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INTRAOCEANIC ISLANDS, EAST PACIFIC RIDGE, ISLAND ARCS: VOLCANISM AND UPPER MANTLE[1]

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SUMMARY

Two classes of volcanic rocks can be distinguished with respect to petrochemistry, namely oceanic and continental classes. Lavas of island arcs belong to the continental type. Lavas of oceanic ridges are close not to the oceanic, but to the continental type.

On petrochemical and geophysical bases the author has drawn the following conclusions:

(1) the foci of volcano feeding lie beyond the limits of the earth's crust – in the upper mantle.

(2) the composition of the upper mantle under continents, oceans, island arcs and oceanic ridges is somewhat different.

(3) the role of assimilation on the passage of magma to the surface is very limited as a rule.

According to these conclusions, volcanism may be considered as a certain indicator of the composition and state of the upper mantle matter. A scheme for the evolution of volcanism is suggested on this basis (as a reflection of the evolution of the upper mantle) which is in an agreement with geological and geophysical facts.

INTRODUCTION

Two classes of volcanic rocks

The author has submitted his report "Petrochemical characteristics of volcanism in connection with the types of earth's crust" (Gorshkov, 1962) to the preceding session (10th) of the Pacific Science Congress. The concepts of that report were also discussed in the other papers (Gorshkov, 1961a,b, 1962, 1963, 1965). All the work was based on the petrochemical calculations according to A.N. Zavaritsky's system (Zavaritsky, 1954). This very convenient system allows the results of a great number of calculations to be considered simultaneously. However, Zavaritsky's system

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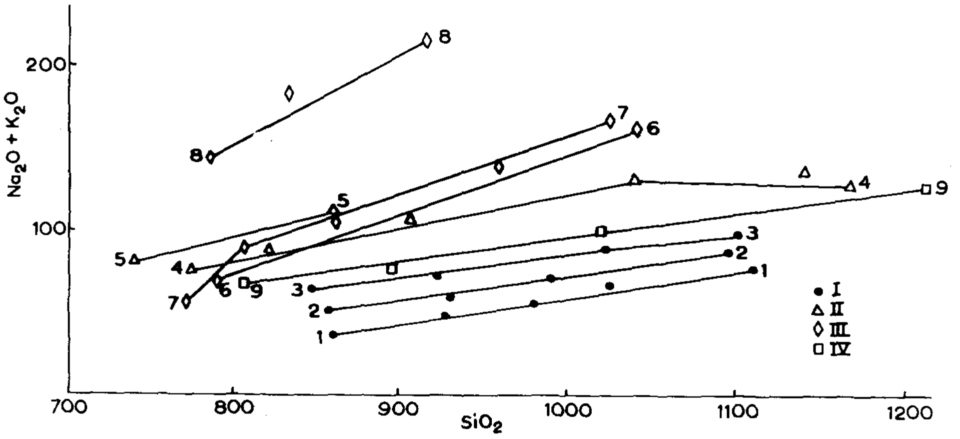

Fig.1 Graph of the relations $Na_2O + K_2O/SiO_2$ in some lavas. *I* = island arcs; *II* = continental lavas; *III* = oceanic lavas; *IV* = East-Pacific Ridge. *1* = Nasu zone (Japan); *2* = east Kamchatka; *3* = middle Kamchatka Ridge; *4* = alkaline lavas of east Asia; *5* = Uyun Kholdonga volcanoes; *6* = Marquesas Islands; *7* = Hawaiian Islands; *8* = Cook's Islands; *9* = Easter Island.

is not commonly known outside the Soviet Union, and the author's conclusions based upon it do not seem to have been completely understandable.

In this report an attempt will be made to elucidate, on the simplest basis, the problems that have been concerned earlier, this basis requiring practically no calculations.

In the previous papers the author has stated that there are two classes of volcanic rocks: the oceanic and continental ones, with the main distinction between them consisting in the rate of the alkalinity increase in the course of their differentiation. Therefore, the discussion of the change in total alkalinity with the change in acidity will be sufficient for this simplified variant. Atomic weights of potassium and sodium being different, it is more convenient to discuss molecular quantities rather than the weight percentage.

Fig.1 represents a graph of the relations $Na_2O + K_2O/SiO_2$ (in molecular quantities) for some islands arcs, continental and oceanic lavas. It can be readily seen that considerable parts of the variational lines of $K + Na/SiO_2$ are rectilinear, and that the straight lines for various island arcs and intracontinental volcanoes are more or less parallel to one another and diffferent in inclination from those for intraoceanic islands, which in their turn, are more or less parallel to each other (excluding Easter Island). It is this circumstance that made the author claim that the lavas of intraoceanic and intracontinental volcanoes constitute two different classes of rocks.

DATA

Petrochemical characteristic of lavas of oceanic ridges

Petrochemical differences of some islands associated with the system of mid-oceanic ridges are of great interest and, from the author's point of view, of high importance. Unfortunately, the scarce analytical data for most of these islands are dated from the very beginning of our century, when the accuracy of chemical analyses was not too high. The author's conclusions are, therefore, of a tentative character.

Lavas of the islands situated directly on the axes of oceanic ridges belong to the continental alkaline (Easter Island, see Fig.1) or calc-alkaline (Iceland) type rather than to the oceanic one. A few analyses which also refer to the continental class available for Saint Paul Island (Indian Ocean).

Lavas of the islands situated 100–200 km apart from the axes of ridges are to a certain degree intermediate in composition between the oceanic and continental ones. (It is evidenced by somewhat obsolete analyses, and new data can modify this notion). Among these are, for instance, the lavas of the Azores with a variational curve passing between the continental and oceanic directions.

Volcanoes of the islands which are still more remote from the axes of mid-oceanic ridges, such as Tristan da Cunha (for new analyses, see Baker et al., 1964), erupt purely oceanic lavas.

Thus, on crossing an oceanic ridge, one seems to encounter a gradual transition from the lavas of an oceanic class to the continental lavas or, anyhow, to the lavas close to the latter. Crossing an ocean-continent boundary or an island arc, one finds an abrupt change in one type of rocks by another. Such an abrupt "jump" can be seen, for example, when going from Guadalupe Island through the Cedros Trench to the coast of the Californian Peninsula.

Geophysical structure of Island arcs and oceanic ridges

The fundamental difference in structure and thickness of the earth's crust of oceans and continents is now well known. The consolidated crust of oceans is 5–8 km thick and consists of a single layer; thickness of the continental crust averages 35 km, the crust being two-layered.

In both cases, at the crust/mantle boundary seismic velocities change sharply, with a "jump", from 6.7–7.0 to 8.1–8.2 km/sec. Further down, these velocities increase monotonously, but at a certain depth in the upper parts of the mantle there is a rather thick layer with seismic velocities decreased again to 7.3–7.5 km/sec (Gutenberg, 1954). This so-called "Gutenberg's layer" of decreased velocities begins at the depth of about 60 km under oceans and about 120 km under continents, extending downward to the depth of 200 km.

Existence of the Gutenberg's layer can, in all probability, be explained in the following way: at proper depths the temperature of material meeting nearly coincides with the real temperatures, that is material being in a state close to the melting point ("asthenospheric layer").

The difference in thickness and position of the asthenospheric layer under oceans and continents shows that these two structures differ in structure of the crust and in structure of upper mantle. This difference extends to the depth of no less than 400 km (Dorman et al., 1960).

Another effect has been recently recognized in the areas of some island arcs. Thus, in the area of the Kurile island arc, the velocity of the longitudinal seismic waves from the base of the crust (about 20 km) to the depth of 70–80 km is less than normal and amounts to 7.7 km/sec. The wave guide or Gutenberg's layer in the upper mantle is either absent or expressed rather indistincly, but at the depths of 60–110 km, and especially of 80–90 km, the absorption of the transverse seismic waves increases strongly (Fedotov, 1965).

Decreased velocities are recognized in the mantle not only in the Kurile Islands, but also in Japan (Usami et al., 1958; Matuzawa et al., 1960; Mikumo et al., 1961), in the Aleutian Islands, in western Canada (Hodgson, 1963), in the volcanic regions of the western U.S.A. (Berg et al., 1960; Pakiser, 1963), in the area of the Tonga Islands, in New Zealand (Eiby, 1958), in the area of New Guinea and the Solomon Islands. There can be little doubt that all the "Pacific ring or fire" is characterized by decreased velocities of the material in the upper mantle.

Everywhere in those regions, the mantle substance immediately below the Mohorovičić discontinuity is distinguished by the velocities of 7.5–7.8 km/sec and by a somewhat decreased density. Such a state of the mantle extends downwards at least over a distance of 100 km, the wave guide or Gutenberg's zone being absent. The zone of decreased velocities of the mantle coincides very distinctly with the zone of recent volcanic activity and does not depend on the nature of the earth's crust.

A somewhat similar pattern can be observed in the areas of mid-oceanic ridges, where a layer with relatively low seismic velocities has been discovered to occur below the Mohorovičić discontinuity. This fact has been recognized for the first time in the Northern Atlantic (Ewing and Ewing, 1959) and then confirmed in other parts of the Mid-Atlantic Ridge as well as in the Pacific and Indian Oceans. There is no doubt that the peculiar structure of the earth's crust and upper mantle is characteristic of the whole system of mid-oceanic ridges. Thickness of the earth's crust is somewhat reduced there as compared with an ocean, amounting to 3.7 km. Seismic velocities in the crust and subcrustal parts of the mantle are also below normal, being 5.8 and 7.3 km/sec respectively.

An increased conductive heat flow is a characteristic of the areas of island arcs and oceanic ridges, the latter being particularly marked by this effect, numerous measurements have shown that a value of heat flow within the narrow zone directly adjacent to the ridge axes is 6–7 times more than an average one (which is rather uniform all through the earth's surface). Such measurements and evaluations are rather rare within the areas of island arcs, but an approximately double value of heat flow is also recognized there.

Thus, island arcs and mid-oceanic ridges have a number of specific features, which make these two main volcanic structures somewhat close to each other. However, the two structures by no means are identical. First of all, their volcanicity is rather similar but not identical. Lavas of the calc alkaline type alone erupt in the areas of island arcs, whereas the alkaline varieties seem to prevail within oceanic ridges, though the calc-alkaline lavas also occur there.

Heat flow in the areas of island arcs does not apparently amount to such high values as are characteristic of oceanic ridges.

The velocities in the subcrustal layer of the mantle have decreased values for both structures but this layer is considerably thinner under oceanic ridges as evidenced by the gravimetric data (Talwani et al., 1965). These decreased velocities are believed to be caused by the peculiar "mixing" of the crust and mantle substances (Cook, 1962). But the term "mantle-crust mix" does not seem satisfactory to the author. It is conceivable that the decreased velocities reflect a peculiar "strained" physico-chemical state of the upper mantle, different from that of the "inert" mantle of other areas.

Reverting to the characteristics of geophysical fields, the sharp difference in the nature of seismicity of island arcs and oceanic ridges should be noted. In the areas of island arcs, earthquakes become deeper in the direction from an ocean to a continent, the strongest and deepest (to 700 km) earthquakes being localized beneath the continent. The areas of oceanic ridges are seismically active too, (unlike the non-seismic parts of an ocean floor), but their seismicity is weaker than that of island arcs, and the depth of earthquakes does not exceed 60 km.

The distribution of gravity anomalies (in Bouguer reduction) is also quite different. A weakly pronounced symmetrical minimum of positive anomalies can be observed above oceanic ridges, the anomalies varying from +400–+450 mgal above an open ocean to +150–+200mgal above a ridge. A more complicated pattern is characteristic of island arcs. The Bouguer anomalies decrease sharply and rapidly from ocean to an island arc and may become negative above a deep trench. Near Puerto Rico, a gradient of anomalies exceeding 500 mgal can be observed over a distance of 100 km. Minor positive and negative anomalies are observed between a deep trench and an island arc, the anomalies above a continent approaching zero ($\pm$ 50 mgal).

It can be seen from the consideration of volcanism, structure of the earth's crust and upper mantle, and geophysical field characteristics that there is more similarity and less difference between oceanic ridges and island arcs than between these structures, on the one hand, and oceanic and continental platforms, on the other.

Evidently, the processes occurring in the upper mantle both under island arcs and oceanic ridges are somewhat similar, though far from being identical.

DISCUSSION

Volcanism and the upper mantle

The concept of a predominant role of contamination and assimilation has until recently unconditionally prevailed in volcanology. Several years ago, the author began to develop an idea of direct connection of volcanic activity with the upper parts of the mantle and slight effect of the crust on the petrochemical characteristics of volcanism.

Some geologists and volcanologists object to such a viewpoint. The supporters of assimilation and contamination for the origin of lava diversity mention the calc-alkaline lavas of island arcs as an example of hybridization. Let us consider from this point of view the Kuril–Kamchatka Arc which is the best investigated as a result of International Geophysical Year work.

Thickness and structure of the earth's crust are rather heterogeneous there. The typically continental crust of Kamchatka and north Kuriles is replaced by the suboceanic crust in central Kuriles, where in the area of Simushir Island the oceanic crust comes closely near to an island arc Galperin and Kosminskaya, 1964). The so-called subcontinental crust appears farther southward. However, in spite of such sharp differences in structure of the crust, all the volcanic rocks, with no exceptions, belong to the same petrochemical type (Gorshkov, 1960). Not only basalt, but also dacitic pumice of Kamchatka and the central and southern Kuriles area of similar chemical and mineral composition, though there are no possibilities of assimilation of acid material in this part of the Kurile Islands. Similar relationships exist in the western part of the Aleutian Islands, while some islands, such as Marianna and Tonga, are situated directly on the oceanic crust, and this circumstance by no means influences their belonging to the "criminal" calc-alkaline type under these conditions.

The nature of volcanic activity and constitutional characteristics of the upper mantle remain to be similar for all the volcanic arcs.

If not at first glance, then after careful consideration, it can be established that volcanism characteristics of other large units, such as oceans, continental platforms, and oceanic ridges, are also independent of the crust.

Everywhere, with very few exceptions, volcanism is a "through-crustal" process. Everywhere, the sources of the feeding of volcanoes are localized beyong the limits of the Earth's crust, in the upper mantle. The composition of volcanic lavas does not depend upon the composition of the rocks of the earth's crust; in other words, the importance of assimilation and contamination is neglible on the upward path of the magma. The lava diversity is caused by the magma itself and processes occurring therein. Thus, volcanic rocks may be considered as a derivative from the substance of the upper mantle. In other words, volcanism is a kind of indicator of the composition and state of the subcrustal parts of the mantle.

Scheme of volcanic evolution and development of the earth's crust

At present it is perhaps premature to draw some concrete conclusions about composition and processes in the mantle proceeding from volcanic phenomena. The elucidated connections are of a too-general character, and further investigations could affect some important postulations to a considerable extent.

In general, it can be said that at present oceanic volcanism can be considered as initial, with a source in the asthenosphere at a depth of about 60 km. A relatively shallow occurrence of the asthenospheric layer gives rise to a wide development of submarine volcanic activity on oceanic platforms.

In certain cases (the cause of which is still not clear) deep-seated differentiation of the mantle substance starts. There are two branches of this process which evolves after the zone-fusion type. When the uppermost parts of the mantle are involved in the process, the crust is not being essentially reworked, and the structures originating in such a case are of the oceanic ridge type. The asthenospheric layer in the upper parts of the mantle appears to be disturbed and the substance of lowered density and decreased seismic velocities "floats" upwards directly to the Mohorovičić discontinuity. Simultaneously, the heat flow increases considerably.

When greater depths are involved in the differentiation process, the structures of an island arc type are originating, the structure of the crust being subsequently reworked from the oceanic type into the continental one. An intramantle asthenospheric layer (or Gutenberg's layer) is disturbed, and the substance with decreased seismic velocities "floats" upwards to the Mohorovičić discontinuity. But in this case, the substance "floats" upwards from the greater depths.

The nature of volcanism changes sharply from the oceanic to the continental calc-alkaline, this processes going on much faster than the rebuilding of the crust and as a result of it a new island arc may originate directly on the oceanic crust. Calc-alkaline lavas go on generating during all the time of deep-seated differentiation. As a rule, the crust is being thoroughly rebuilt at the same time. Gradually dying out, the differentiation process apparently, may continue, after the crust rebuilding has been completed. Anyhow, lavas often retain their calc-alkaline character within the young mountain systems, also. When the phase of the calc-alkaline volcanism is completed, the layer of the "activized" subcrustal mantle disappears, and the upper boundary of asthenosphere "sinks" to the depth of about 120 km, which is characteristic of the continental platform environment. The sour-

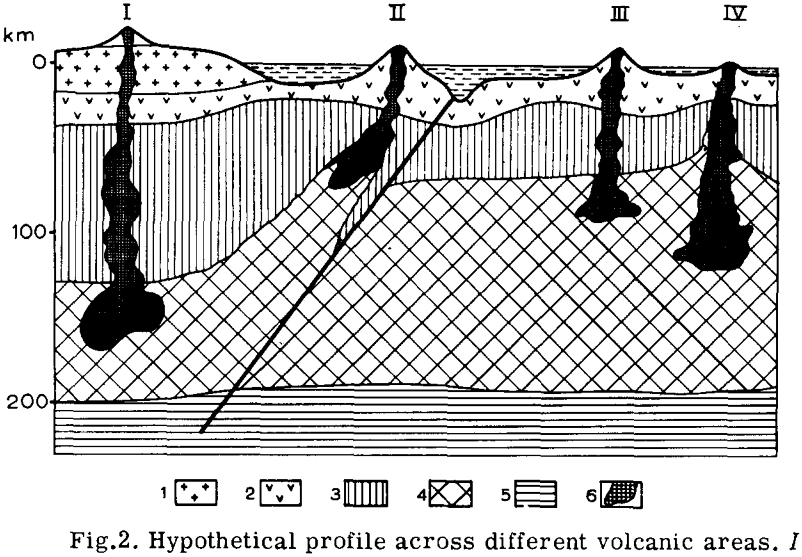

Fig.2. Hypothetical profile across different volcanic areas. *I* = continental volcanoes; *II* = island arcs; *III* = oceanic volcanoes; *IV* = mid-oceanic ridges. *1* = "granite" layer; *2* = "basalt" layer; *3* = subcrustal parts of mantle; *4* = asthenosphere layer (Gutenberg's zone), *5* subasthenosphere layer; *6* = zones of magma generation and volcanic chimneys.

ces of continental volcanism lie much deeper than under the oceans, hence manifestations of continental volcanism are generally weaker.

Judging by the gradual change in space from calc-alkaline lavas to alkaline continental ones, the subcrustal asthenospheric layer of island arcs may gradually turn into the intramantle continental asthenosphere. On the ocean side, the sharp boundary between different types of asthenosphere coincides with the focal plane (Fig.2).

From a petrochemical point of view there is little doubt that the composition of the subcrustal parts of the mantle under the oceans, continents, island arcs, and oceanic ridges have to be different.

The concept of direct relation of volcanism to the upper mantle, and of its "through-crustal" nature of volcanism may be belived to be very promising. The study of volcanism may serve as one of the most powerful instruments to learn about the earth's depths.

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