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Middle and Late Quaternary evolution of Spitsbergen against global changes

ABSTRACT: Attempt of correlation of raised marine beaches and glacial episodes in West Spitsbergen is presented for the Middle and the Late Quaternary. A model of predominating Barents Sea shelf ice sheet during the Saalian and of co-existing distinct local ice domes during the Vistulian is postulated on the basis of varying land uplift. Glacial episodes in Spitsbergen are referred to the ones in continental Europe and North America. Rough prognosis of climatic trends is introduced.

Key words: Arctic, Spitsbergen, Quaternary stratigraphy, glacioisostatic rebound.

Introduction

Studies of the Quaternary evolution of Spitsbergen have been based commonly on relation of glacial sediments to raised marine beaches. The former document cooler intervals that resulted in glacier advances in Spitsbergen. The latter represent mainly climatic warmings whereas incorporated organic remains could be radiocarbon-dated (among others Blake 1961, Lindner, Marks and Pękala 1986, Forman 1990). The paper presents chronostratigraphical correlation of warmings and coolings in Spitsbergen, and therefore - evolution of this area during the Middle and the Late Quaternary. Such reconstruction is based on morphometric and age relations of raised marine beaches and glacial deposits. Thermoluminescence datings of marine and glacial sediments (Butrym *et al.* 1987, Lindner and Marks 1991) as well as amino-acid (Miller 1982, Miller *et al.* 1989) and radiocarbon (Blake 1961, Birkenmajer and Olsson 1970, Péwé *et al.* 1982, Landvik, Mangerud and Salvigsen 1982, Kłysz *et al.* 1988, Forman 1989, Salvigsen *et al.* 1990) datings of marine sediments were especially useful. Informal stratigraphical terms, introduced earlier (Lindner, Marks and Pękala 1983, 1984) and derived from local geographical names, are consequently used in this paper.

The paper is based on the authors' studies, supplemented with results from other areas (*cf.* Figs 1 and 2).

Middle Pleistocene

The **Torellkjegla Interglacial** (Holsteinian) is found at present to be the earliest Quaternary interval, sediments of which have been identified in Spitsbergen. It is

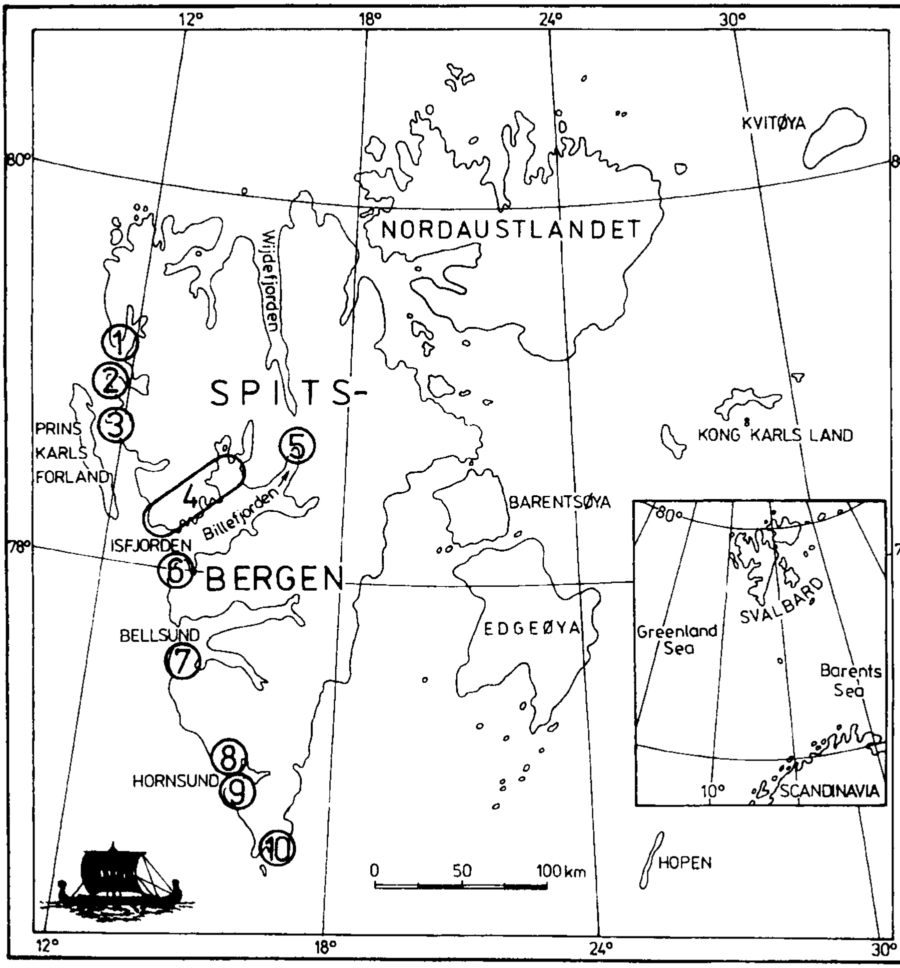

Fig. 1. Location of described regions in Spitsbergen: 1 - southwestern Haakon VII Land, 2 - northwestern Oscar II Land, 3 - western Oscar II Land, 4 - southern Oscar II Land, 5 - western Olav V Land, 6 - northwestern Nordenskiöld Land, 7 - northern Wedel Jarlsberg Land, 8 - southern Wedel Jarlsberg Land, 9 - northwestern Sörkapp Land, 10 - southern Sörkapp Land

represented by marine clays to the north of Hornsund, TL-dated at 383-413 ka (Lindner, Marks and Pękala 1983, 1984, 1986, 1987, Lindner and Marks 1993a). The Torellkjegla Interglacial is to be correlated with the Holstein Interglacial *sensu lato* in continental Europe.

The **Wedel Jarlsberg Land Glaciation** (Saalian) is represented in Spitsbergen both by terrestrial and marine deposits. Terrestrial glacial deposits to the north of Hornsund are composed of two glaciotectonically deformed tills, separated with glaciofluvial sands and gravels. These sediments were TL-dated: the older till at 313-284 ka, whereas sands and gravels at 222-190 ka, and the younger till - at 189 ka (Lindner, Marks and Pękala 1986, Lindner and Marks 1993a). Presence of the Wedel Jarlsberg Land Glaciation is also indicated by glacial sediments to the south of Hornsund, TL-dated at 217 ka (Butrym *et al.* 1987, Lindner and Marks 1993a). Time interval between these two main advances of the Wedel Jarlsberg Land Glaciation in the Bellsund area is represented by marine clays, TL-dated at 181 ka (Pękala and Repelewska-Pękalowa 1990). A younger part of this glaciation is represented to the north of Hornsund by glaciofluvial and glacial sediments, TL-dated at 143-161 ka (Marks and Pękala 1986, Lindner and Marks 1993a), and to the south of Hornsund - by a till, TL-dated at 141 ka (Butrym *et al.* 1987). In the Bellsund region there are presumably two tills of the Wedel Jarlsberg Land Glaciation; they are TL-dated at 156 ka and 130 ka (Pękala and Repelewska-Pękalowa 1990, Lindner and Marks 1991). In Bröggerhalvöya this glaciation is probably represented by the oldest till of the so-called episode C, amino-acid-dated at 130-290 ka (Miller *et al.* 1989).

Warmer intervals during the Wedel Jarlsberg Land Glaciation favoured development of the highest raised marine beaches in ice-free zones. Such questionable beaches occur at 220-230, 200-205, 180-190 and 100-120 m a.s.l. to the north of Hornsund. Sediments of the lowest beach were TL-dated at 163 ka (Pękala 1989, Lindner *et al.* 1991). Soliflucted deposits in this area were TL-dated at 143 ka (Marks and Pękala 1986, Lindner and Marks 1993a). Sediments of the raised beach 65 m a.s.l. in the northern Billefjorden area were TL-dated at 166 ka (Stankowski *et al.* 1989). It seems also probable that during this glaciation, the highest marine beaches in the Bellsund area at 150-180 and 100-150 m a.s.l., the highest beach in the southern Sörkapp Land at 230-270 m a.s.l. and at Bröggerhalvöya at 80 m a.s.l. (amino-acid-dated at 130-290 ka by Forman and Miller, 1984) were formed.

Late Pleistocene

The **Bogstranda Interglacial** (Eemian) to the north of Hornsund is represented by remains of fossil flora, younger than 143 ka (Marks and Pękala 1986, Lindner and Marks 1993a). Presence of this interglacial in the northern Billefjorden is indicated by subtill lacustrine sands and silts, TL-dated at 119 ka (Kłysz *et al.* 1988, 1989). Mollusc shells from marine sediments in the Kapp Ekholm area were ascribed on amino-acid dating to this interglacial and indicate warmer conditions than the present ones (Mangerud and Svendsen 1990). Glaciomarine clays, silts and sands to the south of Bellsund correspond to this interglacial; they were TL-dated at 102 ka and underlain by a bipartite till of the Wedel Jarlsberg Land Glaciation (Pękala and Repelewska-Pękalowa 1990, Lindner and Marks 1991). Sands and gravels of the raised marine beach 70-80 m a.s.l. in the same area were TL-dated at 127-98 ka (Reder 1990). The raised marine beach 60-75 m a.s.l. at Bröggerhalvöya, amino-acid-dated at over 130 ka (Forman and Miller 1984), was presumably formed at this time.

The **Sörkapp Land Glaciation** (Vistulian) is characterized in Spitsbergen by several glacial advances, separated with warmer intervals when the middle raised marine beaches were formed (Troitsky *et al.* 1979, Lindner, Marks and Pękala 1983, 1984, 1986, 1987, Kłysz *et al.* 1988, 1989, Lindner and Marks 1991, 1993a). Due to prolonged intermediate conditions in a sea, glaciers reached their maximum extents presumably during the early stades of this glaciation (*cf.* Larsen *et al.* 1991), when the ice margin occurred at a sea-shelf edge (Landvik *et al.* 1992); such opinion is however contradicted by lack of ice-rafted debris in the Fram Strait (*cf.* Hebbeln 1992).

Till of the first glacial episode in the northern Billefjorden area was TL-dated at 87 ka (Kłysz *et al.* 1988, 1989). The earliest glacial episode (stade?) during this glaciation is represented to the south of Hornsund by a till in substrate of the raised marine beaches 42-56 and 30-38 m a.s.l., TL- dated at 87-88 ka (Butrym *et al.* 1987, Lindner and Marks 1993a). This glacial episode occurred to the south of Bellsund before 105 ka (Landvik *et al.* 1992).

The second glacial episode of this glaciation is represented to the north of Hornsund by a till, TL-dated at 73 ka (Lindner, Marks and Pękala 1986, 1987, Lindner and Marks 1993a). Incomplete zeroing during deposition (Pękala *et al.* 1985), resulted presumably in too high the TL-age of this till. This glacial episode is represented in Kaffiöyra by a till, the age of which was estimated at about 70 ka (Niewiarowski, Pazdur and Sinkiewicz 1993). Similar age is also ascribed to a till in northwestern Spitsbergen (Miller *et al.* 1989) and a local glacier advance to the south of Bellsund started at about 90 ka (Landvik *et al.* 1992).

The younger warming was named the Older Interstade in the northern Billefjorden area. Intertill and subtill sediments were TL-dated at 60-55 ka there, but during this interval the raised marine beaches 70-75, 60-65 and 50-55 m a.s.l. were formed (Kłysz *et al.* 1988, 1989). This warming stade is represented to the south of Hornsund by sediments of the raised marine beach 15-18 m a.s.l., TL-dated at 63 ka (Butrym *et al.* 1987, Lindner and Marks 1993a). The beach 50-60 m a.s.l. was formed to the north of Hornsund at this time; its sediments were TL-dated at 56 ka (Pękala 1989, Lindner *et al.* 1991). In these sediments, TL-dated at another place at 61 ka (Lindner *et al.* 1991), the beach 40-46 m a.s.l. was presumably incised.

The third glacial episode is well documented in Spitsbergen, being dated by Mangerud and Svendsen (1992) to 50-75 ka and also indicated by peak of ice-rafted debris in the Fram Strait (Hebbeln 1992). Glaciers of this stade presumably delimit maximum extent of the Sörkapp Land Glaciation (*cf.* Boulton 1979, Troitsky *et al.* 1979, Lindner, Marks and Pękala 1983, 1987, Kłysz *et al.* 1988, 1989). To the south of Hornsund this episode was named the Lisbetdalen Stage; its coresponding glacial sediments were TL-dated at 47-41 ka (Butrym *et al.* 1987, Lindner and Marks 1993a). The so-called Middle Würm till to the south of Bellsund was TL-dated at 55-59 ka (*cf.* Troitsky *et al.* 1979); it is overlain with glaciofluvial sediments, TL-dated at 43-45 ka (Pękala and Repelewska-Pękalowa 1990, Reder 1990, Lindner and Marks 1991). This glacial episode was defined to the north of Billefjorden as the Petuniabukta-Adolfbukta Stage (*cf.* Kłysz *et al.* 1988, 1989) and correlated to the Billefjorden Stage in the Kapp Ekholm section (*cf.* Mangerud and Salvigsen 1984, Mangerud and Svendsen 1990b). At the northern coast of Billefjorden this episode is represented by a till, TL-dated at 46-53 ka (Kłysz *et al.* 1988, 1989), whereas in the Kapp Ekholm section by a till, TL-datings of which suggest a younger age than 70 ka or 47 ka (Lavrushin 1969, Troitsky *et al.* 1979), whereas radiocarbon datings - less than 41.7 ka and more than 33 ka (Troitsky *et al.* 1979), or more than 46 ka (Mangerud and Salvigsen 1984). According to Stankowski *et al.* (1989) this glacial episode occurred at 35-45 ka.

Successive warming was ascribed in the southern Bellsund area to the Late Würm; it is indicated by intertill marine sediments, radiocarbon-dated at 30-32 ka (Troitsky *et al.* 1979). This warming in the northern Billefjorden is represented by sediments of the Younger Interstade within the last Pleistocene glaciation and by the raised marine beach 40-45 m a.s.l. (Kłysz *et al.* 1988, 1989). In the Kapp Ekholm section marine sediments of this interval were radiocarbon-dated at over 33 ka (Lavrushin 1969, Troitsky *et al.* 1979) and at 46 ka (Mangerud and Salvigsen 1984). Marine sediments of the beach 87 m a.s.l. to the south of Isfjorden were radiocarbon-dated at over 36.1 ka (Mangerud and Svendsen 1990a). The raised marine beach 22-25 m a.s.l. to the north of Hornsund was presumably formed at this time (Lindner *et al.* 1991).

The fourth, youngest glacial episode of the Sörkapp Land Glaciation was defined to the south of Hornsund as the Slaklidalen Stage (Butrym *et al.* 1987, Lindner, Marks and Pękala 1987, Lindner and Marks 1993a). It is represented by a till, TL-dated at 22–28 ka (Butrym *et al.* 1987). To the north of Hornsund a corresponding till was TL-dated at 29 ka (Marks and Pękala 1986), and sediments of the marine beach 16-18 m a.s.l. - at 24 ka (Lindner *et al.* 1991). A till to the south of Bellsund was TL-dated at 26 ka (*cf.* Troitsky *et al.* 1979, Pękala and Repelewska-Pękalowa 1990). This glacial episode to the south of Isfjorden corresponds to a till, radiocarbon-dated at 12.5-17.5 ka; it forms there a substrate of marine sediments of the beach 65 m a.s.l., dated at about 11 ka (Mangerud and Svendsen 1990a). The same age is also suggested for sediments of the raised marine beach 30-33 m a.s.l. in Kaffiöyra (Niewiarowski, Pazdur and Sinkiewicz 1993). This glacial advance correlates with an ice-rafted debris peak in the Fram Strait (Hebbeln 1992). The Late Vistulian ice sheet expansion on the Barents Sea shelf started about 22 ka and ended about 15 ka (Elverhöi *et al.* 1992).

The end of the Pleistocene epoch in northwestern Spitsbergen is indicated by the raised marine beach 20 m a.s.l., radiocarbon- dated at 13.1 ka (Forman 1990). Final vanishing of the Pleistocene glaciers at Kapp Ekholm occurred at 9.7-9.9 ka (Mangerud *et al.* 1992).

Holocene

A beginning of the Holocene in Spitsbergen is indicated by climatic amelioration. Three lowest raised marine beaches (8-12, 4.5-6 and 2 m a.s.l.) to the north of Hornsund were formed and three glacier advances occurred (Lindner and Marks 1989, 1990, 1993a, Lindner *et al.* 1991). The beach 8-12 m a.s.l. was formed at 7.4-9.7 ka (radiocarbon datings of Birkenmajer and Olsson, 1970) or at 8-14 ka (TL-data of Lindner *et al.*, 1991). The beach 4.5-6 m a.s.l. was radiocarbon-dated at 1-0.8 ka and TL-dated at 3.3-4.3 ka (Lindner *et al.* 1991). The beach 2 m a.s.l. was formed during the last few dozen years when distinct supply of terrigenous material occurred to a sea from tidewater glaciers of the Little Ice Age. A preceding advance of glaciers in this area occurred at 2.5-3 ka during the Revdalen Stage (Karczewski, Kostrzewski and Marks 1981) whereas the Early Holocene glaciers advanced about 8 ka (Lindner, Marks and Pękala 1986, 1987) *i.e.* during the Grönfjorden Stage (Punning *et al.* 1982).

Glacier advances to the south of Hornsund occurred during the Little Ice Age. Earlier glacier extents during the Holocene were mostly limited to intramorainal zones - bordered by ice-cored moraines of the Little Ice Age. Sediments of the raised marine beach 9-11 m a.s.l. in southernmost Spitsbergen were radiocarbon-dated at 6.58 ka (Wójcik and Ziaja 1993).

No glacier advances during the Holocene have been recognized to the south of Bellsund. Sediments of the marine beach 18-30 m a.s.l. were radiocarbon-dated at 8.1-10.3 ka (Salvigsen 1977, Troitsky *et al.* 1979). The beach 10 m a.s.l. was formed about 6.2 ka ago whereas sediments of the beach 10 m a.s.l. were radiocarbon-dated at 4.5 ka (Landvik *et al.* 1987). The Late Holocene glacier advance occurred at about 2.5-3 ka. Subsequent warming at 1.5-0.6 ka caused not only considerable glacier retreats but also development of tundra vegetation followed by arrival of people (Dzierżek, Nitychoruk and Rzętkowska 1990a, b). The youngest glacial episode was connected with the Little Ice Age.

The Early Holocene glacier advance in the northern Billefjorden was named the Ebbadalen-Thomsondalen Stage. Its sediments were radiocarbon-dated at less than 8.9 ka and more than 7.6 ka (Kłysz *et al.* 1988). The marine beach 20-25 m a.s.l. was formed simultaneously. According to Stankowski *et al.* (1989), this glacial episode occurred presumably at about 6.5 ka. The lowest marine beaches 12-15, 5-8, 3-4 and 1-2 m a.s.l. were formed during the Middle and the Late Holocene in this area. The Late Holocene glacier advances occurred twice - during the Revdalen(?) Stage and the Little Ice Age. Sediments of the raised marine beaches

60-65 and 12-15 m a.s.l. in the Kapp Ekholm section were radiocarbon-dated at 10.03 ka and 6.5 ka respectively (Salvigsen 1984).

A till covering the marine beach 41-42 m a.s.l. at Erdmannflya was radiocarbon-dated at slightly less than 9.5 ka (Salvigsen *et al.* 1990). Mollusc shells from sediments of the marine beaches 40-42, 31-33, 19-21 and 6-8 m a.s.l. in Blomesletta were radiocarbon-dated at 9 ka, 9.8 ka, 8.9 ka and 6.1 ka respectively (Péwé *et al.* 1982). A similar age was established also for marine sediments at Erdmannflya (Salvigsen *et al.* 1990).

Traces of glacier advances corresponding to the Little Ice Age and to the glacial episode at 2.5-3 ka are noted in Kaffiöyra (Niewiarowski 1982, Niewiarowski, Pazdur and Sinkiewicz 1993). Mollusc shells from marine sediments of the beach 21-24 m a.s.l. were radiocarbon-dated at 9.8 ka (Forman 1989). All lower marine beaches in this area (18-19, 15-17, 12-14, 10-12, 7-9 and 4-6 m a.s.l.) were radiocarbon-dated at 8.6-9.2 ka. A strandflat at 2-10 m b.s.l. was formed during the Middle and the Late Holocene when a sea-level was lower than recently (Niewiarowski, Pazdur and Sinkiewicz 1993). Sediments of the beach 2 m a.s.l. are younger than 2.2 ka (Forman 1990). Marine sediments of the raised beach 4-6 m a.s.l. at Daudmannsöyra (to the north of the entrance to Isfjorden) were radiocarbon-dated at 5.6 ka (Forman 1990). Sediments of the marine beach 15 m a.s.l. in Krossfjorden were radiocarbon-dated at 10.45 ka, of the lower beaches - at 10-9.5 ka, and of the beach 4 m a.s.l. - at 0.165 ka (Forman 1990).

The two Late Holocene glacier advances in northern Spitsbergen (at about 2.7-2.1 ka and 1.3-0.4 ka) have been recognized. Each of them consisted of several smaller oscillations, however with more limited extents than during the Little Ice Age (Furrer 1992).

Glacier and sea interaction

Glacier advances and glacioisostatic rebound of Spitsbergen are the two interrelated phenomena (*e.g.* Jahn 1959, Birkenmajer 1960, Blake 1961, Hoppe *et al.* 1969, Birkenmajer and Olsson 1970, Hoppe 1972, Salvigsen 1978, 1981, 1984, 1989, Péwé *et al.* 1982, Salvigsen and Österholm 1982, Jonsson 1983, Forman, Mann and Miller 1987, Landvik *et al.* 1987, 1988, Forman 1990, Salvigsen *et al.* 1990). Glacioisostasy is strictly dependent on thickness of ice-cover and areal extent of glaciers during successive glaciations, as exampled by ice sheet development over Svalbard and its relation to the Barents Sea shelf ice sheet (*cf.* Szupryczyński 1968, Boulton 1979, Grosswald 1980, Elverhöi and Solheim 1987, Mangerud *et al.* 1987, Landvik *et al.* 1992). Correlation of altitudes and age of raised marine beaches between various parts of Spitsbergen (Fig. 2) helps determine interrelation of land uplift rate and of glaciation magnitude. A much more wide-spread glaciation of Spitsbergen in the past is indicated among others by glacial erosion forms and glacial sediments in the areas which are ice-free at present, the sea- shelf inclusive (*cf.* Ohta 1987).

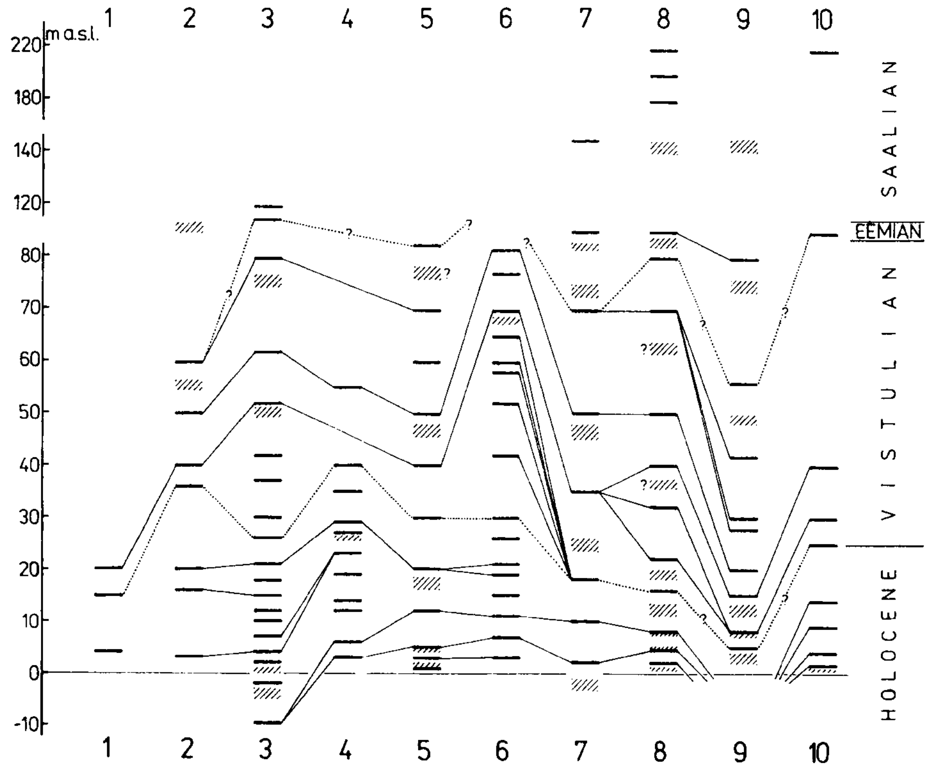

Fig. 2. Correlation of raised marine beaches (thick hatches) and glacial episodes (cross hatches) in ten described regions of Spitsbergen (*cf.* Fig. 1) after Niewiarowski (1982), Péwé *et al.* (1982), Forman and Miller (1984), Mangerud and Salvigsen (1984), Landvik, Mangerud and Salvigsen (1987), Mangerud *et al.* (1987), Forman (1989, 1990), Svendsen, Mangerud and Miller (1989), Miller *et al.* (1989), Pękala (1989), Dzierżek *et al.* (1990), Mangerud and Svendsen (1990a), Pękala and Repelewska-Pękalowa (1990), Reder (1990), Salvigsen *et al.* (1990), Lindner *et al.* (1991), Musiał, Horodyski and Kossobudzki (1991), Niewiarowski, Pazdur and Sinkiewicz (1993), Wójcik and Ziaja (1993)

The highest beaches of undoubted marine origin are observed at altitudes of 100-150 m a.s.l. (Fig. 2). Higher coastal flattenings (*e.g.* at Hornsund, and in southern Sörkapp Land - up to 230 m a.s.l.) are not necessarily marine abrasion surfaces. Based on radiocarbon, amino-acid and thermoluminescence datings, beaches of the Eemian Interglacial age seem to occur at 60-75 (Bröggerhalvöya), 110 (Kaffiöyra), 90 (Billefjorden), 70-80 (Bellsund), 80-95 (Hornsund), 56-75 (Sörkapp Land) and 100-130 (southern cape of Spitsbergen) metres a.s.l. All higher terraces had been probably formed during the Wedel Jarlsberg Land Glaciation (Saalian). Marine beaches of the Sörkapp Land Glaciation (Vistulian) age are at 32-55 (Bröggerhalvöya), 26-80 (Kaffiöyra), 30-80 (Billefjorden), 30 to over 87 (mouth of Isfjorden), 18-60 (Bellsund), 16-75 (Hornsund), 5-56 (Sörkapp Land) and 25 to over 40 m a.s.l. (southern cape of Spitsbergen). The lower marine beaches were formed during the Holocene. There are also submerged beaches near Kaffiöyra and, possibly, also along the western coast of the Sörkapp Land.

Glacioisostatic rebound of Spitsbergen was varying, being strictly connected with extents of glaciations (*cf.* Lindner, Marks and Szczęsny 1986). Quickest uplifting occurred at mouth of Isfjorden, slightly smaller at outlets of Bellsund and Hornsund (*cf.* Fig. 2). Particularly worth-mentioning is a significant uplifting of

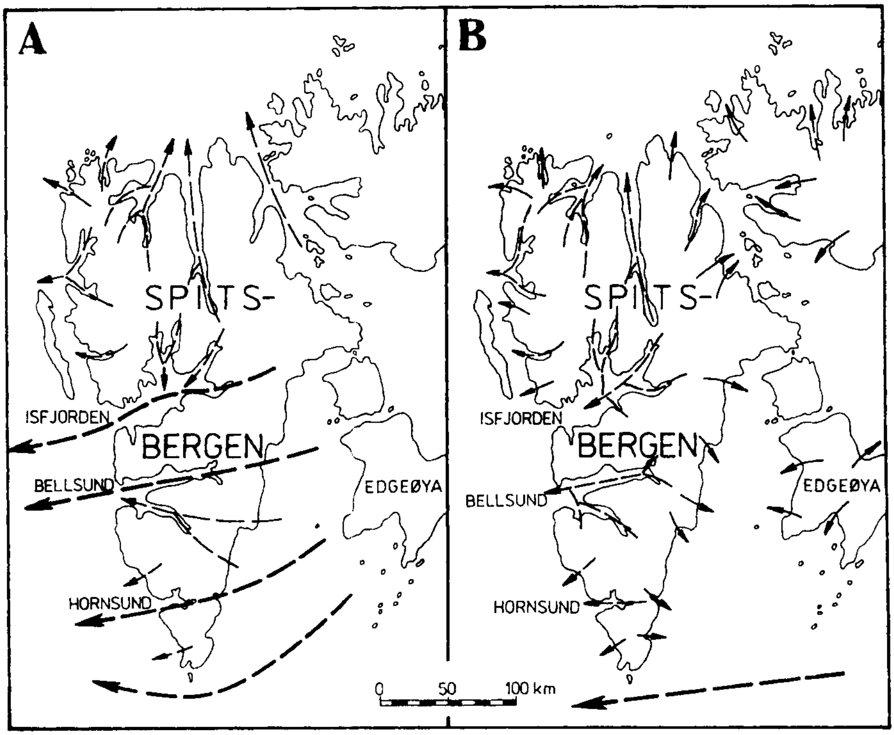

Fig. 3. Probable main (thick arrows) and secondary (thin arrows) glacial stream directions in Spitsbergen during Saalian (A) and Vistulian (B)

the southern Sörkapp Land as compared with considerably smaller values for adjacent area in the north. It was due to a thicker ice-cover just to the south of Spitsbergen and could be the evidence for ice sheet development on the Barents Sea shelf. Moraines noted on sea bottom west from outlets of the Spitsbergen fiords (*cf.* Ohta 1982), reflect maximum extent of glaciers before or after (*cf.* Mangerud *et al.* 1987, 1992, Svendsen *et al.* 1992) the Eemian Interglacial. At the same time, an ice sheet probably occupied the Barents Sea shelf, and the main glaciers of Spitsbergen (particularly the ones along the present large fiords) acted as its outlet glacial streams (Fig. 3A). Local ice domes existed probably also at this time in Spitsbergen but played secondary role in modelling of the area. Such image corresponds well to the "minimum model" of Mangerud *et al.* (1992).

During the Late Pleistocene main outlet glacial streams from the Barents Sea ice sheet flew towards Spitsbergenbanken *i.e.* between Spitsbergen and the Bear Island (*cf.* Elverhöi *et al.* 1992). At this very time, glaciers of Spitsbergen gained

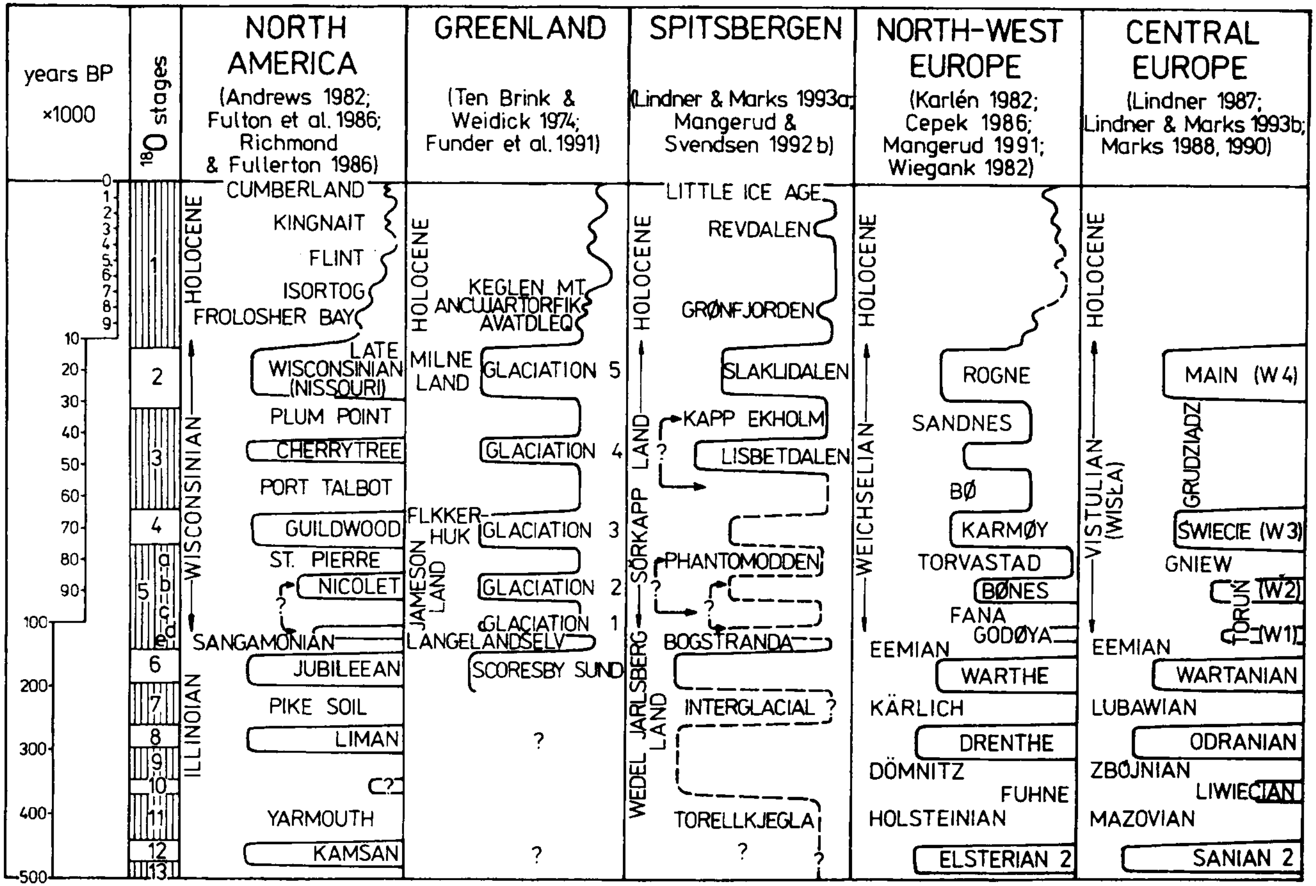

Fig. 4. Correlation of stratigraphical schemes of the Quaternary from North America, Greenland, Spitsbergen and Europe; ^{18}O stages after Shackleton and Opdyke (1973) and Martinson *et al.* (1987)

already a certain autonomy against the ice sheet in the Barents Sea shelf (Fig. 3B). The archipelago was covered with local ice domes but at least some parts of the main fiords could be occasionally ice-free (*cf.* Mangerud *et al.* 1984).

Correlation of the so-called "Late Vistulian (Weichselian) Marine Limit" in various regions of Spitsbergen seems to be of secondary significance as it reflects diversified and asynchronous glacioisostatic rebound of the archipelago.

Far-distance correlations

Middle and Late Quaternary episodes in Spitsbergen can be correlated with the ones in Greenland, Europe and North America (Fig. 4). Marine sediments of the Holstein Interglacial *sensu lato* have been best examined in mid-western Europe, being correlated with the ^{18}O stages 11-9 in deep-sea sediments (Wiegank 1982, 1987, Lindner 1984). Primarily, they were U/Th-dated at 350-370 ka (Sarnthein, Stremme and Mangini 1986). Basing on new data, this interglacial seems to represent the interval 260-440 ka (Barabas *et al.* 1988) and its sediments were TL-dated at 334-400 ka (Harasimiuk, Maruszczak and Wojtanowicz 1988).

In mid-western Europe sediments of the Saalian Glaciation have been formed during two (or three?) advances of the Scandinavian ice sheet (Fig. 4). The earlier advance (presumably bipartite) reached its maximum extent at about 290 ka whereas the younger one - at about 150 ka (Lindner 1988); therefore, their correlation with the ^{18}O stages 6 and 8 in deep-sea sediments seems possible (*cf.* Shackleton and Opdyke 1973, Martinson *et al.* 1987). Previously, maximum extent of this ice sheet was accepted to have been represented by the earlier advance stage (Lindner 1988) but new data suggest that in some areas, it corresponds to the younger advance stage (Marks 1991, Lindner and Marks 1993b).

A climatic warming between these two ice sheet advances could have been marked by glacier retreat (interglacial?) during the Wedel Jarlsberg Land Glaciation (Lindner and Marks 1993a). In the Mediterranean it is indicated by the Senegal-type marine molluscs with *Strombus bubonius*, Th/U-dated at 210 ka (Butzer 1975) and by the pre-Tyrrhenian transgression, U/Th-dated at about 180 ka (Hillaire-Marcel *et al.* 1986). Organogenic sediments of the Lubawa Interglacial in Poland were TL-dated as older than 181 ka and younger than 273 ka (Krupiński and Marks 1986). Carbonate sinters, U/Th-dated at 185-235 ka were formed in the North American caves (Harmon, Forel and Schwarcz 1977).

The Eemian Interglacial in mid-western Europe is expressed by one or two marine transgressions (Miller and Mangerud 1985, Makowska 1986). Marine sediments of that interglacial were TL- dated as younger than 217 ka and older than 97 ka in the Lower Vistula River valley (Makowska 1986) and at 105-119 ka at western coast of Norway (Hütt, Punning and Mangerud 1983); inland sediments in the latter area gave 105-130 ka (Jungner, Landvik and Mangerud 1989). Organic sediments of this interglacial were TL-dated at 108-125 ka in Poland (Karaszewski 1974) and at 97-150 ka in Finland (Forsström 1984). Raising of sea-level resulted in the Mediterranean in the older Tyrrhenian transgression, U/Th dated at 128 ka (Hillaire-Marcel *et al.* 1986); it enables to correlate this interglacial with the ^{18}O stage 5e in deep-sea sediments (Shackleton and Opdyke 1973, Martinson *et al.* 1987). A corresponding warming is named the Sangamon Interglacial in North America. Close to the polar circle in Alaska, organogenic sediments of this interglacial are younger than 149 ka (Edwards and McDowell 1991). In Greenland the Eemian Interglacial was warmer than the Holocene (Funder *et al.* 1991).

The Vistulian Glaciation in Europe is characterizd by 3 or 4 main advances of the Scandinavian ice sheet (*e.g.* Makowska 1976, Marks 1988, Mangerud 1991) and by 3 to 4 advances of mountain glaciers (*e.g.* Beaulieu, Montjuvent and Nicoud 1991, Lindner, Nitychoruk and Butrym 1993). In the case of the Scandinavian ice sheet, the first of these advances is represented in northern Poland by a bipartite till (BI=W1 and BII=W2) of the Toruń Stade (Glaciation?), TL-dated at 113-114 ka (Stańska-Prószyńska and Prószyński 1984). In the southeastern and western extent zones of the Scandinavian ice sheet, it is represented presumably by the Godöya (Till III) and Bones Till (N Sweden Till), correlated with the ^{18}O stages 5d and 5b (Mangerud 1991). It corresponds in North America to deposition of the Becancour Till by the Laurentide ice sheet (Karrow 1984).

Later warming of the Brörup(?) and Odderade interstades, previously defined in northern Poland as the Gniew Interstade and presently also as the Krastudy Interglacial (Makowska 1986), was expressed by considerable (possibly even complete) melting of the Scandinavian ice sheet about 70-90 ka (Jungner, Landvik and Mangerud 1989) during the Torvastad (Jamtland) Interstadial (Fig. 4), correlated to the ^{18}O stage 5a (Mangerud 1991). Rise of sea-level in this time, caused the younger Tyrrhenian transgressions in the Mediterranean, the last of which was U/Th-dated at about 85 ka (Hillaire-Marcel *et al.* 1986). This warming resulted in North America in considerable retreat of the Laurentide ice sheet during the St. Pierre Interstadial (Karrow 1984).

The successive cooling caused renewed advance of the Scandinavian ice sheet, as is indicated in northern Poland by a till (BIII=W3; Makowska 1976, Marks 1988), and in the western marginal zone of this ice sheet probably by the Karmöy Diamicton (Mangerud 1991). The cooling is named the Świecie Stade in the Vistula River valley; its corresponding till was TL-dated at 52-60 ka (Brykczyński, Fedorowicz and Olszak 1987, Marks 1988). Recent investigations indicate that in the Alps (Beaulieu, Monjuvent and Nicoud 1991), the Tatra Mts (Lindner, Nitychoruk and Butrym 1993) and partly also in the Polish Lowland (*cf.* Marks 1988), the glaciers of this episode delimit the maximum extent of the Vistulian Glaciation. Advance of the Laurentide ice sheet during the Guildwood Stadial in North America resulted in deposition of the Bradtville Till and the Sunnybrook Till (Karrow 1984). This glacial episode is correlated to the ^{18}O stage 4.

The successive warming in northern Poland is named the Grudziądz Interstadial (Makowska 1986, Mojski 1991); in the western marginal zone of the Scandinavian ice sheet it correlates to the Bö warming, TL-dated at 40-50 ka (Jungner *et al.*

1989, Larsen *et al.* 1991) and the Sandnes warming, the latter correlated to the Moeshoofd, Hengelo and Denekamp warmings (Mangerud 1991). Sediments of this interstade in the Lower Vistula River valley were TL-dated at 43-51 ka and radiocarbon-dated at 38 ka (Drozdowski 1980, 1986) and over 42 ka (Pazdur and Walanus 1979). This warming in North America was expressed by considerable retreat of the Laurentide ice sheet during the Port Talbot Interstadial (Karrow 1984). It is indicated in deep-sea sediments by the ^{18}O stage 3.

The youngest cooling of the last Pleistocene glaciation resulted in maximum development of the Scandinavian ice sheet during the Main Stadial, indicated in northern Poland by deposition of tills (BIV=W4 and BV; Makowska 1976, Marks 1988). In the western maximum extent zone of this ice sheet, it is presumably indicated by the Rogne Till and the Hangesund Diamicton, correlated to the ^{18}O stage 2 in deep-sea sediments (Mangerud 1991). Tills of the Main Stadial in Poland are defined as younger than 22 ka; the maximum extent of the Scandinavian ice sheet at that time occurred at about 20 ka (Kozarski 1988). Glaciers reached their maximum extents only locally in the Alps (Beaulieu, Monjuvent and Nicoud 1991), the Tatra Mts (Lindner, Nitychoruk and Butrym 1993) and not everywhere in the Polish Lowland (*cf.* Marks 1988). Maximum extent of the Laurentide ice sheet in North America occurred during the Nissouri Stadial at about 18 ka (Dyke and Prest 1987).

The Early Holocene cooling occurred during the Boreal Period in the Northern Hemisphere. The glaciers developed then in the Alps (Piottino Phase, oscillation Schlaton), in the Tatra Mts (phase IV of the Pięć Stawów Polskich Valley) and in Scandinavia (7.5-9 ka; Starkel 1977, Karlén 1982, Nesje and Dahl 1991, Dzierżek *et al.* 1987). The Cockburn advance (8-8.2 ka) appeared during the general retreat of the Laurentide ice sheet in North America (Andrews 1982), and in Greenland there were ice sheet oscillations at about 8.7-8.8 ka and 8.1-8.4 ka (Starkel 1977). Melting of glaciers occurred until the Holocene climatic optimum at about 5-8 ka.

The Late Holocene cooling resulted first as the Neoglacial glacier advance in Scandinavia about 2.8-3.2 ka (Karlén 1982), about 4.4 ka in Alaska (Calkin and Ellis 1982), and about 3 ka in the Alps (Bortenschlager 1982). The successive warming caused melting of these glaciers, which lasted until the climatic optimum of the Middle Ages (950-1200 A.D.), followed by a climatic deterioration (1200-1400 A.D.) of the Little Ice Age (Treskelen Stage?) that ended about 100 years ago. This last glacial episode coincides with increased volcanic activity that polluted the global atmosphere with dust and gases at irregular intervals. The resultant "greenhouse" effect could influence energy exchange between the Earth surface and its atmosphere (Obrębska-Starkel and Starkel 1991).

Future climatic changes

Gradual warming during the Holocene, and particularly the recent "greenhouse effect", favour rapid and strong changes in climate of the world. The data so far collected indicate (Obrębska-Starkel and Starkel 1991) a possible rise of mean yearly temperatures at high latitudes (Fig. 5). However with a low thermal background, evaporation will be low, snowfall in winter poor and sea-ice poorly developed, while parts of the Arctic seas could be even ice-free. According to Schönwiese and Diekmann (1990), as well as Obrębska-Starkel and Starkel (1991), the "greenhouse effect" had already caused the 0.7°C rise of mean temperature at the Earth's surface in the Northern Hemisphere during the last century (Fig. 5). In the Arctic, this rise was equal to 1.7°C as a mean, reaching up to 4°C in winter. During this century, it already resulted in rise of sea-level by about 10-20 cm.

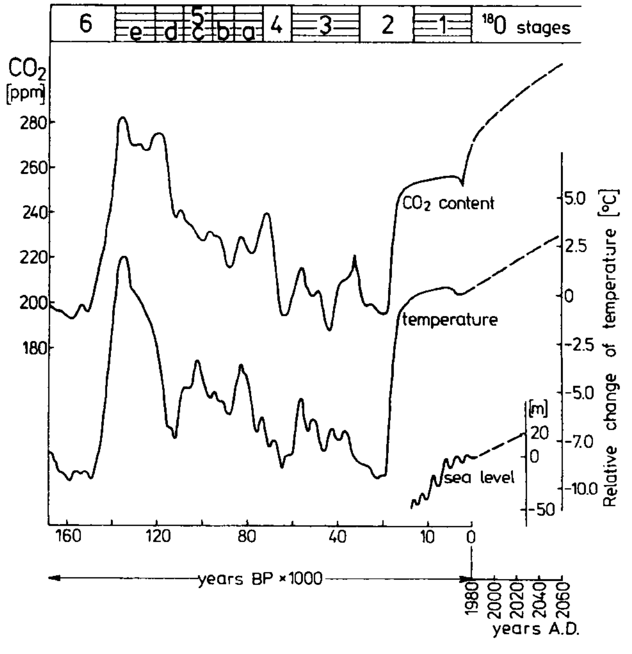

Fig. 5. Correlation of temperature and CO_2 content in atmosphere during the last 160 ka (*cf.* Florkowski 1992) and changes of sea-level in the Atlantic during the last 15 ka (*cf.* Fairbridge 1961), with prognosis until 2060 A.D. (after Zubakov and Borzenkova 1983, and Rotnicki 1992); ^{18}O stages after Martinson *et al.* (1987)

These climatic and sea-level changes play important role in environmental evolution of Spitsbergen. If the Little Ice Age was accepted as a signal of incoming new glaciation, then due to world-wide warming this signal could be considerably less distinct. The progressive warming had caused areal reduction of the land-grounded glaciers, as compared with their maximum extents during the Little Ice Age. Small glaciers with areas below 2 km^2 have been reduced most. Larger glaciers are and will be melting-out mostly at their snouts and considerably less in firn fields. Snout surfaces are decreasing by 2-3 m a year at up to 150 m a.s.l. and by 0.3 m a year at 150-250 m a.s.l. Higher up, they are either decreasing or locally, even increasing above 500 m a.s.l. (Kosiba 1960, Marcinkiewicz 1961, Szupryczyński 1968, Baranowski 1977, Jania 1988, Merta, Ozimkowski and Osuch 1990).

Melting of tidewater glaciers proceeds considerably quicker. They react more rapidly to amelioration of climatic conditions, caused by increasing water temperature in the North Atlantic, amounting to 0.34°C during 1890-1933 period (Szupryczyński 1968). Increasing temperature of surficial marine waters around Spitsbergen, and particularly along its western shores, will result in reduction of winter drift and fast ice in the fiords. Warmer and warmer waters in summer will heat a lower part of the atmosphere, causing increased and more frequent rainfalls, and accelerating melting of the lowest (frontal) parts of glaciers.

Accelerated retreat of Spitsbergen glaciers would result in increasing rates of glacioisostatic movements, however an interplay of these movements and a rising world-wide sea-level would diminish their topographic effect.

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Streszczenie

Na podstawie zespołu wyniesionych tarasów morskich i osadów lodowcowych w 10 szczegółowo zbadanych rejonach zachodniego Spitsbergenu (fig. 1), przedstawiono próbę korelacji epizodów glacjalnych i zmian poziomu morza w środkowym i młodszym czwartorzędzie. Stwierdzono zróżnicowane tempo wypiętrzania lądu (*por.* fig. 2), będące efektem zmieniającego się obciążenia przez narastające masy lodu lodowcowego na Spitsbergenie i na szelfie Morza Barentsa. Intensywniejsze wypiętrzanie lądu w rejonie wielkich fiordów spitsbergeńskich (przede wszystkim Isfiordu, w mniejszym stopniu Bellsundu i Hornsundu) oraz zachowane w ich obrębie ślady licznych epizodów lodowcowych świadczą, że w czasie zlodowacenia Saalian lądolód szelfu Morza Barentsa osiągnął znaczne rozmiary, a lodowce płynące wzdłuż wspomnianych fiordów miały charakter strumieni wyprowadzających z tego lądolodu (fig. 3A). Istniejące zapewne wówczas na Spitsbergenie lokalne ośrodki rozpływania się mas lodowych odgrywały jedynie drugorzędną rolę w tym generalnym układzie strumieni lodowych. Natomiast miały one zasadnicze znaczenie podczas zlodowacenia Wisły wobec istniejącego wtedy prawdopodobnie innego układu strumieni wyprowadzających w obrębie lądolodu szelfu Barentsa (fig. 3B).

Przedstawiono korelację głównych epizodów lodowcowych środkowego i młodszego czwartorzędu Spitsbergenu oraz Grenlandii, Europy i Ameryki Północnej (fig. 4). Naturalny rytm zlodowaceń i transgresji morskich młodszego plejstocenu i holocenu uległ w ostatnich kilkudziesięciu latach wyraźnemu zaburzeniu wskutek coraz bardziej znaczącego efektu cieplarnianego (fig. 5). Dzięki niemu transgresja lodowców Małej Epoki Lodowej została raptownie zatrzymana, a wzmożone ogólnoświatowe topnienie lodu zaznaczyło się podniesieniem poziomu morza.

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