Geo-Mar Lett (2005) 25: 190–195
DOI 10.1007/s00367-004-0200-3

ORIGINAL

S. A. Ogorodov

Human impacts on coastal stability in the Pechora Sea

Received: 30 September 2003 / Accepted: 29 April 2004 / Published online: 18 December 2004

Abstract The geoecological situation in the regions of intense industrial exploitation on the Pechora Sea coast, particularly in the Varandei area, is dangerous. Human factors intensify eolian and slope processes and thermoerosion. Coastal stability decreases and coastal retreat rates are twice as high as in regions unaffected by human activity. Industrial exploitation results in the destruction of natural environments and considerable material losses. Several housing estates and industrial constructions have already been destroyed because of coastal erosion. Damage increases each year as the cliff retreats towards the center of the Varandei settlement. The oil terminal, airport and other industrial objects are also endangered.

Introduction

The Pechora Sea is located in the southeastern part of the Barents Sea (Fig. 1). Unstable permafrost coasts distinguish the Pechora sector of the Barents Sea. Under natural conditions, the Pechora Sea coasts are relatively stable, but they are rapidly being destroyed by human activity (Solomatin 1992). The Varandei area—the most industrially developed coastal region of the Pechora Sea—is used as an example of a human impact upon the coastal system, one that reduces coastal stability. Human impact activates destructive coastal processes that considerably complicate industrial development of the coastal zone and increase expenditures for the elimination of negative environmental impacts and the regeneration of disturbed geosystems. On the other hand, natural morphodynamic processes, such as thermoabrasion, thermodenudation, thermoerosion, deflation, and ice gouging, could themselves be the cause of economic losses. Hence, an investigation of the geomorphology and dynamics of coasts in the Pechora Sea is important in terms of oil industry development of this area.

Beginning in the 1980s, the Research Laboratory of Geoecology of the North (Faculty of Geography, MSU) has carried out permanent monitoring of the coastal dynamics and associated exogenous processes in this region. New data have been obtained in the fields of geology, geomorphology, cryology, morpho- and lithodynamics of the Varandei shore (Popov et al. 1988; Novikov and Fedorova 1989; Ogorodov 2001; Sovershaev et al. 2001; Ogorodov 2003; Ogorodov et al. 2003).

In this paper, we consider the influence of human impacts on the coastal dynamics of the Varandei industrial region. We provide a detailed description of the geological-geomorphological structure, which is one of the most important factors determining the development of coastal processes. We concentrate particularly on anthropogenic disturbances of coastal relief and lithodynamical conditions. The main aim of the paper is to show how human impact has led to accelerated coastal erosion and the loss of land most suitable for utilization.

Methods

The geomorphology and coastal dynamics of the Varandei Region of the Pechora Sea were investigated using standard methods (Kostyanitsyn et al. 1975; Zenkovich and Popov 1980). Most of the data on shoreline recession was obtained by direct monitoring. Specific profiles were surveyed repeatedly using optical theodolite and the geodetic surface leveling method, with well-defined reference points. Measuring tape was used in certain cases as well. In regions unaffected by

S. A. Ogorodov
Faculty of Geography,
M.V. Lomonosov Moscow State University,
119992 Moscow, Russia
E-mail: ogorodov@aha.ru
Fax: +7-95-9328836

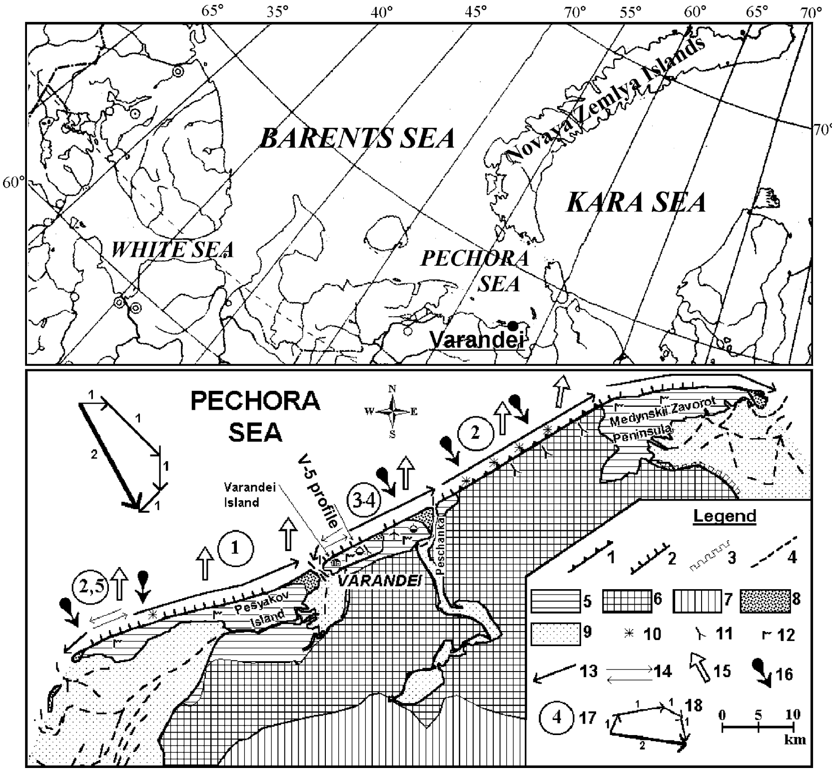

Fig. 1 Detailed coastal geomorphology map of the study area along the Pechora Sea. Key: Types of abrasion coasts: *1* with thermoabrasion or abrasion-thermodenudation cliff in dense boulder loams; *2* with wave-cut cliff in sand and peat beds with low ice content; *3* dead cliffs. Elements of bottom relief: *4* big channels of subaerial and hydrogenic origin. Types of terrestrial relief: *5* Holocene marine transgressive terrace with dune belt (up to 5–12 m a.s.l.) in the frontal part and laida (up to 2.5–3 m) in the inner part; *6* Late Pleistocene-Holocene alluvial-lacustrine terrace up to 5–15 m high with thermokarst dissection; *7* Middle Pleistocene glacial(ice)-marine denudation plain (above 20 m high) with erosional dissection; *8* Holocene free accumulative forms (beaches with well-developed profiles). Elements of morpholithodynamics: *9* areas of lagoonal accumulation within tidal flats and bays; *10* "clayey bench"; *11* regions of active gully thermoerosion; *12* regions of active deflation; *13* average multi-annual directions of sediment flows; *14* areas of bilateral sediment flows; *15* removal of fine-grained material along small discharge channels; *16* release of the rock debris and pebbles from submarine coastal slope; *17* measured average multi-annual rate of coastal bluff retreat, m/year; *18* energetic polygon plotted on the basis of hydro-meteostation Varandei data, where *(1)* rhumb component of the wave energy flow; *(2)* wave energetic resultant, 1 mm of the arrow length = 1 arbitrary unit of wave energy

economic activity, repeated leveling was based on the use of survey benchmarks. In regions with economic activity, buildings were used as reference points. In a few special cases, certain supplementary reference points were defined. Altogether, there are more than 30 reference points within the Varandei industrial zone. The coordinates of the reference points were determined through the use of GPS. In addition to direct monitoring, large-scale maps of the region (1:10,000) were used. These maps were made by various construction firms and other organizations.

Results and discussion

Two main morphogenetic complexes (Fig. 1) are distinguished within the study area. The first complex represents a marine terrace with an average height of 3–5 m formed during the Holocene transgression. The terrace occupies Pesyakov and Varandei islands (that are, in fact, barrier beaches), Peschanka River mouth and Medynskii Zavorot Peninsula (Fig. 1). Its width reaches 2–6 km. The terrace is formed of a fine sand unit underlain by peat-grass pillow. The cryogenic structure of the terrace sediments is characterized by low ice volumes of 5–10% (Novikov and Fedorova 1989). Frontal and seaward, part of the terrace is covered by an a-vandune (ridge-like dune belt) reaching 5–12 m a.s.l. (Fig. 2). At the distal parts of the barrier beaches, the

Fig. 2 Dune belt on the barrier beach separating laida from the sea, Pesyakov Island

avandune turns into a series of ancient and young barrier ridges corresponding to different stages in the evolution of barrier beaches and barrier-spits. Barrier ridges have undergone considerable reworking by eolian processes. The inner parts of the terrace behind the dune belt represent a laida (surge flood plain) up to 2.5–3 m high, with two levels corresponding to the low and high surge recurrence.

At present, under natural conditions, most of the Holocene terrace is being eroded at a rate of 0.5–2.5 m/year (Ogorodov 2001, Fig. 1). The abrasion coast (Fig. 3) has an erosion scarp cut in eolian-marine fine sands. Its height ranges from 1 to 6 m. Close to the zones of wave energy divergence, where the rate of abrasion is higher, the coastal bluff is well pronounced and remains nearly perpendicular for most of the year. In places of sediment transit, due to denudation, deflation and slope processes, the coastal slope is relatively gentle, about 20–50° . However, during years with extraordinarily strong fall storms, this slope is eroded and becomes steeper for a short period of time. Thermoabrasion does not, in fact, erode slopes of the Holocene terrace. The latter is destroyed due to relatively high average annual ground temperatures, small ice volumes and a considerable active layer thickness. Coastal erosion is determined by a combination of different factors including the deficit of coarse-grained beach-forming material (the discrepancy between the grain size and hydrodynamic conditions), the poorly developed profile of the submarine coastal slope, and the high gradient of the avandune slopes. Sediment released due to erosion is accumulated at the distal parts of the Pesyakov and Varandei islands and Medynskii Zavorot Peninsula, where the wave energy flow decreases. Here, the young beach ridges are formed (Fig. 1).

The second morphogenetic complex stretches for 90 km from the western extremity of Pesyakov Island to the eastern extremity of the Medynskii Zavorot Peninsula. It is represented by a 5–15 m high, gently rolling lacustrine-alluvial plain with numerous lakes (Fig. 1), usually referred to as the first terrace of Late Pleistocene-Holocene age (Novikov and Fedorova 1989). The origin of this terrace has long been debated (Danilov 1978), but there is still no concrete evidence for its genesis. The age of the terrace is also uncertain. Although this terrace occupies most of the territory, it reaches the coastline only between the Peschanka River and the base of the Medynskii Zavorot Peninsula. The surface of the terrace is covered with frost polygons and bogs. The base of the terrace is composed of dense ice (perhaps glacial) and marine loams and clays with inclusions (3–5%) of strongly weathered boulders, blocks, rock debris and gravel (three-fourths of the section). The layer of sands and peat represents the upper one-fourth of the terrace section. The terrace sediments include ice wedges and massive ice beds.

Where the first terrace reaches the sea, the thermoabrasion coast (Fig. 4) has a cliff cut in frozen dense boulder loams. The height of this abrasion cliff ranges from 3 to 10 m. Unlike the Holocene terrace, thermoabrasion plays the main role in coastal erosion here. At some places, typical thermoabrasion niches are present. Thermodenudation processes (thermoerosion, solifluction, slumping) considerably affect the coastal dynamics and supply sediment to the coast basement (Fig. 4). The abrasion cliff is surrounded by a narrow (10–20 m) pebbly-sandy beach that gradually turns into abraded tidal flats (Fig. 5)—the so-called ‘‘clayey bench’’. Due to the specific granulometric composition of the sediments, the amount of beach-forming material produced by thermoabrasion is insufficient. The presence of landslides and mudflows, as well as the small beach width, give evidence for relatively low coastal resistance. The average rate of thermoabrasive coastal retreat was estimated at 1.8–2.0 m/year (Novikov and Fedorova 1989).

About 300×10^3 m^3 of fine sand material are supplied to the coastal zone every year due to erosion of the Holocene terrace (Ogorodov 2001). Also, the thermoabrasion coast supplies 130×10^3 of sand, 5×10^3 of coarse

Fig. 3 Wave-cut cliff near the Varandei oil terminal

Fig. 4 Thermoabrasion coast 30 km to the east northeast of Varandei

Fig. 5 Abrasion surface of a tidal flat ("clayey bench"), 30 km to the east-northeast of Varandei

debris, $25{\times}10^3$ of peat and $120{\times}10^3$ of clay to the coastal zone. Part of the sand and all of the clay material are accumulated below the 10-m isobath. All coarse debris and part of the sand material are incorporated into alongshore drift and form beaches and beach ridges at the distal ends of barriers and spits. During eolian transport, the fine-grained fraction is partly evacuated from beaches towards the barriers and settles within the dune belt.

Coastal retreat is accompanied by the erosion of submarine coastal slopes and tidal flats due to abrasion (including thermoabrasion, Fig. 5). This results in increasing water depths. As mentioned by Mel'nikov and Spesivtsev (1995), the presence of permafrost and, hence, the thermoabrasion of the submarine coastal slope, are typical only for thermoabrasion coasts. As a rule, permafrost is absent on the submarine coastal slope of barriers and spits. In the Varandei coastal region, the submarine coastal slope is mainly composed of the same clayey sediments (with inclusions of coarse-grained material, 3–5%) that are exposed at the thermoabrasion part of the coast. A thin layer of sand overlying boulder loams is unable to protect the submarine coastal slope from abrasion during strong storms. Practically no beach-forming material is produced due to abrasion of the submarine coastal slope. Discharge and rip currents evacuate clay particles that move down slope in the form of suspension flows. The currents are restricted to numerous troughs that cut the lower part of the submarine coastal slope at depths of 5–10 m. Coarse-grained material washed out from loams is mainly accumulated in situ, forming a pebbly pavement at some sites along the submarine coastal slope. Where the shifting force of waves is sufficiently great, some fragments reach the coastline and contribute to beach formation. For instance, pebbly beaches at the western extremity of the Pesyakov Island and eastern extremity of the Varandei Island were formed through this mechanism. Coastal bluffs of these beaches are formed of fine sands. Using the method of Shuiskii (1986), we estimated the average layer of effective abrasion of the submarine coastal slope to be 0.02 m/year. It increases slightly at tidal flats. As a result, the amount of sedimentary material supplied to the coastal zone is nearly equal to the amount of sediment released during the course of coastal erosion. However, as shown above, the amount of beach-forming material in this zone is extremely low.

Active exploitation of the Varandei industrial area started in the seventies. Varandei Island was subjected to the strongest human impact. Here, the main industrial base was formed, and Novyi Varandei, a settlement for 3,500 inhabitants, was built. The well-drained dune belt of the Holocene terrace (first morphogenetic complex), composed of sand beds with low ice content, was chosen as the place for the settlement, oil terminal and storehouses, because it seemed to be more stable from the engineering-geological point of view than the surrounding swampy tundra lowland (second morphogenetic complex).

Construction of the settlement and industrial base practically at the edge of the abrasion cliff mandated repeated withdrawals of sand and sand-pebble sediments from the avandune and beach. This is absolutely dangerous for zones of wave energy divergence (Fig. 1, Popov et al. 1988), especially in zones that have been eroded before.

Within the zone of industrial exploitation, the coastal bluff and the coastal zone experienced considerable mechanical landform deformations because of transport ramps, mechanical leveling of coastal declivities and other human disturbances (Novikov and Fedorova 1989; Sovershaev et al. 2001). Uncontrolled use of transport and construction techniques including caterpillars caused degradation of soil and plant covers of the whole dune belt of Varandei Island (Fig. 6). Under conditions of deep seasonal melting, the dune belt formed of fine sands was subjected to deflation and thermoerosion. The extent and rate of these processes has been so great that in places the surface of the island is 1–3 m lower than before the period of exploitation (Fig. 7). Deflation hollows became widespread. Numerous deflation-thermoerosional gullies were

Fig. 6 Uncontrolled use of transport and construction techniques, including caterpillars, caused degradation of soil and plant covers

Fig. 7 During the period of exploitation, the surface of the barrier beach on Varandei Island sank 1–3 m due to deflation and thermoerosion

formed in the abrasion cliff. As a result, the cliff became lower, its homogeneity was disturbed, the amount of sediments supplied to the coastal zone decreased and, finally, the coasts became less stable, and the rate of retreat increased.

During the 2000 field season we measured the rates of deflation and thermoerosion at specially equipped stations (Ogorodov 2001). The averaged data from repeated measurements at more than 50 reference squares have shown that the thickness of the sand layer blown away by wind was 10–14 cm in machinery-deformed regions. At the same time, eolian accumulation took place in regions that were not affected by human activity. At the "erosional" station, we observed the formation of a big gully (up to 4 m deep) in the coastal bluff. Up to 400 m^3 of sand were removed from the gully itself and from its catchment area during the two weeks of snow melting in June.

Coastal protection in the area close to the Novyi Varandei settlement (the region of wave energy flow divergence and, correspondingly, sediment flow formation) caused a decrease in sediment supply to the adjacent areas and, hence, their erosion.

After an earth-dam and a bridge were constructed on the eastern part of Varandei Island, the height of storm surges increased. The latter is an important factor in coastal dynamics. Previously, during high surges corresponding in time with tides, water flowed partly into the branches and channels, thus lowering the surge height and decreasing its influence upon the coast.

As a result of this intensive human impact, the coastal erosion rate increased considerably in the mid to late seventies. In some years and at some sites it was up to 7–10 m/year. The rate of coastal retreat slightly decreased, down to 1.5–2 m/year, after the coastal-protection construction was built near the Novyi Varandei settlement. However, it remained high in the adjacent areas. Recent measurements during 1987–2000 (Fig. 8) have shown that the rate of coastal retreat in the region around the settlement increased and reached 3–4 m/year: that is twice as high as in the regions that are not affected by human activity.

Conclusions

Thus, this paper represents a detailed discussion of the geomorphology and modern coastal dynamics in the Varandei industrial zone of the Pechora Sea. It is shown that human impact (excavation and removal of shoreline sediment for construction; degradation of surface sediment and vegetation cover by machinery and human activities; and building of shore protection structures reduces sediment supply to coast; dams and bridges accentuate tidal storm surge levels and other disturbances) has led to a sharp change of the morpho- and litho-dynamic conditions in the region. Industrial exploitation of the territory resulted not only in destruction of the natural coastal system, but considerable material losses. Due to the rapid retreat of the abrasion cliff, several industrial and residential buildings were destroyed. With further retreat of the coastal cliff towards the center of the settlement, the losses will grow from year to year. The oil terminal, airport and other industrial objects are endangered, because the distance between the coastal bluff edge and the nearest objects is only a few meters (Fig. 3).

Active industrial exploitation of the Pechora region demands a well-thought-out strategy for territorial development and the location for new construction. The Varandei region is a negative example demonstrating the need for a well-developed, ecologically grounded approach to further exploitation of coastal regions.

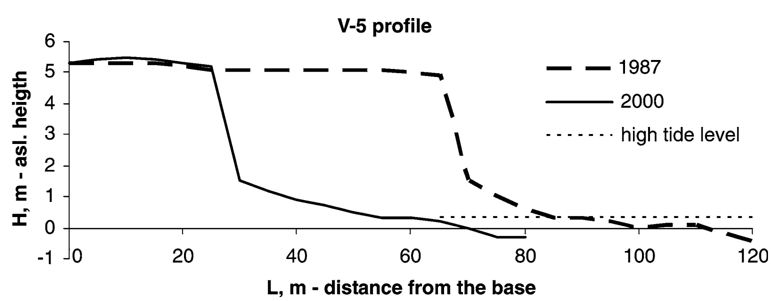

Fig. 8 Amount of shoreline retreat between 1987 and 2000 at the Varandei settlement

Acknowledgements This work was supported by the International Association for the Promotion of Co-operation with Scientists from the New Independent States of the Former Soviet Union (INTAS, Grant No. 03-55-2506).

References

Danilov ID (1978) Pleistotsen morskikh subarkticheskikh ravnin (The Pleistocene of the subarctic marine lowlands) (in Russian). Izd. MGU, Moscow, p 198

Kostyanitsyn MN, Logachev LA, Zenkovich VP (eds) (1975) Rukovodstvo po metodam issledovanii i raschetov peremeshcheniya nanosov i dinamiki beregov pri inzhenernykh izyskaniyakh. (Reference book on methods of research and calculations of sediment drift and coastal dynamics for engineering invetigations) (in Russian). Gidrometeoizdat, Moscow, p 238

Mel'nikov VP, Spesivtsev VI (1995) Inzhenerno-geologicheskie i geokriologicheskie usloviya shel'fa Barentseva i Karskogo morei (Engineering-geological and geocryological conditions of the Barents and Kara shelf) (in Russian). Nauka, Novosibirsk, p197

Novikov VN, Fedorova EV (1989) Destruction of coasts in the southeastern Barents Sea (in Russian). Vestnik MGU, series 5, geografiya, No. 1, pp 64–68

Ogorodov SA (2001) Morphology and dynamics of the Pechora Sea coasts (in Russian). In: Proceedings of the Institute of Oceanology BAN, Varna, vol 3, pp 77–86

Ogorodov SA (2003) Morphodynamic division of the Pechora Sea coastal zone (in Russian). Geomofologiya 1:72–79

Ogorodov SA, Polyakova YeI, Kaplin PA (2003) Evolution of barrier beaches in the Pechora Sea. Doklady Earth sciences, part 2. Geochem Geophys Oceanol Geogr 388:114–117

Popov BA, Sovershaev VA, Novikov VN, Biryukov VYu, Kamalov AM, Fedorova EV (1988) Coastal area of the Pechora-Kara Sea region (in Russian). In: Issledovanie ustoichivosti geosystem Severa (Investigations of the geosystems stability in the North), Izd. MGU, Moscow, pp 176–201

Shuiskii YuD (1986) Problemy issledovaniya balansa nanosov v beregovoi zone morei (Problems in investigations of sediment balance in the coastal zone of the seas) (in Russian). Gidrometeoizdat, Leningrad, p 239

Solomatin VI (ed) (1992) Geoekologiya Severa (Geoecology of the North) (in Russian). Izd. MGU, Moscow, p 270

Sovershaev VA, Ogorodov SA, Kamalov AM (2001) Human factor in development of coasts in the Varandei industrial area. In: Solomatin VI (ed) Problemy obshei I prikladnoi geoekologii Severa (Problems of general and applied geoecology of the North) (in Russian). Izd. MGU, Moscow, pp 126–134

Zenkovich VP, Popov BA (Eds) (1980) Morskaya geomorfologiya. Terminologicheskii spravochnik. Beregovaya zona: protsessy, ponyatiya, opredeleniya (Marine geomorphology. Reference Book. Coastal zone: processes, terms and definitions), Moscow, Mysl; 280pp. (in Russian)