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Rates of formation of forms in a river channel hierarchy: the case of the River Yana in northeast Russia

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Abstract The incised gravel-bed channel of the lower River Yana displays a hierarchy of channel forms. Within the reach where the river cuts through the Kular Ridge, there are 11 valley meanders (macrobends). Superimposed on these macrobends are ordinary incised meanders of smaller size, as well as braided and relatively straight reaches. Despite their great length (25-60 times the average channel width), the macrobends show distinct signs of meander-like development. Reasons for such a development and comparative rates of migration of different channel forms are considered, using a mathematical model of river incision, as well as traditional geomorphological methods.

INTRODUCTION

River channels are characterized by a complex hierarchy of forms: from sandy ripples to macroforms, such as valley meanders (macrobends). Relationships between small size channel forms are considered in numerous scientific publications whereas the development and origin of macroforms have been less investigated. The River Yana within the Kular Ridge represents a suitable opportunity for such research.

Macrobends are characteristic elements of river valleys in the temperate zone. Dury (1965), who conducted the most detailed research on macrobends genesis, explained them as remnants of ancient huge meanders, which were formed during periods of extremely high discharge. Other hypotheses of macrobend formation connect their features with the initial valley sinuosity formed during the period of adaptation of a newly-formed valley to the original relief of the region, with adaptation of the valley pattern to fracturing or fault zones and active tectonic structures, etc.

At present macrobends are not active in most valleys, i.e. their development is not a single process (as ordinary meander development) and represents a complex superposition of channel deformations within ordinary meanders, braided and straight reaches, which complicate the larger first-order bend. In contrast, the morphology of the Yana macrobends reveals distinct features of their development as a single whole.

STUDY AREA

The Kular Ridge is located at the contact between active tectonic structures of the

Verkhoyansk mountainous region and Arctic rift zone. The beginning of the Kular arch uplifting is dated as late Pliocene-early Pleistocene. It developed through the whole Quaternary period and now the ridge is oval in shape with east-northeast orientation, 800-900 m high in the central parts, with the southeastern slope steeper than the opposite one.

To the east from the zone of maximum elevation the Kular Ridge is crossed by antecedent valley of the River Yana. Along the valley the greatest heights of the ridge are about 500-600 m. The River Yana channel averages 400-500 m in width, and mean annual discharge is 928 $m^3 s^{-1}$. The present-day longitudinal profile is concave, with a gentle step at the axis of the ridge.

MORPHOLOGY OF MACROBENDS

The main feature of the channel pattern is a series of 11 meander-like curves with wavelength from 10.8 to 30.4 km. Such forms are usually named "valley meanders". The term "macromeanders", or "macrobends" (Matveev, 1988), seems to be more suitable, because often they are observed in straight valleys and even within a flood plain (Panin *et al.*, 1992). Ordinary meander wavelength does not usually exceed 15-20 times the channel width, whereas for the Yana macrobends this value is from 25 to 60.

The river valley is characterized by regular asymmetry like most valleys within ordinary incised meanders. Valley slopes at the macrobend's convex banks represent series of ancient alluvial terraces, smoothed by slope processes, with adjacent rather wide segments of flood plain and the youngest terrace. The opposite slope (at the concave bank) is steep and without any terraces as a rule. Such asymmetry shows macrobends growth across the valley on the geological time scale. Macrobend migration down the valley results in the regular asymmetry of the profiles across their "spurs".

Evidence of the meander-like development of the Yana macrobends is revealed not only from valley morphology, but also from their specific channel relief. Values of relative stream depth H_r ($H_r = H_{max}/B$, where H_{max} is maximum stream depth and B is channel width under bankfull discharge) and the coefficient of channel asymmetry A ($A = C/B$, where C is distance from the talweg to the concave bank of the macrobend) were calculated. These values averaged for 11 macrobends in undimensional coordinates l_r ($l_r = l/L$, where l is distance from the apex of the macrobend, L is length of the macrobend upper/lower part) reveal a zone of maximum H_r and minimum A (Fig. 1(a)), which represents a pool at the eroded concave bank, i.e. the internal asymmetry of the channel cross section similar to that of ordinary meanders. There is also a distinct tendency of talweg shifting to a convex bank within the upper part of macrobends and to a concave bank in the lower part (Fig. 1(b)), also similar to ordinary meanders.

Moreover, the relatively straight channel reaches between macrobends are the places where systems of riffles or even islands are formed, which can be compared with the location of simple riffles between meanders of ordinary size.

Morphology of the River Yana macrobends is closely related to the longitudinal profile features. Above the Kular Ridge axis, the macrobends have a complex internal structure of channel relief and are complicated by numerous ordinary incised meanders, as well as braided and relatively straight channel reaches with vast above-water parts of riffles and point bars. This is a channel reach with relatively low rates of incision and thus, there are sufficient sediments to provide relatively high rates of horizontal channel

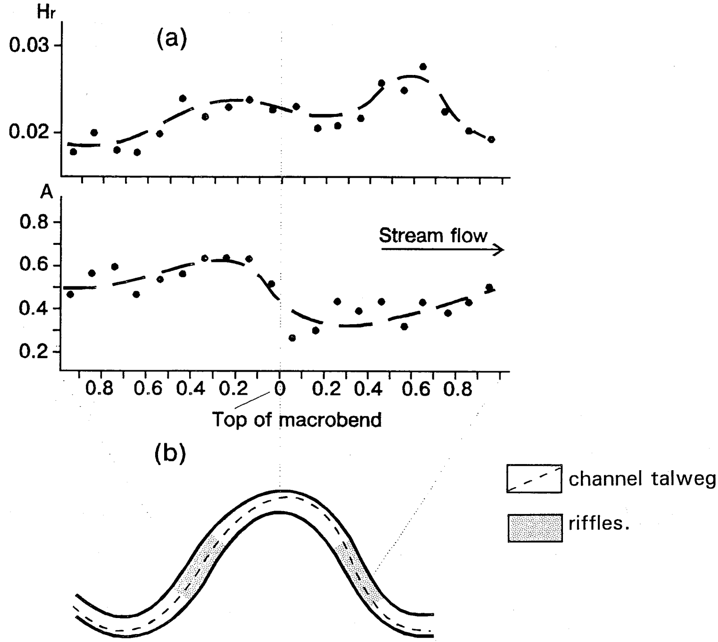

Fig. 1 Morphometric change along the channel (a) and principal scheme of channel relief within macrobends (b).

migration. Below the ridge axis in an active incision zone there are rather simple macrobends, which in fact represent ordinary incised meanders (in the macrobends apexes) divided by extensive straight reaches with riffles or simple island systems. The sediment deficiency, which is evident here due to the absence or small size of above-water parts of channel mezoforms, determines the relatively low rates of horizontal channel migration.

MATHEMATICAL MODEL OF RIVER INCISION

Terrace fragments at macrobend convex banks may allow the reconstruction of channel locations at different periods, and the evaluation of rates of macrobend migration. Mapping of terraces fragments was made during field research, with analysis of geological data and aerial photographs. The lack of exposures of ancient alluvium, their great thickness (up to 40 m), and the frozen state of overlaying slope deposits do not allow the use of traditional methods of geological correlation. The correlation of terrace fragments, which vary greatly in height, was therefore made on the basis of mathematical modelling of river incision into a growing arch.

Transformation of channel height Z in time T and space (distance along the river) X is described by the mass conservation equation:

$$\frac{dZ}{dT} + \frac{dQ_s}{dX} = V_t(X,T) \qquad (1)$$

where Q_s is the specific sediment discharge and V_t is the rate of vertical tectonic movement.

Field measurements of changes in the sediment discharge along an actively incising river (Panin *et al.*, 1990) show that it may be described by the following equation:

$$Q_s = K_1 * Q^2 * I * (X - X_0) \qquad (2)$$

where Q is the specific water discharge, $I = \mathrm{d}Z/\mathrm{d}T$ is channel slope, and X_0 is the coordinate of the beginning of the zone of incision. Using (2), equation (1) may be rewritten as:

$$\frac{\mathrm{d}Z}{\mathrm{d}T} = K_1 * \frac{\mathrm{d}}{\mathrm{d}X}\left[Q^2 * (X-X_0) * \frac{\mathrm{d}Z}{\mathrm{d}X}\right] + V_t(X,T) \qquad (3)$$

This is analogous to a diffusion equation, for which the methods of numerical decision are well-known. Equation (3) was solved for a 1 500 000 year period with the present-day channel profile as the initial condition, $Z(0,T) = 0$ and $Z(X_0,T) = 109$ m, $X_0 = 600$ km from the River Yana mouth – as the border conditions. In order to diminish the influence of the border conditions, calculations were made for the river reach 200-400 km from the mouth. The rates of tectonic uplifting were evaluated according to the form of the Kular Ridge arch $H_x/V_t = K_1 * H_x$. Optimization of coefficients K_1, K_2 was made with regard to correspondence of (1) computed and real channel profile at the end of modelling period with accuracy of 1.0 m, and (2) computed and real (150 m) height of the dated terrace fragment 250 km above the mouth.

The solution of (3) represents the Yana longitudional profiles for different time periods and dated lines of their tectonic deformations, which serve as isochrones for the Yana terrace complex in the Kular zone (Fig. 2). It permits the dating of terrace fragments within the time interval from 60 000 to 400 000 years BP. They are grouped

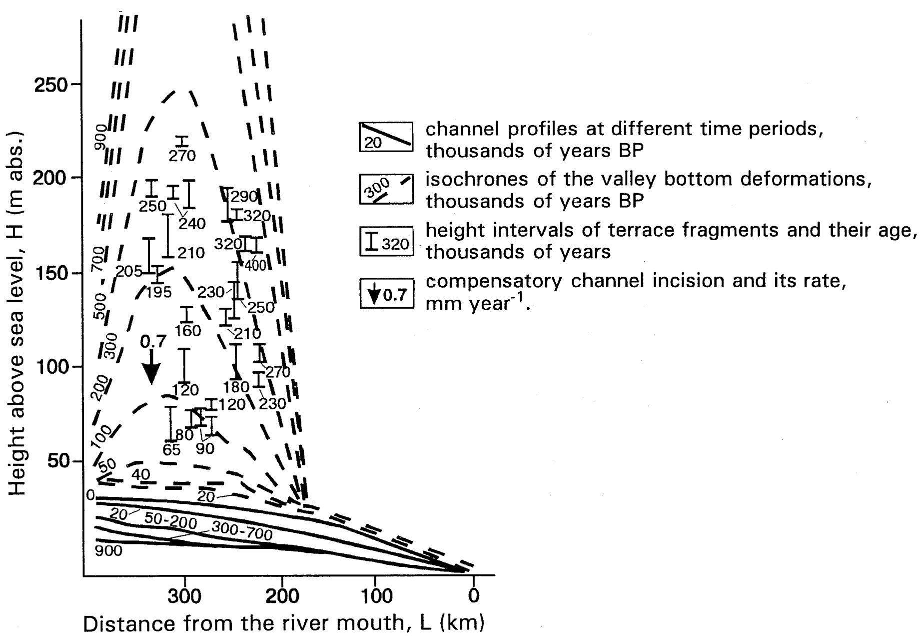

Fig. 2 The River Yana valley development during the Kular Ridge uplift.

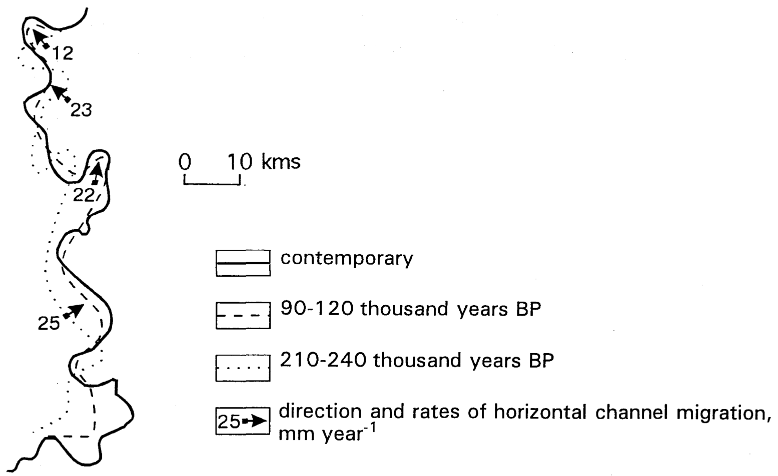

Fig. 3 The River Yana channel position in different Pleistocene epochs.

into two formations – Post-Samarian (210 000-240 000 years BP) and Kazan (90 000-120 000 years BP). For these two stages the location of the Yana channel was reconstructed (Fig. 3). These reconstructions show that macrobends were formed at the initial stages of the Kular arch uplifting. They were developed as the united morphodynamic forms continuously during the whole Pleistocene, with average rates of migration of 15-50 mm $year^{-1}$.

DISCUSSION AND CONCLUSION

The origin of the meander-like development of the macrobends can not be explained by a simple scheme of spiral circulation, which is usually used for meanders because of the great size and complicated internal structure of the macrobends. There may be several ways they have developed. The zones of maximum curvature – the apexes of the macrobends – have sizes similar to ordinary incised meanders. Thus, the apex zones of the macrobends may develop like ordinary meanders. In this case gradual lengthening of channel within macrobends eventually results in the complication of their structure: at first due to formation of additional pool-riffle systems, and later, development of meander series or braided reaches. Two stages of this process are evident in the River Yana valley above and below the ridge axis because of the difference in the rates of horizontal channel migration.

Moreover, the apex zones of macrobends and even the whole macrobends of relatively small size may be influenced by extremely high discharges of water with long recurrence intervals. The morphological effects of such events, when alluvial particles of all sizes are in movement (Tinkler, 1971), can accumulate and lead to development of macrobends in the geological time scale.

The second cause of the meander-like development is the influence of macrobend curvature on the second-order channel forms. Radiocarbon dating and measurements from maps of different ages show that meanders and braids of the lower hierarchical level are shifting along the macrobends at a rate of 0.5-1.5 m $year^{-1}$, i.e. 10 to 100 times faster than macrobends. During their movement, the zone of active erosion is located in turn at concave and convex "banks" of macrobends. However, due to the influence of macrobends, the total erosion of concave sides is much higher. The origin and significance of this influence can be compared with the influence of the Coriolis force on the valley's asymmetry. The actual rate of erosion of the high bedrock banks is about 0.2 m year^{-1} at the time when the zone of erosion is located on the concave side of the macrobend.

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