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Mountain Permafrost on Active Volcanoes: Field Data and Statistical Mapping, Klyuchevskaya Volcano Group, Kamchatka, Russia

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ABSTRACT

Permafrost is widespread in mountainous volcanic areas of the Kamchatka Peninsula. In this paper, we describe geocryological conditions (active layer depths, permafrost temperatures, ground thermal properties and cryostratigraphy) in the Klyuchevskaya volcano group and estimate the spatial distribution of permafrost using a simple statistical model. Measured mean annual ground temperatures (MAGTs) vary from near 0°C around 950 m a.s.l. to −7°C at 2500 m a.s.l. and permafrost is predicted to occur at elevations >~700 m a.s.l. Heat transfer modelling indicates that the maximum permafrost thickness is about 1000 m for the highest summits (~5000 m a.s.l.). Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: Kamchatka; mountain permafrost; active volcanoes; ground temperatures; ground properties; active layer; statistical modelling

INTRODUCTION

Despite the heat associated with active volcanism, permafrost can exist on high-elevation or high-latitude volcanoes (cf. Kellerer-Pirklbauer, 2007) in places such as Hawaii (Woodcock, 1974), Iceland (Etzelmüller *et al*., 2007), Mexico (Palacios *et al*., 2007), Peru, North America and Antarctica. Geocryological conditions in such volcanic areas are of interest to terrestrial permafrost science. They also pertain to planetary and astrobiological research, because Mars contains ground ice in subsurface layers of high-latitude regions (Boynton *et al*., 2002) and basalt lava fields with a similar chemical composition to those on Earth (Squyres *et al*., 2004) are common features of the Martian surface. Additionally, cinder cones have been found near the Martian polar caps. Because of these similarities, permafrost research on terrestrial volcanoes may increase understanding of conditions on extraterrestrial volcanoes (Abramov *et al*., 2004).

Despite the increased interest in permafrost-volcano interactions, permafrost conditions in volcanic areas are poorly known, mainly because of difficult site access and remoteness.

In this paper, we focus on permafrost characteristics and distribution in the Klyuchevskaya volcano group located in central Kamchatka at about 56°N. Layers of frozen tephra and buried ice on Klyuchevsky volcano were encountered in some of the first work on permafrost in Kamchatka (Ermakov and Trubicin, 1965). Since then, a number of investigations have been undertaken in the region but there have been few direct measurements of ground temperature conditions. Between 2002 and 2007, we conducted fieldwork to investigate ground temperatures, their spatial patterns and to estimate the thickness of permafrost. The most important objective was to obtain field temperature measurements in boreholes

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and collect frozen samples from boreholes for microbiological investigations. In this paper, the results of the measurements are summarised and conceptualised in simple models.

STUDY AREA

The Klyuchevskaya volcano group (Figures 1 and 2) is situated in the Central Kamchatka Depression (55–56°N, 160–161°E) and consists of the active volcanoes Klyuchevsky (4800 m a.s.l.), Bezymianny (2900 m a.s.l.), Ushkovsky (3900 m a.s.l.) and Plosky Tolbachik (3100 m a.s.l.) as well as ten other volcanoes that are currently not active and numerous smaller volcanogenic landforms such as cinder cones or extrusive domes (Braitseva *et al*., 1995).

Klyuchevsky is the highest and one of the most active volcanoes (several eruptions per year) and formed over the last 6000–7000 years. Bezymianny, Ushkovsky and Plosky Tolbachik formed during the Late Pleistocene (before 40 000–50 000 years BP, Braitseva *et al*., 1995). Basalt lava plateaus and plains that formed during fissure eruptions are also common. The largest and youngest basalt plateau (formed about 9000–10 000 years ago) is Tolbachinsky Dol situated on the southern foot-slope of Plosky Tolbachik. Here, a large fissure Tolbachik eruption (LFTE) took place in 1975 and 1976, an area of about 500 km^2 was covered by scoria and ash, and three new cinder cones and lava fields were formed (Fedotov and Markhinin, 1983). The regional heat flux in Klyuchevskaya area is in the order of 60 mW/m^2, resulting in common geothermal temperature gradients of 30–40 °C/km (Sugrobov and Yanovsky, 1993).

Vegetation zones in this area are largely controlled by elevation: deciduous forest (*Larix cajanderi* and *Betula platyphylla*) occurs up to 200 m a.s.l., coniferous forest (*Picea ajanensis*) up to 400 m a.s.l., stone birch forest (*B. ermanii*) up to 900 m a.s.l., shrubs and dwarf trees (*Alnus fruticosa* and *Pinus pumila*) up to 1200 m a.s.l., alpine tundra up to 2000 m a.s.l., and isolated patches of grass and lichen at elevations up to 2500 m a.s.l. (Grishin, 1996; Jakubov, 2001).

A first sketch of the permafrost distribution and ground temperatures in Kamchatka as a whole (Bobov and Novoselskaya, 1975) was based on several boreholes in the northern part of peninsula but did not contain any data from mountain areas. The first permafrost maps for the study area were produced by Zamolotchikova and Smirnova (1979, 1982). The MAGTs for their map were calculated from mean annual air temperatures (MAATs) using adjustments for climate, vegetation, glaciers, snow and rain. The thickness of permafrost was also calculated but without corroborating field measurements. For the Klyuchevskaya area, a zone of isolated patches of permafrost with MAGTs > -1°C was shown for 1000–1500 m a.s.l., and discontinuous and continuous permafrost with MAGT between -2 and -8°C for 1500–3000 m a.s.l. These data were later used for the *Geocryological Map of the USSR* (1997) and the International Permafrost Association (IPA) *Circum-Arctic Permafrost Map* (Brown *et al*., 1997), showing isolated patches and discontinuous permafrost with low ice content for the Klyuchevskaya volcano group.

From 1996 to 2001, several joint Russian-Japanese expeditions investigated glaciers and permafrost on Kamchatka. In the area of the active volcano Ushkovsky (Figure 1), several shallow boreholes and pits up to 2 m deep were made at elevations between 350 and 1200 m a.s.l. According to these data, the lower boundary of discontinuous permafrost is situated at about 1000 m a.s.l. (Sone *et al*., 2003).

Permafrost and periglacial features are abundant in the study area (Figure 2). Numerous solifluction lobes, mud-boils, polygonal structures and areas of sorted patterned ground occur between 1000 and 1700 m a.s.l., and needle ice is common. Ice wedges (10–20 cm wide) exist beneath the borders of polygons (Figure 2) which have irregular shapes and are typically 6–15 m (but occasionally up to 30 m) in diameter.

The climate of the study area is characterised by cold winters that are subject to short strong thaws, as well as mild and wet summers that are mainly influenced by cyclonic activity. No permanent meteorological station exists in the mountainous areas, but the Klyuchi station (WMO 32389) situated in the Kamchatka river valley at an elevation of 29 m a.s.l. and about 30–40 km from the central part of volcanic group (see Figure 1) provides a long-term record for the region. The MAAT in Klyuchi is -0.7°C for 1910–2007 and about 0°C for 1970–2007 (Figure 3E). Climate reconstruction supports the general warming trend of about 1°C for the 20th century, and locally, the warming rate was up to 0.02 °C/year during the last three to four decades (Čermak *et al*., 2006). The total annual precipitation in Klyuchi is about 500 mm whereas in the mountains it is estimated to be about 1000 mm (Muravyev, 1999). In Klyuchi, the snow cover usually lasts from October to June. Snow cover thickness is about 1.5–3 m in forested areas and 50–80 cm or less in open areas due to redistribution by strong winds.

Automatic weather stations operated at two locations near Ichinsky volcano (Sredinny ridge) at 1000 m a.s.l. from August 1996 to July 1997 (Figure 1)

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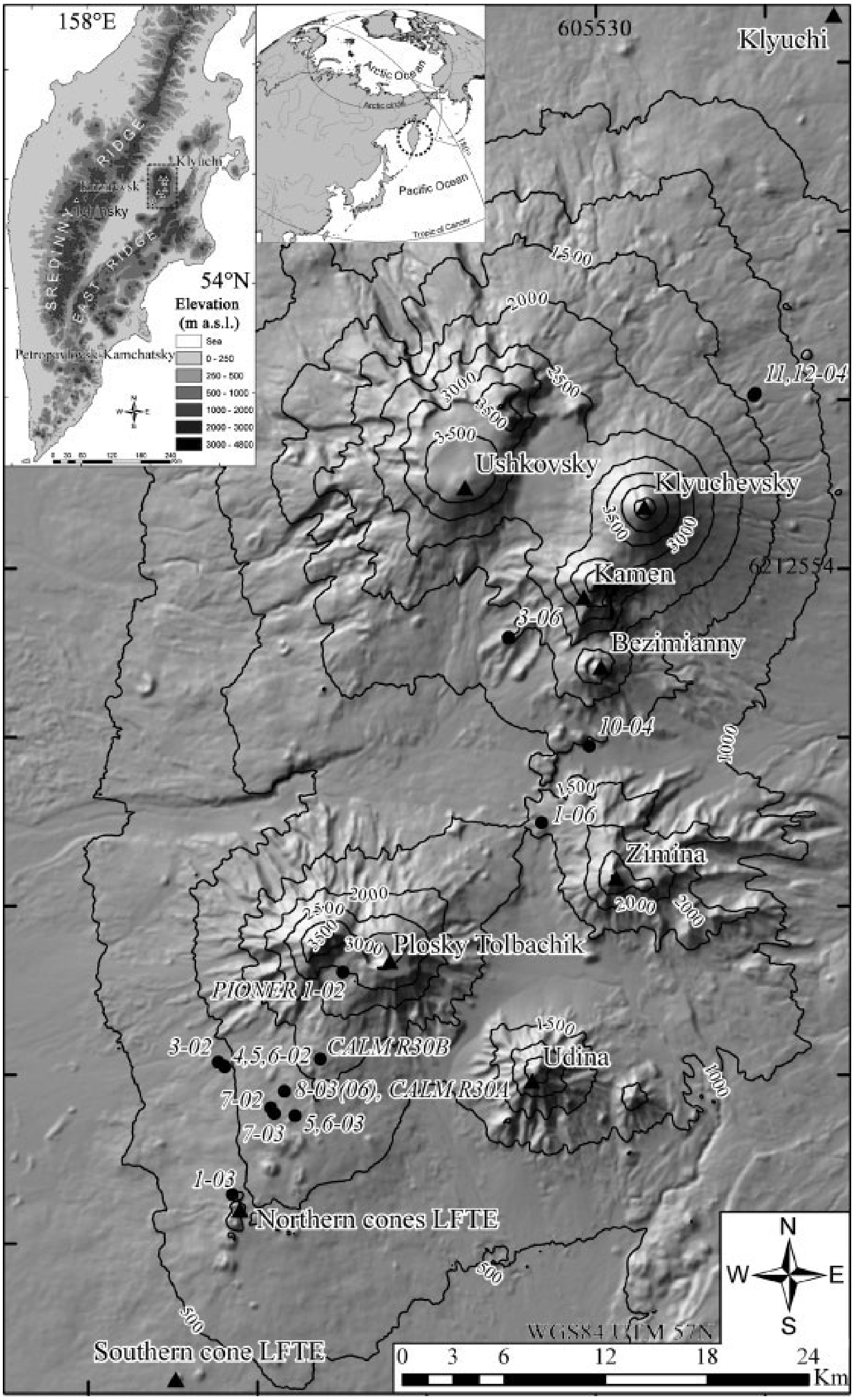

Figure 1 Study area. A digital elevation model was used to hillshade the image. Boreholes (see Table 1) and Circumpolar Active Layer Monitoring sites are shown by black dots and identifiers. LFTE is the large fissure Tolbachik eruption.

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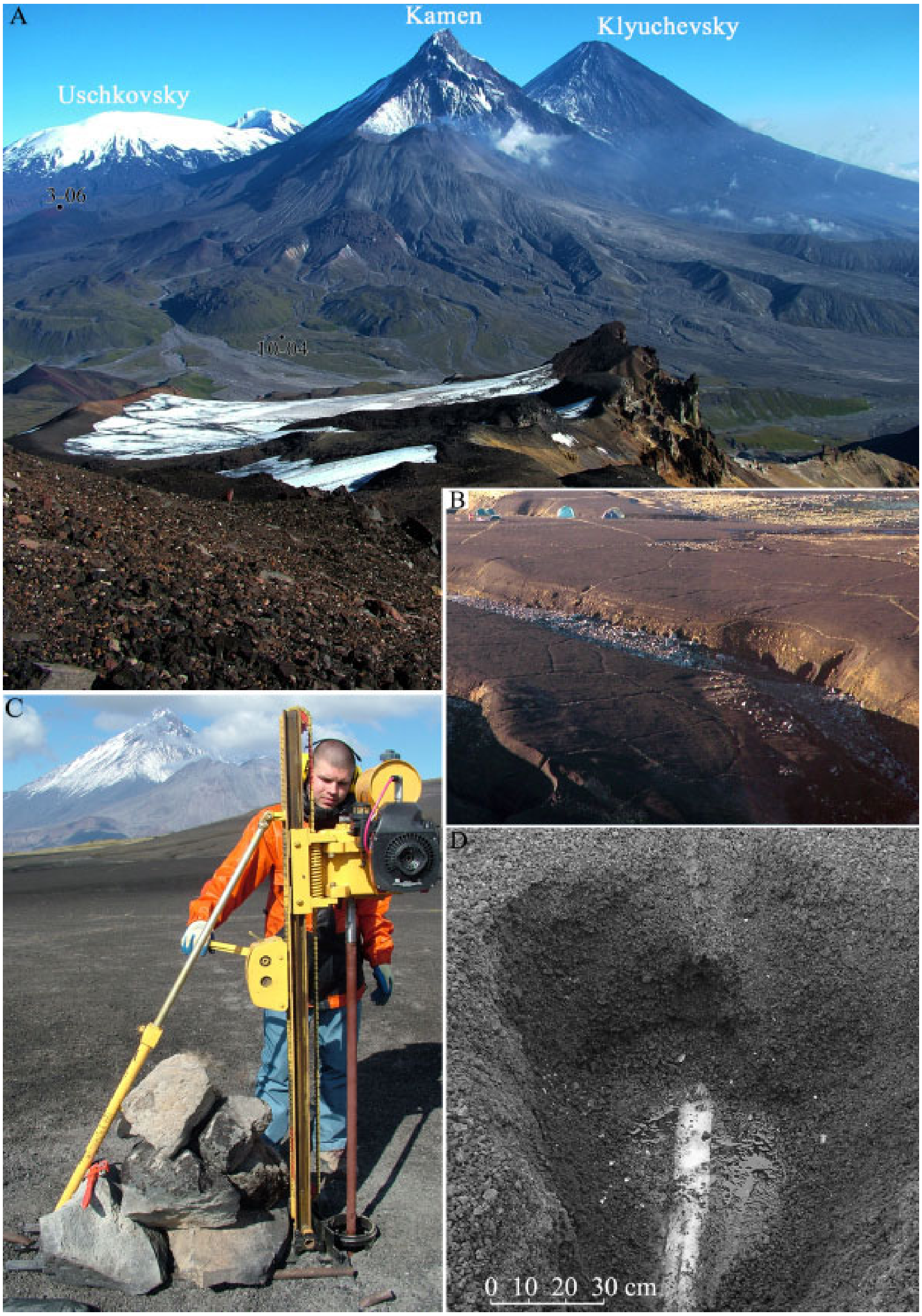

Figure 2 (A) Volcanoes Ushkovsky, Kamen, Klyuchevsky (from left to right) and Bezymianny (in foreground); (B) polygonal structures with frost cracks around borehole 1-06 (note tents for scale); (C) the drilling equipment (UKB-12/25) in operation at the borehole site ''1-06'' (for location refer to Figure 1); (D) an ice wedge in the lower part of a frost crack near borehole 1-06 (for location refer to Figure 1). Photos: A. Abramov and M. Aleksandrin. This figure is available in colour online at www.interscience.wiley.com/journal/ppp.

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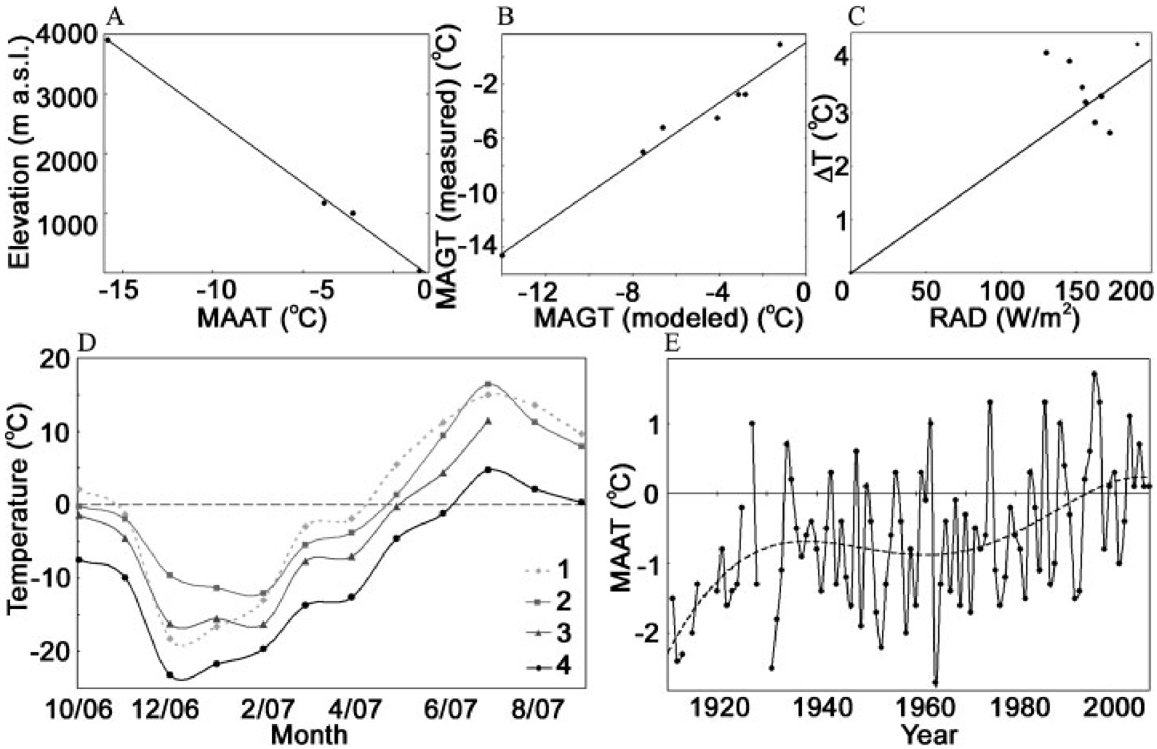

Figure 3 (A) Mean annual air temperature (MAAT) vs. elevation for 1996–97; (B) mean annual ground temperature (MAGT) from model vs. MAGT measured in borehole; (C) the relationship between ΔT and RAD (mean annual potential direct short-wave solar radiation) (see explanation in text); (D) temperatures at different elevations for 2006–07: (1) air temperature at Klyuchi (29 m a.s.l.), (2) ground surface temperature at 950 m a.s.l., (3) ground surface temperature at 1330 m a.s.l., (4) ground surface temperature at 2500 m a.s.l.; (E) MAAT in Klyuchi for 1910–2006; data source: http://cliware.meteo.ru/inter/data.html (for 1914–98) and http://meteo.infospace.ru/wcarch/html/r_sel_stn.sht?adm=575 (for 1998–2007).

(Matsumoto *et al.*, 1999; Sone *et al.*, 2003) and from September 2000 to August 2001 (Sone *et al.*, 2006). MAATs were −2.2°C and −3.8°C, respectively, in 1996–97 and −4.4°C in 2000–01.

On the summit of Ushkovsky (3900 m a.s.l.), a temperature of −14.6°C was recorded in ice at a depth of 27 m (below the depth of zero annual amplitude). At a depth of 10 m, the MAGT in cold firn was −15.8°C (August 1996 to July 1997, Shiraiwa *et al.*, 2001) and provides an approximation of the MAAT (Loewe, 1970). This leads to an estimated regional lapse rate of −0.0045 °C/m (Figure 3A).

Glaciers occupy about 240 km^2 of the study area and many of them are debris covered, especially near their termini. The equilibrium line altitude is situated between 2000 and 2700 m a.s.l. and the mean ice thickness is about 30–60 m for valley glaciers and 100–250 m for glaciers in calderas. Large fields of buried ice exist near Klyuchevsky volcano (Muravyev, 1999).

There are few investigations of the temperature regime of glaciers in this region. A 220 m borehole on the summit of the caldera glacier of Ushkovsky revealed a temperature of −6°C 30 m above the glacier bed. Basal melting is expected beneath thick glaciers and in calderas the glaciers are polythermal (i.e. the central part of the bed is frozen, Shiraiwa *et al.*, 2001; Salamatin *et al.*, 2002). A 114 m deep borehole at 3600 m a.s.l. on Ichinsky volcano (Sredinny ridge) penetrated the glacier and continued into the bedrock where the temperature was −3.4°C (Matobo *et al.*, 2007).

METHODS AND DATA

An overview of boreholes used in this study (locations in Figure 1) and some of their characteristics are given in Table 1. The boreholes were drilled using compact equipment for slow rotary drilling without liquid or air injection (Figure 2C) with the exception of boreholes K2 and N30 which were drilled by others. We used instrumental steel drilling bits with an inner diameter between 5 and 10 cm. The upper 2 m of each borehole was cased with a plastic pipe. During the drilling,

Table 1 Boreholes in the Klyuchevskaya volcano group.

Site[a]	Easting	Northing[b]	Elevation[c] (m)	Depth (m)	Date	MAAT modelled (°C)	MAGT measured/modelled (°C)	MAGST measured (°C)	Comments
3-02[1]	577033	6180814	924	3	08/2002	−4.2	−/−0.9	—	In forest. No permafrost
1-03[1]	577867	6172961	946	4	08/2003	−4.3	−/−1.3	—	On foot-slope of III cone of LFTE, 1.5 m of permafrost, then drilling stopped due to technical problems
6-02[1]	577422	6180555	957	4	08/2002	−4.3	0.9/−1.2	0.1	Near timberline, ice crystals from 1.5–2.8 m depth; logged at 0 and 2 m depths since September 2006
7-02[1]	580147	6178098	1155	12	08/2002	−5.2	−/−2.1	—	No temperature data due to problems with water outflow from upper 1.5 m of permafrost
7-03[1]	580356	6177773	1218	10	08/2003	−5.5	−/−2.4	—	Mainly basalt lava, no temperature data due to damage of borehole
6-03[1]	581576	6177638	1301	6	08/2003	−5.9	−/−2.4	—	Mainly basalt lava, no temperature data due to damage of borehole
8-03(06)[1]	580947	6179087	1326	25	09/2003(06)	−6.0	−2.8/−2.8	−3.0	Situated on CALM site R30A, drilled in 2003 and 2006; logged at 0, 1, 3, 5, 10 and 15 m depths since September 2006. AMS ^{14}C for mosses at 19.5 m is 2500 ± 55 yr BP (UZ-5467/ETH-33847)
12-04[2]	608785	6220437	1410	6	09/2004	−6.3	−/−3.8	—	At the bottom of crater in cinder cone cirque, ash deposits, no permafrost due to seasonal lake formation
10-04[3]	598971	6199531	1428	16	09/2004	−6.4	−2.8/−3.1	—	Mainly basalt lava
11-04[2]	608702	6220319	1445	10	09/2004	−6.5	−/−3.6	—	On the rim of cinder cone crater, no temperature data due to air induction
1-06[4]	596156	6195007	1625	10	08/2006	−7.3	−4.5/−4.1	—	On cinder plateau between Tolbachik and Zimina. AMS ^{14}C for ash is 1475 ± 50 yr BP (UZ-5465/ETH-33846)
3-06[5]	594185	6205979	2103	5	09/2006	−9.5	−5.2/−6.6	—	In crater of cinder cone Kvasova, no temperature data due to air induction; logged at 1, 2, 3 and 4 m depths since August 2006
1-02[1]	584409	6186155	2512	10	08/2002	−11.3	−7.0/−7.5	−9.0	Mainly basalt lava, air induction for 2 days; logged at 0 and 0.5 m depths since September 2005
K2[6]	591610	6214853	3900	219	06/1998	−17.5	−14.6/−14.0	−16.6	Drilled by Shiraiwa *et al*. on Ushkovsky volcano in glacier (Shiraiwa *et al*., 2001)
N 30[1]	577867	6172961	946	54	1978	−4.3	−/−1.3	—	Drilled by M. Lesnih for hot water near III cone of LFTE (Jiruev, 1984). Permafrost from 1.5 m depth

Note: All boreholes except the last two were drilled by A. Abramov and D. Gilichinsky.
[a]Superscript numbers refer to region: [1]Tolbachik region, [2]Klyuchevsky region, [3]Bezymanny region, [4]Zimina region, [5]Kamen region, [6]Ushkovsky region.
[b]UTM zone 57U except boreholes 11-04, 12-04 and K2 (zone 57V).
[c]Obtained from hand-held GPS. MAAT = Mean annual air temperature; MAGT = mean annual ground temperature; MAGST = mean annual ground surface temperature; LFTE = large fissure Tolbachik eruption; CALM = Circumpolar Active Layer Monitoring; AMS ^{14}C = Accelerator Mass Spectrometry radiocarbon date; UTM = Universal Trans Mercator; GPS = Global Positioning System; UZ = University of Zurich; ETH = Swiss Federal Institute of Technology.

the core was described and samples for analyses were collected. The ice content was obtained based on the weight of moisture in samples (due to the low content of unfrozen water). Analysis of density (ρ), pH and total organic carbon content (TOC) were undertaken in laboratories of the Institute of Physicochemical and Biological Problems of Soil Science using standard techniques.

The frozen and thawed thermal conductivities of the pyroclastic material were measured in the field using a needle probe and in the laboratory using α calorimeters. This is a common but probably slightly problematic technique for these types of deposits and the possible error is estimated to be 10–30%. The specific heat was measured using monotonic heating from -125 to 125°C.

Initial temperature measurements in the boreholes were made several weeks after drilling using a thermistor string with an accuracy of ± 0.1°C. Continuous measurements were then made using two and four channel Onset Hobo Pro series dataloggers with an accuracy of ± 0.25°C. One of sensors was usually installed on the surface and the remainder at various depths (refer to Table 1 for details) inside the borehole. Ground and surface temperatures were measured six times per day at four locations from 2005 to 2007.

Two 100 m × 100 m active layer monitoring sites were established as part of the Circumpolar Active Layer Monitoring (CALM) program (Brown *et al.*, 2000) on cinder plateaus at elevations of 1330 and 1630 m a.s.l. (Figure 4). Measurements were made at the end of the thaw season with a steel probe (5 mm in diameter). Probing or observations in pits were undertaken at a number of other sites with elevations between 800–2700 m a.s.l. and the presence or absence of permafrost was recorded (Figure 4).

Air temperature, solar radiation, vegetation and snow cover are the main factors influencing the distribution of permafrost in mountain areas (e.g. Gruber and Hoelzle, 2001). Based on this, we used a simple modelling approach to obtain a first approximation of the spatial patterns of MAGT for the study area. The model input consisted of meteorological data from Klyuchi, temperature measurements in boreholes and a digital elevation model (DEM) with a grid cell size of 90 × 90 m obtained from the Space Shuttle radar topography mission (USGS, 2004).

To calculate the MAAT we use:

$$\mathrm{MAAT} = -0.0045 * \mathrm{h} + \mathrm{T}_0 \quad (1)$$

where h is elevation in metres based on the DEM and T_0 is the estimated MAAT at 0 m a.s.l.

The MAGT was calculated using:

$$\mathrm{MAGT} = \mathrm{MAAT} + 0.02 * \mathrm{RAD} \quad (2)$$

where RAD is mean annual potential direct shortwave solar radiation (W/m^2), calculated using the DEM and the software outlined by Corripio (2003). The coefficient of 0.02 was estimated from the relation between ΔT and RAD where $\Delta T = \mathrm{MAAT} - \mathrm{MAGT}$ (Figure 3C). ΔT was calculated for Klyuchi and for our boreholes where measurements of MAGT are available, and we included the simplifying assumption that $\Delta T = 0$ without solar radiation (cf. Bartlet *et al.*, 2006). Figure 3C illustrates this relation and also the fact that all points have a similar level of radiation because they were drilled in virtually horizontal and open locations. Compared to other statistical models using air temperature and radiation (e.g. Gruber and Hoelzle, 2001; Lewkowicz and Ednie, 2004) this is a poorly sampled situation with respect to the influence of solar radiation but the resulting map is nevertheless useful to guide future measurements in order to improve the dataset and to support better models (cf. Gruber *et al.*, 2003). For validation we use borehole temperature measurements (Table 1 and Figure 5) and data from loggers collected during summer 2007 (Figure 3B).

A Landsat ETM+ image from 22 September 2000 (path 98, row 21, L71098021_02120000922) was used to map glaciers and vegetation. Vegetation was delineated using the soil adjusted vegetation index (SAVI; Huete, 1988) and the thresholds of 0.0 and 0.3 to differentiate between areas without vegetation, alpine tundra, and forest or shrubs.

The SAVI was derived from the Landsat image using:

$$(\mathrm{band}\,4 - \mathrm{band}\,3)/(\mathrm{band}\,4 + \mathrm{band}\,3 + 0.5) * 1.5 \quad (3)$$

Glacier outlines were digitised using the ratio of band 5/band 3 (Rott, 1994) with manual correction for debris-covered parts of glaciers and seasonal snow patches.

Surface cover results were compared with topographic maps and field observations. Considering the simplicity of the land cover classes, the application scale and extent of the study area, the quality of this classification was judged to be adequate.

Permafrost thickness was modelled in the finite-element software COMSOL Multiphysics 3.3 (Comsol AB, Sweden, c.f. Noetzli *et al.*, 2007). We used steady-state simulations to estimate the thickness of

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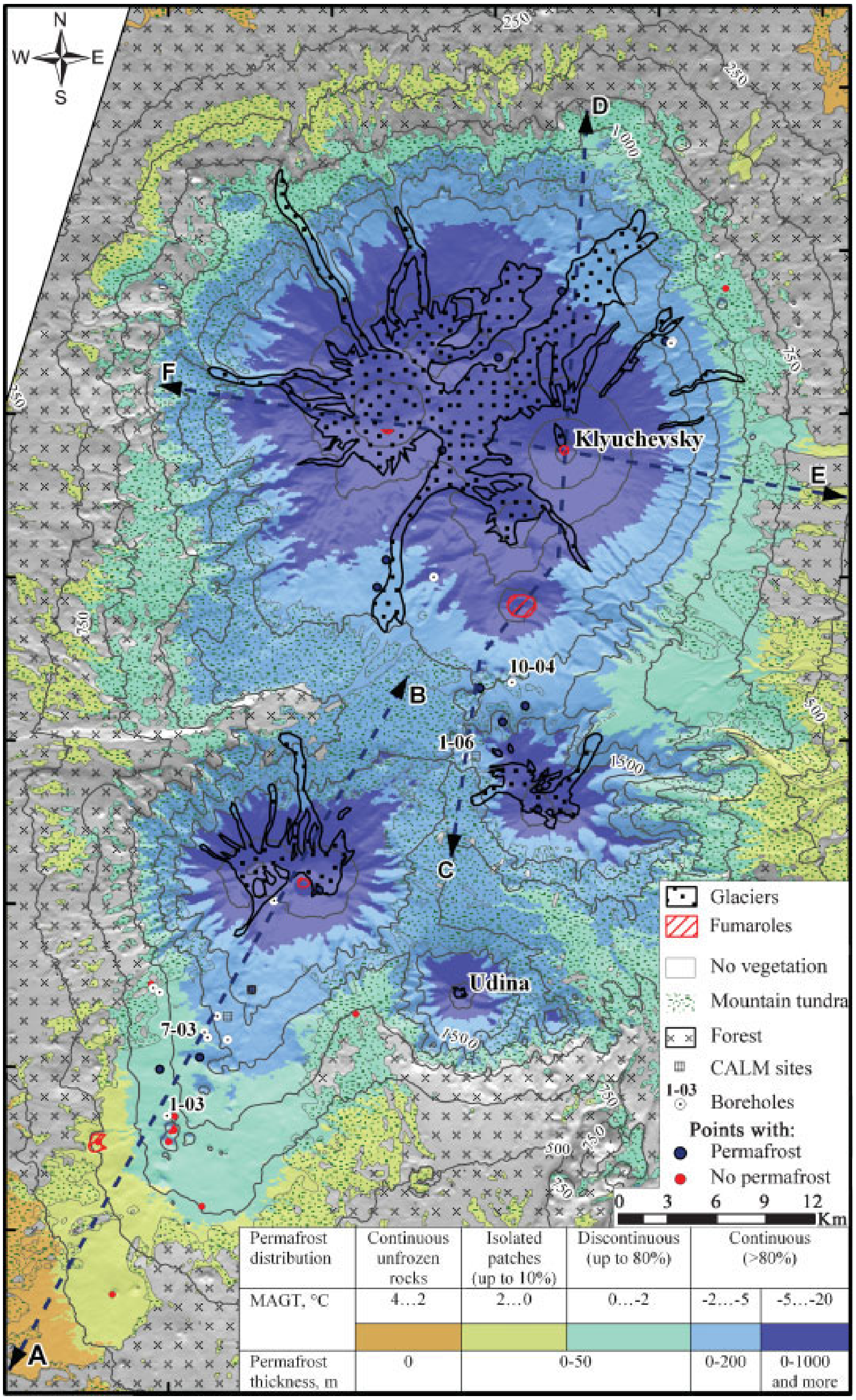

Figure 4 Mean annual ground temperature (MAGT) map with additional permafrost-related information for the Klyuchevskaya volcano group. The profiles in Figure 8 are shown by dashed lines and marked by capital letters. Contour line spacing is 250 m up to 1500 m a.s.l. and 1000 m for higher elevations. For names of boreholes and volcanoes refer to Figure 1.

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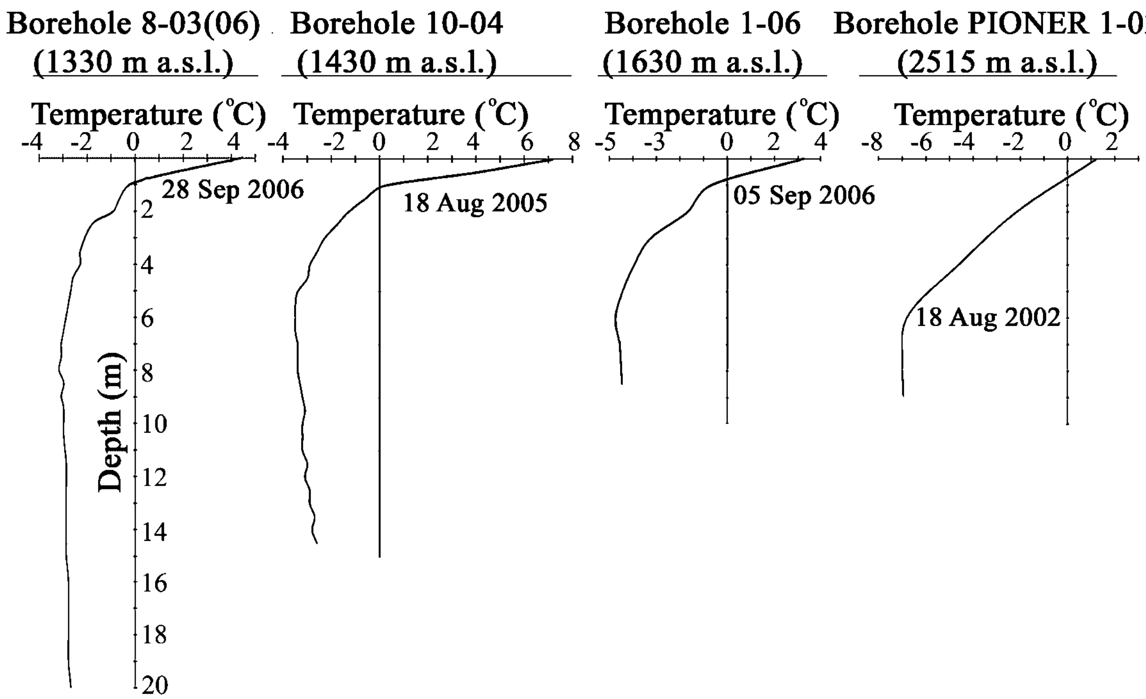

Figure 5 Temperature profiles during late summer and early fall (August-September) in selected boreholes at differing elevations (for location of boreholes refer to Figure 1).

permafrost and transient simulations to estimate the effect that the episodic presence of hot magma in narrow volcanic conduits has on the subsurface temperature field. The upper boundary conditions were derived from the MAGT model, lateral boundaries were set to zero heat flux and a regional geothermal heat flux of 60 mW/m^2 was prescribed at the lower boundary at a depth of 5 km. Given contrasting information on geothermal heat flux in this young volcanic area, this rather low value was chosen and results in conservative estimates of permafrost thickness. Mean properties of basalt without directional anisotropy were used for the model domain: thermal conductivity of 2.5 W/(m·K), specific heat capacity of 850 J/(kg·K) and density of 2600 kg/m^3, based on Čermak and Rybach (1982) and our own measurements. Phase change effects were not included.

Transient calculations of the thermal field around the Klyuchevsky volcanic conduits were performed in two dimensions with axial symmetry, and steady-state calculations were also undertaken in a two-dimensional domain. The diameter of conduits for Klyuchevsky was set to 60 m. The initial temperature in the conduit zone was set to 1200°C and for other areas the initial temperature was taken from a steady-state solution without the magma in the conduit.

RESULTS

MAGT Modelling

A ground temperature map (Figure 4) was created for the study area based on the simple model presented above. On this map, four belts are distinguished based on MAGT: (a) no permafrost, with MAGT = 2 to 4°C; (b) isolated patches of perennially frozen ground (up to 10% of total area) with predicted MAGT = 0 to 2°C; (c) discontinuous permafrost (up to 80% of total area) with MAGT = −2 to 0°C; and (d) continuous permafrost (>80% of total area), with MAGT = −20 to −2°C. These temperature ranges were based on the legend from the *Geocryological Map of the USSR* (1997).

The lower limit of discontinuous permafrost (based on modelled MAGT = 0°C) is at 750–900 m a.s.l. on north-facing slopes and 650–800 m a.s.l. on south-facing slopes. Vegetation also affects this boundary, but we have no data to quantitatively estimate its influence. The difference in temperatures between north- and south-facing slopes is estimated to be 0.6–1.0°C for gentle gradients and about 3°C for steep slopes. West- and east-facing slopes are modelled identically. A comparison of modelled MAGTs with independent borehole measurements shows that temperatures are within about ±1°C of the model prediction (Figure 3B), but larger deviations are possible in other places.

Borehole Data

From 2001–06 we drilled a set of boreholes in different parts of the Klyuchevskaya group at elevations between 900 and 3000 m a.s.l. Of these, nine are <10 m in depth, six are 10–16 m deep and the deepest is 25 m (Table 1). Because these boreholes were used to confirm the presence of permafrost, several were drilled near the timberline. Borehole 3-02 is located in the forest at 920 m a.s.l. and did not encounter frozen ground within the top 3 m. Boreholes 4, 5, 6-02 are located slightly higher than the timberline at 950 m a.s.l. and samples containing ice crystals were recovered at 1.5 m depth. However, in a 2 m deep pit hole near these boreholes we did not observe any evidence of permafrost and logger data revealed the mean annual ground surface temperature for this location to be 0.3°C and the MAGT at a depth of 2 m to be 0.9°C. At a similar elevation, a borehole (N 30 in Table 1) was drilled in search of hot water in 1978, 3 years after the LFTE event took place. It was drilled on the foot-slope of a cinder cone (shown as III in Figure 1) in the LFTE and penetrated 54 m of permafrost (Andreev, 1982; Jiruev, 1984). We drilled a borehole (1-03) at the same location and reached frozen ground at a depth of 1.3 m. The temperature in permafrost was close to 0°C but deeper drilling was impossible due to unstable walls within the borehole.

The measured MAGT decreases with elevation from -2.8°C (1330 m a.s.l.) to −7°C (2500 m a.s.l.) on the southern slope of Tolbachik (Figure 5).

The typical surface cover consists of basaltic volcanic deposits: lava, cinder, sand and ash with many young deposits (0–2500 years BP), an ice content of about 20–80% by weight and mainly basal and massive cryogenic textures (or suspended and structureless, according to Murton and French, 1994) (Figures 6 and 7). Volcanic cinders and basalt lava are very porous and the substrate is not always saturated with ice. Based on the analysis of 110 samples from boreholes and pits, the deposits are ultra pure (no salts), their pH is neutral (mean 6.9 with a range from 5.8–8.1) and TOC is very low (0–2%). Because of this, freezing in the macropores of these deposits occurs at about 0°C. The density (ρ) of the sampled pyroclastic deposits varies between 0.55 and 1.72 g/cm^3 and the mean density for basalts is 2.8 g/cm^3. The thermal conductivity of dry cinder and ash according to our measurements is about 0.15–0.18 W/(m·K). The maximum thermal conductivity is about 1.0 W/(m·K) with an ice content of 35–40%. The heat capacity for these deposits is 800–2300 J/(kg·K). The thermal conductivity for dry basalts is about 1.0–2.0 W/(m·K). This is comparable to values in the literature (Čermak and Rybach, 1982).

In two boreholes on cinder cones (11-04, 3-06) and in one (1-02) on an old lava flow we observed airflow into the boreholes that continued for several days after drilling. Due to the thermal disturbance caused by warm air from the surface being drawn into the boreholes we could not measure reliable temperatures at these locations. One possible reason for this airflow is the presence of cavities with low pressure in subsurface layers, which developed during the formation of cinder cones and lava flows.

Active Layer

Active layer thickness (ALT) decreases with elevation. Our measurements on the two CALM sites did not show significant changes in ALT during the last 5 years (Table 2). In the forest below the lower boundary of permafrost, the seasonal freezing reaches depths of 2.5 m in pits at 900 m a.s.l. near borehole 3-02 and 2 m at altitude 950 m a.s.l. near borehole 5-02. The maximum ALT of 2.0 m was observed in volcanic cinders at an elevation of 960 m a.s.l., while the minimum of 40 cm was observed at 2500 m a.s.l. The ALT may be greater in lava due to its higher thermal conductivity and lower ice content compared to unconsolidated material. Based on surface temperature data from loggers, we assume that only diurnal thawing occurs near the surface at elevations above 4000–4500 m a.s.l.

Permafrost Thickness Modelling

The thickness of permafrost was modelled for three cross-sections shown on Figure 8. The results show that the maximum estimated permafrost thickness is about 1000 m for areas higher than 4500 m a.s.l. such as Klyuchevsky and Kamen. Summits around 3000 m a.s.l. (such as Tolbachik and Zimina) have a possible thickness of permafrost of about 500 m and at elevations of 1200–1600 m, permafrost can reaches thicknesses of 100–200 m.

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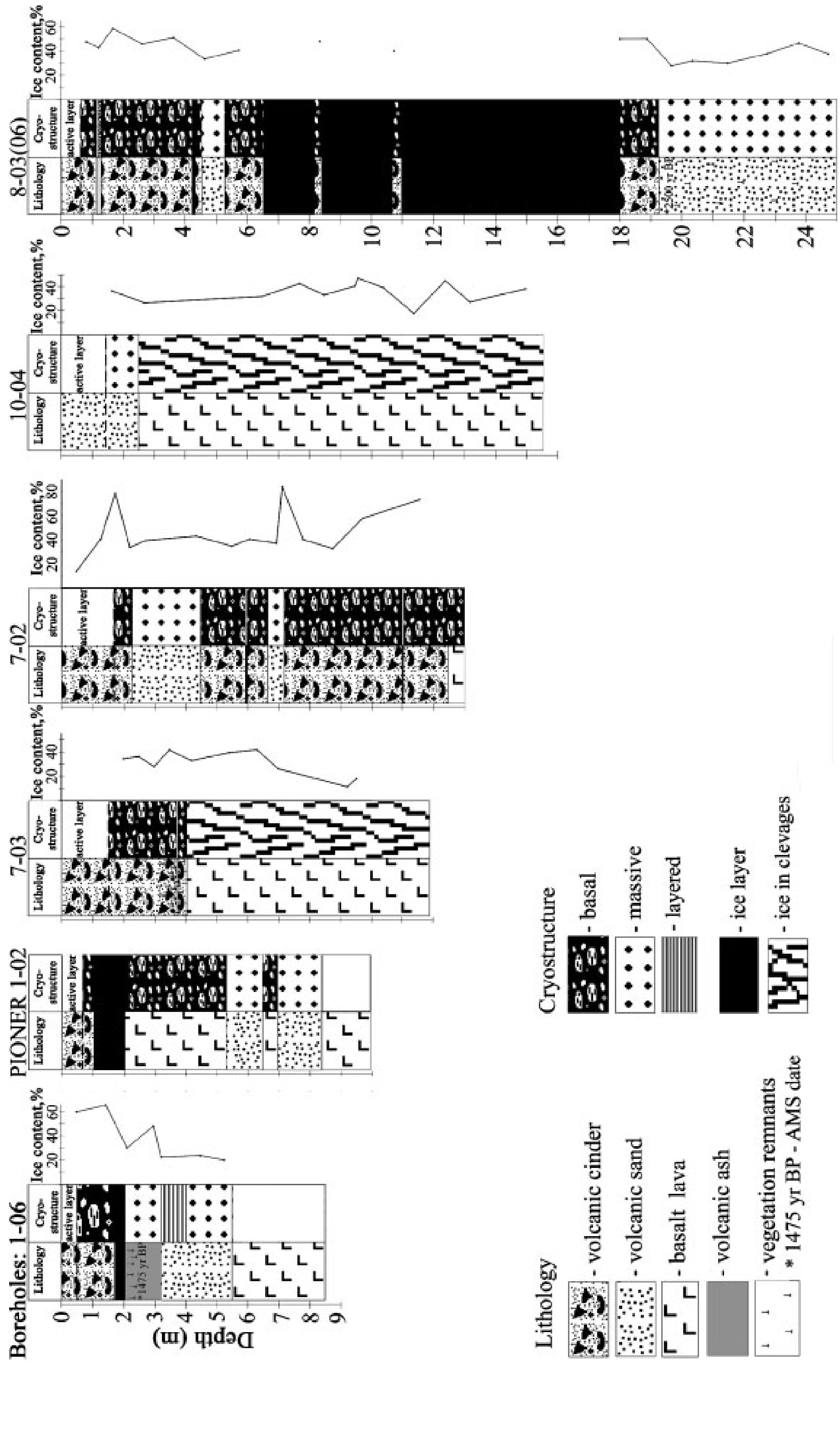

Figure 6 Examples of borehole lithology and cryogenic structures.

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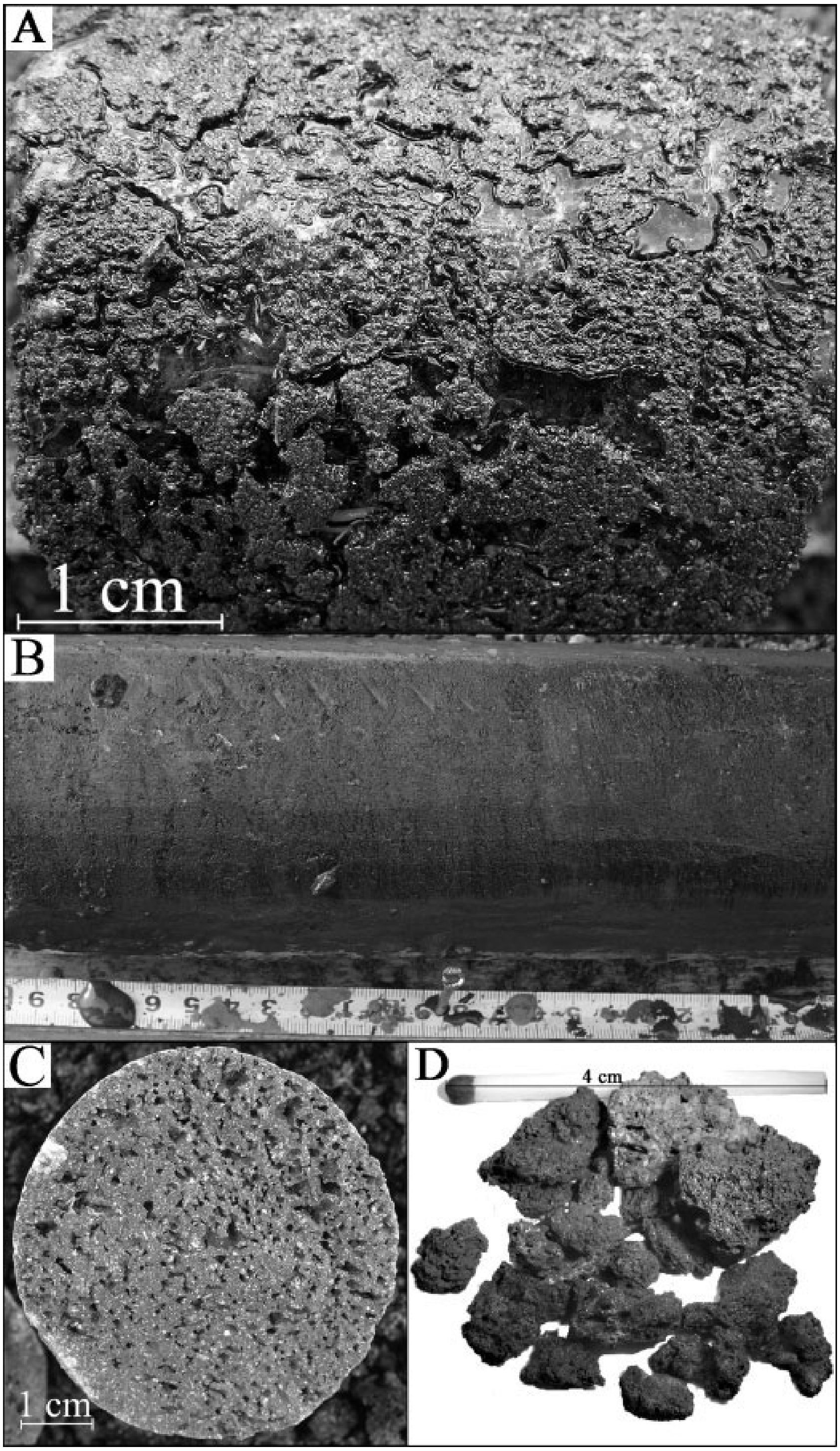

Figure 7 Photographs of the main types of cryogenic structures and deposits observed in cores: (A) basal structure in cinder; (B) layered and massive structure in ash; (C) basalt; (D) cinder particles. Photos: A. Abramov.

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Table 2 Mean active layer depth (z) on 100 m × 100 m sites (on a 10 m grid, 221 points of measurements).

Site name/year		2003	2004	2005	2006	2007
R30A	Date	06.09	28.09	05.09	19.09	18.09
(1330 m a.s.l.)	z, cm	78	67	73	71	72
R30B	Date	—	29.09	06.09	23.09	19.09
(1630 m a.s.l.)	z, cm	—	49	56	54	53

There are localised hot areas (fumaroles) with surface temperatures of 80–600°C in terminal parts of active volcanoes and LFTE cinder cones (shown in Figure 4). Their extent and their activity change from year to year and likely, they influence permafrost distribution only locally. Thaw is not extensive even around the volcanic conduits. This was shown by transient model experiments simulating 5000 years after an eruption and revealing a maximum radius of permafrost thaw due to rising magma within a volcanic pipe of Kluchevsky of about 150–250 m around the conduit.

DISCUSSION

The spatial abundance (or probability at a single point) as well as the temperature and thickness of permafrost are proportional to the modelled MAGTs. Given the large model uncertainties, we did not distinguish a reference depth for MAGT which here is viewed as a proxy for temperatures in the upper few metres of the subsurface. Colder modelled MAGT indicates a higher likelihood, spatial abundance and thickness of permafrost (see Figure 4 legend).

Forest vegetation often increases MAGT by 1–2°C due to high snow accumulation and tundra vegetation can decrease MAGT by 1–1.5°C due to thermal offset (Zamolodchikova and Smirnova, 1979). In the study area, permafrost rarely exists in forests and, therefore, forests are excluded from the temperature map.

The distribution of snow is strongly controlled by small-scale topographic features and wind and its net effect on ground temperatures cannot be quantified in a simple model like the present one. Outlines of glaciers are shown on the map because they alter the temperatures at their beds compared to the model results. Many glaciers in the area (especially small debris-covered ones) are of the cold type and subglacial permafrost can exist beneath them. Due to the high insulation properties of cinders, some isolated patches of frozen ground are present at lower elevations. In case of winter eruptions, snow can be buried by cinders and remain preserved for considerable time periods (cf. Kellerer-Pirklbauer *et al*., 2007). The formation of permafrost during eruptions is controlled by ALT, the thickness of deposited volcanic deposits and the amount of ice buried. A thick (11.5 m) ice layer was discovered in borehole 8-03(06) at 6.5 m depth (Figure 6). We believe that it was formed from buried snow about 1500 years ago (based on radiocarbon dating and eruption history).

The lithological composition in borehole N 30 (Jiruev, 1984) at 946 m shows two sequences of massive ice overlain by volcanic cinders and basalt lava flows. The upper ice layer (21–32 m) is covered by 4 m and the lower one (39–41 m) by 5 m of cinder and ash, and in both cases the ash is overlain by basalt lava 3–5 m thick. This profile demonstrates the strong insulation properties of volcanic cinder, which can protect ice from melting under a lava flow with temperatures of about 1000°C.

The thermal modelling provides a first estimate of permafrost thickness for different altitudinal belts. However, the simplification of mountain topography into two-dimensional cross-sections results in variability in the thickness predictions. This is particularly apparent in the different absolute elevations of the permafrost base beneath the summit of Klyuchevsky in the N-S and in the E-W transects, caused by different MAGTs on slopes with different aspects. The modelling does show that the influence of episodically rising magma in eruption pipes is only locally relevant to permafrost and does not significantly affect overall permafrost thickness. These model experiments add to the small amount of field data that explores the relationship between permafrost and volcanic activity.

Based on our field experience, the most important characteristics of permafrost formation and dynamics in mountain areas that specifically relate to volcanic activity are: (a) the rapid growth and destruction of volcanic landscape features; (b) the infiltration of surface water through near-surface frozen substrates, due to the high porosity of volcanic deposits and their partial saturation with ice; (c) the local thawing of permafrost following eruptions and its slow refreezing; and (d) the preservation of permafrost layers by (fresh) deposits of volcanic cinder due to its high insulation properties. In the case of large explosive eruptions, permafrost can aggrade in surrounding terrain. Especially during winter eruptions, falling cinder has subzero temperatures and can bury significant quantities of snow and ice.

The analysis of climate changes for Kozyrevsk shows slow warming over the last few years (Figure 3C). We can expect some changes at the lower permafrost boundary in the future.

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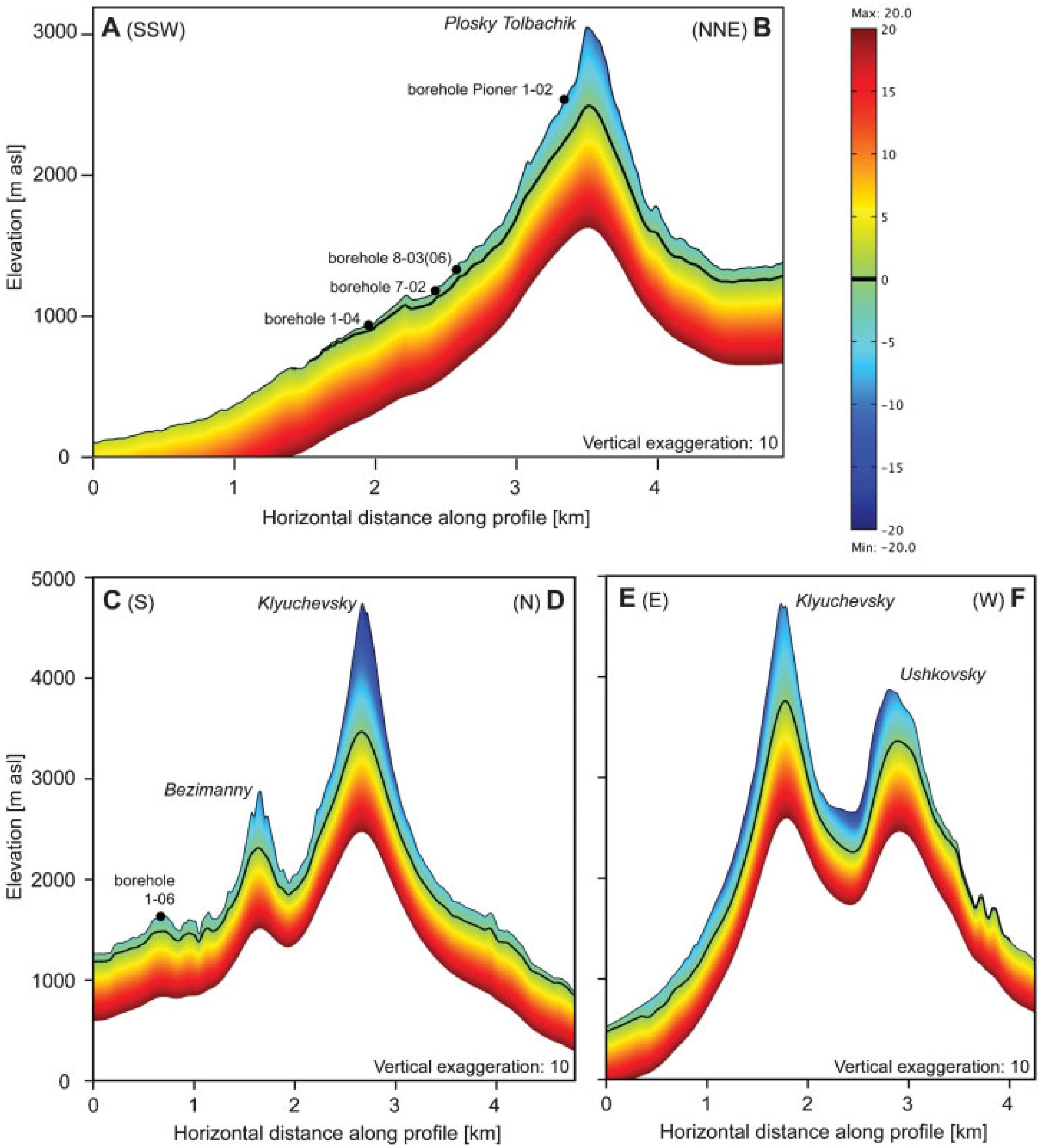

Figure 8 Modelled thermal profiles: (top) for a SSW-NNE profile at Tolbachik volcano; (bottom left) for a S-N profile at the Ushkovsky, Klyuchevsky and Bezymianny volcanoes; and (bottom right) for a roughly E-W cross-profile at the Ushkovsky, Klyuchevsky and Bezymianny volcanoes. The corresponding profiles (AB, CD and EF) are indicated in Figure 4. Temperature fields were calculated using the software package COMSOL. *Note:* The line within the green shading represents 0°C.

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CONCLUSION

Based on borehole measurements and simple modelling, we can summarise the geocryological conditions in the Klyuchevskaya volcano group as follows: (a) contrary to previously published information, modelling suggests that permafrost underlies about 2000 km^2, and periglacial processes and landforms are widely distributed at elevations above 900 m a.s.l.; (b) the lower boundary of permafrost is around 750–900 m a.s.l. on north-facing slopes and around 650–800 m a.s.l. on south-facing slopes without forest vegetation; (c) measured MAGTs vary from -2.8°C at 1330 m a.s.l. to -7°C at 2500 m a.s.l.; (d) the difference in mean ground temperatures between northern and southern slopes is estimated to be 0.6–1.0°C for gentle slopes and about 3°C for steep slopes; (e) the maximum thickness of permafrost is estimated to be in excess of 1000 m for the highest summits (about 4500–4800 m a.s.l.) and up to 500 m for summits of about 3000 m a.s.l.; and (f) the ALT varies from 2–2.5 m at 900 m a.s.l. to about 50 cm at 2500 m a.s.l.

Future work should include improvement of the spatial model for high elevations and further investigation of the relationship between permafrost and volcanic activity. Temperatures during the eruptions can locally be greater than 1200°C and important questions relate to the direct measurement of temperatures underneath lava flows and pyroclastic deposits during the eruptions and their impact on frozen ground. However, based on our modelling, it appears that volcanic activity influences permafrost only locally.

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