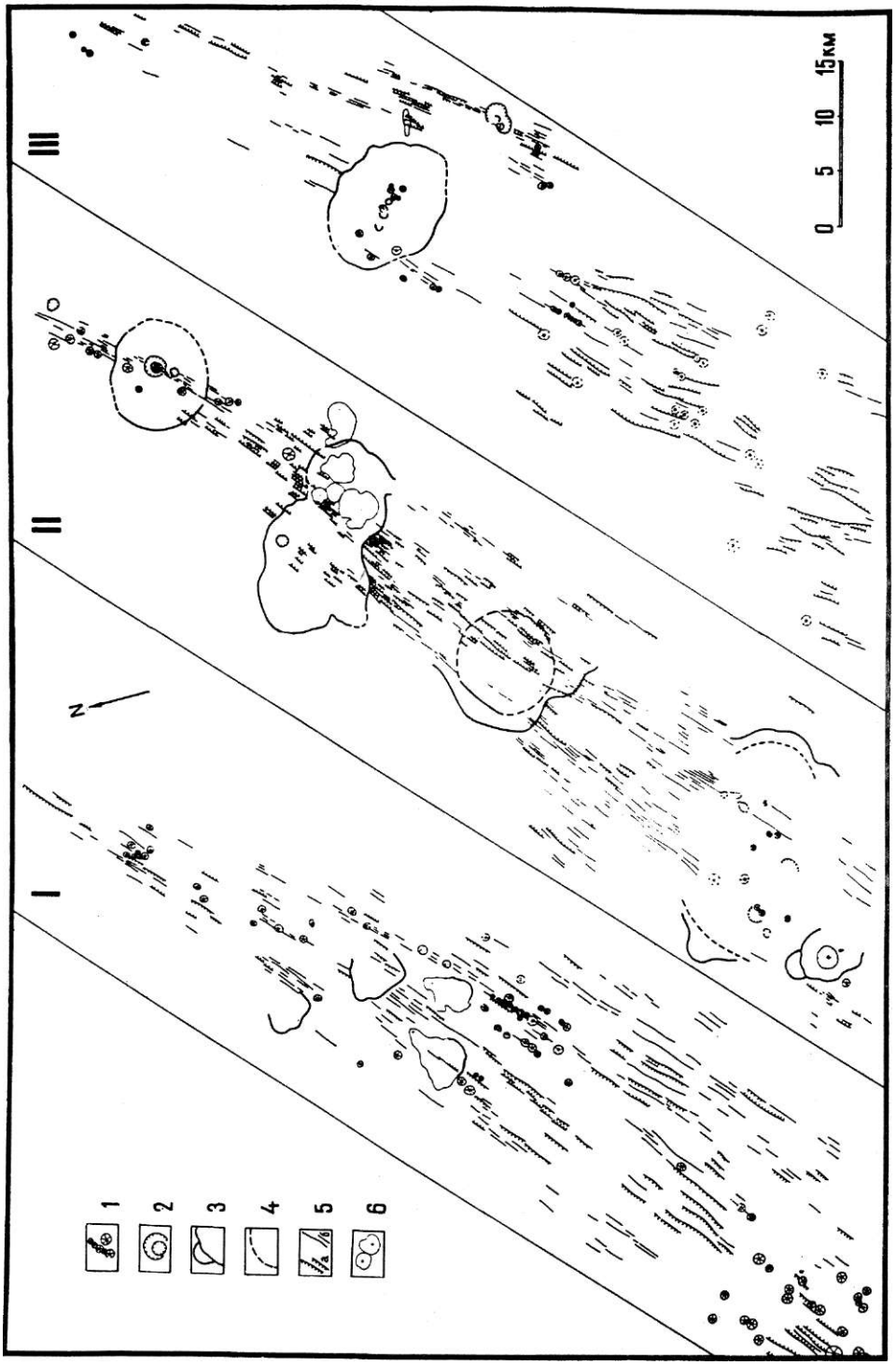


Figure 3 Volcanic centres of the central area of Eastern Kamchatka. I—Karymskiy, according to [5, 21], II—Bol'shesemyachikskiy, III—Uzon-Gezernyy, IV—Krasheninnikov. 1—supposed boundaries of volcanic centres; 2—calderas; 3—generalized contours of the development of volcanic rocks; 4—centres of volcanic structures (a), craters, maars (b); 5, 6—areas occupied by post-caldera volcanic structures: 5—early phase, 6—late phase

authors [10-12,25]. Figure 4 shows rupture disturbances which we have mapped following detailed work carried out in the region of the Bol'shesemyachikskiy and Uzon-Geyzernyy volcanic centres. The diagram shows that the zone of rupture disturbances is 20-22 km wide in the south-western part of the area, but only 4-5 km wide in the north-east. Only isolated faults of this type [10] are noted further to the north-east. These data suggest the conclusion that the zone of the latest rupture disturbances in this area tapers out towards the north-east.

To conclude the description of the structural features of the area of occurrence of Pliocene-Quaternary volcanic rocks in the central area of Eastern Kamchatka we

Figure 4 Rupture disturbances: I—in the region of the Alney-Chashakondzha volcanic massif (Sredinnyy range), II—in the central area of Eastern Kamchatka, III—in the region of the Asacha, Gorelyy and Mutnovskiy volcanoes in Southern Kamchatka. 1—scoriaceous cones, small volcanic structures; 2—craters of volcanoes, maars; 3—morphological boundaries of calderas; 4—supposed structural boundaries of calderas; 5—rupture disturbances: a—normal faults, b—fissures; 6—extrusions of lavas with a rhyolitic composition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note the main regularities which have been revealed here. They reflect the general longitudinal asymmetry of the area and are represented by the following changes from south-west to north-east: first, the contraction of the field of Pliocene-Quaternary vulcanites; secondly, a general 'rejuvenation' of the rocks from mainly Pliocene to Middle-Upper Quaternary; thirdly, a reduction in the diameter of the dome-ring structures; and lastly, the tapering out of the zone of the most recent rupture disturbances.

In addition, as noted at the beginning of the paper, a sequential increase in the natural resources of heat accumulated by the rocks of the known hydrothermal systems is observed from south-west to north-east.

These characteristics are apparently associated with general processes occurring with a successive directional shift towards the north-east. We shall analyse these processes in more detail after an examination of the structural characteristics of the other areas.

THE SREDINNYY RANGE OF KAMCHATKA

This area stretches for a distance of about 250 km in the form of a band with a north-easterly strike from the Icha volcano in the south-west to the Alney volcano in the north-east. It differs from the rest of the area of occurrence of Pliocene-Quaternary vulcanites in the Sredinnyy range in that it has a more complex structure. The largest volcanoes with the most protracted development are concentrated here: Icha, Uksichan, Chashakondzha and Alney, and alongside these, the largest manifestations of thermal activity, namely the hydrothermal systems shown in Figures 1 and 2. The area of development of Pliocene-Quaternary volcanic rocks here merges with the neighbouring areas of similar rocks (Zapadnyy and Kozyrevskiy volcanic regions [18]). On the whole, the same regularities as were revealed in the structure of Eastern Kamchatka (see Figure 2) are traced here. First, the successive change in the ages of the volcanic rocks from mainly Pliocene in the south-west to Lower Quaternary in the centre (in the region of the Uksichan volcano) and mainly Middle-Upper Quaternary in the north-east (in the region of the Anaunskoye elevation and the Chashakondzha and Alney volcanoes). Volcanic rocks of Holocene age are widespread here as they are in Eastern Kamchatka, and the conclusions about these rocks reached above apply here also. Secondly, as in Eastern Kamchatka, a very large ring-shaped structure with a diameter of ~ 100 km (Upper Icha centre of protracted endogenous activity) [9,27] can be reconstructed in the south-western part of the area. To the north-east of this structure there is the Uksichan volcano-tectonic structure with a diameter of ~ 50 km [22], and further to the north-east the Anaunskoye elevation with a diameter of ~30 km. Finally, further still to the north-east there is the volcanic massif of Alney-Chashakondzha with a diameter of ~25-30 km [18]. All these structures have been studied only superficially, but the successive reduction in their diameters from south-west to north-east can be clearly traced.

Detailed work carried out by the authors in recent years in the region of the Alney-Chashakondzha massif has made it possible to identify an extensive zone of recent rupture disturbances with a general north-easterly strike, very similar in its characteristics to the zone of recent rupture disturbances in Eastern Kamchatka (see Figure 4). This zone becomes very much narrower in a north-easterly direction. In the south-west it continues towards the Anaunskoye elevation and the Uksichan volcano. As in Eastern Kamchatka, the majority of the rupture disturbances in this zone are normal faults and fissures, along which there are frequent groups of scoriaceous cones and small volcanoes of Late Quaternary and Holocene age, i.e. this zone also represents a recent zone of extension with a north-easterly strike, gradually narrowing and, apparently, tapering out towards the north-east.

An analysis of the structure of individual volcanic centres situated in this area shows that, like the volcanic centres of Eastern Kamchatka, they are characterised by asymmetry, expressed as the sequential displacement of their volcanic activity to the north-east over time. This is typical of the Icha, Uksichan and Alney centres and also of the Anaunskoye elevation (see Figure 2 [8]).

SOUTHERN KAMCHATKA

The area in which there is a successive increase in the natural heat resources of the known hydrothermal systems here stretches for a distance of ~150 km from the river Golyginoy in the south-west to the Vilyuchik volcano in the north-east. Like the area in the Sredinnyy range examined above, this area adjoins other areas in the north-west and south. In the north-west it adjoins the region of the Opala and Bol'shaya Ipel'ka volcanoes (the 'western branch' of the volcanoes of Southern Kamchatka) and in the south, the vast isometric Pauzhetskaya volcano-tectonic structure (see Figure 2). Let us trace the changes in the structure of this area from south-west to north-east. First, it should be noted that the area of occurrence of the Pliocene-Quaternary rocks here becomes generally narrower. Secondly, as in the areas described above, an extensive field of rocks of mainly Pliocene age is developed in the south-western part of the area. In the centre of the area considerable areas are covered by Holocene basalts which make it impossible to attempt a reliable estimate of the occurrence of older rocks here. However, further to the north-east Lower Quaternary basalts appear from under them, and these are replaced by rocks of mainly Middle-Upper Quaternary age in the region of the Asacha volcano. Thus, the general directional effect of a change in the rocks from mainly Pliocene in the south-west to mainly Middle-Upper Quaternary in the north-east, established in the other areas examined above, is also preserved here. A change is also indicated in the composition of the rocks: in the north-east, in the region of the Mutnovskiy and Gorelyy volcanoes, pyroclastic material, corresponding in its composition to andesitodacites, plays an important role; in the south-west, lavas with a basaltic composition predominate.

One of the most important dome-ring structures (volcanic centres) in this area is the very large Ksudachskiy centre [7]. The Asacha centre (Asacha group of

volcanoes according to [9]) is situated to the north-east of it, and yet further to the north-east lie the Gorelyy and Mutnovskiy volcanic centres (Figures 2 and 5). These structures (Ksudachskaya and Asacha) have been identified conditionally, since there are no detailed descriptions of them in the literature at the present time; they have only been indicated by the authors of the works listed above.

Figure 5 shows the distribution of volcanic rocks of various ages within some of the volcanic centres in this area. It is apparent that there is a sequential displacement of the volcanic activity in these centres in a north-easterly direction in the Quaternary time. Thus, for example, in the Asacha group of volcanoes, which consists of several volcanic formations of various ages, the remains of the oldest shield-shaped structure are situated in the south-western part and the younger Zheltyy and Asacha volcanoes and the Tumanov cone are located on its north-eastern slopes. The youngest Upper Quaternary and Holocene structures are widespread at the foot of the volcano, but the largest single field, with dimensions of 7 x 11 km, lies at its north-eastern foot (see Figure 5, [9]).

The same kinds of regularities are also traced in the region of the Gorelyy and Mutnovskiy volcanoes. Thus, the distance from the edge of the caldera of the Gorelyy volcano to the edge of its pre-caldera structure is 10 km in the south-west and less than 5 km in the north-east. The distance from the crater of the Mutnovskiy volcano to its south-western foot is 7 km and to its north-eastern foot, 4 km. Thus, it is possible to conclude that volcanic activity was displaced to the north-east over time here also. It is likewise not a chance occurrence that a number of small secondary Middle-Upper Quaternary volcanoes on the slopes of the Mutnovskiy volcano are confined to its north-eastern slope (see Figure 5).

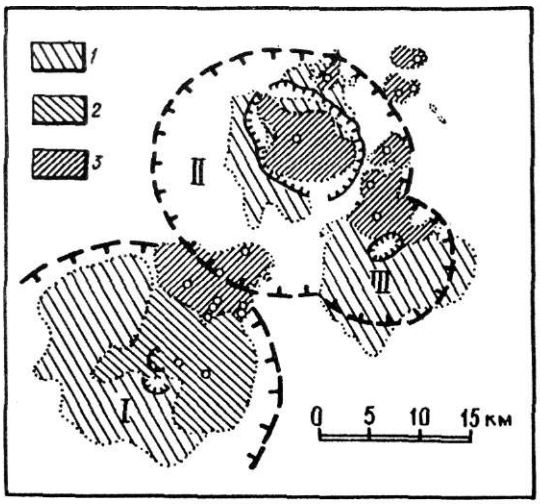

Figure 5 Volcanic centres in Southern Kamchatka. I—Asacha, II—Gorelyy, III—Mutnovskiy. 1–3—areas occupied by Quaternary volcanic rocks: 1—early phase, 2—intermediate age, 3—late phase (according to [9, 13, 14]). Remaining legend see Figure 3

Figure 4 III shows the rupture disturbances occurring in this area. They form several individual groups displaced in relation to each other to form coulisses. As in the areas described above, they are represented mainly by normal faults and fissures of Late Pleistocene-Holocene age [13]. Forming wide graben-formed structures, these disturbances apparently reflect the existence here of a large extension zone, stretching along the axis of the area. The fact that the area of rupture disturbances narrows towards the north-east probably indicates that the extension zone tapers out in this direction.

THE NATURE OF THE REGULARITIES

In the various sections of the Pliocene-Quaternary volcanic belts in Kamchatka it is possible to detect a regular change in the age of the rocks, the dimensions of the volcanotectonic structures and the latest zones of extension along lines with a north-easterly strike. This change coincides with a sequential change in the natural thermal resources of the known hydrothermal systems along the same lines. These regularities should not be regarded as fortuitous. They reflect the action of a general mechanism of some kind, apparently associated with considerable horizontal displacements. Such phenomena are currently usually explained with reference to the concept of hot spots [29-31 and others]. If we examine the phenomena described above in this context, we must assume that Kamchatka, as part of the Sea of Okhotsk plate, has been moving to the south-west over a series of hot spots for the last 5 million years. The rate of such movement is 4 cm/year and for individual areas, as much as 10 cm/year. At the same time, according to existing mobilist theories, Kamchatka has been moving to the north at a rate of about 1 cm/year for the last 10 million years [8]. A possible way out of this contradiction may lie in current theories about the considerable horizontal displacements of the hot spots themselves [32]. However, we find this improbable.

It is possible to explain the above phenomena from other standpoints, in particular the tectonic stratification of the lithosphere of Kamchatka [10,25]. On the basis of seismological data A. I. Kozhurin [10] considers it possible to divide the earth's crust in Kamchatka into 'brittle' and 'plastic' levels. He suggests that the horizontal displacement or flow of matter in a near to plastic state is occurring in the lower horizons of the lithosphere here, while the brittle plate of the upper crust lags behind the movement of the lower layers. Such differentiated displacements could, apparently, explain not only the migration of centres of volcanism in volcanic zones, but also the reduction in the dimensions of the isometric structures reflecting them at the surface, due to the ascent of the volcanic sources in the crust. It also explains why Holocene basaltic volcanism does not usually migrate in this way, i.e. it is associated directly with mantle sources of magma in the area of its generation. At the same time, according to A. I. Kozhurin [10], the mantle matter in the earth's interior in Kamchatka is displaced mainly in a westerly direction, which does not agree with the data presented above. It is also difficult to explain the migration of

volcanism associated with the activity of crustal magmatic centres (extrusions, small volcanoes with 'acidic' products) in this way.

These facts compel us to examine one more possible reason for the regularities described above, namely, the horizontal displacement of magma in the zones of deep faults. Within the framework of his vortical volcanic hypothesis, I. V. Melekestsev [17] has shown that with a rotating earth matter must ascend to the surface, according to Coriolis' law, in an ascending, expanding spiral. In the northern hemisphere this would form anti-clockwise 'vortices', and so within the Kurile-Kamchatka volcanic arc magma must deviate to the north-east. According to [24], the melting of magma in the earth's interior in Kamchatka occurs at depths of 100-200 km, from where it rises to the surface under the influence of hydrostatic forces. The ascent of magma occurs mainly during epochs of tectonomagmatic activation [26]. Irregularities in the structure of the earth's crust cause the magma rising from the area of magma generation, which is generally parallel to the Kurile-Kamchatka island arc to break up into individual lenses and columns under the conditions of the crust. The result of this is that volcanic activity is manifested unevenly at the surface in individual, often isolated areas. In this connection faults dissecting the earth's crust play a major role in the surface control of volcanism. Many such faults can be recognized in Kamchatka, forming a network similar to the network of planetary jointing. Faults with a north-easterly strike are most similar to the strike of the Kurile-Kamchatka island arc (and thus to the strike of the area of magma generation). On the strength of this, they serve as the most favourable channels for the ascending magma. It is clear that such faults are used by magma only in sections situated above the areas of magma generation. Away from them the faults lose their magma-controlling role, and it passes to neighbouring faults, situated further along the strike of these areas. Faults running in other directions (north-westerly, latitudinal, meridional) are used less and in shorter segments, since their strike differs more from the probable strike of the areas of magma generation. Thus, the main distinction of faults, along which hydrothermal systems are concentrated, is that they control magma over the greatest distances.

The ideas presented above show that the regularities described in the preceding sections may be regarded as a feature inherent mainly in zones of faults with a north-easterly strike. It is clear that these zones possess the most favourable conditions for the ascent and, for the reasons indicated above, the gradual horizontal displacement of magma. At the same time, as noted already, the displacement of magma to the north-east over the course of time is typical not only of fault zones as a whole, but also of individual volcanic centres or volcanic structures (see Figures 3 and 5). This is also indicated by the gradual rejuvenation and tapering to the north-east of the zones of the most recent rupture disturbances (zones of extension) (see Figure 4). This all inclines us to the conclusion that the reasons for the phenomena described above should be sought in the forces acting directly on the magma, regardless of the level or conditions under which it occurs. Such structures as large zones of faults with a north-easterly strike apparently promote the horizontal displacement of magma, and therefore the signs of this displacement are most clearly visible on the surface above these zones of faults.

CONCLUSIONS

Having examined the arrangement of the modern hydrothermal systems within the fault zones, we can see that they gravitate towards individual volcanic centres and their capacity depends directly on the age of the centres. The most powerful high-temperature hydrothermal systems in Kamchatka are associated with centres laid or displaying their greatest activity in the Middle-Upper Quaternary time (see Figure 2 [14]). Such systems are Semyachikskaya, Kal'dery Uzon and Doliny Geyzerov in Eastern Kamchatka, Kireunskaya and Dvukh'yurtochnaya in the Sredinnyy range and Severo-Mutnovskaya and Zhirovskaya in Southern Kamchatka. All these systems are situated in the north-eastern part of the areas examined above, i.e. they gravitate towards the north-eastern ends of the fault zones.

Certain regularities are also noted in the arrangement of the manifestations of thermal activity within the above hydrothermal systems. In similar fashion, the Middle-Upper Quaternary volcanic formations gravitate towards the north-eastern slopes of the older structures, and the thermal phenomena are usually confined to the north-eastern slopes of the volcanic centres with which they are associated. This is shown clearly in Figure 6 using the example of the Mutnovskiy geothermal region. Middle-Upper Quaternary extrusions and modern thermal manifestations occur over quite a large area here, but exclusively to the north-east of the Gorelyy and Mutnovskiy volcanoes. No such phenomena are known on the south-western slopes of these volcanoes. Similarly, in the Sredinnyy range the thermal phenomena of the Kireunskaya and Dvukh'yurtochnaya hydrothermal systems are situated to the north-east of the Alney-Chashakondzha volcanic massif. In the region of other hydrothermal systems (Doliny Geyzerov, Kal'dera Uzon, Semyachikskaya) large transverse faults play an important role in the location of modern thermal manifestations [14]. But here also we discover that the thermal manifestations are displaced slightly to the east and north-east of the centre of the structures enclosing them. These regularities could be used in the planning of exploratory and drilling work on actual geothermal deposits in Kamchatka.

Thus, we can formulate the following basic conclusions.

1. Confirming the assertion stated since the time of A. N. Zavaritskiy that the volcanoes and modern hydrotherms in Kamchatka are confined to faults with a north-easterly strike, we consider that three faults, situated in Southern Kamchatka, Eastern Kamchatka and the central part of the Sredinnyy range of Kamchatka, play a major role in the structural control of the modern hydrothermal systems.
2. Along these faults, from south-west to north-east, it is possible to trace a general 'rejuvenation' of the rocks, a reduction in the diameter of the dome-ring structures, the tapering out of the zones of the latest rupture disturbances and an increase in the natural thermal resources accumulated in the rocks of the known hydrothermal systems.
3. Within volcanic centres situated in zones of faults with a north-easterly strike the sequential displacement of the manifestations of volcanic activity in a north-easterly direction can be traced in the Pliocene-Quaternary time. This also fits in

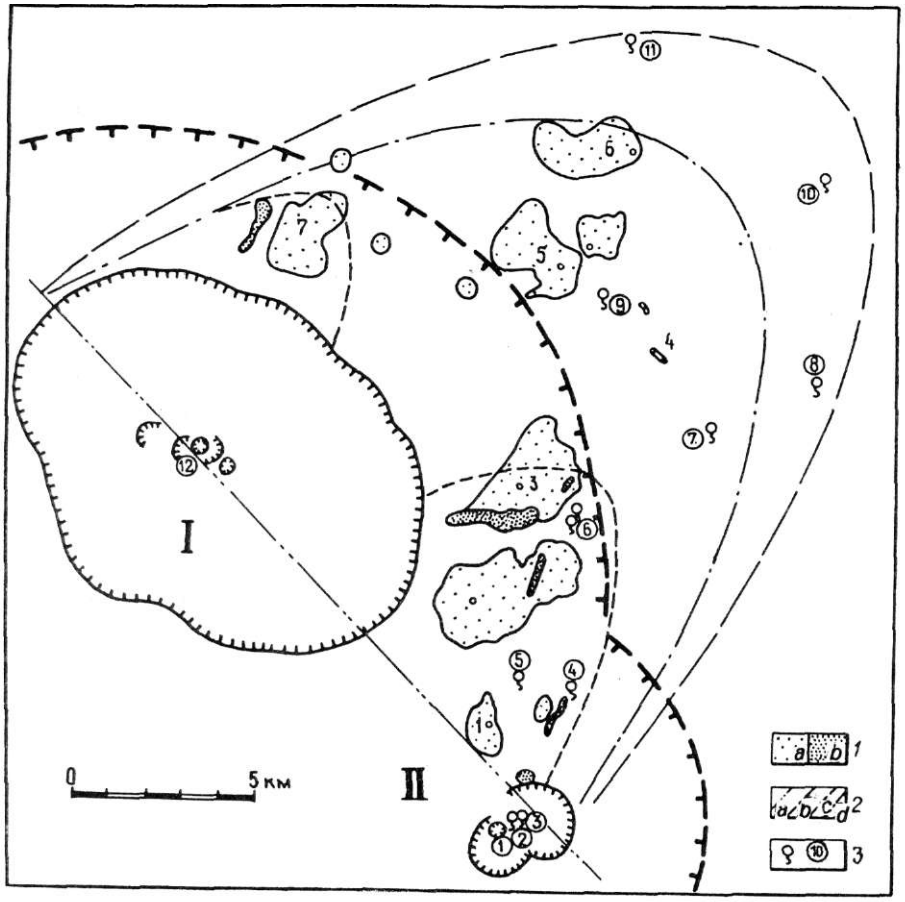

Figure 6 Diagram of the location of Middle-Upper Quaternary extrusions and thermal phenomena in the Mutnovskiy geothermal region. I—Gorelyy volcano, II—Mutnovskiy volcano. 1—complex of Middle-Upper Quaternary extrusions: a—early phase, b—late phase, (1—Pal'chik, 2—Dvugorbaya, 3—Skalistaya, 4—Dlinnaya, 5—Kamennaya, 6—Vilyucha, 7—Ploskaya); 2—axial line of volcanic structures (a), boundaries of sectors of: Middle-Upper Quaternary extrusions (b), Late Quaternary extrusions (c), modern thermal fields and sources (d); 3—thermal fields and sources (1—Aktivnaya cone, 2—Donnoye field, 3—Verkhneye field, 4,5—Severo-Mutnovskoye field (Zapadnaya and Vostochnaya groups), 6—Dachnye, 7—Pereval'nye, 8—Voynovskiye, 9—Verkhnezhirovskiye, 10—Nizhnezhirovskiye, 11—Vilyuchikskiye, 12—active crater and fumaroles of the Gorelyy volcano)

with the distribution of the modern thermal manifestations which are usually confined to the north-eastern slopes of such structures.

4. At the present time there is no satisfactory explanation for the regularities described above. The most probable explanation seems to be the sequential displacement of the ascending magma to the north-east. Thus, faults with a north-easterly strike act as the most suitable conductors of magma and fluid.

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