A guide to the volcanoes of southern Kamchatka, Russia

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WALTHAM, T. 2001. A guide to the volcanoes of southern Kamchatka, Russia. *Proceedings of the Geologists's Association*, **112**, 67–78. The remote sub-arctic wilderness of Kamchatka contains a line of active volcanoes above the Pacific Ocean plate subduction zone. This guide is based on the itinerary of the 1999 GA excursion to sites around Petropavlovsk. Descriptions cover the Uzon caldera and its Valley of Geysers, and the volcanoes of Avacha, Karimsky, Gorely and Mutnovsky.

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1. INTRODUCTION

Kamchatka is a peninsula 1200 km long, fattening out so that it covers an area of 37 000 km^2. Its landscape is dominated by two great mountain chains. The Median Range is a wilderness of old rounded mountains formed of intrusive rocks that are the eroded stumps of older volcanoes; most summits are at around 2000 m and the range continues north through the neck of the peninsula. The Eastern Range contains a great line of active volcanoes with beautiful cones rising to over 4000 m; it continues south into the Kurile Islands. Between the ranges, the Kamchatka River drains north though a broad sheltered valley (Fig. 1). The entire peninsula provides a dramatic wilderness environment, much of which remains pristine due to its inaccessability (Gippenreiter, 1992).

Cut into Kamchatka's southeastern coast, Avacha Bay is one of the world's finest natural harbours. It became home to the Pacific submarine fleet and, consequently, Kamchatka received no foreign visitors between 1940 and 1990. Since the fall of communism, tourist dollars are, as yet, only a minimal substitute to sustain the economy of a very isolated region. Access through Kamchatka is very difficult. The roads of Petropavlovsk extend just across to the west coast and down the Kamchatka River valley to Klyuchi; beyond these, all-terrain trucks and helicopters provide the only transport.

Taiga forms the most widespread natural cover in Kamchatka, with its stunted stone birch, aspen, alder and willow growing on wet, or even swampy, ground amid mosses and other small shrubs. Larch and spruce forests are still important in the central valley. Open treeless tundra of mosses, grasses and low shrubs rises onto the slopes of the volcanoes. Above the tundra zone, the volcanic summits are clad in uncolonized ash and bare rock, with scattered snowfields and glaciers.

Located upwind of the Pacific Ocean, Kamchatka has never been a site of massive snowfall and glacier growth. While it appears that an ice sheet covered much of the peninsula during the earlier Pleistocene glaciations, there was no continuous ice cover during the Devensian. Then there were only individual ice caps and some outflowing glaciers on the higher volcanoes. Permafrost was widespread and deep during the Pleistocene cold stages. Along with most of the glacial landforms, its effects have largely been masked by subsequent volcanic deposition. Today, permafrost is restricted to the northern part of the peninsula and to the high mountains where bare rock and active volcanism minimizses its impact.

Plate evolution of Kamchatka

Kamchatka – along with the Kuriles and Japan, and the Aleutians and Alaska – owes its origins to plate convergence on the forward edge of the world's most active plate – the floor of the Pacific Ocean. Since at least as far back as the early Mesozoic, the Pacific plate (and its oceanic ancestors) has been moving north or northwest, to create island arcs of new andesitic crust over its subduction zones (Fig. 2).

The northwesterly movement of the Pacific plate has created the Kamchatka volcanic province. The Median Range of the peninsula continues north into the Koryaksky Range as the inactive remains of a late Cretaceous island arc. Palaeomagnetic signals indicate that this originated far to the south – relative to both its present position and the North American plate. In Cretaceous times, the Kamchatka–Koryaksky arc was on the advancing front of the Kula plate which, at the time, formed a segment of the Pacific oceanic floor. This was riding over the oceanic fringe of the Siberian plate, which was being subducted in a southeasterly direction. The island arc built up into a substantial mass of Mesozoic igneous rocks. When the oceanic crust of the Siberian plate was all subducted, the arc volcanics constituted a small terrane which collided with and welded to the continental mass of Siberia; the Sea of Okhotsk lies on a shelf of thin granitic crust.

Continued northwestern movement of the coalesced Kula and Pacific plates then caused their subduction beneath Kamchatka. The new subduction zone dipped west and a new belt of mainly andesitic volcanoes formed

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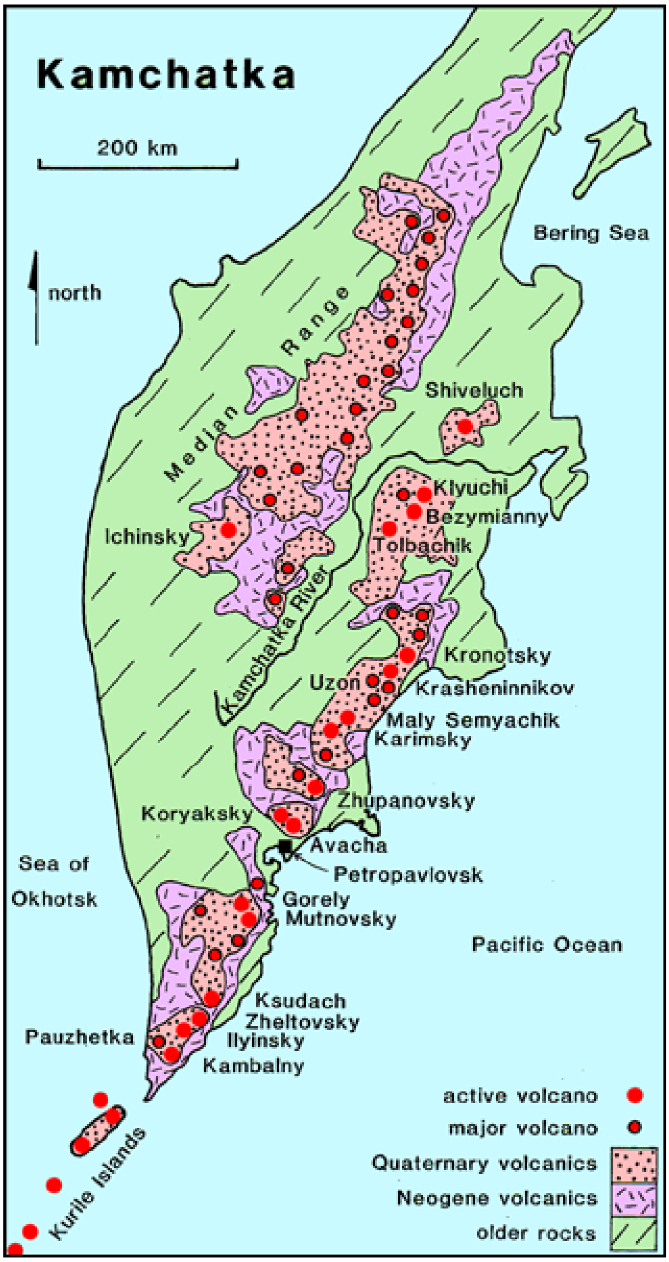

Fig. 1. Main features of the Kamchatka peninsula.

along the eastern side of Kamchatka; successive phases of volcanic activity formed eastwards to add new crust to the leading and growing edge of the overriding plate.

The Bering Fault developed as a massive tear to become a passive or conservative boundary. It isolated the segment of oceanic crust that floors the Aleutian Basin. The Koryaksky Range became inactive, and the Aleutian Islands' chain of volcanoes extended over the newly active subduction zone.

This long history of plate convergence has created parallel volcanic mountain belts that now form the core of the Kamchatka peninsula (Erlich & Gorshkov, 1979). The eastern mountain range is the youngest and contains all the active volcanoes except Ichinsky, which is now only fumarolic. Most of the major eruption deposits have been dated by potassium–argon and radiocarbon methods which has revealed some periodicity in the past activity. Most calderas date from about 30 000 to 40 000 years ago, and most of the present cones on the stratovolcanoes have formed entirely in the last 20 000 years of the late Pleistocene and Holocene (Braitseva *et al.*, 1995).

Volcanic belts of Kamchatka

The cluster of volcanoes in the central zone either side of Petropavlovsk are the most accessible: they are described below as they were the venue of the GA's field excursion. There are further centres of volcanic activity to both north and south (KVERT, 1999; Volcano World, 1999).

Within the northern group, Klyuchi is the highest volcano in Asia, a splendid andesitic cone 4835 m high; it had major eruptions in 1990 and 1991, since when it has frequently emitted tall plumes of steam and ash. Following 1000 years of quiescence, Bezymianny erupted on 30 March 1956 with a huge lateral blast and pyroclastic flows (Gorshkov, 1959; Belousov, 1996); this was almost replicated by the 1980 eruption of Mt St Helens, but unfortunately the significance (and danger) of the summit collapse style of event was only recognized after the St Helens event. Shiveluch also erupted in a massive lateral collapse in 1964 (Gorshkov & Dubik, 1970; Belousov, 1995), though this did not match its prehistoric events (Ponomareva *et al.*, 1998). Tolbachik erupted continuously along a flanking fissure for 17 months in 1975–6; it produced 40 km^2 of basalt lavas, followed by a line of four cinder cones on the dying fissure (Gippenreiter, 1992).

The southern group have scattered activity among their andesitic cones; Ksudach may have produced Kamchatka's largest explosive eruption in AD240 (Braitseva *et al.*, 1996), and also erupted with major pyroclastic flows and ignimbrites in 1907. Pauzhetka is notable for the geothermal power station already operating on steam from boreholes drilled in its old caldera; it is the prototype for the larger Mutnovsky plant which should yield 200 000 kW of geothermal power.

Hydrothermal mineralization is widespread in Kamchatka. Shallow epithermal deposits are a feature of many volcanic centres; both rich mineral veins and extensive disseminated or stockwork ores are currently being explored. Eight gold–silver deposits have been found so far; they contain over 320 tons of workable gold, but none has yet gone into production. Over 8 tons of placer gold have been mined to date. A mine in the north of the peninsula is currently producing 4 tonnes of platinum per year. There are also proven reserves of copper, nickel, cobalt, tin, mercury, lead and zinc, as well as diamonds in the basement. Coal and oil lie in molasse sequences adjacent to the volcanic belts, but are unlikely to match the large oilfields now developed in the western part of the Sea of Okhotsk. Ongoing hydrothermal activity produces 150 groups of hot springs in the peninsula and their energy resources are as yet minimally exploited.

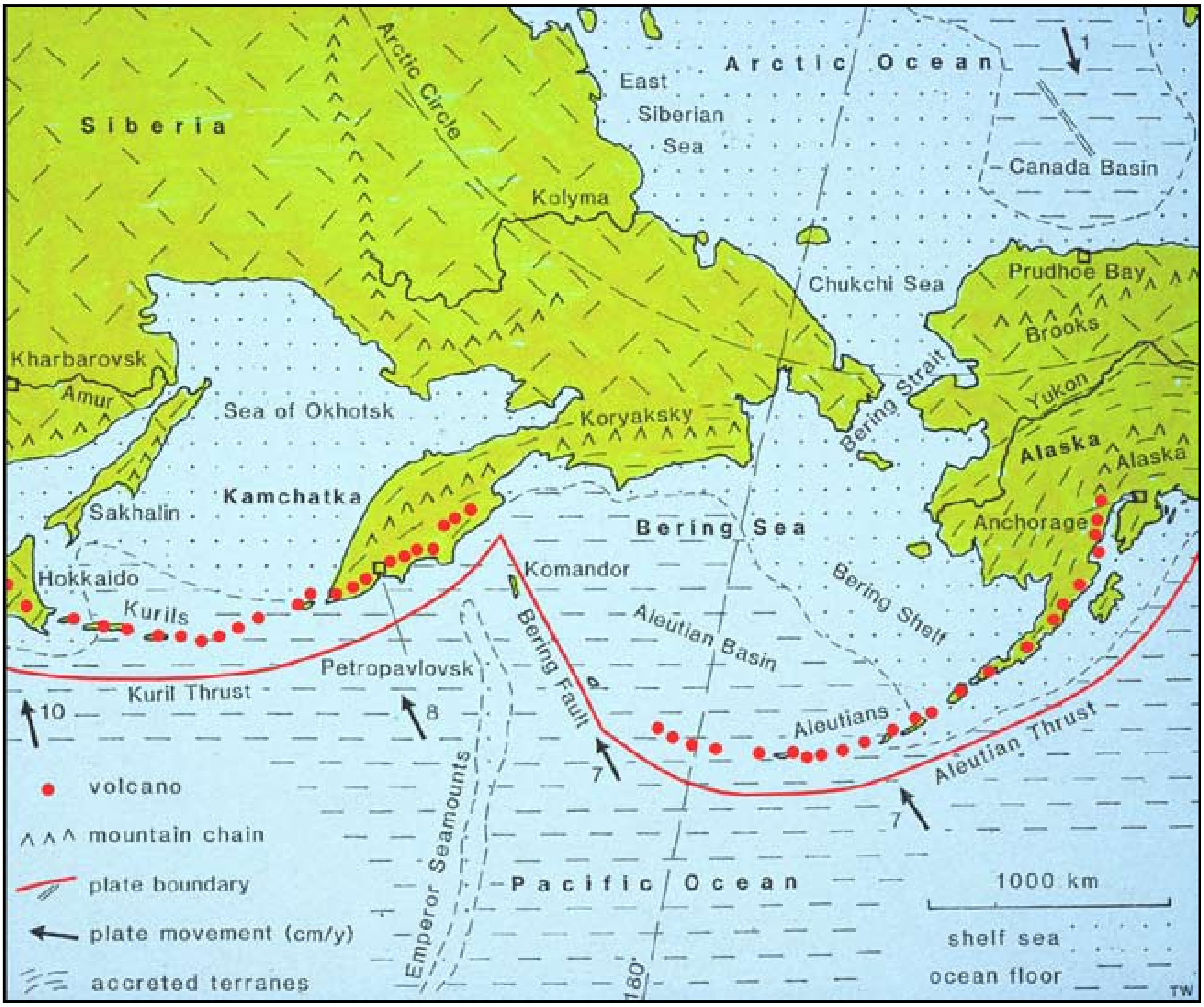

Fig. 2. Structural relationship between the Kamchatka volcanoes and the subducting boundary of the Pacific plate.

2. THE 1999 EXCURSION

The Geologists' Association field tour in 1999 combined visits to both Alaska and Kamchatka, with just over a week spent in each. The Alaska sector was themed on periglacial geomorphology along a traverse from Cordova on the south coast to Prudhoe Bay on the north (Waltham, 1995, 1999), ending with a tour of the oilfields by kind courtesy of BP. The group then flew back to Anchorage, and took the new scheduled flight direct from Anchorage to Petropavlovsk, with a scenic fuel stop among the volcanoes of the Aleutian Islands.

Within Kamchatka, the base was a comfortable hotel in Petropavlovsk (Fig. 3), from where three excursions were taken. Avacha volcano was reached after a night in a cabin camp. The Valley of Geysers was visited in a single day by helicopter, with specially arranged extra landings in the Uzon caldera and at Karimsky Lake. Ascents of the Mutnovsky and Gorely volcanoes involved two nights in tents at a magnificent site out on the tundra reached only by six-wheel-drive go-anywhere trucks.

The excursion proved to be a success, and Kamchatka was voted well worth the effort of travelling to and around it. Generally good weather added to the enjoyment of wonderful Russian hospitality. There was debate over which was the best day of the excursion – the flight to Uzon, Valley of Geysers and Karimsky, or the walk into the Mutnovsky caldera, but the latter probably just won.

3. THE ITINERARY

The following notes have been condensed and amended from the guidebook that was prepared for the members of the 1999 excursion (Waltham, 1999). The logistics of travel in the Kamchatka wilderness mean that any visitor is almost obliged, and well advised, to join one of the very efficient specialist tour operators based in Petropavlovsk. Visits to the northern volcanoes are possible, but do involve at least a day each way by truck on rough roads; for the more hardened traveller, they could extend a geological tour of Kamchatka to at least two weeks.

Petropavlovsk

The city of 300 000 people is spread along the shore of Avacha Bay, wherever buildings can fit between

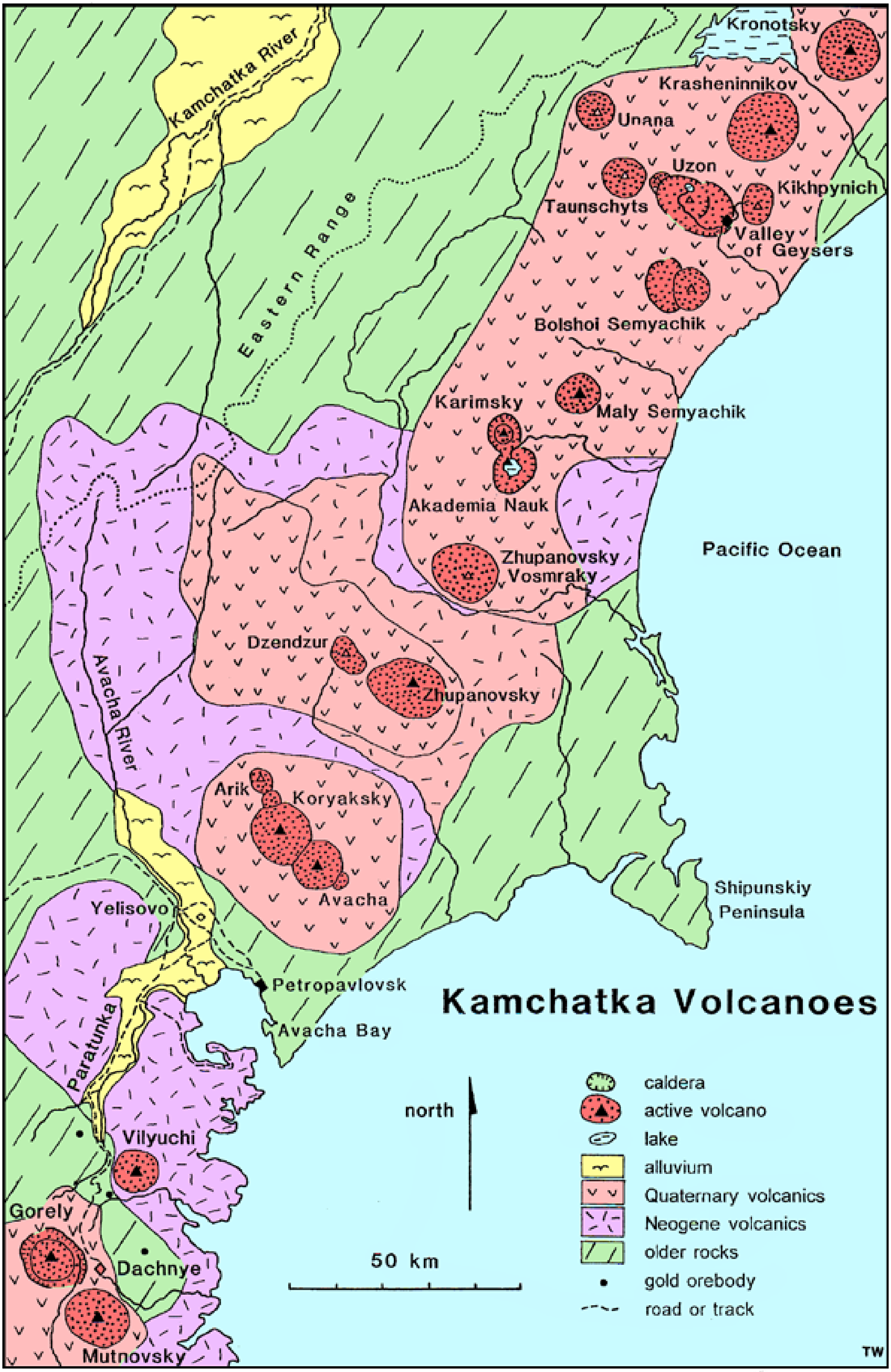

Fig. 3. Outline geology of the volcanoes around Petropavlovsk.

the wooded hills of poorly exposed Cretaceous metamorphics. It is overlooked by the splendid volcanic cones of Koryaksky and Avacha (Fig. 4), both of which provide elements of threat to its inhabitants.

On the edge of town, the Volcanological Institute has an important role even though it has suffered from recent budget cuts. It has networks of seismic stations around all the main volcano groups to monitor earthquakes as eruption precursers and also to monitor fumarole gas emissions (notably the sulphur/chlorine ratios) for the same purpose. Laser beams are in place to detect pre-eruption dilation of the volcanoes above the city. A major concern is to monitor ash clouds from even minor eruptions; these pose a serious threat to planes between North America and Japan that almost follow the plate boundary volcanic arcs on the great circle flight paths. Satellite images of the Kamchatka volcanoes are checked four times a day, and prediction successes have been achieved where multi-spectral images detect hot spots on the volcanoes two or three days before ash eruptions.

Kamchatka also remains seismically active. There have been two earthquakes of Magnitude 8, and four more of Magnitude 7, in the Petropavlovsk region this century (all with foci at depths less than 40 km). Though there has been no major earthquake since 1959, there is concern over the inevitability of future quakes. Close to the Volcanological Institute, some old blocks of flats were seen to have been strengthened to ensure seismic integrity. Large ribs of reinforced concrete up their sides, with steel ties providing tension across their roofs should prevent oscillating shear whereby the floor decks pancake on failed walls, to the serious detriment of the occupants. These buildings are now intended to be safe in earthquakes up to Intensity 9, along with all the newer blocks that have been built to better codes.

The local volcanoes – Avacha and Koryaksky

From the road between Petropavlovsk and Yelisovo (Fig. 3), a track heads past some dachas and disintegrates into a dry river bed as it climbs the lower flanks of the volcanoes. The channel is active annually in meltwater and storm floods, and its banks expose dissected lahars, debris flows and lenses of finer airfall ash.

The track ends at a group of cabins, 25 km from the main road; Avacha volcano is up ahead to the right, and Koryaksky is ahead to the left. On the saddle between the two volcanoes a scatter of old basaltic cinder cones have some shoulders and summits of welded spatter; nodular inclusions of dunite are collectable.

Koryaksky is a tall symmetrical stratovolcano of andesite 3456 m high; it is built of welded and unwelded pyroclastics, with subordinate lavas, some of which are basaltic andesites. This cone buries the site of an ancestral caldera which collapsed over 30 000 years ago. A small eruption in 1956 produced pyroclastic flows from the summit crater and from a radial fissure; since then activity has been limited to fumaroles, but periodic increases in seismicity (the last in late 1997) indicate that future eruptions may be expected. There is serious concern that a flank collapse could produce a landslide, directed blast and pyroclastic flows with devastating impact on the town of Yelisovo directly below.

Avacha volcano

Avacha is an active conical stratovolcano 2741 m high. A large original edifice of andesites and basalts suffered periodic caldera collapses and regrowth. About 30 000 years ago, a major lateral eruption followed massive failure of its southwest flank; this left boulder-grade debris deposits 150 m thick that now survive under the northern part of Petropavlovsk. The resultant crater has

Fig. 4. Koryaksky (left) and Avacha (right) seen from the suburbs of Petropavlovsk. Remnants of the crater walls on Avacha, left after the lateral failure towards the camera 30 000 years ago, are visible just above the snow line on each side of the younger summit cone. (Photos by the author.)

now been almost completely filled by a younger cone, largely built within the last 5000 years of pyroclastics, with the fronts of basaltic andesite lava flows sticking out around its base. The central crater of this has produced 14 historical eruptions. A powerful vulcanian eruption in 1945 left the crater 250 m deep and 330 m across. The most recent eruption was in 1991, when lava filled the crater and overtopped the rim to produce a flow a kilometre long down the southern slope. If past eruption patterns repeat themselves, the plug is likely to be removed explosively within the next few years. Gravity surveys show that the top of its magma chamber is only 2000 m below sea-level.

The Avacha trail heads up pyroclastic slopes, where stream sections expose stratified lapilli tuffs; these become steadily steeper. There are increasingly good views back to the splendid andesite cone of Koryaksky. The steep part of the trail ends where it turns onto a gently rising shoulder, which provides a delightful walk on an easier gradient. The shoulder is the rim of the early lateral blast crater that has been nearly filled and obliterated by the growth of the new summit cone. It is surfaced with loose cinders which lie over partially welded pyroclastic flows; some sections of channels are filled with lava with rubbly tops to individual flows.

From the caldera rim, the newer summit cone rises with its northern slope overlapping and burying the old crater rim, so that the easy shoulder does not continue round. Andesites on the ridge and above have 4 mm augite and 2 mm feldspar phenocrysts. The trail to Avacha's summit starts up some snowfields, but then winds up the steep cinder cone. Its surface is mainly loose, red, oxidized tephra, with areas of airfall ashes, and there are some exposures of the underlying welded pyroclastics.

The summit crater yawned hundreds of metres deep until 1991, when it was filled with andesite lava. The black lava now forms a gentle dome – it is the fresh top of a classic plug dome (Fig. 5). Steam rises through its fissured surface, and there are even more fumaroles and solfataras round its edge, at the contact with the crater walls of red pyroclastics (Taran *et al.*, 1997). A walk round the rim to the north passes giant crescentic flow ribs on the lava's surface, formed as it moved sluggishly east and flowed over the lowest point on the old crater rim. It flowed for a kilometre down the volcano flank, but was so viscous that it came to rest at an angle of nearly 45°; its chaotic surface of blocky andesite is broken by a few steam vents lined with sulphur crystals. Kozelsky, the next cone to the southeast, is inactive.

North to Uzon and Geysernaya

The star attraction just north of Petropavlovsk is the Valley of Geysers, to which commercial helicopter tours are available daily throughout the summer; landings at Uzon and Karimsky are only possible with special permits, as the sites all lie within the Kronotsky Nature Reserve. The flight takes about 75 minutes, normally on a route just west of the chain of volcanoes.

Fig. 5. The crater rim of Avacha, with Koryaksky in the distance. Fumarolic steam rises between the crater wall created by the 1945 eruption (on the right) and the domed plug of lava formed in 1991 (on the left).

The western route heads round the western side of the smaller cones that continue the line of volcanoes northwest from Koryaksky (Fig. 3). It then heads across the interior tundra, keeping west of Zhupanovsky, on its way to Karimsky, where one of the frequent Strombolian eruptions is normally seen during the fly-past. Just to the south, Karimsky Lake lies in the Academia Nauk caldera, which erupts less frequently. Northwards, the flight goes over Maly Semyachik volcano with its spectacular crater lake of green water acidic to pH 3. Past the inactive Bolshoi Semyachik, the route descends to the Valley of Geysers or the flat caldera floor of Uzon.

The Uzon caldera

A shield of basaltic lavas preceded an andesitic stratovolcano that evolved through cycles of collapse and regrowth during much of the Pleistocene. A caldera that is still recognizable collapsed about 40 000 years ago, when huge sheets of welded and unwelded ignimbrite were formed (Fig. 6). The geothermal activity of the Valley of Geysers now lies over the marginal faults of this early caldera (Belousov *et al.*, 1984; Okrugin & Karpov, 1995). A second caldera collapsed in the western half of the first one, and produced the Belaya dacite dome and more acidic tuffs. A third minor collapse created the depression that is now largely filled by lake sediments, and the adjacent tuff-ring that contains the Dalneye maar lake. Geophysical data have identified an underlying magma chamber with its top about 5 km down. There are numerous active hot springs, mud pools and small geysers on the floor of the third collapse. Part of the extinct Uzon volcanic cone survives on the caldera rim. Close to the northwest, the Taunschyts and Unana cones are inactive.

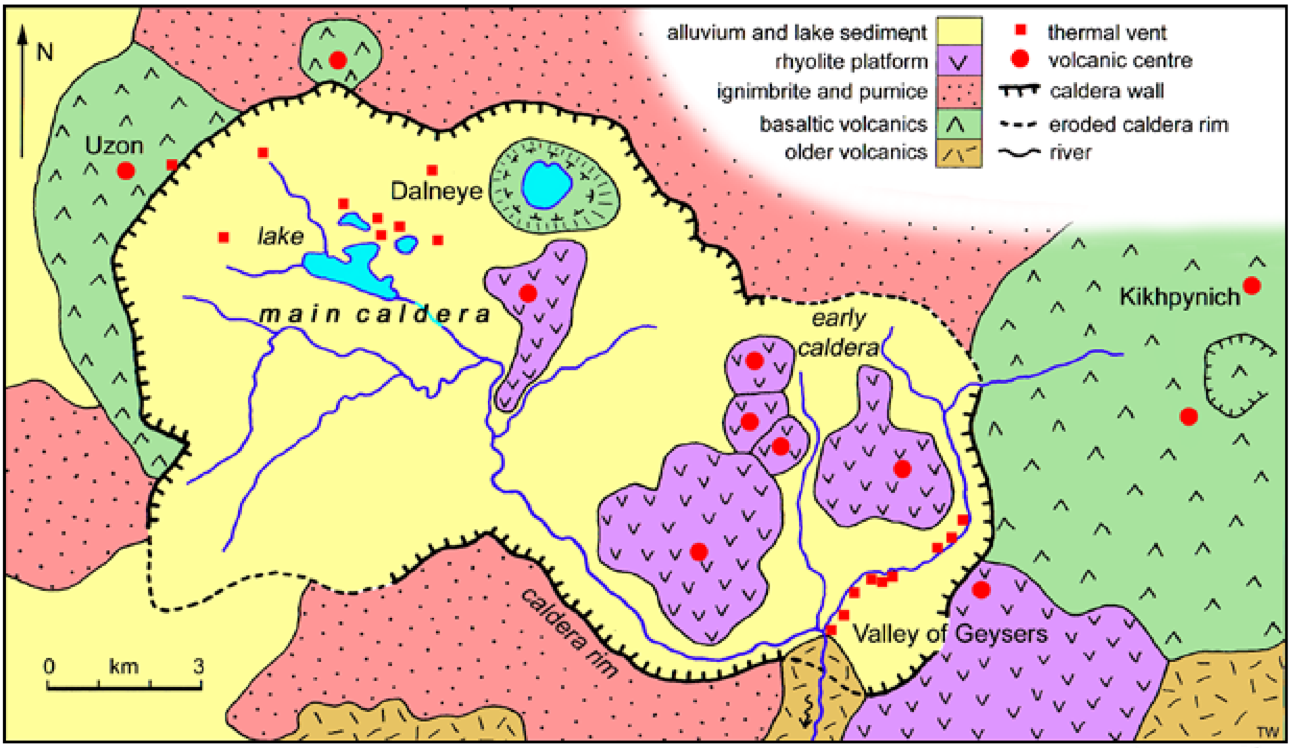

Fig. 6. Main features of the Uzon caldera. The older volcanics are of Middle Pleistocene age and earlier; they are also exposed in parts of the caldera walls. The lake sediments include bedded tuffs. Only the largest thermal vents are marked; all those shown in the Valley of Geysers are active geysers. Sites on the Uzon caldera floor: F, Fumarolnoe Lake; K, Khloridnoe Lake; B, Bannoe Lake; H, helipad. Sites in the Valley of Geysers: B, Bolshoi (and Malyi) Geyser; F, Fountain Platform group; V, Velikan Geyser; H, helipad.

The Uzon depression is bordered to the north and west by steep caldera walls that have survived into the modern landscape. These are essentially features of the second in the series of three caldera collapses; the third collapse merely deepened the depression west of Belaya that is now largely wetland with lake remnants on a floor of lacustrine sediments. The highest ground is formed by the basaltic cone of Uzon volcano, which stands above the western rim of the caldera.

Immediately west of the helipad and volcanologists' house, Bannoe Lake lies over a steam vent that produced an explosive phreatic eruption in 1989, though it is now quiet. The lake is 25 m deep to a false bottom that is a crust of sulphur overlying liquid sulphur at 140°C, which has been probed to another 7 m deep. This situation was discovered when recovery of a temperature probe produced a 60 kg block of black sulphur welded around the end of the cable. The continued activity of the sulphur source is regarded as comparable to a black smoker of the deep ocean floor.

West of Bannoe Lake, trails wind across the marsh ground fringing the shallow waters of Khloridnoe Lake on the caldera floor (Fig. 7). A variety of hot springs, boiling lakes and active mud pots lie within dacitic tuffs, opaline geyserite and lake sediments. Some hot springs have associated sulphur, opal, pyrite and mercury deposits, but most colouring is due to temperature-sensitive algae.

East of the helipad, the Belaya dome is formed of slab-jointed dacite porphyry that varies from dark lava and tuff to glassy obsidian and light pumice. Some is hydrothermally altered, with kaolinite, opal, alunite and sulphur. Adjacent to Belaya, there are two small acid lakes with pH of 2. Further north, Lake Dalneye is nearly 1000 m across, in a splendid maar crater fringed by a tuff ring of very scoriaceous basalt; it was produced by the modest steam explosions of a phreatic eruption from a vent beneath the lakes and marshes of the caldera floor.

The Valley of Geysers

The cluster of geysers, fumaroles and hot springs in this valley were only discovered in 1941. They lie above the marginal fractures of the oldest Uzon caldera. The hot water that emerges is largely recirculated rainfall, mixed with some juvenile water from magma. The magmatic

Fig. 7. Steam from springs and lakes on the Uzon caldera floor.

Fig. 8. Water jets rise obliquely from Malyi Geyser in eruption.

heat source is probably the root of the Uzon volcano, where ground temperatures reach 250°C at about 500 m depth beneath the caldera floor; alternatively, the Kikhpynich volcano may be the heat source (Fig. 6). The Geysernaya River has cut its valley deep into bedded andesitic tuffs that were deposited in a lake in the first Uzon caldera; the southeastern valley slope is the heavily eroded caldera wall, broken into older volcanics. Some dacite lavas and intrusions occur in the tuffs, and all the exposed rocks have been altered hydrothermally. There are extensive deposits of opaline siliceous geyserite, some built into large banks and terraces below the main vents.

The valley contains more than a dozen notable geysers. Half of these are classic geysers with large but brief periodic eruptions, while the others are better described as spouters because their hot water fountains are in almost continuous eruption. There are over a hundred smaller hot springs, boiling pools, fumaroles and solfataras.

The helicopters land in front of the timber lodge that is the access point for all visitors to the trails into The Valley of Geysers (Dolina Geyserov), within the Kronotsky Nature Reserve. A boardwalk leads to the lip of the valley for a fine overall view. The upper slopes of the valley expose cliffs of pumiceous tuffs, some eroded into earth pillars. The valley floor has a lush green plant cover, except where active banks of geyserite have not yet been colonized. A branch boardwalk to the left ends at a lookout over the Bolshoi (Big) and Malyi (Small) Geysers. An eruption of Bolshoi, on the left, throws water about 10 m high amid clouds of steam, for about 10 minutes; it erupts on a cycle of about 75 minutes. Malyi Geyser throws water out at 45° for about 8 m, in eruptions lasting 5 minutes on a 35 minute cycle (Fig. 8).

The main boardwalk descends to a bridge over the Geysernaya River a little further upstream. The river reaches a temperature of 26°C with its geothermal input in the summer; winter snowmelt reduces it to about 16°C. Water from the springs and geysers varies from 35°C to 100°C. Just upstream of the bridge, the Schell Geyser erupts briefly every 35 minutes; it was heavily eroded during a typhoon flood in 1981. The Fountain Platform is a great bank of geyserite producing copious quantities of steam from numerous vents; it is claimed as the world's greatest concentration of geysers and fumaroles and spouters (Fig. 9). Beside the platform, Malachite Grotto is a nearly permanent spouter erupting from a geyserite cone; the Fountain and New Fountain Geysers are connected so that they switch their water spouts every few minutes, combining into almost continuous activity.

The boardwalk ends just before another, smaller bridge. Velikan (Giant) Geyser is inside the river bend just upstream; it erupts with a cascade of water to heights of about 25 m, but only for about a minute, before sending steam jets to far greater heights for another few minutes; its cycle is around 8 hours. A second arm of the boardwalk lies along the terrace above the valley floor; it passes hot pools blue with suspended clay, and boiling mud pots red with iron oxides. It also offers splendid views down onto the geysers and spouters of the Fountain Platform.

Karimsky

Currently the most active volcano on Kamchatka, the modern cone has been formed within the last 5300 years and now rises to 1486 m (Braitseva & Melekestsev, 1991). The 700 m high active cone is formed of andesitic pumice ash, bombs and spatter, armoured with flows of blocky lava. It is currently erupting (and has been for about 500 years) in Strombolian style, whereby blasts of steam, smoke, ash and lava bombs rise to heights of 500–1000 m above the summit crater (Fig. 10); each blast lasts only about a minute, and they occur at intervals of 5–15 minutes, accompanied by minor earthquakes.

The scale and periodicity of the eruptions varies from day to day, and the pattern is temporarily disrupted by

Fig. 9. Steam rises from the multitude of geysers and vents on the Fountain Platform in the Valley of Geysers.

Fig. 10. The smoke plume of a modest Strombolian eruption rises from Karimsky, with the remnants of the old Dvor caldera in the right distance. (Photo: M. Chaplin.)

occasional larger eruptions that may also produce small pyroclastic flows; in November 1998 an ash column reached a height of 6000 m. Some eruptions produce lava flows from the crater, and others create new vents close to the summit; these then evolve into the dominant crater. The Karimsky cone stands inside a caldera 7700 years old whose walls still stand nearly 100 m high; the older Dvor caldera survives as a truncated fragment to the north.

Akademia Nauk caldera is 50 000 years old, is now intersected by the younger Karimsky caldera and contains the hot waters of Karimsky Lake. An underwater dacitic vent erupted explosively in 1996 (simultaneously with a major Karimsky eruption), producing an ash cloud about 8000 m high. Landing the helicopter on a shelf in the southern sector of the Akademia Nauk caldera provided a splendid view across the lake to the Karimsky cone.

South to Mutnovsky and Gorely

Out of Petropavlovsk on the old road towards Yelisovo, a road turns west across the alluvial flatlands at the mouth of the Avacha River valley, and then south into the Paratunka Valley. This is a geothermal zone with a series of hot springs along its floor. Boreholes have proved groundwater at 80°C in the porous volcanic rocks at depths of 80–100 m (Okrugin & Karpov, 1995). The heat source is magma at depth in the fracture zone along the line of the East Kamchatka Volcanic Belt. Buried pipelines take hot water to greenhouses and a fish farm.

On the steep climb south out of the valley, the view east is to the splendid but inactive cone of Vilyuchi volcano, a beautiful and symmetrical andesitic cone, 2173 m high, now almost inactive. The road then dips across the head of the Vilyuchi valley, where the Rodnikovoye gold–silver deposit lies 4 km to the east. Drilling and two exploration adits have revealed reserves of 40 tons of gold and 340 tons of silver in a series of hydrothermal veins of quartz–calcite–sulphide in Pliocene gabbro; the ores were deposited at temperatures of 170–250°C about 2 million years ago (Okrugin & Karpov, 1995).

The road climbs onto the broad plateau close to Gorely; the shield volcano of Gorely lies to the west, beyond the rim of its modest caldera wall; the ice-clad ramparts of the Mutnovsky volcano lie further away to the south (Fig. 11). Ahead, to the south, the better track leads to the Dachnye geothermal basin, and the start of the long walk to Mutnovsky. Right, to the east, a rougher track heads down the Osvysmannya valley, with the best access to both Mutnovsky and Gorely gained from a camp on the tundra just north of the lower Opasny Canyon (whose waterfalls expose fine sequences through the layered volcanics).

Dachnye hot springs

These lie ahead along the main track (Fig. 11). The new geothermal power station and the Mutnovsky gold deposit (with 28 tons of gold reserves in a hydrothermal system of large quartz veins amid a sulphide-bearing stockwork) both lie to the east in the valleys draining to the coast. The maintained track virtually ends where a new tourist hotel is being built above a steaming valley. The Dachnye geo-

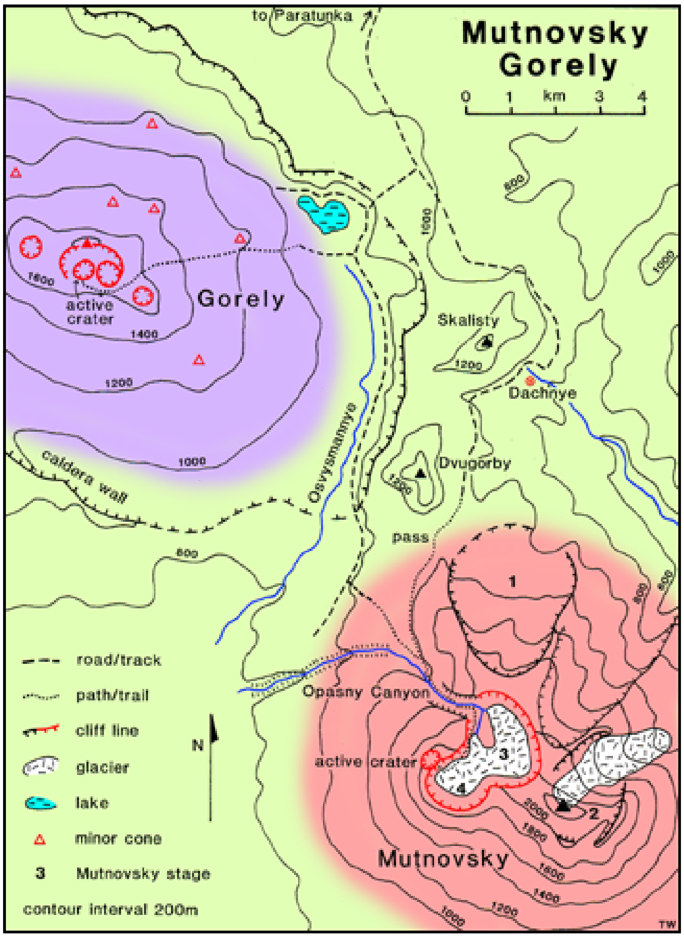

Fig. 11. Main features of Gorely and Mutnovsky.

Fig. 12. A boiling pool in the Dachnye geothermal basin.

thermal basin is the source of the hot water in the steam cloud of the old volcanic vent of Aktivny. Just 200 m across, this contains a host of hot springs, small geysers, fumaroles and boiling mud pools (Fig. 12). They all lie in hydrothermally altered Holocene pumice tuffs and ignimbrites, with fine grained kaolinite, montmorillonite, adularia, marcasite and cinnibar.

A walk up the cold stream reveals exposures of welded ignimbrites containing blocks up to 150 mm across that were components of the pyroclastic flows; fragments of andesite lava contain feldspar phenocrysts 3 mm long. To the west, Skalisty and Dvugorby are remnant hills of Pleistocene volcanoes of rhyolite lavas and pyroclastics.

All around the site there are rusty pipes projecting from the ground spouting large or small flows of steam. These were all exploratory boreholes drilled to assess the geothermal resources. Some are recent, but others are 20 years old and should be treated with respect as they have been known to explode. Most production boreholes for the new power station are 4 km away to the east.

Gorely volcano

The massive shield volcano of Gorely is 1830 m high. Andesite and basalt lava accumulation in the Early Pleistocene was followed about 33 000 years ago by production of about 120 km^3 of ignimbrite accompanied by caldera collapse. Basalts and basaltic andesites then created five volcanoes that coalesced to form most of the modern mountain between 8000 and 6000 years ago; this largely filled the caldera, but sections of the old caldera walls remain visible just outside the shield. The only known lava caves are in older flows north of the caldera. Subsequent activity has been on a reduced scale, producing both lavas and tephras; these are exposed in the walls of the summit complex of craters. Recent eruptions have been explosive; in 1981 ash covered an area of 500 km^2, and the last eruption was in 1986 when a cloud of steam and ash rose 600 m.

A walk up the huge shield volcano starts from the western edge of the large lake that lies in the unfilled eastern crescent of the Gorely caldera (Fig. 11). It is over a mixture of rough grassy tundra with very low dwarf willow. A parasitic cinder cone is rimmed with welded spatter and has landslipped to the north so that its crater is now open and degraded. Exposures of basaltic aa lava flows reveal scoriaceous layers and internal flow structures, and there are also patches of volcanic ash redistributed by the wind.

The best route heads for the saddle between the two low summits which are the raised rims of separate craters, of which the southwestern is dead and rather featureless. Through the saddle and round to the right, the main crater complex is spectacular (Fig. 13). The first large crater contains a cold lake about 100 m below; its surface has ice floes from a small glacier on its internal slope. The walls of all the craters expose profiles through thick sequences of lava flows with a limited component of interbedded pyroclastics. Across a broad shelf inside the very large old

Fig. 13. The summit craters of Gorely seen from their northern rim; the hot acid lakes below are the sites of recent steam eruptions, while the lake over the arete to the left is cold.

Fig. 14. Coarse matrix-supported ignimbrites exposed in Mutnovsky's caldera wall, over 100 m high.

central crater, there is a sudden, unguarded, vertical descent into the active crater. Over 100 m down, a hot acidic lake has active fumaroles and solfataras around its margin and beneath the surface. The recent eruptions of Gorely have been largely steam episodes produced when these vents heated up and increased their output.

Mutnovsky volcano

A complex of four superimposed volcanoes has a summit 2322 m high. Each cycle of activity produced a large cone, before dying and being followed by another whose centre was shifted; it is largely formed of basaltic andesites, with a high proportion of more acidic pyroclastics. Mutnovsky #1 formed about 45 000 years ago; its caldera is now eroded to open out on the north side of the mountain (Fig. 11). Mutnovsky #2 grew to the south in the Late Pleistocene, collapsed in a caldera, and then grew a new cone that forms the present summit. Mutnovsky #3 produced basalts and differentiated dacites and rhyolites (as about 35% lavas and 65% pyroclastics with included lahars), in between the cones of #1 and #2; its huge caldera contains the active fumarole fields that are partly overrun by its own glaciers. Mutnovsky #4 is a small crater on the edge of the #3 caldera, and is also filled with glacier ice. The active crater also lies in the rim of the #3 caldera; it last erupted explosively in 1960, and still contains powerful fumaroles.

Rough trails from both the Osvysmannye valley and the Dachnye hot springs roadhead converge on the upper section of the Opasny Canyon, which is cut into the west flank of Mutnovsky. The walk up the canyon into the Mutnovsky #3 caldera is largely on banks of hard snow and firm ice, that has accumulated in winter avalanches off the rock walls. Much of the surface is covered in wind-blown ash, and some of it is melted into little *astrugi* pinnacles; the caldera drainage flows in snow caves on the rock surface, and is sometimes seen or heard deep in crevasses or collapse areas. The canyon walls are cut in coarse rhyolitic pyroclastic flows (Fig. 14); parts of these are laced with thin dark dykes.

The caldera's eastern glacier lies ahead where it melts out on a steep rock slope, aided by a series of fumaroles; steam from these has created ice tunnels that emerge in the glacier snout. The onward route climbs the slopes of volcanic tephra and glacial till on the right, and descends slightly to the snout of the western glacier, which is also advancing over fumaroles (Fig. 15). A way between the ice and the caldera wall passes beside various geothermal vents; these include fumaroles, mud pools and solfataras, and their style may change within hours as meltwater from the adjacent glacier seeps into the ground and is boiled at very shallow depth. A lake is sometimes dammed up behind the glacier; at other times it drains through the ice, leaving a flat bed of reworked ash pitted by solfataras and boiling mud-pools in front of snow and ice walls that are layered with red volcanic ash. Meltwater streams emerge from the snow and ice fields, and flow back under the glacier toe. The scene changes every year in response to the previous winter's snowfall, against a steady pattern of ice retreat in response to global warming.

The caldera floor is at an altitude of about 1540 m, which is still 800 m below the ice-capped summit of the Mutnovsky volcano. A way up the western snowfields lies below the caldera wall of thinly bedded pyroclastic flows that are probably old surge deposits. A steep scramble aided by rope handlines leads up coarse welded pyroclastics to a knife-edge ridge between the glacier-filled caldera and the active crater. A massive steam plume rises far above the crater; when the wind blows it around, the vigorous fumaroles and solfataras that are its source can be seen on the crater floor and in its southern wall (Fig.16). The crater is 300 m across, and its walls drop 150 m to a flat floor of scree and inwashed ash.

Fig. 15. Fumaroles within the Mutnovsky #3 caldera are overridden by glaciers descending from the left.

Fig. 16. Vigorous fumaroles feed a massive steam plume above the active crater of Mutnovsky.

Though the Valley of Geysers is the most widely known volcanic site in Kamchatka, the Mutnovsky caldera has its rather more modest geothermal features in a setting which is nothing less than spectacular. Any geologist visiting Kamchatka should include a walk into Mutnovsky.

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Footnote: Since this paper was prepared, there have been some changes in the volcanic features of Kamchatka.

In 2007, a major landslie descended the southern slope of the Valley of Geysers; its debris formed a dam in the valley, and the lake formed behind it covered many of the geysers; subsequently the debris dam has been eroded, and the lake level has fallen, so that most of the geysers are now exposed, but with some changes from their previous nature.

Minor eruptions of Mutnovsky have periodically changed conditions within its caldera, and may continue to do so.