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Late Quaternary evolution of the western Nordenskiöld Land

ABSTRACT: Relief of Svalbard is an effect of varied morphogenetic, exogenic and endogenic processes. Tectonic and glacioisostatic movements of the Earth crust have occurred many a time in this region. Glacial, marine and periglacial features are particularly common. During the Late Quaternary the western Nordenskiöld Land underwent several sea transgressions, followed by glacier advances. Basing on erratics of crystalline rocks transported by sea ice, past sea levels have been established up to 250 m a.s.l. Marine terraces above 60 m a.s.l. date back to the Late Pleistocene, the lower ones are of the Holocene age.

Key words: Arctic, Spitsbergen, Quaternary evolution.

The western Nordenskiöld Land between Bellsund, Greenland Sea, Isfjorden and Grönfjorden is a highly diversified area if its geology and landscape are concerned (Musiał 1983, 1984, 1985, Musiał *et al.* 1990). The paper presents research on landscape evolution in polar conditions which has been carried out in western Spitsbergen by academic expeditions organized by the Department of Geography and Regional Studies of the Warsaw University in 1978, 1980, 1985 and 1988.

Seaside plains of Vast Långnes, Isfjorden and Vardeborg stretch westwards into an abrasive platform in which there are lowerings, consistent with the present fiords (Fig. 1). The plains are delimited in the east by two parallel mountain massifs with prominent peaks of Griegfjellet (778 m), Systemafjellet (744 m), Ytterdalsgubben (901 m), Ytterdalssäta (593 m), Vardeborg (588 m), Qvigstad-fjellet (770 m), Foldtinden (730 m) and Flynibba (745 m a.s.l.). Linnedalen, Ytterdalen, Orustdalen, Grönfjorddalen and Dahlfonnadalen are the main valleys of the area. Main rivers have the same names as glaciers and valleys *i.e.* Ytter, Grönfjorden, Orust and Linne. The largest lake in the area (Linnevatnet) is a crypto-depression. Kongressvatnet and Stemmewvatnet are the other perma-

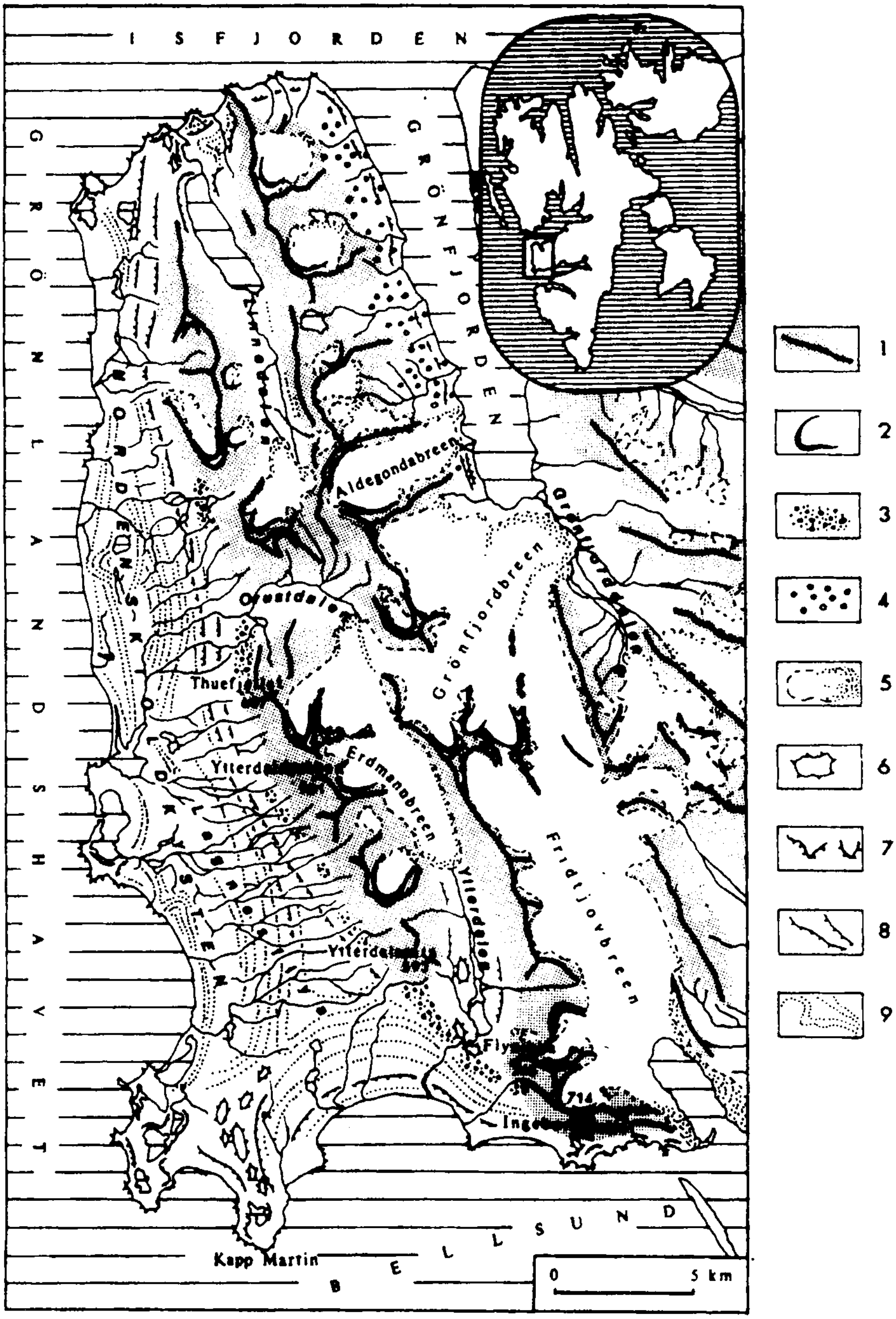

Fig. 1. Geomorphological sketch of the western Nordenskiöld Land (West Spitsbergen), after Musiał *et al.* (1992)
1 - mountains with weathering waste on slopes, 2 - cirque glaciers, 3 - ancient frontal moraine, 4 - ground moraine, 5 - glacier with a frontal moraine, 6 - abrasive relic outlier, 7 - headlands, 8 - edges of marine terraces, 9 - storm ridges on marine terraces

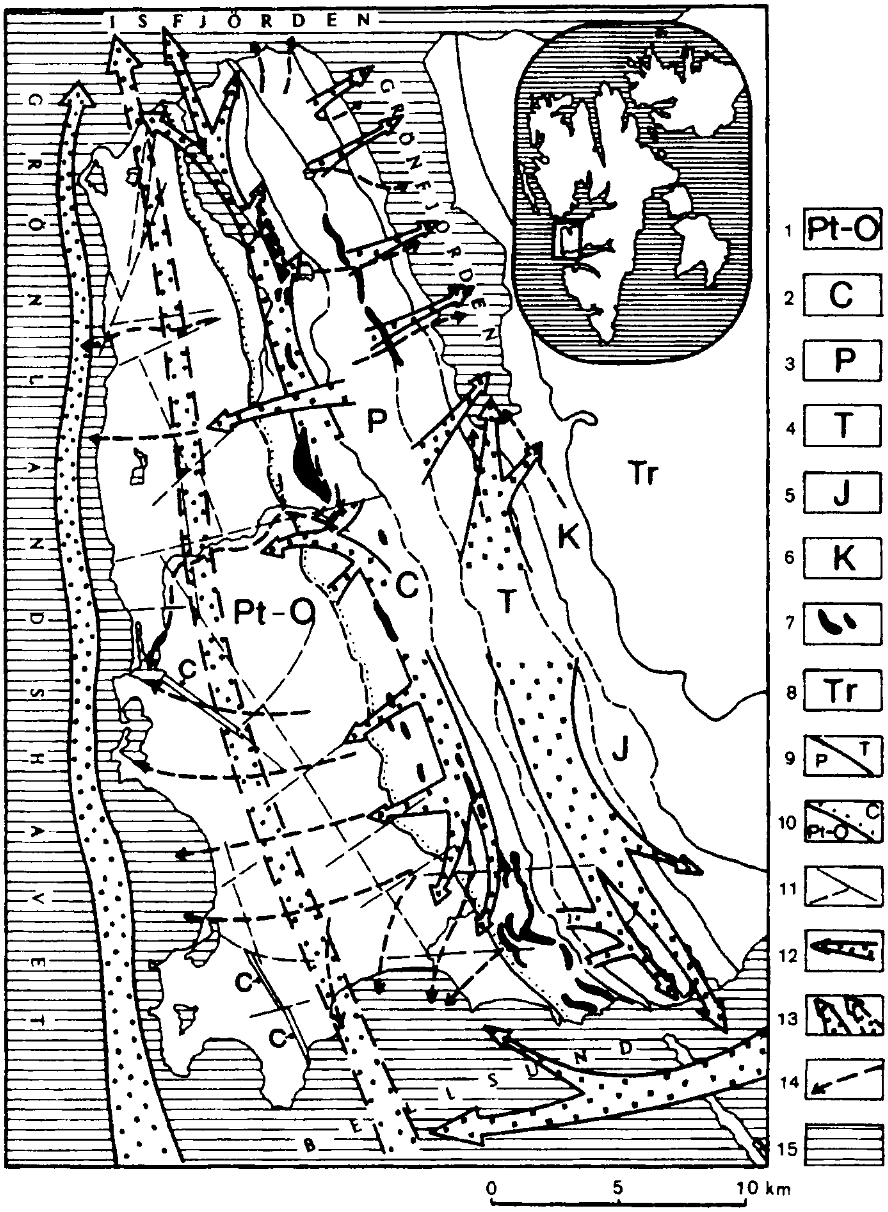

Fig. 2. Geological map (without the Quaternary) with directions of transport of rock material during the Holocene and the Lower Pleistocene

1 - pink, green and grey shales, tillites, locally metamorphosed limestones (Cambrian-Ordovician), 2 - light grey quartzitic sandstones with *Lepidodendron* root-stocks and leaf imprints (Lower Carboniferous), 3 - grey limestones with rich brachiopods (Permian), 4 - fine-grained grey sandstones (Triassic), 5 - silty shales with siderite concretions (Jurassic), 6 - light sandstones and mudstones (Cretaceous), 7 - dolerites (Jurassic? Cretaceous?), 8 - grey sandstones (Tertiary), 9 - stratigraphical boundaries, 10 - stratigraphical discontinuities, 11 - faults, 12 - past directions of glacial transport, 13 - past and contemporary directions of marine transport, 14 - directions of fluvial transport, 15 - waters

nent lakes. There is also a large number of seashore lakes, some of which are flooded during heavy storms. The Gulf Stream flows along the western shore of the area.

At present this part of Spitsbergen is occupied only by a minor glaciation. Apart from the Fridtjov and the Grönfjorden glaciers, it is limited to the upstream valley sections with the Erdmann, Aldegonda, Dahlfonna, Linne, Varde, Voring and Solfonna glaciers. Locally there are rock glaciers, mainly at foot of rocky walls.

Geological structure

In the western Nordenskiöld Land there are several geological units (Fig. 2), the oldest of which comprise metamorphosed rocks of the Upper Precambrian, dissected during the Neogene and the Quaternary by younger faults (Flood *et al.* 1971, Hjelle *et al.* 1986). Structural units from the Palaeozoic to the Tertiary dip eastwards (70-60^{o}) due to tectonic movements.

The western Nordenskiöld Land is located at verge of a tectonic niche, which stretches eastwards from the Grönfjorden-Fridtjovhamma, being filled with the Tertiary deposits (Flood *et al.* 1971, Hjelle *et al.* 1986, Winsnes 1988). Along eastern slopes of the Griegfjellet-Ytterdalsgubben-Ytterdalssäta massif, rocks of the Hecla Hoek Formation contact with the Palaeozoic ones. Outcrops of other sequences are parallel to this line (Musiał 1984).

The Hecla Hoek Formation consists of the Cambrian and the Ordovician rocks - mainly phyllites, shales with quartzites, shales, quartzites, limestones, dolomites and conglomerates. They are discordantly overlain in the east by the Carboniferous grey conglomerates, dipping eastwards at 70^{o}. Further on, they turn into very resistant lightgrey quartzitic sandstones, with well preserved relic fauna and thin inserts of coaly shales. At contact of these and younger series, there are common intrusions of the Jurassic or Cretaceous grey-green dolerites. In the eastern Linnedalen and Orustdalen as well as on slopes of Haroldfjellet (664 m a.s.l.), there are cherry-coloured or red fine- and medium-grained sandstones with a siliceous cement. Dark grey dolomites and limestones, containing numerous coelenteres fossils, are of the Upper Carboniferous age. Dolerite intrusions occur at foot of Voringen (675 m a.s.l.), Foldtinden and Flynibba. Within carbonate series there are single pieces of crystalline gypsum and alabaster.

Summits of the Vardeborg-Qvigstadfjellet-Foldtinden massif are built of the Permian rocks, composed of black siliceous limestones with rich brachiopods and of grey limestones. There are also the Triassic grey-yellow sandstones with well preserved fossils. The Jurassic rocks are represented by black clayey shales with siderite concretions. The western shore of Grönfjorden as well as Aurdalen and Grönfjorddalen are built of pale sandstones and the Cretaceous limestones. In the east there are the Palaeogene grey sandstones.

Compatibility of main geological structures with valleys and mountain ridges is very distinct (Musiał *et al.* 1990). The subsequent Ytterdalen, Fridtjovdalen, Grönfjorddalen and Dahlfonnadalen follow generally the NNW-SSE direction of rock layers (Lacika and Musiał 1988). Mountain ridges follow the same direction. They are dissected by wide valleys (Orustdalen, Kongressdalen and Folddalen), established at transversal tectonic cleveages. These three, as well as a number of smaller valleys are obsequent. Blendadalen, as well as the valleys of the Aldegonda, Saga and Gränut glaciers are resequent.

Variability in geological structure is reflected by character and location of mountain ridges. Many of them have asymmetric transversal sections. Steep rocky walls occur at outcrops of resistant strata, while gentle slopes follow strike-and-dip of beds. Ytterdalsegga and Kalkegga are the two of monoclinal ridges in the area.

Lithology exerted a significant impact on relief evolution in this part of Spitsbergen. Many different rocks, varied in their resistance to weathering, can be found there (quartzitic sandstones, marbles, shales, gypsum, *etc.*). Due to selective application of external processes, resistant rocks have been exposed and soft ones got weathered. Layers of the Lower Carboniferous quartzitic sandstones are the most resistant. Single peaks, hummocks, structural breaks and banks appear in areas with doleritic outcrops. Many of such banks have been dissected by rivers, which form deep gaps *e.g.* in Folddalen. Steep rocky walls of Qvigstadfjellet, Seipfjellet and Vardeborg developed on outcrops of the Permian yellow-grey spiriferous limestones.

Quaternary deposits

Quaternary sediments of the western Nordenskiöld Land are derived from weathering waste of lithologically diversified bedrock of different age, and have been formed due to various morphogenetic processes on land as well as underwater, being redeposited a number of times. Stratigraphy of these deposits could be established on the basis of outcrops in high banks of Linneelva, close to its mouth. In a lower part of the section, a till occurs (Lavrushin 1969) directly on bedrock (of the Lower Carboniferous? age), but such could not be observed during our research (Musiał *et al.* 1991). At depth of 15-16 m (*i.e.* 3-4 m a.s.l.) there are sands and marine shales, with rich mollusc fossils (of *Mya truncata, Saxicava rugosa* and *Saxicava arctica*; Pl. 1. Fig. 1). There are whalebones at the top of the series over 10 m thick. Higher up, there is 1-1.5 m thick layer of brown-red till with boulders and debris. Abrasion of rock material suggests its transport over a small distance. Erratics of the Upper and the Lower Carboniferous as well as of the Permian age are noted. The largest ones are over 2 m in diameter. A contact between the upper till and the marine sediments is very sharp and even, presumably due to destruction of a top of the latter. The till contains occasionally brown-grey clayey sands with pebbles and debris. The terrain in the neighbourhood is paved with beach pebbles, which form ancient storm ridges. In numerous places there are vari-grained sands (probably of marine origin), with signs of aeolian processes. Two tills and a separating marine series have been observed at numerous locations in Svalbard (Boulton 1979, Troitsky *et al.* 1979, Landvik and Salvigsen 1985).

Block-debris and debris-clay mantles have maximum thickness in lower parts of mountain slopes (Musiał *et al.* 1990). They undergo constant transformations due to weathering and gravitation. A boundary between denudation and deposition on slopes occurs usually at 200-300 m a.s.l. On ancient planation areas there is weathering waste, composed mainly of rock debris. In some areas, significant reduction of weathering waste occurred due to glacial erosion. The weathering waste has been transformed by marine abrasion on beds of many valleys (*e.g.* in Linnedalen, Orustdalen and Ytterdalen).

At western foot of Kosterfjellet, there is a consequent slide, composed of random angular blocks, a few metres in diameter each (Drecki 1989). A block downfall occurs in Jarndalen at the foot of Salen (576 m a.s.l.). Rocks, tors and walls establish fronts of structural-denudational thresholds and crests (Voringen 675 m, Heftyefjellet 425 m and Ytterdalsegga 730 m a.s.l.). Talus cones developed at mouths of numerous chutes and at the foot of steep rocky walls. With inclination to 35^{o}, they consist of angular rock material, a size of which has been gravitationally diversified, as exampled at foot of Ingeborgfjellet, Voringen and Vardeborg. On terraced sea plains at the mouth of Tjörnskardet, Orustdalen, Jarndalen, Ytterdalen and Ytterskardet there are sediments, defined by Lavrushin (1969) and Troitsky *et al.* (1975) as glaciomarine ones. They form plateaux from 62 m (Orustdalen) to 94 m a.s.l. (Ytterskardet), composed at tops of vari-grained sands, gravels and the Carboniferous light quartzitic sandstone blocks (to 1.3 x 0.8 x 0.6 m) with slightly weathered edges (Musiał 1989). At mouth of Orustdalen the quartzitic sandstones occur at distance over 2 km from their outcrops amidst the rocks of the Hecla Hoek Formation (Landvik *et al.* 1987). Glacial grooves are well preserved on numerous blocks. At 54 m a.s.l. there is a clear boundary between marine and glacial sediments, reflected by varying abrasion of a rock material. From 54 m upwards, the material indicates marine abrasion, downwards it turns into typical beach pebbles. Such sediment distribution is noted also along the ridges, both at the side facing the Greenland Sea and at the side of valleys, at mouth of which they have been deposited. Best examples of such forms, with large amounts of erratic material and groups of residual abrasion hills in foreland are located at the mouth of Ytterdalen (between Ytterdalssäta and Kleivdalen).

Moraines on Vardeborgsletta (at 30-35 m a.s.l.) are different (Musiał *et al.* 1991). They are composed usually of clayey brown-grey sands, with angular stone debris and blocks (Pl. 1, Fig. 2). Fragments of the Permian and the Carboniferous rocks were found here (light and cherry-coloured quartzitic sandstones). A subjacent layer consists of brown clay with pebbles, underlain by brown vari-grained sands and gravels, to 1 m thick. Moraines on the western shore of Grönfjorden are similar (Musiał *et al.* 1992). They start in glacier forefields and stretch to the fiord. Large glacial boulders of the Permian limestones and light-grey quartzitic sandstones are noted during a low tide on the abrasive platform, several dozen metres from a shore. Greatest agglomerations of these erratics are located downstream in Kongressdalen, Stenbrohultdalen and Blendadalen. They are set in massive clayey basal till, a thin layer of which covers sands and marine shales with many shells of *Mya truncata* and *Saxicava arctica.*

The basal till in this part of the Nordenskiöld Land indicates significant facial differentiation, noted in varying contents of shales. A till predominates in a shore up to 50 m a.s.l. Higher up, it is mostly composed of block-debris with local admixture of shales. In glacier forefield (Varde, Vorig and Heftye) the moraines are reduced due to intensive abrasion by the past glaciers. Erratic material in glacial sediments can be easily traced due to narrow source outcrops as well as varying petrography, resistance and age (Musiał 1983, 1984, 1985). Erratics in this part of the archipelago form *(i)* large angular blocks with no signs of glacial erosion, *(ii)* large blocks with traces of good glacial abrasion, *(iii)* vari-grained rock debris with varying glacial abrasion, and *(iv)* very well abraded beach pebbles.

Rounded boulders of light and cherry-coloured quartzitic sandstones, 12-82 cm in diameter, were noted at various morphological locations , that is *(i)* on marine terraces up to 73 m a.s.l., *(ii)* in areas of the Precambrian Hecla Hoek rocks, *(iii)* on mountain slopes up to 247 m a.s.l., at outcrops of the Carboniferous carbonate rocks (Ytterdalsegga), *(iv)* on ice-moraine ridges of the Erdmann Glacier (119 m a.s.l.), *(v)* at mouth of Folddalen into Ytterdalen (160 m a.s.l.), and *(vi)* on a ridge at 184 m a.s.l. hill in Linnedalen.

Erratic material of crystalline rocks on beaches of Bellsund and the Greenland Sea is particularly interesting. A granite block with large pre-crystals of pink-grey feldspar on a beach in Grönfjorden has over 2 m in diameter. Large red granite blocks were also found on Lågnesvarden (aproximately at 50 m a.s.l.) and on a coastal plain at the mouth of Tjörnskardet (aproximately at 55 m a.s.l.).

Contemporary glacial sediments are noted in a limited zone due to a small area occupied by the present glaciers. These sediments are mainly composed of angular debris of end and lateral moraines. The debris is usually 1-1.5 m thick and mantles cores of glacier ice. Frontal and lateral moraines contain different material, dependent largely on types of rocks along a glacier route. Between moraines and glaciers, in ice-dammed and overflow lakes, there are glaciolacustrine sediments, mainly sands, shales and clays (the glaciers Linné, Erdmann and Dahlfonna).

Outwash plains and fans (Pl. 2, Fig. 1) are the effects of glaciofluvial accumulation. In proximal areas they are composed of macroclastic and non-abraded material, while in distal areas - mainly of sands, shales and clays (forefields of the Linné, Erdmann and Dahlfonna glaciers). In areas with concentrated draining of morainal zones, these sediments resemble rock rubble of mountain streams. In Linnevatnet and Kongressvatnet deposition of slightly abraded gravels, sands, shales and clays occurs.

Field observations in summers 1980, 1985 and 1988 indicated increasing supraglacial covers in morainal zones. Fronts of most glaciers are mantled with mineral material, what influences the ablation rate. Many glaciers, especially the smaller ones, are the rock glaciers. They stretch at the foot of steep rocky walls of Vardeborg, Griegaksla and Seipfjellet.

Close to the ice cover, an intensive drainage occurs which, together with frost action, scoures and segregates rock material. Large rock pieces drop within clays, smaller ones build frost structures in Linnedalen, Ytterdalen and Lågnesflya. Throughout the ablation season meltwaters transport, scour and segregate rock material. In depressions where snow has melted away, there are nival pavements. Seasonal freezing and melting of ground surface results in segregation of clastic material. Periglacial processes create polygon networks, trains, rings and rimstones (Vardeborgsletta, Lågnesflya and Gravsjöen). Slight inclination of slopes (1-2^{o}) causes intensive solifluction that forms covers and mud-rubble tongues. Generally, they move onto ancient marine terraces.

Due to a short transport, river bed sediments are only slightly abraded. At 1.5-2 km from a source, rivers carry mostly a fine material. Larger, slightly abraded pebbles appear only locally.

Marine sediments form vast morphological levels along the Greenland Sea and Isfjorden. The highest raised marine terraces were noted at 72-73 m a.s.l. They are tightly paved with sea pebbles of the Lower Carboniferous lightgrey quartzitic sandstones, often over 25 cm in diameter. Terraces at such altitudes occur at mouth of Folddalen and on Långnesflya. Considerably similar are the terraces 57-58 and 54 m a.s.l. At the outlet of Folddalen and at depth of 5 m (*i.e.* 48 m a.s.l.), there are vari-grained (mostly fine-grained) sands. They are underlain by grey-brown clayey sands, 60 cm thick. In bottom there is brown clay with angular gravel. Thickness of the glacial series exceeded 1 m. The lower marine terraces occur at 43-44, 30-32, 27, 15-18, 10, 7-8, 3-5 and 2 m a.s.l. They consist of vari-grained sands, shales, gravels and pebbles. Ancient parallel storm ridges, composed of gravels and pebbles, are noted on many of the terraces. Marine terraces enter deeply into the valleys, forming narrow ledges at 172, 184 and 196 m a.s.l. (*e.g.* in Ytterdalen). They are, however, less distinct, due to thick solifluction and locally - fluvial cover. In many places there are presumable fossil cliffs, covered with slope sediments *e.g.* in Ytterdalen.

Recent sea beaches, at 3.5-4 m a.s.l., on the northern seashore of Bellsund are covered with aeolian sediments which form initial dunes (Pl. 2, Fig. 2). In their direct neighbourhood at 4 m a.s.l., there are fields of wind-abraded blocks. Blocks of sea-ice, buried by sediments, can be found on beaches throughout summer.

Relief development

Significance and scale of neotectonic movements in this part of the archipelago have not been fully explained yet. According to Semevsky (1967), Svalbard has been uplifted due to neotectonic and glacioisostatic movements. Marcinkiewicz (1968), Kvitkovic (1971) and Salvigsen *et al.* (1991) concluded on the basis of altitudes of marine terraces in Bellsund, that uplifting is not uniform in various parts of West Spitsbergen. Many authors claim the neotectonic processes in this area do not exist or are insignificant (Salvigsen and Nydal 1981, Landvik *et al.* 1987). In their opinion, glacioisostatic movements which took place during the Holocene after retreat of the Pleistocene glaciers, were of primary importance.

At present it would be difficult to define a role of neotectonic and glacioisostatic processes in modelling of the area. They should not be separated from each other, because they occur simultaneously. Glacioisostasy influenced neotectonic movements, which resulted in varying uplifting of the archipelago during the Holocene (Lindner *et al.* 1986). At present the uplifting decreases (Salvigsen 1984). In the Nordenskiöld Land neotectonic movements occur during occasional earthquakes (Barentsburg - *a spoken source*).

Intensive tectonic movements in this part of the world have occurred since the Palaeogene. At that time huge fractures and faults were formed. Isfjorden, Van Mijenfjorden, Grönfjorden, Linnedalen and Ytterdalen developed along such lines (Lacika and Musiał 1988). According to Kvitkovic (1971), these fractures were active throughout the Quaternary. Similar phenomena have been also recognized in other parts of the archipelago (Lindner *et al.* 1986). Due to tectonic processes a sharp border between a shore plain and mountains was accentuated. Development of landscape was significantly influenced by lithology. Rocks, having varied resistance to weathering, facilitated selective action of external processes. In a relatively short time, hard rocks have been exposed, while softer ones got eroded. Thick beds of the Lower Carboniferous quartzitic sandstones proved to be most resistant. At outcrops of the Permian grey-yellow spiriferous limestones, steep rocky walls were created (Ytterdalsegga, Seipfjellet and Qvigstadfjellet). Karst developed on flat carbonate surfaces. Such was the origin of the Kongressvatnet basin (max. depth 53 m) and the lakes on Vardeborgsletta, being examples of a reproduced karst (Salvigsen and Elgersma 1985). Single peaks, hummocks, structural faults and ridges occur on dolerites. Many of such inselbergs are dissected by rivers and deep gaps were formed. Glacial and marine processes, recurring throughout the Quaternary, brought significant relief alternations, resulting in abrasion and transport of rock material.

Marine shingle of the Lower Carboniferous light quartzitic sandstones (to 25 x 22 x 12 cm) on a flattening of Ytterdalsegga, at 237, 247 m a.s.l., indicate past sea transgressions. On similar altitude (250 m a.s.l.), there are levels in Folddalen. At mouth of Tjörnskardet (245 m a.s.l.), pebbles of the Carboniferous light quartzitic sandstones occur too (Musiał 1985). If their altitude is concerned, they coincide with a flattening in Orustdalen *e.g.* on slopes of Systemafjellet.

On northern slopes of this valley (at 200 m a.s.l.), numerous pebbles have been found. From the west, slopes of Griegfjellet-Systemafjellet-Ytterdalsgubben-Ytterdalssäta are undercut and a cliff has been formed, mostly inactive at present as mantled with slope sediments. Outlets of hanging local valleys occur at 160 m a.s.l. *i.e.* 90-100m above a seashore plain.

Until recently, the authors have assumed that pebbles of the Carboniferous light quartzitic sandstones have been redeposited due to glacial transport (Musiał 1985, Musiał *et al.* 1990), *e.g.* on ice-cored moraines of the Erdmann and the Grönfjorden glaciers. However, such view has to be revised. Erratics of crystaline rocks on contemporary beaches and on slopes (at 133 and 159 m a.s.l.) suggest that they have been deposited there by ice pack or icebergs. In summer 1988 an intrusion of sea-ice fields deeply into Van Mijenfjorden was observed.

Such situation proves that between Bellsund, the Greenland Sea and Isfjorden an ancient sea transgression occurred, extent of which remains to be established yet. Its age can be estimated if compared to similar (in altitude) raised marine beaches, ascribed by Lindner *et al.* (1991) to the Wedel Jarlsberg Land Glaciation (Saalian). Such proposal however, questions an extent of the Vistulian Glaciation (Weichselian) as quoted by Salvigsen and Nydal (1981), and Landvik *et al.* (1987).

Position of the oldest tills on bedrock between Isfjorden and Linnevatnet may point out a preceding long erosive interval. On the other hand, lack of the older Quaternary sediments in the area could have been caused by uplifting and the material could be swept away due to detraction. Such situation suggests an occurrence of a lowering in the bedrock, later turned into a cryptodepression of the Linnevatnet (max. depth 59 m). This lowering acted as a glacial plucking basin. In other valleys significant overdeepenings of their bottoms occurred, accompanied with transport of clastic material into their forefields.

According to Lavrushin (1969), the oldest tills in the region were deposited by glaciers of the Riss Glaciation. In the light of the latest research, these forms seem to be much younger, corresponding either to the Vistulian (Kłysz *et al.* 1988, Lindner *et al.* 1983), or to the Early Vistulian (Salvigsen and Nydal 1981). According to them, during the Early Vistulian the archipelago was covered with glaciers. The most recent datings suggest that these tills are older than Late Vistulian (Salvigsen *et al.* 1991).

A following sea transgression, which covered the whole archipelago, is indicated by sands and shales with a rich mollusc fauna. According to Salvigsen and Nydal (1981), it could have occurred during the Middle Vistulian interstadial. All larger valleys in the western Nordenskiöld Land were transformed into fiords in that time and various shoreline processes, development of cliffs, as well as abrasion and accumulation of rock material occurred. Fragments of marine terraces above 60-61 m a.s.l. correspond probably to this time (Landvik *et al.* 1987, Salvigsen *et al.* 1991). On western slopes of Griegfjellet-Systemafjellet-Ytterdalsgubben-Ytterdalssäta massif there are local flattenings at 82 m a.s.l. (mouth of Griegdalen). Pebbles have been observed up to this altitude. Above, there is presumably an ancient cliff.

The following glaciation occurred during the Late Vistulian. According to Salvigsen and Nydal (1981), the glaciers reached their maximum extents at 18 ka B.P. and the glaciation centre occurred on the Kongs Karl Land. Thus, the upper till on Vardeborgsletta at mouth of Linnedalen comes probably from this time. Basing on occurrence of sediments and landforms, glaciers in this time occupied the valleys and flowed into a sea (Musiał 1984, 1985, 1989). These till areas are occupied at present by sea terraces at 54 (mouth of Ytterdalen) and 59 m a.s.l. (mouth of Orustdalen). Datings of these terraces indicate their age of 10-11 ka B.P. (Landvik *et al.* 1987). Therefore, finds of marine shingle at 187 m a.s.l. near Linnevatnet, and in many locations east of the Fridtjov Glacier, gain special significance. They suggest, that the Late Vistulian Glaciation in the western Nordenskiöld Land was limited, and only slightly more extensive than of the contemporary glaciation. A preceding sea transgression, however, must have been much larger than previously expected (Lindner *et al.* 1991). Therefore, the maximum glaciation in this part of the archipelago had occurred earlier.

The glaciers entering Grönfjorden to the east of the Vardeborg-Voringen-Qvigstadfjellet watershed, developed in a different way. They were longer and covered a vast area, the abrasive platform of the fiord included. No sea beaches with marine shingle have been found there above 2-3 m a.s.l. Thus, during the glaciation that formed frontal moraines in forelands of valleys open towards a sea, Grönfjorden must have been filled with glaciers (Musiał 1984, 1985).

Since the end of the Vistulian, mountain slopes in this part of Svalbard underwent several rejuvenations, separated by periods when denudation prevailed. Towards the end of the Vistulian, slopes were undercut by sea and by glaciers. Then, due to slope processes, inclination and altitudes decreased. Later, solifluction covers flowed onto sea terraces. Varying lithology resulted in non-uniform degradation of slopes. The next slope rejuvenation occurred during the Holocene glacial episode, particularly significant upstream the valleys.

Distribution of erratics on sea terraces up to 50 m a.s.l. indicates that at the turn of the Pleistocene and the Holocene, sea currents were similar to the present ones. Ice pack and icebergs could transport rock material from the south northwards (Fig. 3).

According to the Norwegian researchers, after developement of the terrace 64 m a.s.l., sea-level dropped and the large distinct terrace 54-40 m a.s.l., dated at 10.6-10 ka B.P., was formed. The shoreline remained at this altitude for a longer time, as indicated by well preserved ancient beaches. At this time the central part of Orustdalen was an ice-free and shallow sea bay. There were several rocky islands near Lågnesrabbane, growing larger with a progressive drop of sea-level and making grounding of icebergs with erratic material possible. During the next 2 ka, a shoreline dropped at about 40 m (aproximately 1.2-2.2 m every 100 years). The Holocene transgression, which occupied this part of Svalbard, occurred at 8-4 ka B.P., reaching its maximum at about 6 ka B.P. About 7.6 ka B.P. a small (3-5 m) recession resulted in development of the terraces 12.1-10.8 m a.s.l. Later, other terraces were formed at 5-8 m a.s.l. They constitute erosive rock ledges at headlands *e.g.* at Lewinodden, Millarodden and Steinneset.

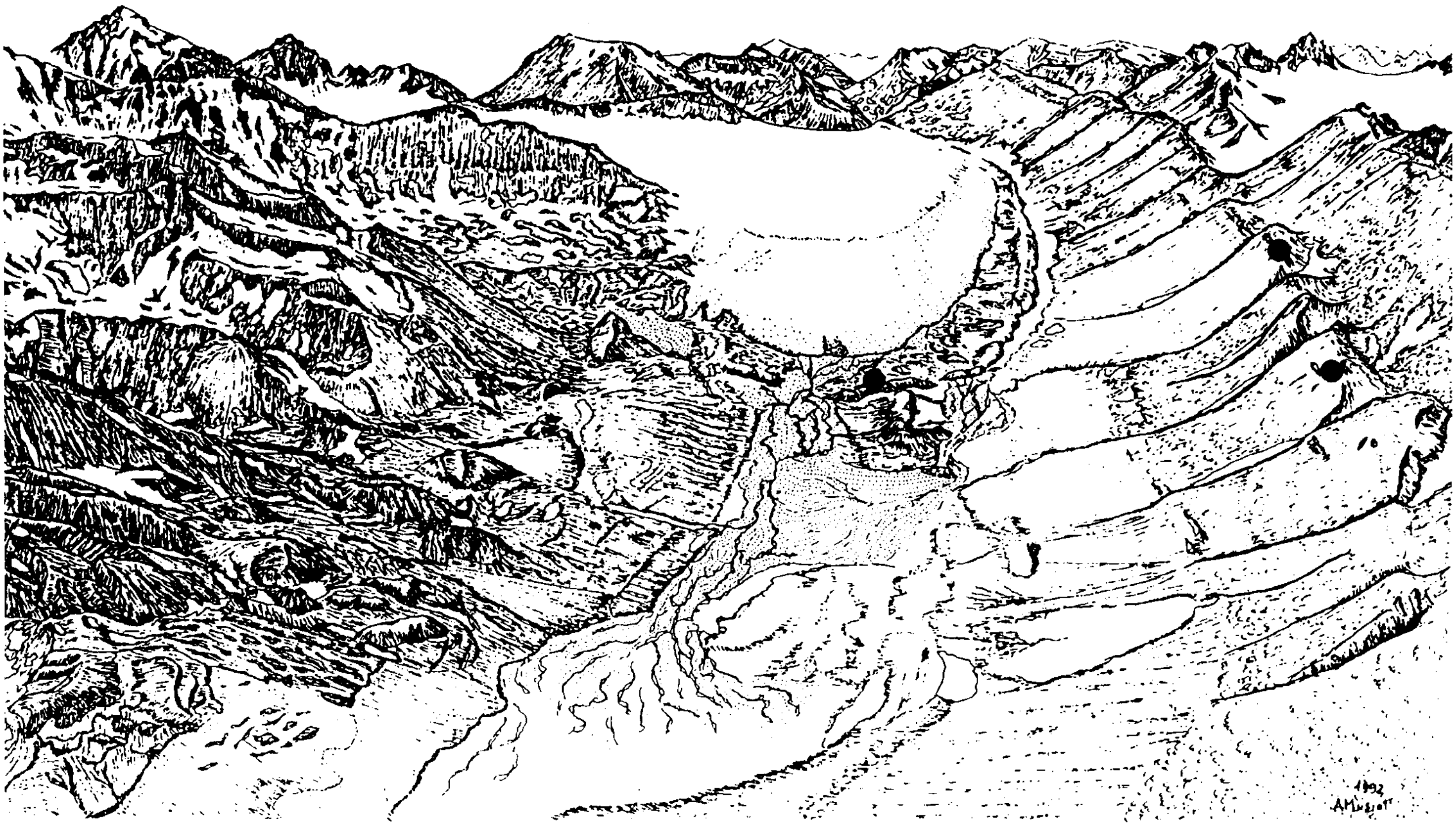

Fig. 3. Upstream Ytterdalen with location of the Carboniferous light quartzitic pebbles (black dots)

During the Holocene, Svalbard underwent three glacial episodes *i.e.* 9-8 ka, 3-2 ka B.P. and the Little Ice Age (Lindner and Marks 1991). At this time glaciers developed upstream the valleys, and their extents were similar to these of the contemporary ones (Kłysz *et al.* 1988). However, in certain cases, the glaciers made occasionally significant surges as early as in historic times, *e.g.* the Grönfjorden Glacier and the Paula Glacier. Research of many ice-cored moraines, supplied with datings of the lichen *Rhizocarpon alpicola*, established that most such structures in the Nordenskiöld Land occurred 40-230 years ago (Frosling *in press*). Only several ice-cored moraines are older; they were dated at 0.97-3.19 ka ago *i.e.* at the Grönfjorden Stage (Troitsky *et al.* 1975). These data, together with observations of glacial surges during the last several dozens years, prove complex dynamics of glacial processes.

At present a young, glacioisostatically uplifted seashore plain which is poorly drained, collects water from melting snow which supports cryogenic processes. Structural soils of different sizes and shapes, built of various material, are common. On peat plains there are thufurs and initial pingos. On a bare sand terrace (3-4 m a.s.l.), aeolian processes and small dunes are active (coast of Van Muydenbukta). Sediments transported by rivers are deposited in seashore lakes and lagoons. High rocky sections of shores are intensively destructed by marine abrasion. Deposition of sands, gravels and locally, of material transported by icebergs and ice-pack, prevails on flat shores. Intensive gravitation processes, mainly sliding, occurs on numerous slopes. Fluvial and glaciofluvial processes concentrate along river beds. Along borders of plains and mountains, as well as in glacier forefields, systems of alluvial and outwash cones develop. In river beds on plains lateral erosion prevails over the bottom one, due to low inclination of the area. Slopes are modelled by snow avalanches in winter and spring.

Recurring sea transgressions and glaciations removed a lot of decomposed rock material from the mountains, and carried it to the plains. Denudation was most intensive in the upstream parts of valleys, where glaciers developed repeatedly. Selection and rounding of rock material is however the best visible in water - on an abrasive platform. Amount of such material quickly decreases with increasing distance from the mountains.

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Streszczenie

Zachodnia część Ziemi Nordenskiölda pomiędzy Isfiordem, Morzem Grenlandzkim, Van Mijenfiordem i Grönfiordem wykazuje silne zróżnicowanie pod względem geologicznym i morfologicznym (Musiał 1983, 1984, 1985, Musiał i in. 1990; fig. 1). Istotny wpływ na rozwój rzeźby omawianych obszarów odegrały warunki litologiczne, w związku z różną odpornością skał na wietrzenie (fig. 2). Występujące tu utwory czwartorzędowe stanowią produkty wietrzenia podłoża w wyniku oddziaływania zróżnicowanych procesów morfotwórczych; głównie glacjalnych, morskich, peryglacjalnych i powierzchniowych ruchów masowych (Lacika i Musiał 1988; pl. 1-2). Powtarzające się transgresje morskie i zlodowacenia doprowadziły do usunięcia znacznej ilości zwietrzeliny skalnej z gór i osadzenia jej na równinach. Stopień wymieszania osadów czwartorzędowych i ich przekształcenia jest zróżnicowany. Największe rozmiary denudacja osiągnęła w górnych odcinkach dużych dolin, gdzie lodowce rozwijały się wielokrotnie. Natomiast największa selekcja i obtoczenie materiału skalnego zachodziło w środowisku wodnym w obrębie platformy abrazyjnej. Ilość tego materiału szybko maleje w miarę oddalania się od łańcuchów górskich. Zapisem dawnych transgresji morskich są otoczaki morskie znajdywane w różnych sytuacjach topograficznych (maks. 247 m n.p.m.), stare klify oraz fragmenty dawnych den dolinnych np. w Folddalen 250 m n.p.m. Obecnie przyjmuje się, że tak wysoko umiejscowione ślady działalności morskiej powstały przed zlodowaceniem Vistulian. Poziomy i osady morskie powyżej 60-61 m n.p.m. pochodzą prawdopodobnie ze środkowego Vistulianu (np. w ujściu Orustdalen), kiedy na Svalbardzie panowały warunki odpowiadające interstadialnym (Salvigsen i Nydal 1981). Na tzw. starych morenach datowanych na młodszy Vistulian plaże morskie sięgają do wysokości 54-59 m n.p.m. (Musiał 1989). Powierzchnie te datuje się na 10 000 - 11 000 lat B.P. (Landvik i in. 1987), zatem rozmiary ostatniego zlodowacenia plejstoceńskiego w tej części Ziemi Nordenskiölda były znacznie mniejsze niż się przyjmuje. Wnosząc po rozkładzie materiału eratycznego pod koniec plejstocenu i w holocenie (fig. 3), układ prądów przybrzeżnych był podobny do obecnego.

1 - Thick series of sands and sea shales with rich mollusc shells, covered with till; mouth of Linneelva, in 1980
2. - Moraines on Vardeborgsletta (30-35 m a.s.l.), in 1980

1. - Glaciofluvial levels in forefield of the Vestre Grönfjorden Glacier in 1985, at mouth of a gap that cuts ancient ice-cored moraine

2. - The terrace 8-10 m a.s.l., modelled by aeolian processes; Vorsolbukta, in 1985