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Landsat mapping of ice-marginal features on the Taymyr Peninsula, Siberia — image interpretation versus geological reality

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To solve the question concerning the age and extent of the latest glaciation in northern Eurasia, several geological investigations were carried out. This paper describes work done on the North Taymyr ice-marginal complex on the Taymyr Peninsula in north central Siberia. The initial remote sensing work aimed to survey fieldwork localities and to acquire a regional geological overview. A Landsat 5 Multispectral Scanner (MSS) image was interpreted, both visually and by computer-based techniques. The ice-marginal zone is clearly visible on the satellite image and it was possible to distinguish spectrally different ground-types. In total, seven ground-types have been discerned and they are described and discussed. A geological interpretation of them was made after combining the initial results with the information gained from ground-truthing, which included sedimentological and morphological fieldwork. It is necessary to take topography and associations of classes into consideration when interpreting the final map, since the identification of some ground-types is not univocal.

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INTRODUCTION

The extent of the Kara Sea ice sheet during the Last Glacial Maximum *ca.* 20,000 years BP has been much debated (e.g. Arkhipov *et al.*, 1986; Rutter, 1995; Astakhov, 1997; Pavlidis *et al.*, 1997; Velichko *et al.*, 1997; Grosswald, 1998; Möller *et al.*, 1999; Svendsen *et al.*, 1999). One of the major aims of the European Union-financed programme "Eurasian Ice Sheets" is to solve this question. Within this programme and under the European Science Foundation's QUEEN (Quaternary Environment of the Eurasian North) umbrella, several research projects are going on in different parts of northern Eurasia.

This paper describes work done on the Taymyr Peninsula (Fig. 1), within the Swedish-Russian project "Ice-marginal formations and former marine levels on the Taymyr Peninsula". It centres on a previously recognized but poorly investigated ice-marginal zone, formally called the North Taymyr ice-marginal complex (Isayeva, 1984; Arkhipov *et al.*, 1986), more informally "the Isayeva-line". Previous researchers (e.g. Isayeva, 1984) considered the North Taymyr ice-marginal complex to date from a deglaciation phase of a Late Weichselian (Sartan) Kara Sea Glaciation, the maximum extent of which was believed to have reached much farther south. Results of more recent research (Möller *et al.*, 1999), however, reject any glaciation south of the Byrranga Mountains during this time period. The North Taymyr ice-marginal complex (Fig. 2) then becomes the most likely candidate for the margin of the Kara Sea ice sheet during the global Last Glacial Maximum (Svendsen *et al.*, 1999) — if this ice inundated what is presently dry land, at all.

To reconstruct and date the distribution of the latest ice sheet on the Taymyr Peninsula, a multi-technique approach was adopted. Remote sensing and geographical information systems were combined with morphological and stratigraphical/sedimentological field studies. The results of the initial remote sensing part of the project are presented in this paper, whereas the results of the geological fieldwork will be published elsewhere. The idea of the present study was to use satellite imagery to survey intended fieldwork areas and to put information gathered during the fieldwork into a regional context, by interpreting the image in a geological sense. A Landsat 5

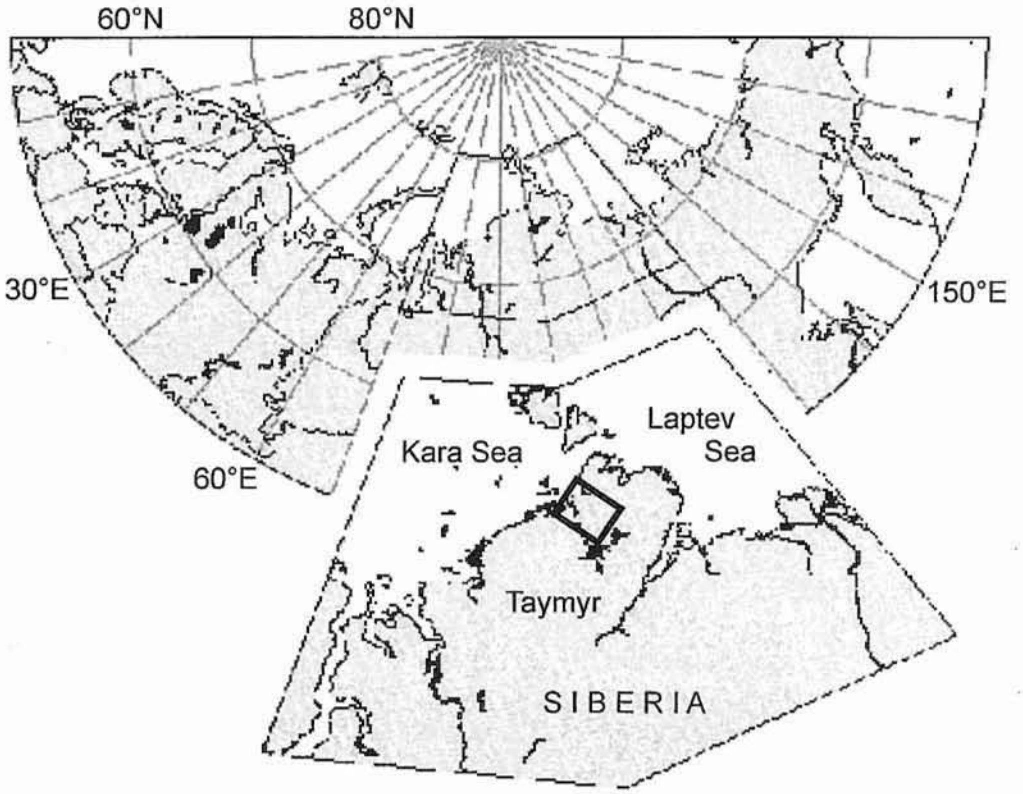

Fig. 1. Map of northern Eurasia and the Taymyr Peninsula, showing the location of the Landsat 5 (MSS) image (black box)

Multispectral Scanner (MSS) image and the image-processing programme IDRISI were utilized. The reason for choosing a Landsat 5 (MSS) data set was mainly economical, as it gives much information at a reasonable cost — considering that the satellite image interpretation was not a main issue in the overall project, but only a useful tool. This paper is thus, strictly seen, not a real methods study, but rather a case study on how satellite images can be used to aid geological fieldwork in a large and poorly known area.

DESCRIPTION OF THE STUDY AREA

The Taymyr Peninsula lies in north central Siberia, between the Kara Sea and the Laptev Sea, and is the northernmost part of the Eurasian mainland (Fig. 1). It is dominated by low-lying tundra, which in the northern part is transected by the Byrranga Mountains, which rise up to 1,146 m high (Fig. 2). The bedrock, which is mostly of late Precambrian (Vendian) and Palaeozoic age, is rather complex, as the area is part of a fold belt. It consists mainly of sedimentary rocks (sandstone, shale and limestone) in the south and magmatic and metamorphic rocks (granite, ophiolite) in the north. Quaternary neotectonism has been suggested for the Byrranga Mountains (Makeev, 1972; according to Kind and Leonov, 1982).

MATERIAL AND METHODS

In this study, one Landsat 5 (MSS) image in digital format (no. 153/006, obtained on August 8th, 1992) has been used. The image covers the area around the Lower Taymyr River in the northwestern part of the Taymyr Peninsula (Figs. 1, 2). The satellite image has been interpreted both visually (analogue image processing) and by computer-based techniques (digital image processing). The latter involved standard operations, e.g. false-colour compositing and data stretching, as well as supervised and unsupervised classification methods available in the image processing programme IDRISI. The classification methods included e.g. maximum-likelihood (Maxlike) and minimum-distance-to-mean (Mindist) procedures, a histogram peak cluster analysis (Cluster) and an iterative self-organising classifier (Isoclust). Descriptions of these methods including their sources of error have been made by e.g. Jensen (1996) and Eastman (1997). The selection of training sites for the supervised classifications was based on the visual interpretation of the image. The computer-based classifications resulted in maps showing the distribution of different spectral classes, which were characterized by a combination of the vegetation and geology at each site.

To determine what these geobotanical classes represented in the real world and to check the reliability of the resulting

Table 1

Properties of the spectral signatures used in the supervised classification (Maxlike) in IDRISI

Class	No. of pixels in training sites	Area (% of total)	Corresponds to
1	3607	11.3	dark-coloured bedrock and peat
2	1931	5.4	light-coloured bedrock
3	192	6.3	unvegetated cobbles, gravels and sands
4	1214	22.9	vegetation-covered fine diamict and coarse sorted material
5	279	11.9	tussocky and dry silt
6	887	4.11	well-vegetated silt
7	538	7.8	waterlogged mud
8	6344	1.7	shallow water
9	10 181	1.0	deep water
10	478	2.3	lake-ice
11	12 604	3.7	thin sea-ice
12	21 906	8.9	thick sea-ice, snow
13	36 107	12.8	clouds

The "area"-column shows the percentage of the total map area, which is covered by the class in the final map (*cf.* Fig. 3)

maps, ground-truthing was carried out during July–August 1998 in two areas on the Taymyr Peninsula: close to Barometric Lake (Ozero Barometricheskoe) and at White Lake (Ozero Beloe), respectively (Fig. 2). The different geobotanical classes were recognized in the field and described. The descriptions included type of soil, type of vegetation and topographic position. The ground-truthed area was approximately 170 km^2, which is less than 1% of the total land area covered by the satellite image. During helicopter flights to and from the work areas the ground was also observed, but direct ground-truthing was not possible then.

When the ground-truthing of the fieldwork areas was completed, further work concentrated on the map which best corresponded to reality. To increase clarity and enhance the geological information on it, one more class ("lake-ice") was added. The map was then interpreted geologically by using the class descriptions done during ground-truthing, together with results from the morphological, sedimentological and stratigraphical fieldwork and information from available topographic maps. Digital elevation models (DEMs) of the fieldwork areas were created from digitized topographic maps (scale 1:100,000). Sub-windows of the satellite image and the geological map were draped over the DEMs to enhance the relationship between different classes and topography.

DESCRIPTION OF THE MAPS

GENERAL

The unsupervised classification (IDRISI Cluster-module) of a composite image (MSS bands 1, 2, 4) resulted in the recognition of 16 different classes, based purely on the appearance of the spectral histogram of the image. Three of these classes represented different ground-types, two represented water, five ice and six clouds. The result of the Isoclust-classification was similar.

The maps created by the two supervised classification methods, maximum-likelihood and minimum-distance-to--mean, were in general rather similar but differed in detail, e.g. in the local extent of some of the classes. The results from the ground-truthing indicated that the map obtained by the maximum-likelihood procedure (IDRISI module Maxlike), which is based on Bayesian probability theory, corresponded best to reality. The following descriptions are therefore based on that map (Fig. 3). The map shows the distinguished spectral classes, which originally were seven types of bedrock/soil, three kinds of ice-cover, two water classes, plus clouds (Tab.1). The two sea-ice classes are, however, here (Fig. 3) shown as one single class, as are lake-ice and the two water classes. The spectral signatures of the bedrock/soil-types are shown in Figure 4. The clouds in the southern (lower right) corner of the image have disturbed the classification and the result is thus not reliable south of the Byrranga Mountains (*cf.* Fig. 2). In this paper I have emphasized the description of bedrock- and soil-types, as in a glacial-history context the other classes are not relevant for more than general information.

DARK-COLOURED BEDROCK AND PEAT

This ground-type consists of both dark-coloured bedrock and peat. The spectral signatures of these two otherwise very different categories are similar and I have not been able to successfully distinguish them from each other by any computer-based classification. In the field there is no problem with this. The class occurs mainly in the western and southeastern

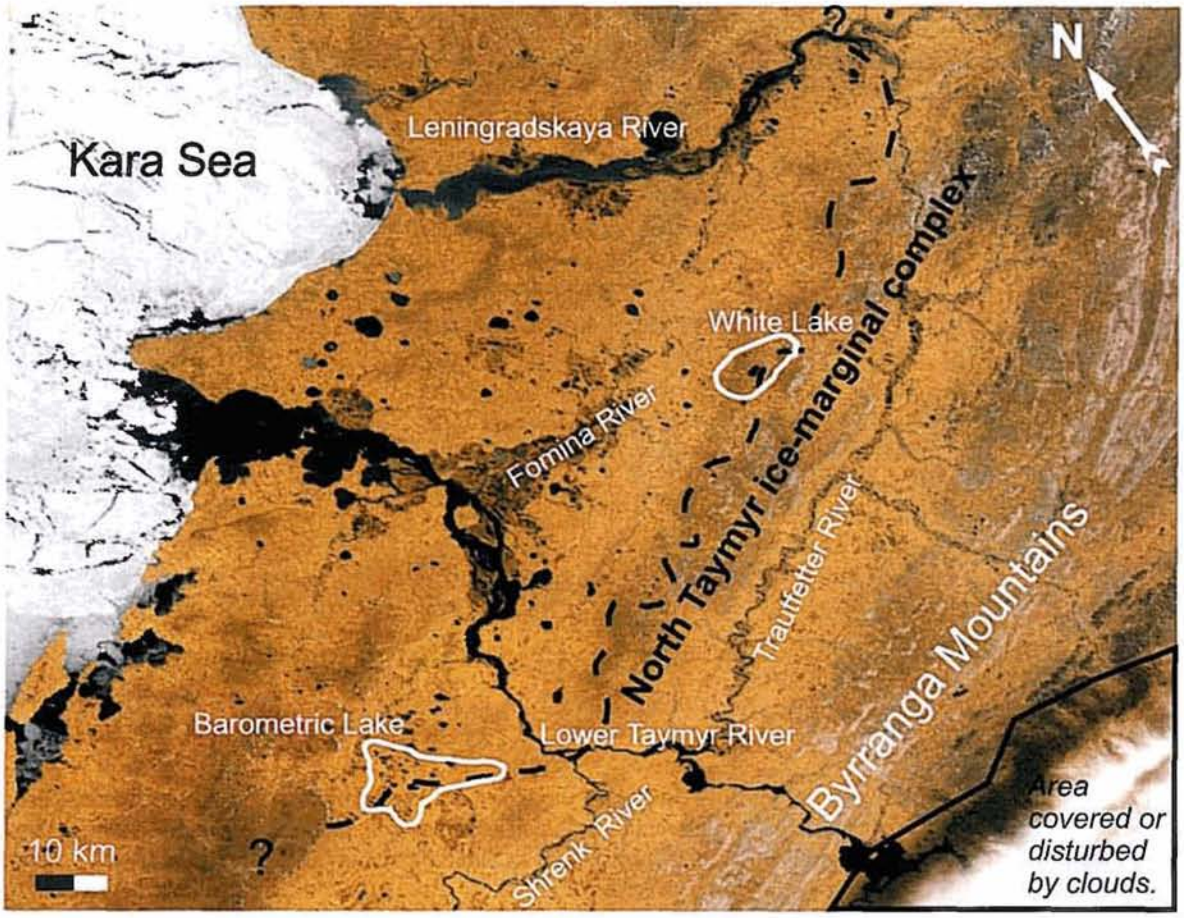

Fig. 2. Locations of features and sites mentioned in the text

The background is a composite image of Landsat 5 (MSS) bands 1, 2 and 3. The hatched line gives the general (in part assumed) position of the North Taymyr ice-marginal complex; for more details see Fig. 3; ground-truthing has been done in the areas delimited by white lines, at White Lake and Barometric Lake, respectively

parts and along some rivers (Fig. 3). Dark-coloured bedrock includes e.g. dolerites and greenschists and is exposed as topographic highs. Dolerite occurs mainly as dykes, running approximately parallel to the Byrranga Mountains (NE–SW), whereas the greenschists e.g. form the higher ground north-west of Barometric Lake. The bedrock surface is usually quite frost-shattered.

The peat-category (Fig. 5A) occurs in front of and below more or less permanent snow fans, and adjacent to lake shores where geese have grazed away most of the grass. The surface consists of dark moss with grasses and herbs. Depending on drainage conditions and season the peat can be more or less waterlogged. In contrast to the dark bedrock sub-class, the peat is found in topographic depressions and on the lower parts of slopes. It is more common at White Lake than at Barometric Lake.

LIGHT-COLOURED BEDROCK

Different kinds of limestone, shale, sandstone and probably also granite are the main constituents of this class. Unconsolidated Cretaceous sand, which occurs locally, is also included in this class since it has a similar spectral signature. The light-coloured bedrock is most common in the southeastern part of the image, i.e. in the Byrranga Mountains and their northern outliers (Fig. 3). The investigated limestone surfaces consist of frost-shattered angular pieces of rock, ranging in size from centimetres to half a metre (Fig. 5B). Some erosional remnants, like tors, exist. The limestone is frequently associated with brownish shales. In the landscape the limestone forms elongate cuesta-ridges with an approximately NE–SW strike. The vegetation on the ridges is very sparse, limited to scattered tufts of

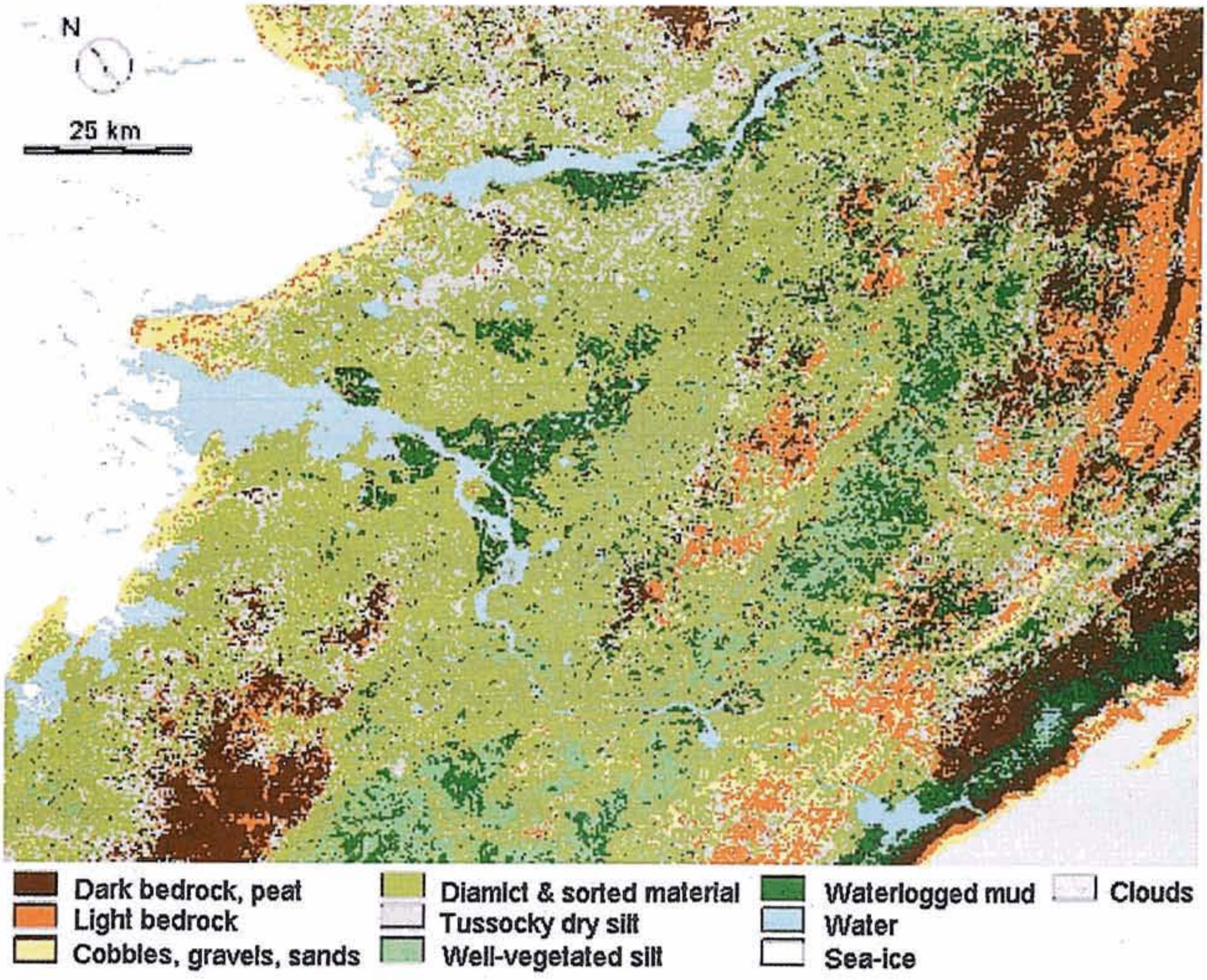

Fig. 3. Geological map of the area around the Lower Taymyr and Leningradskaya Rivers on NW Taymyr Peninsula

The map is based on Landsat 5 (MSS) image path/row 153/006 (8 August 1992) and classified by the maximum-likelihood procedure in IDRISI; compare with Fig. 2 for location of the North Taymyr ice-marginal complex

grass and herbs. Larger vegetated patches may, however, occur near large boulders, which stabilize the ground.

UNVEGETATED COBBLES, GRAVELS AND SANDS

Cobbles, gravels and sands with no or only sparse vegetation cover (generally < 20%) make up this class (Fig. 5C). Some very frost-shattered light-coloured bedrock surfaces (*cf.* discussion below) are also included here. The ground-type occurs mainly along rivers, at and near rocky outcrops (especially such with light-coloured bedrock), along the coast, at the most distal part of the ice-marginal formation in the Barometric Lake area and in large bedrock areas in the Byrranga Mountains and their outliers (Fig. 3). It is a diverse class which encompasses fluvial bars, beaches, boulder fields, dry river beds, hill tops, talus, sediment cliff sections, some earth or rock slides as well as bedrock outcrops. These different categories occupy various topographic positions, ranging from low (rivers, beaches) to high (hill tops). The composition of the coarser material varies and is dependent on the local predominance of crystalline or sedimentary rocks.

VEGETATION-COVERED FINE DIAMICT AND COARSE SORTED MATERIAL

This ground-type (Fig. 5D) is the most frequent on the map (Fig. 3) and it is especially common north of, i.e. inside, the ice-marginal formation, and predominantly in relatively dry and high areas. It also occurs on the lower foothills of the Byrranga Mountains and along some of the river valleys cutting through these mountains. Vegetation covers most of this ground (generally > 90%) with grasses, mosses, lichens and an abundance of herbs (*Dryas*, *Saxifraga*, *Papaver*, *etc.*). Bare sand and gravel patches, however, occur with occasional tussocks. The diamict material is silty, usually not more than a metre thick and underlain by surviving glacier ice. The coarse sorted material is

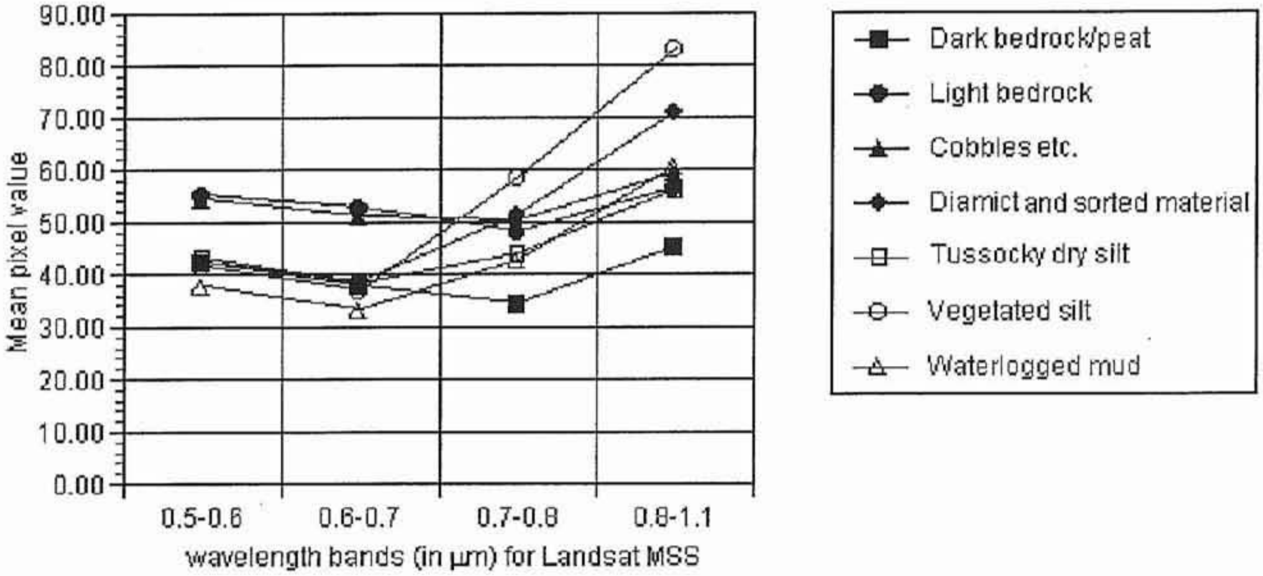

Fig. 4. Spectral signatures of the different ground-types

mainly sand and gravel and may exhibit thickness up to tens of metres.

TUSSOCKY AND DRY SILT

The silt included into this class is so-called frost-boiled silt, i.e. silt that has been subjected to frost-heaving processes, forming small polygonal tussocks (Fig. 5E). If widespread, this feature is sometimes called hummocky tundra. Some vegetation, like herbs, grasses and moss, grows between the tussocks. The vegetation cover varies with e.g. humidity and slope, but is generally *ca.* 50%. The large-scale terrain surface is commonly rather flat or gently undulating. When dry, the silt tussocks are light brown, hard and cracked. When wet they turn dark grey and get sticky and cloggy. This ground-type occurs locally in patches, sometimes near outcrops of dark-coloured bedrock (Fig. 3). Several small streams, resulting in gully formation in a dendritic pattern, cut a field with this type of silt at Barometric Lake.

WELL-VEGETATED SILT

On the surface this is a very patchy ground-type where moss tussocks dominate (Fig. 5F). Large undulating areas are covered with sediments of this class, mainly in the Shrenk and the Trautfetter River valleys between the ice-marginal zone and the Byrranga Mountains (Fig. 2). The predominant sediment is silt, although clay and sand may also be found within areas of this category. The tussocks are usually more than 1 dm high and constitute the micro-highlands within the ground-type. In the depressions between the tussock-areas there is brown moss with scattered grasses (e.g. *Poa*) and sedges (e.g. *Carex*). Larger grass-areas also occur, as well as lichen-dominated patches. Other common plants there are e.g. different species of *Salix*.

WATERLOGGED MUD

This class is characterized by damp to wet grasslands, i.e. marsh-meadows or mires (Fig. 5G). These are common on floodplains with fine-grained sediments and also on recent deltas and around lakes. The class thus occupies low-lying parts of the landscape and is most prominent at the Fomina River mouth (Figs. 2, 3). Humidity varies with topography and season, from wet with standing water in small muddy pools to almost dry. In addition to grasses (*Poa, etc.*) and sedges (*Carex, Eriophorum*) there are herbs like *Saxifraga* and *Chrysosplénium*. Peat-moss (*Sphagnum*) is also found. The large swampy area at the Fomina River mouth also has especially extensive polygonal patterned ground.

ANALYSIS AND DISCUSSION OF THE DERIVED MAP

The spectral classes, mainly based on vegetation, soil and rock differences, were identified as geological classes during the ground-truthing. The so far unpublished morphological, sedimentological and stratigraphical work done in the two field areas (Fig. 2) made it possible to interpret the geological classes further and divide them into genetical units. The interpretation of these classes is valid in the studied areas, but not necessarily

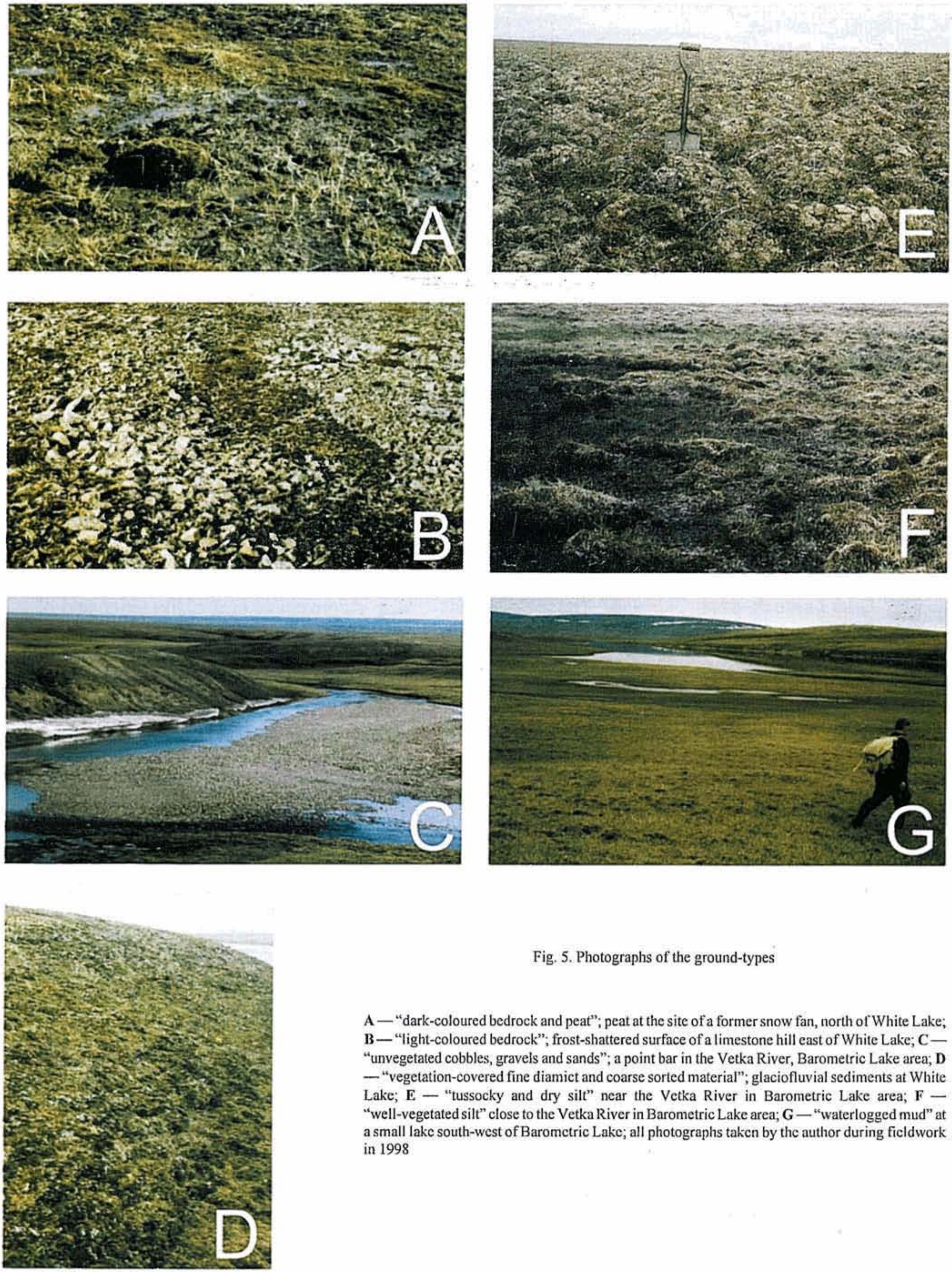

Fig. 5. Photographs of the ground-types

A — "dark-coloured bedrock and peat"; peat at the site of a former snow fan, north of White Lake; **B** — "light-coloured bedrock"; frost-shattered surface of a limestone hill east of White Lake; **C** — "unvegetated cobbles, gravels and sands"; a point bar in the Vetka River, Barometric Lake area; **D** — "vegetation-covered fine diamict and coarse sorted material"; glaciofluvial sediments at White Lake; **E** — "tussocky and dry silt" near the Vetka River in Barometric Lake area; **F** — "well-vegetated silt" close to the Vetka River in Barometric Lake area; **G** — "waterlogged mud" at a small lake south-west of Barometric Lake; all photographs taken by the author during fieldwork in 1998

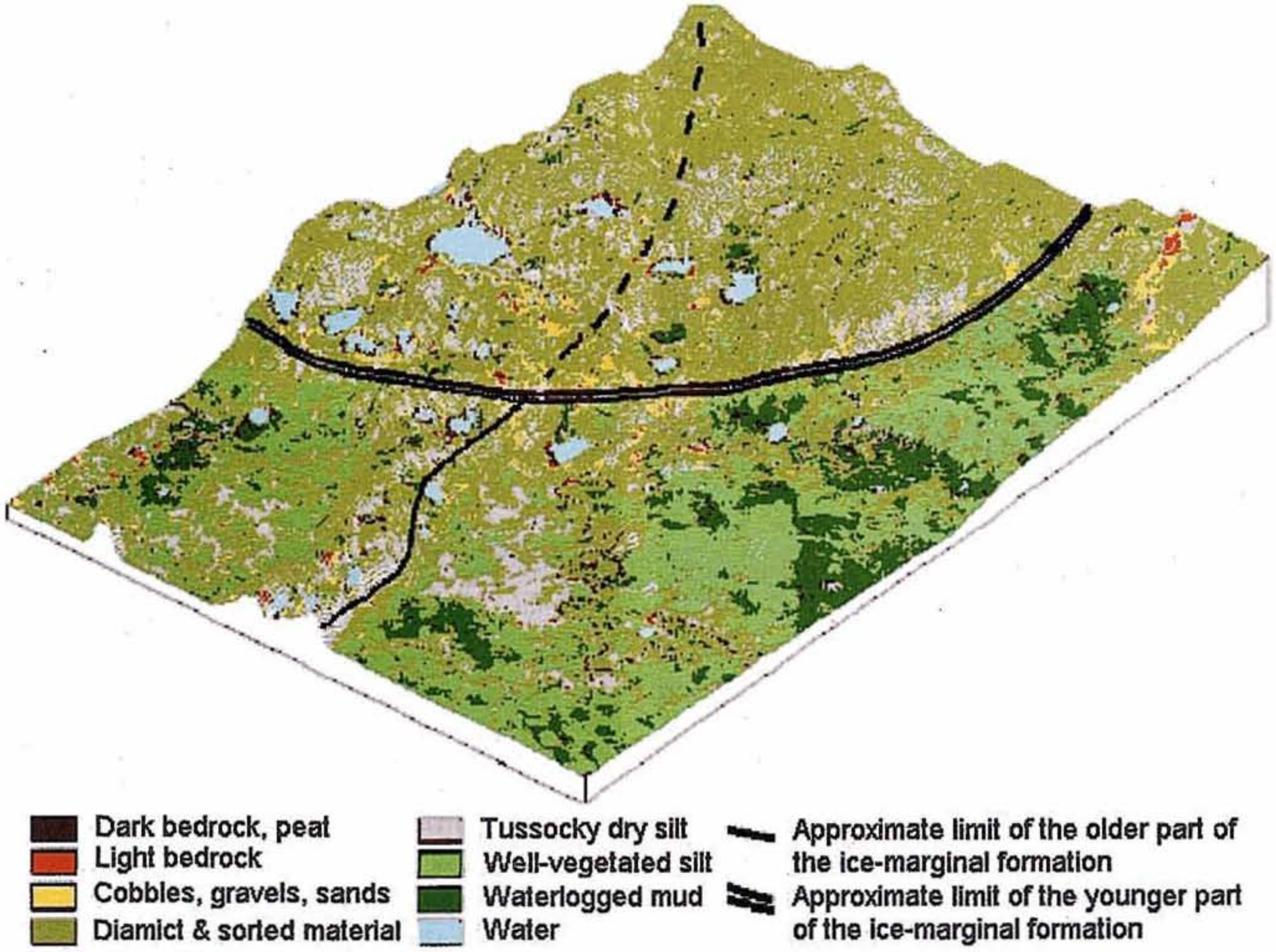

Fig. 6. Geological map of Barometric Lake area (window from map in Fig. 3) draped on a digital elevation model

The area shown in this figure is *ca.* 30 x 20 km and the elevation ranges from 40 to 180 m a.s.l.; here the ice-marginal formation consists of two generations; a ridge (single line), showing the limit of an ice sheet coming from the north, has been overrun by a later ice-advance (double line) from the north-east; the area covered by the young advance has a relatively high relief, probably because it is still ice-cored; ground-truthing showed that no dark-coloured bedrock is present in this area, therefore the dark brown colour here represents only peat

totally so for other parts of the area covered by the satellite image. In the discussion below, less emphasis will be put on the bedrock types than on the soil types, as the latter are most significant in a glacial history perspective.

The peat category may be differentiated primarily from the dark-coloured bedrock sub-class by its topographic position, which is low compared to the bedrock highs (*cf.* Fig. 6). Bedrock outcrops are also usually larger than the peat deposits. As the peat is dependent on humidity, it is associated with run-off from snow fans, with lakes and, occasionally, rivers. On the map (Fig. 3), several rivers appear to consist of peat/dark bedrock. This is probably an effect of the narrowness of the rivers compared to the spatial resolution of the image (*ca.* 57 m). A picture element consisting of both land and water may result in a spectral reflectance similar to that of the peat/bedrock class. This effect may also be seen around lakes. In many cases, however, peat actually surrounds the lakes, although perhaps not at as many lakes as indicated by the map. The peat appeared to be more common at White Lake than in the Barometric Lake area, which at least partly seems to be due to more extensive snow cover and later snowmelt at the first place. The age of the peat is in most cases Holocene, although real datings are few.

The signatures for "unvegetated cobbles, gravels and sands" and "light-coloured bedrock" are very similar (Fig. 4) due to the almost identical textural and lithological compositions of the two classes. In some places "unvegetated cobbles, gravels and sands" is shown on the map at locations where it should be light-coloured bedrock. Essentially, this is not wrong, since the bedrock surface is frost-shattered and consists of boulders, cobbles and gravel but, nonetheless, it would be preferable to be able to tell them apart. Probable bedrock areas can be identified where the "unvegetated cobbles, gravels and sands"-class is closely associated with "light-coloured bedrock", the feature is relatively large, constitutes a topographic high and is oriented approximately SW–NE. Where the class occurs near a river, or has a long, sinuous shape, it most likely corresponds to recent fluvial gravel in bars and banks, or to dried-out river beds. In connection with lakes, it matches gravely and sandy beaches and/or wave-cut cliff sections.

At the ice-marginal formation, especially on its distal side, the "unvegetated cobbles, gravels and sands"-class represents glaciofluvial and glaciolacustrine sediments in exposed sections or at non-vegetated, windblown hill-tops. These sediments belong to sandurs, deltas and kame hummocks (*cf.* below). The areas along the coast which have the "unvegetated cobbles, gravels and sands"-signature could be polar desert, more or less devoid of vegetation. This ground-type is thus quite diverse and of its sub-classes are easily interpreted whereas others are not. To distinguish the different varieties in areas where fieldwork has not been done it is necessary to compare their distribution with a topographical map and check their association with other classes.

In the field work areas the "vegetation-covered fine diamict and coarse sorted material"-class corresponds to areas with silty till and with glaciofluvial and glaciolacustrine sands and gravels. The till cover is in many places not more than a metre thick and is underlain by remnant glacier ice, more than 10,000 years old. The glaciofluvial and glaciolacustrine sediments exhibit greater thickness, as exposed in kame hummocks and relatively large glaciolacustrine deltas. These coarse-grained sediments are mainly concentrated to the distal part of the North Taymyr ice-marginal complex, and are commonly found in association with occurrences of the "unvegetated cobbles, gravels and sands"-class (Fig. 3). Despite the large difference in grain-size, the two categories, silty till and gravely sandy glaciofluvial material, have identical spectral signatures. This is probably because the similarities in vegetation and humidity outweigh the textural differences. Where the class occurs outside the ice-marginal formation, in non-ground-truthed areas, it may e.g. correspond to solifluction material or sediments deposited during an earlier glaciation.

The frost-boiled silt ("tussocky and dry silt"-class) can have different origins. A large field of frost-boiled silt at Barometric Lake was distal glaciolacustrine sediments, whereas at White Lake the main part of the silt areas consisted of silty till, but with less vegetation cover than the till included in the diamict/sorted material class. The till sub-class is also present at Barometric Lake, as small patches within a large lobe of the ice-marginal formation (Fig. 6). The fine-grained glaciolacustrine sediments should be located at relatively low altitudes distal to the ice-marginal formation. They should also be of relatively large extent and preferably associated with the "well-vegetated silt"-class. The silty till may also have a large areal extent, but should occur mainly inside the ice-marginal formation in different topographic positions. Here it is, however, necessary to beware of circular reasoning, since the position of the ice-marginal formation is not exactly determined in its entire length, and that is what the interpretation of the satellite image should remedy. Areas with till from older glaciations may also occur outside the ice-margin. The areas classified as "tussocky and dry silt" in the hills north-west of Barometric Lake and along the Leningradskaya River may consist of silty till, as they are located proximal to the general stretch of the North Taymyr ice-marginal zone (Fig. 2).

The "well-vegetated silt"-class consists of fine-grained glaciolacustrine sediments, at least at Barometric Lake. It is very similar to the glaciolacustrine variety of the "tussocky and dry silt"-class and those two are probably genetically identical but may have slight differences in e.g. grain-size, humidity or nearness to the permafrost. The "well-vegetated silt"-class is predominantly found between the North Taymyr ice-marginal complex and the Byrranga Mountains, in an area which according to topography and reconstructed shorelines (unpublished data) was probably covered by an ice-dammed lake during the latest glaciation. The class is frequently associated with the "waterlogged mud"-category.

"Waterlogged mud" commonly occurs near lakes or rivers and consists of recent muddy sediments deposited in deltas, on flood plains and in other regularly flooded or wet areas. The main part of these sediments has most probably been deposited during the Holocene and some are very young. No dating is, however, available. The occurrence of this class in the Shrenk and Trautfetter River valleys demonstrates the existence of topographic depressions.

A comparison of the final map with a geomorphological map of the Taymyr Peninsula (Kind and Leonov, 1982) shows a fairly good general agreement. The low-lying areas, occupied mainly by "diamict and sorted material", "well-vegetated silt", "tussocky and dry silt" and "waterlogged mud", correspond to basins marked by Kind and Leonov (1982) as occupied with marine, lacustrine and alluvial sediments. The fact that the till belonging to the classes "diamict and sorted material" and "tussocky and dry silt" seems to be identical to the marine and lacustrine sediments of Kind and Leonov (1982) could be explained by the frequent occurrence of shell fragments in the till, which thus may have been misinterpreted as an *in situ* marine deposit. The topographically higher areas, such as the Byrranga Mountains (mainly light-coloured bedrock) and the low hills in the north (dark-coloured bedrock) are on the Kind and Leonov (1982) map matched by areas generally without sediment-cover, but with signs of glacial erosion.

The interpretation of the different ground-types on the map makes it possible to put the information from the localized fieldwork into a regional context of geological environments. The reliability of the final map is, however, variable within the current area, and is best where ground-truthing has been done. At other locations it is necessary to be cautious, and evaluate the classification by comparing with topographic maps or digital elevation models (Fig. 6). But as noted above, it is possible to get a relevant impression of the genesis of the landscape by interpreting the Landsat 5 (MSS) image.

SATELLITE IMAGERY — PROBLEMS AND LIMITATIONS

The use of satellite imagery and analogue and digital image processing is advantageous as the material (data sets and necessary hard- and software) is available at a relatively low cost, the images cover large areas and processing can be done both quickly and systematically. There are, however, limitations to the method, partly because there is no ideal remote sensing system yet. Existing data-collecting and -processing devices are constrained by their spatial, spectral, temporal and radiometric resolution and cannot properly reproduce the complexity of the surface of the Earth (Jensen, 1996). These constraints must be taken into consideration when interpreting satellite images and the scale of the derived map has to be adapted to the given conditions. Landsat 5 (MSS) images have an approximate spatial resolution of 80 m and the most detailed scale for mapping is 1:120,000 (Clark, 1997). This means that objects smaller than 100–150 m is difficult or impossible to detect (*cf.* the problem with the narrow rivers discussed above). For the present study, the spatial resolution seems largely satisfactory, since the primary ambition was only to get an overview of the main geological features of the area. Furthermore, as the main object of the field studies, the ice-marginal zone which is at least 2 km wide and several tens of kilometres long, can in general be seen clearly and is possible to map over long distances.

Recent studies using satellite imagery in glaciated areas have mainly been concerned with the interpretation of tectonic or glacial lineations rather than with surface cover mapping (e.g. Boulton and Clark, 1990*a*, *b*; Aber *et al.*, 1995; Punkari, 1995). Clark (1997, p. 1074) suggests that "...routine mapping of glaciogenic deposits is never likely to be successful." because of the commonly similar spectral response of different glaciogenic deposits (till, glaciofluvial material, *etc.*) due to similar material composition or to resembling vegetation cover. This problem with spectral resolution is well exemplified in this study, as the contrast within the "land-cover spectrum" in the used image is relatively low. As a result, the unsupervised classifications showed only three different land classes compared with approximately four times as many non-land classes (ice, water, clouds). Some of the spectral signatures used for supervised classifications were also similar (Fig. 4). In areas where geological maps are non-existent, of poor quality or even confidential, satellite imagery interpretation may nevertheless be the best way to get an initial overview map of the land surface. But to achieve a satisfactory outcome of the interpretation of the satellite image in the present study, it was absolutely necessary to combine the initial results with information from the geological fieldwork and topographic maps — a procedure, which is standard in most investigations of this type today.

Many investigators (e.g. Punkari, 1985; Aber *et al.*, 1995) have adopted a geobotanical approach in mapping different features on Landsat 5 (MSS) images, since vegetation, which is well represented on such images, is dependent on type of sediment, soil, slope, aspect and drainage conditions. In areas with permafrost, such as in high-latitude regions, the depth of the active layer is also an influencing factor (Crampton, 1975). Although the vegetation on the tundra is not as varied as in more southerly latitudes, different geobotanical ground-types are distinguishable and a simple version of the geobotanical approach proved useful also in this study.

CONCLUSIONS

The original purpose of this study was to survey the fieldwork areas and to get an overview of the region. The field work areas could then be geologically connected to each other and morphological and conclusions made there could be extrapolated into unstudied parts of the region. This has been achieved by the combination of the interpretation of a Landsat 5 (MSS) image with information from ground-truthing, including the results of morphological, sedimentological and stratigraphical fieldwork. Seven different ground-types have been distinguished, described and interpreted, and they are summarized below. The geographical distribution of these classes is illustrated by Figure 3:

— "dark-coloured bedrock and peat" represents both bedrock, e.g. dolerites and greenschists, and recent peat deposits; the two categories are differentiated mainly by their size and topographic position: bedrock outcrops are usually larger and situated higher up, peat deposits are rather small and located in depressions;

— "light-coloured bedrock" consists chiefly of limestone, shale and sandstone;

— "unvegetated cobbles, gravels and sands" corresponds to more or less unvegetated (< 20%) coarse-grained fluvial sediments, beach sediments or glaciofluvial and glaciolacustrine sands and gravels, and in cases to very frost-shattered light-coloured bedrock surfaces;

— "vegetation-covered fine diamict and coarse sorted material" corresponds to well vegetated (> 90%) silty till or sandy/gravely glaciofluvial and glaciolacustrine sediments;

— "tussocky and dry silt" consists of fine-grained glaciolacustrine sediments or silty till with frost-boiled tussocks and a *ca.* 50% vegetation cover;

— "well-vegetated silt" mainly represents almost entirely vegetation-covered fine-grained glaciolacustrine sediments;

— "waterlogged mud" corresponds to vegetated recent floodplain sediments or sediments deposited in similar topographically low environments.

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