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Holocene raised-beach ridges and sea-ice-pushed boulders on the Kola Peninsula, northwest Russia: indicators of climatic change

Jakob J. Møller,[1]* Vladimir Y. Yevzerov,[2] Vasili V. Kolka[2] and Geoffrey D. Corner[3]

([1]Geology Department, Tromsø Museum, University of Tromsø, N-9037 Tromsø, Norway; [2]Institute of Geology, Kola Science Centre, RAS, 184200 Apatity, Russia; [3]Department of Geology, University of Tromsø, N-9037 Tromsø, Norway)

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Abstract: The primary aim of this paper is to describe and discuss the palaeoclimatic significance of mid- to late-Holocene fields of raised-beach ridges at Matalaniemi and sea-ice-pushed boulders at Kutovaya Bay on the Kola Peninsula. These beach features are interpreted as indicating at least 12 periods of stormy conditions alternating with calmer periods of relatively low sea-surface temperature since about 8000 cal. BP. A consistent chronology of climate change is difficult to establish due to considerable uncertainties attributed to local beach processes and relative sea-level displacements. A tentative interpolated chronology is suggested. At present, terrace formation at Matalaniemi and the absence of sea ice at Kutovaya Bay indicate an intermediate windy and mild type of winter climate.

Key words: Raised beach, beach ridges, sea-ice-pushed boulders, winds, storms, climatic change, Holocene, Kola Peninsula, Russia.

Introduction

In formerly glaciated coastal areas like northwest Russia and northeast Norway (Figure 1), raised beach-ridge plains are preserved due to regional glacio-isostatic recovery and beach progradation (Ramsay, 1898; Tanner, 1930; Polkanov, 1937; Larova, 1960; Sollid *et al.*, 1973; Marthinussen, 1974; Donner *et al.*, 1977; Rose, 1978; Rose and Synge, 1979; Koshechkin, 1979; Møller, 1987; Fletcher *et al.*, 1993; Snyder *et al.*, 1996; 1997; Corner *et al.*, 1999; and references therein). Although it has been customary to regard storms as the cause of beach-ridge building, little attempt has been made to correlate changes in wind climate to beach-ridge building. However, Fletcher *et al.* (1993) investigated beach-ridge plains in the Varanger area bordering northwest Russia and argued that beach-ridge complexes are proxies for cyclic periods of high storm frequency and intensity.

On a decadal to century timescale, these northern coastlines are sensitive to changes in wind climate due to oscillations of the coupled ocean-atmosphere system in the North Atlantic (Fletcher *et al.*, 1993; Jansen, 1998; Dickson *et al.*, 1999; Hodges, 2000; Wang and Ikeda, 2000). In wave-dominated shallow marine coastal areas, there is a continuous process of sediment transfer and sorting in the foreshore and shoreface due to varying input of wave energy. Critical site-specific factors, such as exposure, wave energy, coastal-plain gradient, sediment supply and calibre determine beach-ridge building and erosion processes (Møller and Sollid, 1972; Sollid *et al.*, 1973; Møller, 1987; 1995; Taylor and Stone, 1996). In sheltered fjord areas, the sea surface may freeze during very cold winters, causing shore-ice action (Chuvardinskij, 1971; Dionne, 1989; Forbes and Taylor, 1994).

In this paper, raised cobble beaches at the relatively exposed west-facing locality of Matalaniemi in Malaya Volokuvaya fjord, and raised ice-pushed boulders at the sheltered southeast-facing locality of Kutovaya Bay in Motovski fjord on the Sredni Peninsula of northwest Russia, are described and assessed with the aim of discussing mid- to late-Holocene wind-climate and sea-ice formation chronology (Figure 2).

*Author for correspondence (e-mail: jakobm@imv.uit.no)

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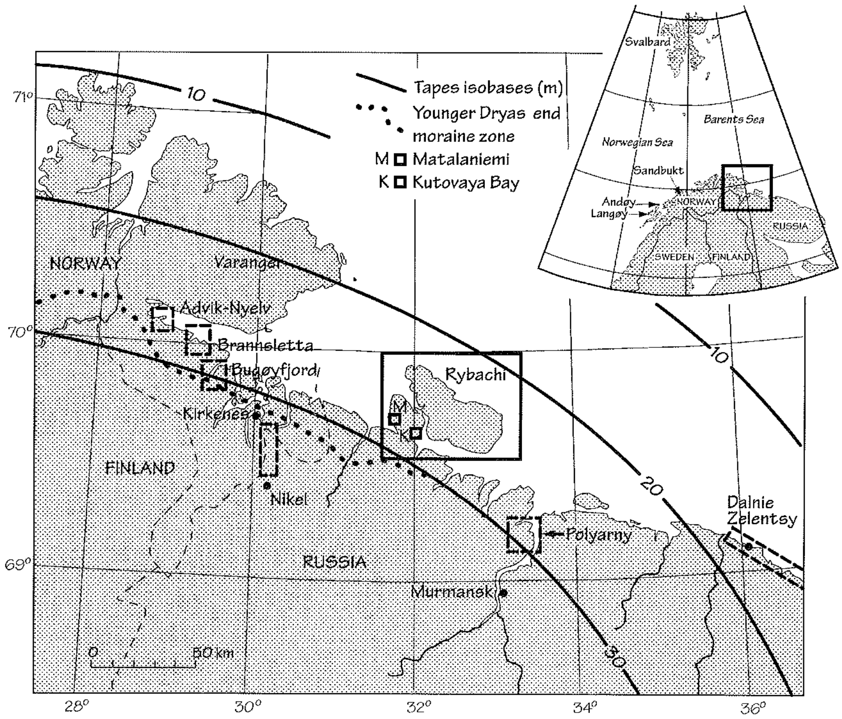

Figure 1 Location map showing the study area (framed), the position of the Younger Dryas (YD) end moraine (after Kristiansen and Sollid, 1986), and the approximate position of the Tapes shoreline/Holocene transgression maximum isobases in m a.s.l. (after Marthinussen, 1974; Rose, 1978; Møller, 1987; Sørensen *et al.*, 1987; Snyder *et al.*, 1996; Corner *et al.*, 1999). Areas investigated previously are stippled.

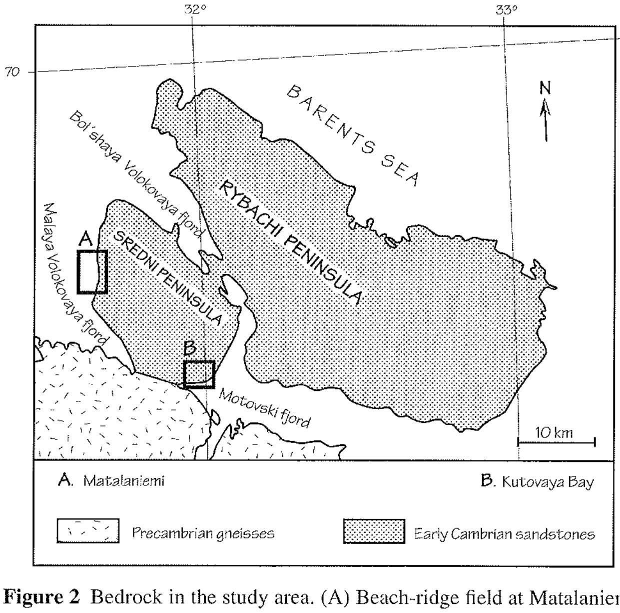

Figure 2 Bedrock in the study area. (A) Beach-ridge field at Matalaniemi. (B) Sea-ice-pushed boulders at Kutovaya Bay.

Geology and geomorphic setting

The bedrock geology of the Sredni and Rybachi Peninsulas consists of early Cambrian sandstones. In the south, at the isthmus between Malaya Volokuvaya and Motovski fjords, the Sredni Peninsula borders the Precambrian shield of the Kola Peninsula (Figure 2). Ice-rafted Precambrian gneissic boulders are strewn all over the Sredni Peninsula, especially in the lowest areas.

The Finnish pioneer geologist Veino Tanner (Tanner, 1930) suggested, based on studies of regional shorelines, that neotectonic dislocations have occurred between these two bedrock provinces during postglacial time, although this has been questioned (Marthinussen, 1974; Yevzerov *et al.*, 1998). Motovski fjord is separated from Bol'shaya and Malaya Volokovaya fjords by low isthmuses, reaching 15–20 m a.s.l. (Figure 2). According to Lyubtsov *et al.* (1989) and Siedlecka (1995), the isthmus between Bol'shaya Volokovaya and Motovski fjords, which separates the Sredni and Rybachi Peninsulas, follows an old fault zone, whereas no tectonic movements are recorded at the isthmus between Malaya Volokovaya and Motoski fjords. Thus, no postglacial dislocation has been recorded so far in the study area.

The Sredni Peninsula consists mainly of an undulating plateau, 200–300 m a.s.l., surrounded mostly by relatively steep hillsides and cliffs. At Matalaniemi and Kutovaya Bay, however, the hillsides slope gently, and at these localities a series of raised beach ridges and raised ice-pushed boulder zones, respectively, are better developed than elsewhere on the peninsula.

Beach ridges, storminess and climate transitions

Beach ridges can provide proxy records of past wind-generated wave-regime and climate conditions (Stapor, 1975; Orford, 1977; Carter, 1986). Taylor and Stone (1996) concluded that the geometry, orientation and elevation of beach-ridge sets are good indicators of past beach morphodynamic and wind-climate changes. Research efforts have focused on the relationship between beach-ridge building, mean sea level and local conditions, such as exposure, fetch, tidal range, sediment size and offshore gradient (Figure 3). Møller (1995) recorded that spilling breakers overwashing relatively recent beach ridges are the mechanism for ridge-building when onshore storm-surge waves coincide with high astronomical tides. Such a storm event, which deposited a 10 cm layer of sand on the crest and on the landward side of a beach ridge, was documented in the autumn of 1993 at Sandbukt in northern Norway (Figure 1). The foreshore and backshore there have been continuously monitored since then. During the following four winters, storm-wave run-up and overwash, which built up an additional 8 cm layer of sand, were recorded. These events demonstrate that complete beach ridges do

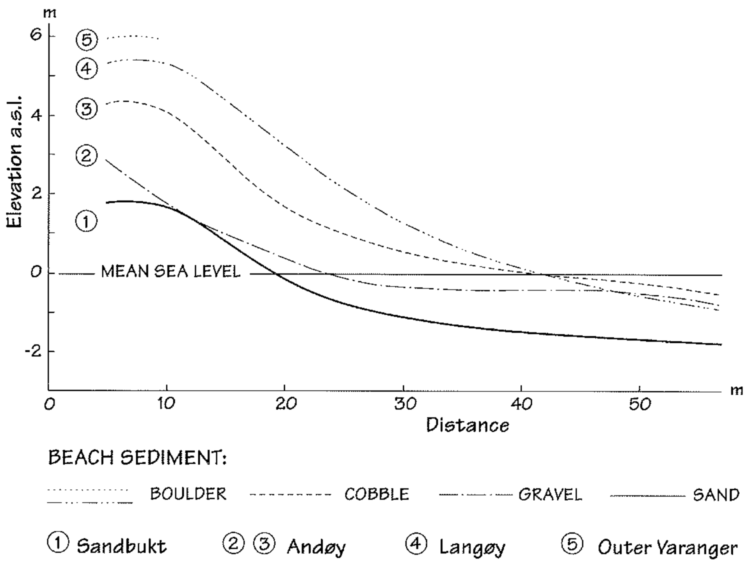

Figure 3 Dynamic beach profiles and height variations, displayed in relation to sediment size and mean sea level (after Møller, 1995 (1), Møller and Sollid, 1972 (2–4) and Fletcher *et al.*, 1993 (5)) (see Figure 1 for location).

not form during a single episodic extreme storm or during a single stormy season, but rather during a period of stormy years. Mason and Jordan (1993) claimed that raised beach-ridge complexes are proxy records of past climatic fluctuation related to storm frequency and intensity. According to Hillaire-Marcel and Fairbridge (1977), the relative uniformity of the 8000-year-old isostatically emerged beach-ridge plain on the eastern side of Hudson Bay is a palaeoclimatic record that displays major storm periods on average about every 45 years. In the Baltic Finland, Simojoki (1957), Helle (1965) and Alestalo (1979) investigated fields of raised beach ridges indicating stormy periods every 22 to 23 years and 11 to 12 years (i.e., double and single sunspot cycles).

Fletcher *et al.* (1993) interpreted raised beach-ridge sets in the Varanger area, near the border area with Russia and facing the Norwegian and Barents Seas (Figure 1), as a proxy for 50- to 500-year-long cyclic climate transitions coupled with profound shifts in the polar front and the Norwegian Atlantic Current. Over recent years, a significant body of research has discussed rapid climate changes in the Norwegian and Barents Seas in relation to variation in the North Atlantic and Arctic Oscillation (Ådlandsvik and Loeng, 1991; Delworth *et al.*, 1993; Vassmann and Keck, 1993; Rahmestorf, 1994; Kaspner *et al.*, 1995; Hurrel, 1996; Hald and Aspeli, 1997; Jansen, 1998; Dickson *et al.*, 1999; Bianchi and McCave, 1999; Hodges, 2000; Wang and Ikeda, 2000). Changes in influx of warm Atlantic waters, thermohaline and atmospheric circulation, deep ocean ventilation and freshwater discharge from Siberian and North American rivers represent a powerful climate forcing and feedback mechanism on a decadal to century timescale.

In this study, we apply the wind-climate mode hypothesis of Fletcher *et al.* (1993), involving an interpretation of the late-Holocene raised beach-ridge plain at Mataliniemi, as a proxy for past wind-climate changes. Beach ridges are interpreted as having formed during periods of beach aggradation when there was a predominantly high frequency and intensity of oceanic winter storms, while steep scarps represent periods of beach erosion, perhaps under more episodic extreme storm conditions. Accumulation terraces and gentle slopes, on the other hand, are interpreted as having formed during predominantly calm continental climate conditions. Raised boulder zones in the sheltered Kutovaya Bay formed during periods having very cold winter conditions and sea ice.

Raised-beach features at Matalaniemi

The altitude and horizontal separation of raised-beach features at Matalaniemi were precisely levelled from present sea level to an elevation of about 34 m above mean sea level (m.s.l.) along a 600 m transect, using a theodolite (Figures 4 and 5). The beach material consists mainly of rounded platy cobbles. Three major morphostratigraphic units (A–C) and five subunits are distinguished along this transect, based on the succession of prominent beach-ridge complexes, single ridges and intervening major and minor swales, terraces, steep scarps and gentle slopes. Except for the truncating mid-Holocene Tapes beach-ridge complex just southwest of the transect, all single beach ridges below the Tapes beach display a distinct continuity within a 400 m broad zone (Figure 4A and B). No bedrock is exposed within the study area.

Description

Unit A (22–34 m a.s.l.) is divided into three subunits. A1 comprises two large beach-ridges fronted by gentle seaward slopes, below which is a terrace and steep scarp. A2 is an 80 m wide, gently sloping terrace bounded seawards by a gentle slope. A3 comprises five small beach ridges with intervening minor swales.

Unit B (9–23 m a.s.l.) is divided into two subunits. B1 contains four groups of beach-ridge complexes comprising a total of 12 single ridges, separated either by a steep scarp or terraces having steep seaward scarps. The highest beach-ridge complex in this unit rises about 1.5 m higher than the landward swale. Subunit B2 contains four single beach ridges, separated by steep scarps and gentle slopes.

Unit C (3.5–11 m a.s.l.) comprises intermittent beach ridges occurring singly or in groups, separated by prominent terraces, gentle slopes or minor swales. The highest beach ridge near the top of the unit C rises about 1 m higher than the swale behind. An extensive terrace of storm-surge cobble sediments and driftwood is presently prograding at the modern foreshore-backshore transition.

Interpretation

The prominent beach-ridge complex at 33–34 m a.s.l. in unit A1 corresponds in elevation to the mid-Holocene transgressive Tapes shoreline (Tanner, 1930), dated elsewhere in northeastern Norway

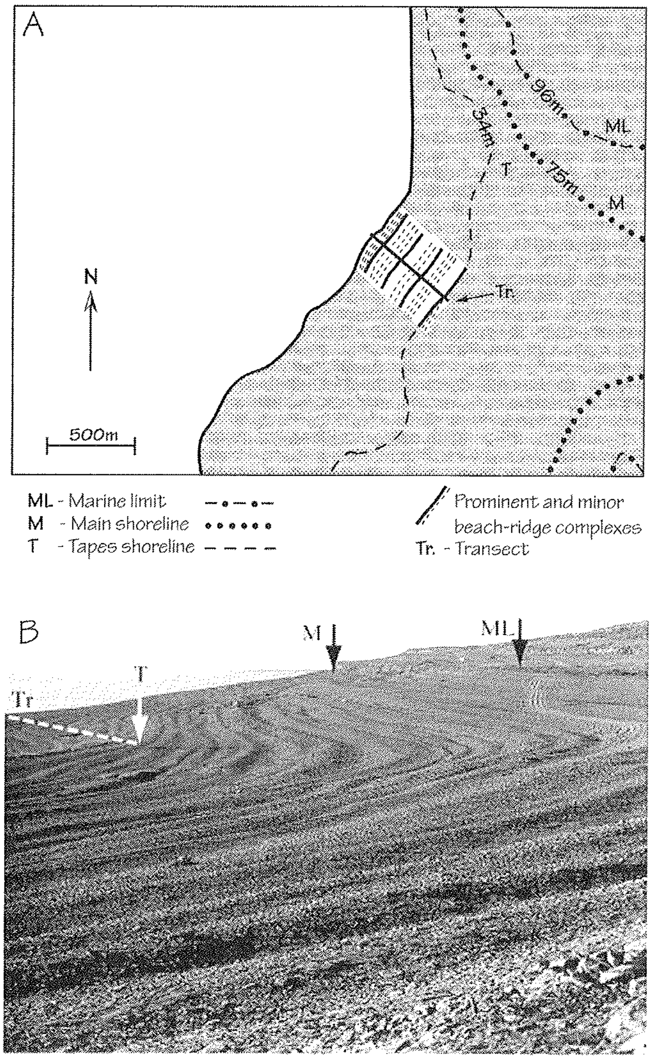

Figure 4 (A) Sketch map showing the levelled transect at Matalaniemi. (B) Photograph looking towards the northwest.

and northwest Russia to 6–7 ^{14}C ka BP. It probably includes several beach-ridge formations. Lower shorelines, on the other hand, formed during the succeeding regressive phase (Helskog, 1978; Rose, 1978; Fletcher *et al.*, 1993; Corner *et al.*, 1999; 2002). Beach-ridge formation in the study area has not been influenced by the bedrock topography.

The morphostratigraphic record below the Tapes shoreline indicates three distinct phases of beach building (units A–C, Figure 5).

The steep seaward scarp in unit A1 is interpreted as reflecting erosional stormy events. The gentle slopes and terrace (A1) and the gently sloping and exeptionally long terrace of unit A2 indicate an extensive period of predominantly calm continental wind-climate conditions. The high-frequency fields of beach ridges and swales in subunit A3 indicate an alternation between periods of repetitive oceanic stormy and continental calm wind-climates.

Unit B starts with an exceptionally large ridge rising above a landward swale, suggesting a marked change in oceanic conditions. Four prominent beach-ridge complexes in unit B1 indicate a significant increase in the frequency and intensity of oceanic storms, whereas intervening minor terraces and steep scarps indicate moderate oceanic wind-climatic conditions with episodic onshore stormy events.

Subunit B2 contains four prominent beach ridges indicating periods of high storm frequency and intensity. Their featureless gentle seaward slopes indicate a predominantly calm continental-type wind-climate, whereas the terraces and steep seaward scarps indicate an alternation between periods of moderately oceanic wind-climate interrupted by episodic onshore stormy events.

The beach-ridge complex at the the top of unit C, which is backed by a large swale, marks a change to increasing frequency and intensity of oceanic storms. Lower down, the beach morphology indicates an alternation between oceanic and continental wind-climate modes. At present sea-level, terrace building rather than beach-ridge building is occurring, indicating moderate oceanic wind-climate conditions.

Ice-pushed boulders at Kutovaya Bay

In the Motovski fjord (Figure 2), numerous boulders are recorded lying upon gravelly cobble-beach sediments (Figures 6 and 7). Particularly at Kutovaya Bay, large boulders comprising mostly ice-rafted Precambrian gneisses from the Kola Peninsula were easy to distinguish from the predominantly smaller boulders (sandstone) of early Cambrian origin from the Sredni Peninsula. No ice-pushed boulders were recorded at heights above 18 m a.s.l. in the area.

Description

Boulders were concentrated in four zones lying 7–9 m (I), 13–14 m (II), 15–16 m (III) and 18 m (IV) above mean sea level (Figures 6 and 7). The boulder zones vary in width. The lowermost zone (I) is widest and is located on a relatively gentle slope (Figure 6A). Here, boulders are spread across the crests and on the landward and seaward side of former beach ridges, over a distance of up to 15 m. Zone I rises gradually in elevation from west to east on gentle slopes (*c.* 0.07 m/m). The higher zones (II–IV), lying on steeper slopes (*c.* 0.15 m/m), tend to be narrower (Figure 6B). However, zone IV, comprising only three boulders, represents the highest limit for shore-ice action in the area rather than a boulder zone.

Several boulders have cobbles and gravel piled up beneath and in front of them and show seaward and landward dipping imbrication. At one location, cobbles and gravels were piled up in front of a large boulder, leaving a shallow oblique trench (Figure 6A).

Interpretation

In today's climate, Kutovaya Bay does not freeze. The raised boulder zones and indications of pushing of individual boulders are interpreted as representing periods of low sea-surface temperature and frequent thick sea ice in Kutovaya Bay, i.e., unusually cold winter climate.

Individual boulders, especially within zones I and II, clearly indicate landward pushing and seaward dragging (Figure 6A). This may have occurred during ice break-up in spring, particulary at times of high tide and windy weather. The fact that boulder zones I and II gradually rise in elevation from west to east (Figure 7), is related to exposure and increasing fetch, and indicate a predominant wind direction from the southeast (i.e., oblique to the shore). The rate of relative sea-level (RSL) fall within the height range 18–13 m a.s.l. (zones IV–II) and 9–7 m a.s.l. (zone I), where landscape gradient is approximately 0.15 and 0.07 m/m (Figure 7), is on the order of 190 ^{14}C yrs/m and 100 ^{14}C yrs/m , respectively (Figure 8). Thus, both narrow (II–IV) and wide (I) boulder zones at Kutowaya Bay (Figure 6, A and B) seem to have formed relatively rapidly (perhaps over years to decades). Chuvardinskij (1971) described a comparable situation of boulders strewn over sea ice and frozen to its underside in the tidal zone of Kandalaksja Bay in the White Sea. In the Antarctic, northern Greenland, the Canadian Arctic, and along other polar and subpolar coasts, sea-ice push and ice-rafting is a dominant process (Hansom and Kirk,

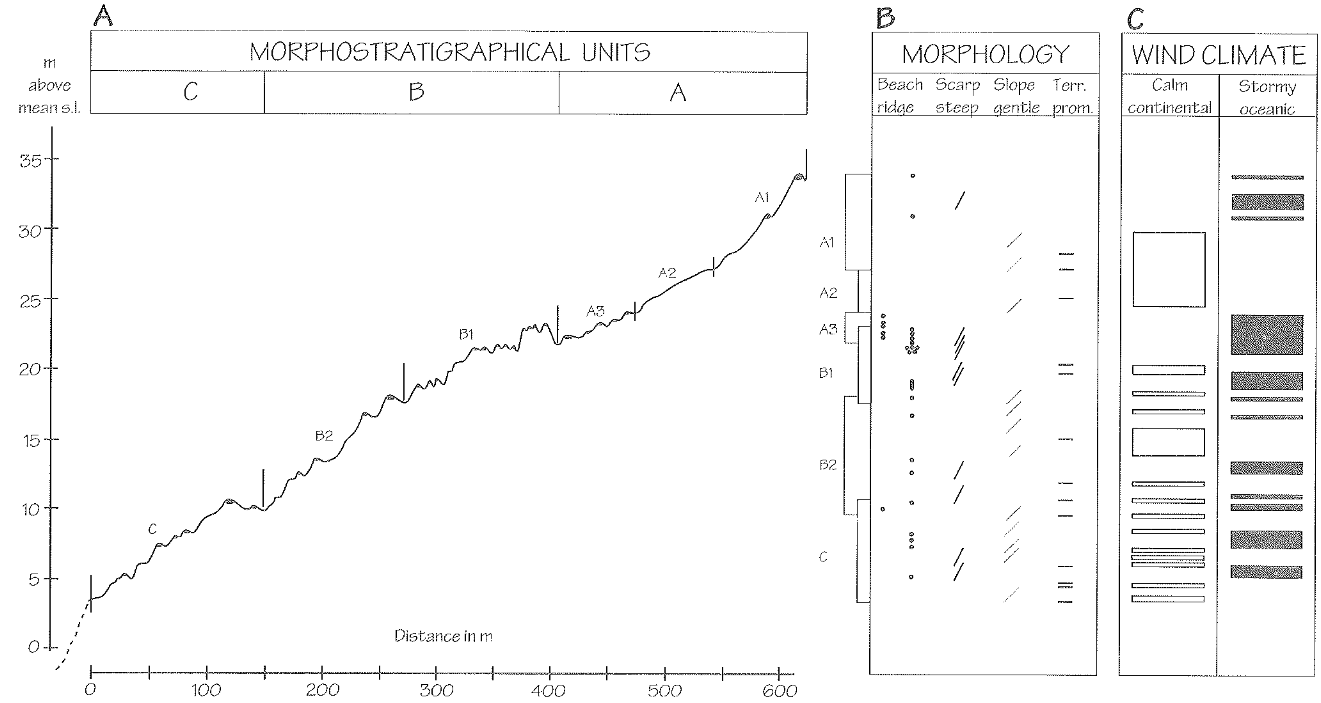

Figure 5 Morphostratigraphy (A), morphology (B), and (C) wind-climate interpretation of raised-shore features at Matalaniemi.

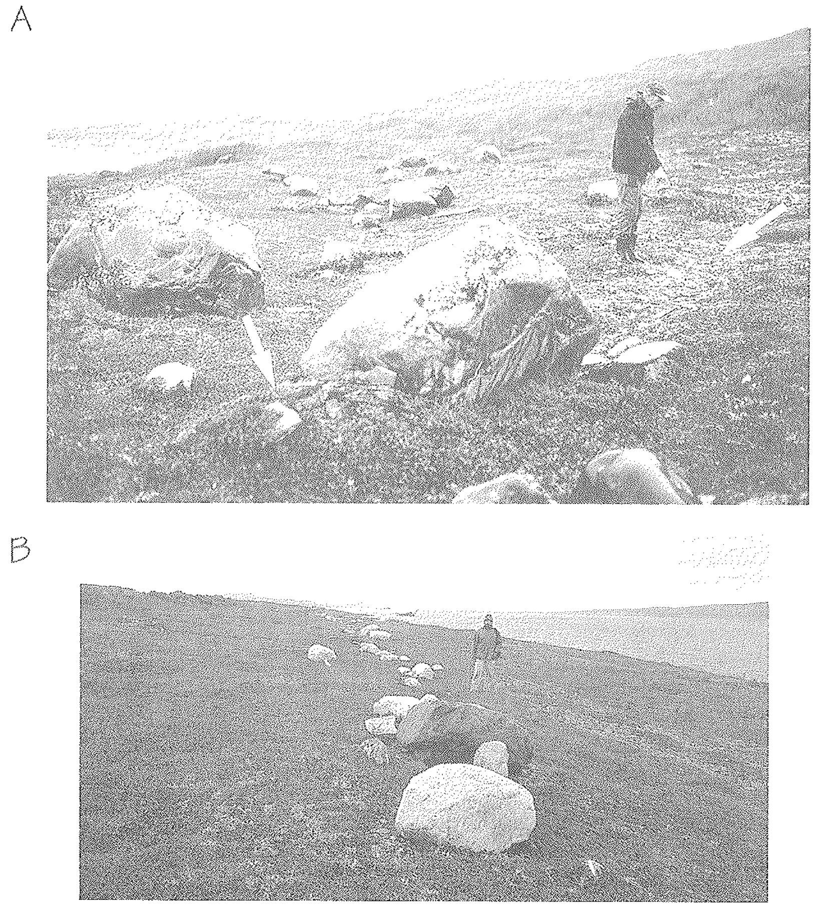

Figure 6 Sea-ice-transported boulders at Kutovaya Bay (Figure 2). (A) Boulder with gravel mound in front and elongated trench behind (arrow), in zone I, which is about 15 m wide and 7–9 m above sea level. Trench orientation indicates that the boulder was dragged obliquely seawards. (B) Boulder zone II, 13–14 m above sea level, situated due west of the area shown in Figure 7.

1989; Dionne, 1992; Forbes and Taylor, 1994; Mason *et al.*, 1995; 1997).

At present, the highest elevation of the isthmus separating Motovski fjord from Malaya and Bol'shaya Volokuvaya fjords is 15–20 m (Figure 2). During uplift, the fjords became separated, creating one sheltered and two ocean-exposed fjords. Once separated, they responded quite differently to variations in sea-surface temperature and climate changes. This explains why boulder

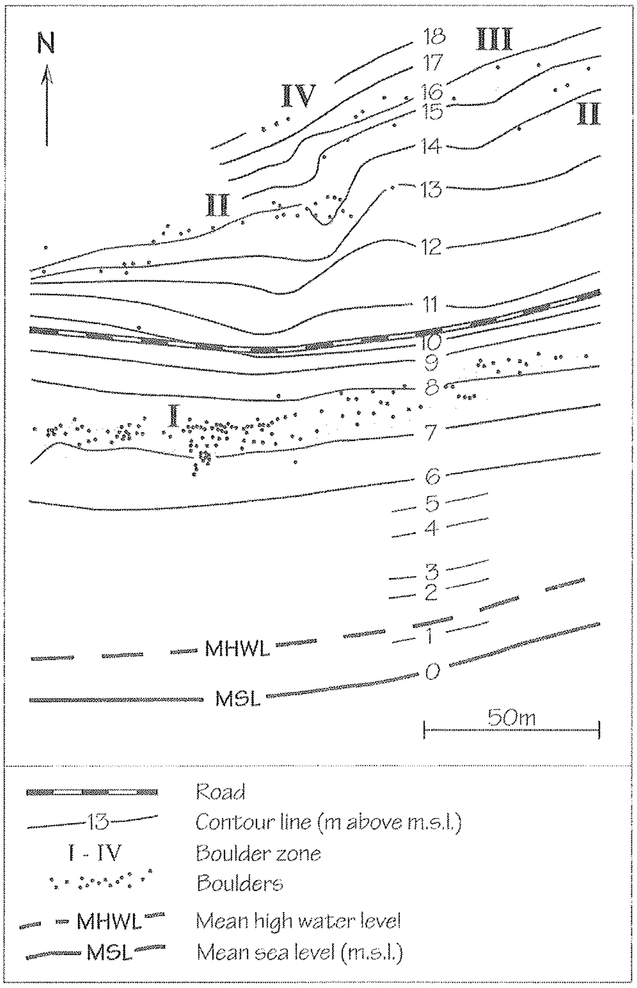

Figure 7 Topographical sketch map of raised sea-ice-pushed boulder zones at Kutovaya Bay. All single boulders were precisely levelled relative to the nearest benchmark (15.7 m above m.s.l.), about 70 m farther east.

zones in Motovski fjord occur below the level of the isthmus but not above.

Beach morphochronology and wind-climate change

An interpolated chronology for late-Holocene beach-ridge formation at Matalaniemi and ice-pushed boulder zones at Kutovaya Bay has been obtained by comparing the elevation of these features with a composite relative sea-level curve derived from relative curves from the region (Figure 8). The uncertainty inherent in this interpolated dating procedure is estimated at ±200 ^{14}C yrs.

The two sites are located at a position of about 28 m a.s.l. relative to the Tapes isobases (Figure 1). The average rate of relative sea-level fall following the Holocene transgression maximum (Tapes) has been on the order of 0.4 m/100 years (Figure 8). This limits the time available for beach-ridge formation.

When comparing raised beach ridges at the west-facing Matalaniemi and boulder zones at the east-facing sheltered Kutovaya Bay to the tentative age-scales (Figure 8), an adjustment was made to compensate for exposure and the elevation of the features relative to mean sea level during formation. Based on Møller and Sollid (1972), Fletcher *et al.* (1993), Møller (1995) and local reconnaissance studies at Sredni, an adjustment of 4 (±1) m a.s.l. is suggested for beach ridges at Matalaniemi, and 2.5 (±1) m a.s.l. for the boulder zones at Kutovaya Bay (Figure 9). The adjustment for the Tapes beach-ridge complex is greater because this major transgressive shoreline probably built to a higher level (about 6 m a.s.l.; Figure 3) over many storm periods.

At Matalaniemi (Figures 5 and 9), 12 stormy periods are recorded between *c.* 7 and *c.* 1 ^{14}C (*c.* 8 and *c.* 1 cal.) ka BP. Beach-ridge building was particularly active between 5.7 and 4.5 ^{14}C (6.3 and 5.0 cal.) ka BP. All four sea-ice-pushed boulder zones at Kutowaya Bay (Figures 7 and 9) seem to coincide with transitions in the wind regime at Matalaniemi.

Accumulation terraces and featureless gentle slopes, indicating predominantly intermediate to calm wind-climate conditions, occur in intervening periods, especially between 6.3 and 5.7 ^{14}C (7.0 and 6.3 cal.) and between 4.5 and 3.7 ^{14}C (5.0 and 4.1 cal.) ka BP.

The tentative interpolated dates of stormy and calm periods at Matalaniemi for the timespan 5.7 to 1.0 ^{14}C (6.3 to 1.1 cal.) ka BP (Figure 9) correlate fairly well with the composite history of climate transitions presented by Fletcher *et al.* (1993) from the Varanger Peninsula (Figure 1). However, a precise correlation is not possible given the dating and elevational uncertainties.

Concluding remarks

Late-Holocene raised-beach ridges and steep seaward scarps at the west-facing Matalaniemi on the Sredni Peninsula are interpreted as indicators of predominantly stormy oceanic wind-climate periods, whereas accumulation terraces and featureless gentle slopes are interpreted as having formed during intervening periods of predominantly calm continental climatic conditions. Although repetitive, beach-ridge building appears to have been particular active between approximately 5.7 and 4.5 ^{14}C (6.3 and 5.0 cal.) ka BP. A prolonged period of predominantly calm conditions appears to have preceded this phase. In the European north, major shifts in the frequency and intensity of the wind regime are probably coupled to the ocean-atmosphere circulation through the North Atlantic and Arctic Oscillation (Fletcher *et al.*, 1993; Wang and Ikeda, 2000; Hodges, 2000; and others).

At Kutovaya Bay, where partial isolation of the fjord arm during emergence, about 4.5 ^{14}C ka BP (5.0 cal. ka BP), created physiographic conditions suitable for sea-ice formation, sea-ice-pushed boulder zones indicate four periods of exceptionally cold winter climate. Even though correlation of raised shorelines is fraught with considerable uncertainty (Figures 3 and 8), these boulder zones generally appear to correspond to wind-climate changes at Matalaniemi (Figure 9; i.e., stormy – calm – stormy transitions).

Mason *et al.* (1997) claimed that late-Holocene prominent beach-ridge complexes along the coastline of Alaska facing the Chukchi Sea correlate with worldwide climatic cooling. For example, during the 'Little Ice Age' the northwest coast of Alaska witnessed frequent storm periods in repeating succession. In this context, the zonation of raised beach-ridge complexes and sea-ice-pushed boulder zones on the Sredni Peninsula are intersting for further studies.

At present, no distinct beach-ridge building is occurring at Matalaniemi. Progradation of beach sediment in front of the relatively recent terrace probably indicates that intermediate wind-climate conditions prevail. Thus, in spite of an increasing concentration of greenhouse gases in the atmosphere and suggested global warming, there is no indication yet of an onset of extreme storminess affecting this northern coast. However, the absence of sea ice in Kutovaya Bay indicates predominantly mild winter-climate conditions. A similar situation is recorded from the northeastern coast of North America (Scott and Collins, 1996).

We believe that further research on raised-beach morphology and continuous monitoring of modern beach profiles along the coast of Subarctic and Arctic northern Europe is needed to provide

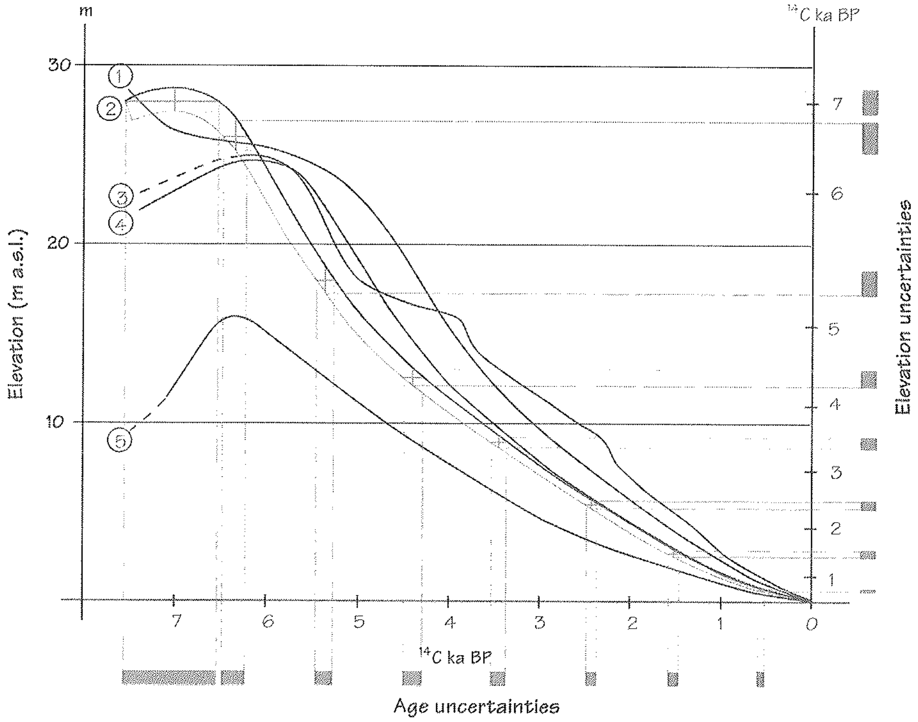

Figure 8 Relative sea-level curves from northwest Russia and northeast Norway. (1) Nikel-Kirkenes (Corner *et al.*, 1999). (2) Polyarny (Corner *et al.*, 2001). (3) Brannsletta (Fletcher *et al.*, 1993). (4) Advik-Nyelv (Helskog, 1978). (5) Dalnie Zelentsy (Snyder *et al.*, 1996) (Figure 1). The shaded zone shows a composite relative sea-level history for the Sredni region. Age and elevation uncertainties are both in the order of ±200 ^{14}C years during the timespan 6 ^{14}C ka BP to the present. For the Tapes transgression maximum, the age uncertainties are suggested to be somewhat higher.

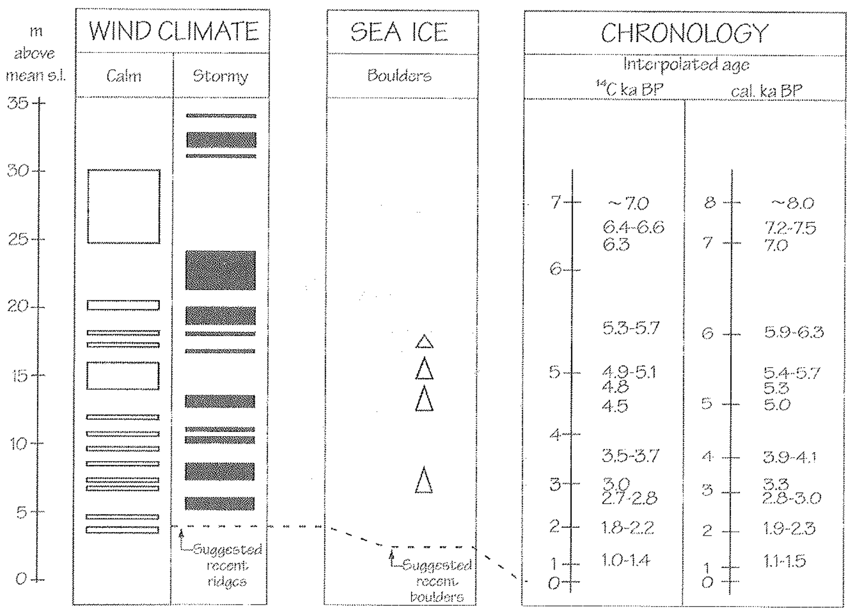

Figure 9 Correlation and tentative interpolated chronology of raised beach features at Matalaniemi and boulders at Kutovaya Bay based on a composite relative sea-level curve for the region (Figure 8).

morphostratigraphic and sedimentological data which can be compared with historical meteorological, geoecological, and oceanographical data, and used to test the significance of beaches as appropriate proxy indicators of climatic change.

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