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Distribution of permafrost on the west slope of Mt. Ichinsky, Kamchatka, Russia

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Abstract

In this study we investigate the distribution and development of permafrost on the west slope of Mt. Ichinsky Volcano, Kamchatka, Russia. Ground temperature measurements during autumn 2000 reveal the altitudinal development of frozen ground and the active layer. Active layer thickness in sandy deposits varied from 3.1 m at 900 m a.s.l. to 0.85 m at 1700 m a.s.l. The lower limit of discontinuous permafrost was estimated to be at least 900 m a.s.l., close to the treeline. We conducted automated meteorological observations of air temperature and wind direction and speed at 1000 m a.s.l. from September 2000 until August 2001. Mean air temperature during this period was −4.4℃. The prevailing SSE winter wind is a controlling factor in the distribution of permafrost, periglacial landforms and vegetation above the treeline.

1. Introduction

Previous studies of permafrost distribution in Kamchatka, Russia (*e.g.* Zamolotchikova and Smirnova, 1979), demonstrate that the southern limit of permafrost lies in Kamchatka itself; this is also shown on the permafrost map of Russia (*e.g.* Lisitsyna and Romanovskii, 1998; Williams and Warren, 1999). In central Kamchatka, discontinuous permafrost appears to mainly occur in mountainous regions, however, detailed information on permafrost distribution is limited (Gorbunov, 1988; Sone *et al.,* 2003; Abramov *et al.,* 2005).

Recent studies have reported warming of permafrost temperatures in many regions of the world (*e.g.* Harris *et al.,* 2001; Ostercamp, 2003; Gruber *et al.,* 2004). In Kljuci, central Kamchatka, mean annual air temperature has tended to increase since the 1970s (Sone *et al.,* 2003). As areas of discontinuous permafrost are a good indicator of climatic change, it is important to document present-day permafrost conditions as a benchmark for future climatic warming. Given the current global warming, we expect that the permafrost environment in Kamchatka is currently undergoing change.

For the current study we investigated frozen ground upon Ichinsky Volcano, Kamchatka, during 2000. We measured near-surface ground temperature at seven locations at different altitudes and identified associated periglacial landforms. We also measured air temperature and wind speed and direction at 1000 m a.s.l. from September 2000 until August 2001. The objectives of this study are to estimate the lower limit of discontinuous permafrost and to discuss the permafrost environment on the west slope of Mt. Ichinsky, Kamchatka. We also discuss the distribution of permafrost and vegetation in relation to the winter prevailing wind, which has not previously been considered in studies of permafrost in Kamchatka.

2. Study area and methods

2.1. Study area

Ichinsky Volcano (55°46′N, 157°55′E, 3607 m a.s.l.) lies within the Sredinny Mountain Range and Bystrinsky National Park, on the western side of central Kamchatka Peninsula (Fig. 1). The volcano is currently active, and first formed during the Middle Pleistocene. There is minor fumarolic activity in the summit area, although no eruptions have been recorded in historic time (Volynets *et al.,* 1991). The summit of Mt. Ichinsky is covered with an ice cap that is drained by several glaciers. The West Ichinsky Glacier flows from the summit downslope to a terminus at 1200 m a.s.l. This glacier is covered by debris at the terminus and appears to be stagnant.

The study area ranges from 900 to 1840 m a.s.l. on the west slope of Mt. Ichinsky (Fig. 1). The upper limit of birch trees (*Betula ermanii*) occurs at about 900 m a.s.l., while Alder shrub (*Alnus fruticosa*) occurs above the treeline at 900 to 1000 m a.s.l.

2.2. Ground temperature observations

In the field we used shovels to dig pits for directly detecting frozen ground, or to indirectly estimate the presence of frozen ground via temperature profiles. Ground temperatures were measured with thermistor sensors (D617, TECNOL SEVEN Co. Ltd.) over the period from August 26 until September 1, 2000. Site 1 (900 m a.s.l.) lies at the upper limit of birch trees, while Site 2 (930 m a.s.l.) is a grassland in a shallow nivation hollow surrounded by dwarf pine (*Pinus pumila*) shrub. Soil at Site 2 consists of loamy volcanic ash soil. Sites 3 (1000 m a.s.l.), 4 (1180 m a.s.l.), 5 (1400 m a.s.l.), 6 (1723 m a.s.l.) and 7 (1840 m a.s.l.) are located above the treeline within the alpine zone. Sites 1, 3, and 4 are situated on outwash terraces that consist mainly of fluvio-glacial sand, while Sites 5 and 6 are situated on the peaks of moraine hills. Site 7 is located on a debris slope, while sites 1, 3, 4, 5 and 6 are situated on windward bare ground with scarce vegetation cover. The characteristics of the different study sites are summarized in Table 1.

2.3. Meteorological observations

Meteorological data are important for discussing permafrost, glaciological and biological environments, however, such data are limited for the mountain regions of Kamchatka (Matsumoto *et al.,* 1997). We therefore measured air temperature and wind speed and direction at Site 3 (1000 m a.s.l.) from September 2000 until August 2001. Temperature and wind sensors were installed at heights of 1.5 and 2.0 m, respectively, above the ground surface. We used thermistor data loggers (Ondotori Jr. TR-52, T and D Corp.) for temperature measurements and Kadec-US, Kadec-UN (KONA System Co. Ltd.) and Young-type

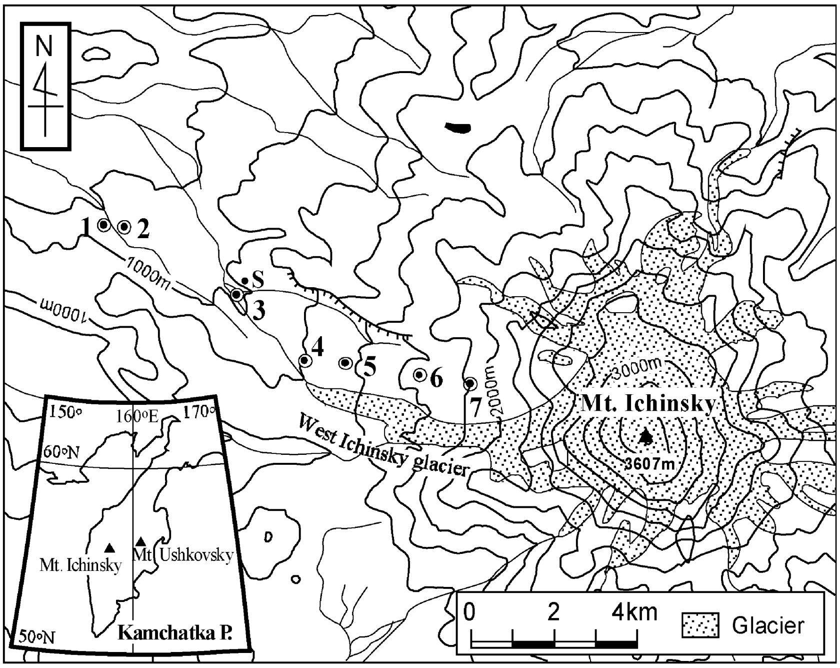

Fig. 1. Locations of study sites (1–7) upon the west slope of Mt. Ichinsky. s: solifluction lobes.

Table 1. Characteristics of survey sites on the west slope of Mt. Ichinsky.

Altitude (m a.s.l.)		Topography	Soil material	Surface condition
Site 1	900	outwash terrace	fluvio-glacial sand	windward bare ground
Site 2	930	nivation hollow	loamy volcanic ash	grass land
Site 3	1000	outwash terrace	fluvio-glacial sand	windward bare ground
Site 4	1180	outwash terrace	fluvio-glacial sand	windward bare ground
Site 5	1400	moraine hill	sandy till	windward bare ground
Site 6	1723	moraine hill	sandy till	windward bare ground
Site 7	1840	debris slope	debris	—

wind sensors for wind measurements. Air temperature and wind direction data were measured and recorded at 1-hour intervals, and wind speed data were measured as hourly mean values.

3. Results

3.1. Ground temperature observations

Figure 2 shows ground temperature profiles for Sites 1 to 7. We directly detected frozen ground at all sites except Site 1. Sites at higher altitude recorded lower ground temperatures, except for Sites 2 and 7.

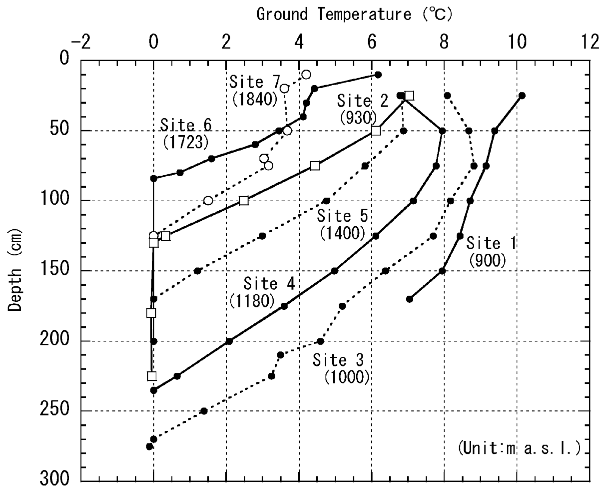

Fig. 2. Ground temperature profiles for sites on Mt. Ichinsky, as measured from August 26 until September 1, 2000. Site elevations (m a.s.l.) are also provided.

The depth of the freezing point at Site 1 is estimated to be about 3.1 m, as determined from temperature gradients at Sites 3–5, which are located on windward bare-ground and underlain by sand. The ground temperature gradient at depth appeared to be constant during the observation period.

3.2. Meteorological observations

Results of meteorological observations are shown in Table 2. Mean annual air temperature from September 1, 2000 until August 31, 2001 was −4.4℃. Maximum and minimum air temperatures were 21.2 and −34.8℃, respectively, while maximum and minimum mean monthly air temperatures were 11.7℃ (July) and −21.4℃ (February), respectively. The annual range of mean monthly air temperature is 33.1℃, indicating a continental climate. The direction of the prevailing winter wind is SSE (Table 2); mean annual wind speed is 4.0 ms^{-1}. Mean monthly wind speeds during January, February, and March were 5.5, 3.7, and 6.2 ms^{-1}, respectively. Freezing and thawing indices were 2731 and 1104℃ · days respectively, while the warmth index was 12.9.

3.3. Development of periglacial landforms

Periglacial landforms such as earth hummocks, turf-banked steps, solifluction lobes, frost-crack polygons, and small-scale sorted patterned ground are observed above the treeline. Turf-banked steps are well developed on windward bare ground between 900 and 1700 m a.s.l. (Fig. 3). While tread surfaces are gently sloping with little vegetation, risers are steeper and

Table 2. Monthly air temperature and wind speed data at 1000 m a.s.l. upon Mt. Ichinsky, as measured from September 2000 until August 2001.

Month	Air temperature (℃)			Wind speed (ms^{-1})		Wind direction	
	Mean	Max.	Min.	Mean	Max.	Mfwd	Fpw (%)
Sep. 2000	4.3	19.6	−6.8	3.8	18.7	SSE	22.5
Oct. 2000	−2.1	6.7	−12.0	5.3	30.0	SSE	33.8
Nov. 2000	−13.4	−3.8	−22.7	3.5	16.4	SSE	18.2
Dec. 2000	−14.0	−5.5	−23.5	3.5	16.7	SSE	21.6
Jan. 2001	−18.1	−6.4	−29.9	5.5	25.4	SSE	28.3
Feb. 2001	−21.4	−3.8	−34.8	3.7	16.4	SSE	16.0
Mar. 2001	−12.9	3.5	−32.0	6.2	37.6	SSE	41.9
Apr. 2001	−6.0	5.6	−18.3	5.2	21.6	SSE	36.2
May 2001	1.5	16.1	−7.7	3.0	13.0	SSE	20.0
Jun. 2001	6.8	17.4	0.6	3.7	17.2	SSE	33.4
Jul. 2001	11.7	21.2	5.4	2.9	15.7	SSE	25.0
Aug. 2001	9.4	19.9	−1.1	2.6	15.3	SSE	17.1
Entire period	−4.4	21.2	−34.8	4.0	37.6	SSE	26.2

Temperature and wind direction data are from hourly measurements. Mean temperature: the mean monthly air temperature calculated from hourly data. Max. and Min. temperatures: the maximum and minimum temperatures from hourly data. Mean wind speed: the monthly mean speed calculated from mean hourly (60 minutes) data. Max. wind speed: the maximum mean hourly (60 minutes) wind speed. Mfwd: most frequent wind direction. Fpw: frequency (%) of occurrence of the SSE wind stronger than 4.0 ms^{-1}.

covered with vegetation. Risers are typically 1 m in height. Frost-crack polygons of 10 to 20 m diameter are distributed on windward flat surfaces (Fig. 4), while earth hummocks of 60 to 80 cm in height occur on the leeside of ridges (Fig. 5). Small-scale patterned ground such as sorted circles, polygons, and stripes are developed on bare ground, typically on the treads of turf-banked steps. A SSW-facing slope about 300 m north of Site 3 contains many turf-banked solifluction lobes (Figs. 1 and 6); the dip of this slope is about 15°, while the largest lobe has a riser height of 3 m.

4. Discussion

4.1. *Development of the active layer*

The active layer is the layer of ground above the permafrost that thaws during summer and freezes during winter. For the research period, the thaw depth appears to be close to the depth of the active layer. We therefore assume that the maximum thaw depth during this period was the active layer. The depth of the active layer in sandy ground tends to be deeper at lower altitudes (Fig. 7). The relationship between active layer depth and altitude is almost linear. The depth of the active layer at Site 1 estimated from altitude corresponds to the depth estimated from ground temperature gradient (3.1 m). Active layers are shallower in loamy volcanic ash soil (Site 2) and deeper in debris material (Site 7) in comparison with adjacent sites in sandy ground. These observations are consistent with the thermal conductivities of the different ground materials: coarser material tends to have higher thermal conductivity (Williams and Smith, 1989). The depth of the active layer varies from 0.65 to 1.2 m in the alpine zone of Mt. Ushkovsky (Fig. 1), located about 150 km east of Mt. Ichinsky (Sone *et al.*, 2003). The depth of the active layer determined in the present study area is deeper than that at Mt.

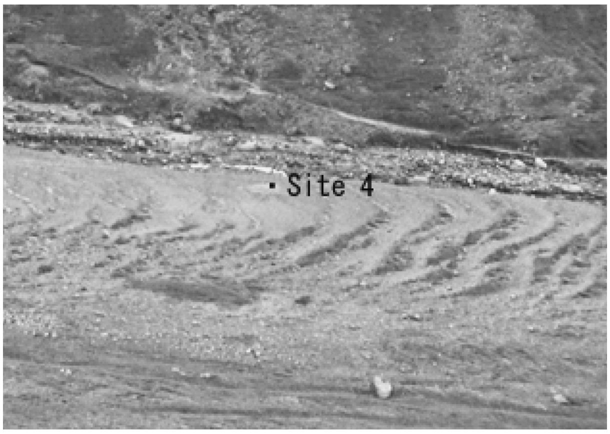

Fig. 3. Photograph of turf-banked steps. Treads are normally 10 m in length. Risers are typically 1 m in height. Site 4 is located on the tread of the turf-banked steps in the center of the photograph. View is to the south.

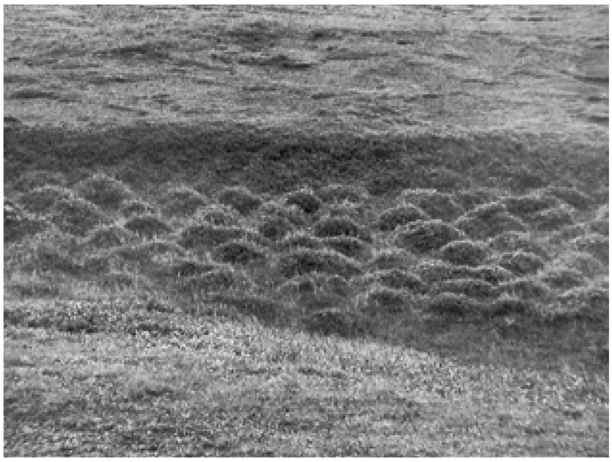

Fig. 5. Earth hummocks of 60 to 80 cm in height near Site 3.

Fig. 4. Frost-crack polygons on a fluvio-glacial terrace near Site 3.

Fig. 6. Solifluction lobes located 300 m north of Site 3.

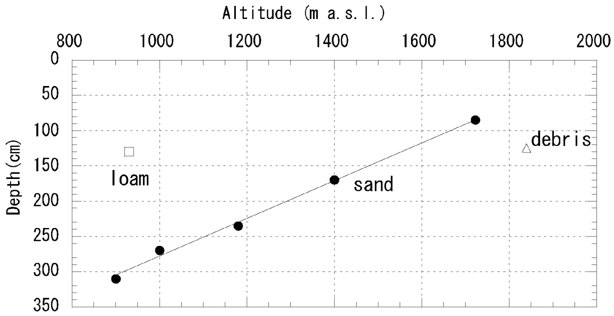

Fig. 7. Depth of the active layer with varying altitude at Mt. Ichinsky, as measured from August 28 until September 2, 2000. Symbols indicate ground type.

Ushkovsky, where the soils are volcanic ash soils.

4.2. Lower limit of permafrost

Permafrost is defined as ground that is perennially frozen over a period of two years or more. There is a good possibility of the existence of permafrost if the ground remains frozen at depth during autumn. Figure 2 shows that the minimum elevation of discontinuous permafrost is at least 900 m a.s.l. on the study slope. Mean annual air temperature is estimated to be about −3.8℃ at 900 m a.s.l., assuming a lapse late in air temperature of 6℃ km^{-1}. In terms of air temperature, permafrost can exist a few hundred meters below the treeline, as mean annual air temperatures are reported to be −3 to −2℃ at the lower limit of permafrost (Ødegård *et al.,* 1992; Sone,1992).

In the middle of the Sredinny Mountain Range, Kamchatka Peninsula, discontinuous permafrost was predicted above 1000 m a.s.l. (Zamolotchikova and Smirnova, 1979). The present study indicates that the lower limit of discontinuous permafrost is lower than this estimate by at least 100 m. There are few shrubs above the treeline (Fig. 8); as there is no clear sub-alpine zone of shrubs, the lower limit of the alpine zone is located immediately above the treeline (Fig. 9).

At Mt. Ushkovsky, the lower limit of discontinuous permafrost is approximately 1000 m a.s.l., and mean annual air temperature is estimated to be −3 to −4℃ (Sone *et al.,* 2003). There is a moderately dense shrub zone between the treeline (600 to 700 m a.s.l.) and the alpine zone (above 1000 m a.s.l.) on the north slope of Mt. Ushkovsky, but there is no permafrost in the zone of alder shrubs (Fig. 9).

Development of periglacial landforms such as frost-crack polygons, solifluction lobes, turf-banked steps, and patterned ground indicates the existence of permafrost in the alpine zone. It is likely that discontinuous, if not some continuous permafrost occurs in the alpine zone of central Kamchatka. The altitude of the treeline on Mt. Ichinsky is probably controlled by temperature conditions, as the warmth index at 900 m a.s.l. is estimated to be 15. It appears that the lower limit of the alpine zone is situated within the original sub-alpine zone and that permafrost occurs at lower altitude on the west slope of Mt. Ichinsky.

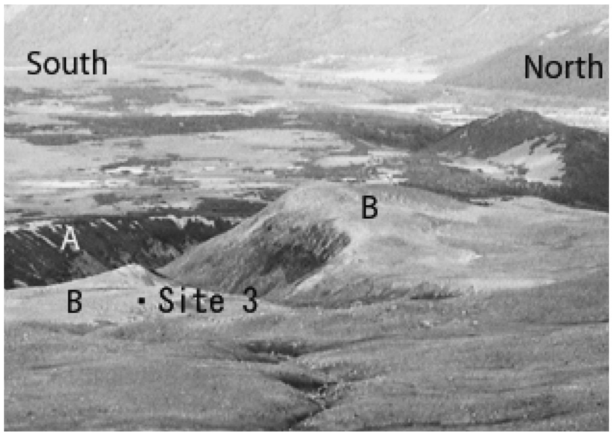

Fig. 8. Landscape elements of the study area, viewed to the west. A: North-facing leeward slope. B: Windward bare ground.

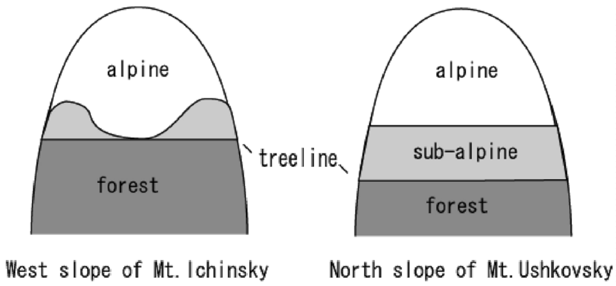

Fig. 9 Schematic environmental zonations upon Mt. Ichinsky and Mt. Ushkovsky.

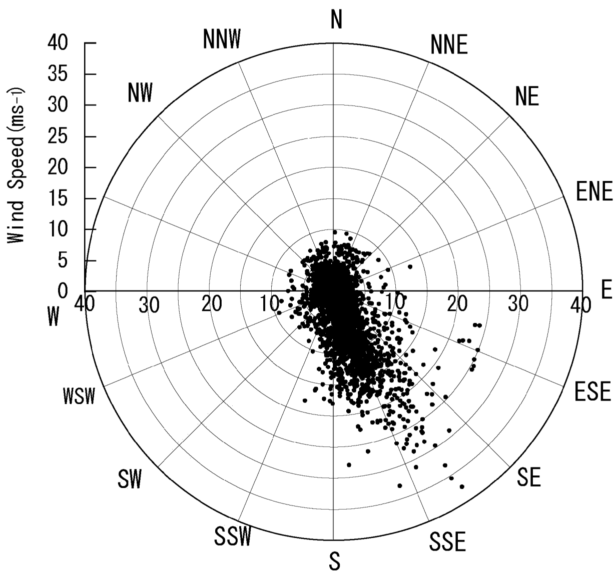

Fig. 10 Wind direction and speed data at 1000 m a.s.l. upon Mt. Ichinsky from October 2000 until April 2001. Dots represent mean hourly wind speeds and hourly measured wind directions.

4.3. *Prevailing winter wind*

Matsumoto *et al*. (1997) measured wind directions upon three mountains in central Kamchatka. Their data indicated that the wind direction during winter was variable, with no obvious prevailing wind. Okitsu (1997) noted an absence of wind-shaped trees along the uppermost timberline ecotone on the western slopes of Mt. Ushkovsky. Prevailing winter winds have therefore not previously been reported in the mountain region of Kamchatka.

In contrast to the above studies, we detected a distinctive prevailing wind at Mt. Ichinsky (Fig. 10). The prevailing wind is one of the important factors in controlling the distribution of snow accumulation, permafrost, periglacial landforms, and vegetation. In our study, the most frequent wind direction during winter was SSE (Table 2). The critical wind speed that results in the movement of surface snow is about 4 to 7 ms^{-1} (Ohmura *et al.,* 1967; Yamada, 1974). The frequency of occurrence of a prevailing wind stronger than 4 ms^{-1} was more than 28.2% during the snow season (October-April). Snow rarely accumulates on windward bare ground, but accumulates on leeside slopes or depressions. The pattern of snow accumulation during winter is therefore probably invariable. The influence of snow on soil temperature appears to be only minor upon windward bare ground where the thin snow condition is favorable for permafrost development. Shrub trees such as alder and dwarf pine occur on leeward slopes where snow accumulates (Fig. 8). The distribution of permafrost, periglacial landforms, and vegetation is therefore influenced by the prevailing SSE winter wind. Development of the subalpine zone is hampered by the fact that shrubs are unable to grow under conditions of severe strong winter winds; this explains why permafrost develops at lower altitudes on Mt. Ichinsky, despite the lower elevation of the treeline on Mt. Ushkovsky (Fig. 9).

5. Conclusions

In this study we investigated frozen ground on the west slope of Mt. Ichinsky, central Kamchatka, during August and September 2000. Our main conclusions are as follows:

1. The active layer thickness in sandy ground varies from 3.1 m at 900 m a.s.l. to 0.85 m at 1700 m. The lower limit of discontinuous permafrost is located near the treeline at an altitude of 900 m a.s.l.
2. The distribution of permafrost, periglacial landforms, and vegetation is influenced by the prevailing SSE winter wind. This wind limits the development of the sub-alpine zone in the study region.
3. Periglacial landforms such as frost-crack polygons, solifluction lobes, turf-banked steps, and small-scale patterned ground are developed above the treeline.
4. Mean annual air temperature from September 2000 until August 2001 was −4.4℃ at 1000 m a.s.l.

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