Article

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# ORIGIN OF THE GREAT NEMUNAS LOOPS, SOUTH LITHUANIA

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ABSTRACT The Nemunas River, one of the largest rivers of the Baltic region, is characterised by a generally straight valley. In the middle part of its course the Great Nemunas Loops are distinct features that occupy an area of 320 km$^2$ near the Birštonas Resort. The Nemunas valley here is 1.5-5 km wide and 45-80 m deep. The loops are cut into a glaciolacustrine plain confined between glacial and deltaic relief complexes and formed during the two last phases of glaciation. The origin of the entrenched loops, as large as 6-10 km, can not be explained in conventional terms of river meandering. The activity of underlying tectonic structures is the major factor, the Great Nemunas Loops being confined to the Birštonas tectonic depression. Despite their small magnitudes the neotectonic structures within the depression significantly influenced the glacial and meltwater sedimentation (hence, the topography) that controlled the geometry of the Nemunas valley. The initial sinuosity of the valley was only a little enhanced by later lateral erosion. Fault activity is indicated by numerous mineral water springs and straight channel segments. Only a few sites of similar mineral water discharge are documented in Lithuania, suggesting the specific structural setting of the Great Nemunas Loops. Inspection of drill cores revealed the inheritance of the Nemunas valley from underlying paleovalleys of Eemian and Holsteinian Interglacials, implying persistence of the controlling factors.

RÉSUMÉ *Origine des Grandes Boucles du Nemunas, sud de la Lituanie.* Le fleuve Nemunas, un des plus grands fleuves de la région baltique, est caractérisé par une vallée généralement rectiligne. À la mi-course du Nemunas, les Grandes Boucles occupent un territoire de 320 km$^2$ dans la zone de villégiature de Birštonas. Ces méandres, d'une largeur de 6 à 10 km, entaillent une plaine glaciolacustre confinée entre des complexes glaciaires et deltaïques formés au cours des deux dernières phases de déglaciation. À cet endroit, la vallée du Nemunas a une largeur de 1,5 à 5,0 km et une profondeur de 45 à 80 m. L'origine de ces boucles profondes ne peut être imputée aux processus habituels de formation de méandres. L'activité des structures tectoniques sous-jacentes est le principal facteur à l'origine de leur formation. Les Grandes Boucles du Nemunas sont confinées à la dépression tectonique de Birštonas, sur laquelle se sont formées des structures néotectoniques de moindre ampleur. Ces dernières ont néanmoins eu une influence significative sur la sédimentation glaciaire et celle associée aux eaux de fonte (et sur la topographie) qui a influencé la géométrie de la vallée du Nemunas. La sinuosité initiale de la vallée n'a été que peu accentuée par l'érosion latérale ultérieure. L'activité des zones de faille est décelée par la présence de nombreuses sources d'eau minérale et le redressement de certains segments du fleuve. Seuls quelques sites ayant des sources minérales similaires sont connus en Lituanie, ce qui met en relief la singularité structurale des Grandes Boucles du Nemunas. L'examen des carottes de forage révèle la filiation entre la vallée actuelle du Nemunas et les paléovallées interglaciaires de l'Eemien et du Holsteinien sur lesquelles elle repose.

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## INTRODUCTION

The origin of the deep meanders associated with entrenched river valleys has attracted the interest of many geoscientists (Miller, 1935; Holmes, 1944; Obedientova, 1975; Sladkopevtsev, 1977; Voznyachuk and Valczyk, 1978; Ehlers, 1996; Knox, 1996; Chamyal *et al.*, 2002). To quote Arthur Holmes "These dig themselves in by oblique erosion while their loops are being enlarged, and are said to be ingrown. If, however, erosion is mainly vertical, the existing loops have less opportunity to enlarge themselves and the resulting incised meanders are distinguished as entrenched. There is, of necessity, every gradation between these two, entrenchment being favoured by relatively rapid rates of uplift and down-cutting" (Holmes, 1944).

The Nemunas River is one of the largest rivers of the Baltic region. Although characterised by a generally straight valley, the Middle Nemunas valley is distinguished by four large loops, referred to as the Punia, Balbieriškis, Prienai, and Birštonas loops. They form a most distinct feature occupying an area of 320 km$^2$ near the Birštonas resort (Figs. 1-2). The Nemunas valley is 1.5-4 km wide and 45-80 m deep, and the loops are as large as 6-10 km. Due to the picturesque landscape, the Nemunas Loops Regional Park was established. The valleys of the largest rivers (Vistula, Dnieper, Daugava, Pripiat, etc.) of the adjacent areas previously covered by continental glaciers have no such large, deeply entrenched loops (Kolupaila, 1940). The formation of the large, entrenched loops cannot be explained in terms of normal hydrodynamic processes.

The pioneering consideration of the origin of the Great Nemunas Loops was provided by Basalykas (1956, 1965), who stressed a link between the recurrent down-cutting of the river and the isostatic uplift of the southern Baltic Upland during late glacial and post-glacial times. He suggested that the Nemunas Loops are related to thermokarst channels. More detailed studies of the morphology, structure and paleogeography of the Nemunas valley led to alternative explanations (Micas, 1959; Basalykas, 1977; Dvareckas, 1976). Inheritance of the recent Nemunas valley from the older interglacial stages was stressed. For instance, the varved clays underlying the till of the Last Glaciation in the Great Nemunas Loops area (*e.g.* Balbieriškis outcrop; see Fig. 3 for location) represent an interstadial valley dammed by an advancing glacier (Mikaila, 1958; Gaigalas and Micas, 1967). The geological mapping of 1972-1973, designed to assess the abundant mineral water resources in the Birštonas resort area, provided the most essential data (Šliaupa, 1978). The role of vertical tectonic movements was then recognised. A relationship of the mineral water springs to active tectonic structures identified in the Cretaceous succession was previously suggested by Kaveckis (1928).

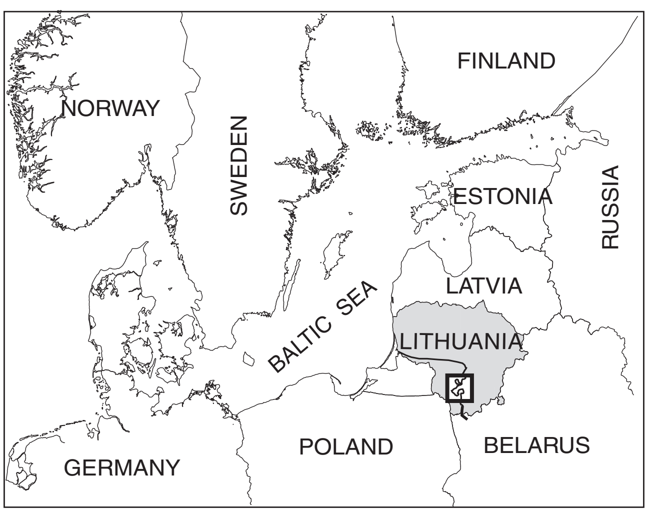



FIGURE 1. Location of the study area.

*Localisation de la région d'étude.*

## METHODS AND DATA

Extensive data on geology, tectonics, geomorphology and paleogeography of the Great Nemunas Loops were collected during detailed geological and geophysical mapping carried out in the early 1970s. Numerous sweet- and mineral-water supply boreholes provided information on the Quaternary and sub-Quaternary geology. The stratigraphy and tectonic fabric of the

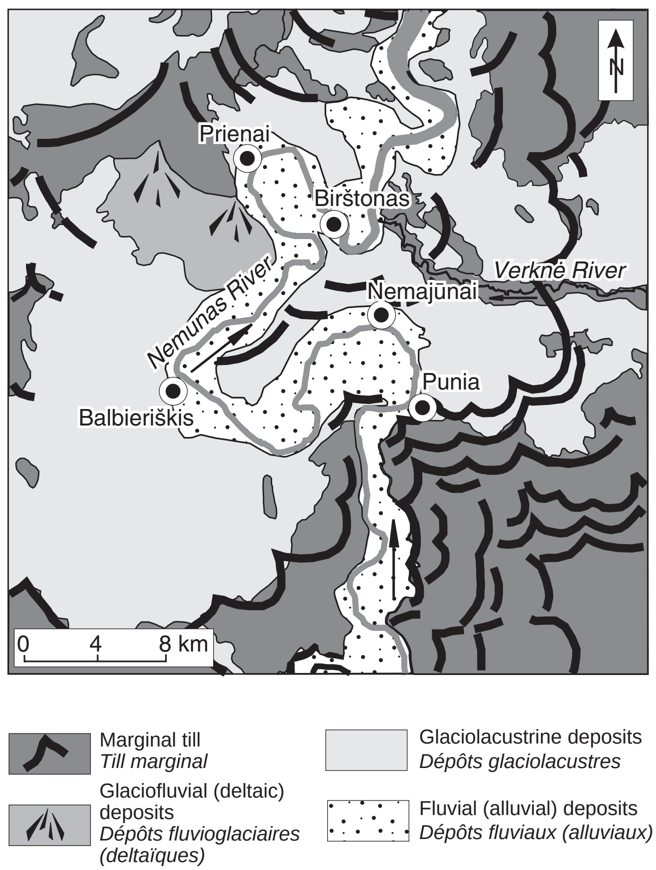



FIGURE 2. Geological setting of the Great Nemunas Loops (modified after Kudaba (1983) and Guobytė (2002)).

*Structure géologique du secteur des Grandes Boucles du Nemunas (modifié d'après Kudaba (1983) et de Guobytė (2002)).*

sedimentary succession was reconstructed from one deep (800 m) well drilled to the crystalline basement, 15 geological mapping wells 200-400 m deep (down to the Permian and Silurian), and several hundred hydrogeological wells. The results of granulometric, mineralogical, petrographic, geochemical, and paleontological (microfauna, spores, pollen, etc.) studies provide a basis for stratigraphic subdivision and correlation of wells and outcrops (Šliaupa, 1978; Baltrūnas, 1995, 2002). The conditions of deposition of glacial sediments is reconstructed based on measurements of azimuth and inclination of gravel and shingle long axes combined with petrographical studies of gravel and pebbles (Gaigalas, 1979; Gaigalas and Melešytė, 2001). Air-borne remote sensing was employed for stratigraphical and genetic interpretation of geological bodies. The interglacial conditions have been reconstructed by Baltrūnas (1995, 2002). These data were summarized in the geomorphological map of the Great Nemunas Loops area (Fig. 3).

The tectonic framework is recognised as an important factor controlling looping of the Nemunas River. Different approaches were applied to identify the ancient and neotectonic structures. It was shown that tectonic deformations in the sedimentary cover are intimately related to the block tectonics of the underlying crystalline basement (Šliaupa and Popov, 1998). Gravity and magnetic maps (scale of 1 : 50 000 and 1 : 200 000) were accordingly used to identify tectonic elements of the crystalline basement that occurs at a depth of 800-900 m. Automated interpretation techniques are preferred. The shadow image is a powerful tool for detection of linear tectonic zones (Arvidson *et al.*, 1982; McDonald *et al.*, 1992). Short-wavelength local anomaly transformations were computed to map density distributions at shallow levels in the earth's crust. A terracing operator (Cordell and McCafferty, 1989) was applied to gravity data to produce a field comprised of uniform domains separated by abrupt boundaries. A map of blocks defined at the mode depths of 1-3 km was computed. In addition, the horizontal gradient maxima technique allows more precise definition of block boundaries.

Tectonic structures in the sedimentary cover were identified by correlating the borehole sections. The geophysical electrical survey data unravelled shallow zones of saline formation waters confined to faults; some of them were proved by hydrogeological testing in boreholes (Šliaupa, 2003).

The neotectonic activity of structures is of primary concern. The sub-Quaternary surface is considered as the major reference level in the neotectonic studies of the Baltic region though a considerable influence of erosional processes is also realized (Šliaupa *et al.*, 1995). The summit altitude map based on data from a few hundred wells was compiled to extract the tectonic factor. The long profile of the Nemunas River extending for about 100 km from Grodno (northwest Belarus) to Kaunas City (central Lithuania) was plotted from detailed topographical maps to identify the vertical deformations. Deviations from the first-order trend reflect neotectonically active structures crossed by the river. Neotectonic lineaments were identified from the drainage network and air-borne photographs.

## GEOMORPHOLOGY AND PALEOGEOGRAPHY

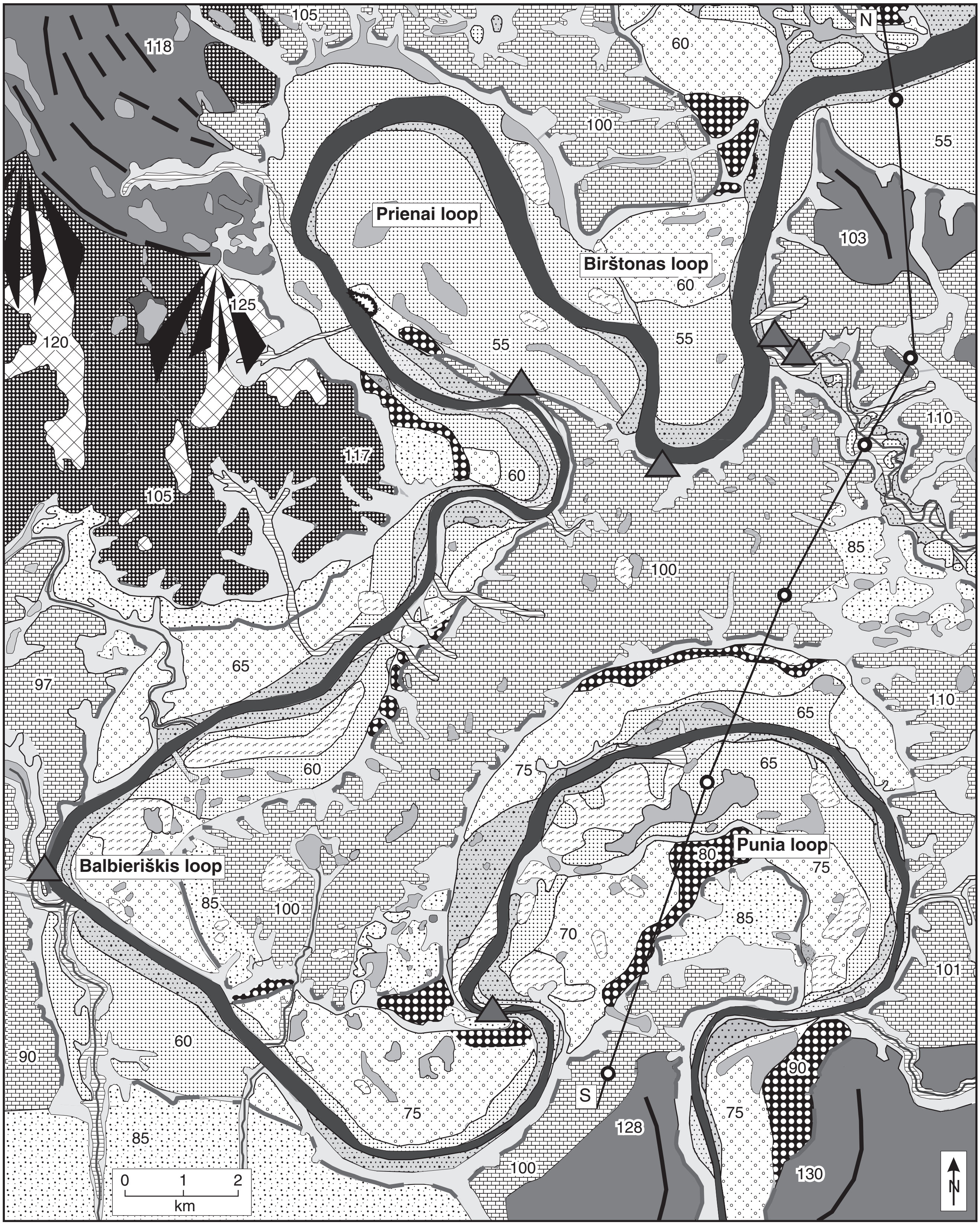
The area of the Great Nemunas Loops represents a part of the Middle Nemunas plateau (Drobnys, 1981; Baškytė and Kulbis, 2000). The surface is dominated by fluvial features (Fig. 3). The remaining part comprises the ridged moraine relief of the East Lithuanian and South Lithuanian substages of the second stage (Baltija = Pomeranian) of the Last Glaciation (Nemunas = Weichselian), undulating and strongly eroded glaciofluvial delta plain, and a glaciolacustrine two-level plain confined between moraine ridges.

The present relief was formed during the last deglaciation. The Great Nemunas Loops are situated within the glaciolacustrine paleobasin (Fig. 2) that existed between the terminal moraine chain containing dead ice massifs in the south and an active ice sheet margin of the South Lithuanian stage in the north. The present altitude of the plain is 85-110 m asl. The original water level of the glaciolacustrine basin is estimated at 120-125 m asl as suggested by the flat surface of glaciofluvial delta identified in the northwest of the study area (Fig. 3). The glaciolacustrine basin accumulated varved clays, giving way to unvarved sandy clays in the central part of the basin between Birštonas and Nemajūnai that implies shallowing of the basin. The section is most representative and thick in the lower level (*e.g.* Balbieriškis outcrop) and is thinner in the upper level.

Two levels of the glaciolacustrine basin are recognised. Most of the sediments are mapped at the altitude of 100-110 m asl, while a lower glaciolacustrine terrace, identified at an altitude of 80-85 m asl, is documented in some local areas (Fig. 3). The lower glaciolacustrine terrace provided a corridor for the Nemunas River. Initially the river was flowing to the south. The progressive melting of the ice sheet and its recession to the northwest resulted in reversal of the drainage direction. The melt waters of the dead ice fields surged through the pre-existing topographic low of the Nemunas valley into the glaciolacustrine basin from the south.

Five fluvial terraces are distinguished above the floodplain of the Nemunas valley. In some places terraces have two levels (sub-terraces). The 5$^{th}$ terrace is 27-32 m above the river channel, and the 1$^{st}$ terrace is levelled at 4.6-6.0 m. The separation of individual terraces is 5-10 m and they are covered by 2-3 m (rarely 6 m) thick alluvium overlying the Quaternary glacial and interglacial deposits. The finely patterned sedimentary architecture and small thickness of alluvium indicate low water discharge, suggesting that the wide valley (1.5-5 km) was formed by lateral erosion rather than by a large water stream. Thermokarst features are abundant in the 5$^{th}$ to 2$^{nd}$ terraces, implying rapid river incision. The contemporary floodplain is fragmentary. It is 2-3 m high, and the width ranges from 5 to 50 m. The floodplain is locally of either erosional or aggradational type.

Following regional paleogeographic implications and radiocarbon dating the formation of the upper fluvial terraces of the Nemunas valley was related to deglaciation and drainage of the glaciolacustrine basins in the Oldest Dryas-Older Dryas (5$^{th}$, 4$^{th}$ and 3$^{rd}$ terraces) and to the Baltic Ice Lake water level fluctuations in Allerød-Younger Dryas time (2$^{nd}$ terrace) (Basalykas, 1956; Micas, 1959; Dvareckas, 1976, 1993; Kabailienė, 1990). The 1$^{st}$ terrace formed during the early part of the Holocene Epoch (Preboreal-Subboreal) and only little modified during the latter part, mostly by high-level flood events. Based on radiocarbon dating of the peat overlying alluvial deposits (Baltrūnas,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Prienai loop
Birštonas loop
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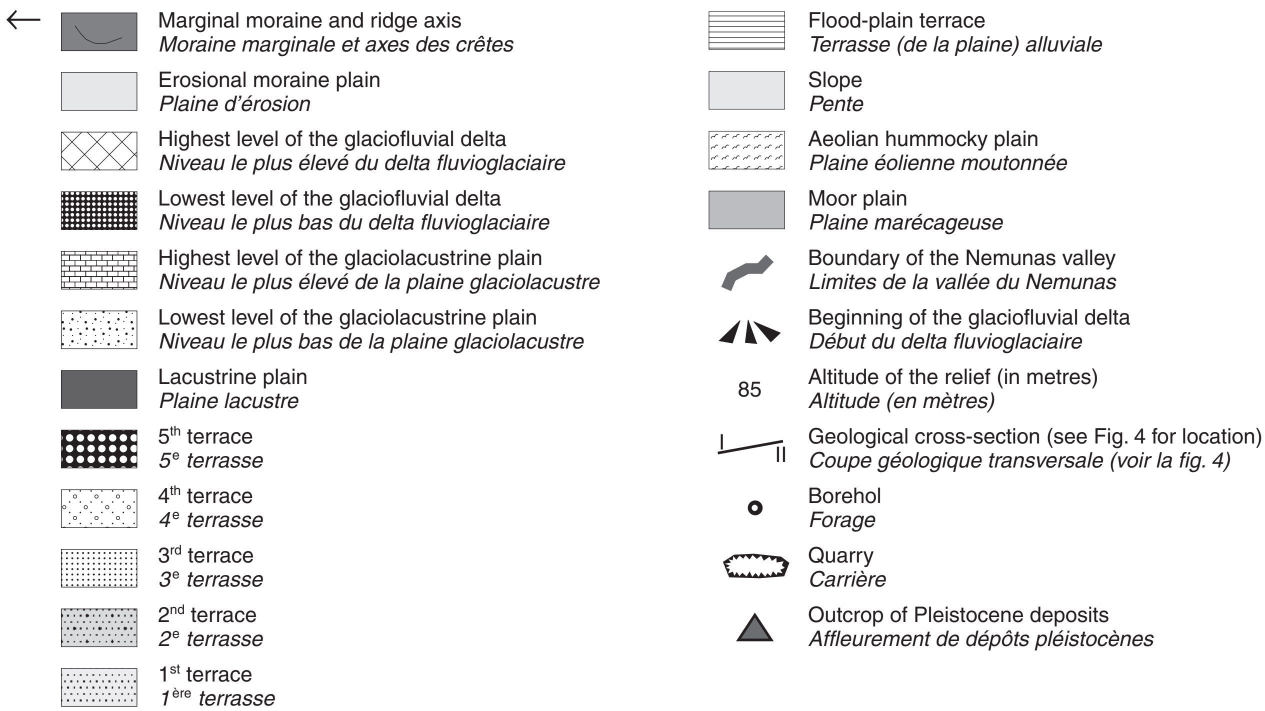



FIGURE 3. Geomorphological map of the Great Nemunas Loops area.

*Carte géomorphologique du secteur des Grandes Boucles du Nemunas.*

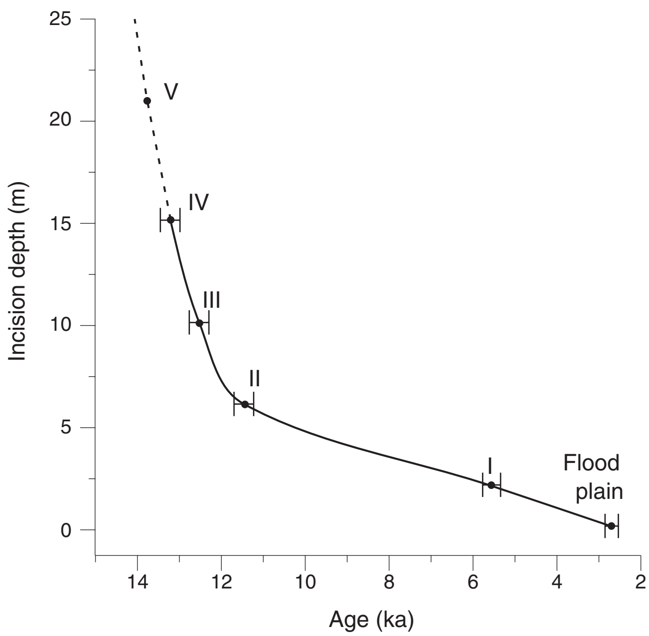



FIGURE 4. Incision rate of the Nemunas River in the Birštonas area defined by $^{14}C$ dating of the pit deposits overlying IV-I terraces and the flood plain. Dating of V terrace is based on regional data. Error bars are indicated.

*Taux d'incision du fleuve Nemunas de la région de Birštonas à partir des datations au $^{14}C$ du puit le plus ancien dans les terrasses de recouvrement IV-I et la plaine d'inondation. La datation de la terrasse V est basée sur les données régionales. Les barres d'erreur sont indiquées.*

1995) a channel incision diagram was constructed (Fig. 4) that indicates exponential deceleration of valley deepening that averaged 6 m/ka during formation of 5th to 2nd terraces, and was as low as 0.8 m/ka during the final stage.

## PALEOGEOMORPHOLOGY OF INTERGLACIALS AND VALLEY INHERITANCE

The thickness of Pleistocene deposits ranges from 14 to 178 m. They comprise Middle and Upper Pleistocene glacial, glaciofluvial, and glaciolacustrine sediments alternating with Turgeliai (Ferdynandowski = Konachowski), Butėnai (Holsteinian = Likhvin = Yarmouth) and Merkinė (Eemian = Mikulin = Sangamon) interglacial deposits. Based on detailed lithostratigraphical studies seven till strata are attributed to the Dzūkija (Elster 1 = San = Don), Dainava (Elster 2 = Wilga = Oka = Kansan), Žemaitija (Odra = Drenthe = Dnieper), Medininkai (Warta = Moskva = Illinoian), Varduva (Świecie = Kalinin), Grūda (Leszno-Poznań = Weichselian = Wisconsinan = Valday) and Baltija (Pomerania = Ostaszkow) sub-formations (Fig. 5; Baltrūnas, 2002).

The reconstruction of the paleogeomorphological conditions indicates the inheritance of the Nemunas valley (Baltrūnas, 2002). The oldest underlying paleovalley is identified in the Butėnai (Holsteinian) Interglacial that was recorded in numerous boreholes (Baltrūnas, 1995). The paleovalley was as wide as 5-8 km, discharging a large amount of water flowing from the south to the north (Fig. 6A). The paleoNemunas valley widens in the Great Nemunas Loop area, suggesting some depression.

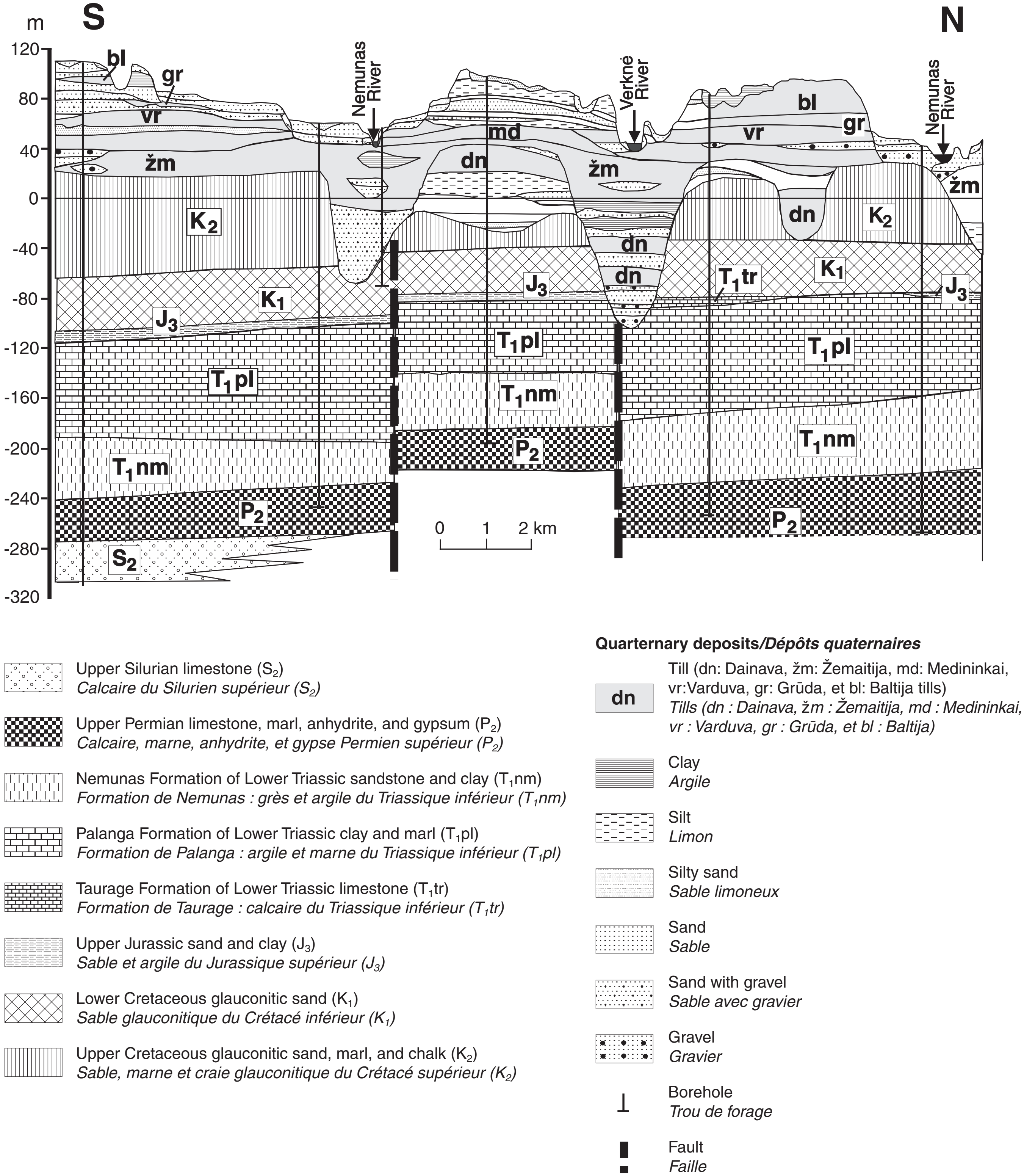



FIGURE 5. Geological cross-section of the Great Nemunas Loops (see Fig. 3 for location).

*Coupe géologique des Grandes Boucles du Nemunas (voir fig. 3 pour la localisation).*

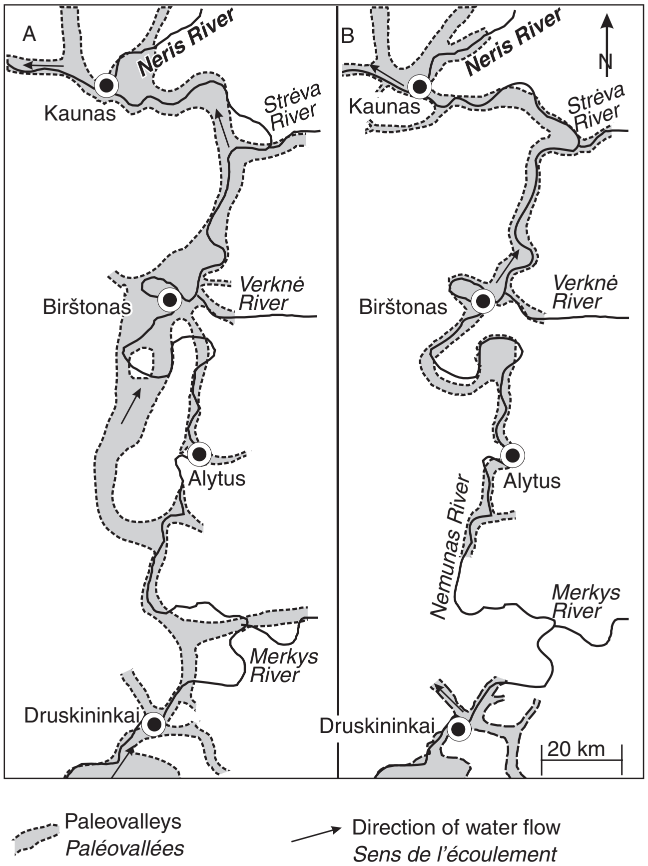



FIGURE 6. Paleovalleys of (A) Butėnai and (B) Merkinė Interglacials in the Middle Nemunas.

*Paléovallées interglaciaires du (A) Butėnai et du (B) Merkinė, moyen Nemunas.*

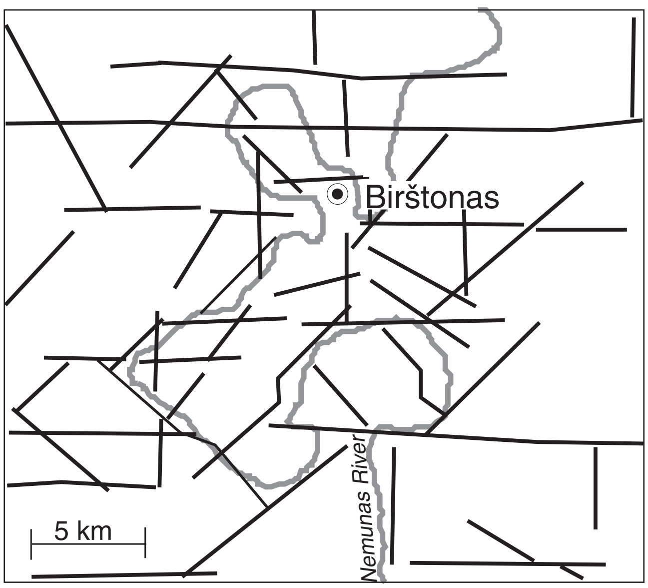



FIGURE 7. Faults of the crystalline basement of the Birštonas area defined by magnetic and gravity lineaments.

*Failles du socle éruptif de la région de Birštonas définie par des linéaments magnétiques et de pesanteur.*

The Balbieriškis Loop encompasses a paleoisland, whereas the Punia Loop is confined to a separate smaller valley. The paleovalley was filled with fine-grained, in some places silty sand of grey and greenish-grey colour inherited from redeposited Neogene and Paleogene terrigens distributed south of the Great Nemunas Loops. An average gradient of the paleoriver, estimated to be 0.3 m/km, is consistent with the present gradient of the Nemunas River (0.5 m/km). Local variations of the paleogradient are recognised. The largest gradient is reported between the Verknė and the Strėva river-mouths and is reflected also in narrowing and the more simple geometry of the paleovalley (Fig. 6A). A lower gradient (0.25 m/km) is defined in the Birštonas area.

During the Merkinė (Eemian) Interglacial a low-topography plain existed for a long time as indicated by a 2-5 m thick crust of weathering mapped at the top of underlying glacial deposits. The Nemunas paleoriver formed again. Compared to Butėnai time, it shows narrower and deeper valley geometry. Its plan-view shape is very close to that of the present valley of the Nemunas River, including the Great Nemunas Loops (Fig. 6B). The average gradient of the paleovalley is 0.4 m/km implying faster water flow than that during the Butėnai time. The sedimentary infill of the paleovalley is rather variable. The deep valley in the Druskininkai area is filled with 1-100 m thick fine-grained sand in an isolated basin, whereas the shallower paleovalley with pronounced terraces in other areas is filled with 20-40 m thick coarse sand.

## TECTONIC FRAMEWORK

Rivers are sensitive to tectonic activity of underlying structures that greatly influence their morphology (Peakall, 1998; Raj *et al.*, 2004; Schumm *et al.*, 2004; Sirocko *et al.*, 2002). Tectonic activity of the earth's crust is well recognised in the Baltic region to influence the present relief, including the drainage network (Šliaupa, 1998). The Nemunas River has a specific structural setting, following the contact zone between the two first-order crustal domains of the West Lithuanian granulites and the East Lithuanian Fold Belt (Šliaupa and Popov, 1998). Smaller scale bocks, bounded by basement faults, are identified within this tectonic zone. W-E and NE-SW trending faults dominate the Birštonas area, showing rather regular spacing of 4-7 km (Fig. 7). Some reaches of the Nemunas River clearly follow the basement faults.

The sedimentary cover overlying the Early Precambrian crystalline basement is 750-900 m thick (Fig. 8). Following data of a regional-scale geophysical electrical survey, the Great Nemunas Loops are situated within the W-E trending Birštonas depression.

Drilling reveals some smaller-scale tectonic structures in the upper part of the sedimentary cover comprising the Upper Permian, Lower Triassic, Upper Jurassic and Upper Cretaceous deposits. The most distinct feature is the Balbieriškis uplift of 20-40 m amplitude that is embraced by the Great Nemunas Loops (Fig. 8). The uplift was formed by vertical movement of the underlying basement block bounded by NE-SW striking faults (Fig. 7). Further south, the Punia Loop accommodates the tectonic depression. The Birštonas-Vilnius fault, well defined

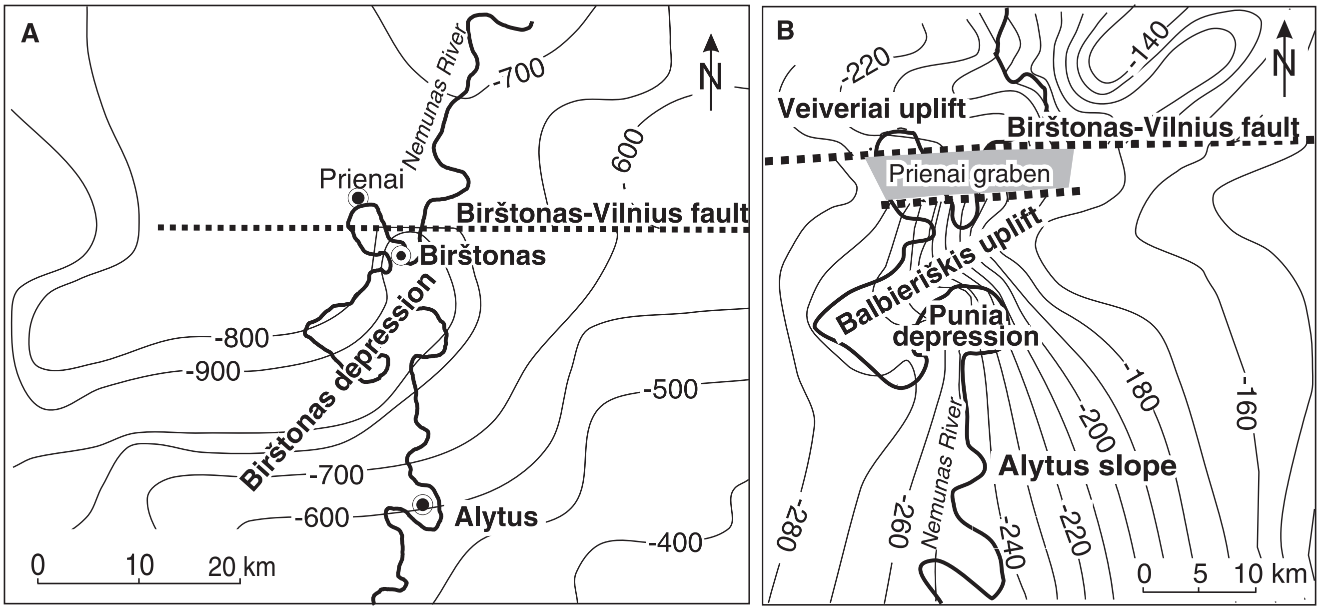



FIGURE 8. Structural maps of South Lithuania and Great Nemunas Loops area. (A) Depths of top of the crystalline basement. (B) Depths of top of the Upper Permian rocks.

*Cartes structurales du sud de la Lituanie et de la région des Grandes Boucles du Nemunas. (A) Profondeur de la surface du socle éruptif. (B) Profondeur de la surface des roches du Permien supérieur.*

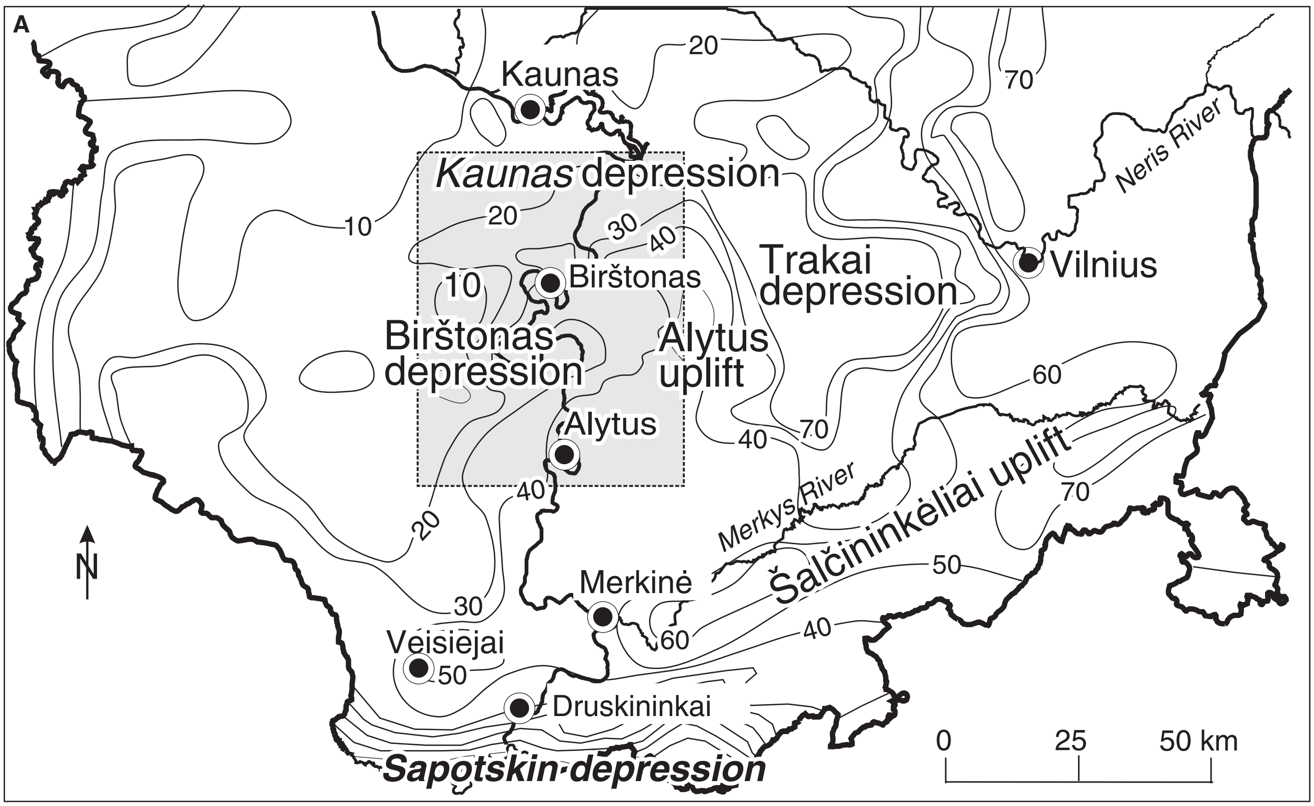
in the basement, is marked by the graben-like feature that is reflected in the Nemunas River geometry by a left-lateral shift of the valley. The fault bounds the Veiveriai uplift located in the north. South of the Punia Loop the straight reach of the river follows the western margin of the Alytus structural slope.

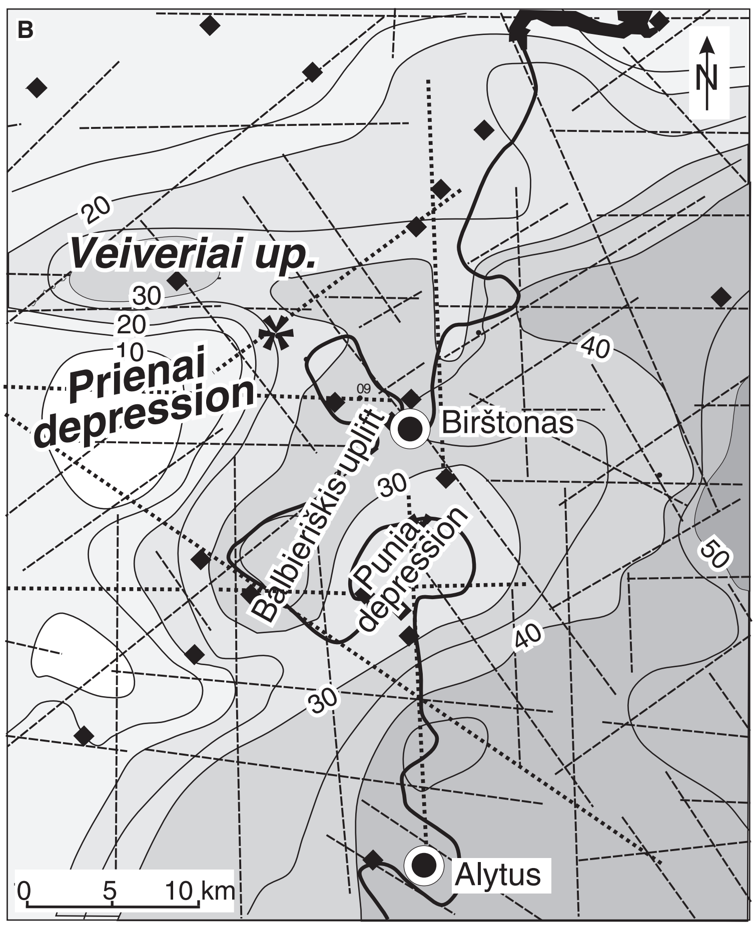
The local structures defined in the Upper Prequaternary layers show persistent activity throughout the Late Paleozoic and Mesozoic. Thickness of the Permian succession shows inverse correlation with depths (maximum thickness of 50-60 m is mapped in the Balbieriškis and Veiveriai uplifts, whereas it is only 30-35 m thick in the Prienai graben and the Punia depression), whereas the Triassic layers have direct correlation. The second inversion phase is recognized in the Albian that shows increased thickness within the Balbieriškis uplift (51 m on the crest, compared with 40 m on the flanks), while the Upper Cretaceous directly reflects the underlying tectonic structures.

The Prequaternary structures were active also during the neotectonic stage. The map of depths of summits of the sub-Quaternary relief reveals numerous neotectonic structures. The sub-Quaternary surface of South Lithuania is generally tilted to the west from +60 m to -20 m (Fig. 9A). Against this background tilting the smaller-scale features are identified. In the south the Nemunas River crosses the deep Sapotskin depression (-20 m to +40 m) that borders the Veisiejai–Šalčininkėliai uplift (+40 m to +60 m), activity of which is well documented by a pattern of aeolian sediments (Baltrūnas *et al.*, 1998). Further north the Nemunas River flows along the western flank of the Alytus uplift (+30 m to +40 m) and enters the Birštonas depression (+10 m to +30 m). In the north the Nemunas River crosses the Verknė uplift (+30 m to +35 m) and turns sharply to the west in the Kaunas depression (+10 m to +20 m). At the local scale, the structures defined in the Prequaternary succession of the Great Nemunas Loops are easily discernable in the sub-Quaternary surface (Fig. 9B). The amplitudes of the Punia depression, Balbieriškis, and Veiveriai uplifts are in the range of 5-15 m.

The neotectonic structures deform the long-profile of the Nemunas River (Fig. 10). The local neotectonic structures were derived by subtracting the linear trend (gradient 0.5 m/km) from the long-profile. The amplitudes of the local structures range from -4.0 m to +4.6 m. These values are consistent with the amplitudes of the Holocene tectonic vertical movements recorded in other areas of Lithuania (Šliaupa *et al.*, 2005). The most distinct subsidence (-4 m) occurs in the Sapotskin depression. The Veisiejai-Šalčininkėliai uplift is reflected in a positive deformation (+2 m) that likely caused formation of the Merkinė Loop. By contrast, the Great Nemunas Loops are confined to the Birštonas neotectonic depression, comprising the lower-order Punia and Prienai depressions (concave-shape deformations) and the Balbieriškis uplift (convex-shape deformation). These data indicate that ancient structures continued to develop during the latest Pleistocene-Holocene times when the Nemunas River sculpted its valley.

A rather regular network of neotectonic lineaments is documented in the Great Nemunas Loops area (Fig. 9B). The river partially reacts to this network. A sharp change in the flow direction at the entrance to the Punia Loop is caused by the west-east trending lineament coinciding with the fault defined in the crystalline basement. A 5 m difference in terrace altitudes implies its neotectonic activity, the southern flank showing an uplift trend. East of the Punia Loop this fault controls the southern limit of the glaciolacustrine sediments. The NW-SE tending



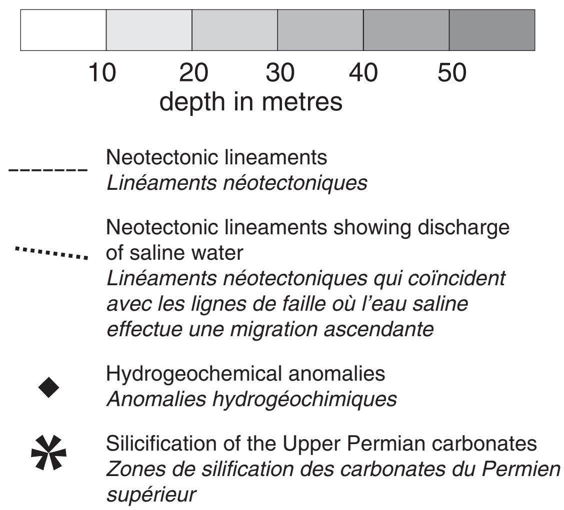




FIGURE 9. Structural map (summit depths) of the sub-Quaternary surface. (A) South Lithuania; major rivers and Great Nemunas Loops area (shaded) are indicated. (B) Great Nemunas Loops area.

*Cartes structurales des surfaces sub-quaternaires : (A) sud de la Lituanie avec les principales rivières et la zone des Grandes Boucles du Nemunas (délimitée par le rectangle pointillé). (B) Zone des Grandes Boucles du Nemunas.*

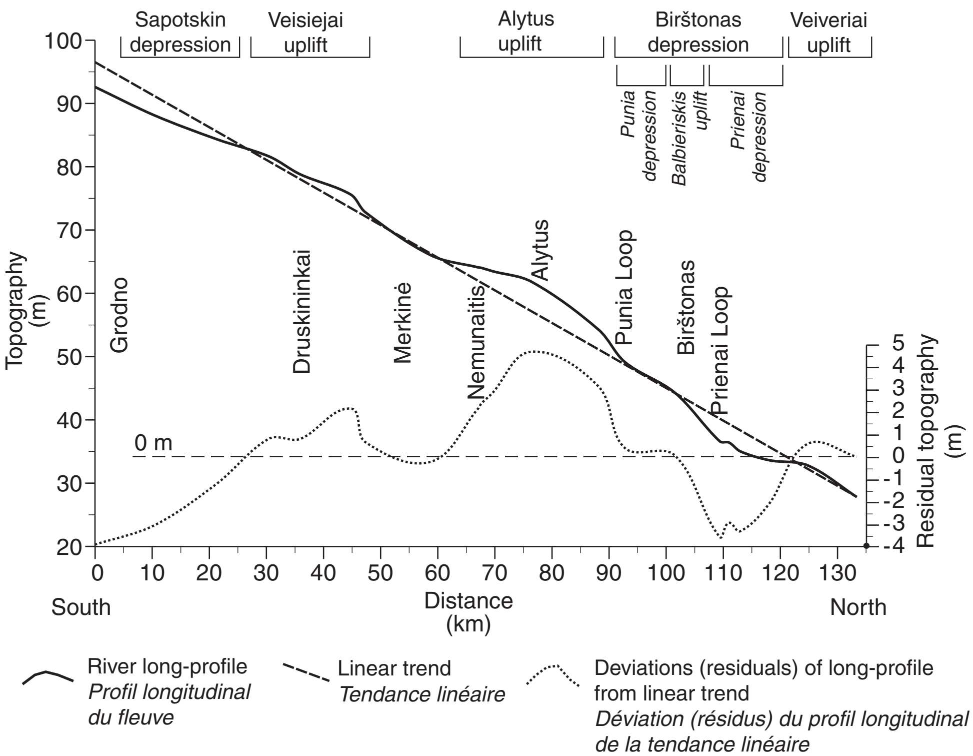



FIGURE 10. Long-profile of the Nemunas River from Grodno (northwest Belarus) to Kaunas (central Lithuania).

*Profil longitudinal du fleuve Nemunas entre Grodno (nord-ouest du Belarus) et Kaunas (centre de la Lituanie).*

straight segment of the Balbierškis Loop is controlled by a swarm of neotectonic lineaments of the same orientation that correlates with the geophysical lineament. The Prienai Loop is confined to the neotectonic swarm striking NW-SE.

The mineral water springs are a specific feature of the Great Nemunas Loops area that was the reason for the establishment of the famous Birštonas Resort. It is comparable to only the Druskininkai Resort located 90 km to the south of Birštonas. The springs are evidence of increased activity of the faults. The mineral water migrates along the faulted pathways from the Upper Permian through 170 m thick Lower Triassic claystones to reach the Jurassic, Cretaceous and Quaternary aquifers (Šliaupa *et al.*, 1986). A cluster of anomalies is mapped in the Prienai graben (Fig. 8B). The N-S, W-E and NW-SE oriented faults that control the Punia and Balbieriškis Loops also show increased hydrodynamic activity. These are reactivated ancient fault systems as indicated by associated hydrothermal silicification documented in the Upper Permian carbonates (Fig. 9B).

## DISCUSSION

The impact of tectonic factors on river morphology is recognised in many regions (Burnett and Schumm, 1983; Sirocko *et al.*, 2002; Chamyal *et al.*, 2002; Raj *et al.*, 2004). It is identified by river confinement to tectonic lineaments, changes in river planform and longitudinal profiles, terrace formation, variations in sinuosity and channel-belt width. The adjustment of the river to external (tectonic) forcing is in most cases reported from regions showing significant tectonic activity (Berryman *et al.*, 2000; Peakall, 1998), whereas cratonic areas, essentially those subjected to glaciation during the Quaternary, are little considered. Furthermore, alluvial rivers are believed to show much higher sensitivity to external factors then do the bed-rock bound rivers (Schumm *et al.*, 2000) such as the Nemunas River.

The intense looping of the Nemunas River in the Birštonas area can not be explained in conventional terms of meandering. As indicated by the pattern of alluvial sediments, the present shape of the river is close to that of the initial river geometry (Fig. 11). The loops are as large as 6-10 km, while the lateral erosion is in the range of only 1-3 km as indicated by the pattern of terrace sediments (Fig. 3). The Great Nemunas Loops formed during the initial stage of the river development and were only little modified in a plan view during succeeding stages. The lateral erosion was most intense during the initial stages of postglacial valley formation, except the Prienai Loop. Similarly, the vertical incision of the river channel was greatest during the initial stages of the valley development, exponentially decreasing with time (Fig. 4). The rapid channel incision is indicated by terrace dating and numerous thermokarst depressions. Only the lowest terrace was established during the Holocene Epoch, whereas the other terraces are of late Pleistocene age. The base of erosion is related to the ice lake system formed in front of the receding glacier and to the Baltic Sea. The terrace formation is related to the drastic lowering of the erosion base related to the lake system along the margin of the retreating glacier, leading to intense channel incision, while sedimentation marks the equilibrium phase of the river profile.

The rapid incision resulted in the dominantly rectilinear geometry of the valley of the Nemunas River along most of its length. The anomalous sinuosity of some reaches is related to specific local conditions. The Great Nemunas Loops are situated in a tectonic depression; the Merkinė Loop is confined to a distinct tectonic uplift in the south. The tectonic activity (despite being of low rate) impacted the glacial and post-glacial processes and related relief features which, in turn, affected the river formation.

At a regional scale the Nemunas River follows the first-order tectonic zone separating two large-scale crustal domains. Vertical movements of smaller-order blocks caused activity of local structures in the overlying sedimentary cover. Abundant mineral water springs indicate that faults penetrate both the Prequaternary and Quaternary successions, *i.e.* are neotectonically active.

By contrast to the simple-geometry of the Merkinė Loop that coincides with a distinct neotectonic uplift, the Great Nemunas Loops have a more complex shape and are situated in a tectonic depression superimposed by smaller-scale tectonic features. They show persistent activity during the Prequaternary and Quaternary times. The confinement of the Great Nemunas Loops to a neotectonic depression is an essential factor, as the decrease in gradient results in higher sensitivity of the river to small-scale topography undulations. Tectonic structures defined in the sedimentary cover correlate with the tectonic grain of the underlying crystalline basement, such as NE-SW trending basement faults controlling the Balbieriškis uplift and the distinct activity of some W-E striking faults in the north and the south of the study area. Most of basement faults coincide with neotectonic lineaments.

Neotectonic structures influenced the paleogeogaphic situation during retreat of the last glacier. The Birštonas depression hosted the large lake confined between the ice sheet margin in the north and dead ice field in the south. The Veiveriai uplift represented a topographical obstacle for ice advancement. The Nemunas River accommodated the pre-existing topographic low of the Birštonas glaciolacustrine basin (Fig. 3), as indicated by confinement of the valley to the lower glaciolacustrine terrace. It is levelled at 85 m asl, whereas the flanking glaciolacustrine sediments occur at altitudes of 95 to 110 m asl (Fig. 11).

Activity of the Balbieriškis neotectonic uplift accounted for the origin of the largest (10 km) Balbieriškis Loop (Fig. 11). This uplift, well recognised in the Permian-Mesozoic succes-

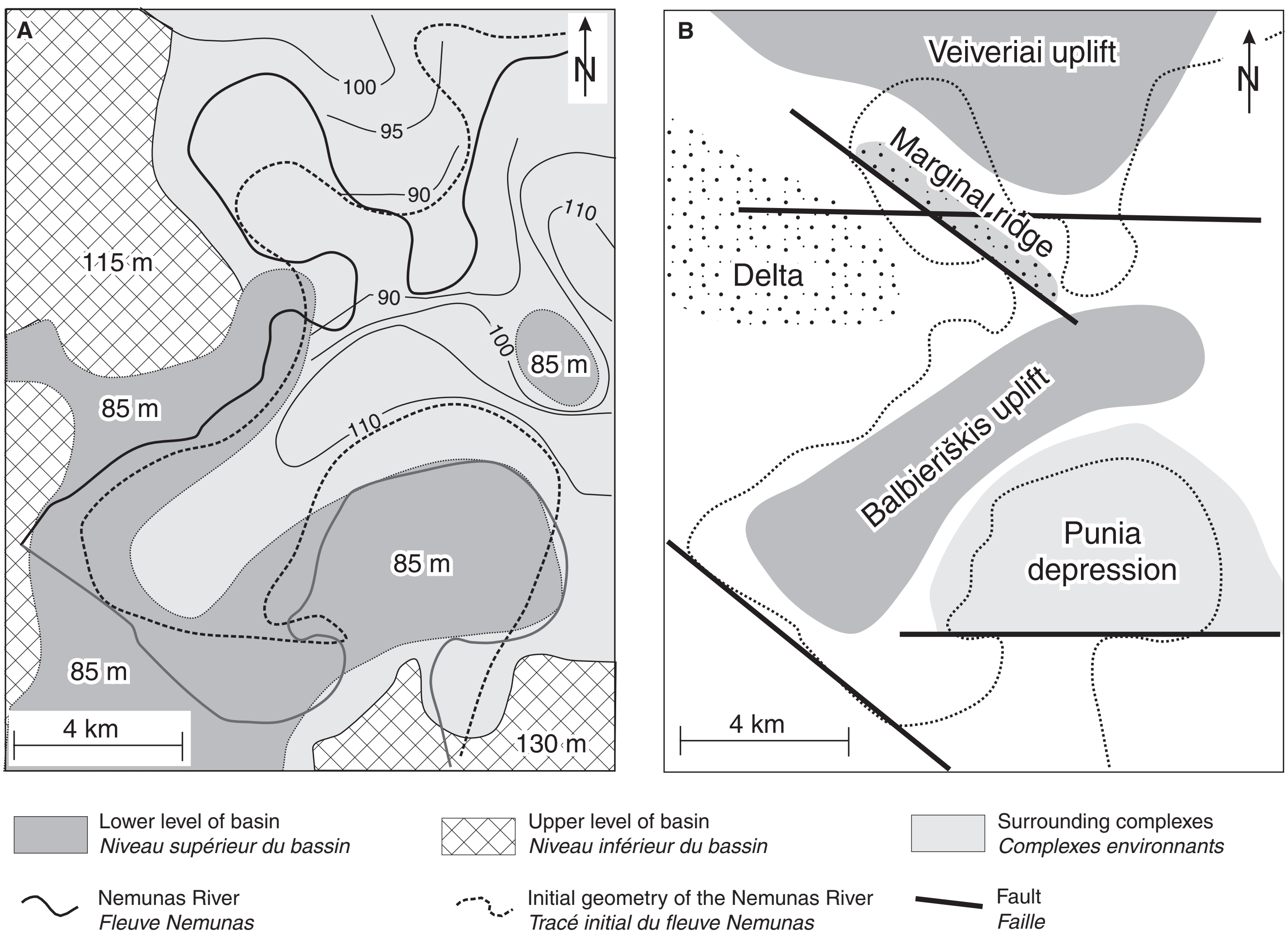



FIGURE 11. (A) Present topography of glaciolacustrine basin sediments and (B) major features controlling looping of the Nemunas River in the Birštonas area.

*(A) Topographie actuelle des sédiments glaciolacustres du bassin et des (B) principaux facteurs de contrôle de la formation des méandres du fleuve Nemunas dans la région de Birštonas.*

sion and the sub-Quaternary surface, also is defined by the lithological pattern of the Quaternary succession, as indicated by a systematic increase of the percentage of the clayey layers in the succession towards the uplift crest (Šliaupa, 1991). Furthermore, the sediments of the Birštonas glaciolacustrine depocentre show a decrease of thickness and basin shallowing trends towards the crest of the Balbieriškis uplift that suggests topographical uplift before the establishment of the Nemunas River. The present elevation of the glaciolacustrine plain is higher (110 m asl) on the Balbieriškis uplift than on the flanks (100 m asl; Fig. 3).

The Punia Loop marks the local neotectonic depression, bounded in the south by west-east trending fault which resulted in sharp changes (about 90°) of the river flow azimuth (Fig. 11). Judging by the altitude differences of the upper terraces, the northern flank was relatively uplifted. Fault activity is corroborated by the W-E trending limit of the glaciolacustrine sediments further east (Fig. 3). In the north the Nemunas River was close to developing a straight valley across the Birštonas uplift. However, rapid incision has favoured preservation of the initial geometry of the Great Nemunas Loops.

The sharp excursion of the Nemunas River to the northwest in the Prienai Loop was caused by the interaction of several factors. Scarce remnants of the glaciolacustrine deposits suggest that the river followed the lower (+80 m) level of the glaciolacustrine topography, which presented a corridor between the delta in the west and marginal moraine ridge in the east. The latter seems to be controlled by the fault zone trending NW-SE (Fig. 9A). This marginal moraine ridge presented the topographic high that changed the river flow from the northeast to the northwest. Further north the river changes flow direction by almost 180° because of the activity of the Veiveriai uplift. This structure is well defined in the present topography of the glaciolacustrine deposits that are tilted to the southeast from 105 to 95 m asl (Fig. 11).

The drilling data indicate that the Nemunas River roughly coincides with an older river system developed in the Holsteinian and Eemian Interglacials. This coincidence is particularly close to the Eemian paleochannel system that is reflected in not only the general river flow direction but also river looping. Persistence of the pattern of the drainage system, regardless of changing paleogeographic situation, points to long-termed favourable conditions that can be reasonably explained only in terms of continuing activity of the underlying tectonic structures.

## CONCLUSIONS

The origin of the Great Nemunas Loops is accounted by a complex interaction of tectonic and paleogeogaphic processes. Channel incision was quite rapid during the initial stages of the valley development, whereas lateral erosion was rather limited. The prominent sinuosity in the Birštonas area was established during this initial stage. The main factor that forced the river to change flow direction is the activity of the tectonic structures. The amplitudes of the vertical movements of the earth's crust are rather small, however they were sufficient to significantly influence the glacial and post-glacial sedimentation processes that formed topographic undulations controlling the river flow. Persistence of these factors is well defined in valley inheritance from the preceding Holsteinian and Eemian interglacial stages. The Nemunas River marks the first-order tectonic zone separating two major basement domains. This transition is complicated by smaller-scale blocks that show activity during Paleozoic-Cenozoic times. The Great Nemunas Loops accommodated the Birštonas depression which is associated with some decrease of the channel gradient, thus resulting in more sensitive reaction of the river to activity of the smaller scale tectonic structures. A paleoglaciolacustrine basin formed in this depression just before the Nemunas River establishment. The basin topography was slightly deformed by neotectonic structures. After the basin was drained the Nemunas River followed the pre-existing topographic lows. The fault tectonics, though minor in terms of vertical displacements, was an important factor that controlled drastic changes of the river direction.

This case study indicates that bed-rock bound rivers of the cratonic areas previously covered by the ice sheet can be significantly influenced by neotectonic activity of ancient structures, even though the magnitudes of displacement are very low. This influence might be of an indirect nature, via the impact of the tectonic structures on the glacial and post-glacial processes and related relief forms that later accommodated the river channels.

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## REFERENCES

Arvidson, R.E., Guiness, E.A., Strbeck, J.W., Davies, G.F., Shulz, K.J., 1982. Image processing applied to gravity and topography data covering the continental U.S. Eos, 63: 257-261.

Baltrūnas, V., Pukelytė, V., Šliaupa, S., 1998. Pietų Lietuvos eolinių nuogulų susidarymo ir paplitimo ypatybės (Formation and distribution of aeolian deposits in South Lithuania). Geologija, 23: 106-118 (in Lithuanian).

Baltrūnas, V., 1995. Pleistoceno stratigrafija ir koreliacija (Stratigraphy and Correlation of the Pleistocene). Academia, Vilnius, 180 p. (in Lithuanian).

Baltrūnas, V., 2002. Stratigraphical subdivision and correlation of Pleistocene deposits in Lithuania (methodical problems). Institute of Geology, Vilnius, 74 p.

Baltrūnas, V., Dundulis, K., Karmaza, B., Gadeikis, S., 2003. Character of erosional landslide processes in the region of the Large Meanders of the Nemunas River. Journal of Environmental Engineering and Landscape Menagement, 11: 100-109.

Basalykas, A., 1956. Nemuno upės paleodinaminės fazės Alytaus-Kauno atkarpoje ir kai kurie neotektoninio aktyvumo klausimai (Paleodynamic phases of the Nemunas River between Alytus and Kaunas and some neotectonic considerations). Lietuvos TSR mokslų akademijos darbai, serija B, 4: 55-67 (in Lithuanian).

Basalykas, A., 1965. Lietuvos TSR fizinė geografija, II (Physical Geography of Lithuania SSR, II). Mintis, Vilnius, 492 p. (in Lithuanian).

Basalykas, A., 1977. Fiziniai geografiniai Nemuno baseino ypatumai (Physical geographical pecularities of the Nemunas River basin), p. 16-34. *In* J. Maniukas, ed., Nemunas, 1. Mokslas, Vilnius, 124 p. (in Lithuanian).

Baškytė, R. and Kulbis, A., 2000. Great Nemunas Loops. Lututė, Kaunas, 100 p. (in Lithuanian and English).

Berryman, K., Marden, M., Eden, D., Mazengarb, C., Ota, Y. and Moriya, I., 2000. Tectonic and paleoclimatic significance of Quaternary river terraces of the Waipaoa River, east coast, North Island, New Zealand. New Zealand Journal of Geology and Geophysics, 43: 229-245.

Burnett, A. and Schumm, S.A., 1983. Neotectonics and alluvial river response. Science, 222: 49-50.

Chamyal, L.S., Maurya, D.M., Bhandari, S. and Raj, R., 2002. Late Quaternary geomorphic evolution of the lower Narmada valley, Western India: Implications for neotectonic activity along the Narmada-Son Fault. Geomorphology, 46: 177-202.

Cordell, L. and McCafferty, L., 1989. A terracing operator for physical property mapping with potential field data. Geophysics, 54: 621-634.

Dvareckas, V., 1976. Stroeniye i razvitiye rechneekh dolin Litvee v pozdnelednikoviye i golotsene (Structure and development of river valleys in Lithuania during the late glacial and Holocene), p 51-57. *In* A. Basalykas and V. Gudelis, eds., Geographia Lituanica. Academy of sciences, Vilnius, 319 p. (in Russian).

Dvareckas, V., 1993. The development of the Lithuanian river valleys in late glacial and Holocene. Geografija, 29: 13-18.

Ehlers, J., 1996. Quaternary and Glacial Geology. John Wiley, Chichester, 578 p.

Gaigalas, A., 1979. Glatsiosedimentatsionniye tsikli pleistotsena Litvee (Glaciosedimentation cycles of the Lithuanian Pleistocene). Mokslas, Vilnius, 98 p. (in Russian).

Gaigalas, A., and Melešytė, M., 2001. Nemuno ledynmečio nuogulų paplitimas ir sudėtis (Distribution and composition of the Nemunas Glaciation), p. 46-54. *In* V. Baltrūnas, ed., Stone Age in South Lithuania (according to geological, paleogeographical and archaeological data). Institute of Geology, Vilnius, 260 p. (in Lithuanian).

Gaigalas, A. and Micas, L., 1967. K voprosu ozerno-liednikovogo osadkoobrazovaniya v raiyone srednikh techeniy rek Nemunas i Neris v pozdnelednikoviye (On varved deposits of glaciolacustrine character in the Nemunas and Neris River valleys during the Postglacial period). Lietuvos TSR mokslų akademijos darbai, serija B, 2: 141-148 (in Russian).

Gaigalas, A., Pazdur, A., Halas, S., Pawlyta, J. and Kazakauskas, V., 2001. Stable isotopes as record of climatic changes of Daniglacial in Lithuania. Geochronometria, 20: 81-86.

Guobytė R., 2002. Lithuanian surface: geology, geomorphology and deglaciation. Abstract of doctoral dissertation, Vilnius University, Lithuania, 31 p.

Holmes, A., 1944. Principles of Physical Geology. Thomas Nelson, Edinburg, 509 p.

Kabailienė, M., 1990. Lietuvos holocenas (Holocene of Lithuania). Mokslas, Vilnius, 175 p. (in Lithuanian).

Kaveckis, M., 1928. Vasaros 1926 metų geologinės ekspedicijos darbų apyskaita (Geological Expedition report of Summer 1926). Lietuvos universiteto matematikos-gamtos fakulteto darbai, IV: 220-263 (in Lithuanian).

Kolupaila, S., 1940. Nemunas. Šviesa, Kaunas, 220 p. (in Lithuanian).

Knox, J.C., 1996. Late Quaternary Upper Mississippi River alluvial episodes and their significance to the Lower Mississippi River system. Engineering Geology, 45: 263-285.

Kudaba, C., 1983. Lietuvos aukštumos (The Uplands of Lithuania). Mokslas, Vilnius, 188 p. (in Lithuanian).

Drobnys, A. (ed.), 1981. Lietuvos TSR atlasas (Atlas of Lithuania SSR). Valstybinis plano komitetas, Maskva, 216 p. (in Lithuanian and Russian).

McDonald, A.J.W., Fletcher, C.J.N., Carruthers, R.M., Wilson, D. and Evans, R.B., 1992. Interpretation of the regional gravity and magnetic surveys of Wales, using shaded relief and Euler deconvolution techniques. Geological Magazine, 129: 523-531.

Micas, L., 1959. Nemuno slėnio struktūra Merkinės-Prienų ruože (Structure of Nemunas valley in Merkinė-Prienai segment). Lietuvos TSR MA Geologijos ir geografijos institutas, Moksliniai pranešimai, Geologija, Geografija, 10: 27-45 (in Lithuanian).

Mikaila, V., 1958. Lietuvos stambesniųjų limnoglacialinių baseinų nuosėdos ir jų ryšiai su paskutiniuoju ledynu (Sediments of the large glaciolacustrine basins of Lithuania and their connections with the last glaciation). Lietuvos TSR MA Geologijos ir geografijos institutas, Moksliniai pranešimai, Geologija, Geografija, 7: 5-17 (in Lithuanian).

Miller, A.A., 1935. The entrenched meanders of the Herefordshire Wye. Geographical Journal, 85: 158-178.

Obedientova, G.V., 1975. Formirovaniye rechneekh sistem russkoy ravninee (Formation of river systems of Russian Plain). Nedra, Moscow, 174 p. (in Russian).

Peakall, J., 1998. Axial river evolution in response to half-graben faulting: Carson River, Nevada. Journal of Sedimentary Research, 68: 788-799.

Raj, R., Mulchandani, N., Bhandari, S., Maurya, D.M. and Chamyal, L.S., 2004. Channel shifting of a highly sinuous meandering river in alluvial plain, Vishwamitri river, Mainland Gujarat. Current Science, 86: 1647-1653.

Saint-Laurent, D. and Guimont, P., 1999. Dynamique fluviale et évolution des berges du cours inférieur des rivières Nottaway, Broadback et de Rupert, Jamésie (Québec). Géographie physique et Quaternaire, 53: 389-399.

Schumm, S.A., Dumont, J.F. and Holbrook, J.M., 2000. Active Tectonics and Alluvial Rivers. Cambridge University Press, Cambridge, 276 p.

Sirocko, F., Szeder, T. , Seelos, C., Lehne, R., Rein, B., Schneider, W.M. and Dimke, M., 2002. Young tectonic and halokinetic movements in the North-German-Basin: its effect on formation of modern rivers and surface morphology. Netherlands Journal of Geosciences, 81: 431-441.

Skridlaitė, G. and Motuza, G., 2001. Precambrian domains in Lithuania: evidence of terrane tectonics. Tectonophysics, 339: 113-133.

Sladkopevtsev, S.A., 1977. Noveishiy etap razvitiya rechneekh dolin (The newest stage of development of river valleys). Nedra, Moscow, 200 p. (in Russian).

Šliaupa, A., 1978. Sviaz' sovremennogo reliyefa i gidrograficheskoy seti Yuzhnoy Pribaltiki s geologo-tektonicheskim stroiyeniyem (Correlation of the recent relief and drainage system of the southern Baltic region with the geological and tectonic structures). Geologija ir Geografija, 14: 103-110 (in Russian).

Šliaupa, A., 1997. The sub-Quaternary relief of Lithuania and of adjacent territories. Litosfera, 1: 46-57.

Šliaupa, A., 1998. Neotectonic structures of Lithuania and adjacent territories. Litosfera, 2: 37-46.

Šliaupa, S., 1996. Major neotectonicaly active fault zones in Lithuania. Lithosphere, Litosfera, 5: 108-115.

Šliaupa, S., 2002. Influence of the last glaciation to stress field and tectonic activity of faults of the Baltic region. Geologija, 39: 12-24.

Šliaupa, S., 2003. Neotectonics as a hazardous factor. Annual Report of Lithuanian Geological Survey for 1999, p. 35-37.

Šliaupa, A., Gelumbauskaite Z., Straume J. and Šliaupa S., 1995. Neotectonic structure of eastern part of Baltic Sea and adjacent land area. Technika Poszukiwan Geologicznych, 3: 63-65.

Šliaupa, A., Kondratas, A. and Imbrasaitė, G., 1986. Tektonicheskiye usloviya formirovaniya mineralneekh vod kurortov Druskininkai i Birshtonas (Tectonic conditions of the formation of mineral waters in the healt resorts of Druskininkai and Birštonas). Geologija, 7: 49-58 (in Russian).

Šliaupa, S., Bitinas, A. and Zakarevicius, A., 2005. Predictive model of the vertical movements of the earth's surface with respect to the land use of the Lithuanian coastal area. Recent Developments in Environmental Protection, Social Strategies, 40: 221-235.

Šliaupa, S., and Popov, M., 1998. Linkage between basement and neotectonic linear structures in Lithuania. Litosfera, 2: 36-45.

Voznyachuk, L.N., and Valczyk, M.A., 1978. Morfologiya, stroiyeniye i istoriya razvitiya dolinee Niemana v neopleistotsene i golotsene (Morphology, geology and development of the Niemen valley in Neopleistocene and Holocene). Nauka i tekhnika, Minsk, 212 p. (in Russian).