Quaternary Calderas of Kamchatka

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Introduction

By the term *caldera* we mean a regular round-shaped structure genetically associated with a volcanic process. In this sense, according to R. van Bemmelen and R. L. Smith, we do not differentiate from a genetic point of view between calderas and volcano-tectonic depressions. It is advisable, however, to keep both terms with just a quantitative difference between them, using the term « caldera » for structures with a diameter less than 12 km, and giving the name of « ring volcano-tectonic depressions » to larger structures. In a more detailed classification based on the type of volcanism with which the formation of the Kamchatka calderas is associated, the therminology suggested by H. WILLIAMS (1941) will be used. Explosion funnels of even the largest size are not included into the « caldera » group and will not be discussed in this paper.

Setting of Calderas according to Geological and Geophysical Data

The distribution of calderas and volcano-tectonic depressions in Kamchatka is shown in Fig. 1.

Being localized in the graben-synclinal structures controlled the volcanic belts as a whole, the volcano-tectonic depressions and the Krakatau-type calderas do not reveal any direct connection with active zones of disjunctive dislocations. The linear arrangement of the calderas of the eastern volcanic belt is determined by the general strike of the graben-synclines.

In these synclines the distribution of the volcano-tectonic depressions and of the Krakatau-type calderas is governed by large (20-50 km) negative Bouguer anomalies with concentric contour lines. The characteristics of these anomalies are nearly identical. Their cross section (Fig. 3) shows the presence of relatively gentle gravity gradients before and after the minimum. The anomalies have similar shapes and are of almost equal intensity with similar values of the horizontal gradients. Only the Uzon anomaly is characterized by a higher intensity.

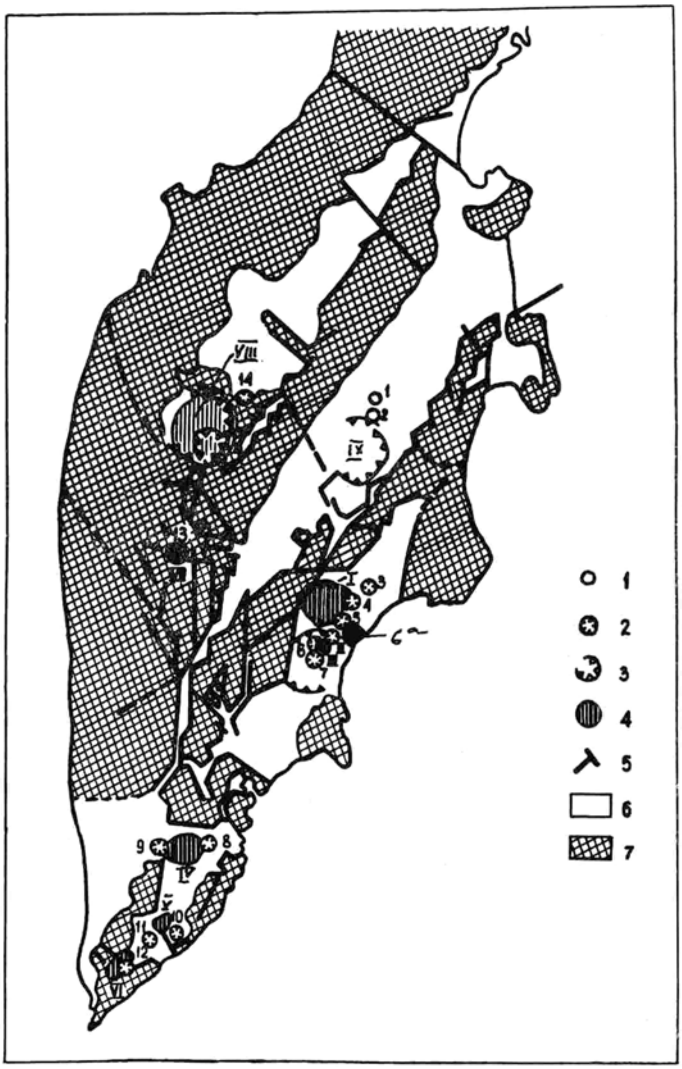
Two groups can be distinguished in the distribution of the volcano-tectonic depressions and calderas with respect to the above mentioned anomalies.

In the first group, *e.g.* the Pauzhetka, Bolshe-Semiachinsky, and Khangar ring volcano-tectonic structures, the volcano-tectonic structures coincide with the negative gravity anomaly. The Karymsky anomaly is located on the very large Zhupanovsky ring structure but it occupies only a very small part of it. On the eastern, northern and western parts the anomaly contour lines nearly coincide with the contours of the geological structures, but are somewhat displaced towards the center of the ring structure, so that Karymsky, Berezovy and Maly Semiachik volcanoes — which are in a volcano-tectonic depression — stand along the periphery of the gravity anomaly.

In all cases a large dome is observed on the surface, on the background of which there is a ring volcano-tectonic depression, 20-40 km in diameter. These depressions have a « telescopic » structure, *i.e.* they consist of a number of concentrically subsided zones, each of which is bounded by ring faults, morphologically evidenced as scarps. The amplitude of the subsidence along the faults increases from the periphery towards the center of the structure and varies from several tens to one thousand meters (Erlich, 1966).

The depth of the gravity centers of the anomaly-causing bodies (in the group under discussion) has been computed according to the N. N. Afanasiev's method with corrections for the lack of infinity in the integration limit. The following values have been obtained: 8 km for the Karymsky anomaly; 10 km for the Bolshe-Semiachinsky anomaly; and 10-15 km for the Pauzhetka anomaly. The mass deficiency determining the anomaly has been computed according to the Green's formula and it is: 12×10^{16} *g* for the Karymsky anomaly, and 15×10^{16} *g* for the Pauzhetka and Bolshe-Semiachinsky anomalies. The depth of the top rim of the anomaly-causing bodies, computed according to the approximate formula of Botte and Smith, appears in all cases to be about 5-6 km. Therefore, the computed parameters of the anomalies in the group under discussion are almost identical, which in itself indicates the identity of their nature.

Gravity anomalies of the second group have no correspondence to surface structures. It is characteristic, however, that complex volcanic structures with a highly differentiated lava composition are located around such anomalies in areas of large horizontal gradients of gravity. Moreover, such a location is also characteristic of the



largest calderas of the Krakatau type. So, the Taunshitz, Unana, Uzon and Bolshoi Semiachik volcanoes are located along the periphery of the Uzon anomaly, while the Opala, Asacha and Gorely volcanoes are located along the periphery of the Tolmachev anomaly.

The Uzon anomaly occupies an area of 50×45 km and is characterized by high intensity and considerable peripheric gradients. The depth of the anomaly center of the body that causes the Uzon anomaly has been determined to be 14-18 km and the mass deficiency is about $200 \div 250 \times 10^{16}$ g.

For the Tolmachev negative anomaly, the depth of the top rim of the anomaly-forming body exceeds 12 km. A characteristic feature of the magnetic field in the Tolmachev region is the presence of a positive magnetic anomaly that connects the Gorely, Asacha and Opala volcanoes forming a closed polygon. The Krakatau-type calderas — Gorely and Opala — are located on the intersections, *i.e.* in the corners of the polygon and are associated with intense magnetic anomalies.

The similar characteristics of the negative gravity anomalies, their general connection with areas of acid volcanism, the substantial depths of the anomaly-causing bodies and their relatively low density lead one to the conclusion that such anomalies are due to the presence within the crust of magmatic masses of acid composition. The correctness of such conclusion is confirmed by the negative magnetic anomaly of secular duration in the area of Pauzhetka. The eastern branch of this anomaly coincides exactly with the Pauzhetka gravity

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FIG. 1 - Distribution of Quaternary calderas and volcano-tectonic depressions in Kamchatka.
Key: 1: Hawaiian-type calderas; 2: Krakatau-type calderas; 3: Main volcano-tectonic disjunctive dislocations; 4: Zones of negative gravity anomalies; 5: Tectonic disjunctive dislocations; 6: Areas of continuous development of Quaternary volcanic and volcano-sedimentary rocks; 7: Pre-Quaternary rocks.
Arabic numerals: Calderas
Latin numerals: Large negative gravity anomalies
Calderas: 1 - Dalnaya Ploskaya sopka; 2 - Plosky Tolbachik; 3 - Krasheninnikov; 4 - Uzon-Geyser valley; 5 - Semiachik; 6a - Maly Semiachik; 6 - Karymsky volcano; 7 - Karymsky lake; 8 - Gorely; 9 - Opala; 10 - Ksudach (Stübel caldera); 11 - Prizrak; 12 - Kurile lake; 13 - Khangar; 14 - Uksichan.
Negative Gravity Anomalies: I - Uzon; II - Bolshe-Semiachik coinciding with the same name ring-structure; III - Karymsky anomaly inside the Zhupanov ring-structure; IV - Tolmachev; V - Golygin; VI - Pauzhetka; VII - Khangar; VIII - Ichinsky; IX - Tolbachik volcano-tectonic depression.

anomaly and can be explained by the presence of a high-temperature mass at a depth of about 10 km (according to I. M. Pudovkin).

An attempt to interpret these anomalies using computation charts

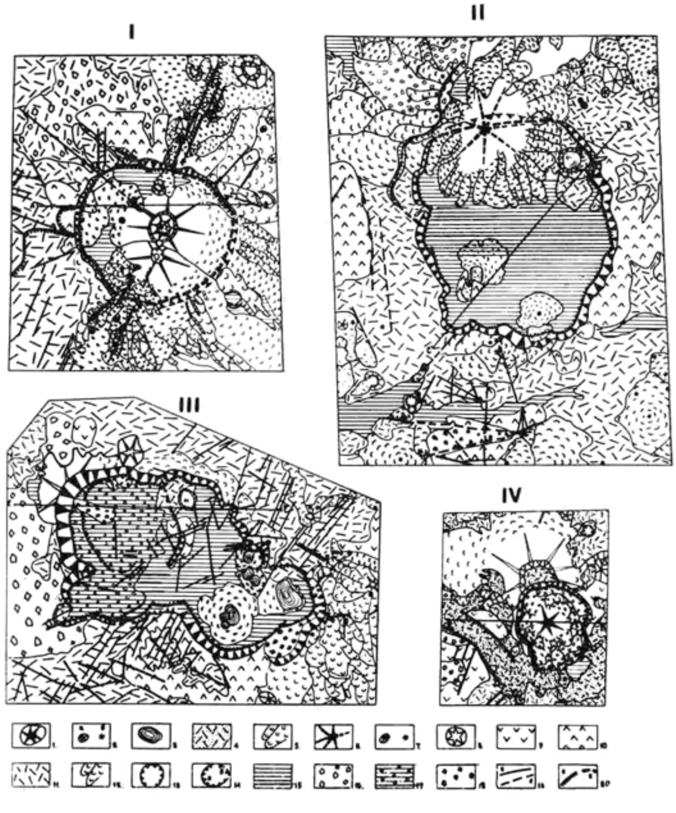

FIG. 2 - Geological sketch maps of Krakatau-type calderas.
I - Krasheninnikov caldera; II - Opala caldera; III - Uzon caldera; IV - Karymsky volcano caldera.
1: Holocene strato-volcanoes; 2: Holocene slag and lava cones (a - in scale; b - not in scale); 3: Holocene and upper Pleistocene extrusive domes; 4: Holocenic pyroclastic pumice flows; 5: Holocene lava flows; 6: Late Pleistocene-Holocene strato-volcanoes; 7: Upper Pleistocene slag cones (a - in scale; b - not in scale); 8: Middle-upper Pleistocene volcanoes; 9: Remnants of middle-upper Pleistocene volcanic structures; 10: Remnants of ruined or buried lower-middle Pleistocene volcanic structures; 11: Upper Pleistocene pumice and ignimbrite sheets; 12: Upper Pleistocene lava flows; 13: Upper Pleistocene maars and explosion funnels; 14: Caldera scarps (a - relief formations; b - ruined or buried); 15: Upper Pleistocene-Holocene exogenic accumulation plains; 16: Glacial deposits; 17: Accumulation plains, partly overlapped by glacial deposits; 18: Seismotectonic collapse deposits; 19: Small volcanotectonic disjunctive dislocations (a - established; b - assumed); 20: Main volcanotectonic disjunctive dislocations.

constructed for a cylinder and for a cone with the bases on the surface (*i.e.*, when the subsided parts of a ring structure or of a gigantic explosion funnel are filled with loose material) did not give a satisfactory agreement with the observed curve. The difference between the depths of the gravity center of the anomaly-causing body in the case of a group of anomalies coinciding with the volcano-tectonic depressions and in the case of anomalies with no surface evidence may, possibly, be associated with different stages of development and ascent of the crustal magma. Apparently, the ascent of the magma to a depth smaller than 10 km causes the formation of volcano-tectonic depressions.

One can say that, if fissure volcanoes are associated with tensional fractures filled by dykes and if the rows of strato-volcanoes represent a series of cylindrical vents located along weakened zones of the basement, calderas and volcano-tectonic depressions reflect on the surface large magma-chambers in the crust. Regional tectonics determine the location of the magmatic masses, while the position of the calderas, and especially of the volcanoes within the calderas, is determined by the strains generated by this magmatic mass. In this way, the geographical distribution of calderas reflects the specific features of the tectonics in a given region.

The majority of the Quaternary calderas and volcano-tectonic depressions in Kamchatka is associated with the eastern volcanic belt. With the exception of the Opala and the Bolshie Bannye Kliuchi calderas, all the calderas are located along a north-eastern line which is known as the « caldera line of Kamchatka » (1). The Avacha somma-volcano is also located on this line. In a number of places these calderas are intercalated with rows of normal stratovolcanoes. Generally speaking, the location of the major part of the volcano-tectonic depressions and calderas in the frontal zone of the eastern volcanic belt together with massive effusions of basalt in the rear part of the belt and in the Sredinny range are important features of transverse zonation of the Kamchatka volcanoes. Similar conditions can, however, be found also in other regions. Important examples are the Opala caldera and the Bolshie Bannye Kliuchi ring structure located in the rear part of the southern Kamchatka graben-syncline near its northern flank. In the Sredinny range the calderas are located in the

(1) See *Geology of the USSR*, vol. 31, 1964.

southern part of the volcanic zone (Ichinsky ring structure) or are superimposed on the uplifted pre-Quaternary complex (Khangar). In other words, they are localized in slowly uplifting areas of tectonically quiet regions.

Age and Geological Features

The formation of the calderas and the ring volcano-tectonic depressions in Kamchatka was almost synchronous geologically. Most of these structures originated during the Middle and Upper Pleistocene. Age determinations on the calderas and on the associated pumice and ignimbrite sheets, based upon their relations with the Upper Pleistocene glaciation, data of spore-and-pollen analyses, and tephrochronology, demonstrated that part of the structures (mostly in the Sredinny range in Kamchatka) originated during the second half of Middle Pleistocene, that is during the Middle Pleistocene glaciation. Furthermore, most of the calderas and ring volcano-tectonic depressions in the eastern volcanic zone of Kamchatka formed during the second half of the upper Pleistocene — 80-40,000 years ago (MELEKESTZEV, 1967).

This synchronism is not accidental, but shows a strict relationship between tectonics and volcanism in the region. The formation of calderas is associated with the final phases of the pleistocenic first volcanic cycle, which led to the formation of consecutive eruptive centers of more and more silicic rocks — from fissure effusions of basalts and large basaltic, andesite-basaltic shield volcanoes to andesitic stratovolcanoes. When the calderas formed, the volcanic activity was characteristic of a more and more acid magmatic material — namely, outbursts of juvenile pyroclastic material (pumices, ignimbrites) with composition corresponding to acid andesite, dacite and liparite-dacite. The volume of the acid pyroclastics which formed during the Middle-Upper Pleistocene in connection with the formation of the calderas, comes to 2,000-2,500 km^3 in the only eastern volcanic zone.

Intense uplifts of the horst-anticlinal zones adjacent to the volcanic belts are related to the phase of formation of the calderas — it is at that time that the Beregovoi and Vostochny mountain ranges formed (BRAITZEVA and MELEKESTZEV, 1966).

Another important geological feature of the Kamchatka calderas is the autonomous development of volcanic centers within them, which do not show any relation with the further evolution of the volcanism in the volcanic area as a whole. As a result, during Upper Pleistocene-Holocene, when massive basaltic and andesite-basaltic effusions occurred all over the volcanic belt marking the beginning of a new volcanic cycle, centers of acid volcanism directly associated with the first volcanic cycle continued to be very active within the calderas and the volcano-tectonic depressions, *i.e.*, outbursts of pumices (7,450 ± 200 years, GIN-320) and effusions of dacitic lavas from the Karymsky volcano; outbursts of pumices, Kurile Lake (8,000 ± 40 years, GIN-207 and 8,340 ± 40 years, GIN-211), and Stübel calderas; the formation of the Diky Greben extrusion; the youngest acid extrusions of the Ichinsky volcano, etc.

The intensity of this activity was less violent than the activity associated with the main stage of formation of the calderas. For instance, the total amount of pumices formed during Holocene does not exceed 40-50 km^3.

The formation of caldera-shaped structures also continued, but on a minor scale.

During this period, calderas representing parts of already existing volcano-tectonic depressions formed (*i.e.* the calderas of the Karymsky volcano and of the north-eastern section of the Kurile Lake depression).

However, despite the autonomy of the post-caldera volcanism, the largest outbursts of pyroclastic material were almost synchronous. As a matter of fact, such as the quoted figures show, most of the pyroclastics are 7,000-8,000 years old. During the same period a general volcanic activity is recorded all over the Circumpacific belt.

A peculiarity of the majority of the calderas and volcano-tectonic depressions of Kamchatka is that they « overlie » the volcanic structures of the pre-caldera phase — as a rule, all the observed calderas are not associated with a single volcano but they truncate many structures of different age and type (Fig. 2). *E.g.*, the scarps of the Krasheninnikov, Uzon, Maly and Bolshoi Semiachik and Opala calderas truncate volcanic structures of Lower to Upper Pleistocene. Among the volcanoes truncated by the faults limiting the calderas, there are stratovolcanoes, shield volcanoes, extrusive domes and volcanic plateaux associated with phenomena of areal volcanism.

There are, finally, cases where the calderas are directly superimposed on dislocated rocks of the pre-Quaternary basement. A most striking example of these structures is the Khangar volcano-tectonic depression, the flanks of which consist of granitic gneisses of problematic (pre-Tertiary, in any case) age.

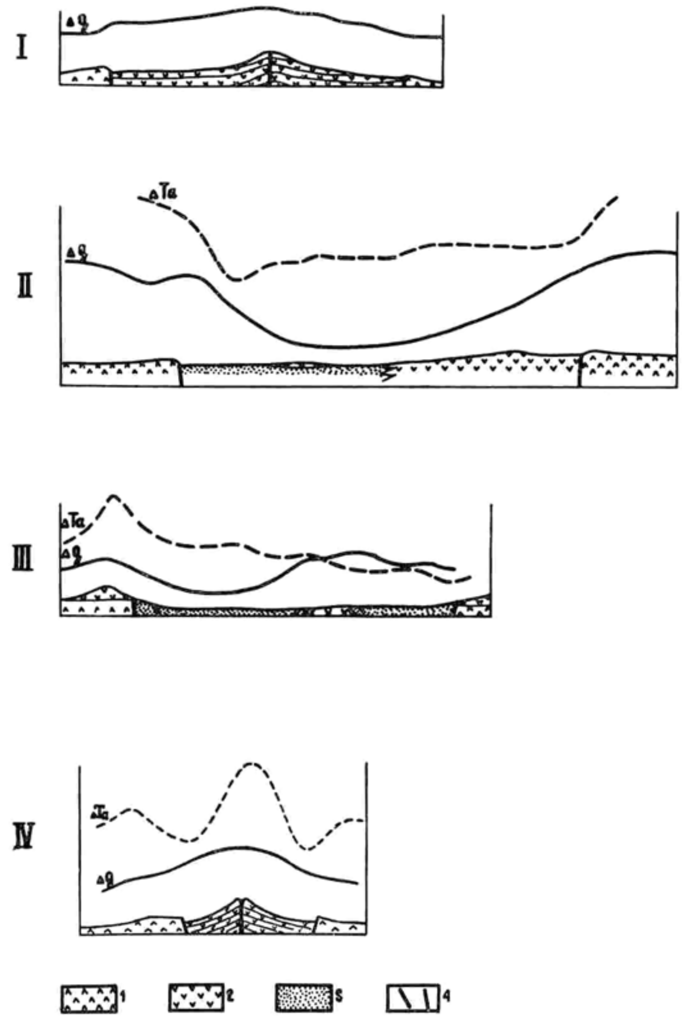

FIG. 3 - Δg and ΔTa diagrams across Krakatau-type calderas.
1: volcanic rocks of upper Pleistocene and Holocene ages; 2: volcanic rocks of lower-middle Pleistocene age; 3: volcano-terrigenous and volcano-sedimentary deposits; 4: volcano-tectonic dislocations.
I: Krasheninnikov caldera; II: Opala caldera; III: Uzon caldera; IV: Karymsky volcano caldera.
Geophysical profiles are shown in Fig. 2.

These facts would indicate a change in type and position of the feeding magmatic chambers of the caldera-phase volcanic cycle as compared with its earlier stages.

The faults limiting the calderas are arcuate and festoonlike. They are normal faults. The fault plane is nearly vertical or dips at a steep angle inside the depression. The apparent throw ranges from tens of meters in the faults of the outer boundaries of the volcano-tectonic depressions to several hundred and even thousand meters in the faults of the Krakatau-type calderas. The morphology of the faults indicates that the area involved was subjected to tensile stresses. Thus the mechanism of formation of these structures is close to that of resurgent cauldrons.

The system of radial fractures and dykes usually accompanying the calderas is another evidence for general tensile conditions.

Petrochemistry of the Rocks Associated with the Calderas

A general petrochemical feature of the pre-caldera volcanic rocks is a high rate of alkali during magma differentiation — the variation curve projected on a plane *asb* in the A. N. Zavaritsky's diagram makes an angle of 22-30°, whereas for the non-caldera volcanoes this angle comes to 7-15°.

The representative points of the ignimbrites associated with the formation of a caldera lie on the extrapolation of this curve. This means that these rocks belong to a normal original basaltic magma differentiation series. The increase in alkalies with differentiation is due to a predominantly larger amount of K_2O.

The rocks of the pre-caldera phase in the regions where the formation of calderas was not accompanied by outbursts of acid pyroclastics and formation of ignimbrites — the volcano-tectonic depression on the South of the Kliuchevskaya group volcanoes, the Uksichan caldera in the Sredinny range — have analogous features.

After the formation of the calderas, two types of volcanism can develop inside them:

In the first case, phenomena of the second volcanic cycle are superimposed on the caldera — this cycle being characteristic of the whole volcanic belt. In this case, the caldera acts passively such as a tectonically favourable site to the settlement of volcanoes whose development does not differ at all from the general evolution trend characteristic of all the volcanoes of that area. Examples can be the basaltic cones in the calderas of the Gorely or Krasheninnikov volcanoes. In calderas of this type and near them there are no phenomena of hydrothermal activity or associated altered rocks.

The second case is characterized by the development inside the caldera or near it of a volcanism with specific features: general reverse cycle of evolution, great role of the gas phase during eruptions, a relatively small amount of alkalies and an accumulation of anorthitic component in the rocks with a general increase in their acidity (ERLICH, 1966*b*). In this case, one can speak of phenomena of a specific post-caldera volcanic stage.

Depending upon the differentiation degree of the melt, the composition of the volcanic rocks of the post-caldera phase can vary from acid andesite to liparite, or even from basalt to liparite. However, in both cases the most basic rocks differ from the rocks normal for that area for a lower alkali content and a higher anorthitic lime and silica contents. In the regions where a specific post-caldera volcanism is developed, there is an intense gas-hydrothermal activity and wide-spread zones with hydrothermally altered rocks.

Relation between Geophysical Data and Geology

It has been established by gravity surveys that the Krakatau-type calderas are characterized everywhere by both positive and negative gravity anomalies (Fig. 3).

The Karymsky volcano positive anomaly almost coincides with the Karymsky caldera. The anomaly is isometric and rather strong. On the basis of geological data an appraisal was made of the gravity effect of the lava masses filling the caldera. The residual anomaly recalculated into the lower semispace showed that the depth of the gravity center of the anomaly-causing bodies is about 4-5 km. Then, it can be assumed that under the Karymsky volcano there is a minor intrusive body feeding the volcano. The kind of magnetic anomaly and the downward recalculation of the field would indicate the presence of a limited body whose top rim is at about 1 km below the sea level (ZUBIN *et al.*, 1969).

The positive anomaly above the Ksudach volcano is very extensive (its position is somewhat excentric in respect to the caldera) and very strong. Direct interpretation methods determine the depth of the gravity center of the anomaly-causing body at about 5-7 km. The positive anomalies above the Krasheninnikov volcano and in the eastern part of the Uzon caldera are not large and do not extend beyond the calderas. One can assume that such anomalies are due to lava masses filling the caldera, and to the protrusion of the basement (Krasheninnikov volcano). The gravity anomaly above the caldera of the Gorely volcano is generally negative and is of a rather complex nature. Such complexity may be explained by the different heights of the blocks of the fractured basement. Depth determination of the anomaly-causing body gives a value of about 2 km.

The negative gravity anomalies above the Opala and Uzon volcanoes (eastern part) can be interpreted as the result of caldera depressions having been filled by relatively light materials.

The above considerations show that the sign of a gravity anomaly has no relevance for the solution of the problem of the genesis of calderas (see, I. YOKOYAMA, 1963). At the same time, even with insufficient geological data, in a number of cases the interpretation of gravimagnetic data can suggest the presence of intrusive masses under the calderas. Everywhere, however, the volume of pyroclastic materials associated with the formation of a caldera exceeds the volume of the mass deficiency computed from the gravity anomalies (200-250 km^3 vs. 160 km^3 for the Gorely volcano; 200-250 km^3 vs. 120 km^3 for the Opala caldera, etc). This fact can indicate a partial compensation of the negative anomalies by bodies of larger density located underneath. The Khangar volcano negative anomaly can be an example of the relation between a Δg minimum and a body of granodioritic composition located below the caldera.

The absence of explosion deposits near the Krakatau-type calderas commensurable with the volume of the caldera cavities, and the presence at the base of the scarps limiting the calderas of ring faults frequently associated with dykes indicate that these type of calderas originated as the result of a collapse. This conclusion is confirmed by the analysis of the type of the movements along the faults and by the fact that with the given energy values, explosion funnels with a diameter major than 7-8 km were impossible to form (ZUBIN *et al.*, 1969).

Calderas of the Hawaiian type have been found on the Dalniaia Ploskaia and the Plosky Tolbachik volcanoes. They were formed during Holocene and are very closely associated with massive effusions of basalt of the second volcanic cycle. Both the Dalniania Ploskaia and

Plosky Tolbachik calderas are concentrically located on the strato-volcanoes formed during the preceding volcanic cycle, but the caldera formation and the nature of the post-caldera volcanoes is in no way connected with the preceding stage of volcanism. Both calderas are associated with linear fracture zones of slag cones and small basaltic lava volcanoes (Fig. 4). In both cases the strike of the fractures turns

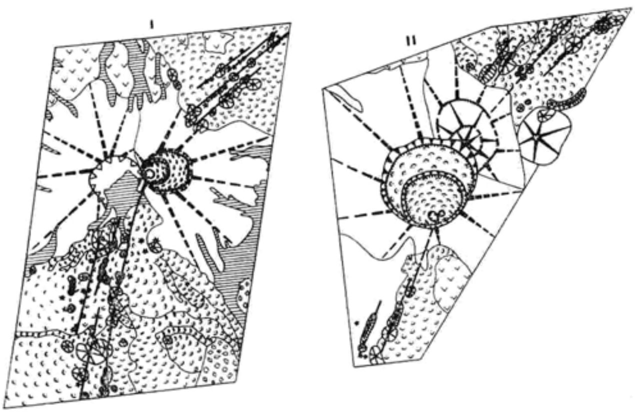

FIG. 4 - Geological sketch maps of Hawaiian-type calderas.
I: Tolbachik volcano caldera; II: Dalnaia Ploskaia sopka volcano caldera. The symbols are the same as in Fig. 2.

sharply after crossing the calderas. The strike of the main fracture (in both cases located on the South of the volcano) coincides with the orientation of the regional fault systems — N-20°NE — whereas the fracture systems located on the North of the calderas have a 40-45°NE orientation, absolutely uncharacteristic of the region.

The gravity anomaly above the Plosky Tolbachik volcano is of a complex nature and, since it was determined by only one profile, its interpretation is difficult. At the height of about 2,000 m the gravity curve reaches its maximum value followed by a sharp drop of its intensity towards the summit of the volcano. The summit caldera is characterized by a general minimum, on the background of which there is a local maximum associated with the present active crater. Most probable is the hypothesis that the caldera reflects the position of a large cylindrical magma column persistently existing in the crust. The injection of this magma and the subsequent outflow of magmatic material as large effusions in the zone of fissure volcanism led to the formation of the Hawaiian-type calderas which can at present be observed [2].

Conclusive Remarks

From the above data a common genesis for the various types of calderas and volcano-tectonic depressions can be inferred. The formation of all these structures is associated with the location in the

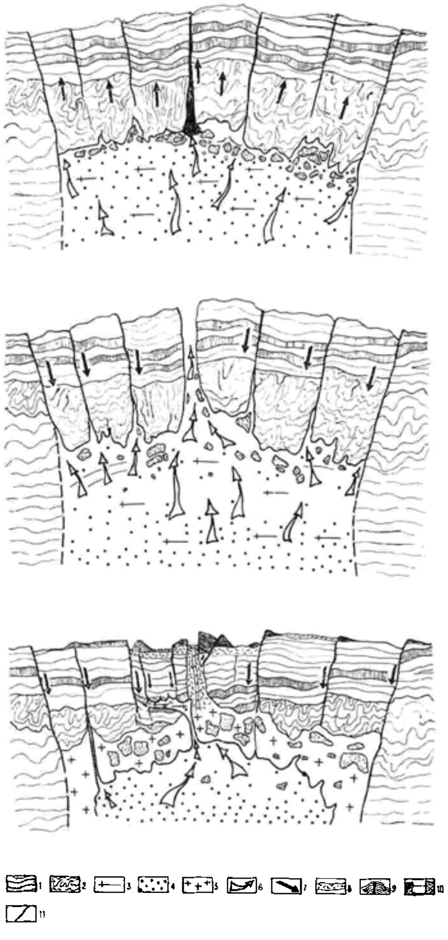

FIG. 5 - Scheme of formation of the Krakatau-type calderas.
1: Complex of volcanic rocks of the cover; 2: complex of folded basement rocks; 3: undifferentiated melt; 4: differentiated melt (density of points is proportional to the magma basicity); 5: solidified contact parts of the peripheral chamber; 6: direction of magma movement; 7: direction of crustal blocks movements; 8: pumices and ignimbrites; 9: post-caldera volcanoes; 10: crater lakes; 11: faults.

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[2] Deep seismic soundings carried out on the Hawaii (FURUMOTO, 1965) have shown that the Hawaiian calderas are a surface evidence of a column of magmatic material whose roots descend into the mantle.

earth's crust of big masses of magmatic material. The subsidence of the caldera floors along boundary ring faults is a reaction to doming strains developing when the intrusive masses are injected and juvenile material is ejected. An additional factor governing the formation of calderas is the emptying of the top part of a magma chamber. A scheme showing how a caldera can form is shown in Fig. 5. The possibility of subsidence ring structures is confirmed by CLOOS (1939), PARKER and MCDAWELL (1951). Relations between calderas and doming have been recorded by WISSER (1964). We would add that domes and caldera subsidences are the surface evidence of a system of ring and conical dykes recorded on eroded volcanoes. The mathematical model of these dyke complexes (ANDERSON, 1936) can fully be applied to the types of structures under discussion.

In conclusion it should be noted that while explosion structures are predominant in the normal island arcs (Kurile, Aleutian Is., etc), the formation of calderas and volcano-tectonic depressions is characteristic of tectonic systems of the type of Kamchatka. The average diameter of calderas in the island arcs of the normal type comes to 2-4 km, their maximum size not exceeding 10 km. In Kamchatka the average diameter of calderas is 8-12 km and the largest volcano-tectonic depressions are 40-60 km in diameter. The caldera-formation stage represents the transition of a volcanic area to the stage of volcano-plutonic development, the number and sizes of calderas being an index of the intensity and scale of the intrusive process.

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