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Channel processes and erosion rates in the rivers of the Yamal Peninsula in western Siberia

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Abstract The variability of processes in channels and on flood plains in the valleys of the River Se-Yaha and the River Mordy-Yaha was investigated in connection with development of a natural gas field. Average rates of bank erosion and sediment accumulation in this little-known region were determined from aerial photographs and radiocarbon and dendrochronological dating. A geodynamic map has been prepared and predictions made for the next 50 years.

INTRODUCTION

The Yamal peninsula is one of the most promising regions for natural gas fields in Russia. Their development faces specific difficulties, which are usual for areas affected by permafrost: thermokarst, thermoerosion and various cryogenic slope processes, which are able to damage pipelines and other constructions. Relatively high relief features, especially slopes, are the most unstable areas under such conditions. Taking into consideration this problem, schemes for gas field development are often designed so that engineering structures are assigned to the bottoms of river valleys. On the other hand, such locations increase the danger of damage by natural deformations of the river channel. The object of the research was the determination of the pattern and rates of channel deformations of the Se-Yaha and the Mordy-Yaha rivers within the area of the Bovanenkovo gas field. The erosion of flood plain and terrace banks by the process of gradual migration of large channel forms may reach rates, which are dangerous for constructions located next to a bank. Special attention must be paid to the river reaches experiencing recent drastic changes of channel pattern or to those where such changes may soon occur. For the rivers under consideration, recent and future cut-offs of single meanders or of their groups represent the most serious problem. During relatively short periods of adjustment of the newly formed channel considerable migration usually takes place which is accompanied by bank erosion with the rates far above the long-term average. In addition, not only the rates, but also the type of the channel deformations (accumulation/erosion) change during this period.

STUDY AREA

The Yamal Peninsula is situated at the northern part of the western Siberian plain (Fig. 1). At the central-western part of the peninsula the mean annual air temperature

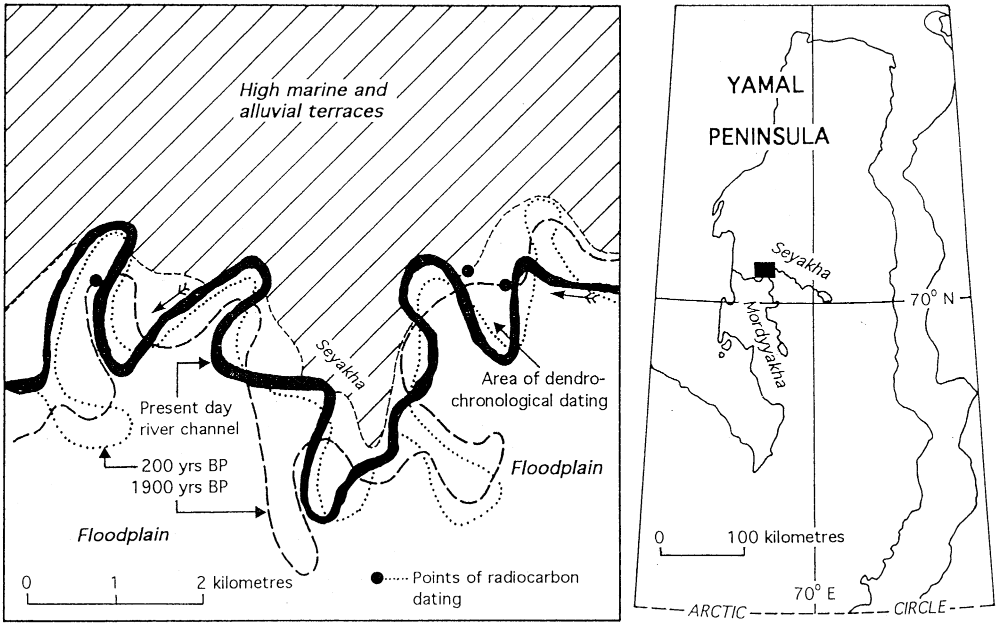

Fig. 1 Se-Yaha River meandering channel at different periods of time and location on the Yamal Peninsula.

is −8.3 °C. There are 223 days of negative temperature a year, and it leads to a deep permafrost layer. The thickness of the summer thaw layer extends 0.6-1.2 m in August-September. The runoff for the snowmelt period is 220-250 mm. Precipitation in the form of rain occurs generally in June-September, with an average of 470 rainy hours. The mean rainfall for this period is 140 mm.

The area represents a typical tundra landscape with a complex of Quaternary marine terraces with heights between 20-45 m a.m.s.l. The mainly fine-grained marine deposits contain lenses and sheets of ice with thickness up to 50 m and spatial dimensions of individual bodies up to several kilometres. Small areas are occupied by lower alluvial terraces. In the bottom of the main river of the area – the Mordy-Yaha and its right tributary the River Se-Yaha – there is a vast area of the flood plain. Its surface is flooded annually by river water to depth up to 1.5-2.0 m. The average width of the lower reaches of the main rivers near their confluence is 80-150 m.

METHODS

Difficult access and inadequate exploration of the region have necessitated the use of indirect methods in this study. The main method was the interpretation of aerial photographs of various scales in order to construct a 1:20 000 geomorphological map of the whole area of river valley bottoms within the area of the gas field (approximately 400 km^2). This scheme describes successive positions of the river channels in the past, determined from the pattern of flood plain levees and ox-bow lakes. Serious limitations of the method are created by the thermokarst development on relatively young flood plain surfaces. Thermokarst processes change the initial relief features of the fluvial flood plain.

From a preliminary interpretation of the aerial photographs, locations for sampling were determined, and several samples of peat were obtained from them during the field research in 1990-1991. Radiocarbon dating has permitted the evaluation of the long-term average rates of river bank erosion and also the age of the cut-offs according to their position on the geomorphological sequence. Several paleochannels of different ages are shown in Fig. 1.

Short-term average rates of erosion were determined by the dendrochronological method. This method, as applied to a flood- plain, is based on the assumption that certain species of vegetation are gradually replaced with other ones as the flood plain grows in width and height due to flood sedimentation.

The youngest level of the flood plain is represented by the highest parts of point bars covered with grass. The grassed flood plain on the banks of meanders is up to several tens of metres in width. The higher and more remote levels of the flood plain are covered with grass and shrubs – dwarf willow. The age of the willows clearly increases with the distance, the first tens of metres into the shrubs flood plain area varying from willow shoots to mature plants. Assuming that the rate of horizontal growth of an accumulative flood plain segment is relatively constant over the last decades, the average rate of this process can be determined by division of the distance between the shoots and the mature plants by the age of these plants. For remote sensing evaluation of the rates of bank erosion in different parts of the area, it was convenient to determine the maximum age of the grass flood plain, which is easily identified both on the aerial photographs and in the field. This age may be considered as constant for this limited area and can be determined by division of the grass flood plain width by the average rate of growth. In turn, the width of the dated grass flood plain on an accumulative bank is an excellent indicator of the rates of erosion of an opposite bank at the river reaches with relatively constant channel width. Thus, the rates of erosion determined by radiocarbon dating can be verified by evaluation of the age of the grass flood plain at a number of points.

The procedure was carried out for four profiles on the accumulative convex bank of one of the River Se-Yaha meanders (Fig. 1, Table 1). The profiles had smooth convex shapes without sharp bends, consistent with the condition of the constant rate of bank growth. The average rates are from 0.44 to 0.90 m year^{-1}, regularly increasing toward the apex of the meander. These results agree very closely with those from the

Table 1 The average rates of flood plain horizontal growth and the age of the grass flood plain (for four profiles).

Grass flood plain:		Shrubs flood plain:			Average rate of growth (m years^{-1})	Age of grass flood plain (years)
Width (m)	Height above previous level (m)	Width (m)	Height above previous level (m)	Age of willow (years)		
23.5	1.91	10.5	0.32	24	0.44	53
21.8	1.68	12.2	0.34	18	0.68	32
33.6	1.87	14.4	0.09	16	0.90	37
37.5	2.07	13.0	0.05	15	0.87	43

interpretation of the aerial photograph and radiocarbon dating for this meander. The maximum age of the grass flood plain is approximately 40 years, an average value for four profiles.

The geomorphological scheme for the territory shows the expected future position of banks which are subjected to erosion. The magnitude of erosion during the next 50 years, probable period of the gas field exploitation, was predicted by extrapolation of present rates determined by examination of the width of the young flood plain levels.

RESULTS

According to an interpretation of the aerial photographs, several generations of flood plain have been determined. The convex banks of meanders are outlined by the young grass-shrubs flood plain with an approximate age of up to 200 years. This level is characterized by distinct primary fluvial relief, with clearly identified levees and sparse ox-bow lakes.

The belts of young flood plain gradually give way to a mature grass-moss-shrubs flood plain, which forms the greatest part of meander spurs. Its age is 200-1900 years. Side by side with the fluvial relief features, there are polygonal soils with a specific microrelief and pattern identifiable on photographs. The most ancient parts of this level contain rare thermokarst lakes. The period therefore required for the formation of these lakes on the flood plain coincides with the age limit of the mature flood plain.

The next flood plain generation is situated near the bases of the meander spurs next to terraces. Devoid of the fluvial relief features, the surface of this ancient level is covered with moss and dense shrubs and is characterized by mature polygonal soils. The age of the level is more than 1900 years. One of the radiocarbon dates showed an age of 2300 years, but older ones are probable.

The main part of the valley bottoms near their confluence represents the most ancient flood plain generation. Its surface is completely reworked by thermokarst processes and has microrelief and a vegetational pattern which shows different stages of the thermokarst lakes development. Despite substantial differences in photographic image of the area, the primary fluvial origin of the whole ancient flood plain is evident from the results of drilling. Holocene deposits of mainly sandy-loam alluvium with layers of peat form united lens inserted in deposits of the Middle Pleistocene marine terrace and the Late Pleistocene fluvial terrace.

The maximum height of the flood plain is 5-6 m above low water level. The flood plain generations do not have distinct differences in their height and are characterized by low microrelief of the surface. The results of dendrochronological and radiocarbon dating permit the evaluation of the rates of the vertical growth of the flood plain. Because of annual flood sedimentation, the surface of the youngest grass flood plain grows in height at an average rate of up to 50 mm year^{-1} (36-53 mm year^{-1} for 1-4 profiles; Table 1). The lowest parts of the grass-shrubs flood plain grow at an average rates between 3-19 mm year^{-1}. The higher parts of the mature flood plain are characterized by very low rates of accumulation. Two samples of peat were taken for radiocarbon dating from different depths in a flood plain bluff in the upper part of one of meander bends: the lower sample (1.35-1.5 m beneath the surface of the flood plain) was 1800 years BP; the upper one (1.1-1.2 m) was 1430 years BP. Thus, the average rate of accumulation is not more than 0.7 mm year^{-1}. Internal areas of the ancient flood plain generations should have even lower rates of accumulation.

The rates of bank erosion are much less than 1 m year^{-1} for the majority of river reaches. The highest rates were identified for concave banks near apexes of actively migrating meanders and for reaches where recent changes of channel pattern had occurred.

The average rates of erosion of the flood plain banks at the axes of free meanders are 0.5-0.7 m year^{-1} along the lower River Se-Yaha for a 200-year period. Relatively high terrace banks at the axes of the so called "adopted" meanders retreat with almost the same rates of 0.4-0.6 m year^{-1}. This is quite unusual, because high banks seriously limit erosion rates. In the case of the Yamal rivers the reasons for this are the rapid destruction of the slopes of terrace banks by cryogenic processes and intensive thermoerosion of marine and alluvial material of the terraces. Especially high rates of thermoerosion were found where there were thick layers of buried ice in the base of such banks. Cryogenic landslides often cause specific a shape of terrace banks, with numerous concave arcs. The irregular shape of a bank in turn causes formation of large turbulent structures in the flow, which create very deep local pools of more than 20 m and thus accelerate bank erosion.

For the River Mordy-Yaha the highest rates of erosion were determined for several free meanders just below the confluence with the River Se-Yaha with rates of 1.0-1.5 m year^{-1}. Up valley, the average rates of erosion at the apexes of free meanders gradually decrease to 0.7-0.8 m year^{-1}. The maximum observed rate of erosion of the terrace bank is 0.9 m year^{-1}.

The cut-offs along the rivers are formed when single meanders reach the shape of loops with the coefficient of sinuosity more than 5-6, i.e. when the opposite sides of the bends almost touch each other. Such conditions for cut-off formation are as a rule characteristic for rivers with low erodibility of flood plain deposits and (or) with relatively low magnitude flood discharge over the flood plain surface. In this case, the main reason is that spring flood water crosses the still frozen surface of the flood plain, which, moreover, is covered with a peat layer highly resistant to erosion.

The process of the cut-offs formation is more typical for the lower River Se-Yaha, its total coefficient of sinuosity being 2.2. The three most recent cut-offs here were formed approximately 30-40; 40-50 and 70-80 years ago. The most ancient identifiable cut-off was formed 1400-1800 years ago. The cut-offs of the River Mordy-Yaha are more rare because of the lower coefficient of sinuosity of 1.6. The most recent one also occurred 30-40 years ago.

The cut-offs of single meanders cause substantial acceleration of the rate of channel deformation on a newly formed reach and adjacent channel forms. For example, the rate of migration of the free meander, which was formed 30-40 years ago due to the cut-off on the lower Se-Yaha river, was 2.5-2.7 m year^{-1}, i.e. approximately 5 times more than the average rates for this reach of the river.

Relatively recent cut-offs of meander series were determined on the lower River Se-Yaha. These features are characteristic because of the high sinuosity of the main channel and the specific relief of the flood plain. Newly formed reaches are developed according to the complex pattern of ox-bows and numerous linear depressions, which connect thermokarst lakes and their residual depressions on the surface of the flood plain. Hence newly formed channels acquire a primarily sinuous pattern and begin to adjust themselves to changed flow conditions. During the adjustment period the rates of channel deformation are much higher than those before the cut-off formation. On the River Se-Yaha the cut-off of meander sequences took place 200-250 years ago. The rates of bank erosion within newly formed meanders were up to 1.5-2.0 m year^{-1}, i.e. 3-4 times higher than the average ones for this reach. Due to high sinuosity of the new channel and high rates of bank erosion, this reach is the place where a new cut-off may occur quite soon. The width of the spur of the meander loop near the confluence with the River Pelkhatose is now 260 m. If present rates of erosion don't change during the next 50 years, the width of the spur will be only 180 m, so the possibility of a cut-off is high.

The acceleration of the process of cut-off formation in the future may occur due to human influence on the flood plain relief. In particular, construction of certain engineering structures (roads, fill for buildings, etc.) are able to create local gradients of the water surface during floods and canalize flood discharge over the flood plain surface. The most dangerous directions and points can be determined by joint analysis of the geomorphology and a model of the flood flow over the flood plain surface generated by computer which takes into account the designed distribution and parameters of engineering structures.