COASTAL DYNAMICS IN THE PECHORA SEA UNDER TECHNOGENIC IMPACT

S.A. Ogorodov

Faculty of Geography, Moscow State University, Moscow, Russia, ogorodov@aha.ru

Abstract

The geoecological situation in the regions of intensive industrial exploitation on the Pechora Sea coast, particularly Varandei area, is at an almost critical state. The technogenic impact causes the intensification of eolian and slope processes, thermoerosion and thermokarst. The stability of the coasts decreases, and the rate of their retreat grows. Industrial exploitation results in not only destruction of natural environments, but also, considerable material losses. Several housing estates and industrial constructions have been already destroyed in the course of abrasive cliff retreat. The damage will grow every year following the cliff retreat towards the center of the Varandei settlement. Oil terminal, airport and other industrial objects are endangered.

Introduction

Under natural conditions, the Pechora Sea coasts are relatively stable, but become rapidly destroyed under technogenic impact (Geoekologiya... 1992). The case in point is the Varandei industrial area where expeditious measures on protection of industrial and residential buildings are necessary. Technogenic impact upon the Varandei area activates abrasion because of improper exploitation that does not consider the peculiarities of coastal relief and dynamics (Novikov and Fedorova 1989; Ogorodov 2001a,b; Sovershaev et al. 2001). Coastal erosion of the Varandei area threatens the settlement, oil terminal and airport. Therefore, it is necessary to thoroughly analyze coastal morpholithodynamic schemes before the natural environments are disturbed.

Results and discussion

Two main morphogenetic complexes (Fig. 1) are distinguished within the studied area which has an extent of 90 km from the western extremity of the Pesyakov Island to the eastern extremity of the Medynskii Zavorot Peninsula.

The first complex represents a young marine accumulative terrace with an average height of 3-5 m formed during the Holocene transgression. The terrace occupies the Pesyakov and Varandei islands (that are, in fact, barrier beaches), Peschanka River mouth and Medynskii Zavorot Peninsula. Its width reaches 2-6 km. The terrace is formed by a fine sand unit underlain by peat-grass pillow. The cryogenic structure of the terrace sediments is characterized by small ice volume of 5-10% (Novikov and Fedorova 1989). The frontal, seaward, part of the terrace is covered by an avandune (dune belt of the barrier beach) reaching 5-12 m asl (Fig. 2). At the distal parts of the barrier beaches, the avandune turns into a series of ancient and young beach ridges corresponding to different stages in evolution of barrier beaches and barriers-spits. The barrier ridges have undergone considerable reworking by eolian processes. The inner parts of the terrace behind the dune belt represent a laida up to 2.5-3 m high with two levels corresponding to the surges of low and high recurrence.

At present, under natural conditions, most part of the Holocene terrace is being eroded at a rate of 0.5-2.5 m per year (Ogorodov 2001 a,b; 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 during most part of the year. In the regions of sediment transit, due to denudation, deflation and slope processes the coastal slope is relatively gentle, about 20-50°. However, during years with extraordinary strong fall storms the 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 temperature, small ice volume and a considerable thickness of the layer of seasonal melting. Coastal erosion is determined by a combination of different factors including a deficit of coarse-grained beach-forming material (discrepancy between the grain size and hydrodynamic conditions), a not well developed profile of the submarine coastal slope, and a high gradient of the avandune slopes. Sediment material released due to erosion is accumulated at the distal parts of Pesyakov and Varandei islands and Medynskii Zavorot Peninsula, where the wave energy decreases. Here, the young beach ridges and high-water surge berms are formed (Fig. 1).

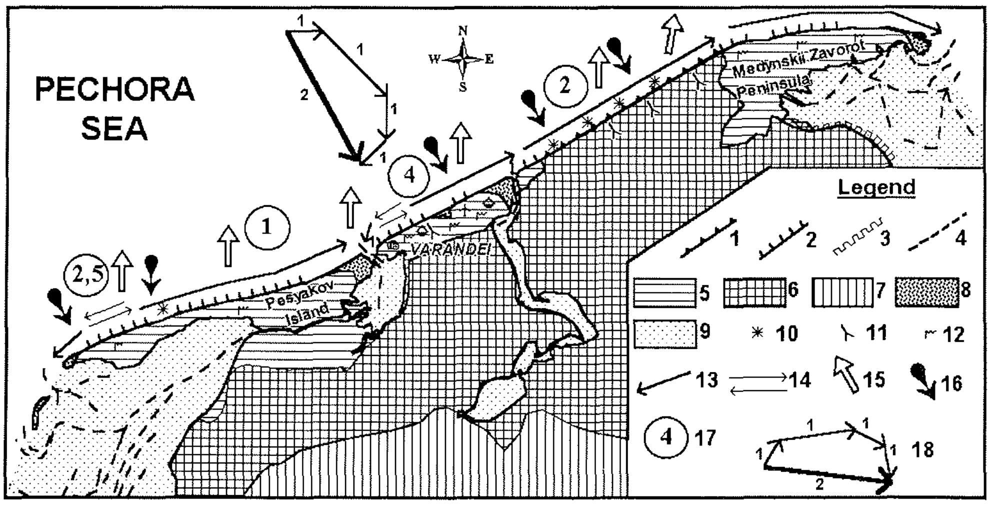

Figure 1. Morpholithodynamics of the Pechora Sea coasts near Varandei settlement. Key: Types of abrasion coasts: 1 – with thermoabrasion or abrasion-thermodenudation cliff in dense boulder loams; 2 – with wave-cut cliff in sand and peat beds with low ice content; 3 – dead cliffs. Elements of bottom relief: 4 – big channels of subaerial and hydrogenic origin. Types of terrestrial relief: 5 – marine transgressive terrace (QIV) with dune belt (up to 5-12 m asl) in the frontal part and laida (up to 2.5-3 m) in the inner part; 6 – alluvial-lacustrine terrace (QIII-IV) up to 5-15 m high with thermokarst dissection; 7 – glacial(ice?)-marine denudation plain (QII) (above 20 m high) with erosional dissection; 8 – free accumulative forms (QIV) (beaches with well-developed profile, high-water surge berms). 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 multiannual 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 multiannual rate of coastal bluff retreat, m/year; 18 – energetic polygon plotted on the base of the 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.

The second morphogenetic complex is represented by the 5-15 m high gently rolling lacustrine-alluvial (?) plain with numerous lakes (Fig. 1) usually referred to as the First terrace of the 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. Also, the age of the terrace is still uncertain. Though this terrace occupies most part 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 (terrace socle) of the terrace is composed of dense ice(glacial?)-marine loams and clays with inclusions (3-5%) of strongly weathered boulders, blocks, rock debris and gravel (¾ of the section). The layer of sands and peat represents the upper ¼ part 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 worked out in frozen dense boulder loams. The height of the abrasion cliff ranges from 3 to 10 m. Unlike the Holocene terrace, here thermoabrasion plays the main role in coastal erosion. At some places, typical thermoabrasion niches are present. Thermodenudation processes (i.e. thermoerosion, solifluction, slumping, suffosion) considerably affect the coastal dynamics supplying sedimentary material to the coast basement (Fig. 4). The abrasion cliff is surrounded by a narrow (10-20 m) pebbly-sandy beach that gradually turns into an abraded tidal flat (Fig. 5) – the so-called "clayey bench". Due to specific granulometric composition of the sediments, the amount of beach-forming material produced by thermoabrasion is insufficient. The presence of landslides and mud-flows, as well as small beach width give evidence for the relatively low resistance of the coasts. The average rate of thermoabrasion coast retreat was estimated at 1.8-2.0 m per 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 2001a). The thermoabrasion

Figure 2. Dune belt on the barrier beach separating laida from the sea, Pesyakov Island (photo of N.N. Lugovoi).

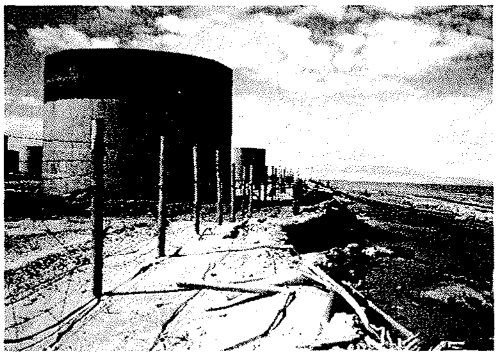

Figure 3. Wave-cut cliff near the Varandei oil terminal.

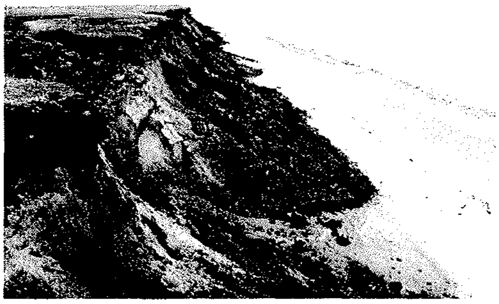

Figure 4. Thermoabrasion coast 30 km to the east-northeast of Varandei settlement (photo of N.N. Lugovoi).

coast supplies 130×10^3 of sand, 5×10^3 of coarse debris, 25×10^3 of peat and 120×10^3 of clay to the coastal zone. Parts of the sand and all clay material are accumulated below the 10 m isobath. All coarse debris and parts of the sand material are incorporated into alongshore drift and form beaches and beach ridges at the distal ends of barriers and spits. In the course of eolian transportation the fine-grained fraction is partly evacuated from the beaches towards the barriers and settles within the dune belt.

Coastal retreat is accompanied by erosion of the submarine coastal slope and the tidal flat 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, 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 by 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 sands in places 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 downslope in the form of suspension flows. The currents are restricted to numerous troughs that cut the lower part of the submarine coastal slope at a depths of 5-10 m. Coarse-grained material washed out from loams is mainly accumulated *in situ* forming a pebbly pavement at bottom swells. Where the shifting force of waves is sufficiently high, some fragments reach the coastline and take part in 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 (Fig. 6). Coastal bluffs of these beaches are formed of fine sands solely. Using the method of Shuiskii (1986), we estimated the average layer of effective abrasion of the submarine coastal slope at 0.02 m/year. It slightly increases at tidal flats. As a result, the amount of sedimentary material supplied to the coastal zone is nearly equal to the amount of sediments released in the course of coastal erosion. However, as shown above, the amount of beach-forming material in this zone is extremely low.

Figure 5. Abrasion surface of tidal flat ("clayey bench"), 30 km to the east from Varandei settlement.

Figure 6. Pebbly beach on the eastern end of the Varandei Island.

Active exploitation of the Varandei industrial area started in the seventies. Varandei Island was subjected to the strongest technogenic impact. Here, the main industrial base was formed, and Novyi Varandei settlement for 3.5 thousand inhabitants was built. The well-drained dune belt of the Holocene terrace (first morphogenetic complex) composed by sand beds with low ice content was chosen as a 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).

The construction of the settlement and industrial base that was held practically at the edge of the abrasion cliff demanded repeated withdrawals of sand and sand-pebble sediments from the avandune and beach. This is absolutely unallowable for the zones of wave energy divergence (Fig. 1) (Popov and Sovershaev 1988), especially in the zones that has been eroded before.

Within the zone of industrial exploitation, the coastal bluff and the coastal zone experienced considerable mechanical deformations of the landforms because of transport ramps, mechanical leveling of coastal declivities and other technogenic disturbances (Novikov and Fedorova 1989; Sovershaev et al. 2001). Systemless use of transport and construction technique including caterpillars caused the degradation of the soil and plant covers of the whole dune belt of Varandei Island. Under conditions of deep seasonal melting, the dune belt formed of fine sands is subjected to deflation, thermoerosion and thermokarst. The extent and rate of these processes are so great that in places the surface of the island became 1-3 m lower than before the period of exploitation (Fig. 7). Deflation hollows and thermokarst depressions became widespread. Numerous deflation-thermoerosional gullies were formed in the abrasion cliff. As a result, the cliff becomes lower, its homogeneity is disturbed, the amount of sediments supplied to the coastal zone decreases and, finally, the coasts become less stable, and the rate of their retreat grows.

During the 2000 field season we measured the rates of deflation and thermoerosion on the specially equipped stations (Ogorodov 2001b). The averaged data of repeated measurements at more than 50 reference squares have shown that the thickness of the sand layer blown away by wind was 10 to 14 cm at technogenically-deformed territories. At the same time, eolian accumulation took place at the territories that are 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.

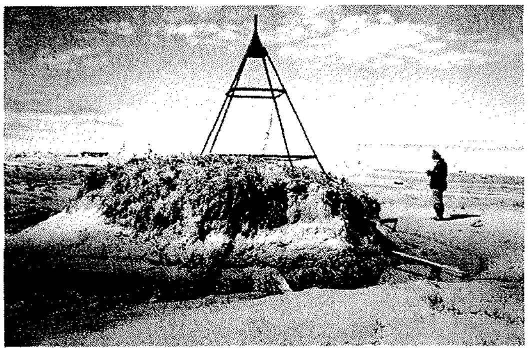

Figure 7. During the period of exploitation, the surface of barrier beach on the Varandei Island became 1-3 m lower due to deflation, thermoerosion and thermokarst.

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

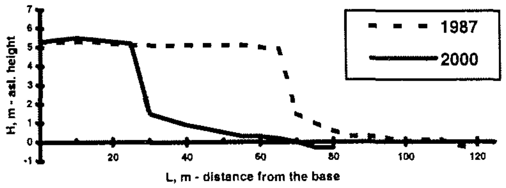

Figure 8. Dynamics of the coast near Varandei settlement.

After the earth-dam and bridge across the Promoi River branch were constructed in the eastern part of the Varandei Island, the height of the storm surges increased. The latter is an important factor of coastal dynamics. Previously, during high surges corresponding in time with tides water was partly flowing into the Promoi branch and then to the Varandeiskii Shar channel, thus lowering the surge height and decreasing its influence upon the coast.

Under existing conditions of intensive technogenic impact, the abrasion rate considerably increased in the middle-late seventies. In some years 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 protecting construction was built near Novyi Varandei settlement. However, it remained high at 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

The geoecological situation on the Varandei Island is almost critical. The industrial exploitation of the territory resulted in not only the destruction of the natural coastal system, but also in considerable material losses. Due to rapid retreat of the abrasion cliff, several industrial and residential buildings were destroyed by October 2000. With further retreat of the coastal cliff towards the center of the settlement, the losses will grow from year to year. The oil terminal is endangered, because the distance between the coastal bluff edge and the nearest oil storage tank is less than 6 m (Fig. 3).

Active industrial exploitation of the Pechora region demands a well-thought-out strategy of the territory development and the finding of proper areas for new constructions. The negative example of the Varandei region requires a well-developed ecologically grounded approach to further exploitation of coastal regions.

After many years of investigations in the Pechora Sea region, the Research Laboratory of the Geoecology of the North, MSU, has worked out a unique methodology of morpholithodynamic research and created a database on the coastal morpholithodynamics of this area that will be a basis for solving both fundamental and applied problems arising in course of coastal reclamation.

References

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

Geoekologiya Severa (Geoecology of the North), 1992. Solomatin, V.I. (ed.), Moscow, Izd. MGU, 270 pp. (in Russian).

Mel'nikov, V.P., Spesivtsev, V.I., 1995. Inzhenerno-geologicheskie i geokriologicheskie usloviya shel'fa Barentseva i Karskogo morei (Engineering-geological and geocryological conditions of the Barents and Kara shelf). Novosibirsk, Nauka, 197 pp. (in Russian).

Novikov, V.N., Fedorova, E.V., 1989. Destruction of coasts in the southeastern Barents Sea. Vestnik MGU, ser. 5, geografiya, 1, 64-68. (in Russian).

Ogorodov, S.A., 2001a. Morphology and dynamics of the Pechora Sea coasts. Proceedings of the Institute of Oceanology BAN, Varna, vol. 3, P. 77-86. (in Russian).

Ogorodov, S.A., 2001b. Functioning of the Pechora Sea coastal systems under technogenic impact. In: Sedimentologicheskie protsessy i evolyutsiya morskikh ekosistem v usloviyakh morskogo periglyatsiala (Sedimentological processes and evolution of marine ecosystems under marine periglacial conditions). Apatity, Izd. KNTs RAN, P. 82-90. (in Russian).

Popov, B.A., Sovershaev, V.A., Novikov, V.N., Biryukov, V.Yu., Kamalov, A.M., Fedorova, E.V., 1988. Coastal area of the Pechora-Kara Sea region. In: Issledovanie ustoichivosti geosystem Severa (Investigations of the geosystems stability in the North), Moscow, Izd. MGU, P. 176-201. (in Russian).

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

Sovershaev, V.A., Ogorodov, S.A., Kamalov, A.M., 2001. Technogenic factor in development of coasts in the Varandei industrial area. In: Solomatin, V.I. (ed.) Problemy obshei I prikladnoi geoekologii Severa (Problems of the general and applied geoecology of the North). Moscow, Izd. MGU, P. 126-134. (in Russian).