4.4 Multi-sensor optical remote sensing of periglacial tundra landscapes

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4.4.1 Research aim

The geomorphology of the region, formed by thermokarst and thermo-erosion, is an important source of information for the reconstruction of the Late Pleistocene and Holocene paleo-environment. Periglacial surface structures are indicators for certain stages of regional landscape development. To understand the extensive surface transformation since the Late Pleistocene it is essential to use remote sensing. Satellite remote sensing provides the large scale data vital for the up-scaling of geomorphological and geological field data from key sites like the area around Cape Mamontov Klyk.

It is possible to differentiate geomorphological units formed under periglacial conditions by their surface properties. Therefore the interpretation and classification of remote sensing data allows the large scale quantification of periglacial landscape units in the investigated area. Because of minor vegetation cover, relief structures like thermokarst depressions or thermo-erosional valleys are excellent to identify with satellites images in visible and infrared wavelengths. For the examination of the key site Mamontov Klyk and the coastal plain we use multi-spectral, medium resolution Landsat-7 ETM+ data together with panchromatic, high-resolution CORONA data. The extracted information can be used as an excellent complementary tool, together with sedimentological, cryological and paleontological field data, for the characterization and reconstruction of the Holocene landscape history in the region. The field data from the expedition "Lena-Anabar 2003" act as ground truth information and allow a generalization for the structures identified and mapped in the remote sensing imagery.

The resulting data is prepared for input into a geographical information system (GIS). Together with data from geological maps, geo-cryological field surveys and height information from digital elevation models (DEM), the GIS provides new insights into complex multi-source data structures.

One expected result is the estimation of quality, quantity and distribution of extensive thermokarst and thermo-erosional processes during the Holocene for the investigated region at Cape Mamontov Klyk and the entire coastal plain in front of the Pronchishchev Range.

4.4.2 Satellite data

For the investigation of the field area several satellite images are available. A Landsat-7 satellite image from 04-Aug-2000 (Path 139, Row 8) is used for the regional study of the surface conditions in the sedimentary plain from the Pronchishchev Range to the coast. The multi-spectral Landsat-7 ETM+ image has six medium-resolution data bands ranging from visible to mid-infrared wavelengths, one thermal band and one high-resolution panchromatic band (Table 4.4-1).

Table 4.4-1: Landsat-7 image properties

Band	Ground resolution (m)	Wavelength range (nm)	
1	30	450 – 520	Blue
2	30	530 – 610	Green
3	30	630 – 690	Red
4	30	780 – 900	Near infrared
5	30	1550 – 1750	Middle infrared
6	60	10400 – 12500	Thermal
7	30	2090 – 2350	Middle infrared
8	15	520 – 900	Panchromatic

Additionally, several CORONA satellite images from different dates were used during the field work (Table 4.4-2). CORONA images are very high-resolution, panchromatic images, acquired from 1960-1980. We use these images for the high-resolution study of local periglacial surface features, namely thermokarst depressions, thermokarst valleys, retrogressive thaw slumps, snow patches, pingos, and patterned ground.

Table 4.4-2: CORONA image properties

Image	Ground resolution	Acquisition date	Camera system
DS1007-1052DA030 DS1007-1052DA031 DS1007-1052DA032	9 feet (3 m)	23-06-1964	KH-4A
DS1022-1005DA047 DS1022-1005DA048	9 feet (3 m)	20-07-1965	KH-4A
DZB1210-500140L003001	30 feet (10 m)	14-07-1975	KH-9

4.4.3 General geomorphology in the Lena-Anabar interfluve

The regional scale geomorphology is determined by the Pronchishchev Range in the south, stretching parallel to the coast from NW to SE, and a 28-38 km wide sedimentary plain in front of these mountains (Figure 4.4-1). The hills are up to 270 m high. The sedimentary plain is very gently inclined towards the Laptev Sea coast with heights from 60-75 m close to the hills and 30-35 m at the coast (inclination angle of ~0.07°). The river valleys in the region can be assigned to one of two major flowing directions: S-N or W-E. Some of the major rivers cross the SE Pronchishchev hills on their flow northwards. This probably points on neotectonic activity in the Pronchishchev Range. Thermokarst depressions are widely distributed in the sedimentary plain. They not only occur along river valleys but often are arranged linear on interfluves between the river valleys. This spatial pattern probably points on paleo-valley systems below the cover deposits of the Ice Complex. The cryo-lithological properties of the sediments accumulated in these supposed paleo-valleys possibly support the formation of thermokarst in the Ice Complex cover during the Holocene. Therefore the linear arrangement of large thermokarst basins is considered as a finger print of succeeding relief forms. The surface of the plain is densely incised by thermo-erosional valleys.

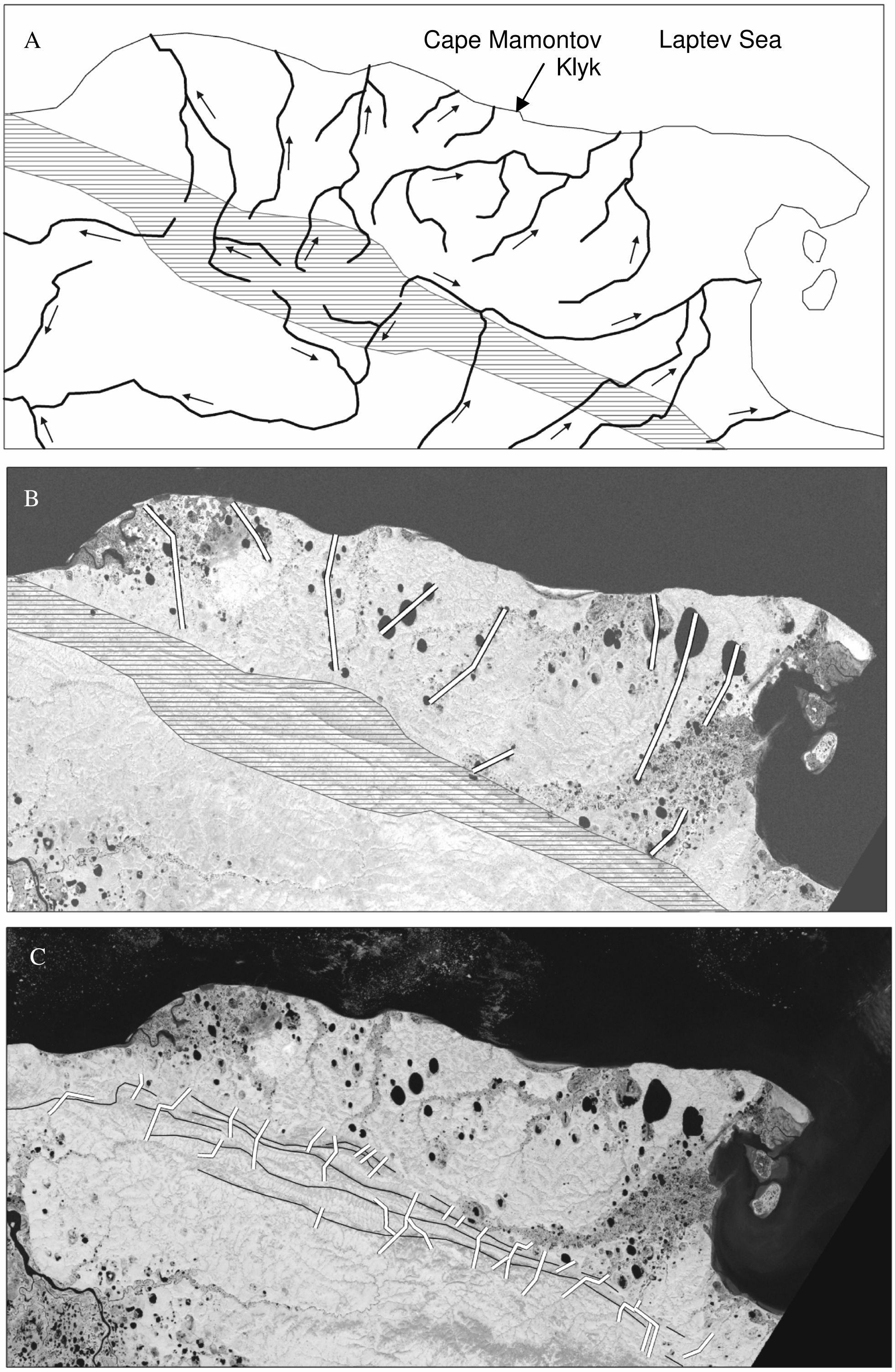

Figure 4.4-1: Regional structures in the Lena-Anabar coastal area (Landsat-7 ETM+ image)

A – River discharge regime: North of the Pronchishchev Range (horizontal lines) the rivers flow towards N or NE; the western Pronchishchev Range acts as watershed, while the eastern Pronchishchev Range does not

B – Linear arrangement of large thermokarst basins not connected to recent river systems possibly indicate paleo-river structures, where the cryo-lithological conditions during Ice Complex deposition within these valleys gives benefit to Holocene thermokarst formation.

C – Black lines indicate ridges in the Pronchishchev Range, white lines represent deep valleys incising these ridges. Note the valleys in the SE, crossing the entire Pronchishchev Range.

4.4.4 Geomorphology in the investigation area near Cape Mamontov Klyk

The investigation area near Cape Mamontov Klyk consists of Edoma elevations (20-40 m a.s.l.), which are separated by erosional features and thermokarst depressions (Figure 4.4-2). A major structure is the meandering river valley of the Nuchcha-Dzhiele with sand banks, flood plains, undercut slopes, extent slip-off slopes and an estuary-like mouth. Close to the river mouth a large oxbow lake has formed, containing large amounts of driftwood. Large driftwood fields exist on the sandbanks of the estuary. Probably ice-rafted driftwood trunks several kilometres upstream indicate the occasional marine influence on the river flood land in the hinterland. Several thermo-erosional valleys incise the Edoma surface. Most of them are heading towards the river valley, only a few in the direction of the recent coast. The field camp was situated in one of these valleys close to the river. The slopes of the valleys are often covered by small thermokarst mounds (< 1m, Ø 2-4 m). The coast is subject to very fast thermal erosion and marine abrasion. Steep cliffs with 70-80° inclination have formed, in places with more gently retrogressive thaw slumps.

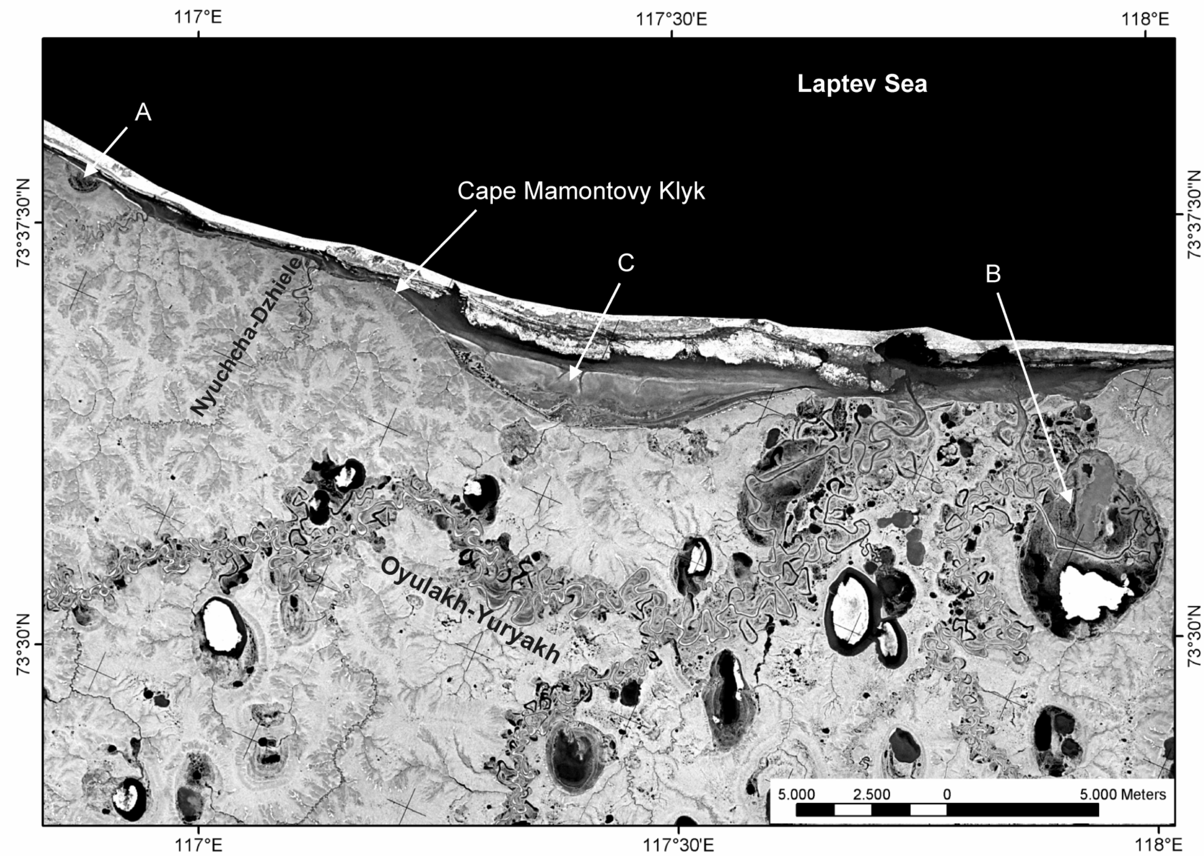

Figure 4.4-2: Satellite map (CORONA) of the region near Cape Mamontov Klyk; Note the location of the rivers Nuchcha-Dzhiele and Oyulakh-Yuryakh;
A – thermokarst site 1
B – thermokarst site 2
C – wide bay with marine terrace

One thermokarst depression occurs in the closer area of the cape. This flat depression is about 8-12 m deep and does not contain water bodies. Large nival niches with remnants of snow patches were discovered at several slopes in the depression and in some ravines heading into the depression. One thermo-erosional valley discharges from this depression towards the river Nuchcha-Dzhiele. A more remote thermokarst depression is situated 8 km NW of the river mouth (Figure 4.4-2). This depression is actively eroded by coastal erosion. Several large polygonal and irregular water bodies with more than 25 m in diameter are situated within the depression. The mean depression floor is situated 5 m a.s.l. and the surrounding surface is approximately 20-25 m a.s.l..

In the region south of Cape Mamontov Klyk the Edomas are incised by several thermo-erosional valleys. About 7 km to the south, the large river Oyulakh-Yuryakh is situated in a wide river valley. Different from all other rivers in the region, this strongly meandering river is flowing from W to E. Several thermokarst depressions are associated with the wide river valley. The river valley strongly widens when approaching the coast 18 km east of the cape. In this region, many large thermokarst depressions and thermokarst lakes are located. Some of them have already amalgamated to larger basins. In the largest at least 4 pingos occur. Between Cape Mamontov Klyk and the Oyulakh-Yuryakh River mouth a wide bay is located at the coast (Figure 4.4-2). In this bay a 11.5 km long and 1.5 km wide terrace has formed consisting of marine deposits up to 0.5-1.0 m a.s.l.. The inner zone of the terrace contains many small freshwater lakes.

4.4.5 Field data

During field work, various surface parameters were observed and described for 178 geo-located sites in the vicinity around Cape Mamontov Klyk (Figure 4.4-3). The closer area around the camp site contributes 129 sites (Figure 4.4-4) and two remote thermokarst depressions (see above) contribute another 49 geo-located sites (Figure 4.4-5 and 4.4-6). The recorded surface parameters include relief type, slope inclination, major vegetation, portion of dry vegetation, estimation of soil moisture, active layer depth and occurrence and type of small scale water bodies (Table 4.4-3). A schematic view of the parameters "major relief type", "relief position" and "slope" is shown in figure 4.4-7. In table 4.4-4 a description of the major relief features in the investigation area is given.

Samples of surface sediment were taken at 10 sites. An image database contains more than 200 photos from 115 of the geo-located sites. The detailed recordings and measurements for each site are presented in the appendix (tables Appendix 4-1 and Appendix 4-2).

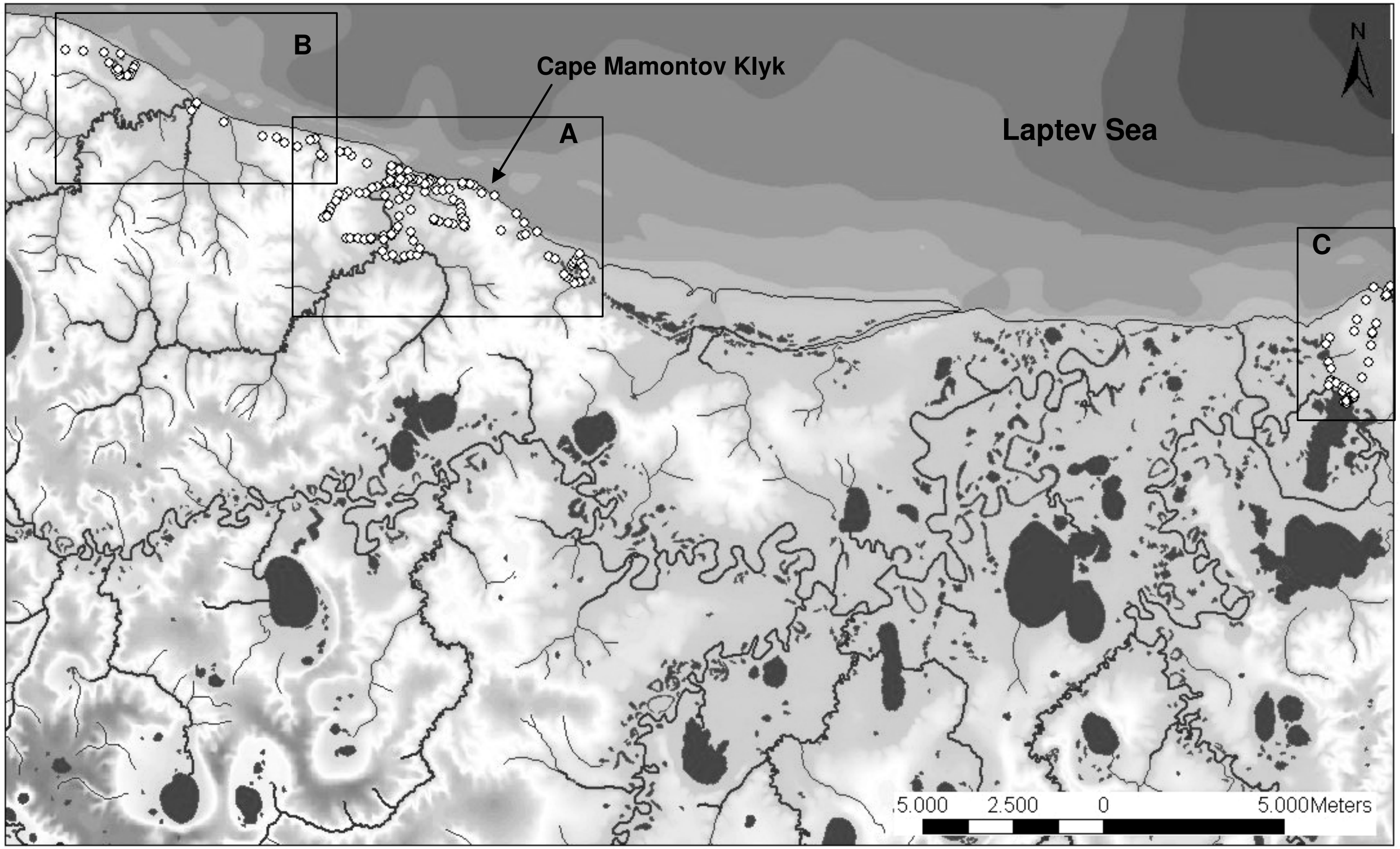

Figure 4.4-3: Elevation map with geo-located ground-truth sites (white circles); Detailed images for A, B and C are shown in separate figures

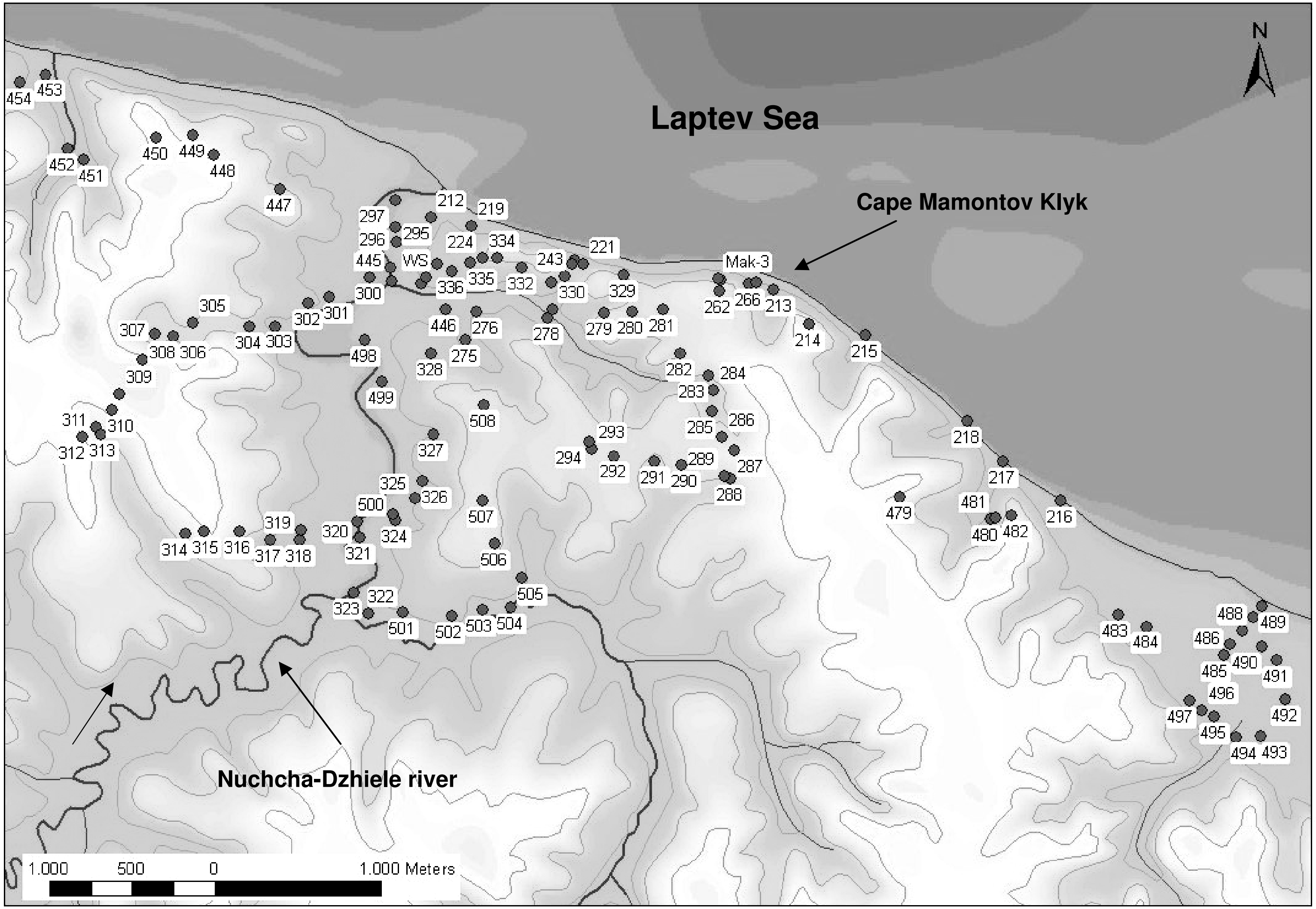

Figure 4.4-4: Detail image for Fig. 4.4-3 A with geo-located sites close to the camp at Mamontov Klyk

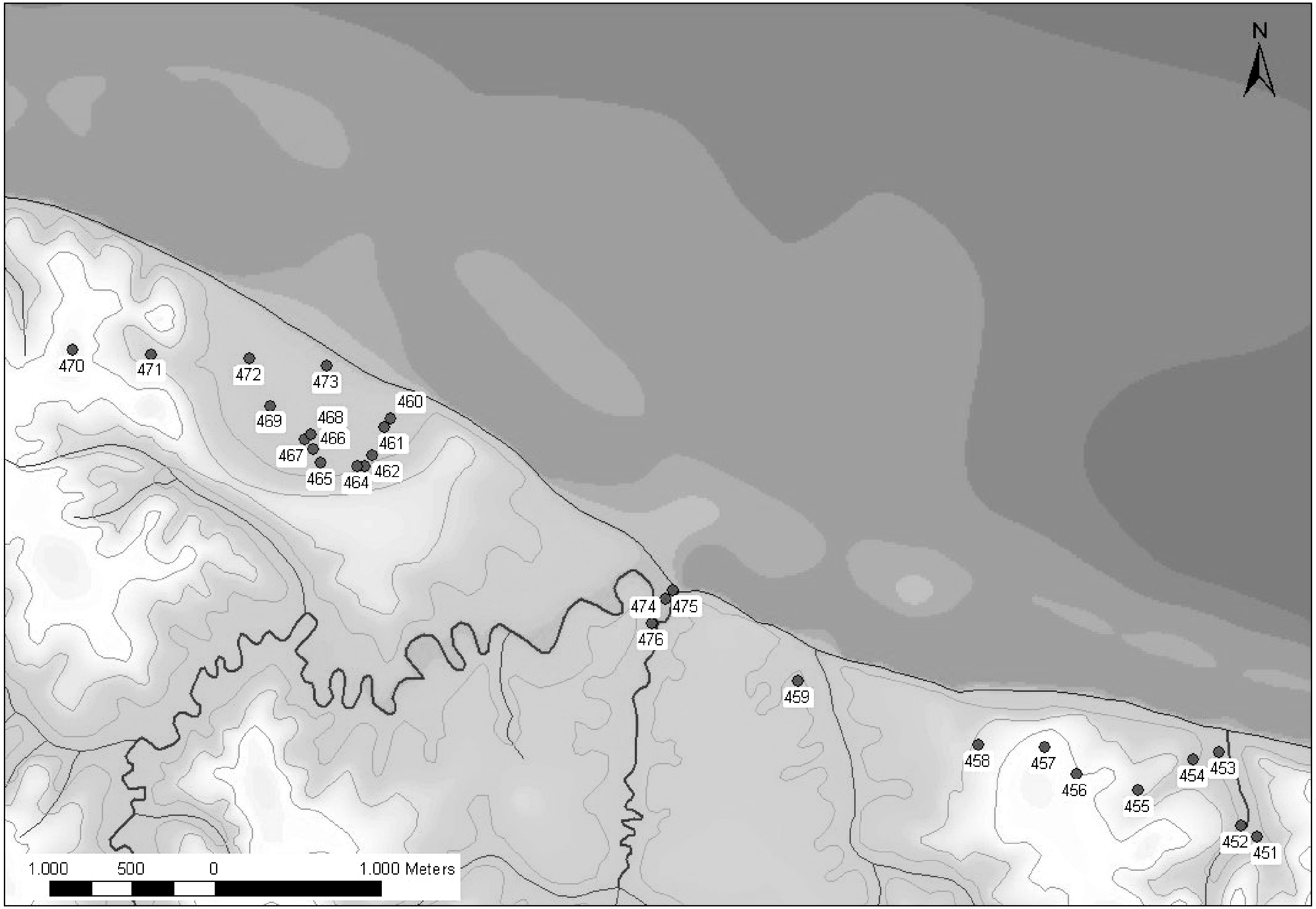

Figure 4.4-5: Detail image for Fig. 4.4-3 B with geo-located sites in a thermokarst depression west of Cape Mamontov Klyk

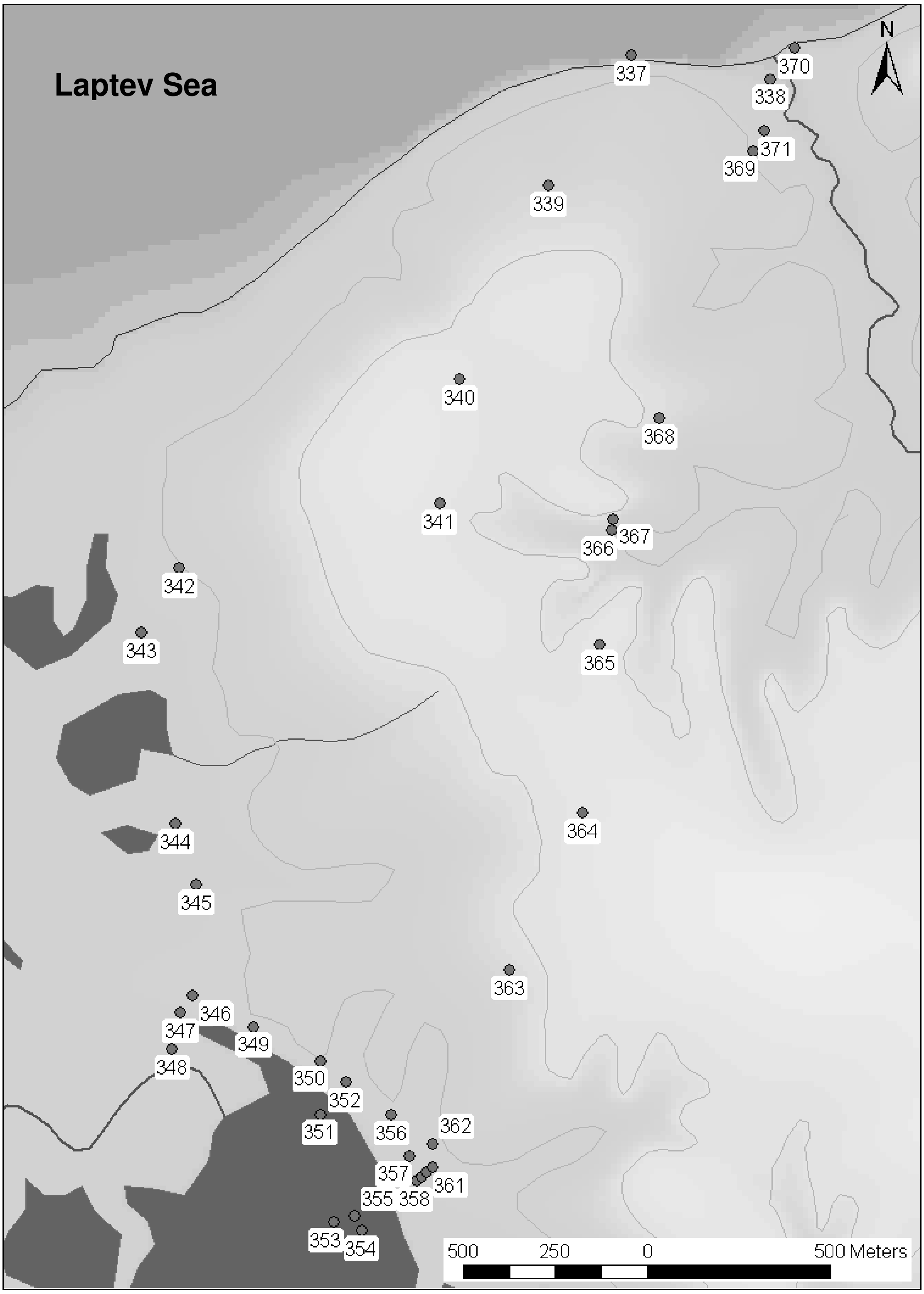

Figure 4.4-6: Detail image for Fig. 4.4-3 C with geo-located sites in a thermokarst depression east of Cape Mamontov Klyk

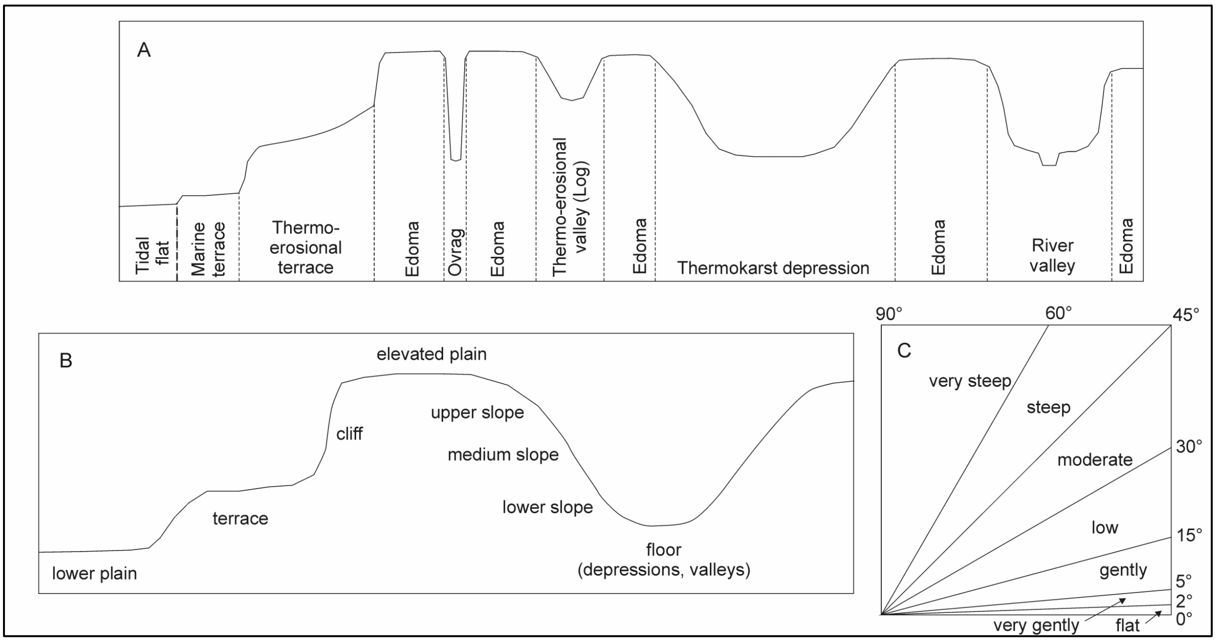

Figure 4.4-7: Classification of relief type
A – Major relief forms; B – Site location within the relief; C – Slope inclination at site

Table 4.4-3. Variable elements of the recorded features for the geo-located ground truth sites

Recorded feature	Elements
Major relief type	Edoma, thermo-erosional valley (Log), thermokarst depression, thermo-erosional ravine (Ovrag), thermo-erosional terrace, river valley, marine terrace, tidal flat
Relief position	Elevated plain, upper slope, slope, lower slope, terrace, lower plain, floor, cliff
Meso and micro relief features	Nival niche, river bank, sand bank, sediment fan, thermokarst mounds, solifluction, mud flow, drainage channels, polygonal structures
Slope	Inclination
Active layer depth	Up to 15 measurements per site
Vegetation	Major and minor plant groups, portion of dry vegetation
Surface / soil moisture	Estimation (wet, very moist, moist, moderate moist, less moist, dry)
Water bodies	Occurrence (yes/no), type (surface discharge, polygonal, irregular, channels), size, depth
Surface sediment samples	
Photographic documentation	
Remarks	

Table 4.4-4: Description of major relief types in the investigation area

Major relief type	Description
Edoma	Frozen sequences of organic and mineral soils, containing large amounts of ground ice (ice wedges, segregated ice); erosional remnants of Late Pleistocene surface;
Thermo-erosional valley (Log)	Dendritic, U-shaped valleys with flat floor; dense grass/sedge vegetation; very moist, often with surface water and little ponds; two main types: wide and shallow, narrow and deep; length of valleys varies from 50 to 2000 m, width about 50 m;
Thermokarst depression	Deep subsidence area due to thermokarst often with large extent; associated with ice-rich permafrost; shape circular, ellipsoid or sometimes irregular; thermokarst lakes and pingos may occur in the depressions; the steep slopes are incised by erosional valleys; depressions close to each other may amalgamate; diameters range from few 100 m to several km; depth of depressions is, depending on age and subsidence rate, in coastal areas down to sea level; the depressions are dominated by wet tundra vegetation (mosses, grass), nevertheless zones from different soil moisture are visible sometimes;
Thermo-erosional ravine (Ovrag)	Deep incised V-shaped valley; formed by rapid thermo-erosion and flowing water; associated with ice-rich ground; valleys are often rather short;
Thermo-erosional terrace	Formed in front of large thermo-erosional cirques; associated with ice-rich permafrost and Edomas in the hinterland; widely U-shaped structure at coastal or fluvial sites; length of structures is 100 m up to several 100 m, width varies from 25 to 200 m;
River valley	Wide valleys with strongly meandering rivers;
Marine terrace	Coastal terrace with marine deposits, but elevated above recent sea level; often sparsely vegetated; large amounts of driftwood may occur
Tidal flat	Shallow intertidal area in front of the coast; sea level in this region fluctuates because of diurnal tides and/or wind-forcing; area is up to several 100 m wide;

4.4.6 Tachymetric survey of periglacial surface features

During the field season some periglacial surface features were surveyed in detail with a laser tachymeter. Such features were a thermo-erosional valley near the camp site (Figure 4.4-8 and 4.4-9) and thermokarst hills, where the distances between their tops were measured (Figures 4.4-10 to 4.4-14). The valley is also the location of the methane measurement site (see chapter 4.5). Thermokarst hills represent the sediment remnants of polygon centers of a eroded ice wedge polygonal net. The distance between the tops of the hills within a cluster of thermokarst hills characterizes the size of the polygons in the eroded polygonal ice wedge net. The distances also give hints on the ice wedge width between the former polygon centers. The height of the thermokarst hills is dependent on cryolithological factors, climatic factors and stage of development.

The data are used for comparison with features surveyed previously at other locations in the Laptev Sea coastal area.

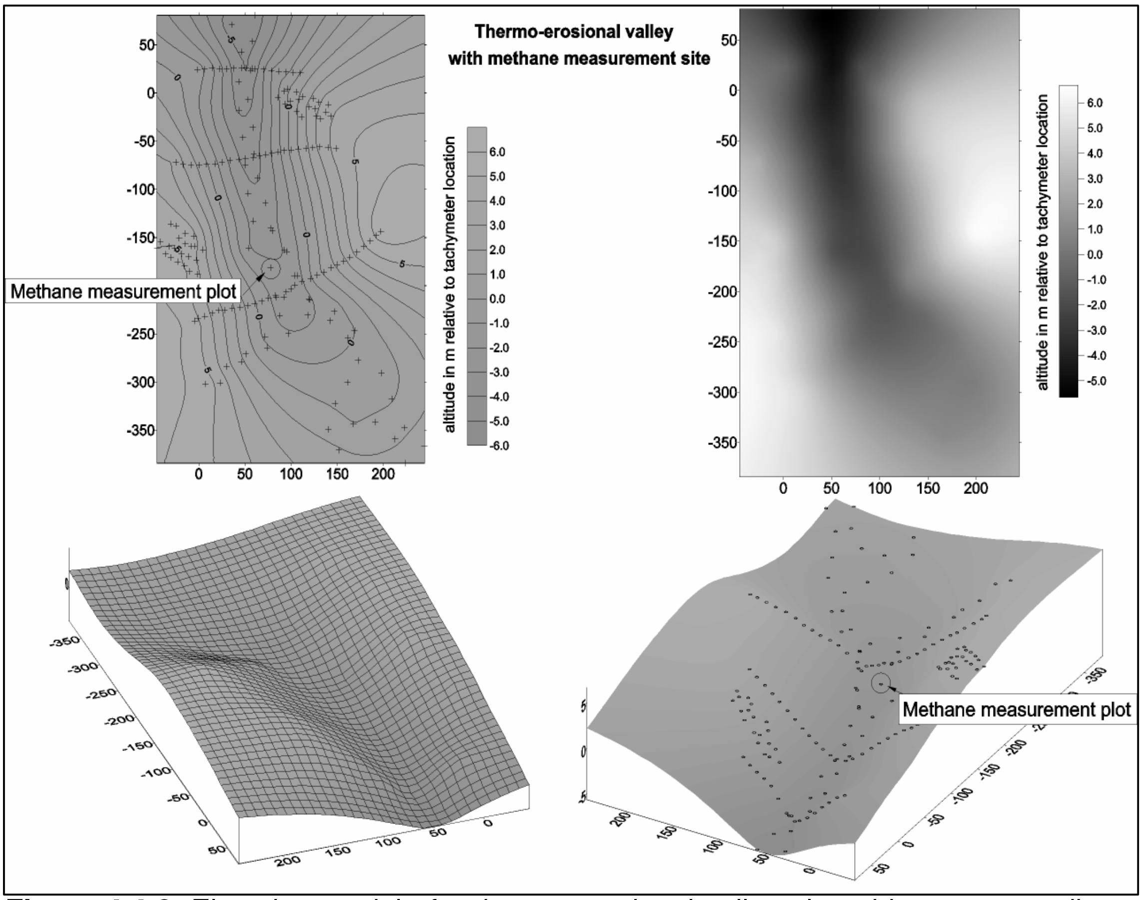

Figure 4.4-8: Elevation model of a thermo-erosional valley plotted in a xyz-coordinate system from a tachymetric survey near the camp. Altitudes are relative to the tachymeter position. The methane measurement site was situated in this valley.

Figure 4.4-9: View over the thermo-erosional valley, where methane-related studies were carried out. At the bottom of the valley, areas dominated by *Eriophorum angustifolium* (with white stands of fruit) could be observed next to wetter patches dominated by *Carex aquatilis*.

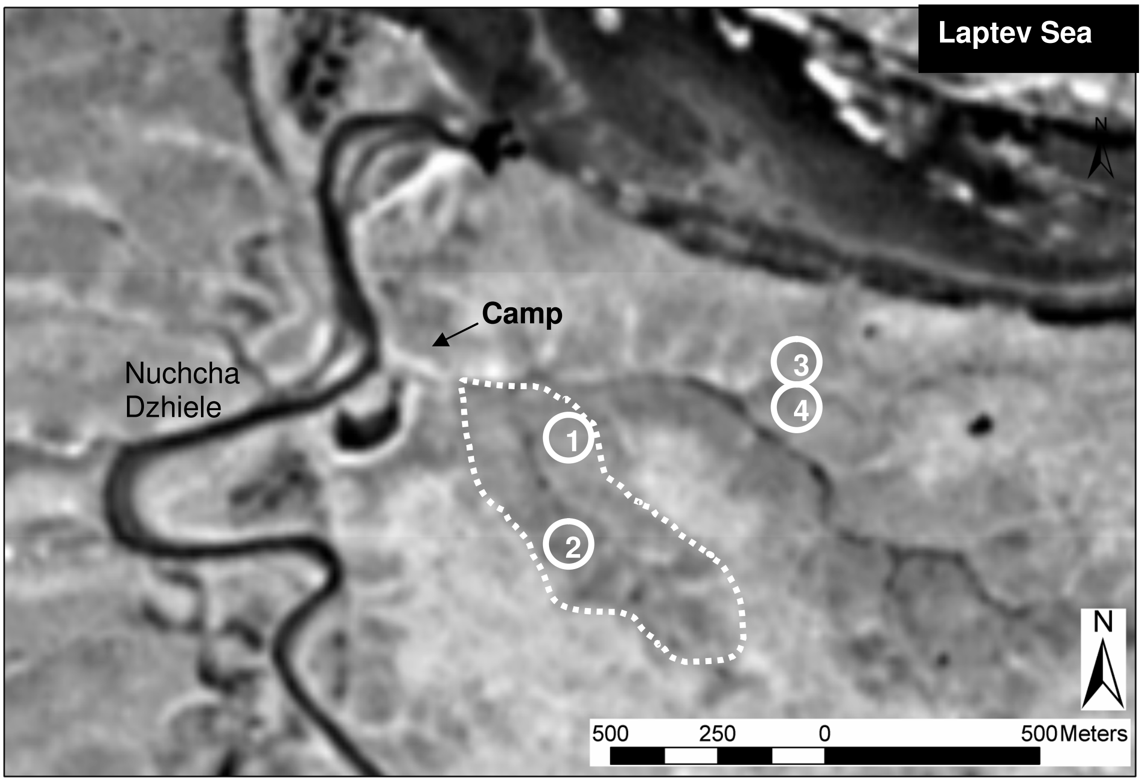

Figure 4.4-10: CORONA satellite map of the sites, where clusters of thermokarst hills were surveyed with a laser tachymeter (white circles with site numbers). The dotted white line marks the thermo-erosional valley with the methane measurement site.

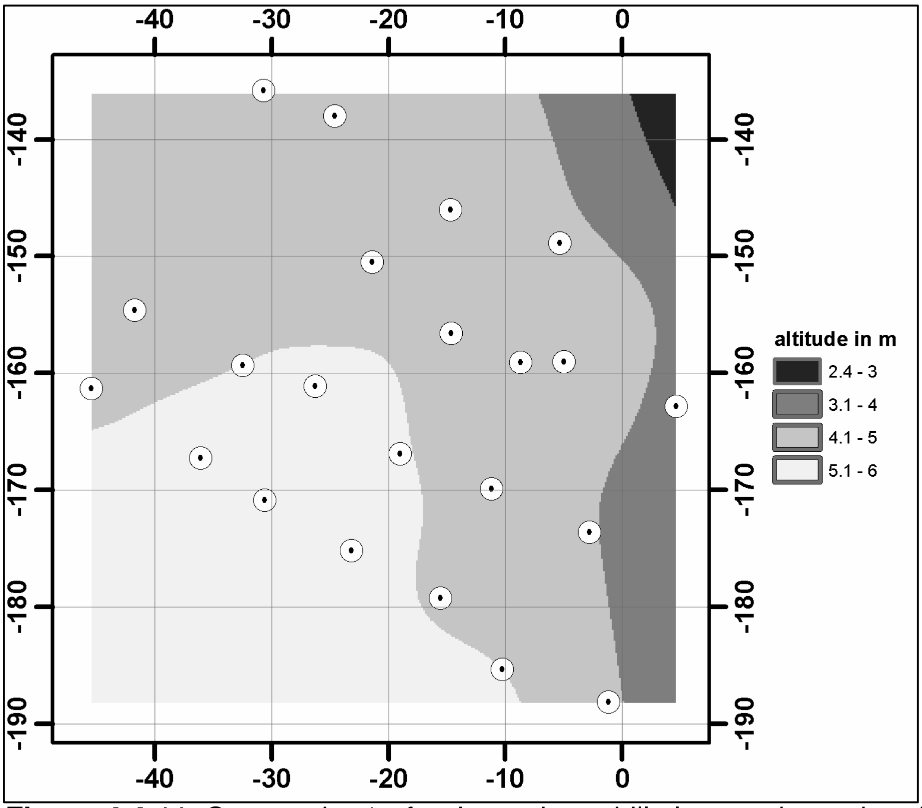

Figure 4.4-11: Survey site 1 of a thermokarst hill cluster, situated at the eastern slope of the thermo-erosional valley southeast of the camp (methane measurement site)(altitude relative to tachymeter position, xy-coordinates in m).

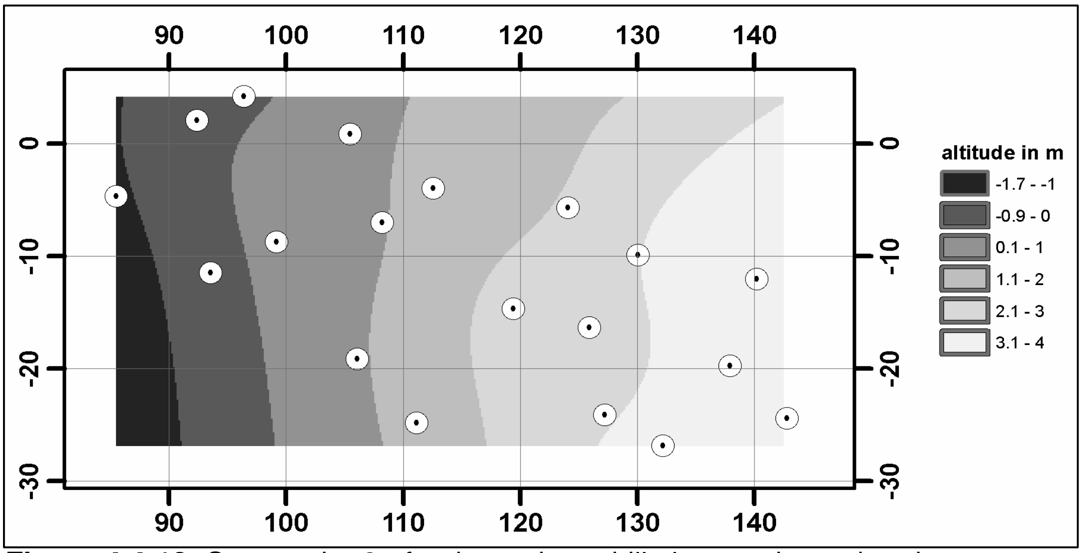

Figure 4.4-12: Survey site 2 of a thermokarst hill cluster, situated at the western slope of the thermo-erosional valley southeast of the camp (methane measurement site) (altitude relative to tachymeter position, xy-coordinates in m).

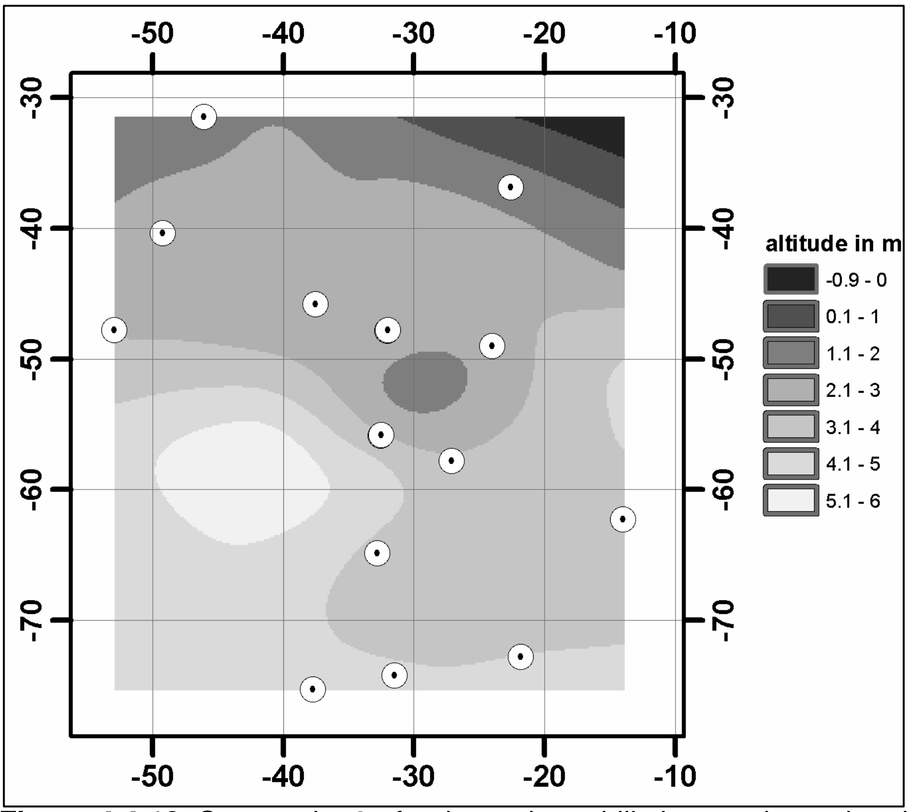

Figure 4.4-13: Survey site 3 of a thermokarst hill cluster, situated at the northern slope of a thermo-erosional valley east of the camp (altitude relative to tachymeter position, xy-coordinates in m).

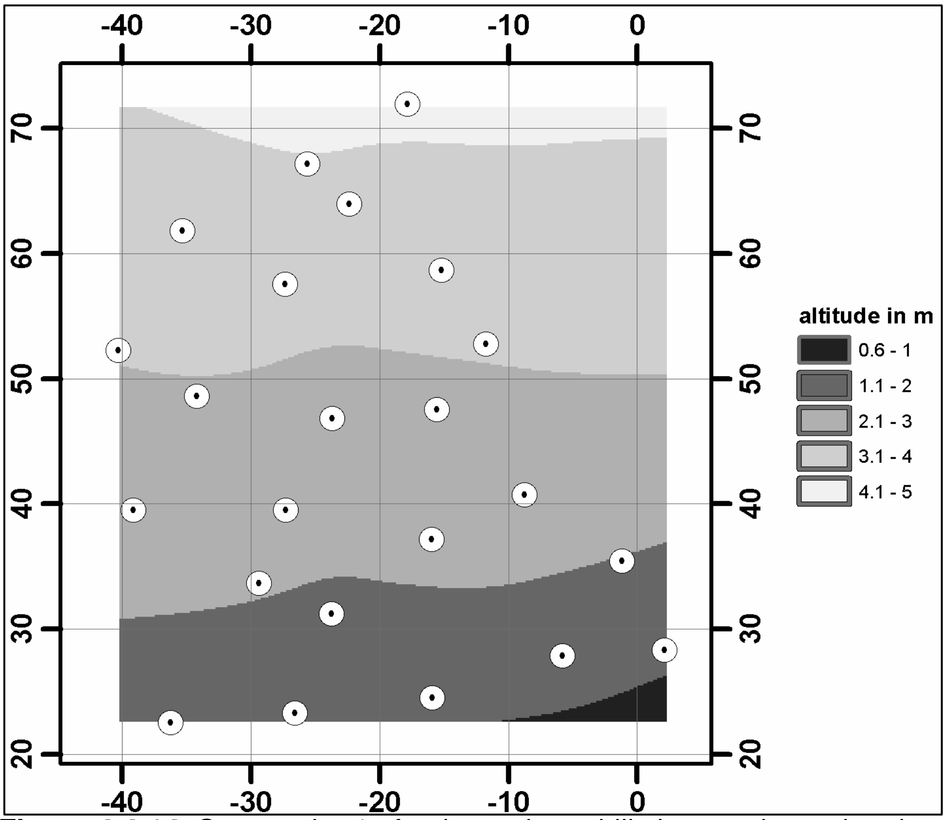

Figure 4.4-14: Survey site 4 of a thermokarst hill cluster, situated at the southern slope of a thermo-erosional valley east of the camp (altitude relative to tachymeter position, xy-coordinates in m).

4.4.7 Characterisation in situ surface properties with a soil probe at a typical elevated Edoma plain

During the field season almost continuous loggings of soil temperature and soil moisture were conducted with a soil probe at an Edoma site in the vicinity of the camp. The site at 17 m a.s.l. was chosen because of its typical appearance for an elevated tundra surface atop an Edoma. The main vegetation consisted of grass, and the soil surface was slightly tussocky. The soil probe sensors were fixed in 5 cm depth. The measurement interval was 5 min. The logging lasted from 9th August (04:38 GMT) to 26th August (03:48 GMT). The breaks in the logging period are caused by failure of power supply for the probe. Table 4.4-5 shows the extreme values during the logging. Whereas the temperature shows diurnal variation and a slight decrease during the whole period (Figure 4.4-8), the logging of volumetric soil moisture showed an almost constant moisture content of 0.4 $m^3 \times m^{-3}$ in the upper soil during the measurement period without diurnal variation.

Table 4.4-5: Values for in situ soil temperature and soil moisture (measured as electric soil voltage) logged with a soil probe in the upper 5 cm of a soil atop an Edoma surface

	Min	Max	Mean	Sd (+/-)	Logged values
Soil temperature	1.81 °C (24-08-04)	5.59 °C (13-08-04)	3.62 °C	0.84	3745
Volumetric soil moisture	0.4 $m^3 \times m^{-3}$	0.4 $m^3 \times m^{-3}$	0.4 $m^3 \times m^{-3}$	0.0	3867

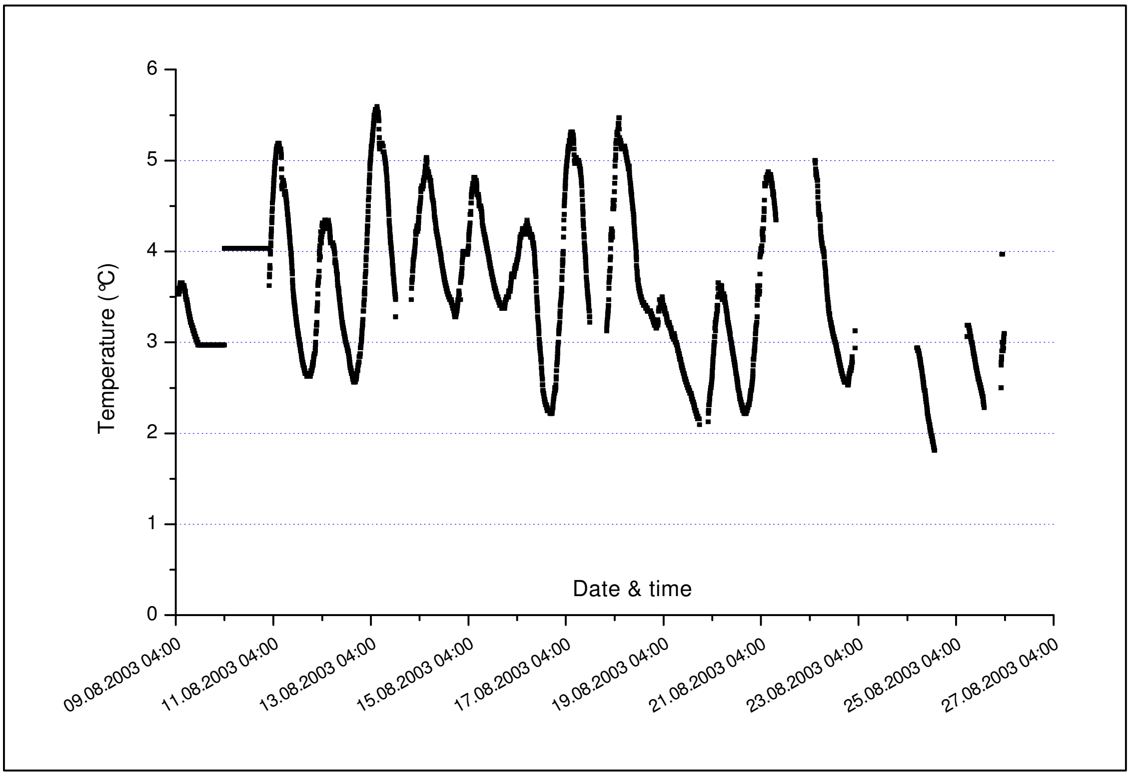

Figure 4.4-15: Diurnal variations in soil temperature within the upper 5 cm of an Edoma surface