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Fluvial dynamics in a deep permafrost zone – the case of the middle Lena river (Central Siberia)

E. Gautier & D. Brunstein
University Paris 8 & CNRS Laboratoire de Géographie Physique, France

F. Costard
UPS-CNRS, Orsay Terre, Université Paris-Sud, Orsay Cedex, France

R. Lodina
Soils Erosion and Fluvial Processes Laboratory, Lomossov University, Moscow Russia

ABSTRACT: The objective of this study is to understand the dynamics of fluvial hydrosystems dominated by outburst floods within a deep, continuous permafrost zone. The Lena basin rivers (Lena, Aldan and Vilioui) present specific fluvial forms: they consist of multiple wide channels separated by sandy bars and vegetated alluvial islands; sinuous and narrow branches can be observed in the floodplain and on the islands. Interactions between hydrodynamics and specific periglacial processes (thermal erosion on the banks, ice-dams and dam-breaks) are examined. Firstly, a diachronous fluvial forms analysis (satellite images and Navigation Survey maps) is conducted; this meso-spatial-scale approach allows the evaluation of the effects of the thermal erosion on the mobility of the fluvial units. Secondly, on the basis of the observation of sedimentary structures, the specificity of the depositional processes is underlined and deposits associated with log-jams and ice-jams are identified.

1 INTRODUCTION

1.1 *Periglacial context*

Central Yakutia is on the Arctic circle in Oriental Siberia. It is limited to the East by the Verkhoyansk Mountains, up to 2900 m high, and to the West by the Siberian shield ranging between 200 m and 1000 m (Fig. 1). The extreme continental climate in Yakutia is dominated by long and cold periods with minimum surface temperatures of −72°C. During the summer, the maximum surface temperature can reach +38°C. Low precipitation (180 mm.year^{-1}), and high evaporation and sublimation rates are characteristics of a very dry periglacial climate (Katasonow & Soloviev 1969). This climate favours intense development of thermokarst, possibly the most spectacular worldwide due to its exceptional scale and development. The lack of glaciers combined with a thin snow cover favour deep frost penetration and the formation of a thick permafrost. The average thickness of the Siberian permafrost is about 350 m (Anisimova et al. 1973). The maximum thickness of permafrost was recorded in Central Yakutia in Oïmiakon. A 1450 m deep borehole indicated the existence of permafrost in which pressure conditions and temperatures were favourable to the formation of clathrates. This permafrost contains 50% interstitial ice, but ice segregation represents 80% of the ice content (Anisimova et al. 1973). Massive icy beds may have an ice content as high as 250% (by mass). The thickness of the active layer varies

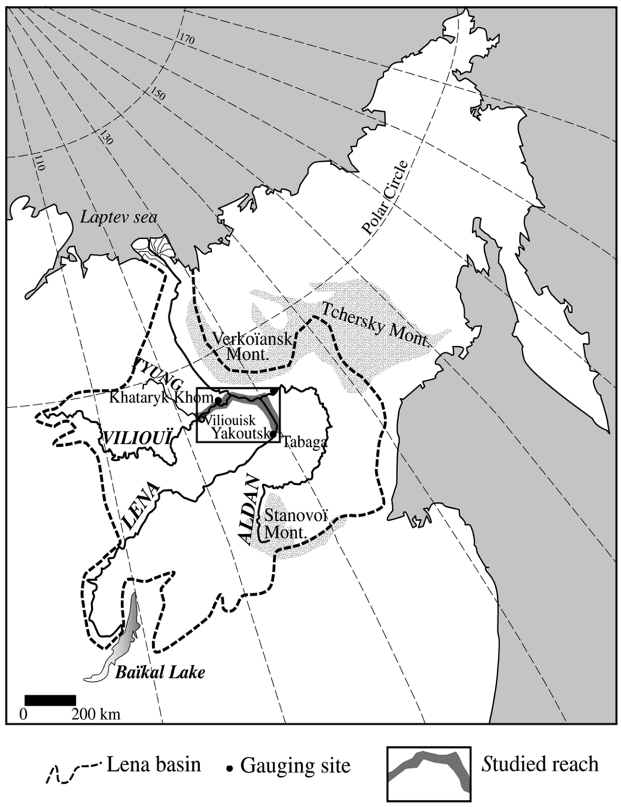

Figure 1. Location map.

between 1.5 m and 2 m in the silts and 4 m in sands. The temperature of continuous permafrost at the depth of minimum annual seasonal change varies from −5°C to −13°C. Unfrozen ground is nevertheless present

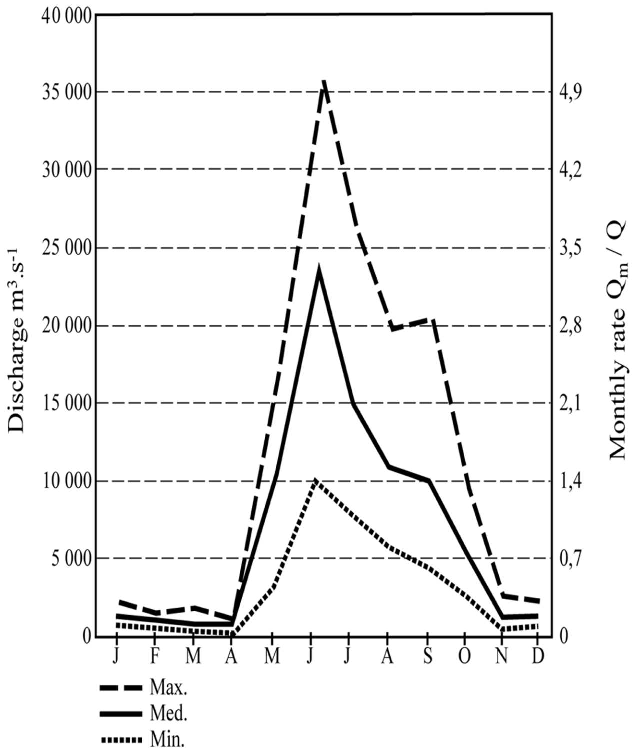

Figure 2. Regime of the Lena River.

under river beds in the form of taliks of varying depths and sometimes as isolated taliks (soil without ground-ice).

1.2 *Fluvial hydrodynamics*

The total length of the Lena river exceeds 4000 km and the width of the floodplain can reach 25 km downstream Yakutsk (62°N). Due to its large catchment (2.49 million km^2), the Lena river annually conveys 525 km^3 of water to the Laptev Sea. The hydrology of the Lena and its tributaries is characterised by an excessive regime (Antonov 1960, Gordeev & Sidorov 1993, Gautier & Costard 2000). The long drought during the winter is strongly influenced by the Yakutian climate: under a layer of thick ice, the discharge of the river was extremely reduced (900–1500 $m^3.s^{-1}$ at the Tabaga gauging site, near Yakutsk, and 4–12 $m^3.s^{-1}$ for the Vilioui River, a left side tributary also evoked in this study) and reached the lowest level at the end of the winter, a few weeks before the flood (Fig. 2).

The South-North course of most Siberian rivers involves a fluvial outburst delay of 30–50 days between the upper basins and the middle valleys. This delay explains the extent of the break up period. In the middle Yenisseï valley, Yamskikh et al. (1999) also observed that the break-up of the ice of the river precedes the increase of the atmospheric temperatures by 20–25 days. Figure 2 shows the instantaneous discharge versus time and suggests that the majority of the discharge occurs during the short break-up period of about 1 month. The South-North direction of the river favours a fast increase in discharge; on average it reaches 24000 $m^3.s^{-1}$, but can attain a peak discharge of 50000 $m^3.s^{-1}$ at Tabaga, and 100000 $m^3.s^{-1}$ at the Aldan junction. The presence of ice-jams and log-jams contribute to the accumulation of deposits in the floodplain. Such dams can raise the water level up to 8–10 m and inundate the first terrace above the floodplain. During the fluvial outburst, the sediment load is very high: 75% of the annual sediment load, that is approximately 7–8 million tons for the Lena river near Tabaga (Antonov 1960, Iakutsk Navigation Survey data, in Gautier & Costard 2000).

2 INTERRELATIONSHIPS BETWEEN FLUVIAL DYNAMICS AND THERMAL EROSION PROCESSES

Are (1983) described particularly efficient processes of thermal erosion on the banks of periglacial rivers. The efficiency of these mechanisms imply rapid rates of bank retreat and thus, a relative instability of the river forms. Two facts partially seem to cancel the assumption of a strong instability of the forms: (i) the stability of the main fluvial planforms (active channels, islands and bars) is highlighted by a diachronic analysis and (ii) log and ice jams favour mechanisms of flow rerouting on the flood plain and the islands, but the brevity of these processes does not allow a complete avulsion (new channel formation).

2.1 *Fluvial thermal erosion*

The high discharges during the spring flood interact with ground ice and other frozen obstacles, resulting in the erosion of the river banks. This process is a complex phenomenon involving at least two different processes: (1) thermal action, and (2) the mechanical transport of sediments.

Are (1983) observed recession rates of Siberian river banks of 19 to 24 $m.yr^{-1}$ (40 $m.yr^{-1}$ in front of islands). During our fieldwork, it was observed along most of the Lena river that the thermal erosion rate is less than 5–10 $m.yr^{-1}$. However, when thermal and mechanical erosion act simultaneously, rapid bank retreats occur along Siberian rivers. These rates are exceptional and mostly occur in a few specific areas, which has been confirmed by the planform analysis.

During flooding, thermal erosion may lead to particular types of bank morphology. Thermo-erosional niches are commonly observed, which contribute to the disequilibrium of the bank by thermokarstic subsidence with subsequent large slumps along the river banks (Walker, 1983). Some of the variations in their

Figure 3. Thermo-erosional niching along the Villoui river.

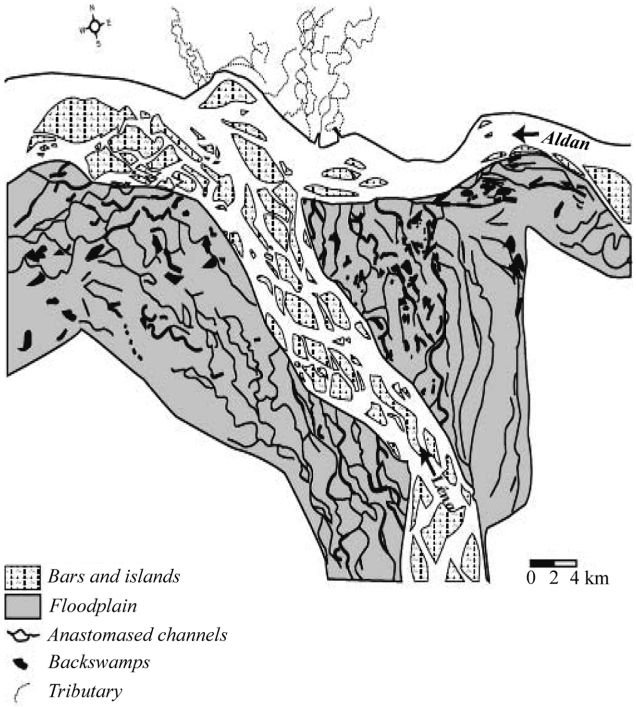

Figure 4. Fluvial landforms of the Lena river at the Aldan junction.

growth rate have been identified as resulting from discontinuities between sand and silt materials. The water level does not seem to be the primary factor explaining the corresponding level of thermo-erosional niching. Various field observations were made indicating the variation of the thermo-erosional niching as a function of the lithological discontinuities (Fig. 3). Channel margins and terraces are mostly capped with 10–35 cm of silt. These river banks show sand deposits usually overlain by silt/clay materials with different ice contents. They have a coarse non-cohesive substratum and a relatively more cohesive top stratum. In most places, the deepest thermo-erosional niching usually corresponds to the interface between these two types of material.

2.2 *Stability of the fluvial forms*

The fluvial forms of the Siberian rivers exhibit a large number of shallow and wide channels separating very long islands and sandy bars (Fig. 4). The width of the channels varies between several hundred metres and three kilometres. These multiple channels enclose large forested islands from 1 to 5 km long and large sandy bars. Many narrower anastomosed channels (a few tens of metres wide), which are often sinuous, cross the islands and the floodplain. A great number of topographic depressions occupied by lakes or swamps can also be observed on plains and islands (Fig. 4). Downstream from Yakutsk, the Lena river develops a wide forested flood plain (up to 15 km wide). A certain number of channels are not directly connected with a main channel, or even eventually disappear downstream. These anastomosed channels, which are flooded during the peak discharge, are rapidly dewatered. The low specific stream power of the Lena river and its tributaries is due to their very gentle gradient (0.0001 $m.m^{-1}$).

The approach is based on an analysis of various morphodynamic variables, in both a synchronic and diachronic manner. The different functioning units have been distinguished: active units (main and secondary channels and their associated bars), stabilised forms (vegetated lateral margins and islands) and anastomosed branches. Morphodynamic parameters (mainly width and position of the active bend, of the islands and the anastomosed branches) were measured on satellite images (Corona and Landsat), topographical maps (navigation maps) and field data. The variables were quantified and integrated in a Geographical Information System. This diachronic approach reveals that the fluvial forms are relatively stable: there are few channel migration or avulsion processes and the islands show also a reduced mobility. Some sites, which are subject to erosion (in terms of bank retreat), have been identified: e.g. concave banks, upper sections of islands and junctions of channels. The bank retreat does not seem to be very much higher than on comparable fluvial hydrosystems (in terms of discharge and width), even if widespread local retreats can be observed. The main difference of the periglacial rivers lies in the interactions between thermal erosional processes (creating thermal erosion niching on the bank – see Fig. 5a).

2.3 *Identification of specific deposits*

Specific deposits bordering the main active channels are identified, which could be associated with the log-jams and ice-jams that generate major sedimentation

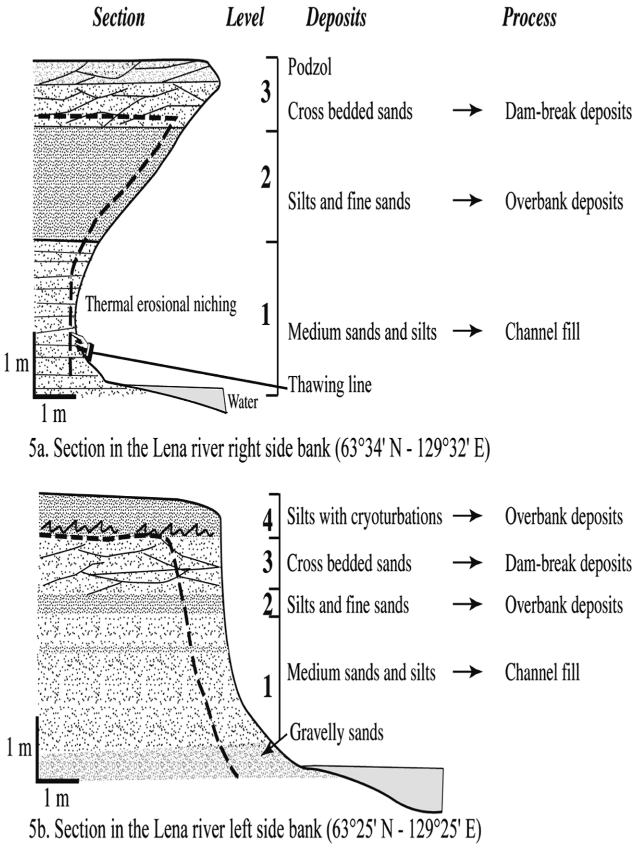

Figure 5. Sections in the Lena (from Gautier & Costard 2000).

processes. Sedimentary sequences located along channel margins have a certain number of common sedimentary features: at the base, sub-horizontal layers are composed by well sorted medium sands which are covered by silts and sands showing marked oblique stratifications (Fig. 5). These deposits with oblique stratifications are of great interest. In order to understand the genesis of these deposits one can attempt to relate the sedimentary characters of these deposits with the hydrodynamics of the river.

At the beginning of the outburst flood, the river transports great quantities of ice and tree logs, which create local jams. The conjunction of several elements explains the jam formation: (i) the thickness (up to 2 m) of the river ice during the winter; (ii) the density of the vegetation on the islands and the flood plain, which provides a great quantity of logs transported during the flood and which favours the formation of jams on the lateral margins. The accumulation of ice and logs causes a transitory rise in the water level, before the jam-breaking. This mechanism involves the "re-routing" of the water of the channel towards the plain or inside an island, thus creating a new channel inlet. In the channel inlet thus formed, sediments are similar to those of the nearby active channels. The presence of marked oblique stratifications is associated with the progradation of the sand and silts. It is to some extent the first stage of the mechanism of avulsion and this process seems to be common on the Lena river and its tributary. The hydrodynamics of the Siberian rivers are probably at the origin of the frequency of this process. The breaking of the log- and ice-jams initiates the mechanism of avulsion and the deposition of specific sedimentary features on the channel margins. Only the sudden increase in the water energy makes it possible to explain the presence of these sands on the high parts of the islands and channel margins. However, as a consequence of the brevity of this particular phenomenon and of the morphogenic discharges, the inlet of channels is rarely prolonged downstream. Moreover, because of a very low gradient, the hydraulic power is very limited. Thus the mechanism of avulsion is frequently blocked in its initial stage. Finally, it can be supposed that in central Siberia, the jam-breakings and their associated deposits occur on a still frozen ground. This would mean that the process is carried out just at the beginning of the outburst flood.

An interesting comparison was made with the study conducted by Smith & Pearce (2002) on the Milk River (Alberta and Montana), where channel ice jams also reroute river water across meander lobes and create gully erosion. In this case, the ice-jams force flow to avulse, forming a gully that initiates a new channel, thus a complete avulsion occurs. Smith & Pierce (2002) also describe scour holes in the Milk river flood plain, which are formed by water vortices beneath and between ice blocks. The same origin could be proposed for the numerous depressions present on the Lena river plain (Fig. 4).

3 CONCLUSIONS

The Siberian fluvial hydrosystems can be compared with anabranching rivers, which present a pattern of multiple-channels and permanent-islands (Smith 1986, Knighton & Nanson 1993, Nanson & Knighton 1996). These fluvial systems optimise sediment transport under very low gradients and short, efficient discharges. Concerning the periglacial Siberian rivers, the interactions between hydro-climatic characteristics and the deep permafrost introduce a pronounced specificity. The thermal and mechanical erosion on the banks provide a sediment load that exceeds the flow capacity because of (i) the weakness of the specific stream power ($10\,W.m^{-2}$) and (ii) the brevity of the morphogenic discharges (the flood). Therefore, the sediment load (mainly sandy deposits) probably does not migrate over long distances downstream and accumulates on wide bars and long islands (Gautier & Costard 2000). The sediment accumulation probably explains the geometry of the main channels (a high width/depth ratio). The shape of the anastomosed branches (more sinuous, often discontinuous and with a lower width/depth ratio) and their associated sediment features depends on specific mechanisms dominated by the ice and logs breakups.

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