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2 authors, including:

Sergey L. Senyukov
Kamchatka branch of the Geophysical Service of Russian Academy of Sciences

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On a Seismic Crustal Model for Avacha Volcano, Kamchatka

L. I. GONTOVAYA* and S. L. SENYUKOV**

* *Institute of Volcanic Geology and Geochemistry, Far East Division, Russian Academy of Sciences, Petropavlovsk-Kamchatsky, 683006 Russia*

** *Kamchatkan Experimental Seismological Team, Geophysical Service, Russian Academy of Sciences, Petropavlovsk-Kamchatsky, 683006 Russia*

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Observations of seismic waves from explosions and earthquakes were used to develop a crustal seismic model beneath Avacha Volcano down to a ~20-km depth. Major discontinuities and compressional velocities were determined in the crustal layers. Structural differences were found between the upper and middle crust: steep interfaces and faults, dipping at lower angles further downward, and the variation of elastic and density anomalies. A magma chamber was located at a depth of 12–18 km, and the upper boundary of a peripheral chamber was delineated beneath the volcanic cone. Possible courses for magma migration are indicated.

INTRODUCTION

The Avacha volcanic group is situated at the boundary between the southern and the northern Kamchatka blocks. The area has well-defined transverse fold-block deformations superimposed upon the general northeast trend of the East Kamchatka volcanic belt [6]. The northwest trending features show higher seismicity and a considerable intensity of recent movements (see, e.g., [11], [17]).

The study of the deep structure of lithosphere beneath the active Avacha and Koryakskii volcanoes began in the 1960s and is still underway. The problem is largely related to the predicting possible catastrophic eruptions of the volcanoes which are merely ~30 km distant from the largest cities of the peninsula, Petropavlovsk-Kamchatsky and Elizovo.

Extensive geophysical investigations conducted in the area revealed the regions of abnormal geophysical values, apparently due to magma chambers. These include abnormal seismic wave attenuation in the upper mantle and lower crust based on seismological results [1], [11], [16], [17] and abnormally low electric conductivity in the middle crust [13], [14].

The crust beneath Avacha Volcano is best known from geophysical data, which is primarily due to the easy accessibility of the area (e.g., [2], [8], [10], [18]). It was found that the volcanic edifice stood on the northeastern slope of a depression in the Cretaceous basement; V_P velocities and seismic discontinuities have been determined; a region of higher *P*-wave attenuation was located and delimited beneath the cone, apparently due to a peripheral magma chamber of this volcano (e.g., [2], [3], [4], [5]).

However, many problems related to the deep structure remain unresolved. For example, no data are available for velocities in the middle and lower crust, on relations between surface and deeper features, on the 3-D positions of seismic inhomogeneities, and so on. In this paper we discuss some new results derived from the records of seismic waves produced by explosions and volcanic earthquakes.

SEISMIC STRUCTURE ALONG A REFRACTION LINE

The knowledge of the upper crustal structure beneath the Avacha volcanic cone is largely based on a northeast seismic refraction line shot across the cone [4], [9].

Here we discuss data on deeper crustal structure derived from interpretations of seismic time-distance curves as far as about 80 km from shotpoints 3 and 18 (Fig. 1). The time-distance curves involve considerable observation gaps around the volcanic cone and in the Avacha R. floodplain. The results for middle crust are therefore rather approximate.

It appears from the structure shown in Fig. 1 that the seismic discontinuities have conformable shapes down to 10–15 km depths, the deepest points of the discontinuities being in the Avacha River area. The top of the Cretaceous basement behaves in a more complicated manner. There is a well-defined deep (as deep as 5 km) narrow graben southwest of the volcanic edifice. The V_P velocities are much lower in the graben-filling rocks, and a seismic waveguide was identified at the graben base [4], [9].

The velocity structure shows an obvious difference in seismic discontinuities for the upper and lower crust: a zone of relatively lower velocities in the depth range of 10–25 km lies beneath the volcano, and the "Cretaceous" graben is above the southwestern edge of this zone.

An elastic-density model for the Avacha volcanic group area, based on teleseismic records and 3-D gravity modeling, was derived previously [7], [12]. According to this model, the anomalies in the upper crust trend northwest, while those in the lower crust

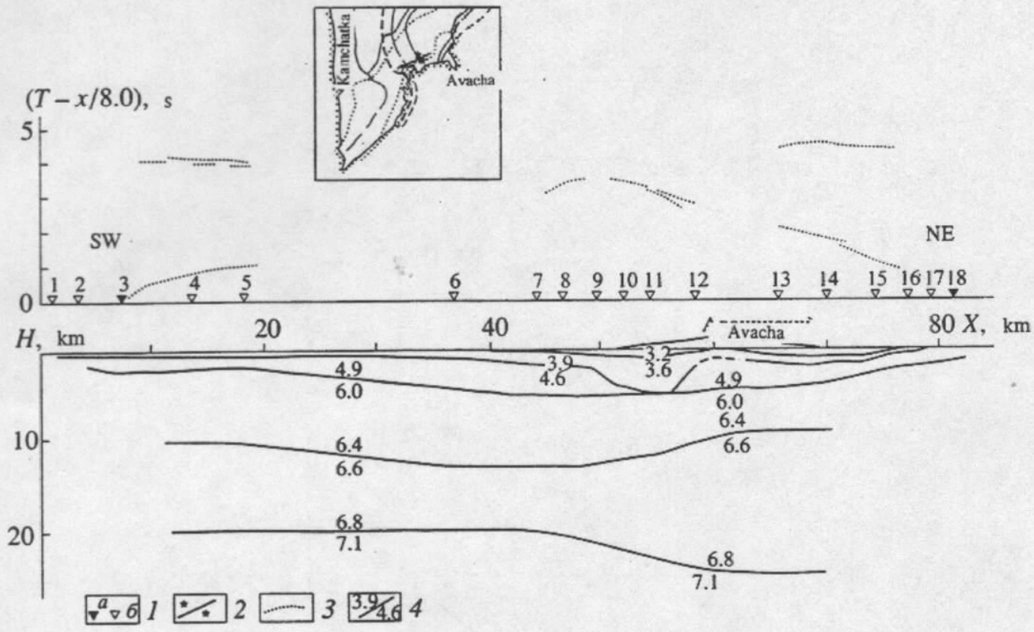

Figure 1 Velocity structure along the refraction line: *1* – shotpoints of time-distance curves shown in this Figure (*a*) and in [4] (*b*); *2* – Avacha volcanic group and the position of the refraction line; *3* – reduced time-distance curves, reduction velocity of 8.0 km/s; *4* – lines of equal velocity and velocity values, the velocity increasing linearly from top to bottom of a layer; *T* is the time as given by the observed time-distance curves.

and possibly in the upper mantle trend mostly northeast (Fig. 2). The results of the interpretations of seismic records of teleseismic earthquakes and explosions consistently show that the features across the East Kamchatka volcanic belt are superimposed.

Figure 3 summarizes the seismic evidence for the upper and middle crustal structure. This cross-section exhibits several features that reflect the dynamics of the processes going on there. Zones of abnormal *P*-wave velocity and attenuation are shown (Fig. 3: *A*, *B*, *C*, and *D*). One can clearly see the positions of reflectors derived from near-vertical reflected waves. The upper crust contains a number of reflectors having the same dip as those in the southwestern depression of the Cretaceous basement. The reflectors become horizontal from a depth of about 10 km downward, and are absent in the depth range of 12–18 km. The lower velocities in this depth range suggest the presence of magma melt in a crustal chamber.

The overall behavior of reflecting interfaces along the seismic line is consistent with the current knowledge of seismic crustal discontinuities. For example, the steeply dipping

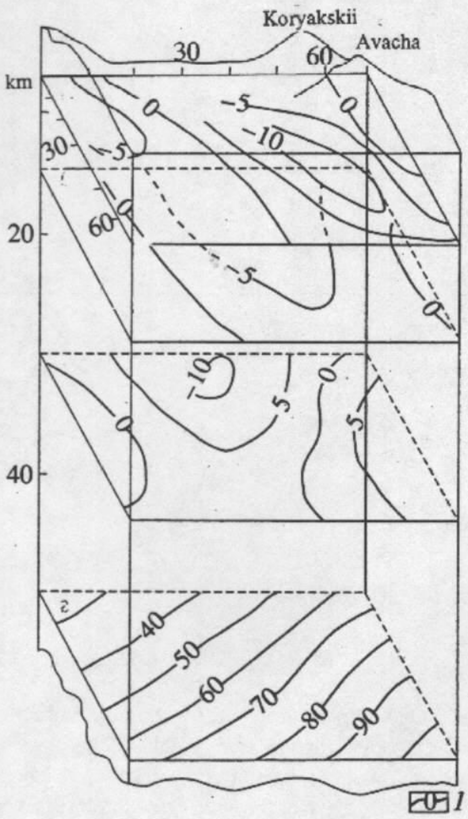

Figure 2 Elastic density model of the Avacha volcanic group area for crustal layers: *a* – 0–7, *b* – 7–15, *c* – 15–30, *d* – 30–50 km; *1* – lines of equal gravity in rel. units.

reflectors and fault zones become horizontal at depths of 10–15 km almost in all regions over the world (young tectonically active regions, cold crystalline shields, etc.). It was postulated that the properties of crustal rocks had been modified and a weakened, highly fractured layer was present in this depth interval [15]. It can therefore be concluded that crustal magma chambers are generated in this layer of a subduction zone.

SEISMICITY OF THE AVACHA VOLCANO AREA

Figure 4 presents the results of the interpretation of the digitized records of volcanic earthquakes made at telemetric stations (AVH, SMA, SDL, UGL) in 1994. Computer

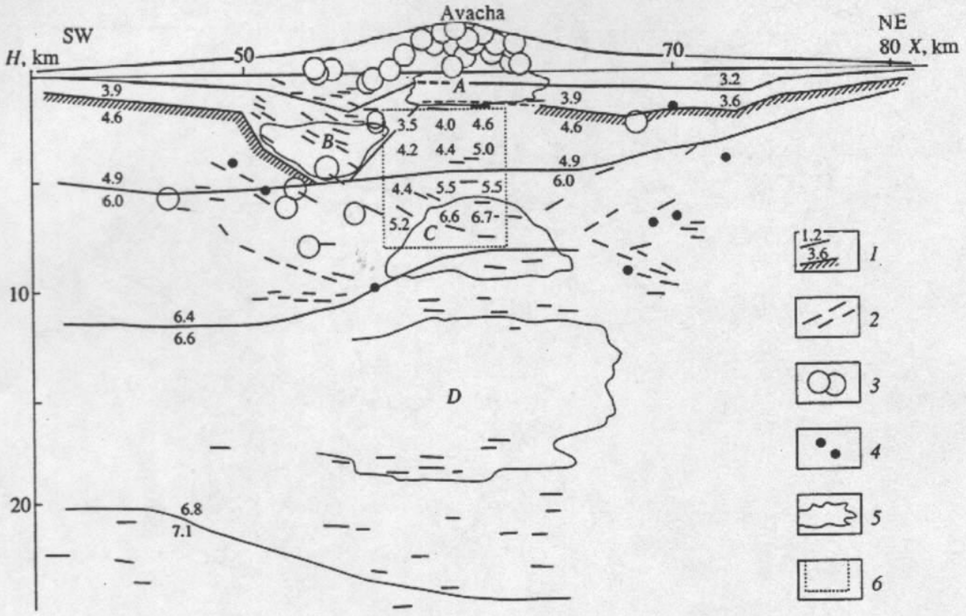

Figure 3 Velocity structure beneath the Avacha volcanic cone: *1* – velocity contours (*a*) and top of Cretaceous basement (*b*); *2* – reflectors; *3* – earthquake hypocenters; *4* – diffraction points; *5* – tentative limits of anomalous zones; *6* – region where V_P velocity was calculated by the tomographic method [9]. For explanations see the text.

processing of the records considerably (by factors of 3–5) enhanced the accuracy of reading *P* and *S* wave arrival times. The hypocenter location for the Koryakskii and Avacha volcanoes was based on two different 1-D velocity structures found by trying many different models. It was found that the deviation in *P* velocity in the Avacha Volcano edifice and in the upper layer could not be in excess of 0.1 km/s, the accuracy of *P* arrival reading being within 0.1 s.

The earthquake epicenters are mapped in Fig. 4. The hypocenters were projected onto the velocity structure described above (Fig. 3). This procedure revealed relations of the seismicity to the tectonics and magma sources in the area, in particular, to a peripheral magma source. It is seen from Fig. 3 that the bulk of tectonic earthquakes occurred above 10 km depth, extending the graben, as it were, down to this depth. This corroborates our inference that the steeply dipping reflectors gradually vanish toward the middle of the crust, and that the Avacha graben is a major crustal fault which is still active. The fault may have served as a channel for magma rising from a crustal chamber. The high velocities beneath the cone at 6–7 km depth seem to be evidence of a cold intrusion there,

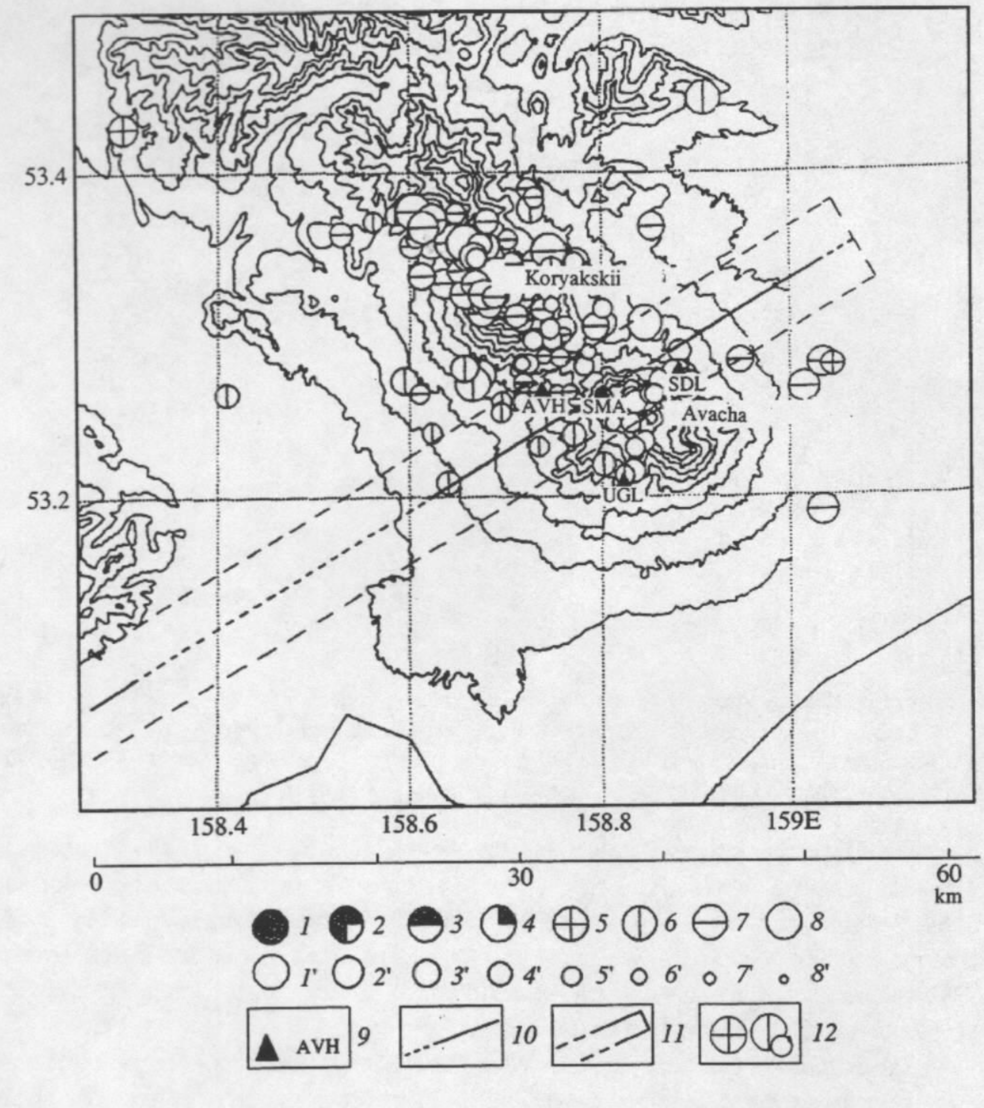

Figure 4 Map of volcanic earthquakes recorded by the Avacha local telemetric network in 1994. Depth (km): *1* – >30; *2* – 25–30; *3* – 20–25; *4* – 15–20; *5* – 10–15; *6* – 5–10; *7* – 0–5; *8* – (−5–0). Energy K_S: *1'* – >6; *2'* – 5.5–6.0; *3'* – 5.0–5.5; *4'* – 4.5–5.0; *5'* – 3.0–4.5; *6'* – 2.0–3.0; *7'* – 1.0–2.0; *8'* – 0–1.0; *9* – seismic station; *10* – seismic line; *11* – area along the line from which earthquakes were used to plot Fig. 3; *12* – earthquake epicenters.

whose top is as high as the bottom of the peripheral chamber (2–3 km below sea level). The top of the chamber can hardly be above sea level where most earthquakes have occurred. The rocks in the chamber are probably enriched in magmatic material. This is confirmed by the considerable attenuation of explosion *P* waves, as well as by the absence of earthquakes directly under the young cone of Avacha Volcano below sea level.

CONCLUSIONS

1. A velocity model was derived for the upper and middle crust along a 80-km seismic refraction line whose northeast segment traverses the Avacha cone. The morphology of crustal seismic discontinuities was determined, in particular, for the Cretaceous and the crystalline basement, as well as for a crustal interface at 10–15 km depth. Differences were discovered between the structural plans of the seismic discontinuities.

2. The behavior of the reflectors based on near-vertical reflections was examined and found to be consistent with the modern geophysical views on the existence of a weakened layer in the middle crust.

3. Regions of abnormal elastic parameters (V_P velocity and attenuation) and seismic discontinuities at various depths beneath the volcano were found to be caused by magma sources in the crust having different states of the matter.

4. The 1994 seismicity on the volcano was found to be related to the tectonics of the area. Magmatic material seems to be rising to the cone from a peripheral magma source. The deeper earthquakes that had been recorded during that year were caused by "living" crustal faults. The deepest fault is confined to the Avacha graben, magma from the crustal chamber probably rising through this channel.

5. It is advisable to continue observation and analysis of *P* and *S* from shallow and deep earthquakes. The expanded digital data base will help determine elastic parameters in the region of hypothetical magma chambers, locate channels through which upper mantle magma rose to the ground surface, and reconstruct the dynamics of the volcano's activity. A solution to this problem is vital for predicting possible catastrophic eruptions.

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