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Influence of 1996 Eruptions in the Karymsky Volcano Group, Kamchatka, on Vegetation

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Abstract We have estimated the impact of eruptions of the Karymsky and Academii Nauk volcanoes on the vegetation of eastern Kamchatka, in the Russian Far East. Karymsky, one of the most active volcanoes in Kamchatka, had shown no activity for 14 years. Academii Nauk volcano, located on the bottom of Lake Karymskoye, exploded under water after 5000 years' dormancy. The simultaneous eruptions destroyed and damaged the surrounding vegetation. We discuss scale, the main destructive factors, and vegetation survival.

Key words: Karymsky Volcano, Academii Nauk Volcano, Kamchatka, eruption, vegetation.

On 2 January 1996, two neighboring volcanoes in eastern Kamchatka, Karymsky and Academii Nauk, started erupting simultaneously, throwing out different materials. The eruption of Karymsky continues with a rhythmic stability today but the eruption of Academii Nauk was a short-term blast. Although the latter occurred underwater, it damaged the terrestrial vegetation around the crater. Despite rather limited areas of damage, these eruptions attracted great attention because of their location in a well-studied region.

The aim of this study was to document the changes in the surrounding vegetation after the eruptions.

Study Area

Eruptions

Both volcanoes lie approximately 120 km northeast of Petropavlovsk-Kamchatsky City and 30 km west of the Pacific Ocean coast (Fig. 1). Karymsky has a perfect cone, centered within a caldera approximately 5 km in diameter (Figs. 2, 3). The top of the cone lies approximately 1500 m a.s.l. and approximately 700 m above the surrounding land surface. Karymsky is one of the most active volcanoes in Kamchatka. It was formed approximately 6000 years ago; the most powerful recent eruptions happened 400 and 250–200 years ago, and during 1962–1981 (Braitseva and Melekestsev, 1989). The effusive material of the 1996 eruption consisted of andesite pyroclastics

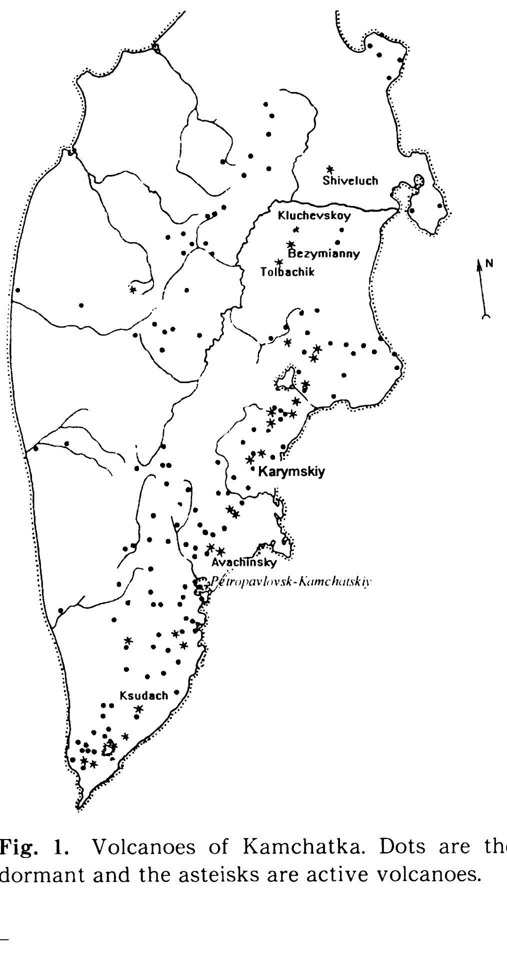

Fig. 1. Volcanoes of Kamchatka. Dots are the dormant and the asteisks are active volcanoes.

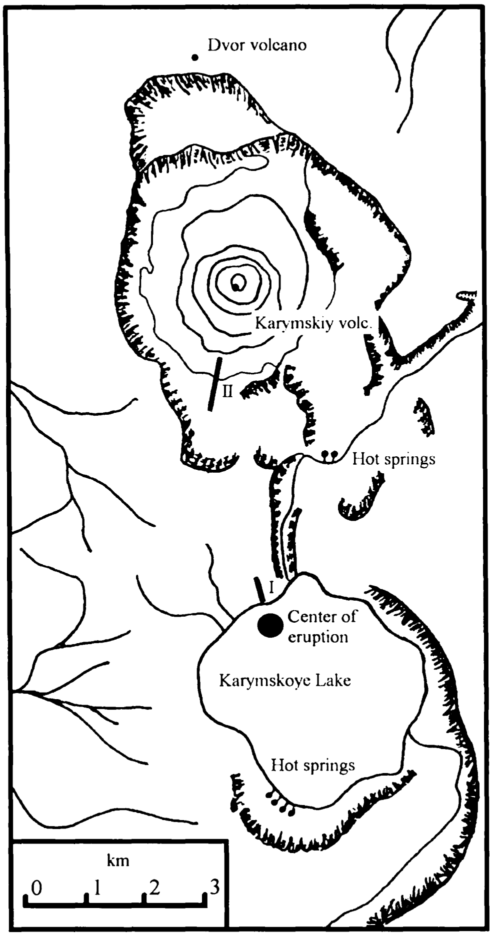

Fig. 2 Study area. Italic digits indicate the tnansect locations.

and lava. The eruption proceeded as a series of explosive hourly ash-gas ejections from the central crater, and as a slow-moving lava flow down the south-western slope.

The Lake Karymsky caldera (Academii Nauk volcano), formed during the Upper Pleistocene, lies 6 km south of Karymsky. The 1996 eruption, according to the most recent research (A. Belousov, pers. comm.), was the third in the Holocene. All three eruptions happened underwater in the northern part of the lake. The first two, with an estimated age of 5000 years, were separated by a short interval and left deposits of 10 and 2 m thick respectively. The 1996 eruption proceeded as a series of explosions with a power equivalent to 100000 t of TNT (Fedotov, 1997). The explosions threw out the juvenile basalt, other volcanic rocks, sediment from the lake bottom, and large blocks of ice that covered the lake at the time. The center of eruption lies 200–300 m from the shore. A huge crater more than 600 m in diameter was formed; its outlines are visible through the shallow water. The ejected materials were later re-washed in and re-deposited. An ash spit was formed between the underwater cone and the shore.

Climate

The climate of eastern Kamchatka is characterized by long mild winters, short cool summers, and relatively high annual precipitation (=900 mm). Climatic data from the Semlyachiki meteorological station, on the Pacific coast, shows the average air temperature of the warmest month to be +12.9℃, and that of the coldest to be −7.5℃ (Anonymous, 1966). The bioclimatic Kira index, +21.8℃, indicates that the study area belongs to the northern boreal zone (Grishin, 1995). The local climate, however, is more severe than the zonal climate because of the mountainous terrain (the surface of Lake Karymskoye is 625 m a.s.l.) and the greater distance to the ocean.

Materials and Methods

To estimate the scale and severity of the vegetation disturbance caused by the 1996 eruptions, we established two transects (Fig. 2). Transect I lies on an internal slope of the Lake Karymsky caldera, close to the crater formed in 1996. It starts near the flat ridge of the caldera, at approximately 720 m a.s.l. It is 300 m long and follows the axis of thrown materials (azimuth 340°). The vegetation in a 10-m-wide strip was described and mapped.

Transect II lies on the southern slope of the Karymsky volcano (azimuth 190°), at 800–910 m a.s.l. It is 900 m long. The upper half of the transect has a gradient of 20° and lies in the same direction as flows of andesite lava containing gray porous rocks 30–50 (100) cm in diameter. The lower half of the transect crosses ridged terrain on the lower parts of the cone slope. Every 100 m along the transect we established plots of 20×20 m, each containing 20 regularly distributed subplots of 1×1 m. In each subplot we measured the cover of vascular plants, mosses,

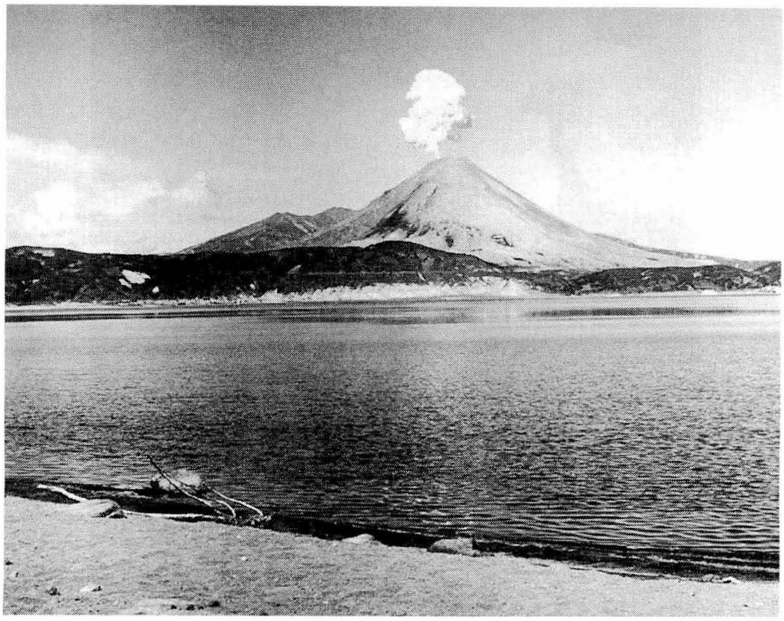

Fig. 3. Erupting Karymskiy volcano on the background of Karymskoye Lake.

and lichens; tephra depth; and other site parameters. Six permanent plots of 20×20 m were established for monitoring vegetation changes. The flora and vegetation were also surveyed in an area of approximately 100 km^2 around the volcanoes.

The nomenclature for vascular plants follows that of Kharkevich (1985–1996), except for *Alnus fruticosa*, where we use the broader species concept.

Results and Discussion

Regional Vegetation

The vegetation zonation in eastern Kamchatka includes the forest zone of stone birch (*Betula ermanii*), growing from sea level to 500–700 m a.s.l.; and the subalpine zone composed of meadows and dwarf alder (*Alnus fruticosa*) thickets, growing between the tree line and about 1000 m a.s.l. From this elevation, the subalpine zone gradually changesto the alpine zone, represented by shrubby tundra with snow patches. In areas at 600–1200 m a.s.l., subalpine vegetation dominated by dwarf alder covers slopes, and boggy vegetation dominated by willow (*Salix arctica*) plus tundra-like communities on flat dry sites cover the river valleys, which are exposed to cold drainage and frost pockets in spring and early summer.

Specific volcanic vegetation, formed of several communities appearing during the postvolcanic succession, covers the slopes of the central cone of Karymsky. The local flora includes 177 species of vascular plants. The number of species on Karymsky is 2/3 that on the Uzon volcano caldera, 50 km to the northeast (V. Yakubov, pers. comm.). The lower species diversity in the area may be explained by the influence of volcanic activity, the recent origin of the territory, and the long distance to undisturbed areas with relatively rich subalpine and alpine flora.

Vegetation around the Karymsky Volcano

The Karymsky volcano cone (1000–1500 m a.s.l.) and the slopes below it at 750–1000 m a.s.l. are free of vegetation (Fig. 4). The lack of vegetation may be explained by the high volcanic activity: the cone and adjacent slopes are covered by numerous lava flows 200–400 years old, pyroclastics, and mudslide deposits from recent eruptions (Braitseva and Melekestsev, 1989). Scattered alder thickets, mountain ash (*Sorbus sambucifolia*) thickets and patches of grasses grow on the upper vegetation border. Ridges 15–20 m in height have abrupt southern slopes and

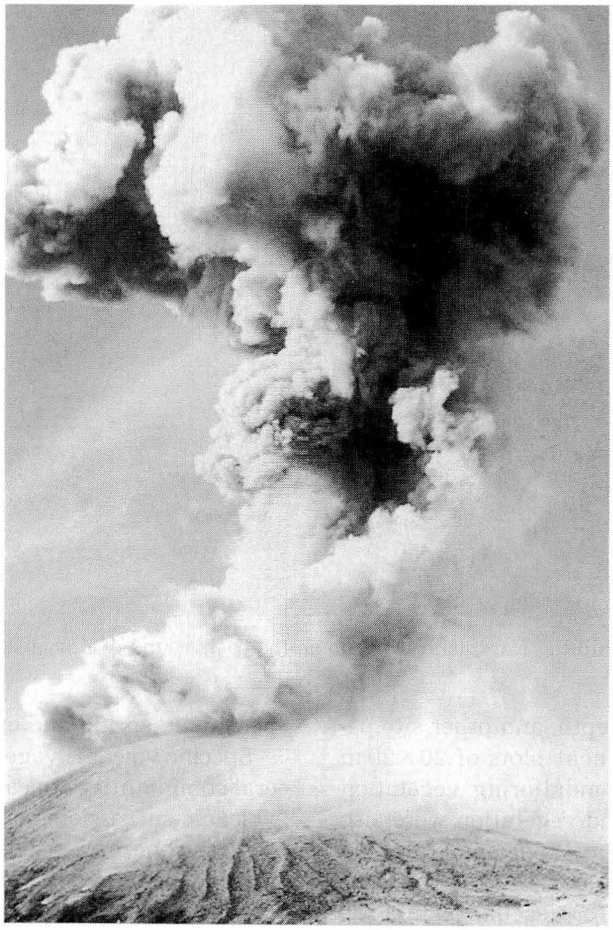

Fig. 4. Ash cloud above Karymskiy volcano.

narrow tops. They are covered by alder thickets alternating with bare volcanic deposits, forming strips 50–200 m wide.

A soil pit at the higher end of transect II showed the following horizons: 0–1 cm-very fine, light, grayish ash; 1–5 cm-dark gray tephra of varying structure and sizes; 5–15 cm-yellowish gray tephra of different sizes; below 15 cm-black tephra with coarse sand.

At 500 m from the top, the horizon with the black tephra decreased to 5 cm thick. A thick (>20 cm) horizon of yellowish, very porous gravel 2–4 cm in diameter appeared. At 700 m from the top, on a ridge covered by young alder thickets, under friable sod and a layer of newly formed soil 6 cm deep, we found a layer of yellowish gravel 18 cm in thickness deeper than 20 cm. At the end of transect II, 900 m from the top, the thickness of the yellowish gravel layer decreased to 15 cm.

The vegetation cover along the transect reflected the decreasing strength and frequency of volcanic influence: from extremely scattered groups in the upper part of the transect to closed alder thickets at the lower end of the transect.

A relatively high frequency of cover was found only for the grasses *Calamagrostis purpurea* and *Poa malacantha*, the forb *Pennellianthus frutescens*, the shrub *Spiraea beauverdiana*, and the pioneer moss *Politrichum piliferum.* Young dwarf alder and mountain ash grew in closed thickets 0.8 m high×3–4 m wide below 400 m from the top of the transect. They first appeared at 200–300 m where they were protected from direct volcanic influence by ridges. The remnants of larger dwarf alders with a diameter at the base of the trunk of 10–15 cm, killed probably by an

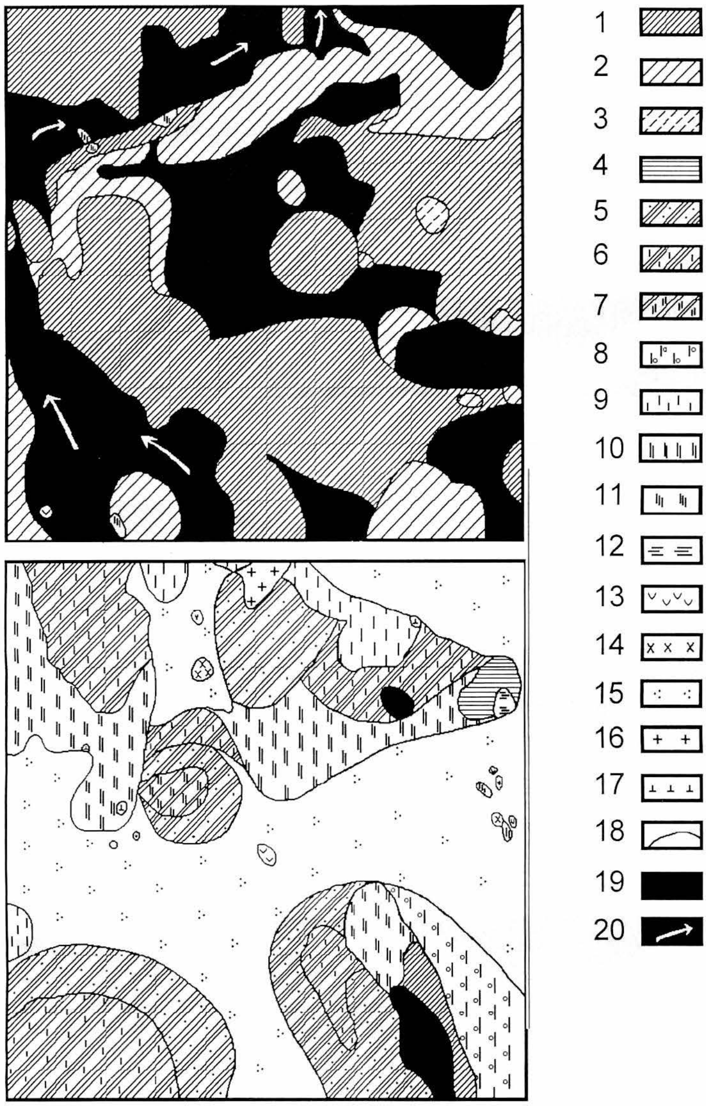

Fig. 5. Permanent plots 20 by 20 m mapped in 1996 on the southeast slope of Karymskiy cone at elevation 750 m. Vertical side corresponds to the azimuth 110 degrees. The categories of vegetation cover: 1, *Salix arctica* (>50% cover); 2, *S. arctica* (30–50%); 3, *S. arctica* (<30%); 4, *Spiraea beauverdiana* (95%); 5, *Salix arctica* (60–95%) +*Poa malacantha* (10%); 6, *S. arctica* (60–95%) +*Calamagrostis purpurea* (10–20%); 7, *S. arctica* (50%) +*Calamagrostis purpurea* (45%); 8, *Calamagrostis purpurea* (20%) +*Saussurea pseudo-tilesii* (25%); 9, *Calamagrostis purpurea* (5–15%); 10, *C. purpurea* (45–50%); 11, *C. purpurea* (70–95%); 12, *Chamaerion angustifolium* (80%) +*Calamagrostis purpurea* (20%); 13, *Pennellianthus frutescens* (50–95%); 14, *Carex koraginensis* (70–85%); 15, *Poa malacantha* +*Pennellianthus frutescens* +*Carex koraginensis* (total cover <5%); 16, *Polytrichum piliferum* (15%); 17, *Artemisia arctica*; 18, boundaries between categories; 19, barren volcanic deposits; 20, direction of water flows.

eruption in the early 1960s or earlier, were found at 400 m from the top of the transect. At around 700 m, scattered alders reached 2 m in height and 6–8 cm in diameter at the base of the trunk. At the bottom end of the transect, alders reached 2.5 m and their diameters at the base reached 10 cm. Their age was estimated from annual growth rings at 39 years.

On the south-eastern slope, at 750–1000 m a.s.l., we established a series of permanent plots for monitoring of vegetation dynamics.

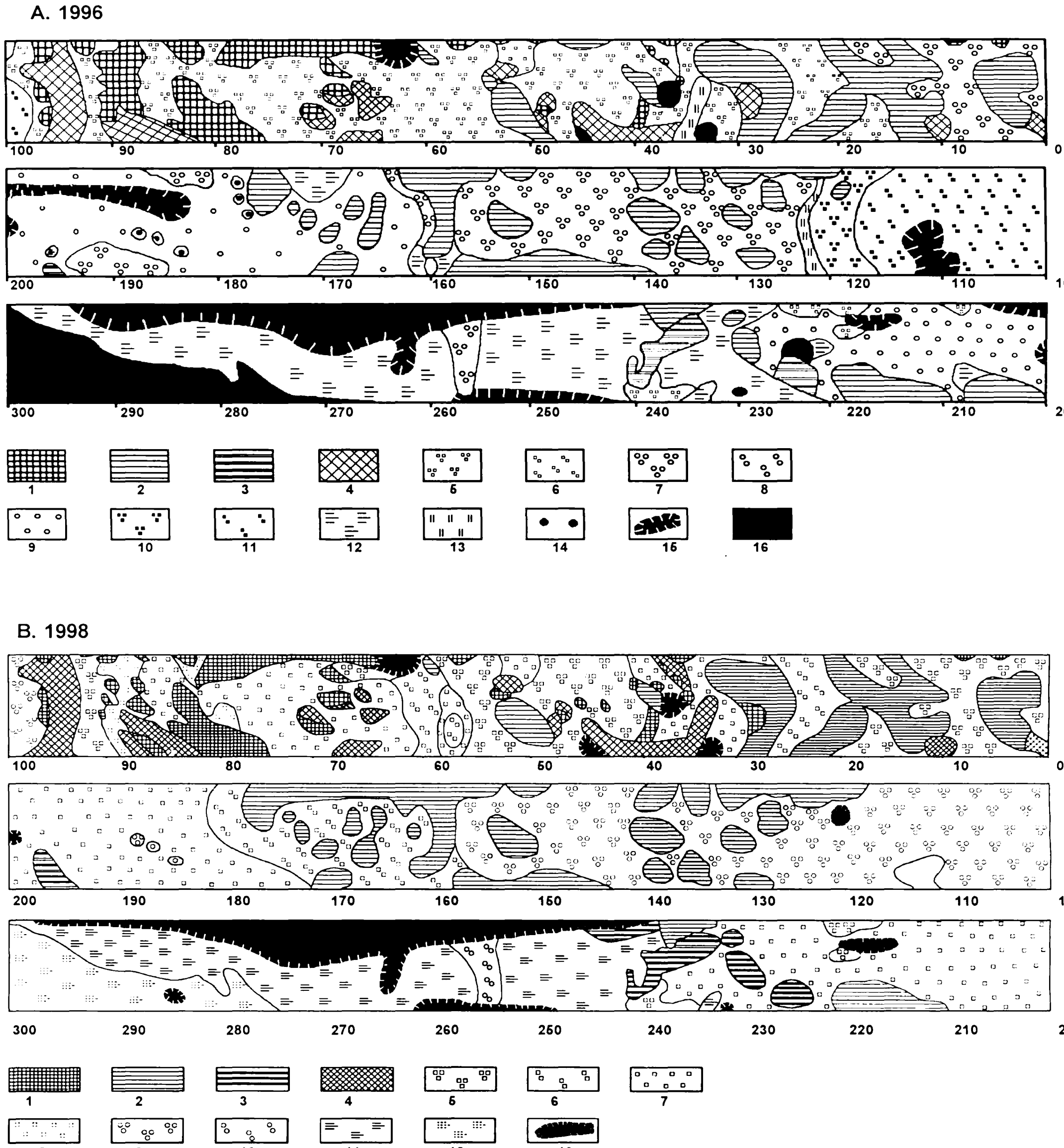

Fig. 6. Transect on the inner slope of caldera Academii Nauk volcano mapped in 1996 (A) and remapped in 1998 (B). A: 1, *Pinus pumila*; 2, *Alnus fruticosa* (survived); 3, *Alnus fruticosa* (dead); 4, *Sorbus sambucifolia*; 5, *Calamagrostis purpurea* and *Chamaerion angustifolium*, 60–100%; 6, same, cover 20–60%; 7, same, cover 2–20%; 8, same, cover <2%; 9, *Calamagrostis purpurea*, *Heracleum lanatum* and *Veratrum oxysepalum*, cover 60–100%; 10, same, cover 20–60%; 11, pure *Calamagrostis purpurea*, cover 60–100%; 12, same, cover 2–20%; 13, barren sand without vegetation. B: 1, *Pinus pumila*; 2, *Alnus fruticosa* (survived); 3, *Alnus fruticosa* (dead); 4, *Sorbus sambucifolia*; 5, *Calamagrostis purpurea* and *Chamaerion angustifolium*, 60–100%; 6, same, cover 20–60%; 7, *Heracleum lanatum* and *Veratrum oxysepalum*, cover 60–100%; 8, same, cover 20–60%; 9, same, cover 2–20%; 10, *Artemisia opulenta*; 11, *Aruncus dioicus*, *Saussurea pseudo-tilesii*; 12, pure *Calamagrostis purpurea*, cover 60–100%; 13, *Chamaerion angustifolium*; 14, scattered *Heracleum lanatum* patches; 15, barren sand without vegetation.

According to volcanologists' surveys (Fedotov, 1997) and from our own observations, the eastern slope was covered mostly with deposits of tephra (dark gray sand) that fell during the summer of 1996. Tephra covered about 50% of the plot surfaces (Fig. 5). Open grass-shrub vegetation that grew on these plots (small clumps of *Poa malacantha, Chamerion angustifolium, Salix arctica, Spiraea beauverdiana*) was badly oppressed (yellow, perforated dry leaves). Leaves on the alders growing at the edges of thickets exposed to the crater were also oppressed. Thus, several major factors affected the vegetation during the light ash fall: burial by tephra (bottoms of concave sites), dusting of the leaves, abrasion of foliage and bark (especially near the ground) by fine tephra carried with the wind, and possible chemical influence on plants and soil.

The survey of flora and vegetation around Karymsky showed that complete destruction of the vegetation was localized within a radius of 1–1.5 km, partial disturbance occurred at 2–2.5 km, and relatively weak influence occurred at 5–6 km from the volcanoes. The continuous and regular influence of different volcanic factors on vegetation and other components of the ecosystem (animals, soil) presents a unique opportunity for monitoring disturbance and the processes of plant and animal recovery on volcanoes.

One year after the first observation, the vegetation on both transects and permanent plots had changed. In most patches formerly dominated by willow, a well-expressed layer of *Poa malacantha* and *Calamagrostis purpurea* had developed. Patches of barren ash had been settled by *Pennellianthes frutescens, Carex koraginensis, Poa malacantha*, and *Calamagrostis purpurea*, which reached 10% cover. Patches of *Artemisia arctica, Chamerion angustifolium, Saussurea pseudo-tilesii*, and *Hieracium umbellatum* increased considerably in cover and biomass.

Vegetation around the Academii Nauk Volcano

Three sorts of material were produced during the eruption of Academii Nauk: juvenile material, muddy deposits from the lake bottom, and blocks of ice from the frozen lake surface. These materials were thrown out by the explosion and unevenly distributed on the adjacent internal caldera slopes. A tsunami, formed during the eruption, washed out the lakeshore closest to the epicenter and killed vegetation around the lake. Vegetation was killed up to 20 m from the closest shore and up to a few meters from the shore around the rest of the lake. Abundant remains of dwarf pine were found float-

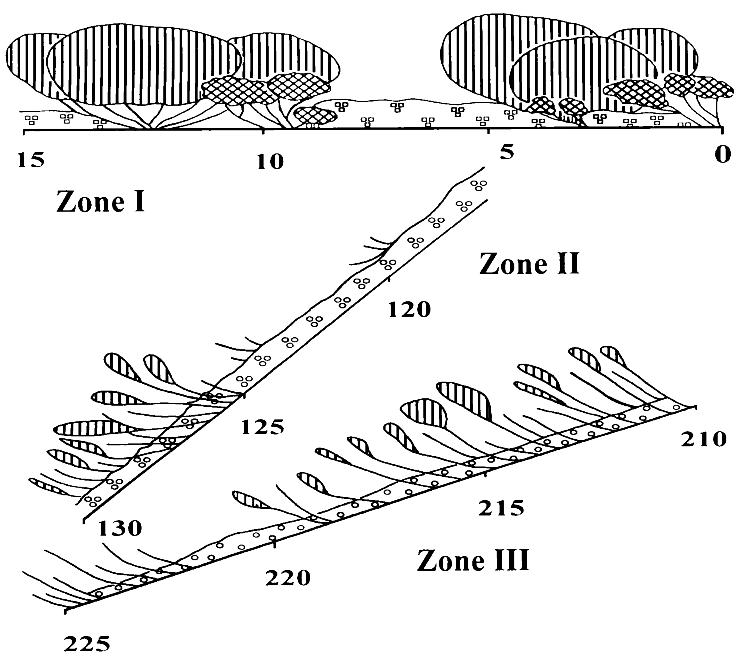

Fig. 7. Fragments from the profile diagram for the transect I. Numbers are distances from zero point.

ing in the water near the worst affected shore. The acidity of the water was abruptly increased after the eruption, killing all aquatic biota.

The vegetation along the transect was mapped at a scale of 1 : 100 (Fig. 6). At the top of the transect, the basic vegetation types were the subalpine complex of dwarf alder thickets (bushes up to 3 m high and 12 cm in basal diameter), *Sorbus sambucifolia* bushes (1.5–2 m high, diameter of branch bases to 5–6 cm), *Pinus pumila* bushes (to 2 m high, diameter of trunk bases 8–10 cm), and meadows dominated by *Heracleum lanatum* (1.5 m high), *Chamerion angustifolium* (1.3 m high), and *Calamagrostis purpurea* (0.8 m high).

Deposits from the explosion were unevenly distributed along a gradient of distance from the explosion center, smoothing the relief heterogeneity. The upper part of the transect had a flat surface, which immobilized the deposited materials. Juvenile material and muddy bottom deposits of different thicknesses covered the surface of the slope, breaking off and gently damaging shrub branches.

A soil pit at the higher end (zero point) of transect I showed the following horizons: 0–19 cm, fine-grained soil consisting of fine dry gray gravel (up to 0.5 cm in a diameter) and very coarse sand on top, fine moist grayish brown sand and silt on bottom; 19–24 cm, sod; 24–34 (39) cm, brown soil with abundant coarse roots; 34 (39)–43 (48) cm, yellowish sand with a brown layer in the middle, approximately 1 cm thick; 43 (48) cm, buried soil.

From 0 to 100 m along the transect, the depth of deposits varied from 10 to 20 cm;

Fig. 8. Stems of dead alder on the transect I. On the background: crater on Academii Nauk volcano.

from 100 to 200 m it varied from 20 to 30 (50+) cm, and from 200 to 300 m it varied from 20 to 100+ cm.

Large falling blocks of ice formed small craters 1–3 m in diameter (some reached 8 m in diameter and 2–3 m in depth) in the frozen soil. In zone I (0–90 m from the lower end of the transect), the depth and cover of deposits gradually increased. The alder thickets were slightly damaged, but most survived. Branches were slightly scratched on the sides facing the explosion. The pine thickets were strongly damaged. They had snapped branches and 30% defoliation at 0–10 m from the lower end of the transect and 100% defoliation at 80–90 m. *Sorbus sambucifolia* bushes survived, producing leaves, flowers and fruit, even when almost completely buried by deposits. The ground vegetation was killed by the deposits. However, the grass *Calamagrostis purpurea*, the tall herb *Heracleum lanatum*, and the small sprouting herbs *Maianthemum dilatatum* and *Trientalis europaea* were able to grow through the layer of deposits. Most species typical of alder thickets (*Moehringia lateriflora, Viola selkirkii,* and *V. epipsiloides*) did not survive.

In zone II (90–150 m from the lower end of the transect), dense meadow vegetation with isolated elfin-wood thickets dominated before the eruption. Because of the very steep slope (45°) and deep snow cover, explosion materials moved down the slope, and thus vegetation was only slightly damaged (Fig. 7). Nevertheless, the deposits at the higher end of this part of the transect (140 m) were rather deep, reaching 20–25 cm. Small craters formed by fallen blocks of ice were found there. The species composition in the zone was similar to that before the eruption. Very distinct abrasions were observed on dead alder branches. Dwarf pines did not survive.

Zone III (150–280 m from the lower end of the transect) was a deposit accumulation zone. The depth of deposits reached 1 m or more. Alder thickets were all dead: trunks without bark on the side facing the crater, wood deeply gouged (Fig. 8). *Heracleum lanatum* and *Calamagrostis purpurea* sprouted through the thinner deposits. Deposits more than 20 cm deep buried all grassy vegetation completely. In a soil pit, the etiolated runners of *Heracleum* and *Calamagrostis* were found. These deposits consist of a layer of friable sandy material (upper 18 cm) lying on a 2 cm layer of older clayey deposits (like lake sediment). Scattered forbs and grasses (*Geranium erianthum, Carex koraginensis*) occurred, carried by a landslide from a steep slope above the site.

Thus, from 200 to 500 m from the crater, the eruption caused damage to the subalpine vegetation, ranging from complete destruction (zone III) to partial damage (zone I). Disturbance factors included the volcanic deposits (juvenile material, materials from the last eruptions, and lake bottom deposits); impact shock from blocks of ice; possible chemical influence from volcanic deposits; changes in chemical, hydrological, and physical properties of the soil; and exposure of branches and runners to freezing because of snow cover melting. An unusual additional factor was a lake tsunami, which washed away coastal vegetation.

Brief Conclusion

Volcanologists considered these eruptions to be the most remarkable and interesting volcanic events after the Tolbachik eruption of 1975–76 in Kamchatka (Fedotov, 1997). However, the vegetation cover of the region has never been studied. We presented the first data on the direct influence of the eruptions on the vegetation at the time of eruption. We expect to revise the number of plots every year for 5 years and will publish our results. Continuing environmental monitoring and the proposed creation of a national park around Karymsky have increased the importance of such data. Besides the two volcanoes discussed in this paper, the Karymsky group of volcanoes includes the dormant Dvor volcano and the active Semiachik volcano. The vegetation on the slopes of these two shows no traces of volcanic influence and may provide a near ideal model for future studies of volcanic influence.

Acknowledgments

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1996年の Karymsky 火山群による噴火が植生に及ぼした影響

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1996年に起きた，カムチャッカ東部のカリムスキーおよびアカデミーナウク火山による噴火の影響について推定した．カリムスキー火山は，カムチャッカ半島における最も活動的な火山であるが，最近14年間は休止状態であった．アカデミーナウク火山の火口は，カリムスコエ湖の湖底にあるが，5000年に渡って休止状態であった．両火山の同時噴火は，周辺の植生に大きな被害を与えた．本論文では，噴火の規模，周辺植生を破壊した要因，および植生の生残について論じた．