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EARLY MIOCENE BRAIDED RIVER AND LACUSTRINE SEDIMENTATION IN THE KALNIK MOUNTAIN AREA (PANNONIAN BASIN SYSTEM, NW CROATIA)

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Abstract: Early Miocene deposits of fresh-water environments are characteristic in the Kalnik Mountain area, at the SW marginal zone of the Pannonian Basin System. Alluvial and lacustrine sediments varying from gravel to marl accumulated by different depositional processes during the Ottnangian. In the early, alluvial phase pebbly braided rivers developed. Deposition was characterized mostly by bar conglomerates and flood plain siltstones. Alluvial deposition was controlled by both autocyclic and allocyclic processes, in a semi-arid climate. During the later, lacustrine phase, sedimentation was mostly represented by marls and occasional coarser material, in a humid climate. Fresh-water deposition was terminated by marine transgression during the Karpatian. Lower Miocene fresh-water deposits of the Kalnik Mountain can be correlated with similar deposits in the wider area of Northern Croatia. The Kalnik Mountain represents the boundary area between two Early Miocene basins, the north-western one being characterized by marine deposition, and the south-eastern by contemporaneous fresh-water deposition, both belonging to the Central Paratethys.

Key words: Croatia, Early Miocene, braided river, hydrologically open lake, synsedimentary tectonics.

Introduction

The Lower Miocene sedimentary complex of the Kalnik Mountain (Figs. 1, 2) disconformably overlies Mesozoic-Paleogene basement, but in some localities the contacts are tectonic (Šimunić et al. 1981, 1982, 1994; Fig. 3). The total thickness of the Lower Miocene complex is approximately 470 m (Šimunić et al. 1982). The stratigraphic dating of these deposits is still uncertain. On the basis of marine, brackish and fresh-water faunas the deposits were correlated with coal bearing deposits of Oligocene age (Poljak 1942; Anić 1952). Later, this complex was interpreted as marine to brackish-water neglecting the existence of fresh-water sediments, and dated as Egerian to Eggenburgian in age (Šimunić et al. 1981).

Recent investigations at the Kalnik Mt demonstrate the presence of unfossiliferous red beds directly overlying Egerian-Eggenburgian fossiliferous deposits. However, a part of the Lower Miocene succession contains an assemblage of sporomorphs and fresh-water algae which have not been found in this area before. They allow correlation with similar deposits of Ottnangian age in the Pannonian Basin System. Early Miocene sedimentation came to an end with deposition of marine marls during the Karpatian time (Hećimović 1995). There is thus a relatively complete Lower Miocene succession in the Kalnik Mt (Fig. 5). The nature of the transition between the stages, as well as the areal distribution is unknown at present, and the Lower Miocene complex is still not covered by geological maps in details. In order to determine the depositional evolution of the Lower Miocene fresh-water succession of the Kalnik Mt and to correlate it with deposits in other parts of Northern Croatia, two geological sections, located in the central part of the mountain have been investigated in details (Figs. 3, 5, 6). Lower Miocene fresh-water deposits are subdivided into a Lower, unfossiliferous unit, and an Upper unit with fresh-water fossils.

Geological setting

The Miocene rock complex of the Kalnik Mountain belongs to the south-western marginal area of the Pannonian Basin System (Figs. 1, 2). The sediments were deposited in the Central Paratethys bioprovince (Rögl & Steininger 1983; Rögl 1998). The pre-Miocene basement is geotectonically interpreted as part of the Supradinaricum, that is the NW part of the Inner Dinarides (Herak et al. 1990). The formation of the Pannonian Basin System commenced in the Early and the Middle Miocene as the consequence of the continental collision of the

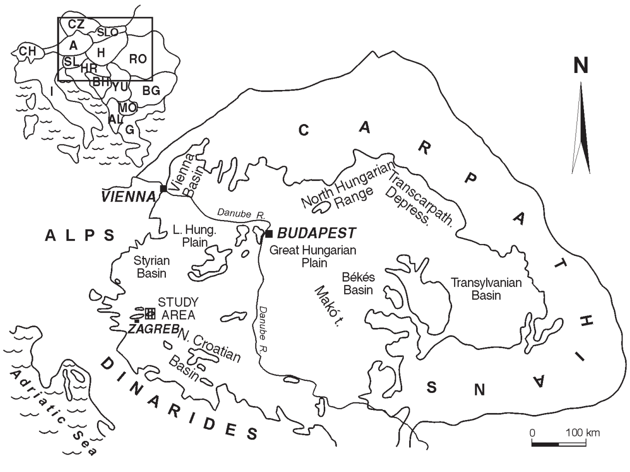


Fig. 1. Geotectonic position of the Pannonian Basin System, with location of study area.

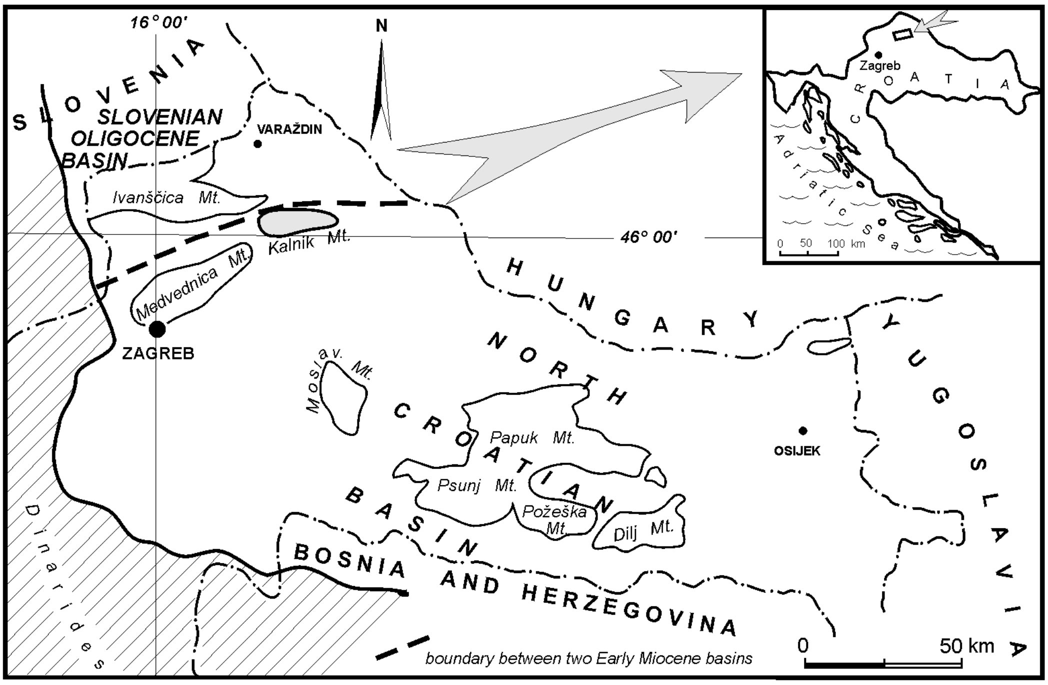


Fig. 2. Location map of Kalnik Mt. The boundary between Slovenian Oligocene Basin and North Croatian Basin is marked in the area of Kalnik Mt and Medvednica Mt.

African (= Apulian) and European plates, and deposition in the entire basin was influenced by important extensional tectonics (Horváth & Royden 1981; Royden 1988; Horváth 1993; Kováč et al. 1997).

Marine connections between the Central Paratethys, Mediterranean and Indopacific oceans were temporarily established and interrupted during the Miocene (Rögl & Steininger 1983; Rögl 1998). The isolated nature of the Central Paratethys has led to establishment of a local system of Miocene stages (Fig. 4). During transgressions, especially in the Early Miocene, the Central Paratethys was not flooded completely. Therefore, the underlying deposits were disconformably covered by deposits of different ages, ranging from the Early to the Late Miocene. In the Early Miocene deposition took place in different environments, including marine, brackish and fresh-water, and in some parts of the basin continental environments also existed temporarily (Rögl & Steininger 1983; Rögl 1998; Sztanó & Józsa 1996; Kováč & Hudáčková 1997; Hudáčková et al. 2000).

Lower Miocene (Ottnangian) fresh-water sediments represent a part of Rzehakia (= Oncophora) Beds, and cover large areas of the Paratethys. They are probably of Late Ottnangian or, maybe, Early Karpatian age (Rögl & Steininger 1983; Rögl 1998; Nagymarosy & Müller 1988). Lower Miocene fresh-water deposits in the neighbouring Styrian Basin (Fig. 1) studied by multi-disciplinary stratigraphical methods are of Ottnangian age (Steininger 1998).

Lower unit of fresh-water deposits

Description and interpretation of facies

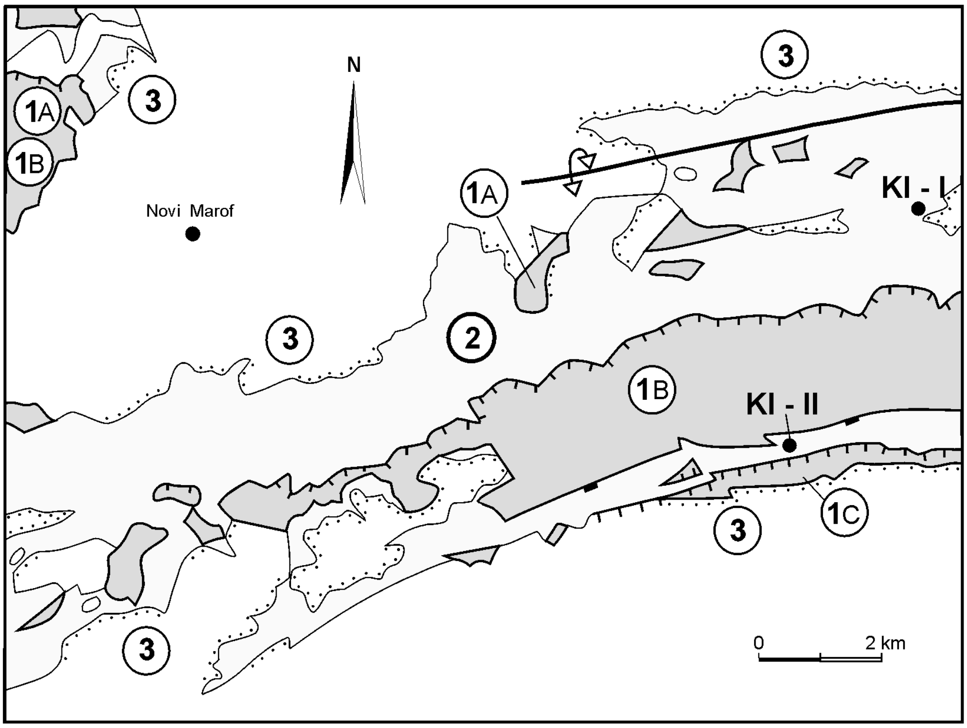
The lower, unfossiliferous part of the succession is 62.8 m thick and consists of siliciclastic rocks (Fig. 6). It is characterized by the predominance of siltstones in the lower part, and common alternations of conglomerates and sandstones in the upper part.

The sediments are subdivided into eight facies, which form fining- and coarsening-upward cycles. The lower part of the fresh-water deposits forms two megacycles, with the lower characterized by coarsening-upward trend (Fig. 6).

Facies Gc — massive clast-supported conglomerates

This facies occurs in the upper part of the succession of the Lower unit (Fig. 6). The conglomerates form horizontally bedded clast-supported massive beds, 40–130 cm thick. Their lower boundaries are erosional. The clasts are mostly of coarse pebble size, while cobbles are uncommon and mostly found in the basal part of units. Clasts up to 26 cm in diameter are very rare. The matrix is composed of coarse-grained sandstone to fine-pebble conglomerate, and in some places the facies is characterized by a bimodal composition. The matrix content is very variable, although it generally increases towards the upper parts of most beds. In some cases pebbles are imbricated (type $a_{(t)}b_{(i)}$).

The facies represents deposits of very powerful currents, as indicated by erosional lower boundaries, clast size and imbrication of the $a_{(t)}b_{(i)}$ type. The bimodal composition and variable portion of matrix indicate multi-storey accumulation of material, suggesting pulsation of the current velocities (Steel & Thompson 1983). The structures of the conglomerates and their massive appearance indicate deposition on longitudinal bars (according to Smith 1974; Rust 1978; Steel & Thompson 1983). The cobbles in the basal parts of some beds represent basal lags. The increased matrix content in the uppermost parts of some fining-upward beds is explained by gradually decreasing current velocities.



LEGEND: 1A Middle-Upper Triassic: dolomite, dolomitic breccia, limestone boulders; 1B Cretaceous: sandstone, shale, marl, limestone, chert, diabase, spilite; 1C Paleogene: carbonate breccia; 2 Lower--Middle Miocene: sandstone, conglomerate, marl, clay; 3 Upper Miocene - Quaternary: sandy and clayey limestone, marl; transgressive boundary; nappe front; subsided block; overturned anticline axis; KI -I, II position of the sections

Fig. 3. Geological sketch-map of the investigated area (simplified after Šimunić et al. 1982).

Facies Gp — planar cross-bedded conglomerates

This facies also occurs in the upper part of the Lower unit (Fig. 6). Beds are 50 to 110 cm thick, and have erosional lower boundaries. The conglomerates are mostly clast-supported, rarely matrix-supported, and are characterized by planar cross-bedding. Clast sizes range from coarse pebbles and rarely to fine cobbles up to 9 cm long. The matrix is well sorted coarse-grained sandstone.

The clast size (up to 9 cm) and erosional lower boundaries indicate strong currents, while planar cross-bedding suggests deposition by avalanching mechanisms. The bed thickness (up to 110 cm) indicates relatively large bedforms which could be transversal bars migrating in channels of gravelly braided rivers (Smith 1974; Steel & Thompson 1983).

Facies Ge — conglomerate lenses

This facies occurs throughout the succession of older deposits, with increased abundance in the upper part (Fig. 6). The conglomerate beds are lens-shaped, 10–40 cm thick and up to 5 m long. They are most common within siltstones of facies F2 or overlying conglomerates of facies Gc or Gp. Conglomerates of facies Ge are clast-supported, with clasts ranging in size from fine- to medium-grained pebble, rarely with cobbles up to 8 cm wide. The matrix is coarse-grained, well- to medium-sorted sandstone. Some clasts show imbrication of $a_{(t)}b_{(i)}$ type.

The facies Ge was deposited from high velocity currents, as indicated by erosional lower boundaries and clast size (up to 8 cm). The imbrication of the $a_{(t)}b_{(i)}$ type indicates deposition by bed-load traction. Association with siltstones of facies F2, interpreted as flood plain deposits, indicates deposition in similar alluvial environments. The conglomerates might represent crevasse channel deposits (Steel 1974; Hughes & Lewin 1982). Outcrops where conglomerate lenses cover bar deposits (facies Gc and Gp) probably represent deposits in shallow channels cutting into bars during periods of waning flow (Rust 1978; Steel & Thompson 1983).

Facies Sh — horizontally laminated sandstone

This type of sandstone occurs in the central and upper parts of the measured succession of the Lower unit (Fig. 6). The sandstones most commonly alternate with conglomerates of the facies Gc, while sporadically they cover sediments of the facies Ge (Fig. 6). The sandstones are medium to well sorted and form 20–40 cm thick beds characterized by horizontal lamination and irregular lower boundaries. They are medium- to fine-grained, and contain rare pebbles up to 2 cm in size.

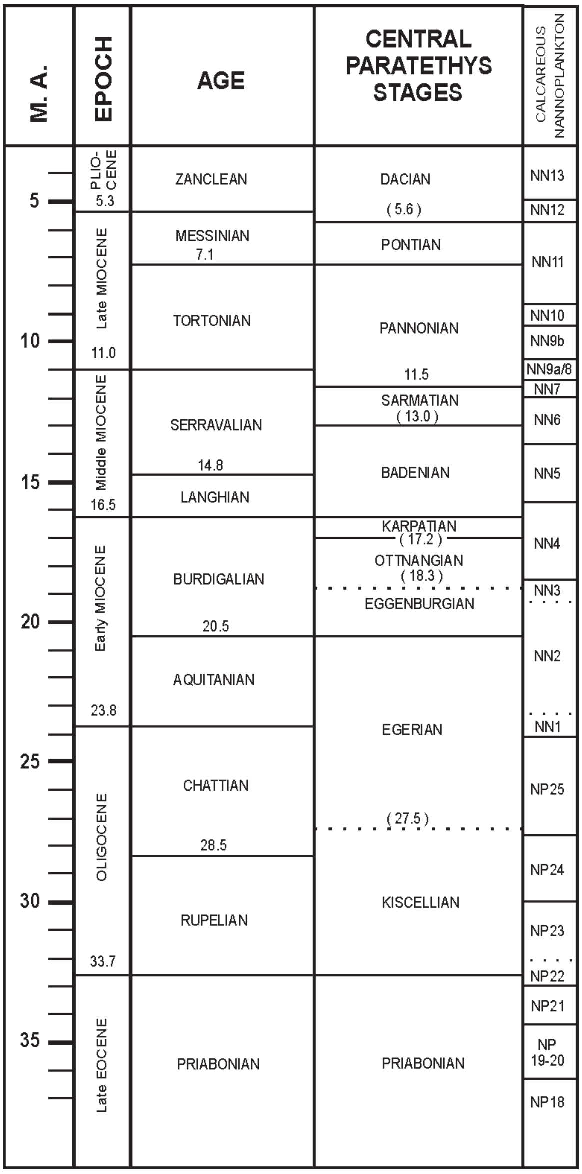


Fig. 4. Chronostratigraphic scheme showing the correlation of the Central Paratethys stages to the standard time scale (after Rögl 1998).

Fine- to medium-grained bioturbated sandstones in the central and upper part of the succession of older deposits, were also included in this facies in spite of their massive appearance. They form units 100 to 210 cm thick (Fig. 6).

The grain size and horizontal lamination indicate deposition by traction in the upper flow regime, while their overlaying conglomerates of the facies Gc and Ge suggest deposition on bars and in shallow channels in periods of waning flow after the flood, and at lower water levels (Rust 1978). The presence of relatively thick beds could be explained by long-lasting uniform depositional conditions. The bioturbation was probably caused by small mammals.

Facies Sr — cross-laminated sandstone

This facies occurs only at the top of the Lower unit (Fig. 6), and alternates with conglomerates of the facies Ge. They form two units, 15 and 20 cm thick, respectively. The lower boundaries are irregular. The beds are characterized by a weakly expressed fining-upward trend.

The grain size and cross-lamination indicate deposition by traction from currents in the lower flow regime. The position of the cross-laminated sandstones overlying conglomerates of the Ge facies and the fining-upward trend suggests sediment deposition in shallow channels under lower flow regime conditions.

Facies Se — sandstone lenses

Sandstones of this facies occur in the lower and central part of the Lower unit (Fig. 6), where they are interbedded with sediments of facies F1 and F2 (Fig. 6). They form 6–20 cm thick lenses, extending laterally up to 6 m in outcrop. Their erosional bases were originally concave up. The sandstones are fine- to coarse-grained, in some places passing into silt sized sediments, and are characterized by a fining-upward trend and medium sorting. Cross-lamination occurs sporadically.

Occurrences of cross-lamination indicate deposition by traction in the lower flow regime. The fining-upward trends indicate decreasing of flow velocities. Depositional structures, lensoid geometry and position within sediments of facies F1 and F2 interpreted as flooding plain deposits, suggest a crevasse splay origin (Steel 1974; Hughes & Levin 1982; Guccione 1993).

Facies F1 — massive siltstone

This type of siltstone occurs in the middle part of the succession of the Lower unit (Fig. 6). Siltstone is interbedded with sandstone lenses of facies Se. The siltstone units are 10–250 cm thick, and their lower boundaries are irregular. They are massive, very well sorted, and characterized by grey colour.

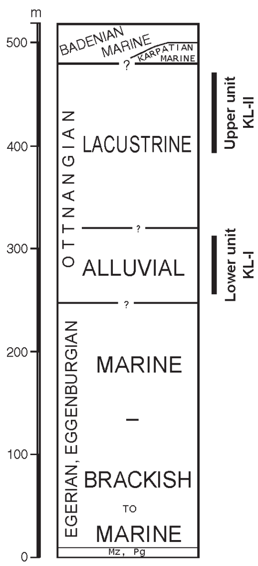


Fig. 5. Environmental changes in the Lower Miocene succession with the stratigraphic position of the sections KL-I and KL-II at Kalnik Mt. Compiled and simplified after Šimunić et al. (1981, 1982), Hećimović (1995) and Pavelić (1998).

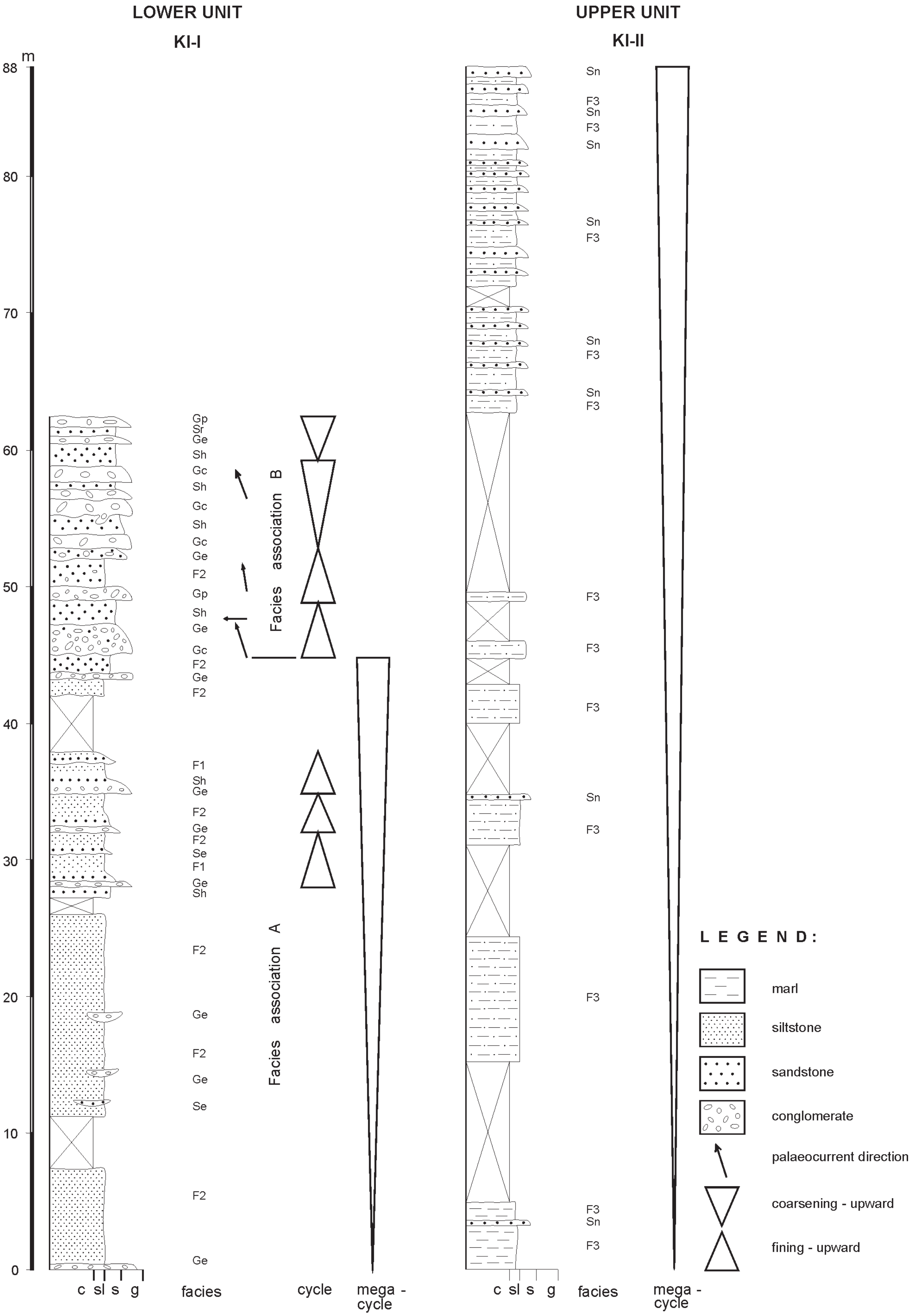


Fig. 6. Sections KL-I and KL-II show the Ottnangian sedimentary evolution of the fresh-water environments at Kalnik Mt. The stratigraphic position of the sections see in Fig. 5. Facies codes are explained in the text.

The massive siltstones were deposited from suspension, characterized by very weak flow. The massive nature, thickness and interbedding with sandstone of facies Se indicate deposition on a flood plain. The environment was not characterized by reworking in subaerial conditions, as indicated by sorting, colour and lack of bioturbation. These characteristics also suggest frequent floods in part of the flood plain relatively close to the river channel.

Facies F2 — modified siltstone

This type of siltstone occurs in the entire succession of the Lower unit except the uppermost part, and it represents the predominant lithotype in the lower and middle part of the succession (Fig. 6). The siltstone contains lenses of facies Se and Ge. In one outcrop the siltstones are underlain by facies Gp, and overlain by facies Gc (Fig. 6). The facies form 0.2–14 m thick units, and their lower bedding planes are irregular. The siltstones contain irregular sandy zones, and uncommon pebbles up to 0.7 cm in diameter. The siltstones are very rarely clayey, the sorting is poor, and the structure massive. They contain carbonate nodules and ferruginous concretions and scattered coal clasts. The sediments are partially bioturbated, and predominantly by dark red or sporadically grey spots.

Siltstones were deposited out of suspension from very weak flow, and the thickness up to 14 m indicate persistance of very similar conditions. The association with facies Se, Ge, Gp and Gc, which are interpreted as alluvial, and the lack of fauna, suggest the same depositional environment. In alluvial settings thick successions of siltstones are common in flood plains (Rust 1978; Miall 1996). Coal fragments could originated from the Egerian-Eggenburgian sediments which commonly contain coal beds (Šimunić et al. 1981).

The siltstones show some signs of post-depositional alteration. The red pigmentation, in some places dark-red, could be a result of chemical disintegration of unstable ferruginous minerals and diagenetic covering of detrital grains by hematite in conditions of rapid drying, temporary moisturizing and high temperatures (review in Collinson 1996). The formation of concretions could also have been generated by drying and infiltration of minerals into the soil. The very rare irregular sandy zones and small pebbles in the siltstone probably represent a sedimentary substitute for rotten vegetation roots. Facies F2 is accordingly interpreted as a paleosoil.

Paleotransport

Measurement of 31 imbricated platy pebbles from alluvial conglomerates of facies Gc and Ge in the Lower unit indicate flow direction towards the NW (Figs. 6, 7). However, the newest paleomagnetic results from Lower Miocene sediments from north-western Croatia show moderate counter-clockwise rotations generated by tectonic events in the Pliocene (Márton et al. 2001). It means that the real flow directions might be towards the N.

Vertical facies relationships

Vertical alternation of facies, and changes in average grain size in the Lower unit show small cycles and two megacycles.

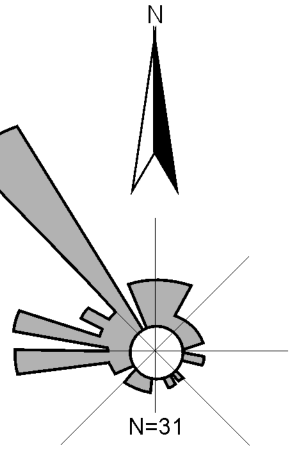


Fig. 7. Paleocurrent rose-diagrams from alluvial conglomerates show flow direction generaly towards NW. However, the block might be moderate CCW rotated in the Pliocene.

Facies associations

Two facies associations are recognized in the Lower unit. Facies association A comprises the lower and middle part of the Lower unit (0–45 m, Fig. 6). It is composed of siltstone facies (F2 and F1) deposited in flood plain, mostly influenced by subaerial conditions. It contains conglomerate lens facies (Ge), and horizontally laminated sandstones facies (Sh), which represent shallow channels, and sandstone lens facies (Se), interpreted as crevasse splays.

The upper part of succession is represented by Facies association B. It is composed of massive clast-supported conglomerates (Gp) interpreted as longitudinal bar deposits, planar cross-bedded conglomerates (Gp) interpreted as deposited on transversal bars, conglomerate lenses (Ge), cross-laminated sandstones (Sr) deposited in shallow channels, horizontally laminated sandstones (Sh) representing bar covers, and altered siltstones (F2) interpreted as paleosoil facies.

Interpretation

The association of sediments deposited predominantly by traction currents on a flood plain indicates an alluvial depositional environment for the Lower unit (Fig. 8). The conglomerate bodies interpreted as longitudinal and transversal bar deposits, and the lack of sediments deposited by gravity flows suggest a pebbly braided river (Williams & Rust 1969; Rust 1978; Smith 1974; Steel & Thompson 1983).

A predominance of flood plain sediments (F2 and F1) in Facies association A is probably a consequence of distal position with respect to the active channel, while thick deposits indicate a frequent supply of fine-grained material by floods. Active flow probably occurred from time to time, resulting in formation of crevasse channels and splays. The succession is characterized by dominant flood plain over channel deposits indicate deposition in the lower alluvial plain of the braided river (Fig. 8).

A characteristic of a pebbly braided river is the small preservation potential of flood plain deposits, as braided flows show a tendency to occupy the entire river valley, resulting in ero-

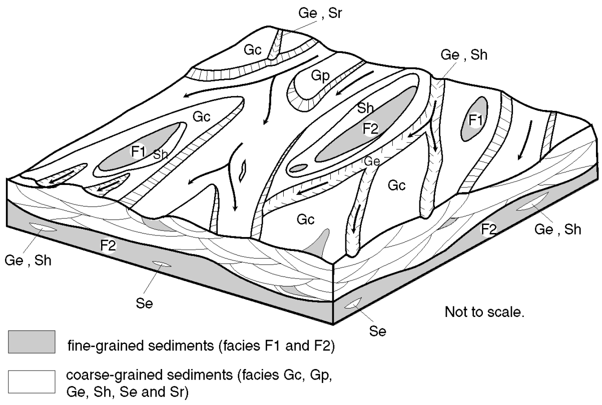


Fig. 8. Block-diagram shows facies model for an early Ottnangian pebbly braided river at Kalnik Mt. A relatively abrupt transition from the flood plain to the channel belt is marked. Facies code explanation see in the text.

sion of fine-grained deposits. The flood plain deposits have a high preservation potential in conditions of free movement of the river channel belt because of lack of valley walls which would restrict this process (Friend 1978). Shifting of the channel belt could also be restricted by vegetation. However, traces of vegetation are very uncommon, indicating unfavourable, semi-arid conditions. The same conditions are indicated by the appearance of carbonate nodules in the siltstones of facies F2 and lack of coal beds, which are common in alluvial successions in regions with a humid climate. The flood plain deposits of Facies association A is unusually thick. Therefore, the succession and preservation of the flood plain deposits in the braided river system, following an unrestricted valley, could be attributed to the rapid subsidence of the basin by tectonic influence, when the possibility of erosion of fine-grained deposits is minimal (see Miall 1996).

Facies association B was mainly deposited in a high-energy environment. Pebbly facies, especially river bars (Gc and Gp), was deposited by active flow (Fig. 8). Variable grain sizes, from silt-sized particles to cobbles 26 cm in diameter, indicate changes in flow velocities, while the frequency of oscillations suggest pulsating character of the currents, which might be attributed to seasonal events.

Vertical tendency — cycles and megacycles

In the lower part of the succession, both fining-upward or coarsening-upward cycles are found. Fining-upward cycles are dominant in the middle and upper part of the succession, where coarsening-upward cycles may occur seldom (Fig. 6).

The fining-upward cycles have an erosional base and show a gradual decrease in average grain-size, associated with a thinning of the conglomerate beds. In the middle part of the Lower unit succession (Fig. 6), in Facies association A, the erosional surface is overlain by conglomerates (Ge) and sandstones (Sh), which are interpreted as crevasse channel deposits. They are followed by flood plain siltstones (F2 and F1), including thin crevasse splay sandstones (Se). In the upper part of the sequence, in Facies association B, the basal parts of the fining-upward cycles are composed of channel lag and bar conglomerates (Gc and Gp) overlying erosional surfaces (Fig. 6). They are covered by shallow channel conglomerates (Ge) and bar blanket conglomerates (Sh) or modified siltstones of the flooding plain (F2).

Coarsening-upward cycles are characterized by gradual increase of clast lengths in bar conglomerates (Fig. 6, 56–59 m interval) or in a sharp transition from bar blanket sandstones to bar conglomerates (Fig. 6, from 59 m to the top).

In the lower and middle part of the Lower unit (Facies association A), a gradual coarsening-upward trend in clast size is recognized (Fig. 6, from the base of the section to 45 m). This trend is indicated by increasingly common occurrences of conglomerate and sandstone facies with respect to siltstone facies. Therefore, deposits of the Facies association A may be regarded as a single coarsening-upward megacycle.

The conglomerates with erosional bases of fining-upward cycles in Facies association A indicate a sudden beginning of a deposition under high-energy conditions, while the fining-upward trend indicates gradual decrease of the flow velocity. The interpretation of the conglomerates as crevasse channel fills, and their vertical transition into flood plain siltstones suggests that deposition might have been generated by floods. The predominance of flood plain deposits in Facies association A indicates intense flood plain development by input of fine-grained material by weak floods. The coarse-grained material was deposited only occasionally, during strong floods, when crevasse channels were formed, in which pebble-sized sediments were deposited, overlain by sandstones. Isolated layers of sandstone within the siltstone suggest sporadic, relatively weak floods, resulting in the formation of crevasse splays. The interpretation of these cycles as the consequence of flood events suggests independence of external influences, that is the influence of autocyclic processes in the flood plain.

The erosional base and composition of the fining-upward cycles in Facies association B also indicate abrupt onset of depositional events followed by gradual weakening of flow velocities. The vertical stacking pattern of the cycles suggests repetition of events. The facies sequences indicate vertical aggradation of bars and formation of macroforms. As bars grow vertically, flow velocity decreases, resulting in deposition of fine-grained sediments, mostly sands forming bar blankets. Some sandstone units are intensely burrowed by small mammals at the top, suggesting subaerial emergence. Only in one example was bar aggradation concluded by flood plain siltstones, which may be explained by lateral channel migration. The maximal depths of braided channels were mostly 0.5 to 1 m, but in some cases more than 2.5 m. The fining-upward cycles of Facies association B indicate dominance of autocyclic processes in formation of the upper part of the alluvial deposits.

The coarsening-upward cycles in Facies association B indicate increasing water energy. The composition of the lower cycle (Fig. 6, 56–59 m) indicate vertical aggradation of bars comprising progressively longer clasts, probably due to the increasing flow velocities. The uppermost cycle is composed of deposits of a different facies, as the result of a specific sequence of depositional events (Fig. 6). The sandstones in the cycle base, interpreted as sediments of bar blankets, were deposited during water lowstands, and their thickness (1.8 m) indicate long periods of deposition by relatively weak flows, as a consequence of the lateral migration of the channel. Bioturbation recorded in the uppermost part of this unit might indicate long-lasting dry conditions, perhaps associated with abandonment of the channel. Shallow channel conglomerates in the middle part of the cycle reflect a new flow and deposition of coarse-grained material under higher energy conditions. The formation of a transverse pebble bar in the upper part of the cycle indicates very high energy and deposition in the active channel. The topmost coarsening-upward unit may have formed by gradual filling of a temporarily abandoned channel, as reactivation of abandoned channels is a process typical for braided river systems (cf. Costello & Walker 1972). Such cycles thus most likely represent autocyclic processes in the alluvial environments.

The coarsening-upward megacycle in Facies association A (Fig. 6, from bottom to 45 m) reflects increasing occurrences of sediments deposited in progressively higher energy environments. This trend represents a consequence of increasingly common formation of crevasse channels and splays in the flood plain, due to stronger floods. The upwards increase in grain size could be attributed to the approach of the active channel belt, due to progradation of the alluvial system.

The upper boundary of the megacycle (Fig. 6, 45 m level) is characterized by an abrupt transition from the flood plain (Facies association A) to the channel belt (Facies association B) (Fig. 8). The Upper unit deposits are generally interpreted as deposits of pebbly braided river, and the migration of the channel belt may be explained in two ways. Relatively rapid tectonic subsidence probably caused preservation of a thick flood plain succession, and tectonic activity may have forced channels into more rapidly subsiding areas of the flood plain (cf. Bridge & Leeder 1979).

Upper unit of fresh-water deposits

Description and interpretation of facies

The upper unit deposits were investigated in an 88 m thick section (Fig. 6). They are dominated by marls (F3), while sandstones (Sn) are subordinated. The succession shows a vertical coarsening-upward trend, recognizable in the upward increase in occurrence and gradual thickening of sandstone beds.

Facies Sn — normally graded sandstones

The sandstones are most common in the upper part of the Upper unit, while they are rare in the lower part (Fig. 6). They alternate with marls of facies F3 (Fig. 6). The sandstones appear as interbeds 1–20 cm thick, occasionally up to 60 cm thick, with obvious trend of bed thickening towards the upper part of the succession (Fig. 6). The bases of the sandstone beds are erosional or flat. The sandstones are mostly fine-grained, rarely medium-grained, with good to very good sorting. Thinner beds (<20 cm) show millimetre scale horizontal lamination in the lower part and normal grading. In some beds marl intraclasts are found. Thicker beds (>20 cm) exhibit no lamination, and appear massive. The sandstones contain tiny fragments of carbonized plant remains.

The weakly erosional bed bases indicate deposition from low velocity flows, while the grain-size and horizontal lamination in the thicker beds suggest deposition from sandy high-concentrated turbidity currents (Lowe 1982). Parts of beds without lamination were also probably deposited from turbidity currents. Normal grading indicates gradual waning of flow. The beds may have been deposited directly out of suspension from sandy high-concentrated turbidity currents, where traction mechanisms are suppressed due to the fast deposition (Lowe 1982). Massive and relatively thick sandstones may also have been deposited from "quasi-steady currents" which do not deposit sediment *en masse* but continue to flow, while sediment aggrades (Kneller & Branney 1995). The massive structure of the thicker beds suggests deposition from underflows (hyperpycnal flows), formed when river water containing large quantities of material due to the difference in density and water temperature descend below the lake water-level and deposit material at the bottom (Talbot & Allen 1996). Sandstones containing marl intraclasts indicate an erosive system and/or relatively close source. They could represent sediments also deposited from such "quasi-steady currents".

Facies F3 — horizontally laminated marls

Marl is the prevailing facies in the Upper unit. Marls show a gradual tendency of decreasing occurrence towards the upper parts of the succession and are interlayered with facies Sn (Fig. 6). The marl units are from 3 cm to 8 m thick, generally thinning upward in the succession. The marl beds have flat bases. Marls are rarely very silty, show millimeter-scale horizontal lamination and are grey to dark-grey.

Marls commonly contain fragments of partially carbonized continental plants, but also completely preserved leaves, mostly concentrated in some laminae. The marls contain sporomorphs and fresh-water algae throughout all the succession (Fig. 9). The sporomorphs include those of subtropical ferns. *Leiotriletes* cf. *wolffi* W. Krutzsch 1962 is typical of Ottnangian coal-bearing sediments. *Polypodiaceoisporites cyclocingulatus* W. Krutzsch 1967, *Polypodiaceoisporites schoenewaldensis* W. Krutzsch 1967 and *Polypodiaceoisporites corrutoratus* Nagy 1985 (Planderová 1990) occur in Lower and Middle Miocene deposits. The pollen *Pterocaryapollenites stellatus* (R. Potonie 1931) Thiergart 1937, forms *minor* and *media* also occurs, and is characteristic of the Early Miocene, while individual specimens of *Pterocaryapollenites stellatus* f. *media* indicate the Ottnangian (Planderová 1990). Tricolpate pollen (probably *Quercuspollenites*) has also been determined. The coniferae are represented by the somewhat more common pollen *Pinuspollenites* type *Haploxylon*. This type of pollen is most common in Lower Miocene deposits (Planderová 1978). The green alga *Botryococcus braunii* Kützing 1849 is typical of temperate to tropical fresh-water environments throughout the Tertiary, but is more common in deposits of Ottnangian and Upper Badenian–Sarmatian (Planderová 1990). The palynofacies composition is characterized by a dominance of vitrinite, accompanied by more or less amorphous liptinite. The palynological assemblage clearly indicates fresh-water environments, and suggests the Ottnangian MF-4 microfloristic zone (Planderová 1990).

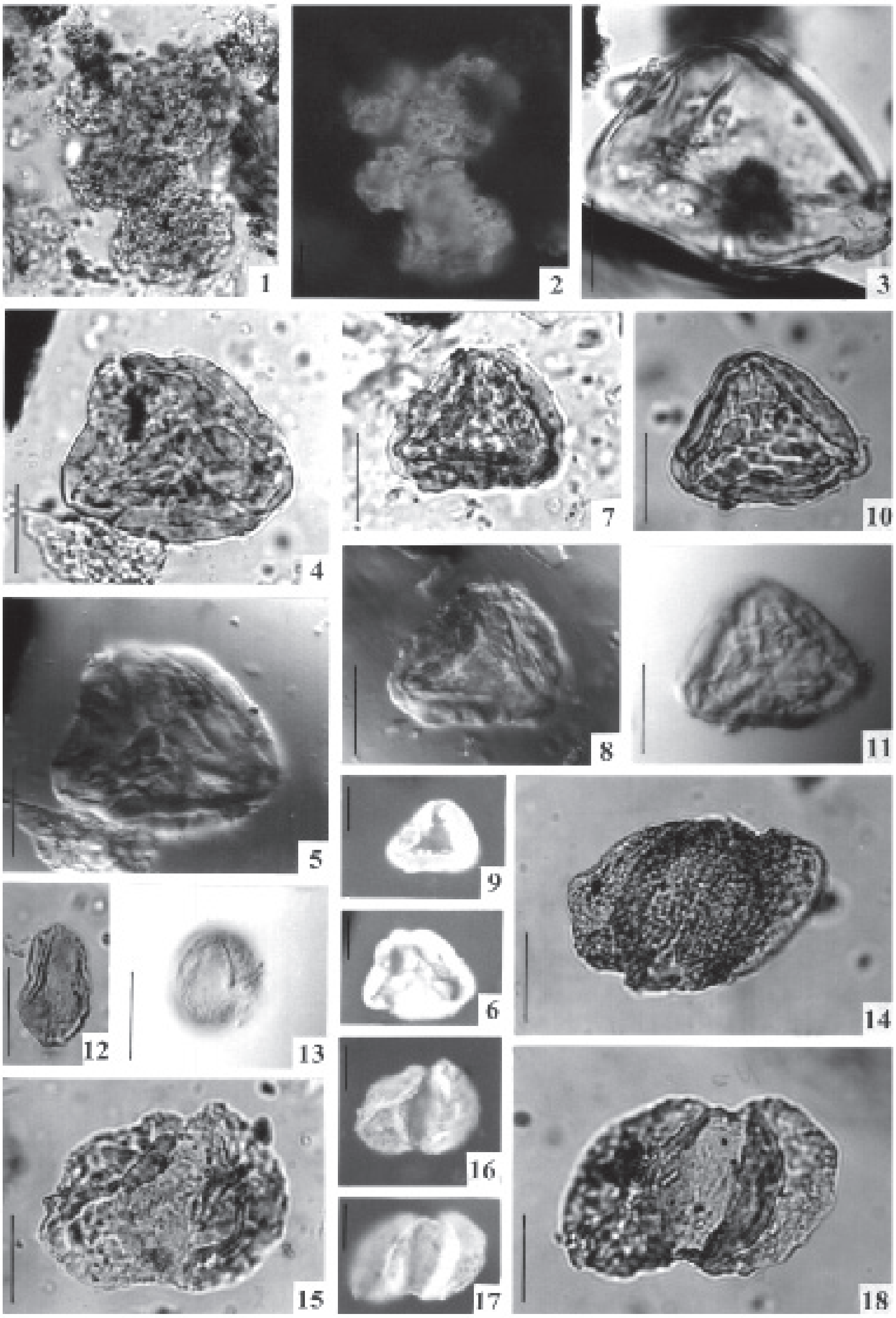


Fig. 9. **1.** *Botryococcus braunii* Kützing 1849. Sample A. — Transmitted light. **2.** *Botryococcus braunii* Kützing 1849. Sample A. — Fluorescence light. **3.** *Leiotriletes* cf. *wolffi* W. Krutzsch 1962. Sample 1/21. — Interference contrast. **4.** *Polypodiaceoisporites corrutoratus* Nagy 1985. Sample 1/27. — Transmitted light. **5.** *Polypodiaceoisporites corrutoratus* Nagy 1985. Sample 1/27. — Interference contrast. **6.** *Polypodiaceoisporites corrutoratus* Nagy 1985. Sample 1/27. — Fluorescence light. **7.** *Polypodiaceoisporites cyclocingulatus* W. Krutzsch 1967. Sample 1/27. — Transmitted light. **8.** *Polypodiaceoisporites cyclocingulatus* W. Krutzsch 1967. Sample 1/27. — Interference contrast. **9.** *Polypodiaceoisporites cyclocingulatus* W. Krutzsch 1967. Sample 1/27. — Fluorescence light. **10.** *Polypodiaceoisporites schoenewaldensis* W. Krutzsch 1967. Sample B. — Transmitted light. **11.** *Polypodiaceoisporites schoenewaldensis* W. Krutzsch 1967. Sample B. — Interference contrast. **12.** *Pterocaryapollenites stellatus* (R. Potonie 1931) Thiergart 1937 forma *media*. Sample A. — Transmitted light. **13.** *Tricolporopollenites* sp. Sample 1/21. — Interference contrast. **14.** *Pinuspollenites* type *Haploxylon.* Sample B. — Transmitted light. **15.** *Pinuspollenites* type *Haploxylon.* Sample A. — Transmitted light. **16.** *Pinuspollenites* type *Haploxylon.* Sample A. — Fluorescence light. **17.** *Pinuspollenites* type *Haploxylon.* Sample B. — Fluorescence light. **18.** *Pinuspollenites* type *Haploxylon.* Sample B. — Transmitted light. Scale bar = 20 μm.

The facies commonly contains dispersed, monotypic assemblages of fresh-water molluscs *Pisidium* sp. with both shells preserved. Analysis of calcareous nannoplankton indicated complete lack of the Miocene species.

The marls were deposited in very quiet conditions, as indicated by grain-size and small and thin shells of molluscs. The horizontal lamination and molluscs paleoecology indicate fresh-water lacustrine environment, while the dark colour, remains of terrestrial plants and lack of bioturbation indicate frequent anoxic conditions and deposition below thermocline, in a relatively deep lake. This interpretation is supported by interlayering with sandstones deposited by gravity flows (facies Sn).

The palynological assemblage indicate deposition in a fresh-water basin fed by rivers, which transported fragments of terrestrial plants, sporomorphs of ferns and higher plants inhabiting the river banks, but also with eolian input of coniferae pollen from somewhat higher environments. The prevalence of vitrinite over amorphous liptinite suggests dominating anoxic conditions at the lake floor.

Facies association

The facies association is composed of marls (facies F3) with sandstones beds (facies Sn) (Fig. 6). The upper part of the Upper unit exhibits a general thickening and coarsening-upward trend, indicated by increasing number and thickness of sandstone beds, accompanied by thinning of the marl beds (Fig. 6).

The marls (facies F3) of the Upper unit were deposited in a fresh-water lake, mainly in the basinal part (Murphy & Wilkinson 1980) (Fig. 10). The lake was relatively deep, as indicated by lack of bioturbation and probably of carbonized remains of continental plants caused by anoxic conditions. Abundant continental plants in lacustrine deposits indicate humid climate during deposition. The transition from alluvial to deep-water lacustrine deposition may reflect onset of a new tectonic phase in the extensional basin.

Gravity flows which transported terrigenous material into lake, could have been generated by resedimentation of formerly deposited unconsolidated material in the delta front, or the material was deposited from underflows directly from a river during floods on the land. Sandstones (facies Sn) and marls (facies F3) indicate alternation of short-lived periods characterized by input of terrigenous material by gravitational flows with long-lived periods of quiet basinal deposition typical for a prodelta (Fig. 10). The coarsening and thickening up nature indicate constant progradation of the prodelta.

The further Miocene depositional sequence is unclear in Kalnik Mt. Lower Miocene fresh-water deposits are transgressively overlain by Badenian deposits (Fig. 5) (Šimunić et al. 1981, 1994). Karpatian marine deposits may, however, also be present, implying that the lacustrine phase was succeeded by reestablishment of marine deposition already by the end of the Early Miocene (Hećimović 1995). This event is the consequence of short-lasting marine transgression, which in the Karpatian affected wide areas of the Pannonian Basin System due to the opening of a Paratethyan seaway to the Mediterranean along the middle Slovenian corridor (Rögl & Steininger 1983). In the area of neighbouring Medvednica Mt this marine transgression is explained by subsidence due to tectonism (Pavelić et al. 2000).

Correlation of Ottnangian fresh-water deposits between Sava and Drava rivers

The succession of Ottnangian fresh-water deposits at the Kalnik Mt can be lithostratigraphically correlated with similar rocks described from hills between the Sava and Drava rivers in the Early Miocene North Croatian Basin (Fig. 2) (Pavelić 1998, 2001). The presence of alluvial deposits and their transition into lacustrine deposits at the Medvednica Mt was recognized by Basch (1983). The alluvial part of these sediments was deposited in a pebbly braided river flowing towards the N-NE and E, in a semi-arid climate (Pavelić et al. 1995). Lacustrine deposits at the Medvednica Mt were laid down in a hydrologically open lake, formed during a humid period (Pavelić 1998). Deposition was regressive with development of coarse-grained fan delta close to the end of the lacustrine phase, under the influence of synsedimentary tectonics. At the Moslavačka Mt marsh and lacustrine deposits contain remnants of *Dinotherium bavaricum* Kaup (Fig. 2) (Krizmanić 1995). At the Psunj and Papuk Mountains a transition from alluvial to lacustrine environments was also documented, and deposition was connected with tectonic activity (Jamičić et al. 1987). The deposits at Papuk Mt were laid down in a hydrologically open lake in humid climate (Pavelić et al. 1998). Alluvial and lacustrine deposition at the Požeška Mt were influenced by synsedimentary tectonics (Šparica & Buzaljko 1984; Pavelić 1988). Alluvial deposition took place in braided alluvial fans in a semi-arid climate, and transport was generally towards the north (Pavelić & Kovačić 1999). The lacustrine environments at Požeška Mt developed during a period of humid climate (Pavelić 1998, 2001). Deposition at all these localities

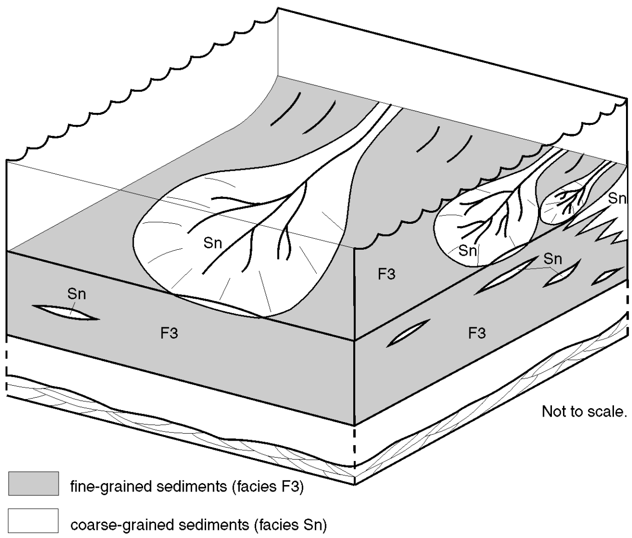


Fig. 10. Block-diagram shows facies model for a lake at Kalnik Mt which evolved over pebbly braided river sediments. Prodelta progradation was a characteristic for the late Ottnangian. Facies code explanation see in the text.

was terminated in the Karpatian by establishment of marine environments (Basch 1983; Jamičić et al. 1987; Šparica & Buzaljko 1984; Pavelić 1998, 2001).

The Ottnangian succession was thus characterized by a transition from alluvial to lacustrine environments in the wide area between the Sava and Drava rivers. The climatic conditions were similar at all localities. During the alluvial phase the climate was semi-arid, while humid conditions characterized the period of lacustrine deposition. The alluvial deposits generally show overall transport towards the north, but sometimes varying from NW to E. Terrestrial deposition was terminated at all localities by marine transgression in the Karpatian. Sedimentation was strongly influenced by tectonic activity throughout the Early Miocene (Pavelić 2001).

The succession from alluvial to lacustrine environments in the whole region suggests a regional character of this event, indicated by similar climatic changes and relatively similar alluvial transport directions. The hydrologically open nature of the lakes suggests that they were connected (Kochansky-Devidé & Slišković 1978), or perhaps there was one, very large lake (Pavelić 1998, 2001). During the Ottnangian fresh-water environments existed in the area between the Sava and Drava rivers, while penecontemporaneous deposition in the area west of the Kalnik Mt took place in marine environments (Fig. 2) (review in Šimunić 1992). Evolution of the depositional area west of the Kalnik Mt started already in the Egerian, and was a part of the seaway between the Mediterranean and the Central Paratethys. This succession can be correlated with the youngest part of the Slovenian Oligocene Basin fill (Fig. 2) (*sensu* Jelen et al. 1992). The succession of Kalnik Mt comprises the oldest Miocene deposits, which have not been found east of this mountain. The Ottnangian fresh-water deposits lacking in the Miocene basin west of Kalnik Mt are characteristic of the SE situated area. It might be concluded that this mountain represented a boundary zone between two basins in the Early Miocene: the Slovenian Oligocene Basin with marine sedimentation untill the Early Miocene on the NW and the Early Miocene North Croatian Basin, characterized by fresh water sedimentation during the Ottnangian on the SE (Fig. 2).

Conclusion

Ottnangian fresh-water deposition in the area of Kalnik Mt took place in alluvial and lacustrine environments following each other.

1) In the early (alluvial) phase pebbly braided rivers developed, represented mainly by bar conglomerates and flood plain siltstones. Paleocurrent data indicate transport towards the north-west, and the climate was semi-arid. Alluvial deposition was controlled by both autocyclic and allocyclic processes.

2) The alluvial phase was followed by the lacustrine phase later, mostly represented by marls and occasional coarser material deposited from sediment gravity flows, mainly turbidity currents. The end of the lacustrine phase, which was characterized by a humid climate, was characterized by prevalence of sand deposition, in a prograding deltaic environment.

3) Synsedimentary tectonics generated subsidence of the basin, which resulted in formation and preservation of a thick succession of flood plain deposits in the pebbly braided river environment. Tectonic activity constantly caused lateral migration of the channel belt or progradation of the alluvial system and was succeeded by formation of a deep lake. Prodelta progradation took place during the period of reduced intensity of tectonic activity by the end of the lacustrine phase.

4) The succession of fresh-water deposits, climatic conditions and influence of the synsedimentary tectonics of the Kalnik Mt area are very similar to the evolution of fresh-water environments at the Medvednica, Psunj, Papuk and Požeška Mts.

5) The Kalnik Mountain area represents a boundary zone between two contemporaneous basins during the Ottnangian. One was located in the area north-west of Kalnik Mt, and was characterized by marine deposition. It can be correlated with the younger part of the sedimentary succession of the Slovenian Oligocene Basin. In the same period, the second, North Croatian Basin was located south-eastward of Kalnik Mt, and was characterized by deposition in fresh-water environments.

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