Origin of the Great Nemunas Loops, South Lithuania
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Résumé de l'article
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 km² 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’Eémien et du Holsteinien sur lesquelles elle repose.
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 km² 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 glacio-lacustrine 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.

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RESUME  Origine des Grandes Boucles du Nemunas, sud de la Lituanie. Le fleuve Nemunas, un des plus grands fleuves de la région baltoque, est caractérisé par une vallée généralement rectiligne. À la mi-course du Nemunas, les Grandes Boucles occupent un territoire de 320 km² dans la zone de villégiature de Birštonas. Ces méandres, d’une largeur de 6 à 10 km, entaillent une plaine glacio-lacustre confinée entre des complexes glaciaires et deltaïques formés au cours des deux dernières phases de déglaçiation. 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 des 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 paléovallees interglaciaires de l’Eemien et du Holsteinien sur lesquelles elle repose.
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; Charnyi 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, Balbieriskis, Prienai, and Birštonas loops. They form a most distinct feature occupying an area of 320 km² 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, 1969; Basalykas, 1977; Dvareckas, 1976). 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).

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
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 more than 1000 hydrogeological wells. The results of granulometric, mineralogical, petrophysical, geochemical, and palaeontological (microfauna, spores, pollen, etc.) studies provide a basis for stratigraphic subdivision and correlation of wells and outcrops (Šiaupa, 1978; Baltroinas, 1995, 2002). The conditions of deposition of glacial sediments are reconstructed based on measurements of azimuth and inclination of gravel and shingle long axes combined with petrographic studies of gravel and pebbles (Gaigalas, 1979; Gaigalas and Melėlytė, 2001). Air-borne remote sensing was employed for stratigraphical and genetic interpretation of geological bodies. The interglacial conditions have been reconstructed by Baltroinas (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 (Šiaupa and Popov, 1998). Gravity and magnetic maps (scale of 1:50 000 and 1:200 000) were automatically interpreted 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 (Šiaupa, 2000).

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 (Šiaupa 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 Grotučiai (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; Balškytė and Kubiš, 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 substrates of the second stage (Baltija = Pomeranian) of the Last Glaciation (Nemunas = Weichselian), undulating and strongly eroded glaciolacustrine 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 masses 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 glaciolacustrine delta identified in the northwest of the study area (Fig. 3). The glaciolacustrine basin accumulated sandy clays, giving way to unwarped sandy clays in the central part of the basin between Birštonas and Nemaižiai 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 5th terrace is 27-32 m above the river channel, and the 1st 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 flow events. Based on radiocarbon dating of the peat overlying alluvial deposits (Baltoinas, 2003).
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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), Buteinai (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), Zemaitija (Odra = Drenthe = Dnieper), Medininkai (Warta = Moskva = Illinoian), Varduva (Öwiecie = Kalinin), Grūda (Leszno-Poznan = Weichselian = Wisconsinan = Valdaja) and Baltija (Pomerania = Ostaszkow) sub-formations (Fig. 5; Baltrunas, 2002).

The reconstruction of the paleogeomorphological conditions indicates the inheritance of the Nemunas valley (Baltrunas, 2002). The oldest underlying paleovalley is identified in the Buteinai (Holsteinian) Interglacial that was recorded in numerous boreholes (Baltrunas, 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.
Upper Silurian limestone (S2)
Calcaire du Silurien supérieur (S2)

Upper Permian limestone, marl, anhydrite, and gypsum (P2)
Calcaire, marne, anhydrite, et gypse Permien supérieur (P2)

Nemunas Formation of Lower Triassic sandstone and clay (T1nm)
Formation de Nemunas : grès et argile du Triassique inférieur (T1nm)

Palanga Formation of Lower Triassic clay and marl (T1pl)
Formation de Palanga : argile et marne du Triassique inférieur (T1pl)

Taurage Formation of Lower Triassic limestone (T1tr)
Formation de Taurage : calcaire du Triassique inférieur (T1tr)

Upper Jurassic sand and clay (J3)
Sable et argile du Jurassique supérieur (J3)

Lower Cretaceous glauconitic sand (K1)
Sable glauconitique du Crétacé inférieur (K1)

Upper Cretaceous glauconitic sand, marl, and chalk (K2)
Sable, marne et craie glauconitique du Crétacé supérieur (K2)

Quaternary deposits/Dépôts quaternaires
Till (dn: Dainava, zm: Žemaitija, md: Medininkai, vr: Varduva, gr: Gruda, and bl: Baltija tilles)
Tills (dn : Dainava, zm : Žemaitija, md : Medininkai, vr : Varduva, gr : Gruda, and bl : Baltija)

Clay
Argile

Silt
Limon

Silty sand
Sable limoneux

Sand
Sable

Sand with gravel
Sable avec gravier

Gravel
Gravier

Borehole
Trou de forage

Fault
Faille

FIGURE 5. Geological cross-section of the Great Nemunas Loops (see Fig. 3 for location).
Coupé géologique des Grandes Boucles du Nemunas (voir fig. 3 pour la localisation).

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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 (Silaupa, 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 (Silaupa and Popov, 1998). Smaller scale buckles, 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...
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 Palaeozoic 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 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 (Šlaupa et al., 2005). The most distinct subsidence (-4 m) occurs in the Sapotskin depression. The Veisiejai-Šačiūninkeliai uplift is reflected in a positive deformation (+2 m) that likely caused formation of the Merkinia 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 trending

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.
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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.

straight segment of the Balbieriskis 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 Birtonas Resort. It is comparable to only the Druskininkai Resort located 90 km to the south of Birtonas. 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 Balbieriskis 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; Chamyat 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 tectonic 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 Birtonas 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, exponen- tally 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 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 Merkine 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 paleogeographic 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-

![Diagram](https://example.com/diagram.png)

**FIGURE 11.** (A) Present topography of glaciolacustrine basin sediments and (B) major features controlling looping of the Nemunas River in the Birštonas area.
ers in the succession towards the uplift crest (Šiaupė, 1991). Furthermore, the sediments of the Biržtonas glaciolacustrine depocentre show a decrease of thickness and basin shallow-
ing trends towards the crest of the Balbieriškis uplift that sug-
gests topographical uplift before the establishment of the Nemunas River. The present elevation of the glaciolacustrine plan 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 Biržtonas 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 north-
west in the Priena Loop was caused by the interaction of sev-
eral factors. Scarse remnants of the glaciolacustrine deposits suggest that the river followed the lower (c.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. 5A). This marginal moraine ridge pre-
vented 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 Veiviriai 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 Inter glacials. This coincidence is par-
ticularly close to the Eemian paleochannel system that is re-
lected in not only the general river flow direction but also river looping. Persistence of the pattern of the drainage sys-
tem, 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 paleogeographic 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 Biržtonas 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 inter-
glacial stages. The Nemunas River marks the first-order tec-
tonic zone separating two major basement domains. This tran-
sition is complicated by smaller-scale blocks that show activity during Paleozoic-Cenozoic times. The Great Nemunas Loops accommodated the Biržtonas 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 paleoglacialustrine basin formed in this depression just before the Nemunas River establish-
ment. The basin topography was slightly deformed by neo-
tectonic structures. After the basin was drained the Nemunas River followed the pre-existing topographic lows. The fault tec-
tonics, 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 sig-
nificantly influenced by neotectonic activity of ancient struc-
tures, 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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