Explosive Volcanism of Kamchatka

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Abstract

This manuscript is a review of a great number of publications devoting to the explosive volcanism of Kamchatka (Russia), both modern and Quaternary. Detailed data on different fields of investigations are presented. The data on the main volcanic zones, their productivity, areas covered with Quaternary volcanic deposits, hazard for population and economy are discussed. Peculiarities of volcanic belts, main tectonic conceptions on origin of the Kamchatka volcanism, association with seismicity are reviewed. Volcanic production rate of Kamchatka is estimated and compared with that of Japan and the other areas of the world. We also give main quantitative parameters of active volcanoes, calderas and big explosive craters, particularly historic ones. We present data on the strong explosive eruptions in the last 10 years, including paroxysmal eruption of the Klyuchevskoy volcano of 1994. We describe the growth of huge andesitic lava domes in the Shiveluch and Bezymianny volcanoes. Information on a unique phenomenon - simultaneous eruption started in 1996 in the Karymsky volcanic center is cited. One of these eruptions happened in the old caldera filled with a deep lake and caused an ecological catastrophe in the lake.

1. Cenozoic Volcanism of Kamchatka

The peninsula of Kamchatka is an area of old and intensive modern volcanism. About 240 polygenetic and over 2000 monogenetic Quaternary volcanoes (small cinder and lava cones, extrusive domes, explosive craters, maars and ignimbrite sheets) are found here. Presently, 28 volcanoes are active (Fig. 1). Kamchatka volcanoes are part of the "Pacific ring of fire" of which 380 volcanoes are presently active. Kamchatka is a link of this chain, comprising only 2% of the general length of the "fire ring" . Nevertheless, it includes about 8% of overall number of volcanoes in the "fire ring" (Guschenko 1979: 473pp, Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp). Kamchatka volcanoes are more productive than those of Kurile Islands and Japan. Located here is one of the world largest magmatic centers - Klyuchevskaya group of

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Fig. 1. Volcanoes of Kamchatka (space view from the south):
The Eastern volcanic belt:
Northern Kamchatka:
1-Shiveluch *, 2-Klyuchevskoy *, 3-Kamen, 4-Bezymianny *, 5-Ushkovsky *, 6-Plosky Tolbachik *, 7-New Tolbachik volcanoes
Eastern Kamchatka:
8-Kizimen *, 9-Gamchen *, 10-Komarov *, 11-Kronotsky *, 12-Krasheninnikov *, 13-Kikhpinich *, 14-Valley of Geysers, 15- Uzon Caldera *, 16-Bolshoi Semyachik volcanic massif *, 17-Maly Semyachik *, 18-Karymsky *, 19-Zhupanovskiye Vostryaki, 20-Zhupanovsky *, 21-Dsenzursky *, 22-Arik and Aag, 23-Koryaksky *, 24-Avachinsky *, 25-Kozelsky, 39-Bakening
Southern Kamchatka:
26-Vilyuchinsky, 27-Mutnovsky *, 28-Gorely *, 29-Asacha, 30-Khodutka, 31-Ksudach *, 32-Zheltovsky *, 33-Iliyinsky *, 34-Kambalny *, 35-Koshelev
Volcanic massif *
36-Pauzhetka, 40-Tolmachev, 41-Opala *, 42-Bolshaya Ipelka, 43-Malaya Ipelka
The Sredinny (Median) volcanic belt:
37-Ichinsky *, 38-Khangar
Note: * - active volcano (in historical time)

volcanoes with the Klyuchevskoy volcano about 4,800 m in height. About 60 million tons of basalt was erupted per year. It is 2.5% of the volcanic rocks ejected by all 850 active volcanoes of the world. It is 35 times more than the average productivity of a terrestrial volcano (Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp). The composition of the products ejected by Kamchatka volcanoes are: basalt, basaltic andesite, andesite and dacite. The volcanoes also eject a great amount of gaseous and liquid products.

Kamchatka has two Neogene-Quaternary volcanic belts: the Eastern volcanic belt and the volcanic belt of the Sredinny (Median) range, which extend in the north-eastern direction for a distance of 850 and 450 km, respectively (Figs. 1 and 2). Presently active Eastern volcanic belt contains 27 active volcanoes and about 100 polygenetic and from 1000 to 1100 monogenetic volcanoes of Quaternary age. The total volume of volcanic products ejected during the Quaternary (about one million years) is estimated to be about 16,000 km^3, the area covered is about 50,000 km^2 (Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp).

Volcanic activity in the Sredinny (Median) range ceased a few thousand or hundred years ago. Nowadays solfatara activity is only observed on the Ichinsky volcano, which on this base is considered to be an active one. It is interesting that not long ago this belt was very active. In Quaternary almost 120 polygenetic and about 1,000 monogenetic volcanoes occurred here. The total amount of the Quaternary volcanic products is about 6,000 km^3; the area covered is about 19,000 km^2 (Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp).

Based on the age of volcanoes and on the composition of erupted products, the Eastern volcanic belt is divided into three volcanic zones: Northern Kamchatka, Eastern Kamchatka and Southern Kamchatka (Fig. 1). Volcanic belts and their zones were not simultaneously active: much earlier the Sredinny (Median) volcanic belt and the South Kamchatka volcanic zone were formed, where the Miocene, Pliocene and Quaternary cycles of activity were established. Later in the Pliocene, volcanoes formed in the Eastern Kamchatka, where the activity was continuing during the Quaternary and until the present. More recently (in the Quaternary), the volcanic activity has manifested itself in the Northern Kamchatka and is continuing here now (Kozhemyaka 1995: 581-594, 1996: 621-636).

The location of the Quaternary volcanoes within the volcanic belts of Kamchatka reflects the latest stage of their evolution. For example, the concentration of volcanism in its axial zones, widely developed caldera building and focussing of volcanic activity in separate zones (so called "long-lived volcanic centers") (Masurenkov 1980: 34-49, Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp). Some of these centers are distinguished in the Eastern and Southern volcanic belts of Kamchatka (Masurenkov 1980: 34-49, Kozhemyaka 1995: 581-594, 1996: 621-636).

All hazardous eruptions of volcanoes in Kamchatka, moderate and small eruptions of the Northern

Fig. 3. Two active volcanoes: the Koryaksky (to the left) and the Avachinsky (to the right), are located at a distance of about 25 km from Petropavlovsk-Kamchatsky populated by about 200,000 peoples. Photo by N.P.Smelov.

group of volcanoes - Shiveluch, Klyuchevskoy, Bezymianny, Tolbachik; volcanoes of the Avachinskaya group - Avachinsky, Koryaksky (Fig. 3) and volcanoes in the area of Mutnovskaya Geothermal power plant - Koshelevsky and Kambalny, expose population of Kamchatka and its industry to a danger.

Every day about 200 international wide - body jet aircraft carrying about 20,000 people and million dollar of air cargo fly along the eastern coast of Kamchatka. Ash clouds produced during strong explosive eruptions of Kamchatka volcanoes may be an extreme hazard for the airfreights (Miller and Kirianov 1995: 88-89).

2. Seismicity and Volcanism of the Northern Sector of the Kurile-Kamchatka Island Arc

The peninsula of Kamchatka is the northern link of the Kurile-Kamchatka island arc, which is 2,000 km in length. Kamchatka lies in the transition zone between the Pacific Ocean and Asian continent. The following main morphostructure elements are distinguished here: deep-sea trench of Kamchatka, Wadachi-Benioff seismofocal zone, Kamchatka island arc, where volcanism was manifested from the Early Cretaceous, and also the Okhotsk sea (Avdeiko 1998:77, Seliverstov, 1998) (Fig. 2). Seismicity is closely connected with volcanism: seismofocal zone starts from the deep-sea trench, first goes parallel to the earth's surface, and then sinks beneath Kamchatka with angle of about 50° to the depths of about 600 km. The volcanoes of the eastern volcanic belt are projected to the depths of 125-175 km of middle surface of the seismofocal zone and to the depths of 100-150 km of its upper margin (Fig. 4). It is significant that the andesitic volcanoes are projected to the shallower depths as compared to the basaltic ones (Fedotov et al.

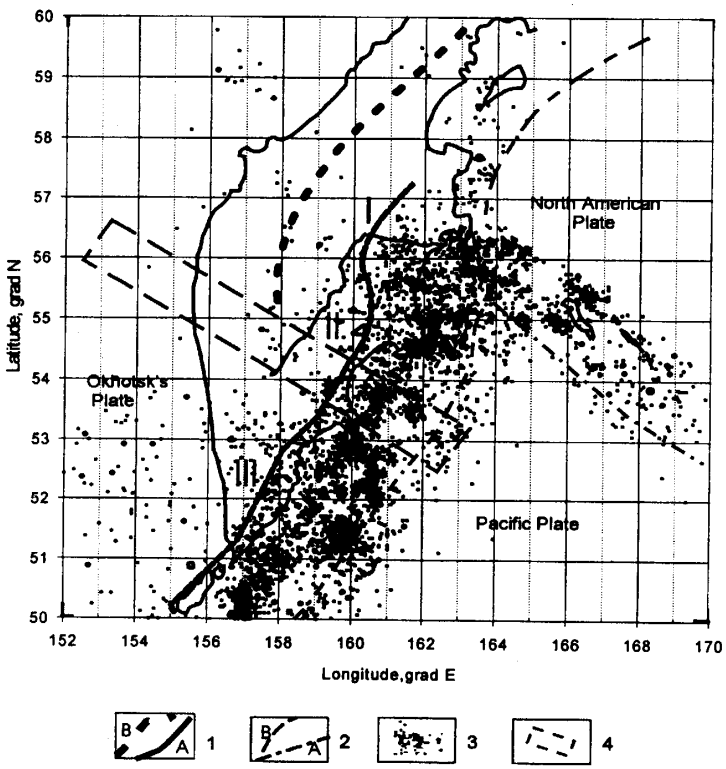

Fig. 2. Kamchatka and the Komandor islands area: position of volcanic belts, trenches and seismicity with the foci 0-500 km in depth (in 1962-1996), energy classes Ks>=8.5 (M>=2.6). 1- volcanic belts: A -the Eastern belt (I-Northern Kamchatka, II-Eastern Kamchatka, III-Southern Kamchatka); B - the Sredinny (Median) range belt. 2 - axes of modern trenches (A) and suggested paleo continuation of the Kuril--Kamchatka trench (B) (according to Seliverstov (1998)). 3- earthquakes. 4 - position of a vertical section perpendicular to Wadachi-Benioff zone for the Eastern volcanic belt of Kamchatka (see Fig. 4).

1988: 593-613). The deep-sea trench of Kamchatka, projection of the seismofocal zone on to the surface and modern Eastern volcanic belt of Kamchatka follow parallel one after another. Eastern volcanic belt is located at the distance of about 200-220 km from the deep-sea trench axis. This suggests that modern volcanic belt of Kamchatka, deep-sea trench and seismofocal zone are elements of a single global tectonic process. On the contrary, the active volcanic belt of the Sredinny (Median) range of Kamchatka is projected onto the seismofocal zone at the depths of about 370 km and is not connected with the modern seismofocal zone. The origin of this belt is still under discussion.

In the north of peninsula the Kurile-Kamchatka island arc intersects with the western sector of the Aleutian structures; for the latter the analogous morphostructure elements as Aleutian deep-sea trench, Aleutian island arc (the Kommandor islands) and marginal Beringov sea are distinguished (Fig. 2). Volcanism is absent at the Kommandor islands, however it has been widely manifested not long ago within the wide zone of shift dislocations along the Aleutian structure to the east of Kamchatka and presently in the Bering sea (Seliversov 1998: 164pp). Earthquakes on the Kommandor islands occur at the depths less than 125 km, mainly up to 70 km, the earthquake zone is not inclined, as it is beneath the Kamchatka, but

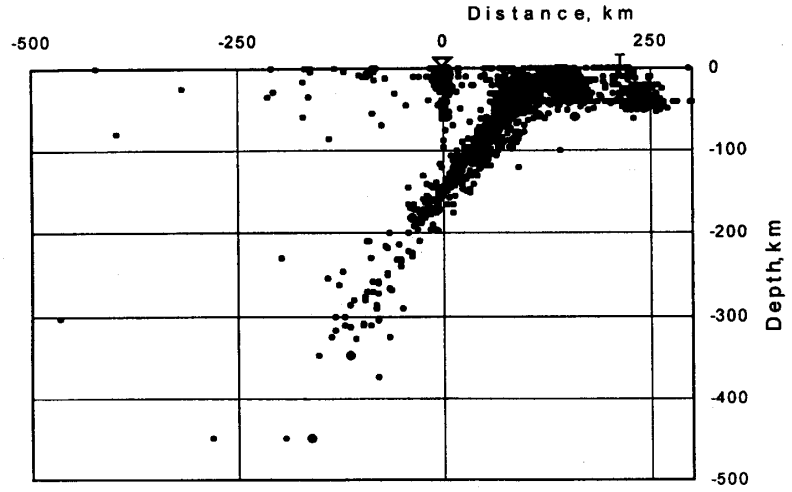

Fig. 4. Vertical cross section of the seismofocal zone for the Eastern Kamchatka area, perpendicular to the modern volcanic belt, width of layer is 140 km (see Fig. 2). Dots are earthquakes, triangle - position of the Eastern volcanic belt axis, T - Kamchatka trench.

almost vertical. i.e., seismofocal zone of the western sector of the Aleutian arc differs significantly from that of Kamchatka (Fedotov et al. 1974: 35-46).

At present, there is no agreement regarding the origin of volcanism and seismicity on Kamchatka. There are three differing points of view. The first is relevant to the evolution of the traditional conception of geocyncline (for example, Nauka 1984: 504pp). The second viewpoint is based on the global tectonic conception (Avdeiko 1974:95-110: Avdeiko 1998: 77, Seliverstov 1998: 164pp). The third point of view to the tectonics and the origin of volcanism on Kamchatka suggests that in the area of the transition zone between the Asian continent and the Pacific ocean a wide shift take place rather than subduction. As a result zones of extension occur and conditions appear for the ascending convective flows and for volcanism (Sharapov, Simbiriova, Bondarenko 1984: 199pp, Sharapov, Simbiriova, Bondarenko 1992: 162pp, Nauka 1997: 591pp). According to the conception of global tectonics, a collision of the two lithospheric slabs - Okhotskaya and Pacific - takes place on Kamchatka, and the Pacific oceanic slab subducts under Kamchatka (Fig. 2). This process is considered to supply with energy and to maintain the volcanic activity on Kamchatka for the last 80 million years. Subduction is marked out by a layer of earthquakes sinking beneath Kamchatka (Avdeiko 1974: 95-110, 1998: 77, Legler 1977: 171pp, Seliverstov 1998: 164pp) (See Fig. 4). Another collision between the Pacific and the North American plates is also suggested to take place along the Aleutian structure (the Kommandor islands) (Fig. 2). The Kurile-Kamchatka and Aleutian structures intersect in the area of the Northern Kamchatka. The proximity of the Aleutskaya structure and the relative movement of the Pacific and North American plates, which is of the transformal character nowadays, also play an important role in the development of volcanism and seismicity on Kamchatka (Seliverstov 1998: 164pp). The conception of global plate tectonics clarifies some peculiarities of volcanic

belts of Kamchatka. The first peculiarity is unusual position of volcanoes of Northern Kamchatka. In this place, the Eastern volcanic belt shifts up to 70 km to the west forming the Northern Kamchatka group of volcanoes (Fig. 1). Simultaneously, the seismofocal zone in this region deviates to the west and its angle of inclination decreases to the surface (Fedotov et al. 1988). Seliverstov (1998) suggested that this phenomenon may be explained by the subduction of warmer and lighter Pacific slab beneath Kamchatka at more steep angle in this area.

A number of authors considered the nature of the Sredinny (Median) belt of Kamchatka from the standpoint of global tectonic conception. Avdeiko (1974, 1998) and later Legler (1977) suggested that in the Oligocene-Miocene subduction of the Pacific plate beneath Kamchatka took place 200 km west from its recent position and then unevenly replaced to the east. Consequently, it caused the uneven migration of volcanic activity eastwards from the Sredinny range to the location of modern Eastern volcanic belt. Seliverstov (1998) in his conception of the gradual development of western section of the Aleutian arc holds another viewpoint to the formation of the Sredinny volcanic belt. According to this conception, formation of main structures of the Aleutian arc was preceded by the initial stage of development of a wide zone of shift dislocations. This process caused large-scale manifestations of tectonic-magmatic activity to the east of the Kamchatka subduction zone. The subduction of thermodynamically activated unconsolidated lithosphere beneath Kamchatka and the decrease of the inclination angle of Kamchatka subduction zone are considered to be the main reason for a significant displacement of the Oligocene-Miocene zone of island-arc magmatism to the West into the area of the Sredinny range. The subsequent migration of island-arc magmatism in the opposite direction during the Pliocene-Quaternary is associated with increasing inclination angle the Kamchatka subduction zone. It was caused by the sharp decrease of tectonic-magmatic activity to the East of Kamchatka after formation of main structures of western sector of the Aleutian arc in the Late Miocene, and subduction of the "cold" and denser Late Mesozoic lithosphere started beneath Kamchatka.

3. Quaternary silicic Volcanism of Kamchatka

The history of the Kamchatka volcanism goes back to the early Cretaceous. The activity has been the most intensive since the Upper Pliocene during the last 2-2.5 million years (Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp).

The detailed investigations of volcanic activity in Kamchatka have been carried out for the period of the last 850,000 years (Melekestsev 1980: 211pp, Polyak and Melekestsev 1981: 22-37, Braitseva, Melekestsev, Ponomareva and Sulerzhitsky 1995: 383-402). The comparison of volumes of the products and share of the silicic products erupted in different volcanic zones of Kamchatka during that period are

Table 1. The Erupted Products Volume(V) and Share of Silicic (SiO_2>57%) products (K) in 4 Volcanic zones of Kamchatka during the last 0.85 Ma (according to data of Polyak and Melekestsev (1979))

Volcanic zone	V, km^3	K, %
Northern Kamchatka	7300	6
Sredinny(Median) range Volcanic belt	6100	5.5
Eastern Kamchatka	5300	16
Southern Kamchatka	3200	23

tabulated in Table 1. It should be mentioned that the share of silicic products erupted in Southern and Eastern Kamchatka is 3-4 times higher than that in Northern Kamchatka or in the volcanic belt of the Sredynny range (5.5-6% against 16-23%). It is also important that the productivity of the volcanoes was maximal in Northern Kamchatka and was gradually decreasing southward.

In terms of the global tectonics, mafic composition of products and high productivity of volcanoes in Northern Kamchatka are probably attributed to the fact that the northern area of the Pacific plate subducting beneath Kamchatka has essentially different thermodynamic properties. And its velocity is higher compared to that of the southern part of the plate (Seliverstov 1998: 164pp). Thus, it can be expected that the associated with this process, velocity of deformation of the extension in the northern part of Kamchatka volcanic arc can be greater than in southern sector of the arc. This can be treated as the reason for greater crust permeability and increased magma discharge (Leonov 1993: 411-417).

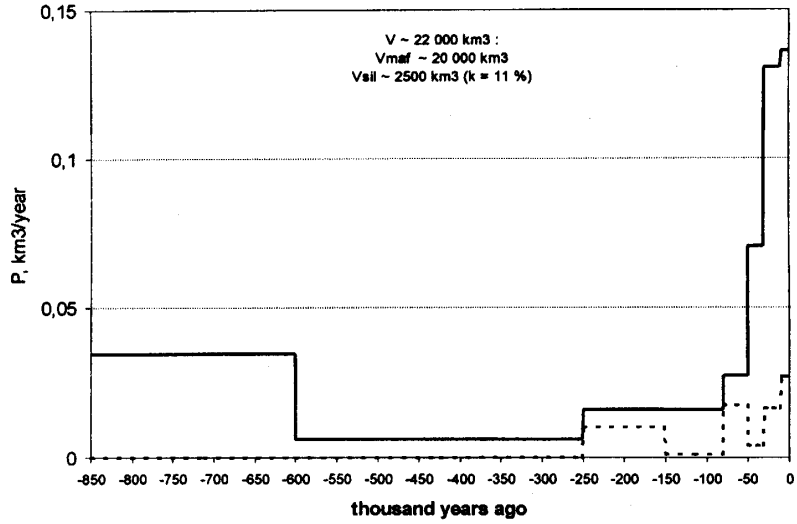

Fig. 5. Time variations of productivity of eruptive volcanism in Kamchatka for the last 0.85 Ma. P - output of mafic (SiO2<57%; solid line) and silicic (SiO2>57%; broken line) products. Inscription on the graph: V, Vsil, Vmaf - cumulative volumes of products erupted in the last 0.85 Ma (total, silicic and mafic ones, respectively), k - average part of silicic products for the period. Data from Polyak and Melekestsev (1981).

Fig. 5 presents variations of productivity P of the eruptive volcanism in Kamchatka during the last 0.85 Ma based on the data of Polyak and Melekestsev (1981). Note some interesting peculiarities: (1) During the last 80 thousand years volcanic activity increased considerably and it is about 5 times greater than the median values. (2) The first stage of the study period (0.85-0.25 Ma) was mainly associated with mafic (basaltic) eruptions; silicic volcanism in Kamchatka started about 0.25 Ma ago after a long period of manifestation of mafic volcanism. (3) For the last 0.85 Ma volcanoes of Kamchatka have ejected about 22,000 km^3 of volcanic products or 0.025 km^3 per year in average. (4) Silicic products comprised 11% of the total volume of all volcanic products. It is notable that there were a few periods of the increased explosive activity, each followed after long periods of the mafic volcanic activity. In some periods the share of acid products (SiO2) reached 80%.

The problem of origin of the silicic magmas and explosive caldera-forming eruptions has not been solved yet. One of possible mechanism lies in the following. At the first stage peripheral magma chambers are formed mostly at the expense of foundering of the surrounding rocks around volcano-feeding channels during long period of their existence (Fedotov 1980: 3-29). Due to differentiation processes silicic magmas are gradually formed in peripheral chambers preventing more mafic and dense magmas from rising. The mafic magmas continue entering the magma chamber and excess pressure gradually increases. Finally, a number of strong caldera-forming eruptions ejecting acid volcanic products take place. After that volcanoes grow again inside the formed calderas. This process is cyclically repeated until the volcanic activity decreases (Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp). Several such cycles are distinguished in the Eastern volcanic belt of Kamchatka (Nauka 1980: 300pp). Polyak and Melekestsev (1981) compared linear heat power in megawatts per 1 km of a volcanic arc for different regions of the World during the last 1,000 years (Table 2). Linear power of eruptive volcanism in Kamchatka is about 5 times greater than that in the Kurile Islands or Japan and it is exceeded by the Icelandic one only. Iceland is characterized by intensive basaltic volcanism and strong explosive eruptions are not common there. Thus, at present Kamchatka is one of the main areas for studying explosive volcanism.

Table 2. Linear Heat Power (N) in Megawatts per One Kilometer of a Volcanic Arc in the last 1,000 years (According to Polyak and Melekestsev (1981))

Volcanic area				
Kamchatka (900 km)	Japan (1800 km)	Kuril Islands (1200 km)	New Zealand (1200km) (for the period of 10 thousand years)	Middle Atlantic Rage (Island, 500 km)
10	2.5	2.5	2.1	15

4. Volcanoes and Calderas of Kamchatka

Volcanic formations of different types are observed in volcanic zones of Kamchatka. The first type is presented by monogenetic volcanoes composed of cinder cones, lava flows, maars and so on, which are associated with the dispersed volcanic activity of areal type. The period of their formation is from several days to 1-2 years (Sirin 1968: 196pp, Fedotov 1984: 636pp, Ponomareva 1990: 714-741, Dirksen and Melekestsev 1999: 3-18). In the Eastern volcanic belt of Kamchatka the areal type of activity was the only one up to Late Pliocene; concentration of the activity in volcanic centers and formation of polygenetic volcanoes started only from the Late Pliocene (Selyangin 1987: 148pp).

Table 3. Volcanic eruptions in Kamchatka in 1991-1999

The eruption character	Parameters of eruption	Influence on the environment, dangerous phenomena	References
	The Avachinsky volcano 13-30 January 1991		
Mild terminal explosive-effusive eruption. It happend after 46 years of dormancy and had no precursors. Vulcanian explosions in the active crater, lava and mud flows were accompanied by volcanic tremor.	Products : basaltic-andesite Lava flows : volume – 12 mln .m³, length – 1.6 km Pyroclastic : volume – 0.7 mln. m³ height of ash clouds – 1.5km (above the crater)	Area covered : with ash ~4000km², with lava 0.33 km² Max. length of mud flows ~ 5 km Water and air pollutions :total output of elements ~3400 tonns(1600 tons of Cl, 170tons of F,"). Red-hot avalanches at lava flows,mud flows	Droznin and Muraviev (1994) Ivanov et al. (1996)
	The Klyuchevskoy volcano July-September 1993		
Mild terminal explosive-effusive eruption. Strombolian and Vulcanian explosions in the active crater. Lava founting, flowing along the Krestovsky trench at the volcano slope and trench at the volcano slope and entering into gletchers, phreatic explosions. Volcanic Tremor.	Products : basaltic-andesite Lava : volume ~ 30 mln. m³, length ~ 5km the founting height – up to 1.3 km Phreatic explosions: max height – 4km Length of mad flows ~30km	The most dangerous were: -explosions and mud flows during entering of lava into gletchers, -pollutions of the Kamchatka river by mud flows, -agriculture lands destruction over the area of 0.04 km² (by mud flows), -roades destruction for 4 km	Fedotov et al. (1995)
	Klyuchevskoy volcano September-October 1994		
Mild terminal explosive-effusive eruption; subplinian activity at the final stage, October, 1, 1994 Strombolian and Vulcanian explosions in the active crater. Lava founting, its flowing along trenchers at the volcano slopes and entering into gletchers, phreatic explosions.The subplinian column and pyroclastic flows formation on October, 1, 1994	Products : basaltic-andesite Lava : volume ~30 mln. m³ length ~ 5km, Mad flows length ~30km **Oct., 1 1994: at the subplinian stage :** absolute column height of – 12-13 km ash plum height – up to 2000 km lava fountings height – up to 2km phreatic explosions up to 4km hight	**The most dangerous were:** -subplinian column Oct,1,1994 for airplains and helicopters, -phreatic explosions and mud flows during the entering of lava into gletchers, -pollutions of the Kamchatka river by mud flows, -destruction of a road near Klyuchi town at the length of about 1 km	Ozerov et al. (1997)
	The Bezymianny volcano 1993-1998		
Periodic (once or twice a year) growth of intracrater lava dome associated with explosive eruptions. Viscous lava block injections,ash clouds, pyroclastic flows. One episode usually lasts about a week. It takes place in the crater sized 1.5 x 2.8 km, formed during the gigantic explosion on March, 30, 1956	Products : andesite **For one episode of the dome growing:** Pyroclastic flows:volume ~ 0.02 km³, length – 5-12km; Lava flows(from 1977) : volume ~ 0.02 km³,length ~700m; Debris avalanches during a collaps of the lava dome : volume ~ 0.006km³. Ash: max.height of clouds - 18km, volume~0.02km³	**The most dangerous phenomena of the dome growth episode :** -pyroclastic flows and pyroclastic surges and debris avalanches at the distance of up -ash clowds at the distance up to 300km for aircrafts and helicopters, -seldom lapilli injections over the area of about 50 km²	Gorshkov and Bogoyavlenskaya (1965) Belousov et al. (1998)
	Shiveluch volcano 1993-1995		
The 2-nd stage of the lava dome growth. Viscous lava block injections, ash clouds. The initial phase, on April, 22, 1993, was associated with strong explosions and pyroclastic flows formation. It happened in the crater sized nearly 1.5x3 km, formed during the gigantic explosion on November, 12, 1964.(The 1-st stage took place in 1980-1982, and then a dome of 180 m in height appeared, volumed nearly 0.02 km³	Products : andesite **During the explosion on April,22,1993:** Volcanic ash : max. height ~18km, weight ~5 mln. ton Pyroclastic flows: length ~8km Mud flows : length 28 km,volume 0.015km³ **Lava dome (at the end of 1995) :** height– 350m, rim diameter – 650m, the basement size – 1000x1700m, volume ~ 0.2km³.	The area covered by: volcanic ash ~ 20,000 km², mud flows ~ 50 km² Brought water -soluble components: about 40,000 tonns(Cl~ 2,500 tonns, SO_4 ~25,000 tonns,...) **The most dangerous phenomena:** pyroclastic flows at the distance of up to 8km and mud flows.	Bogoyavlenskaya et al. (1985) Dvigalo (1988) Khubunaya et al. (1995) Firstov et al. (1995)

Table 4. Some calderas and big craters in Kamchatka (ages according to Braiseva et al. (1991))

N (see Fig.1)	Name of caldera(crater)	Age, years	Diameter km	Volume of enjected material, km³	Types of erupted rocks	Associated processes	References
			Late Pleistocene calderas				
1	Shiveluch	30,000	9	50-60	Andesite	Explosions,collapes, landslides	Fedotov and Masurenkov (1991a, b)
12	Krasheninnikov	35 000-38 000	9	50	Dacite	Collaps	Fedotov and Masurenkov (1991a, b)
15	Uzon	39,000	9 x 12		Andesite,dacite	Ignimbrite inject.	Florensky (1984)
17	Maly Semiachik	25 000-30 000	7	8	Andesite,dacite		Selyangin (1987)
18	Lake Karymsky(Akad.Nauk)	28 000-48 000	6	6	Dacite		Nauka (1980)
24	Avacha(Somma Vesuvius)	29 000-30 000	4.5 x 4				Melekestsev et al. (1991)
28	Gorely	33 000-34 000	12 x 13				Fedotov and Masurenkov (1991a, b)
31	Ksudach : caldera I	30 000-40 000	7	40	Andesite ignimb.	Slow collaps	Selyangin (1987)
	caldera II	30 000-40 000	7	40	Andesite ignimb.		Selyangin (1987)
36	Lake Kurilskoe(old)	40 000-41 000					Melekestsev et al. (1991b)
37	Ichinsky(Somma Vesuvius)	Late Pleist.	3 x 5		Dacite ?		Fedotov and Masurenkov (1991a, b)
38	Khangar	38 000-40 000	13 x 19				Melekestsev et al. (1996)
41	Opala	39 000-40 000	15 x 15	50	Andesite	Pumice injections	Fedotov and Masurenkov (1991a, b)
			Holocene calderas and big craters				
5	Ushkovsky(Plosky Dalniy)	8600				Hawaiian-type	Braitseva et al. (1995b)
6	Plosky Tolbachik	7000	3			Hawaiian-type	Fedotov and Masurenkov (1991a, b)
12	Krasheninnikov (caldera of the northern cone)	2200-2400	2				Fedotov and Masurenkov (1991a, b)
18	Karymsky	7700-7800	5 x 6	12.5-16	Dacite,rhyodacite	Pumice injections, pyroclastic flows, caldera collaps	Braitseva and Melekest (1990)
31	Ksudach : caldera III	8700-8800	2 x 3 ?	2	Adnesite,dacite		Braitseva et al (1995a,b,c)
	caldera IV	6000-6100	5 x 6	9-11	Adnesite,dacite, rhyodacite		Braitseva et al (1995a,b,c)
	caldera V	1700-1800	4 x 6.5	18-19	Rhyodacite	Pyroclastic flows, pyroclastic surges, tephra enjections	Braitseva et al (1995a,b,c)
36	Caldera Lake Kurilskoe- - Iliinskaya	7600-7700	8 x14	120-140	Rhyodacite		Braitseva et al. (1995a,b,c)
38	Khangar(summit crater)	6900-7000	2 x 2.5	10	Dacite	Tephra enjections	Melekestsev et al. (1996)
			Historic big craters				
1	Shiveluch	35 (in 1964)	1.5x3	1--2	Andesite	landslides,phyroclast. and tephra enjections	Bogoyavlenskaya et al. (1985) Belousov and Belousova (1996)
4	Bezymianny	40 (in 1956)	1.3 x 2.8	1--2	Andesite		Gorshkov and Bogoyavlenskaya (1965)
31	Ksudach (crater Shtubel)	90 (in 1907)	1 x 1.7		Andesite,dacite	Pumice injections	Fedotov and Masurenkov (1991a, b)
33	Iliyinsky	95 (in 1901)	0.8 x 1.2			At the slope of the volcano	Fedotov and Masurenkov (1991a, b)

Table 5. The two simultanious phenomena in the Karymsky vocanic center : an underwater eruptioon in the Karymsky lake (2-3 Jauary 1996) and a Karymsky volcano eruption

Character of eruption	Parameters of eruption	Influence on the environment	References
Stage 1: January 1, 1996, magma rising : rising of basaltic magma from a deep (20-25km) magmatic chamber up to the earth surface, large earthquakes large earthquakes with M of up to 7 Stage 2 January 2, 1996: the beginning of the two simultaneous eruptions: A) The explosive- effusive eruption of the Karymsky volcano. It has been uninterruptive for more than 3 years by now. B)A strong underwater eruption within the Karymsky lake Akademii Nauk caldera), a tuff ring and the formation of a new peninsula. This was a one-day eruption (January, 2-3, 1996). The distance between two eruptive centers was about 6 km.	**Three types of products were erupted:** -andesites of Karymsky volcano -basalts of underwater eruption in the lake -rhyolites from the magmatic chamber of Akademii Nauk caldera, entrained by basalts of underwater eruption (about 1% of volume of basalt) **Huge ground deformation in stage 1:** extention up to 2.3 and vertical displacement up to 1.6m (at a base of 3 km). Big fissures formation at the northern cost of the Karymsky lake (above the feading dike). Formation of new hot springs and diapearance of old hot springs. **The underwater eruption in the Karymsky lake on 2-3 Jan. 1996:** Nearly 100 underwater explosions with the heat equivalent of 12-80 Kton of trotyl, occured within the lake. An underwater cinder basaltic cone (tuff ring) volumed 0.04 km³ and a new peninsula were formedt. The crater of the tuff ring has the diameter 650m and the depth of about 50m. **The Karymsky volcano eruption,1996-1999:** a) A new explosive crater of diameter with a diameter of about 400 m was formed at the slope of volcano not far from its top, a new cinder cone was formed in this crater. b)Volcanic ash ~20 mln. tonns; c)Lava flows: length 1.4 km,width 600m, area ~0.55 km², volume ~0.008 km³	**During the underwater eruption in the Karymsky lake on 2-3 January 1996 (an ecological catastrophe in the lake):** a)Base surges and big tsunami waves up to 80m within the lake, devastation of its coast by the waves, great changes of the cost relief. b)Transformation of the fresh lake volumed 0.5 km³ into an acid lake (pH 3.2), heating the water. Total mass of volcanic components injected into the lake estimated by about 350,000 ton (Cl ~ 25,000 ton, S ~ 250,000 to,"). It coincides of degassing of about 1 km³ of fresh magma. As a rezult, water became not usable for many centuries biocenoz. Fito-Zooplankton and unique population of red salmon died out. Art present now slow recovering of water contents takes place.	Fedotov (1998) Muraviev et al. (1998) Grib (1998) Maguskin et al. (1998) Leonov (1998) Ushakov and Fazlullin (1998) Braitseva (1998) Vergasova et al. (1998) Gordeev et al. (1998) Vakin and Pilipenko (1998) Zobin and Levina (1998) Karpov and Lupikina (1998)

The second type of activity is characterized by repeated eruptions and formation of the numerous separate scutiform, shield and cone-shaped polygenetic volcanoes. The period of their formation is from several to tens thousands years and very seldom is over 200,000 years (Melekestsev 1980: 211pp).

The third type of volcanic formations is "long-lived volcanic centers" . Volcanic centers are complexes comprised of volcanoes of various morphogenetic types and age (shield and scutiform volcanoes, stratovolcanoes, large extrusions, thick assemblages of dikes, intrusive bodies) (Nauka 1980: 300pp, Kozhemyaka 1996: 621-636). Long-lived volcanic centers are characterized by an anomalously long duration of volcanism up to 2-3 Ma and in some cases up to 20 Ma. Obvious or potential incompleteness of development is typical of them (Nauka 1980: 300pp, Kozhemyaka 1988: 481-494). These are great edifices, the diameter of their basement is from 15 to 45 km, and volume is up to 300 km^3. They are regularly joined by the evolution of a large single or by a series of smaller magmatic chambers. These chambers are probably deeply located which attributes for a long duration of the development of those volcanic centers. From 30 to 70% of volcanic products ejected during the Quaternary are accumulated in the volcanic centers, that is those centers are main chambers for discharge of the material and energy. Kozhemyaka (1996) points out three main long-lived volcanic centers: (a) large shield volcanoes; (b) complex volcanic massifs, and (c) complex stratovolcanoes with collapse calderas.

The most interesting volcanic formations in terms of studying explosive volcanism of Kamchatka are presented in Tables 3, 4 and 5. They are based on the data of Polyak and Melekestsev (1980), Braitseva, Melekestsev, Ponomareva and Kirianov (1995), Braitseva, Melekestsev, Ponomareva and Sulerzhitsky (1995), Braitseva, Melekestsev, Ponomareva, Sulerzhitsky and Litasova (1995), Kozhemyaka (1995). In Table 3 data on active volcanoes of Kamchatka are presented. The Late Pleistocene and Holocene calderas are described in Table 4. Table 5 presents an information on some interesting fresh monogenetic forms of explosive activity. Below is a brief description of explosive volcanism given to each volcanic zone of Kamchatka (References see in Tables 3, 4 and 5).

4.1. Northern Kamchatka Volcanoes

Active and the most productive volcanoes are Shiveluch, Klyuchevskoy and Bezymianny volcanoes (Fig. 1, Table 3).

The Klyuchevskoy volcano (Fig. 6) is a giant basaltic and one of the most active volcano in the world. It is the highest volcano in Eurasia (its altitude is 4850 m). At present it erupts on average 60 million tons of volcanic products in a year; its productivity is about 35 times greater than of an average land volcano (Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp). Frequent summit and flank eruptions are typical of this volcano. Its slopes are covered with thick glaciers and very often lava flows outpour inside them

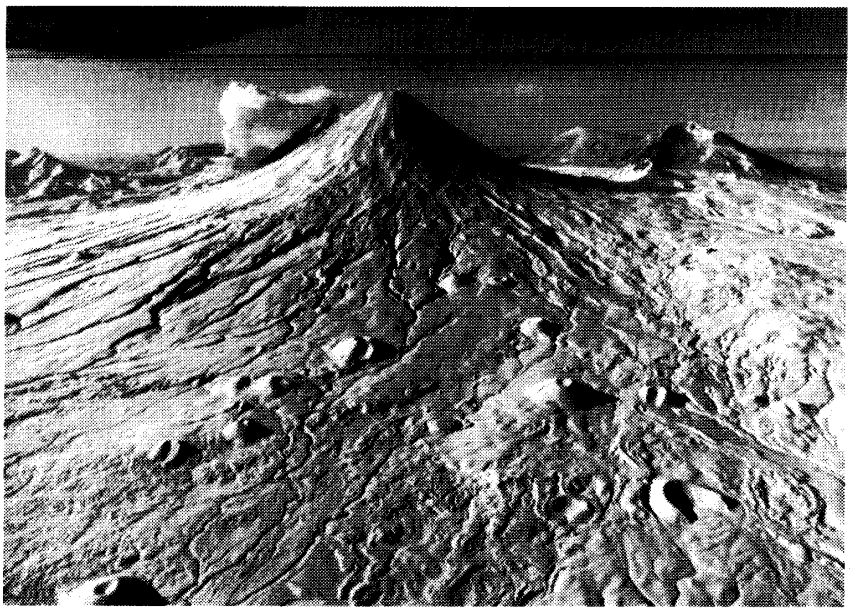

Fig. 6. Klyuchevskoy (Northern Kamchatka), a giant basaltic and one of the most active volcanoes of the world, the highest volcano of Eurasia (the altitudet is about 4800 m). Its cone is made of lava, pyroclastic and ice layers. The volcano slopes are covered with thick glaciers. Numerous cinder cones on the eastern slope of the volcano appeared as the result of lateral volcano eruptions. A strong gas-steam plume of Bezymianny volcano is seen at the background. Photo by V.A.Podtabachny.

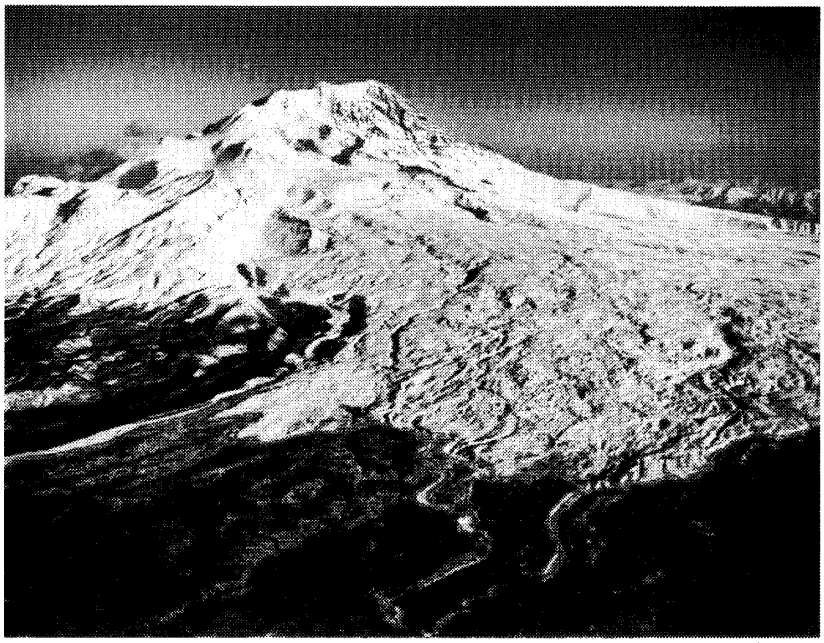

Fig. 7. Shiveluch, the northernmost and the most dangerous volcano of Kamchatka. Recurrent growth and destruction of lava domes inside its active crater (contoured in the picture) and strong explosive eruptions are characteristic for this volcano.

A large field of strata deposited by its explosive eruptions covers the area of about 300 km^2. The woods at the foot of the volcano were buried by directed blasts. Pyroclastic flows of the last large 1964 eruption extended to a distance of 18 km from the active crater. View from the southwest, the beginning of 1980s. Photo by N.P.Smelov.

leading to a formation of extent lahars and secondary explosions.

Shiveluch (Fig. 7) is the northernmost active volcano of Kamchatka located closer than the others are to a joint of Kurile-Kamchatka and Aleutian island arcs. Its altitude is 3335 m, and the basement is 1650 km2 width. It is developed during 65,000 years and its productivity over this period is on the average 36× 106 t/year (Polyak and Melekestsev 1981: 22-37) (Table 4).

Bezymianny volcano is located in the central part of the Klychevskya group of volcanoes at the southern spurs of the extinct Kamen volcano about 9 km SSW from the Klyuchevskoy summit. It is well known by its catastrophic eruption in 1956 (Gorshkov and Bogoyavlenskaya 1965: 172pp), which started a new stage of its activity after a thousand-year rest. Age of the volcano is 4,700 years; dominating rocks are andesite. Its altitude was 3100 m until 1956. After the directed blast of 1956, the altitude decreased to 250 m. On its top, the crater 1.3×2.8 km in size and about 700 m in depth was formed, which was opened to the southeast. According to the character of eruption and its consequences, Bezymianny is considered to be a twin of widely known St Helens volcano. Shiveluch and Bezymianny are the most dangerous volcanoes in Kamchatka. Their eruptions are associated with periodic growth and destruction of lava domes, strong explosions, pyroclastic and mud flow formation.

Tolbachinskaya regional zone of cinder cones is considered to be very active. In 1975-1976, the largest basaltic eruption of the 20-th century with a volume of ejected products of 2.2 km^3 occurred in this area (Fedotov and Markhinin 1983: 341pp, Fedotov 1984: 636pp).

Formation of calderas is not typical for the Northern Kamchatka. In the Upper Pleistocene moderate calderas were formed at Shiveluch, Plosky and Plosky Tolbachik volcanoes (Table 4).

4.2. Volcanoes of Eastern Kamchatka

Silicic volcanism is well developed in the Eastern Kamchatka zone. There is a lot of calderas and caldera depressions here (Fig. 8, Tables 4 and 5). In the Uzon-Geyzernaya caldera depression a strong zone of hydrothermal discharge is situated (Kamchatka Geysers Valley). The Uzon caldera is a natural laboratory to study mineral deposit formation. The double Krasheninnikov volcano with its areal zone of cinder cones is especially interesting. At the top of the Maly Semyachik volcano a big crater lake is located, which is saturated with caustic volcanic products. Sharp variations of temperature, water level and its chemical composition are observed at changing the intensity of outpouring chemical components into the lake. This is a very attractive object for studying hydrothermal process.

Karymsky volcano was one of the most active volcanoes in the 20-th century in Kamchatka that is under eruption nowadays (Fig. 8). The volcano is located in the central area of the Eastern volcanic belt, at about 120 km to the north-east from Petropavlovsk-Kamchatski. This is not a big volcano (its altitude is

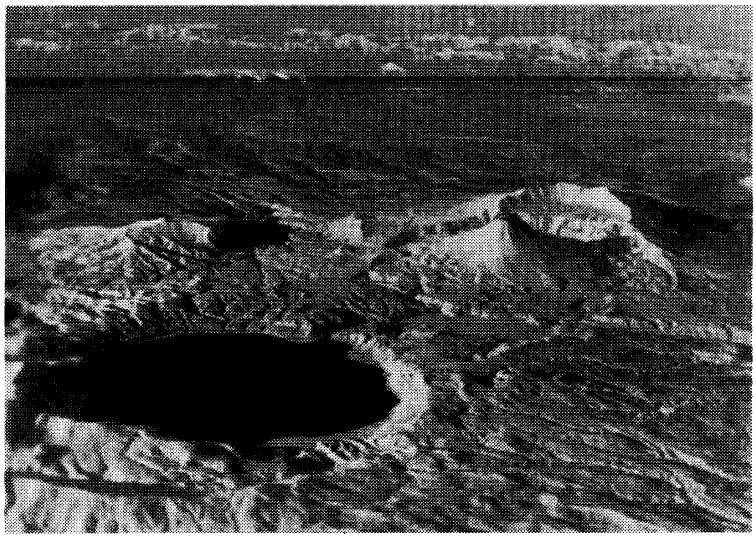

Fig. 8. Two neighboring calderas (Eastern Kamchatka) two years before the 1996-1999 eruption: the Karymsky caldera (to the right), inside is the active Karymsky volcano, and the old Akademii Nauk caldera filled with a deep lake (to the left). View from the southeast. Distance between centers of the calderas is about 8 km, their diameters are 5-6 km. Photo by A.P. Khrenov.

1540 m) which has been formed in caldera about 5,300 years ago. Strombolian are the main types of its eruptions, and the productivity is 2×106 tons per year (Polyak and Melekestsev 1981: 22-37), but over the period from 1965 to 1982 it was in average 16×106 tons per year (Tokarev 1990: 117-126).

Two active volcanoes - Avachinsky and Koryaksky are located in the vicinity of Petropavlovsk-Kamchatski (Figs.1 and 3). The last eruption of Avachinsky volcano occurred in 1991. Koryaksky volcano is resting for a long period and might have accumulated a great deal of excess magma in its chamber. During the last years its seismic activity increased, therefore a strong explosive eruption is quite possible. The volcanoes are quite easy to access. It is important to study them for better safety of Petropavlovsk-Kamchatski.

4.3. Southern Kamchatka

Within the Southern Kamchatka silicic volcanism is also well developed. The average value for the silicic products (SiO_2>57%) was 23% here for the last 850,000 years (see Table 1). The Ksudach volcano with its big caldera system at the top is a very interesting object for studying the explosive volcanism (Table 4). The last strong eruption of this volcano took place in 1907. As the result, 1×1.7 km crater was formed (Table 4). The Mutnovsky volcano is a unique object for volcanic-chemical studies. Frequent phreatic-magmatic ash explosions and the system of big craters at its top characterize the Gorely volcano. In 1901 at one slope of the Iliynsky volcano a big explosive crater, 0.8-1.2 km in size and up to 400 m in depth, was formed during its eruption (Table 4). Studying the consequences and modeling events of this eruption will allow revealing the nature of such phenomena. Flood basalt (areal) volcanism is also

widespread in this area.

4.4. The Sredinny (Median) volcanic belt

The Sredinny (Median) volcanic belt is the area of widespread basaltic areal volcanism (near 100 monogenetic volcanoes). Alongside with this, about 120 polygenetic volcanoes, both separate and involved into the long-lived volcanic centers are distinguished here. During the last 0.85Ma about 350 km^3 of silicic products (SiO_2 >57%) were ejected in the Sredinny (Median) volcanic belt. Presently, the only active volcano here is Ichinsky, which is characterized by solfatara activity. It should be noted that during a long period of the geologic history this volcanic belt was active concurrent with the Northern Kamchatka volcanic belt, parallel to it. The problem of the Sredinny volcanic belt origin has not been solved yet. An interesting example of explosive volcanism is a big (2×2.5 km) crater with lake at the top of the Khangar volcano. It was formed about 7,000 years ago.

Table 4 presents data on some monogenetic Holocene and historical explosive craters, maars and tuff rings. The latest example: four years ago a short-term underwater eruption took place in the Karymsky lake and a tuff ring with the diameter of about 650 m was formed.

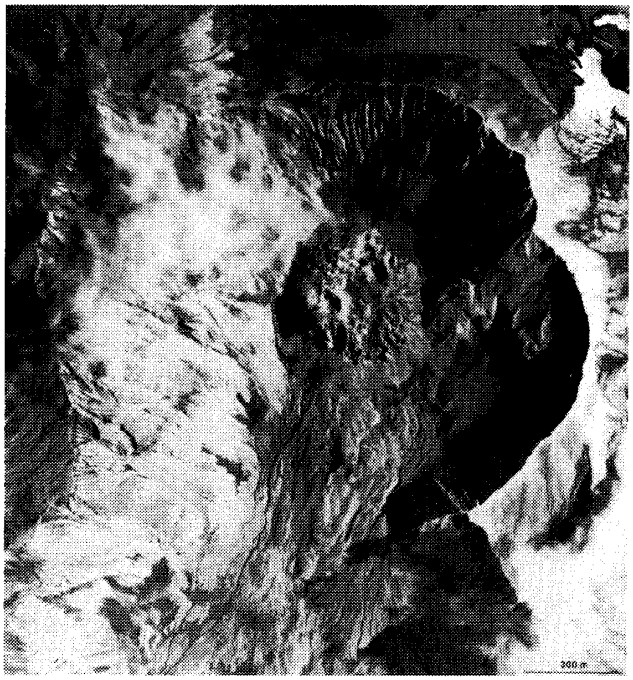

Fig. 9. The active crater of the Shiveluch volcano appeared after catastrophic 1964 explosion (aerophoto, 1984). The crater is 2 km in diameter and its average depth is 400m. Inside the crater there is a lava dome which has grown since 1980-1981.
The height of the dome is 180m, its corona diameter is about 350m. On the top and at the base of the dome there are several smaller explosive craters 10-40 m in diameter. Later with increase of explosive activity one larger crater was formed.

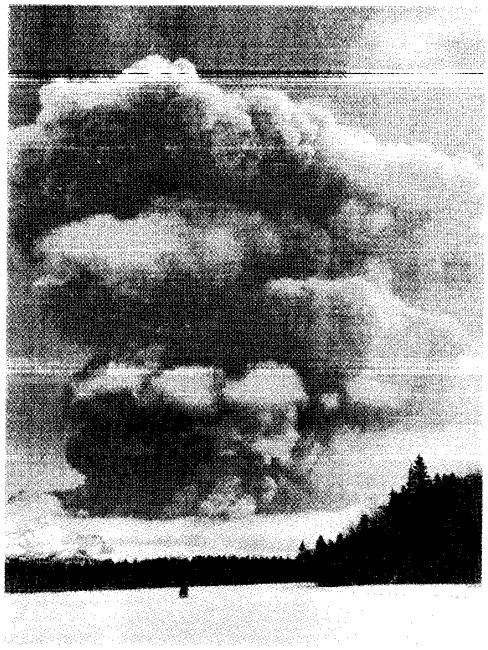

Fig. 10. A sub-Plinian column and pyroclastic flows of the strongest explosion of Shiveluch volcano, 22 April 1993. It accompanied the initial most intensive stage of the intracrater lava dome growth. Ash plume rose to the height of 16 km and resulted in the strong ash falls in the Ust-Kamchatsk settlement at a distance of 87 km. Bright lightnings up to 500m in length were seen in the ash cloud and thunder roars were heard. Pyroclastic flows and intensive ash falls caused snow melting at the volcano slopes which resulted in the formation of long mud flows. Photo by N.P.Smelov.

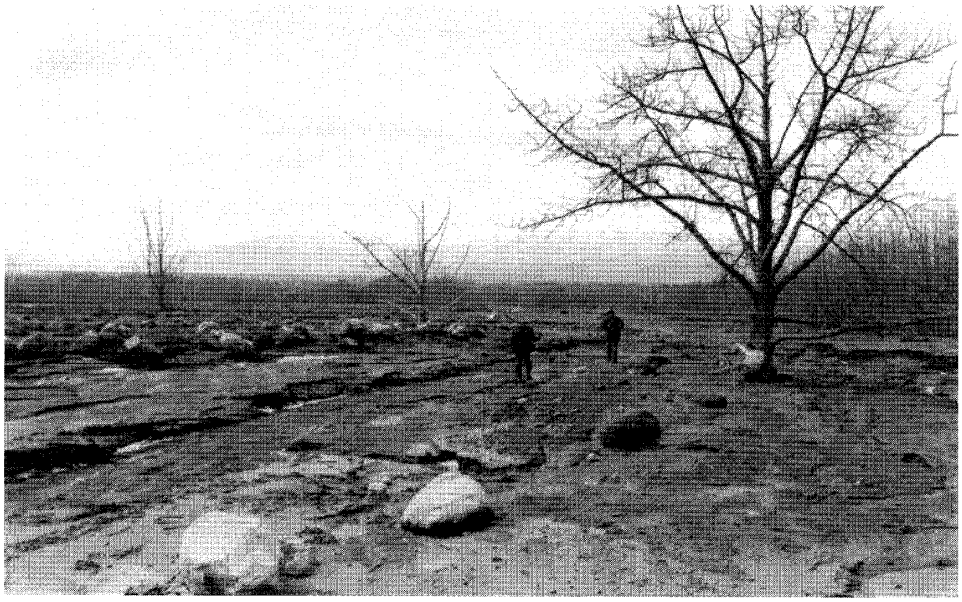

Fig. 11. Deposits of mud flows formed immediately after the strong Shiveluch explosion on April 22, 1993 at a distance of 20 km from the active crater of the volcano. Photo by N.P.Smelov.

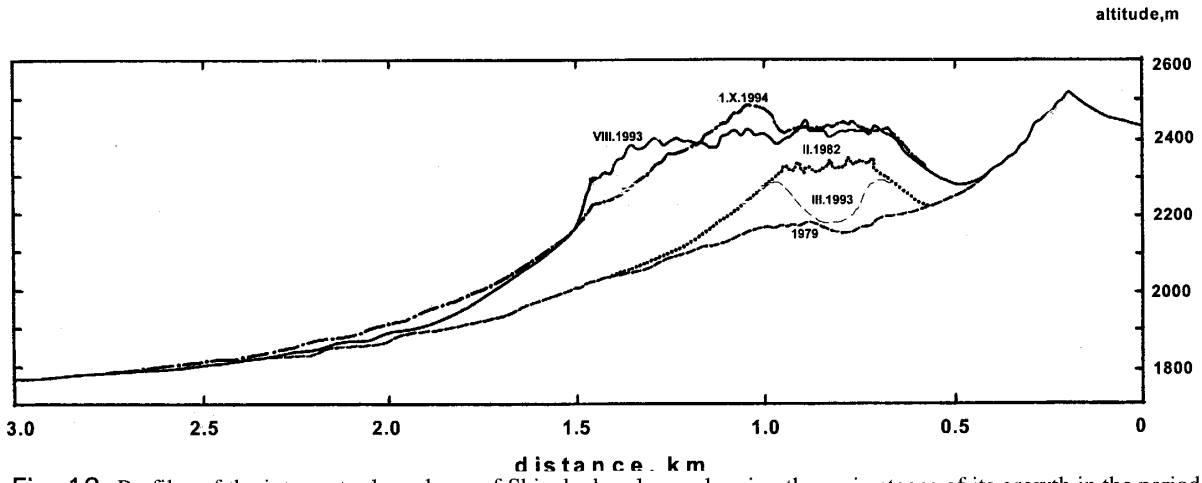

Fig. 12. Profiles of the intracrater lava dome of Shiveluch volcano showing the main stages of its growth in the period from 1979 to 1994 (meridional section). The sharp peak (to the right) is the northern edge of the active crater. Profiles: 1979 - before the beginning of the new dome growth; II.1982 - at the end of the 1-st stage of the dome growth; III.1993- by the beginning of the 2-nd stage of the dome growth, 1.X.1994 - at the end of the 2-nd stage of the dome growth. By October 1994 the dome was measured as follows: height - 350 m, corona diameter - 650 m, the basement size - 1 x 1.7 km and volume of about 0.2 km^3.

5. Explosive Eruptions in Kamchatka

One or two eruptions per year occur in the Kamchatka peninsula (Tokarev 1993: 703-710). Last decades are characterized by a sharp increase of activity of the base volcanoes of Kamchatka. In this section we are making an attempt to give a brief characteristic of this period at the example of volcanoes of mostly explosive eruptions.

Shiveluch volcano. Active crater of the volcano is located in the southwest sector of the summit having an altitude about 2300 m (Fig. 7). The last large eruption of a type of the "directed blast" happened on November 12, 1964. As a result, an extrusive dome of the hornblende andesite "Suelich" was destructed. A newly formed and opened southward crater was 1.5×2 km^2 in size and 500 m in depth (Fig. 9). The total amount of resurgent and juvenile material evacuated by the explosive eruption exceeded 1.5 km^3.

The volcano was in state of a weak fumarolic activity till July 1980. That month the first external evidence of the next activity of the volcano was fixed during. It was reflected in a full disappearing of the thermal lakes that existed in the crater over 15 years. Beginning from August 1980, a new extrusive dome pressed out in the Shiveluch crater. During a year and a half the volume of its eruption reached 0.021 km^3 and its height became 180 m (Fig. 9).

In December 1981, growth of the dome stopped and the volcano was calm for two years.

In the early spring of 1984, the volcano became active again. At first its activity manifested itself in blasts dispersed at the surface of the dome and around its basement causing formation of separate vents up

to 40 m in diameter and up to 20 m in depth (Fig.9). Later, continuous increasing of frequency of explosions and their power were observed. Gas and ash clouds were gradually growing in size, volume of the ejected material increased, mud flows and then debris avalanches appeared. By 1989 explosive activity localized in the two vents at the dome top that caused its gradual destruction. Later, in 1990 the craters jointed forming an explosive crater measured 350 x 220 m and 100 m in depth.

The explosive activity of the dome continued till April, 1993 and its sharpness increased accompanied with ejecta clouds up to a height of 16 km above the crater (Fig. 10). The formation of pyroclastic and long mud flows (up to 30 km) (Fig. 11) was followed by a new extrusive eruption. During the next 18 months the volume of dome increased up to 0.2 km^3 and its height reached almost 300 m (Fig. 12).

In 1980-1981 and in 1993-1994, the processes of extrusive dome formation were accompanied by shallow long-period earthquakes and volcanic tremor. Usually rate of magma injections was at the initial stage of an extrusive eruption, during this volcanic earthquakes were taking place uninterruptively flowing together in one record (Fedotov et al. 1995: 117-131).

Klyuchevskoy volcano (see Fig. 6). The last cycle of its activity, which to our opinion can be limited from 1979 to 1994, was the most characteristic for the Klyuchevskoy volcano. During this period 11 flank eruptions took place on the background of constantly increasing explosive - effusive activity of the summit crater. A paroxysm of October 1, 1994 (Fig. 13) completed this cycle.

Some remarkable regularity was observed in the character of the eruption during the study period.

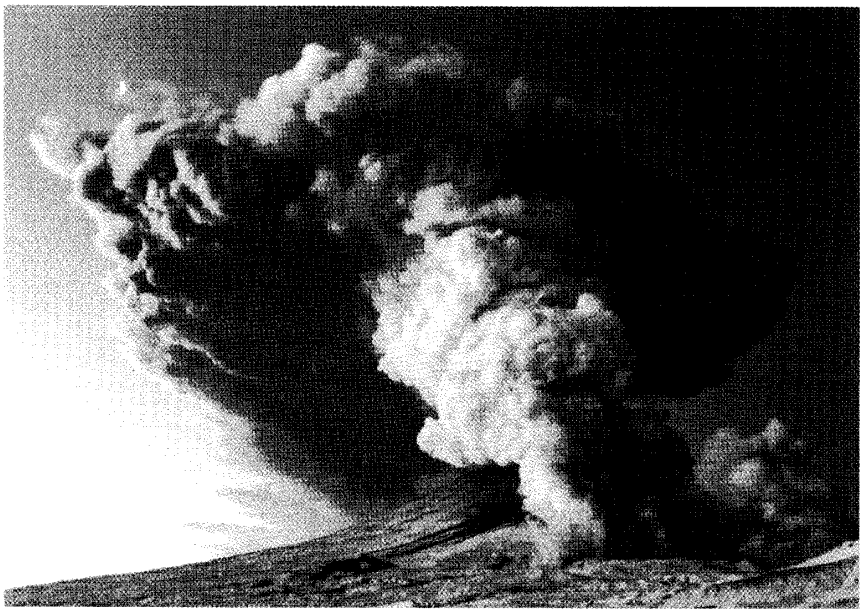

Fig. 13. The Klyuchevskoy volcano; eruptive cloud during the paroxysm of October 1, 1994, morning, the view from the north. The altitude of the eruptive column is 12.5 km, its maximum once reached 20 km above the sea level. Pyroclastic flows (autoexplosive avalanches) (lower right) are in the foreground. By 8 p.m. the ash plum reached 1000 km in length. The paroxysm lasted about 10 hours. Photo by N.P.Smelov.

It is necessary to note first, that the levels of flank eruptions were gradually increasing from the first (June 3, 1989) occurred at the height of 1,800 m to the last two (May 2 and July 26. 1989) formed at the heights of 4,400 and 4,300 m.

All flank breaks were formed on the fissures combined into an arc-like zone cutting the southeast sector of slope of the Klyuchevskoy cone. According to Leonov (1993) a collapse of the southeastern sector of the cone can take place in this zone later as it has once happened at the neighboring volcano Kamen.

Each decrease of the volcano activity was accompanied by the subsidence in the active zone of the summit crater. Forming collapses increased in size proportionally to the period of the passive state of the volcano. The next activity of the volcano was preceded by the stabilization of the subsidence.

Paroxysm of October 1 1994 formed an eruptive column, rising to a height over 12 km and eruptive plum over 100 km in length (Fig. 13). Lava flows and numerous incandescent avalanches lowering onto the glaciers of the Klyuchevskoy volcano caused thick mud flows which passed over 30 km and reached eastern outskirts of the town of Klyuchi. The roads have been washed away at the distance up to 6 km in length, a considerable harm has been made to the woods and agricultural lands.

Paroxysmal eruption abrupted sharply on October 2 1994. From that time an immense collapse is being formed at the volcano top. By the autumn of 1995 it reached 450 m in depth and its rim diameter is about 700 m. During the period over 5 years the volcano is manifesting a weak fumarolic activity which is sometimes disturbed by the ash-dusty outbursts from the large failures in a forming crater.

Bezymianny volcano. After the 1956 explosion of the Bezymianny volcano an extrusive dome "Novyi" was formed in its crater; its volume has reached 0.4 km^3 by now.

The authors of the paper (Fedotov and Masurenkov 1991a: 413pp, 1991b: 300pp) point out three stages of the dome evolution within modern period of the volcano activity:

At the first stage (1956-1965) pressing out of the rigid blocks of the dome took place, which was accompanied by a strong explosive activity during the eruptions followed with an interval of 2-3 years.

During the second period (1965-1977) alongside with a slow pressing out of the rigid blocks and low explosive activity, lava swells and small domes formed by plastic lava.

At the third stage, which began in 1977, growth of volume of the dome "Novyi" mainly took place due to viscous lava flows outpouring to its surface at the end of its every activation.

Dome growth was studied in more details during the third stage. Regular aerial photographic survey in 70s-80s made it possible to determine some regularity in the character of the volcano activity. Some of them can be considered as precursors of the eruptions. It has been established that since 1977 all eruptions of the volcano have taken place according to almost the same scenario, with regular manifestation of the

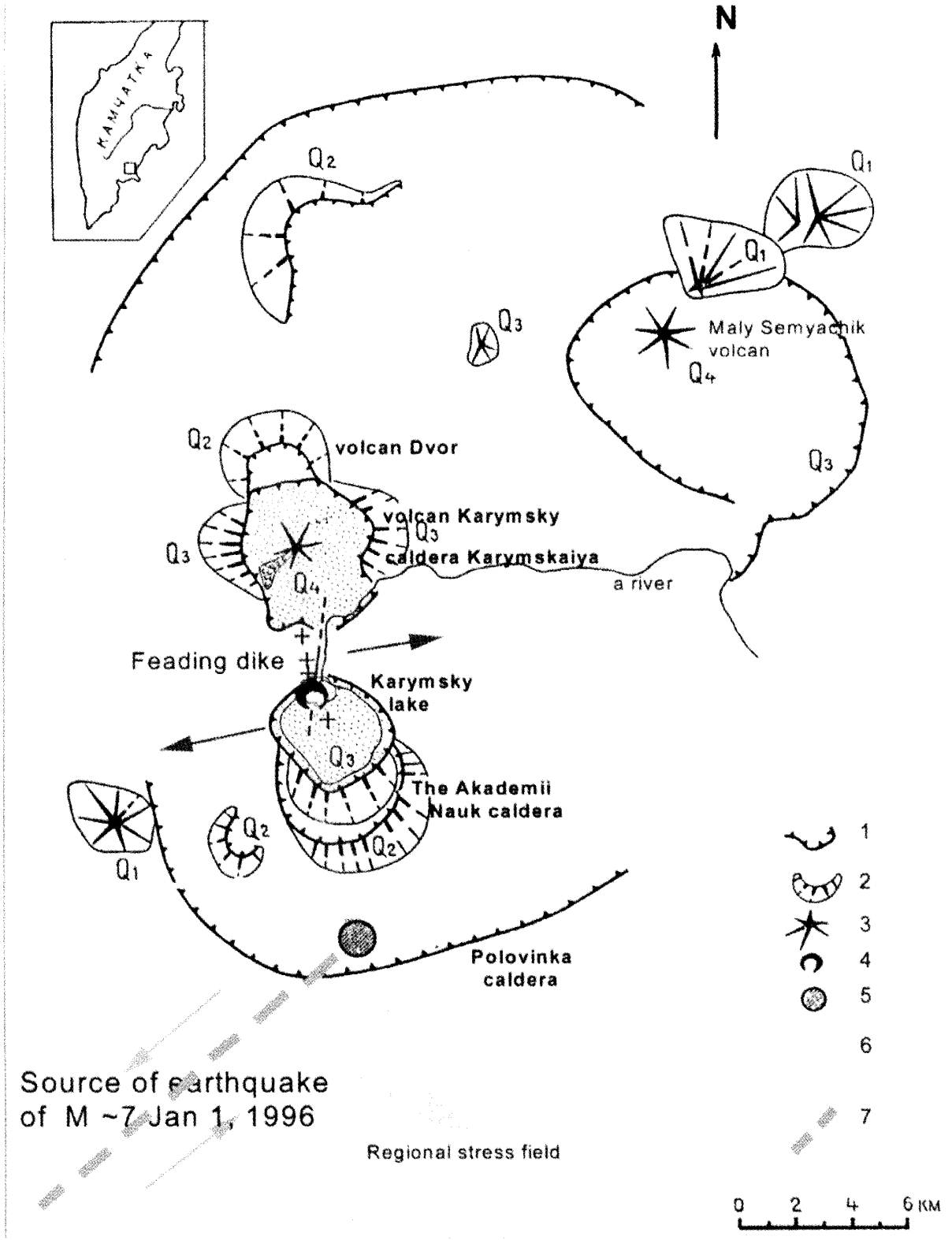

Fig. 14. Karymsky volcanic center: a scheme of magma intrusions and source of earthquake of M~7, January, 1-2, 1996: 1 - caldera scarps, 2- extinct volcanoes, 3 - active volcanoes, 4- underwater crater and new peninsula, 5- instrumental epicenter of main shock on January, 1, 1996, with M ~ 7; 6 - proposed position of feeding dike, 7 - proposed position source of the earthquake with M ~7. The map of volcanoes is given after Fedotov (1998). The sceme is compiled by V.V. Ivanov.

same features, only their intensity and duration vary.

The characteristic feature of the third stage is that before the eruption the upper part of the extrusive dome including magma-feeding funnel was covered with dense lava flows (from 10 to 60 m thick) of the previous eruption.

Eruptions alternate with the rest periods when energy accumulates for the next eruptions that occur from one to two times a year. The rest period and the eruption following after it make up a cycle of activity having four main phases: rest and accumulation of energy, extrusive and effusive eruptions. Main characteristics of each phase are given below.

Phase of rest lasts from a half of a year to a year. Very often fumarolic activity is observed above the dome; sometimes it is strong.

Phase of a weak extrusive eruption lasts from 1 to 3 months. During this period lava plug is slowly pressing out of the magma-feeding channel. At first thawed patches (in winter) and fissures appear in the area of the vent funnel. After that, blocks of lava elevated above the lava field surface are slowly pressing out of the funnel to the surface of the lava field. This can be considered the first precursors of the next explosive-effusive eruption.

Extrusive phase is completed by an explosive eruption forming long ash-gas plums and thick incadescent pyroclastic flows, which are the serious hazard. Large explosive vents, collapse and erosion grooves appear at the dome.

Usually short - term explosive phase transits into the effusive one with the outpouring of the viscouse lava flow which seals up the volcano funnel and completes the cycle of its activity.

This process recurs during 20 years and can be the basis for the mid-term prediction of the volcanic eruptions at its regular airal photographic survey.

Karymsky volcano. The preceding eruptive cycle terminated at Karymsky in October, 1982. The characteristic feature of that cycle was formation of the extrusive-effusive domes in the crater that periodically shut up the funnel. The strongest eruptions of the volcano were closely connected with the destruction of those lava plugs. From 1983 to 1995 the volcano remained in its rest stage. Around the volcano and southward from it strong earthquake swarms not associated with the eruptions took place very often (Leonov and Ivanov 1994: 115-131).

Since 1985 local seismicity has been concentrated around the Karymsky volcano and neighboring old caldera Akademii Nauk, where the volcanic activity stopped about 28,000 years ago (Fig. 14, Table 5). Level of seismicity gradually increased. An unusually strong for the continental Kamchatka earthquake of M 6.6 occurred in this area on January 1, 1996. It is suggested that the earthquake should be initiated by a quick rise of magma along the fissure to the ground surface.

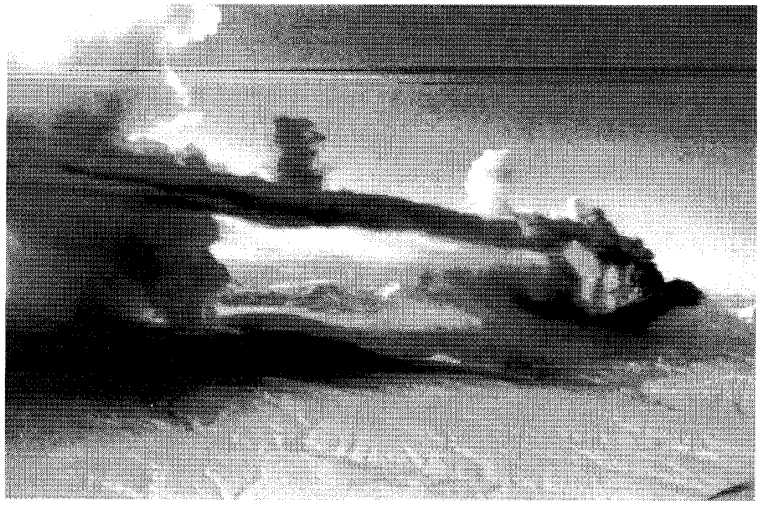

Fig. 15. The two simultaneous eruptions in the Karymsky volcanic center, on January 2, 1996. Right - the summit Karymsky eruption, left - the underwater eruption in the Karymsky lake (Akademii Nauk caldera). The distance between the craters is about 6 km (after Muravyev et al. (1998)). Photo by V.A.Podtabachny.

On January 2, 1996 a simultaneous eruption of the andesitic Karymsky volcano began and a new basaltic volcanic center started its growth at the bottom of the Karymsky lake (6 km southward from the volcano) in the Akademii Nauk caldera (Fig. 15). The activation of the old caldera is an extremely interesting phenomenon.

During 14 years of rest magma in the feeding channel of the volcano Karymsky solidified and did not move. That is why a new explosive funnel has been formed beyond the crater, at the southwestern slope of the cone, 100 m lower of the summit. During the first day of eruption (January 2, 1996) a continuous emission of the ash and gas took place from a new funnel having the diameter about 30 m. Then the outpouring was accompanied by strong explosions of Vulkanian type causing formation of the pyroclastic flows. Such an activity continued during half of a month. At the beginning of the second half of January, the explosive eruption was changed to explosive-effusive. A lump lava flow began outpouring from a new crater, 120 m in diameter.

During next years up to nowadays-strong explosions with periodical outpouring of lava flows to the south-east slope have been taking place at the Karymsky volcano.

Almost simultaneously with the activation of the Karymsky volcano another eruption began at the bottom of the Karymsky lake in the northern sector of the Akademii Nauk caldera, caused by the intrusion of basaltic magma along the fissure. This eruption continued almost a day and was accompanied by the strongest underwater explosions (Fig. 16) giving rise to a formation of large waves at the lake surface. The water temperature in the lake covered by ice increased up to 25 ℃ during a few hours. A peninsula with the diameter of the crater about 650 m was formed around the eruptive center (Fig. 17).

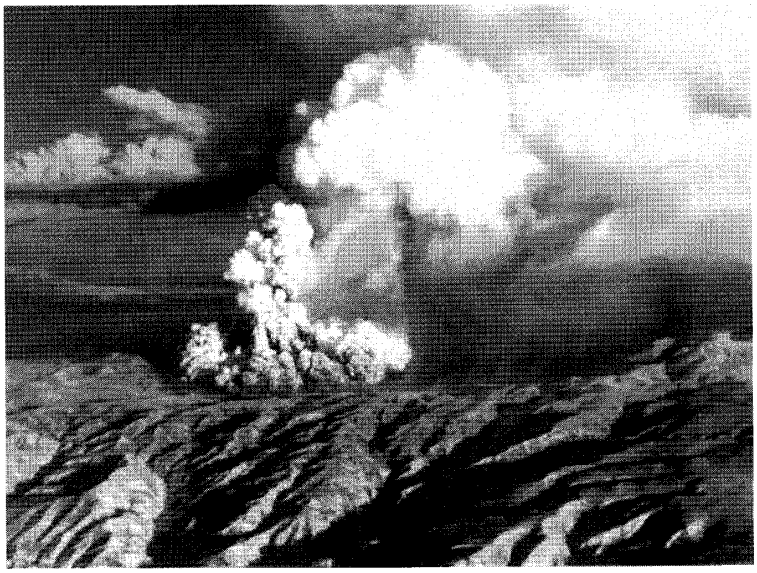

Fig. 16. One of the strong underwater explosions in the Karymsky lake (Akademii Nauk caldera, about 3:30 p.m., January 2, 1996). Relative height of the eruptive cloud top is 2.8 km, the diameter of base-surge diverging along the surface of the lake is about 2 km. View from the west-west-south. Photo by V.A. Podtabachny.

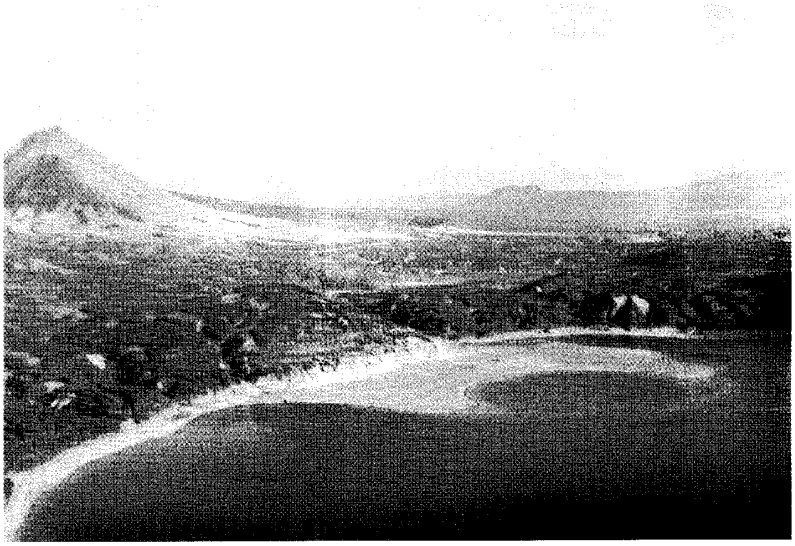

Fig. 17. Two explosive centers in the Karymsky area after stop of the simultaneous eruptions: the andesitic Karymsky volcano (to the left) and the new basaltic tuff ring (cinder cone) at the northern coast of the lake (to the right). The tuff ring looks like a new peninsula and its diameter is 650 m. Photo by A.V. Sokorenko.

Fresh and clean water of the lake became saturated with a great number of ejecta and acid. A great amount of fishes (a kind of red salmon) in the lake have died. The tsunami waves up to 15 m in height caused by the explosions washed out the lake shores and destructed all plants. This eruption led to the ecological catastrophe in the Karimsky lake and adjacent territory.

This eruption was followed by significant deformations of the earth surface. Maximum horizontal (up to 2.5 m) and vertical (up to 1.5 m) displacements have been revealed around the center of the eruption. Later, a system of fissures has been found which extended toward the Karymsky volcano to a distance up to 1 km (Fig. 18).

Avachinsky volcano (see Fig. 3) is located in the vicinity of Petropavlovsk-Kamchatski (25 km) and Elizovo (30 km). The volcano is of Somma-Vezuvian type consisting of the late Pleistocene somma collapse-explosive 4.5×4.0 km crater, formed about 30,000 years ago as a result of catastrophic eruption and of the active cone Molodoy which starting formation about 3,800 years ago (Melekestsev, Litasova and Sulerzhitsky, 1991). An altitude of the volcano is 2,730 m.

The last eruption of the volcano of January 13-19, 1991 happened after almost 46-years of rest. The eruption started from two blasts and was not preceded by either increasing of the seismic activity or any obvious deformations around the volcano.

During the eruption about 13×10^6 m^3 of lava was erupted to the surface. Lava filled the crater and outpoured to the southeastern slope of the cone as a flow 1.6 km in length and up to 350 m in width and about $0.15\text{-}0.20\times10^6$ m^3 of pyroclastic. By the lava and pyroclastic ratio, the 1991 eruption is effusive, by the quantity of the erupted material and intensity of magma effusion it is moderate or weak.

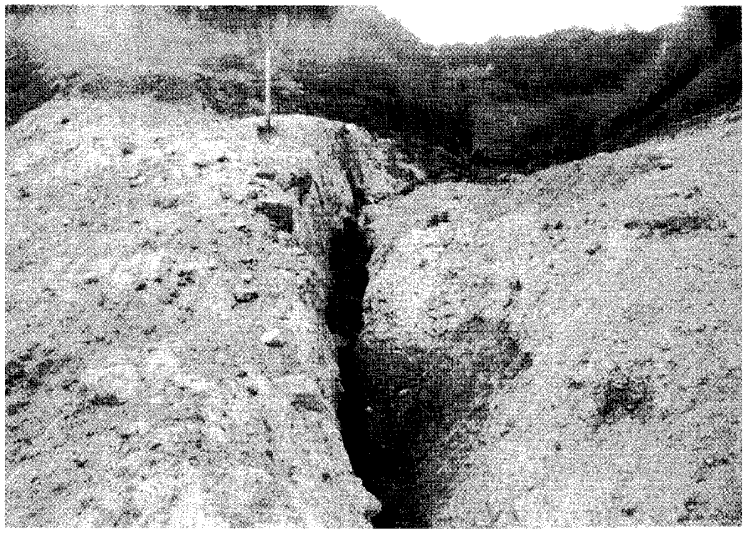

Fig. 18. Fractures at the northern coast of the Karymsky lake, along the fault produced by the injection of a basaltic magma into a feeding dyke on January 1-2, 1996. This was accompanied by strong earthquakes. Vertical displacement is about 1 m. Photo by V.L. Leonov.

Dense lava plug about 170 m thick and about 20 million tons in weight was formed as a result of the eruption. It makes difficult lava effusion and heat discharge by fumarolic steams between eruptions. That is why the possibility of the next strong eruption of the volcano increases. It should be noted that failure of the cone top faces to inhabited regions. It is quite possible there are weakened areas in the southern sector of the cone, closer to its top.

6. Conclusion

On the basis of the analyses of a great number of publications the main peculiarities of explosive volcanism of Kamchatka are following:

1. There are two modern volcanic belts of Kamchatka elongated in the north-north-east direction: the Eastern volcanic belt and the Sredinny (Median) range volcanic belt. At present the main activity is concentrated in the Eastern volcanic belt. The Eastern volcanic belt contains 27 active volcanoes; its length is about 850 km. The Sredinny belt is parallel to the Eastern belt, 200 km to the west of it. The activity of the Sredinny (Median) range volcanic belt ended several hundred yeas ago, and now there is only one active volcano Ichinsky and only solfatara activity is presented at this volcano.

2. Volcanism is closely connected with seismotectonic processes in the transition zone between the Asian continent and Pacific Ocean. The seismic focal zone is sinking under Kamchatka at the angle of about 50o. The volcanoes comprising the Eastern volcanic belt of Kamchatka are projected onto the seismofocal zone at the depths of about 100-220 km.

3. Northern Kamchatka is the area of the Kuril-Kamchatka and the Aleutian arc intersection. Relative transform movement of the Pacific and the North American plates at the western part of the Aleutian arc is of great importance for this area. The formation of the basic Aleutian arc structures was preceded by the initial stage of wide shear dislocations zone development, which caused wide-spread appearance of tectonic and magmatic processes in the area to the east of the Kamchatka subduction zone. The subduction of relatively "warm" and light lithosphere under Kamchatka and consequent decrease of the Kamchatka subduction zone incline angle are considered as a basic factor causing the Oligocene-Miocene arc magmatism zone shift to the West into the area of the Sredinny (Median) range.

4. The position of Northern Kamchatka volcanoes is quite an unusual one. Here the Eastern volcanic belt of Kamchatka shifts about 70km to the west. Besides, the seismofocal zone deviates to the west and the angle of inclination decreases. Seliverstov stated that this phenomenon coincides with the processes mentioned in point 3.

5. The history of Kamchatka volcanism starts from the Cretaceous. The activity becomes most intensive since the Upper Pliocene during the last 2-2.5 Ma. For this period, about 100 and 120 polygenetic

volcanoes were formed in the Eastern and in the Median (Sredinny) range volcanic belts, respectively. Besides, nearly 2,000 monogenetic volcanic structures (cinder and lava cones, extrusive domes, blast craters, maars and ignimbrite sheets) appeared. For the last 0.85 Ma, volcanoes of Kamchatka produced about 22,000 km^3 of erupted products (i.e., about 0.025 km^3 per year). 11% of them are the silicic ones (SiO_2>57%). The first stage of this period (850-250 thousands years ago) was characterized only by mafic (basaltic) eruptions. Silicic volcanism started about 250,000 years ago after a long period of mafic activity. At present, wide distribution of the silicic volcanism may be caused by large-scale development of magma differentiation processes within magmatic reservoirs in thick (40 - 50 km) earth crust of Kamchatka.

6. There are a great variety of interesting volcanic forms in Kamchatka. There are 28 active volcanoes here. The Klyuchevskoy volcano, one of the biggest basaltic centers of the world, Shiveluch and Bezymianny andesitic volcanoes with massive lava domes inside them, the Karymsky volcano and some others are the most notable among them. The Eastern volcanic belt of Kamchatka contains more than 20 Late Pleistocene - Holocene calderas and big explosive craters up to 19 km in diameter. In this century, 4 big explosive craters from 0.6 to 3 km in diameter were formed in Kamchatka: Iliynsky, 1901; Ksudach, 1907; Bezymianny, 1956; Shiveluch, 1964 and in the Karymsky lake, 1996.

7. Areal (one-act) volcanism is widespread in Kamchatka. In the past this type of volcanism was the main form of activity in Kamchatka. Such kind of volcanism is widespread within the Tolbachik and the Klyuchevskoy volcanoes areal zones, in Tolmachev Dol (Southern Kamchatka), in the basin of the Avacha river, and especially in the Sredinny (Median) range volcanic belt. It is possible that this type of eruptions will occur in Kamchatka in future. The most recent one-act eruptions took place in 1975-1976 within the Tolbachik areal zone and on January 2-3, 1996 in the Karymsky Lake.

8. The intensity of eruptive volcanism in Kamchatka is rather high. During the last 1000 years volcanoes of Kamchatka were 5 times more productive than the Japanese or the Kuril Islands ones. In 1991-1999, 12 eruptions took place in Kamchatka; the strong explosive eruptions of Shiveluch, 1993-1995, Klyuchevskoy, 1994, and inside the Karymsky volcanic center are notable among them. A huge lava dome of 350m in height, with the 1,000×1,700m^2 basement and the volume of 0.2 km^3 grew in the active crater of the Shiveluch volcano. Klyuchevskoy is a very active volcano; usually it is in the eruption state for about 20% of all the time. The Karymsky volcano is still erupting. That is why Kamchatka can be considered to be one of the most interesting areas for explosive volcanism studies in the world.

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