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Seismic activity at Koryakski volcano in 1994: hybrid seismic events and their implications for forecasting volcanic activity

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Abstract

A small swarm of 80 earthquakes was observed beneath Koryakski volcano between March 1 and May 31, 1994. These earthquakes ranged from 0 to 8 km in depth and from −2.0 to 1.5 in magnitude (M_L). The swarm under Koryakski volcano was primarily of volcano–tectonic character although a special type of event has been identified with a small amplitude signal preceding the P-wave onset. These precursory signals had varying durations ranging between a few seconds and a few tens of seconds. The source of the signal invariably coincided with the hypocenter of the subsequent earthquake. The origin of these signals may be conjectured to be magma emplacement into weakened zones, which generated a rupture giving rise to a normal tectonic earthquake. The existence of this kind of signals may indicate magmatic activity under the volcano and provide a method for estimating futher development of volcanic activity.

Keywords: volcano seismicity; hybrid earthquake; volcanic activity prediction

1. Introduction

Koryakski volcano is a classical strato-volcano, 3456 m high, in the Avacha group of volcanoes, located in the southeast of Kamchatka (Russia), 25–30 km from the two main cities of Kamchatka (Petropavlovsk–Kamchatsky and Elizovo) with a total population of about 300 000 people.

Koryakski volcano is an andesitic volcano and is located at the intersection of two fault systems, trending north–west and north–east. Its most intensive volcanic activity took place in the Holocene, 3500–7000 years ago, with its last large eruption about 3500 years ago. Small historic eruptions prove that Koryakski is still active; the most recent weak explosive eruption took place from December 1956 to March 1957. During this eruption a crack about 500 m long formed in the summit part of the cone; the discharge of gas from this crack still remains quite intensive today. The present lengthy period of repose at Koryakski volcano may precede a new stage of explosive activity, similar to that at the nearby Avachinski volcano which produced a catastrophic eruption 30 000 years ago.

Eruptions of andesitic volcanos after long quiet periods are usually preceded by intensive seismic activation. This is due to processes of magma in-

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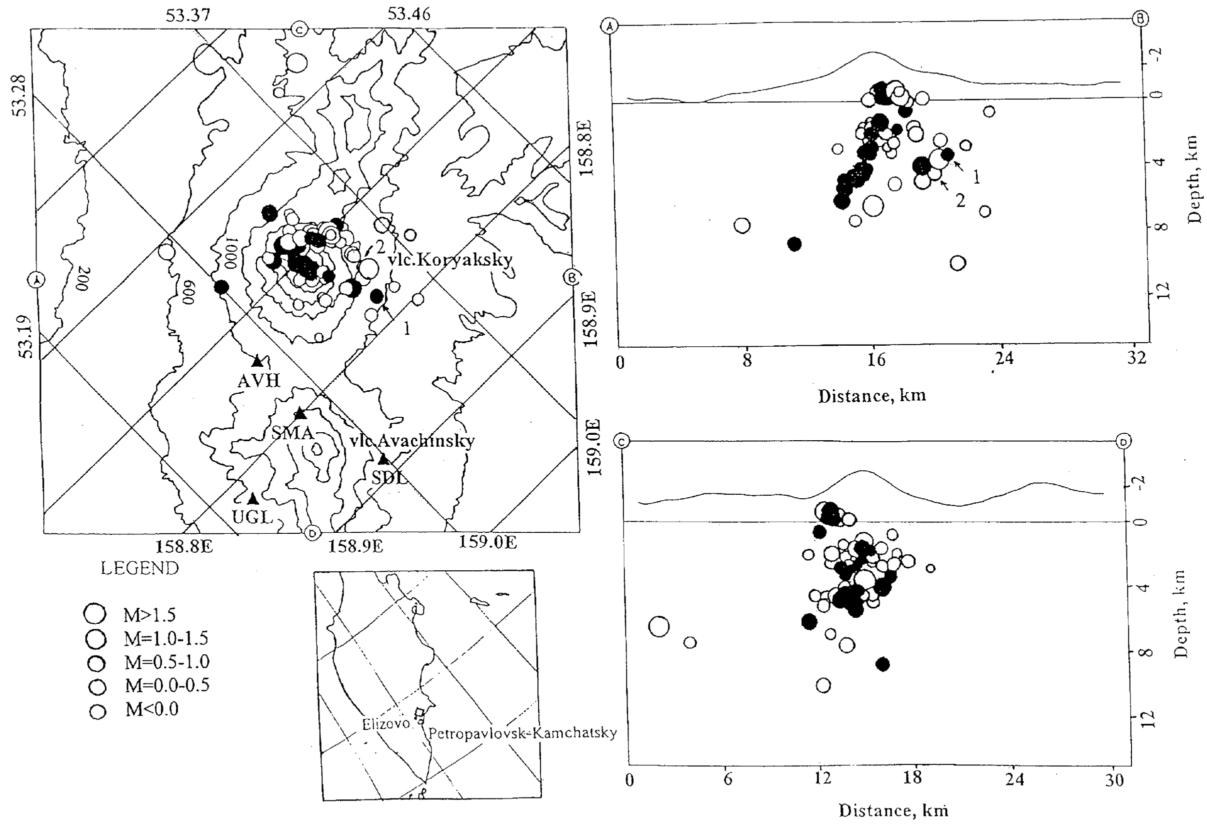

Fig. 1. Epicentral map and cross sections of earthquake hypocenters for the swarm of earthquakes at Koryakski volcano. Triangles mark the sites of seismic stations. The numbers show the locations of an unusual earthquake (1) and a typical earthquake (2) from Fig. 4. Filled circles mark unusual earthquakes. The level contours are shown for every 400 m.

troduction and degassing which lead to rupture within the edifice. Earthquakes generated by this process are referred to as volcano–tectonic (VT) and normally begin months, and sometimes years, before the eruption. Recent eruptions of the volcanoes Redoubt (Alaska, USA), Spurr (Alaska, USA), Tokachi–dake (Hokkaido, Japan), and St. Helens (Cascade mountains, USA) (Power et al., 1994; Power et al., 1995; Okada et al., 1990; Malone, 1983) have shown typical development of seismicity before eruptions. A similar development of seismic activity was observed in Kamchatka before the catastrophic eruptions of the Bezymyanny volcano in 1956 and Shiveluch in 1964 (Tokarev, 1981).

The presence of a local seismic network, established near the Avacha group of volcanoes at the end of 1992, allowed us to record and study the microseismicity of the Avachinski and Koryakski volcanoes. A swarm of VT earthquakes with hypocenters not deeper than 8 km began in early March 1994 under the cone of Koryakski volcano. By mid-May of 1994 the number of earthquakes drastically decreased without any subsequent volcanic activity. Though the swarm of VT earthquakes at Koryakski did not result in an eruption, detailed analysis of the sequence can help us to assess future eruptive hazards and seismicity at Koryakski.

2. Spatial and temporal characteristics of the swarm of VT earthquakes

The network of seismic stations around the Avacha group of volcanoes consisted of four

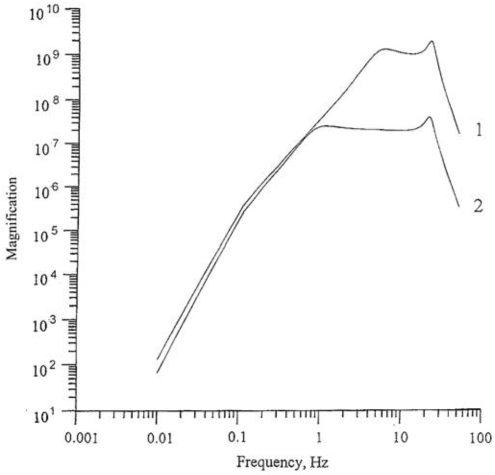

Fig. 2. Frequency responses for the velocity of the high-frequency, high-sensitivity (1) and standard (2) seismic channels.

three-component seismic stations (AVH, SDL, SMA, UGL) (Fig. 1), each of which was also equipped with a high-frequency, high-sensitivity vertical channel. The frequency responses of high-frequency, high-sensitivity and standard channels are shown in Fig. 2. The seismic acquisition system is analog with total dynamic range 54 dB and all records were digitized with a sampling rate of 50 Hz. The earthquake locations were determined using a velocity model determined by a seismic refraction study of the Avacha group of volcanoes (Gontovaya et al., 1990). The model was constructed of layers with differing velocity gradients, with velocity increasing from the upper to the lower boundary of each layer. The seismic network located earthquakes from the swarm with an accuracy no worse than 1 km in depth and surface coordinates. The epicentral map and cross sections of earthquake hypocenters are shown in Fig. 1.

The hypocenters are suggestive of a planar structure under Koryakski volcano (Fig. 1). The swarm of earthquakes under Koryakski volcano began on March 1, 1994, and ended in the middle of May (Fig. 3). The total number of earthquakes in the swarm was about 80. The entire magnitude range in the swarm was from −2.0 to 1.5. The distribution of earthquakes with depth was close to uniform, covering the whole range of depths from 0 to 8 km (Fig. 3). The largest (M = 1.5) earthquakes in the swarm took place in the middle and end of the sequence. No peculiarities in the rate of energy release or in the number of events per day was noted.

3. Hybrid earthquakes and their parameters

About one third of all earthquakes within the swarm had an unusual signal before the P-wave onset. The duration of this signal varied for different earthquakes from several seconds to tens of seconds. The level of the precursory signal remained practically constant over its entire duration, and had an amplitude approximately 20 times smaller than that of the main signal (P-wave) amplitude. Examples of signals from one of these unusual earthquakes (No. 1, Fig. 1), and of a normal VT earthquake (No. 2, Fig. 1), recorded on the high-frequency, high-sensitivity channel (vertical component) and on the standard horizontal channel are shown in Fig. 4. The phase identifications were made from three-component records. Both earthquakes happened at almost the same time (Fig. 3) and were about 9 km dis-

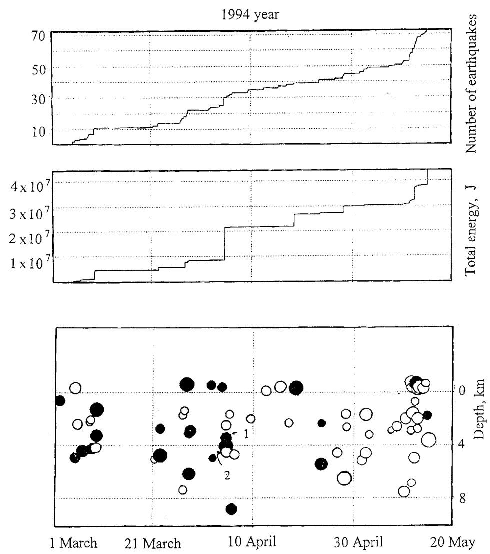

Fig. 3. Temporal parameters of development for the swarm of earthquakes. Filled circles mark unusual earthquakes. The numbers show the locations of the unusual (1) and typical (2) earthquakes from Fig. 4.

tant from the seismic station (Fig. 1). The duration of each precursory signal for event No. 1 (see Figs. 1 and 3) at various seismic stations is the same (Fig. 5). The location of the source of the precursory signal, which was calculated from the onset of this signal at different seismic stations, coincides with the location of the VT earthquake, which was calculated from the P-wave onset. It is evident that the signal before the P-wave onset is real, since it is several times higher than the usual microseismic noise at the recording site, and scales in time between the recording site and earthquake location. A map of epicenters and

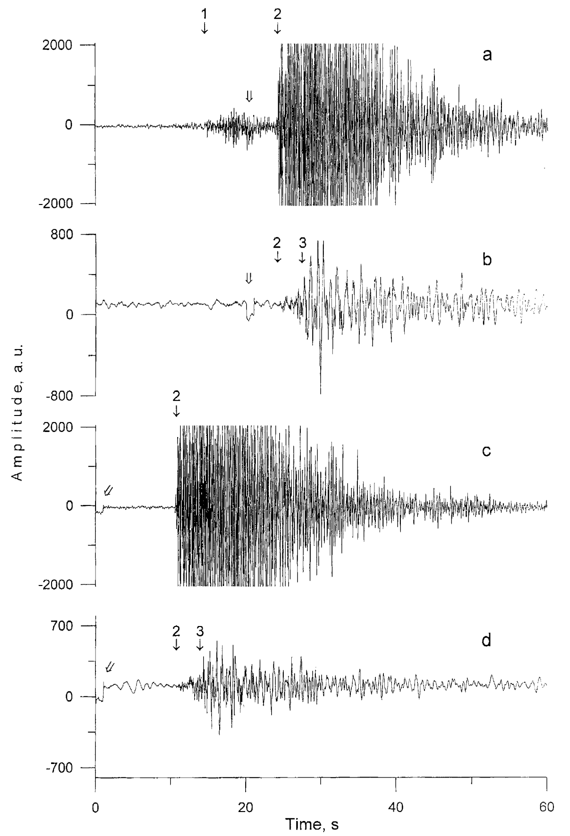

Fig. 4. Examples of an earthquake (No. 1, Fig. 1) with a precursory signal (a,b) and one (No. 2, Fig. 1) without a precursory signal (c,d) at seismic station AVH, recorded by a high-frequency vertical channel (a,c) or a standard horizontal (EW) channel (b,d). The numbers indicate: 1, onset of precursory signal; 2, onset of P-wave; 3, onset of S-wave. The hypocentral distance for the unusual earthquake is 9.0 km, that for the typical earthquake is 9.5 km. Double arrows show minute marks.

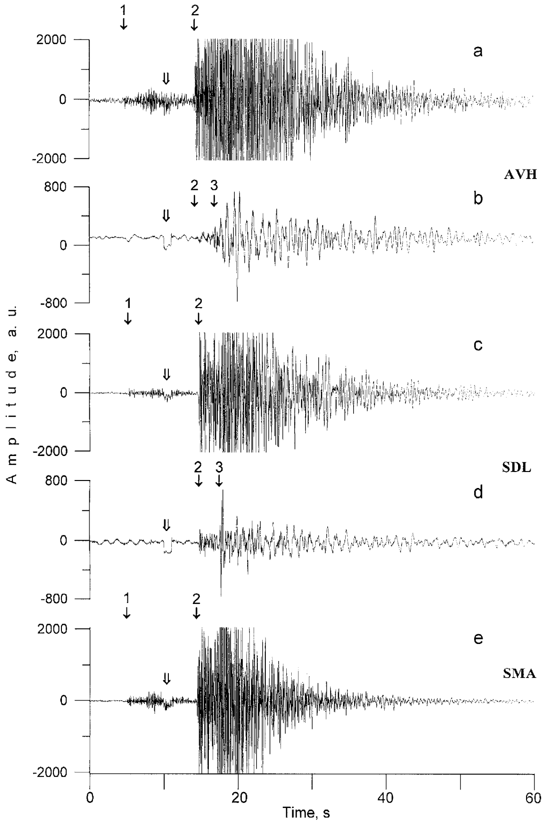

Fig. 5. Examples of unusual earthquakes (No. 1, Fig. 1) at different seismic stations: AVH, high-frequency vertical channel (a); AVH, standard horizontal (EW) channel (b); SDL, high-frequency vertical channel (c); SDL, standard horizontal (EW) channel (d); SMA, high-frequency vertical channel (e). Numbers correspond to: 1, onset of precursory signal; 2, onset of P-wave; 3, onset of S-wave. The hypocentral distance for the AVH station is 9.0 km, that for the SMA 9.8 km, and that for SDL 10.5 km. Double arrows show minute marks.

cross sections of hypocentral locations of the unusual precursor signal earthquakes (filled circles) is shown in Fig. 1. One can clearly observe that the hypocenter locations form a planar structure stretching from depth up to sea level.

At the beginning of the swarm (March 1–20) earthquakes with precursory phases exceeded 50% of the total activity, from March 20 to April 10 about 50%, from April 10 to 30 less than 20% and about 7% at the end of the swarm (April 30 through May 15) (Fig. 3). This could be explained by the fact that magma was actively introduced

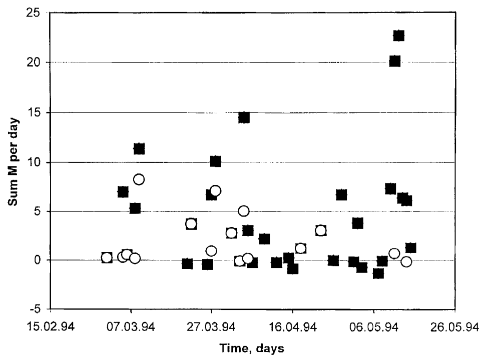

Fig. 6. Temporal dependence of a total energy for typical (black square) and unusual (open circle) earthquakes.

within the first half of the swarm, but then stopped. A similar correspondence can be observed between the magnitudes of the unusual and normal VT earthquakes. The magnitudes were calculated from coda-wave durations for

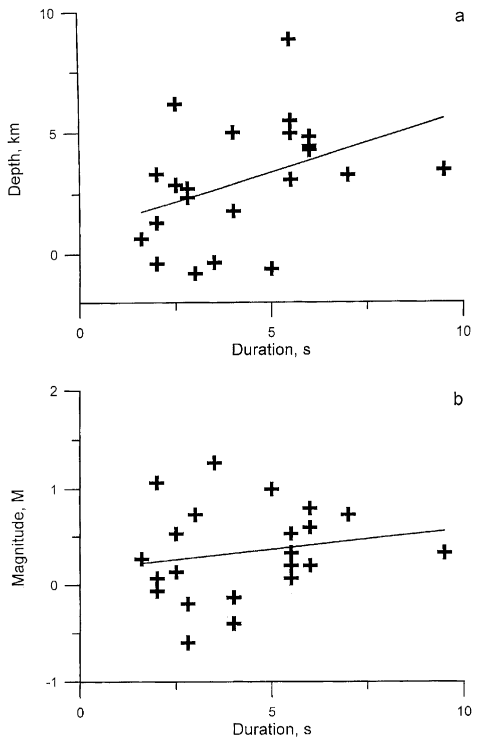

Fig. 7. Dependence of duration of the precursory signals for unusual earthquakes. (a) On depth (regression coefficient 0.47; coefficient of correlation 0.39). (b) On magnitude (regression coefficient 0.042; coefficient of correlation 0.18).

the unusual and normal earthquakes. Temporal plots of the sum of magnitudes per day for both types of earthquakes are shown in Fig. 6. It is clear that the unusual earthquakes show a steady tendency of energy release reduction, whereas for the normal earthquakes one can note some increase of energy release at the end of the swarm.

The range of depths for the unusual earthquakes coincides with the range for the normal earthquakes, from sea level to 8 km deep (Fig. 3). No change of earthquake depth with time was noted, even though the lithostatic pressure in the media varies considerably over the depth of 1–10 km (from 0.3 up to 3 kbar).

The most convenient parameter of the precur-

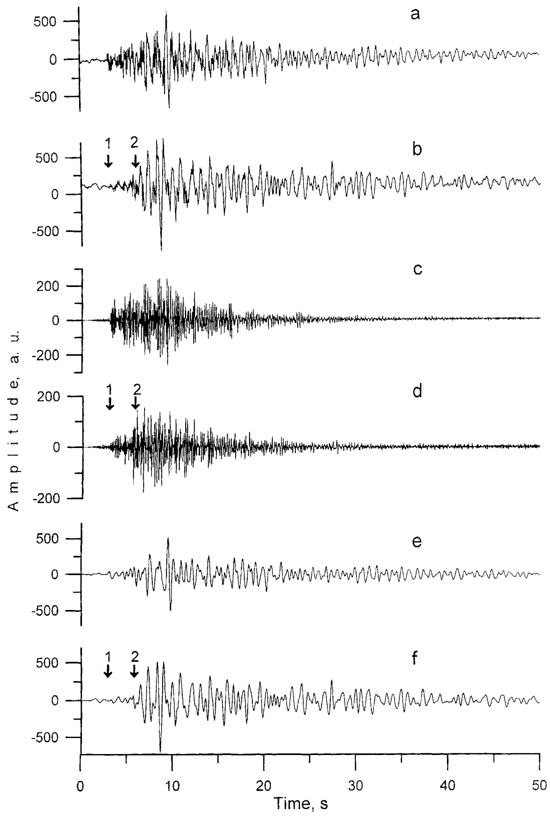

Fig. 8. Examples of an unusual earthquake (AVH, No. 1) at vertical standard channel (a) and horizontal (EW) standard channel (b). High-frequency filtering part (4–25 Hz) at vertical channel (c) and horizontal (EW) channel (d). Low-frequency filtering part (0.04–4 Hz) at vertical (e) and horizontal (EW) (f) channels. Numbers indicate: 1, onset of P-wave; 2, onset of S-wave.

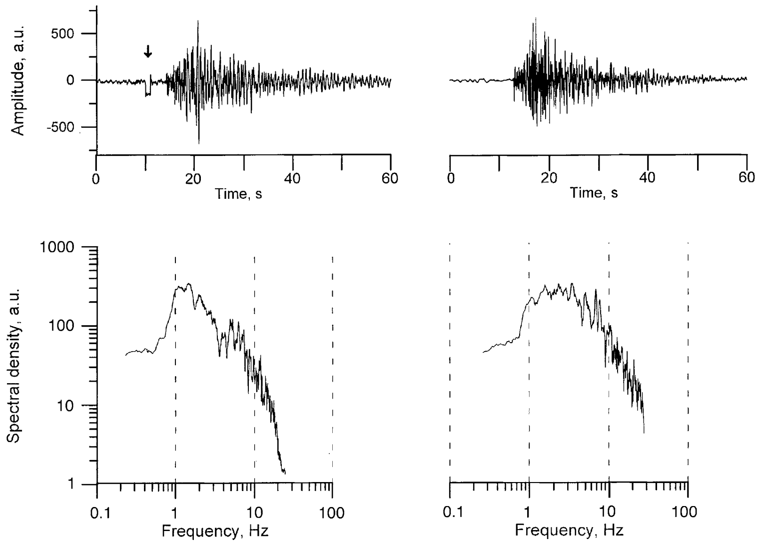

Fig. 9. Record (vertical standard channel) and spectra of the unusual earthquake (AVH, No. 1) (left) and a typical VT earthquake (right) with the same hypocentral distance. Arrows show minute marks.

sory signals is their duration, since it can be related to the energy of the signal with very similar station–source distance. Dependence of duration of the precursory signals on depth is shown in Fig. 7. It is possible to note some increase of signal length with depth, although this dependence has a large scatter, which is probably connected with the non-uniformity of the media and the significant role the fault plays in magma intrusion.

The dependence between duration of a precursory signal and magnitude of the main signal for unusual earthquakes (Fig. 7) was also considered. Here, the absence of any significant dependence is obvious, also with a large scatter.

The precursory signals at Koryakski volcano were easily recognized due to the high-frequency and high-sensitivity seismic channel available at all seismic stations near the Avacha group of volcanoes. The same earthquakes recorded at seismic stations AVH, SDL and SMA on the standard components and the high-frequency, high-sensitivity vertical channels is shown in Fig. 5. The record on the standard channels differs from that on the high-frequency, high-sensitivity channels. The intensive low-frequency signal on the standard channel corresponds to a typical low-frequency volcanic earthquake. In its initial part it is possible to single out a high-frequency component of the signal which, after filtering, represents a normal VT earthquake. An example of high-frequency (4–25 Hz) and low-frequency (0.04–4 Hz) earthquake components separated by filtering is given in Fig. 8. The ranges of the filtering were chosen by comparing the spectra of unusual and normal VT earthquakes (Fig. 9). In the spectra of unusual earthquakes there is an increase of the high-frequency (higher than 4 Hz) part, which can be produced by a different process.

4. Discussion

The difference between two filtered components (Fig. 8) allows us to anticipate their various origins. The high-frequency component corresponds perfectly to a normal VT earthquake, while the low-frequency component corresponds to the low-frequency volcanic earthquake (Fig. 8). Similar records of volcanic earthquakes (high-frequency beginning and low-frequency subsequent record) have been found at many volcanoes and are named 'hybrid earthquakes' (Chouet, 1996). Such earthquakes frequently occur at the initial stage of activation of a volcano. Usually they precede the explosive activity of volcanoes. It is presumed that hybrid earthquakes represent a superposition of two events of differing nature: (1) a normal VT earthquake caused by growth of a crack due to critical stress caused by magmatic overpressure, and (2) low-frequency volumetric vibrations of a gas-saturated magma, excited by an elastic reaction of the surrounding media arising due to crack growth. Such processes can exist only in systems where magma volumes are in contact with the surrounding elastic media. Critical stress within an elastic medium that is not in direct contact with gas-saturated magma creates normal VT earthquakes with a dominant frequency of 8–10 Hz.

The unique feature of the unusual earthquakes recorded in the swarm at Koryakski volcano is the presence of precursory weak signals of various durations. Such signals have never been observed before. It is quite possible that such signals are typical of the impact of overpressure of the gas saturated magma on the surrounding media and their detection can only occur at recording sites with very low noise, high gain instruments. The installation of a special seismometric channel or high-frequency filtering of the original broadband signal can give information on the processes inside the volcanic structure related to magma activity. This can help to predict the evolution of eruptive activity. The presence of hybrid and low-frequency earthquakes is considered to be a reliable measure of volcanic activity. Low-frequency and hybrid earthquakes were detected before the eruptions of the volcanoes Meyakan–dake (Japan) in 1987 (Coordinating Committee on Prediction of Volcanic Eruptions, 1988), Redoubt (Alaska) in 1989–1990 (Power et al., 1994), Pinatubo (Philippines) in 1991 (Pinatubo Volcano Observatory Team, 1991), Spurr (Alaska) in 1992 (Power et al., 1995), and also before many eruptions of other volcanoes (Fehler and Chouet, 1982; Malone, 1983; Koyanagi et al., 1987; Okada et al., 1990).

5. Conclusions

The 1994 initiation of VT seismicity at Koryakski volcano after a long period of calm may indicate its awakening. Unusual earthquakes with precursory signals of various durations (from several seconds to tens of seconds) were detected among VT earthquakes of Koryakski volcano. These signals were observed only in hybrid earthquakes, and can be explained qualitatively by the introduction of magma into new cracks with the subsequent development of a fault, which generates a normal tectonic earthquake. Existence of such precursory signals can be considered evidence of magma activity. The decrease of energy and number of unusual earthquakes in the second half of the Koryakski volcano earthquakes may be due to decreased magmatic activity, indicating that the magmatic energy was insufficient to cause an eruption. The detailed analysis of volcanic earthquakes may be a reliable method for the assessment of developing volcanic activity and forecasting eruptive behavior.

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