

Vegetation Dynamics and Ecological Consequences of the 1996 Eruption in Karymsky Volcanic Center, Kamchatka

V. G. Dirksen and O. V. Dirksen

*Institute of Volcanology and Seismology, Far East Division, Russian Academy of Sciences,
bul'var Piipa 9, Petropavlovsk-Kamchatskii, 683006 Russia*

e-mail: dirksen@kscnet.ru

Received December 26, 2005

Abstract—This paper provides an assessment of the degree and character of vegetation damage due to the 1996 phreatomagmatic eruption in Akademii Nauk Caldera and considers the mechanisms of post-eruptive vegetation recovery. Key features of the primary succession at the Novogodnii Peninsula have been revealed. The vegetation cover prior to the 1996 eruption is reconstructed, and the effect of minor ashfalls that occurred in 1996–2003 is examined.

DOI: 10.1134/S0742046307030025

INTRODUCTION

Karymsky Volcano, Kamchatka, resumed its activity on January 2, 1996, after a 14-year-long period of quiescence. Simultaneously, an eruption took place in the lake of Akademii Nauk Caldera. This unique event attracted great scientific interest and resulted in the publication of a number of works describing its different aspects—the course of its eruption, the composition of its products, surface deformation, and other features [10, 13, etc.]. Meanwhile, the environmental consequences of this eruption and its effect on the soil and vegetation in particular have not received appropriate

attention [1, 20]. In this paper we aim to assess the degree and character of the imprint that the eruption in Karymskoe Lake left on the local vegetation and reveal the features of its post-eruptive recovery.

DESCRIPTION OF THE AREA

Karymsky Volcanic Center is located 120 km north-east of the city of Petropavlovsk-Kamchatsky (Fig. 1a). It is a complex geologic structure consisting of a number of volcanic edifices of different compositions and several imposed calderas of different ages [8]. The

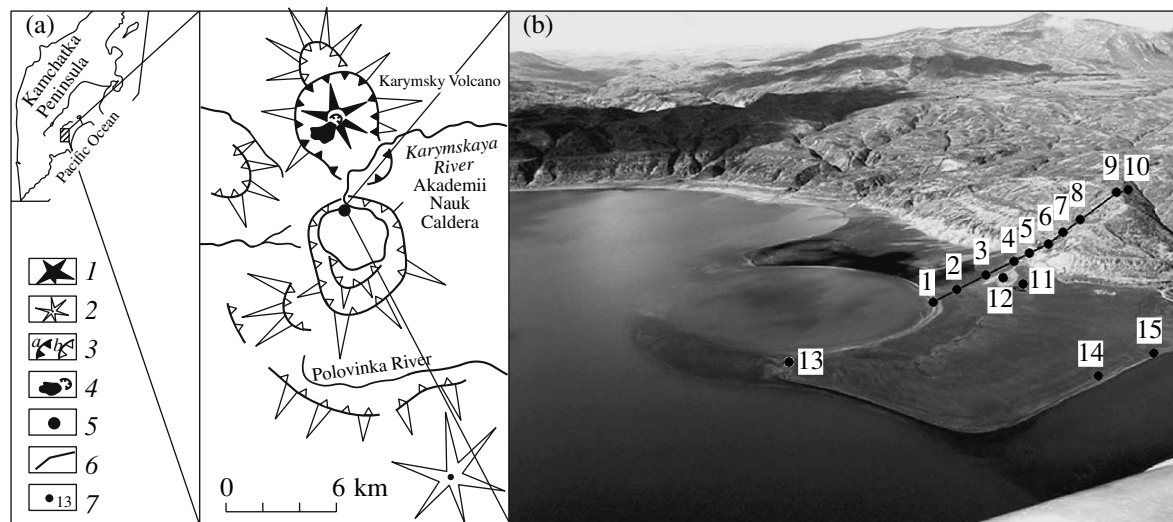


Fig. 1. Location of the study area; a—scheme of Karymsky Volcanic Center, modified from [8]: (1) Karymsky Volcano; (2) Pleistocene volcanoes; (3) caldera walls ((a) Holocene, (b) Pleistocene); (4) lava flow of the 1996 eruption; (5) eruption center in Karymskoe Lake; b—northern part of the Akademii Nauk Caldera wall and Novogodnii Peninsula (photo by V. V. Ivanov); (6) geobotanic profile; (7) location and numbers of observation points.

youngest caldera, Karymsky, was formed about 7.9 ^{14}C ka BP [3], and the volcano with the same name, the Karymsky volcano (54°03'N, 159°27'E), began to grow inside of the caldera about 5.3 ^{14}C ka BP [2]. This is one of the most active Kamchatkan volcanoes; its frequent eruptions have formed a cone about 700 m above the caldera floor; its altitude is approximately 1500 m above sea level (a.s.l.). The last cycle of its activity was observed in 1962–1982.

Akademii Nauk Caldera is about 30 ka old [8]. In contrast to Karymsky Caldera, the activity here was much weaker during the last 10000 years. Only one eruption, which occurred 6.5 ^{14}C ka BP, has been reliably reconstructed [2]. The eruption source was located near the head of Karymskaya River, quite near the place where a new center originated in 1996. Volcanic activity here is controlled by a deep longitudinal fault serving as a magma conduit [10].

Just prior to the eruption which occurred 6.5 ^{14}C ka BP, a large landslide took place at the head of the Karymskaya River that dammed the river and caused the lake level to rise [2]. As a result, a lacustrine terrace was formed around the lake, with an elevation of ca. 80 m above the present lake level.

The climate is relatively mild, with an average air temperature of -14°C in January and $+10^{\circ}\text{C}$ in July. Snow cover on the eastern (windward) slopes may exceed 2 m in the winter [7].

The vegetation of the area has not been studied in detail, although some general features were reported in [6, 20]. A zone of stone birch (*Betula ermanii*) forest extends from the Pacific coast to 400–500 m above the ocean. Yet higher, a zone of subalpine bushes is located, in which shrub alders (*Alnus fruticosa*) dominate. In the upper part of this zone, on the gentle slopes of ancient volcanic edifices, dwarf pine (*Pinus pumila*) occurs. Mountain dwarf-shrub and lichen tundra dominate between 900 and 1100 m a.s.l. Inversion tundra appears at leveled surfaces in depressions within the forest and subalpine zones.

The eruption on January 2, 1996, began simultaneously from two sources, in a newly formed crater close to the summit of Karymsky Volcano and in the northern sector of Karymskoe Lake. Its main parameters are reported in [10, 13].

The eruption of the volcano was purely explosive for the first 13 days and then passed into an explosive–effusive phase that has lasted until the present time. Lava flows, mainly of andesitic composition, descended the northern slope of the volcano, almost completely lacking vegetation, to the caldera wall. The volume of lava reached 11 mln m^3 by January 3, 1997. The initial tephra fell southwest and southeast of the volcano at distances up to 50 km away. Later ashfalls were observed eastward due to the prevailing wind direction. The thickness of ash falling outside of Karymsky Caldera, as estimated by [1], was about 3–6 mm per year.

The phreatomagmatic eruption in Karymskoe Lake was much shorter, and on January, 3, volcanic activity ceased. The height of the eruption column was 5 to 8 km. Strong explosions were accompanied by base surges and tsunamis that hit the sides of the Akademii Nauk Caldera. Muraviev et al. [10] estimated the surge temperature as 300–400°C. The ash cloud drifted primarily to the southeast. As a result of the eruption, a new peninsula, later called Novogodnii, was formed in the northern part of the lake and dammed the head of the Karymskaya River (Fig. 1b). The lake level rose by more than 3 m. The aquatic vegetation and fauna were completely destroyed. On land, the caldera wall proximal to the eruption center was especially devastated. Prior to the eruption it had been covered by dense vegetation. This area was chosen for our study. The main devastating agents of phreatomagmatic eruption of 1996 were (i) base pyroclastic surges, (ii) tephra, and (iii) tsunamis. Periodic small ashfalls from the activity of Karymsky Volcano since 1996 should be considered as an additional agent.

APPROACH AND METHODS OF STUDY

The vegetation of the area was studied in 2003 based on geobotanical descriptions of plant communities from habitats characterized by different eruption impact. A geobotanical profile was made on the northern wall of Akademii Nauk Caldera (Fig. 1b) where the strong, single-stage, and spatially localized impact of the phreatomagmatic eruption (1996) was the most pronounced. The profile was traced from the lake level to the watershed outside of the caldera at altitudes of 624–756 m a.s.l. A series of geobotanical plots were described at Novogodnii Peninsula (Fig. 1b). The total percentage of vegetation cover, the coverage of each vegetation layer, and each species of vascular plants were estimated within plots 10 × 10 m across. Species of mosses and lichens were not identified. We evaluated mean height, phenologic status, and vitality of dominant species, and for bushes, in addition, mean and maximum stem height and diameter were measured. Vascular plant nomenclature is given according to [12]. Geobotanical data are presented in Tables 1 and 2. At the studied plots, the upper 20–30 cm of soil–pyroclastic sequence (SPS) were examined.

At the caldera rim (point 9 at Fig. 1b), four samples from SPS, each 0.5–1 cm thick, were taken for pollen analysis. These were processed by standard technology [18]. Three samples had relatively high pollen concentrations. The rates of pollen taxa were calculated as a percentage of their sum (Table 3). The sample from the bottom 1996 eruption tephra contained only 22 pollen grains, so the percentages of taxa were not calculated in it.

Table 1. Geobotanic records along the profile

Numbers of points at the profile	1	2	3	4	5	6	7	8	9	10
Altitude above sea level, m	624	632	640	644	653	678	697	719	756	754
Overall projective coverage, %	+	1	2	1	+	45	55	70	90	95
Projective coverage of mosses, %								+		+
<i>Calamagrostis purpurea</i>	+	+	1	1	+	3	3	4	4	1
<i>Rorippa palustris</i>	+	+	+	+						
<i>Chamerion angustifolium</i>		+	+			3	2	3	3	
<i>Poa malacantha</i>		+	1	+	+	+				
<i>Artemisia opulenta</i>		+	+	+						
<i>Tanacetum borealis</i>			+				1			
<i>Oxyria digyna</i>			+							
<i>Carex koraginensis</i>			+		+		+			
<i>Heracleum lanatum</i>			+	+		1		2		
<i>Salix arctica</i>				+			1			
<i>Alnus fruticosa</i>			+			+	1	2	2	3
<i>Spiraea beauverdiana</i>						+			+	+
<i>Veratrum oxycephalum</i>						+	+	+	+	
<i>Artemisia arctica</i>							2			
<i>Geranium erianthum</i>			+				1			
<i>Saussurea pseudo-tilesii</i>							1	1		
<i>Castilleja pallida</i>							+			
<i>Pedicularis resupinata</i>							+			
<i>Bistorta vivipara</i>							+			
<i>Thalictrum minus</i>							+			
<i>Senecio cannabifolius</i>								+		
<i>Sorbus sambucifolia</i>								+	4	4
<i>Pinus pumila</i>								+	+	4
<i>Maianthemum dilatatum</i>									+	1
<i>Trientalis europaea subsp. arctica</i>									+	+
<i>Aruncus dioicus</i>									+	
<i>Streptopus amplexifolius</i>									+	

Note: Indicators of abundance of a species combined with the values of projective coverage correspond to the following grades of the Drude scale: +—less than 1% (un); 1—1–5% (sol); 2—5–10% (sp); 3—10–25% (cop-1); 4—25–50% (cop-2). Only alive plants were accounted when measuring the projective coverage. Moss species were not identified.

RESULTS AND DISCUSSION

Damage of vegetation by the eruptions of 1996 and main mechanisms of its recovery were reconstructed based on the complex data we obtained in 2003 and the materials published by other researchers. It should be mentioned that, despite the large number of publications on the 1996 eruption in Akademii Nauk Caldera, it appeared impossible to estimate the contribution of each agent (tephra, pyroclastic surges, tsunamis) separately. Likewise, the role of individual ashfalls that occurred at Karymsky Volcano in 1996–2003 can hardly be assessed because of the thinness of deposits and vigorous redeposition of pyroclastic material wher-

ever not fixed by vegetation. Thus, we are forced to consider mainly the integral influence of volcanic activity on the vegetation of the study area unless the character of damage enables us to identify the contribution of particular agent.

By the data collected along the profile, eight localities were outlined in the habitats that differ by their distance from the source of the 1996 explosive eruption. These localities show various character of damage and mechanisms of post-eruptive recovery.

Locality 1 includes the narrowest part of Novogodnii Peninsula from the shoreline of Karymskoe Lake to

Table 2. Geobotanic records at Novogodnii Peninsula

Numbers of observation points	11	12	13	14	15
Overall projective coverage, %	2	2	7	3	9
Projective coverage of mosses, %	+		5	2	6
<i>Calamagrostis purpurea</i>	1	+	2	+	3
<i>Rorippa palustris</i>	1	+	+	+	+
<i>Chamerion angustifolium</i>	+		+	+	+
<i>Poa malacantha</i>		1	5	1	1
<i>Artemisia opulenta</i>	+	+	+	+	+
<i>Tanacetum borealis</i>		1			
<i>Oxyria digyna</i>		+			
<i>Carex koraginensis</i>		+	+	+	+
<i>Heracleum lanatum</i>		+			+
<i>Salix udensis</i>	+			+	+
<i>Salix arctica</i>	+				
<i>Alnus fruticosa</i>		+	+	+	
<i>Equisetum arvense</i>	+				+
<i>Juncus sp.</i>	+		+		+
<i>Eleocharis palustris</i>	+		+		
<i>Saxifraga sp.</i>				+	
<i>Geranium erianthum</i>		+			
<i>Lerchenfeldia flexuosa</i>					+
<i>Leymus interior</i>					+
<i>Epilobium glandulosum</i>					+
<i>Stellaria sp.</i>					+

Note: The sign “+” means that a species was present in the test site. Moss species were not identified.

the foot of the caldera wall. The vegetation dynamics here is considered in a separate subsection below.

Locality 2 is a slope 30–35° steep in the lower third of the caldera wall. Considering the undisturbed vegetation around the lake, the communities dominated by shrub alder had to occupy this locality before the eruption (Fig. 2). The alder perished completely. The erosion by pyroclastic surges and tsunamis, favored by the proximity to the eruption source and convex profile of this part of the slope, utterly removed the soil and exposed the bedrock tuff. Only primary succession occurs here because of total damage of vegetation (Fig. 3). After seven years, only sporadic herbs, mainly the graminoids, are found (column 5 in Table 1).

Locality 3 is outlined at the subhorizontal surface of the lake terrace (Fig. 3). A thick layer of alder branches and stems is found beneath the 1996 tephra bed. A few dead stems, up to 15 cm in diameter, are kept in a vertical position; their bark is totally abraded from the lakeside. From the opposite side, it is charred and locally preserved. These features suggest that the speed and temperature of surges were quite high here. The combination of thermal, mechanical and, possibly,

chemical impact caused almost complete destruction of vegetation in this locality. The average thickness of coarse pyroclastic material deposited here is 8 cm. Nevertheless, the volcanic influence was not uniform here; some patches of buried soil remain under the dead bushes and pyroclasts. Redeposition of loose material locally decreased the initial thickness of ejecta. In such places, *Calamagrostis purpurea*, *Heracleum lanatum*, *Veratrum oxycephalum*, and several other species able to grow through a thin tephra apron [20], appeared (column 6 in Table 1). In general, wood-reed (*Calamagrostis purpurea*) and fire weed (*Chamerion angustifolium*), up to 1.6 and 2 m tall, correspondingly, dominate the modern vegetation.

Pioneer herbs are grouped in spots on bare surfaces associated mainly with local pits. In some pits, where the roots are able to reach the buried soil, plant cover may exceed 40–50% (column 6 in Table 1) that gives evidence of rather high rates of recovery. Also, accidental adults of alder up to 70 cm tall were observed here. The recovery of alder can be ascribed to vegetative regeneration due to roots preserved in the buried soil [5]. Thus, secondary succession develops on the subho-

Table 3. Palynologic characterization of the periods of recent history of study area

Sample number	1		2		3	4	
Time period	buried soil		top of buried soil		tephra base	modern surface	
Amount of taxa (# and %)	#	%	#	%	#	#	%
<i>Pinus pumila</i>	118	25.1	146	27.7	10	39	7.7
<i>Betula platyphylla</i>	1	0.2	1	0.2			
<i>Betula ermanii</i>	47	10.0	51	9.7	3	8	1.6
<i>Betula divaricata</i>			1	0.2			
<i>Betula exilis</i>			4	0.8			
<i>Alnus hirsuta</i>	1	0.2	1	0.2			
<i>Alnus fruticosa</i>	97	20.6	113	21.4	3	102	20.2
<i>Salix</i>	3	0.6	1	0.2		1	0.2
Sum of tree and bush pollen	267	56.8	318	60.2	16	150	29.8
<i>Ericaceae</i>			1	0.2			
<i>Cyperaceae</i>	13	2.8	4	0.8		10	2.0
<i>Poaceae</i>	135	28.7	145	27.5	5	132	61.9
<i>Artemisia</i>	4	0.9	2	0.4			
<i>Saussurea</i>			1	0.2			
<i>Cirsium</i>			1	0.2			
<i>Senecio</i>			1	0.2			
<i>Polygonaceae undif.</i>	1	0.2	1	0.2			
<i>Rumex</i>			1	0.2			
<i>Rosaceae undif.</i>	10	2.1	6	1.1		2	0.4
<i>Filipendula</i>			1	0.2			
<i>Sanguisorba officinalis</i>			2	0.4			
<i>Ranunculaceae undif.</i>	2	0.4	3	0.6			
<i>Thalictrum</i>			3	0.6			
<i>Geranium</i>	1	0.2				1	0.2
<i>Heracleum</i>	7	1.5	3	0.6	1	13	2.6
<i>Chamerion angustifolium</i>	1	0.2	1	0.2		15	3.0
<i>Rubiaceae</i>	1	0.2					
<i>Violaceae</i>	3	0.6	10	1.9			
<i>Liliaceae</i>			3	0.6			
<i>Trientalis</i>			1	0.2			
Undetermined	4	0.9	6	1.1			
Sum of herb and bush pollen	182	38.7	196	37.1	6	353	70.0
<i>Sphagnum</i>	20	4.3	13	2.5			
<i>Polypodiaceae</i>	1	0.2	1	0.2			
<i>Diphasiastrum alpinum</i>						1	0.2
Sum of spores	21	4.5	14	2.7	0	1	0.2
Totally	470	100	528	100	22	504	100

Note: Percentage of taxa: # means absolute amount of pollen and spores, %, percentage

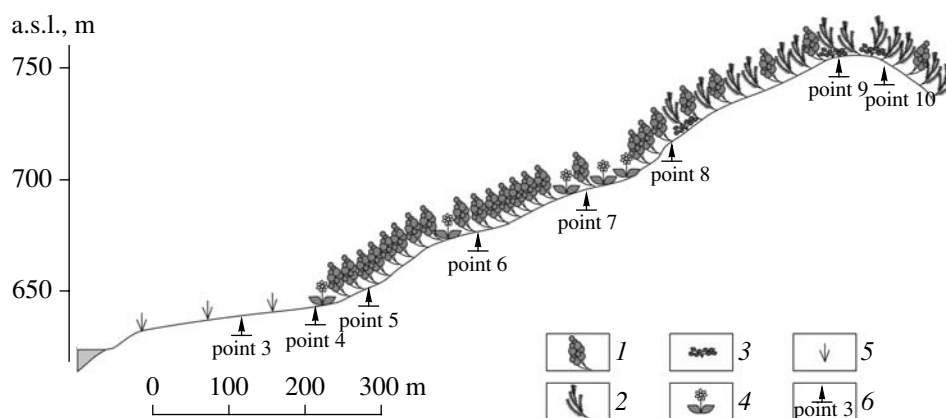


Fig. 2. Geobotanic profile across the Akademii Nauk Caldera wall. Vegetation before the eruption of 1996: (1) shrub alder; (2) dwarf pine; (3) participation of dwarf rowan in plant communities; (4) forb sub-Alpine meadows; (5) relatively less dense plant groupings along the lake shore; (6) observation points at the 2003 profile.

horizontal surface of the lake terrace, with participation of vegetatively recovering species.

In *Locality 4* (that is, the gently inclined rear of the lacustrine terrace and the foot of the adjacent bedrock bluff—Fig. 3), diverse subalpine meadows with alder stands and tall grasses in the understory had to predominate (Fig. 2) before the eruption. Here the soil and vegetation cover were damaged selectively, depending on microtopography. Some bushes survived in the pits and gullies (including the individuals of alder up to 2.3 m tall, and *Salix arctica*, up to 0.5 m). The bark is severely abraded but not burnt at the dead stems. Such a mode of devastation could be determined by heavy snow cover that protected, to some degree, the vegetation from pyroclastic surges at the rear of the terrace. This is supported by relatively high species diversity (see column 7 in Table 1), as well as the presence of species quite sensitive to volcanic influence and unable to reproduce vegetatively (*Geranium erianthum*, *Pedicularis resupinata*, *Thalictrum minus* and others). The height of the surviving alder suggests that the snow cover in concavities of the slope and in the pits had to be more than 2.5 m thick. Hence, the secondary succession began to form in *Locality 4* with shrubs and mesophytic herbs (*Geranium erianthum*, *Artemisia arctica*, *Saussurea pseudo-tillesii* and others), which participated in pre-eruptive plant communities. In general, the rate of secondary succession growth here is quite high owing to closer sources of recovery and accessibility of buried soil.

Locality 5 spans along the upper steep part of the caldera wall with an angle of about 45° (Fig. 3). This area was likely covered by alder communities with spirea (*Spiraea beauverdiana*), dwarf rowan (*Sorbus sambucifolia*), and tall herbs in the understory before the eruption. Dwarf pine was residing closer to the caldera rim (Fig. 2). Most of the bushes died in the eruption; only a few alders, up to 2 m tall, with a stem diameter of approximately 10 cm, were observed to

survive in pits and gullies on the slope, where the snow cover was the thickest. Surviving rowan and dwarf pine, two individuals of each species, have been found in similar habitats. The latter is extremely sensitive to volcanic activity [14] and could survive only if protected by heavy snow packs. In the modern vegetation, wood-reed up to approximately 1.7 m tall dominates, co-dominant is fire weed 2 m high and taller (see column 8 in Table 1). The plant composition is similar to that in *Locality 3* (column 6 in Table 1) but the vegetation cover is denser and some mosses, mesophytic herbs (*Saussurea pseudo-tillesii*) and tall herb species specific for Kamchatka (*Senecio cannabifolius*) occur sparsely. At the same time, the steep and convex slope at this locality had to be ruined more severely than the rear of the terrace represented by *Locality 4*, as the species diversity and the rate of meadow mesophytes are lower here. As in *Locality 3*, secondary succession involves vegetatively reproducing plants.

Outside of the caldera the profile goes toward the watershed area, which is truncated by a steep slope of the Karymskaya River valley. The watershed marks a distinct border dividing the southeastern slope facing the caldera, which was severely damaged, and the northeastern slope with much weaker evidence of eruption impact.

Locality 6 includes the southeastern slope from the caldera rim to the top of the watershed (Fig. 3). Throughout the slope, broken stems of bushes are found, which remain vertical. Among these, stumps of dwarf pine up to 21 cm in diameter are abundant. Dwarf pine was killed here completely. Alder was damaged selectively—some bushes were heavily abraded and perished, while others were not and continued to grow and reproduce. Bear in mind that protection by snow cover was unlikely here because of the total absence of other surviving shrub species. A number of reasons for the weaker volcanic damage here can be proposed, (i) the sharp slope, bent from 45° below to 10°–15°

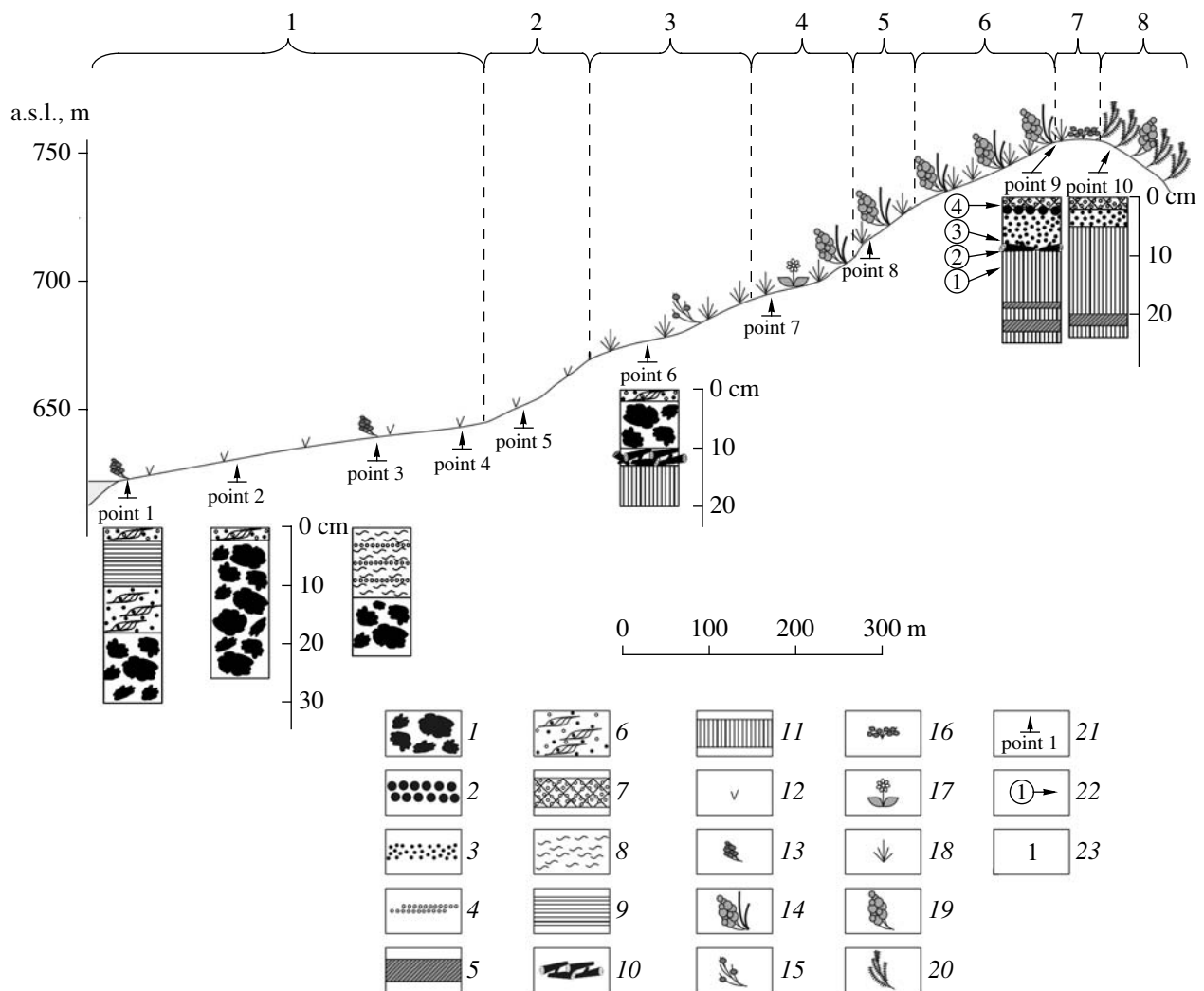


Fig. 3. The profile across the Akademii Nauk Caldera wall documenting the vegetation dynamics after the 1996 eruption: (1–3) pyroclasts of the phreatomagmatic eruption: (1) coarse, mainly bombs; (2) lapilli; (3) sand-sized; (4–5) tephra of Karymsky Volcano: (4) 1996–2003; (5) 1962–1982; (6) redeposited pyroclastic material; (7) pyroclastic material fixed by vegetation; (8) alluvial fans; (9) lacustrine loam; (10) buried trunks and branches of bushes; (11) buried soil; (12–13) primary succession: (12) pioneering groups of weeds; (13) shrub alder offspring; (14–18) secondary succession, with: (14) shrub alder, more or less wounded; (15) shrub alder, reproduced vegetatively; (16) dwarf rowan; (17) forb meadows; (18) *Calamagrostis* and willow-herb; (19–20) recovery of plant communities: (19) shrub alder communities; (20) dwarf pine communities; (21) location and numbers of observation points; (22) location and numbers of sampling sites; (23) particular areas of devastation and recovery of vegetation.

above, and further away, to a yet more gentle angle of the watershed surface outside of the caldera, could decrease the kinetic energy of the surges, (ii) the surges hit this place by their upper part, which is less sediment-laden, (iii) distance from the eruption source decreased both the temperature and mechanical impact of a surge—indeed, the abrasion of alder stems is weaker here than in previous localities, and burnt bark is not found at all. Perhaps all three reasons played their role in the selective damage of the shrubs. A portion of the shrub alder, which is not that sensitive to volcanic impact [9], survived, while other shrubs, the dwarf pine first of all [14], did not. The plant composition observed here is the same as in localities 3 and 5, but the rate of secondary succession is higher. The 5.5–7 cm thick

layer of pyroclasts of 1996 eruption has been partially fixed by wood-reed roots and fall that has decreased post-eruptive aeolian and other kinds of redeposition and, hence, favored plant colonization.

Locality 7 occupies the top of the watershed (Fig. 3). Broken stems and bush stumps are also met here but the cover of surviving bushes is much higher and reaches 40–45%. Alder (up to 2.5 m tall, stem diameter up to 10 cm), dwarf pine (2.0 m and 17 cm, correspondingly), and spirea (0.5 m tall) are present in modern vegetation (see column 9 in Table 1). The dominant species is dwarf rowan 1.0–1.7 m tall, which covers about 35% of the surface. Among the herbs, wood-reed and fire weed predominate. Small herbs common to the

understory of subalpine bushes in southeastern Kamchatka, such as *Linnaea borealis*, *Viola biflora*, *Lycopodium annotinum*, some species of mosses and others [11], are still absent. Nevertheless, *Maianthemum dilatatum* and *Trientalis europaea* subsp. *arctica* appear in the ground layer for the first time along the profile in locality 7 (column 9 in Table 1). These species are among the most sensitive to volcanic activity [16, 19]. They were found together with *Aruncus dioicus* and *Streptopus amplexifolius* under the canopies of large bushes, where the pre-eruption turf remains uncovered by tephra. Even a few individuals of these small herbs in the present vegetation indicate significant weakness of volcanic impact. As well, the number of survivors increases in this locality and includes individuals of dwarf pine beyond the watershed. The plant composition observed here is quite unusual. This may be explained by selective volcanic affect and the character of the secondary succession. It could be hypothesized that before the eruption there were dwarf pine stands with dwarf rowan and alder as minor components (Fig. 2). The eruption hit the dwarf pine more severely than the alder, even at the edge of the devastation zone. After this, the dwarf rowan, due to its ability for vegetative regeneration, greatly increased in number and occupied the habitats previously taken by dwarf pine (Fig. 3).

Locality 8 (Fig. 3) begins beyond the break in slope dividing the gentle slope of the watershed area and the steeper (about 35°) slope of the Karymskaya River valley. In the upper part of the valley slope, dwarf rowan, dwarf pine, and alder cover up to 100% of the surface (column 10 in Table 1), and no perished or damaged individuals are found among the bushes. Dwarf pine 1.5–2 m tall predominates, with a mean stem diameter of 12 cm. Diverse meadows with some spirea are subordinate. Wood-reed is strongly decreased, and fire weed almost absent in this locality, despite the fact that these two species dominate almost the entire profile. The influence of the pyroclastic material which erupted in 1996, which is about 3 cm thick here, is manifested in lower species diversity, lesser density of understory herbs, and almost total absence of mosses. In similar dwarf pine—dwarf rowan communities beyond modern volcanic influence, as described in Kronotsky Natural Resort, Kamchatka, the cover of mosses may reach 80% [11]. The absence of dead dwarf pines provides evidence of a drastic decrease of the destructive capacity of pyroclastic surges and/or for the thick snow cover at the leeward and concave slope of the Karymskaya River valley that protected the soil and vegetation. Thus, most of the species that existed here before the eruption were preserved and are successfully reproducing, which determines the general trend of vegetation recovery in this locality.

The described profile characterizes the northern part (as wide as ca. 1 km) of Akademii Nauk Caldera proximal to the explosive crater of 1996. Southwest of it, (Fig. 1b) within a distance of ca. 500 m, the impact of

the 1996 eruption on the vegetation was quickly decreasing. In the lower part of this area the soil cover was not disturbed at all. Similar to localities 4–6, only the microtopography-controlled selective damage of bushes is observed. Wood-reed and fire weed predominate in modern plant communities, and shrub alder is associated with pits and gullies. At the lacustrine terrace and the adjacent slope of the caldera wall most of the alder survived. Southwestward, the caldera wall is covered with dense alder bushes with no traces of eruptive impact.

It should be noted that most of local plant communities, which are prone to weak but frequent ashfalls produced by the ongoing eruption of Karymsky Volcano, must be regarded as more or less volcanically disturbed. For example, in the southeastern part of Akademii Nauk Caldera, about 4 km away from the center of phreatomagmatic eruption we described tundra and meadow communities having similar features to the dwarf pine community in locality 8, near the source of eruption. Both are characterized by unclosed plant cover, alternation of vegetated spots and barren surfaces where aeolian redeposition of tephra continues. Nevertheless, no dead mature individuals of bushes and dwarf shrubs (*Salix arctica*, *Empetrum nigrum*, *Vaccinium uliginosum*, etc.) were observed. Still, the inhibition of ground plant layers determines poor species diversity and, likely, lower biological production of these communities in general.

Primary succession at Novogodnii Peninsula is characterized by four plots on the profile (Fig. 1b and columns 1–4 in Table 1) and five plots not on the profile (Fig. 1b and columns 11–15 in Table 2).

The surface of the peninsula is covered by coarse pyroclastic material (observed size up to 1 m across). Fresh scoria may be chemically aggressive; this substrate is poor in nutrients and has low water-holding capacity; erosion and aeolian denudation are rather strong—all these conditions are stressful for plant invasion. Seven years after the eruption, 95% of the peninsula remains deserted. Invasion of the first colonizing species is observed mostly along the coastline, in a zone 15–20 m wide (sites 1, 2, 13–15), where the groundwater depth is about 40 cm, and the scoriae are covered with a 5–20 cm thick apron of wet sand reworked by water. The most successful advance of vegetation takes place in a narrow band of 3–4 m wide in 1 to 3 meters away from the shoreline (sites 13, 15). Vegetation cover is sparse, the pioneer plants are grouped in strips parallel to the shoreline stretching along small coast bars. Sporadic plants were found in explosive pits within the peninsula (site 11) at the groundwater discharge at the bottom or walls of the pits. As is seen from the above description, the initial stage of primary succession takes place only if plants are able to reach groundwater.

The diversity of species is rather high, but graminoids such as *Calamagrostis purpurea*, *Poa malac-*

tha, *Leymus interior*, etc., which commonly are pioneers on immature volcanic substrates, are the most common species [15]. Another important group is represented by species of wide ecological range, which also often pioneer the vegetation recovery—*Chamerion angustifolium*, *Artemisia opulenta*, and several others. *Rorippa palustris* and *Eleocharis palustris* can likely be regarded as facultative thermophiles [11, 15] and are present in areas of geothermal activity in the peninsula (site 11, explosive pit; site 13, edge of crater). This pioneer vegetation is most diverse in the narrowest part of the peninsula between the northern side of the caldera and the edge of explosive crater, and at the periphery of fans (sites 3, 12). Meadow mesophytes (*Geranium erianthum*, *Heracleum lanatum*), petrophytes (*Oxyria digina*) and some typical subalpine species (*Carex koraginensis*, *Salix arctica*) appear at the initial successional stage, obviously, due to washout of their seeds by seasonal streams from the caldera wall, where they participate in local communities. Spatially the mesophytic herbs, which are not as adapted to extreme conditions of scoria substrate, are confined to the fans forming thin loamy crusts on the surface of coarse tephra. These crusts have greater water-holding capacity and are rich in nutrients coming down from the caldera wall with the erosion of buried soils. Mature plants able to reproduce have not been found among these species and, therefore, the role of such species in the primary succession cannot be evaluated.

Shrub alder is the most interesting participant of the primary succession. This species is nutrient-demanding [14] which restricts its role in colonizing immature substrates. Notwithstanding, viable alder seedlings 5–30 cm tall were seen in the pioneering groups in the coastal zone of the peninsula, in 10 to 15 m from the shoreline (sites 13, 14). Several pits were dug beneath them, which showed that the roots of these seedlings are related to a layer of bedded gray loam 0.5 m deep in 5 m, and 8–10 cm, in 15 m away from the shoreline. The thickness varies from 1 to 13 cm, a horizontal lamination occurs near the bottom. Alder seedlings are strictly related to this layer, and their roots may spread horizontally, following it for a meter or more. Along with the coastal zone of the peninsula, such a layer was found at the eastern shore of the lake. Its bedding suggests a lacustrine origin that can be related to the rise of lake level. Such an event took place in 1996 after the eruption when the new peninsula dammed the lake and thus increased its level to three or four meters [10]. Later in 1996 the Karymskaya River made a new bed and resumed the discharge of the lake. The lake level dropped to the virtually initial mark [10] and, as a result, the newly formed layer of lacustrine deposits was exposed to the surface. The nutrient values in this layer must be enough to support the growth of alder seedlings. In addition, low-permeable loam can hold enough water to feed the root systems. Similar properties perhaps are inherent to the fine-grained deposits of proluvial fans that allowed some individuals of alder

seedlings up to 20 cm tall to survive at their periphery (sites 3, 12).

Vegetation dynamics. Palynological data from the top of the watershed (site 9 in Fig. 3) allow us to reconstruct the vegetation in different periods (Fig. 4): in the 1982–1996 quiescence period (samples 1 and 2), at the beginning of the 1996 eruption (sample 3), and after the eruption until the present (sample 4).

Pollen data from the paleosol suggest that dwarf pine dominated the watershed before the 1996 eruption, and alder was subordinate. By the onset of the eruption (sample 2 in Table 3) the species diversity was rather high. Among the herbs, the mesophytic species common for subalpine meadows with alder clumps—*Saussurea pseudo-tilesii* (taxon *Saussurea*), *Cirsium kamschaticum* (taxon *Cirsium*), *Thalictrum minus* (taxon *Thalictrum*), as well as small herb species typical for the understory of dwarf pine and alder communities unaffected by modern volcanism—*Trientalis europaea* subsp. *arctica* (taxon *Trientalis*), possibly *Maianthemum dilatatum* (taxon *Liliaceae*), and *Viola* sp. (taxon *Violaceae*) were present. The nearest source of long-distance transported birch pollen may be the stone birch forest at the head of the Kedrovaya River 5 km southwest of the study area.

The most significant changes were detected in the posteruptive pollen assemblage (sample 4, Fig. 4). These reflect the character of vegetation damage and current recovery process on the watershed (site 9, Fig. 3). Dwarf pine that dominated here before the eruption was damaged more severely than the alder. This resulted in a change of dominants among shrub pollen taxa. Heavy injury of ground plant layer is expressed in the almost total absence of spores and herb pollen. Meanwhile, the secondary succession is documented quite well—the pollen of graminoids dominates absolutely and pollen of vegetatively-reproduced species (fire weed and cowparsnip) increase. A decrease in transported stone birch pollen may indicate the negative influence of frequent ashfalls at Karymsky Volcano on the birch forest despite the small thickness of ash and the distance between this forest and the eruption center. However, this issue requires further investigation.

Special consideration is needed for the pollen spectrum from the base of the 1996 tephra (sample 3 in Table 3). The pollen concentration there is very low and only regional components are present [21], while local taxa are not found. Thus, the spectrum comprises dwarf pine pollen, which can travel long distances because of its morphology; stone birch and alder taxa, known for their high pollen production; and pollen of graminoids, which are widespread in regional vegetation. Strictly speaking, only one pollen grain can be regarded as local in this spectrum, that of *Heracleum* [21]. Thus this pollen assemblage can be considered as a “background,” because most of its components are present in the pollen rain that falls throughout the year, and local taxa are virtually absent [17]. Such “background” spectra are

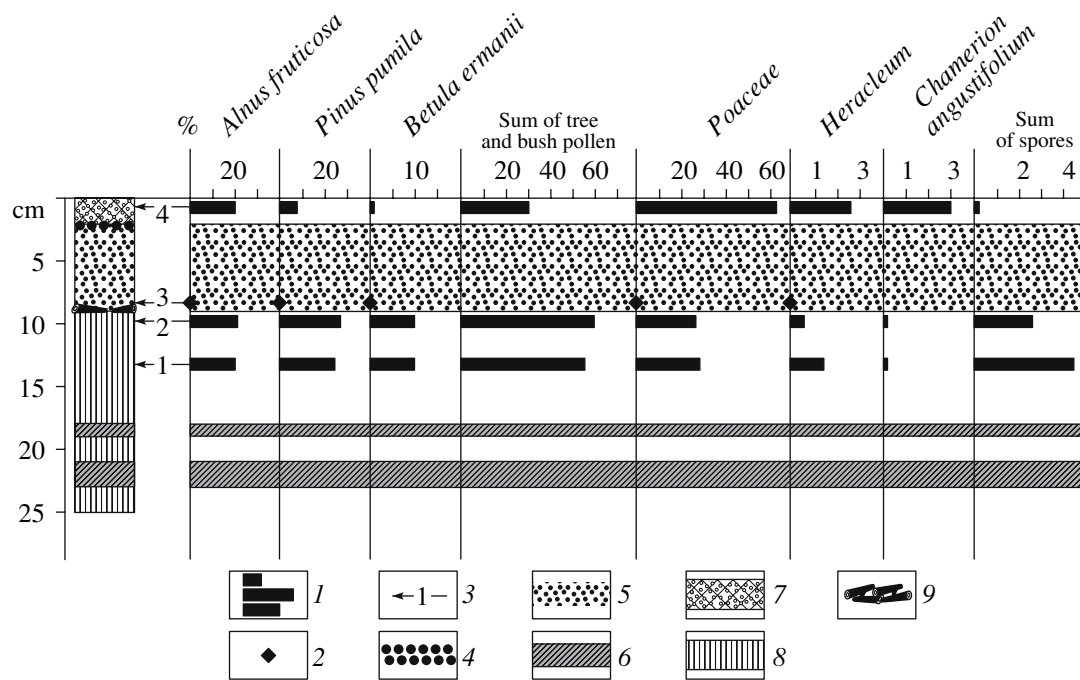


Fig. 4. Spore and pollen diagram showing main taxa of vegetation in different periods of recent history of the study area: (1) percentage of taxa in spore and pollen spectra; (2) accidental occurrence of taxa in spore and pollen spectra; (3) location and numbers of sampling sites; (4–9) see legend for Fig. 3.

typical, e.g., for glaciers above the upper vegetation limit, where local sources of pollen are absent [4]. It has been proved that pollen does not migrate along the considered profile with ground water; hence, the pollen assemblage of each ash layer is synchronous with the formation of that layer [6]. Thus, the pollen spectrum of the 1996 tephra could characterize the season of the beginning of the eruption, because a spectrum with such parameters could only form in the winter (i.e., before the beginning of vegetation season). If so, the composition of pollen spectra at the base of tephra layers could be used in the future to reconstruct the season of the beginning of pre-historic eruptions. We have already performed such an investigation [5], and our conclusions are confirmed by other data (Anderson, personal communication).

CONCLUSION

The obtained data allow us to identify the main patterns of vegetation dynamics caused by volcanic activity in the study area.

1. Primary succession started on the substrates of the newly formed peninsula. The main factors which limit the plant colonization are lack of nutrients and insufficient water supply in volcanic deposits.

2. The strongest devastation of vegetation occurred within a narrow zone, 1 km or less, at the northern side of Akademii Nauk Caldera southwestward of the head of the Karymskaya River (Fig. 1b). Combined effects

of a number of eruptive agents caused the almost total elimination of soil and vegetation in the lower part of caldera wall (locality 2 in Fig. 3), and primary succession began there after the eruption. Heavy impact of pyroclastic surges and tephra on the vegetation took place at the gently inclined lacustrine terrace (locality 3 in Fig. 3). Here the secondary succession developed, with domination of plants able to reproduce vegetatively.

3. In the upper part of the slope (localities 4–6) vegetation was damaged selectively depending on the topography and snow cover. Local species that were present in pre-eruptive communities participate in the secondary succession as well. The composition and contribution of these species are specific for each locality and are determined by the degree of volcanic impact. Similar features are observed outside of the considered profile, in a locality approximately 500 m long at the northern side of the Akademii Nauk Caldera southwestward of Novogodnii Peninsula (Fig. 1b).

4. Beyond the watershed (locality 7), the volcanic impact decreased drastically, and the most sensitive species survived. Rates of vegetation recovery are the highest here. There is no damage of vegetation at all at the steep side of Karymskaya River valley (locality 8) and in 500 m away from the eruption center. Thus the devastating effect of the 1996 phreatomagmatic eruption decreased very quickly and was dependent not only on distance but also on topography.

5. The intense activity of Karymsky Volcano, the frequent ashfalls in particular, determines the specificity of local plant communities, which are permanently at different successional stages.

6. Complex studies in the Karymsky Volcanic Center involving both the monitoring and pollen data provide a unique opportunity to take close look at vegetative recovery after volcanic crises. The patterns seen here may be used in the future to assess the stability and forecast the evolutionary trends of ecosystems in volcanic areas.

ACKNOWLEDGMENTS

The investigation was supported by Russian Foundation for Basic Research (grants no. 05-05-64517-a, 05-01-02901RFBR-JSPS, 05-05-66942RFBR-JSPS) and Foundation for Support of National Science.

The authors are grateful to G.A. Karpov and E.G. Lupikina for the aid in organization of field work funded by the grant of Presidium of Russian Academy of Sciences no. 03-3-A-05-063, and our colleagues I.V. Melekestsev and L.I. Bazanova for their consultations and kind advice. The comments of anonymous reviewers led the authors to correct the manuscript and, hopefully, improve it.

REFERENCES

- Andreev, V.I., Karpov, G.A., Magus'kin, M.A., and Miroshnikov, V.M., On the Influence of Eruptions in Akademii Nauk Caldera and Karymsky Volcano in 1996–2000 on the Environment (Landforms, Aquifers, and Vegetation), *Vestn. KRAUNTs*, 2003, no. 1, pp. 60–73.
- Braitseva, O.A., Phreatomagmatic Eruption in Karymskoe Lake (Eastern Kamchatka) ~6500 14— Years Ago and Pulses of Basaltic Material Supply in the Area of Karymsky Volcano in the Holocene, *Vulkanol. Seismol.*, 1997, no. 5, pp. 138–144.
- Braitseva, O.A., Melekestsev, I.V., Ponomareva, V.V., et al., Strong and Catastrophic Explosive Eruptions in Kamchatka during the Last 10 ka, in *Geodinamika i vulkanizm Kurilo-Kamchatskoi ostrovoduzhnoi sistemy* (Geodynamics and Volcanism of the Kuril-Kamchatka Island Arc System), Petropavlovsk–Kamchatskii, 2001, pp. 235–252.
- Dirksen, V.G., Palynological Peculiarities of Modern Landscapes in the Mountains of the North of Inner Asia, *Cand. Sci. (Geogr.) Dissertation*, St. Petersburg State University, 1999, p. 256.
- Dirksen, V.G. and Dirksen, O.V., Reconstruction of Vegetation Recovery After the Catastrophic Eruption of Kuril Lake–Ilyinskii Volcano 7600 14— Years Ago in Southern Kamchatka, *Vestn. KRAUNTs*, 2004, no. 3, pp. 57–86.
- Egorova, I.A., Palynological Characterization of Volcano-Sedimentary Deposits in Application to Stratigraphy, in *Vulkanicheskii tsentr: stroenie, dinamika, veshchestvo (Karymskaya Struktura)* (A Volcanic Center: Structure, Dynamics, and Composition of Karymskaya Structure), Moscow: Nauka, 1980, pp. 52–76.
- Kondratyuk, V.I., *Klimat Kamchatki* (Climate of Kamchatka), Moscow: Gidrometeoizdat, 1974.
- Leonov, V.L. and Grib, E.N., *Strukturnye pozitsii i vulkanizm chetvertichnykh kal'der Kamchatki* (Structural Setting and Volcanism of Quaternary Calderas of Kamchatka), Vladivostok: Dal'nauka, 2004.
- Man'ko, Yu.I. and Sidel'nikov, A.N., *Vliyanie vulkanizma na rastitel'nost'* (The Influence of Volcanism on Vegetation), Vladivostok: Dal'nauka, 1989.
- Muraviev, Ya.D., Fedotov, S.A., Budnikov, V.A., et al., Volcanic Activity in the Karymsky Center in 1996 — Summit Eruption of Karymsky Volcano and Phreatomagmatic Eruption in Akademii Nauk Caldera, *Vulkanol. Seismol.*, 1997, no. 5, pp. 38–70.
- Rastitel'nost' Kronotskogo gosudarstvennogo zapovednika (Vostochnaya Kamchatka)* (Vegetation of the Kronotsky Nature Reserve, East Kamchatka), St. Petersburg: Botanical Institute, Russian Academy of Sciences, 1994.
- Sosudistye rasteniya sovetskogo Dal'nego Vostoka* (Vascular Plants of the Soviet Far East), 8 vols., Leningrad: Nauka, 1985–1998.
- Fedotov, S.A., On the Eruptions in the Akademii Nauk Caldera and Karymsky Volcano, Kamchatka, in 1996, Their Investigations and Mechanism, *Vulkanol. Seismol.*, 1997, no. 5, pp. 3–37.
- Khomentovskii, P.A., *Ekologiya kedrovogo stlanika (Pinus pumila (Pall.) Regel) na Kamchatke (obshchii obzor)* (Ecology of Dwarf Pine (Pinus pumila (Pall.) Regel) in Kamchatka — A Review), Vladivostok: Dal'nauka, 1995.
- Yakubov, V.V. and Chernyagina, O.A., *Katalog flory Kamchatki (sosudistye rasteniya)* (Catalogue of Kamchatkan Flora — Vascular Plants), Petropavlovsk–Kamchatskii, Kamchatpress, 2004.
- Antos, A.J. and Zobel, D.B., Recovery of Forest Understories Buried by Tephra from Mount St. Helens, *Vegetatio*, 1985, vol. 64, pp. 103–111.
- Cour, P., Zheng, Z., Duzer, D., et al., Vegetational and Climatic Significance of Modern Pollen Rain in Northwestern Tibet, *Review of Palaeobotany and Palynology*, 1999, vol. 104 (3–4), pp. 183–204.
- Fægri, K. and Iversen, J., *Textbook of Pollen Analysis*, Caldwell, 1989.
- Grishin, S.Yu., del Moral, R., Krestov, P.V., and Verkholat, V.P., Succession Following the Catastrophic Eruption of Ksudach Volcano (Kamchatka, 1907), *Vegetatio*, 1996, vol. 127, pp. 129–153.
- Grishin, S.Yu., Krestov, P.V., and Verkholat, V.P., Influence of the 1996 Eruption in the Karymsky Volcanic Group, Kamchatka, on Vegetation, *Natural History Res. Special Issue*, 2000, no. 7, pp. 39–48.
- Janssen, C.R., Local and Regional Pollen Deposition, in *Quaternary Plant Ecology*, Oxford, 1973, pp. 31–42.