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Evidence for a very low-energy fluvial system: a case study from the dinosaur-bearing Upper Triassic rocks of Southern Poland

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The Upper Triassic succession in S Poland in which dinosaur bones have been found consists predominantly of siltstones and claystones. Three units are distinguished. The lowermost and the uppermost units reflect an alluvial environment, whereas the middle one represents lacustrine facies. The lower alluvial unit is interpreted as a record of ephemeral, sinuous, suspended-load channels with rapid vertical accretion. Channel barforms are lacking. The environment is interpreted as a low-energy anastomosing fluvial system. The clayey middle unit is interpreted as having formed in a wide long-lived lake. The top of the lacustrine deposits shows signs of vertisol-type pedogenesis, most probably under subtropical conditions, with seasonally-induced wet and dry intervals. The upper unit reflects a low-energy meandering river system. Silty point bars were abundant and the channels migrated freely. The energy level of this fluvial system was slightly higher than that of the earlier one, which is interpreted as an effect of base-level lowering in combination with an increasingly humid climate. The almost exclusively silty/clayey alluvial deposits represent an exceptionally rare facies. The drainage basin must have been an extremely flat lowland. The presence of vertebrate bones within the anastomosing and meandering river deposits indicates that low-energy alluvial plains were apparently favourable habitats for both reptiles and amphibians during the Late Triassic: under the subtropical, seasonally dry conditions, the animals must have preferred moist low areas, i.e. the flood basins and abandoned channels on the flat valley floors.

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INTRODUCTION

The Upper Triassic (Keuper) deposits of the German Basin are developed in Middle Europe as a thick, regressive succession. It is widely accepted that the epicontinental Muschelkalk sea evolved into a brackish basin, then into a continental playa interrupted by some marine ingressions. Exposures of the Keuper are rare in Poland. One of them is an abandoned open-cast mine of claystones and siltstones near Krasiejów in the Opole Lowland, directly south of the Mała Panew River valley (Fig. 1A, B). This site has become famous in the last decade due to finds of numerous vertebrates, representing one of the most important events in Polish geology at the end of the 20th century. These include amphibians such as capitosauroids and phytosaurs (the first find of *Metoposaurus diagnosticus* in Poland) and reptiles (among others the dinosaur *Silesaurus opolensis*) (Dzik *et al*., 2000; Dzik, 2001, 2003; Sulej, 2002). The Keuper amphibians and reptiles were found in three bone-bearing horizons, which are present in the lower and upper part of the excavated succession (Fig. 1C, D).

A reconstruction of the sedimentary environment of the deposits with the bone horizons is the main objective of this study. A detailed sedimentological study of the Krasiejów site was published 30 years ago (Bilan, 1975) and another paper has appeared recently (Szulc, 2005), but our study of the depositional environment comes to significantly different conclusions.

GEOLOGICAL SETTING AND PREVIOUS STUDIES

The Upper Triassic deposits of Poland are developed as a monotonous succession without clear marker horizons. All lithostratigraphic correlations are consequently difficult and still uncertain. Bilan (1975) suggested that the lower part of the upper Keuper in the Opole Lowland correlates with the “Upper Gypsum Series” (late Carnian), and the upper part (containing the

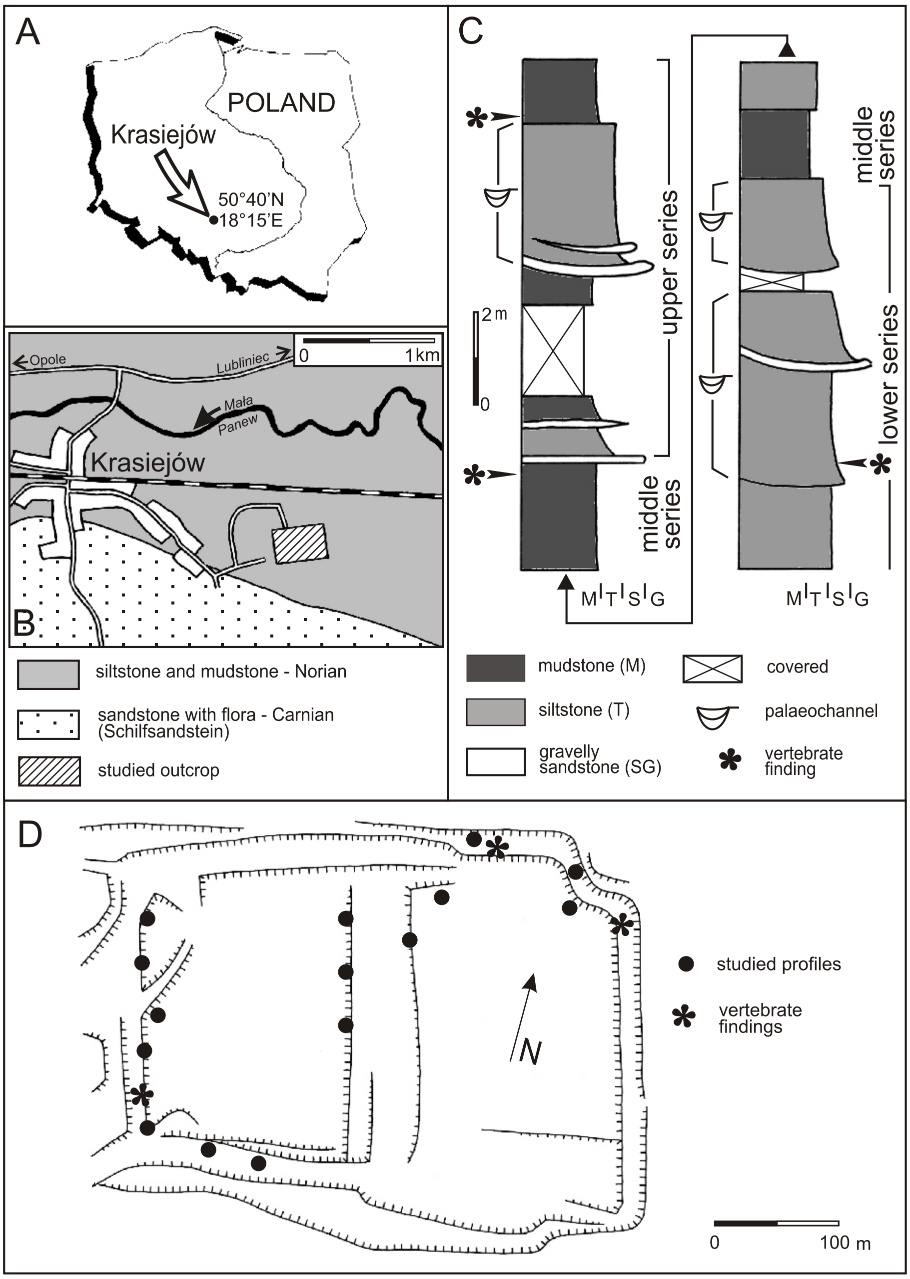


Fig. 1. Geological setting of the Krasiejów site

A — position of the Krasiejów site within Poland; **B** — schematic geology of the Krasiejów area, without Quaternary cover; **C** — simplified sedimentological log of the Krasiejów sections (note the position of the bone-bearing horizons); **D** — detailed map of the outcrop with location of the studied profiles

bone-bearing section) with the "Lisów Breccia". The stratigraphic position of the latter is still not clear; it used to be correlated with the Jarkowo Beds or Zbąszynek Beds, i.e. with the mid or late Norian (Grodzicka-Szymanko, 1971; Mader, 1997).

The fauna encountered so far has not provided new insights into the stratigraphy of the Krasiejów deposits. The reptiles are comparable to those from the Carnian Red Sandstone Formation, a Polish equivalent of the Schilfsandstein (Dzik *et al*., 2000) in the German Triassic. The silty/clayey Krasiejów Beds lack sandstones and therefore must be younger, correlating rather with the Norian Drawno Beds. Dzik *et al*. (2000) and Dzik (2001, 2003) considered that the Krasiejów bone-bearing horizons correlate with the German Untere Bunte Mergel Formation, i.e. with the Carnian, whereas Sulej (2002) correlated them with the Drawno Beds, i.e. with the Norian. The latter view is supported by the lack of gypsum intercalations. This corresponds well with the opinion of Deczkowski *et al*. (1997), that the sedimentation of gypsum had stopped in the Opole Lowland at the Carnian–Norian boundary. Taken together, the chronostratigraphy of the Krasiejów profile is still uncertain in detail, but a correlation with the late Carnian and/or Norian is most likely (Fig. 2).

All species found in Krasiejów (vertebrates, bivalves, crustaceans, foraminifers) lived in a fresh-water environment (Dzik *et al*., 2000; Olempska, 2004), but Zatoń and Piechota (2003) do not exclude marine brackish conditions, as suggested by the sodium content in these beds.

Bilan (1975) investigated two sedimentary units in cores from nearby boreholes. He interpreted the lower one, built mainly of cross-stratified claystones and siltstones, as deposited by a meandering river. The upper one, built of massive claystones and siltstones intercalated with carbonate-marly conglomerates, was interpreted to have been deposited in a brackish sea. The Krasiejów section belongs mainly to the upper unit. The results of our sedimentological analysis are in conflict with Bilan's interpretation of a marine origin these mentioned deposits, because alluvial palaeochannel bodies are found to be abundant.

Dzik *et al*. (2000) described the horizons with vertebrate bones as a lake deposit formed during the maximum phase of a large-scale transgressive cycle. The transgression must have started with the Schilfsandstein (Fig. 2), which is commonly considered as an alluvial deposits. Dzik (2003), however, proposed that the same strata were formed in a floodplain (i.e. alluvial) environment. Nevertheless a deltaic origin of the bone-bearing deposits were still favoured by some researchers

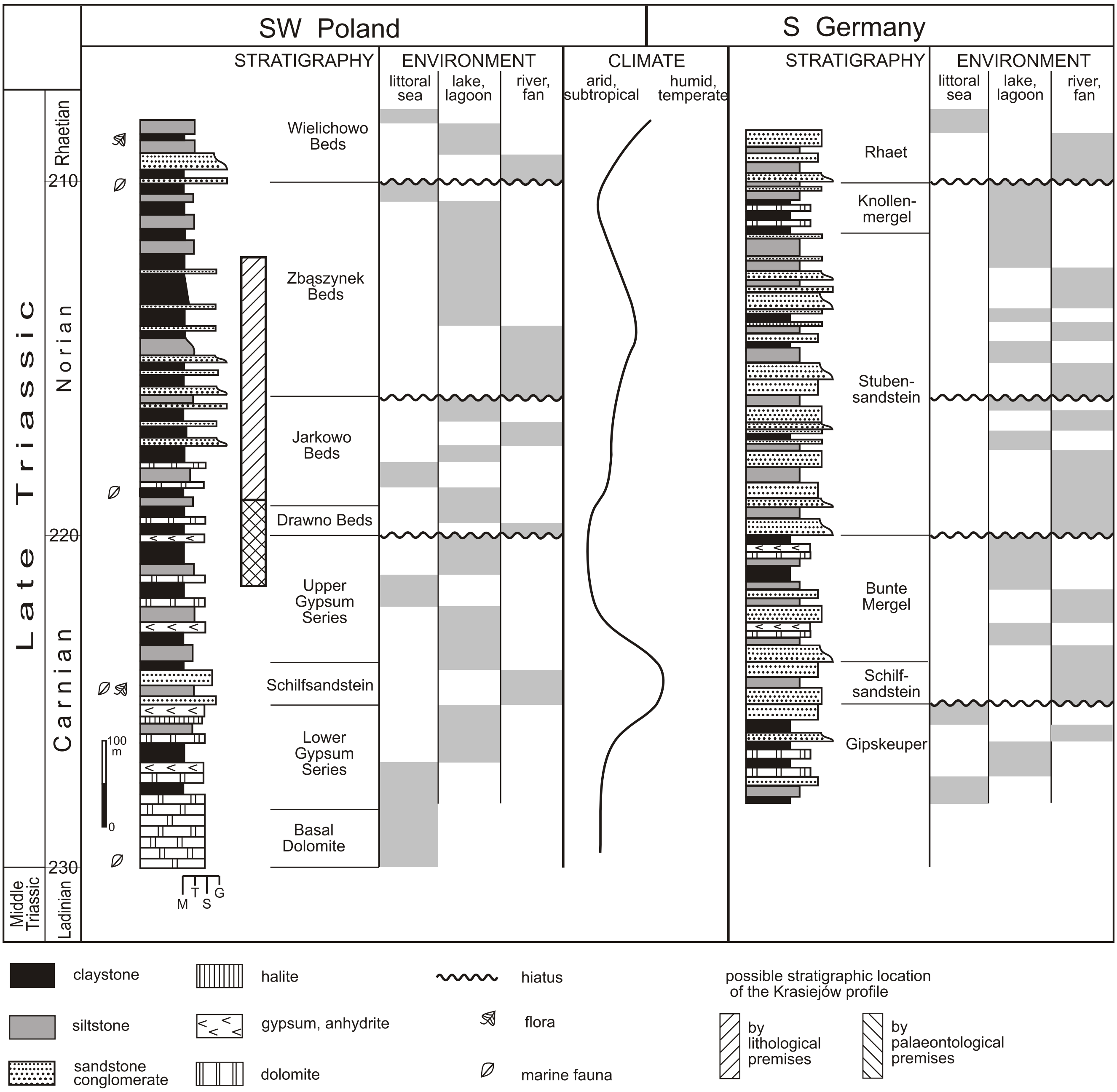


Fig. 2. Comparison of the lithostratigraphy, sedimentary environments and climatic conditions of the Polish and German Upper Triassic (based on: Dadlez and Kopik, 1963; Kotlicki, 1973; Haisig *et al*., 1979; Aigner and Bachman, 1992; Deczkowski *et al*., 1997; Mader, 1997; Hornung and Aigner, 2002*a*, *b*)

(Olempska, 2004; Sulej, 2005), even though no sedimentological evidence was put forward. Recently, Szulc (2005) carried out a sedimentological analysis of the Krasiejów section, which he interpreted as a typical sheetflood facies containing debris-flow horizons, deposited as a fan close to tectonically-induced elevations.

Any discussion of the Keuper in Poland should take into account the results of German researchers. The Keuper of Bavaria, Thuringia and Baden–Württemberg is lithologically well documented, and the palaeoenvironments and the stratigraphy are known in detail. The late Carnian and Norian are represented by two interfingering facies: Sandstein–Keuper and Steinmergel–Keuper. The Sandstein–Keuper contains alluvial sandstones consisting of material derived from the Bohemian Massif and transported to the German Basin. The rivers formed large alluvial fans. In the hot climate, the fluvial systems changed downstream gradually into shallow, ephemeral sheetflows (Hornung and Aigner, 2002*a*). The Steinmergel–Keuper Formation represents the more central part of the basin, and is built of playa-type deposits: siltstones, claystones, dolomites and gypsum. During periods with a warm and humid climate, the alluvial fans prograded into the central part of the basin. By contrast, the fans retreated during periods with a hot and dry climate, so that the semi-desert area with evaporatic sedimentation became enlarged (Reinhardt and Ricken, 2000; Hornung and Aigner, 2002*b*). This climatically controlled facies migration extended over an area hundreds of kilometres long. Five such major dry/humid cycles have been identified in the Late Carnian and Norian of Germany.

PARAMETERS OF PALAEOCHANNELS AND PALAEOFLOWS — METHODS OF ESTIMATION

Lithological data enabled calculation of three basic physical parameters, characterizing palaeochannels: channel lithology parameter (*M*), channel sinuosity (*sn*), and the ratio between the width and depth (*w*/*d*). The channel lithology parameter was calculated as the percentage of silt and clay in the bed and banks of a palaeochannel. The channel sinuosity *sn* (nondimensional) was calculated from the Langbein and Leopold (1966) formula, modified by Miall (1975) and later by Reddy and Prasad (1988):

$$sn = 1/\,[1 - (V_1\,/\,252)]^2$$

where: V_1 — difference between the modal palaeoflow azimuths calculated from different palaeochannels.

The dynamics of channel flows depositing coarse silt in a rippled bed configuration was interpreted on the base of palaeohydraulic formulas. The unit stream power ω (W m^{-2}) was estimated from equations by Bridge and Jarvis (1982) and Allen (1982). Then the value of stream power was converted to an average flow velocity *v* (m s^{-1}) (*cf.* Rees, 1966). Due to the small size of the quarry and the poor exposure of the deposits, an estimation of the channel slope was, unfortunately, impossible. Thus, other palaeohydraulic equations have not been used in this study.

DESCRIPTION OF THE DEPOSITS

Three sedimentary unit are distinguished in the Krasiejów exposure. Their lithological characteristics are as follows.

LOWER UNIT

The lower units exposed over a vertical distance of about 6 m; its base is below the bottom of the quarry. Numerous channels characterize this unit. Four sinuous channels have been mapped (Fig. 3A). The depth of the channels ranges from 2 to 4.5 m, and they are 125–150 m wide. The channel-fills themselves are built of coarser deposits, and are embedded within the claystones.

The channels are infilled with siltstone beds 15–25 cm thick that alternate with thinner layers of claystones. Claystones within the channels are of secondary importance, although they make up to 16% of the deposits (Fig. 4A). The siltstones (38%) and sandy siltstones (45%) comprise the majority of the deposits, and show ripple cross-lamination (also climbing-ripple cross-lamination), horizontal lamination, or are massive (Fig. 5A). The claystones and sandstones are always massive. Coarse-grained sandstone/conglomerate basal beds are rare. Sandstones and conglomerates make up to 1% of the deposits only (Fig. 4), and grains >1 mm are extremely rare (Fig. 6A).

Successions of graded beds averaging 20–30 cm thick each have been noted within the channel-fills. These beds are simple couplets in which a thicker layer of coarse-grained sandy siltstone with ripple cross-lamination (TSr) is overlain by a thin layer of claystone with a massive structure (Mm) or by siltstone with horizontal lamination (Tl) (Fig. 7A). Reverse graded couplets (Tm → TSrc) are present as well (Fig. 5A). Erosional surfaces are very rare in the channel-fills. Deposits with a massive structure or horizontal lamination dominate the upper parts of the channel-fills. Claystones are more common in these top parts, and the thickness of the individual layers decreases to the top.

The layers within the channels dip slightly (up to 9°), following their basal, large-scale erosional surfaces, but they are asymmetrical with respect to the channel axis (Fig. 8A). Rhythmic colour alternations between beds from red dark brown to silver grey are common, but these changes do not coincide with lithological changes or with and sedimentary structures (Fig. 7B). A horizon that is rich in vertebrate bones is located in the basal layer of the lowermost palaeochannel.

MIDDLE UNIT

This unit is dominated by claystones (Fig. 6A). Its thickness reaches 6.5 m. It is a monotonous interval of dark brown massive claystones. No systematic tendencies in grain-size have been found in this part of the succession. The frequency of siltstone intercalations increases slightly in the uppermost part of the unit.

The upper part of the unit shows numerous deformation features. These are found in a layer 0.8–1.2 m thick. In the lower part of the deformed layer slickensides are common. These microfaults are up to 1 m long and dip at angles of

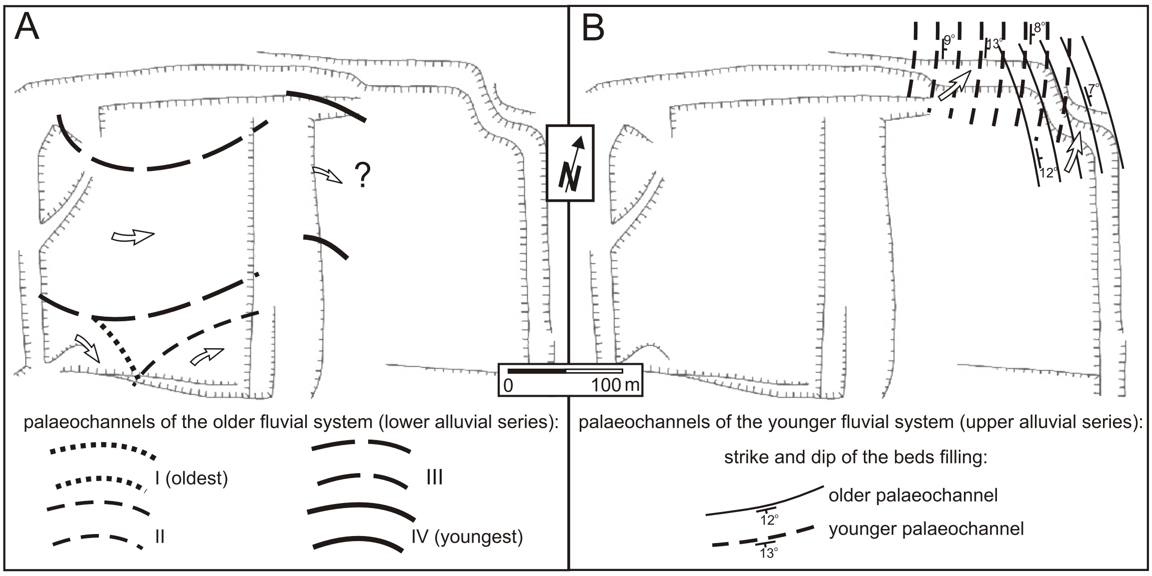


Fig. 3. Palaeochannel generations of the lower and upper fluvial units

A — four palaeochannels identified in the lower unit; **B** — two palaeochannels identified in the upper unit; palaeochannel axes marked by arrows

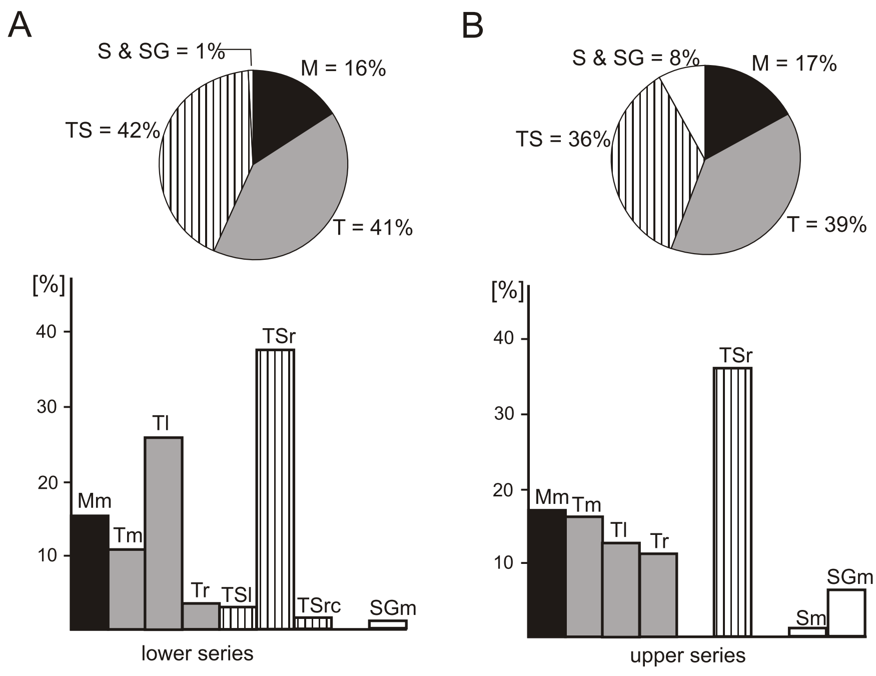


Fig. 4. Frequency of lithofacies within the palaeochannels of the lower (A) and upper (B) alluvial units

Grain-size: M — claystone (mudstone), T — siltstone, TS — sandy siltstone, S — sandstone, SG — gravelly sandstone; structure: m — massive structure, l — horizontal and low-angle cross-lamination, r — ripple cross-lamination, rc — climbing ripple cross-lamination

25–45° in two complementary sets of planes with opposing directions (Fig. 9A, B, C). Their surfaces are formed by thin laminae of grey clay. Shear striae are present on the surfaces of well-developed slickensides (Fig. 9D). This deformed zone gradationally passes upwards into massive bluish clay with calcareous nodules, that are 3–5 cm in diameter (Fig. 9B). The main palaeontological finds of vertebrate bones at the Krasiejów site have been made in the uppermost bed of this unit, immediately above the deformed layer.

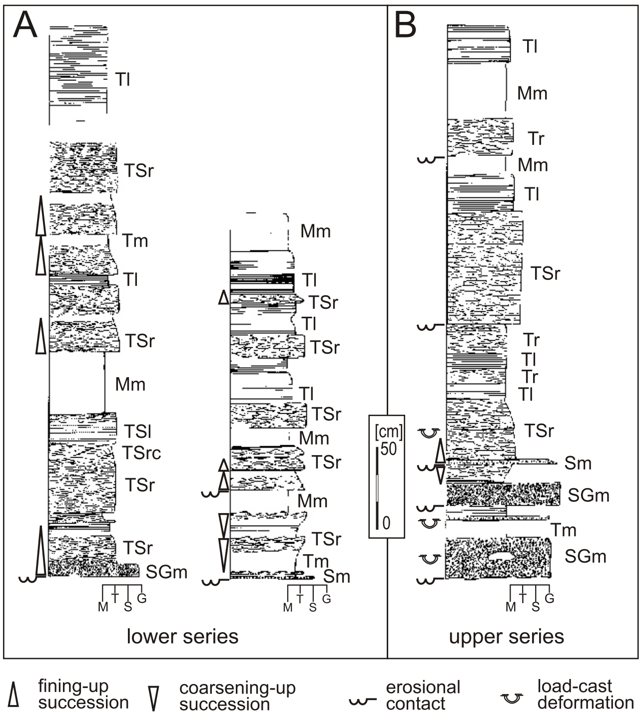


Fig. 5. Sedimentary logs of the lower (A) and upper (B) units

For lithofacies code see Figure 4

UPPER UNIT

The upper unit is 4 m thick. Its lithology is similar to that of the lower unit. Palaeochannels filled mainly by siltstones have been also found within the massive or laminated claystones. The main difference is that the upper unit contains a significant number of coarse-grained (sandstone/conglomerate) deposits (Figs. 4B and 6A). The coarse-grained beds are most common in the basal parts of palaeochannel-fills (Figs. 10 and 11A). These sandstone/conglomerate lithofacies consist of reworked soil-derived calcareous nodules up to 1 cm in diameter (*cf.* Szulc, 2005). Because of the limited exposure in the Krasiejów quarry, only two palaeochannel-fills have been studied in detail (Fig. 3B). The depth of the larger one is 3 m. The channel bodies of the upper unit are substantially wider than those in the lower unit: the width of one of them exceeds the length of the wall of the quarry; its total width may reach some 300 m. The channel base is almost flat (Fig. 8B). A second substantial difference between the channels of the lower and upper units is formed by the shape and dip of the individual beds. The layers filling the channels of the upper unit dip at steeper angles (7–13°). They do not parallel the channel bases but converge with them. All the layers dip in the same direction, almost perpendicular to the channel axis (Fig. 11B). The thicknesses of the inclined layers are usually larger than those in the channels of the lower unit; siltstone beds with ripple cross-lamination are over 0.5 m thick. Repeated successions of normally or reverse graded beds have not been found in the upper unit. Erosional surfaces between infilling beds and small-scale deformation

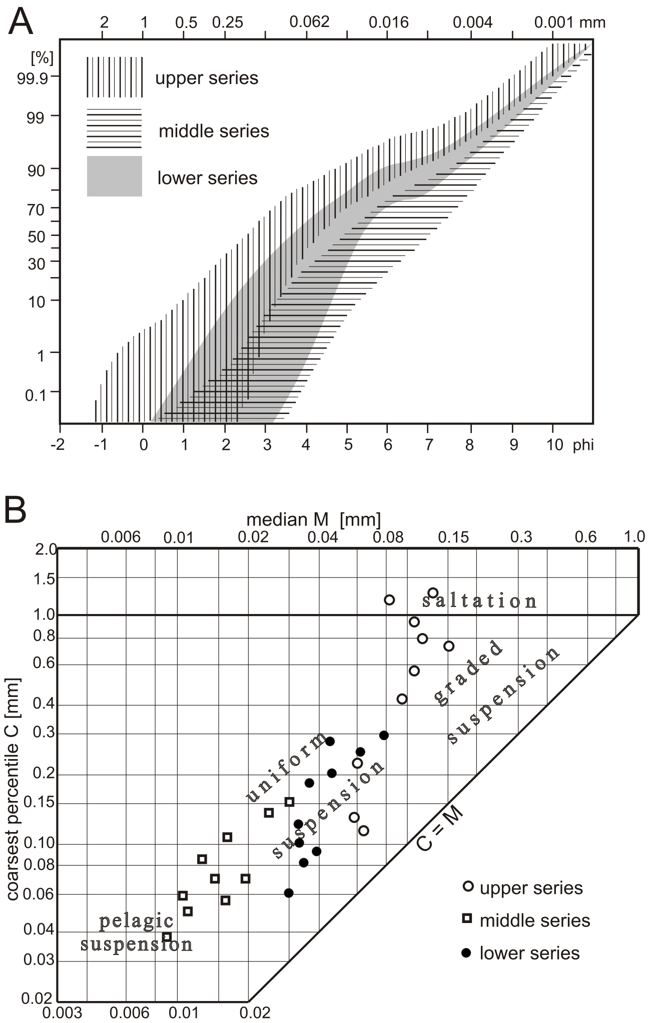


Fig. 6. Areas covered by cumulative curves (A) from deposits of the three units studied; Passega diagram (B) with the deposition types: suspension and saltation, counted for each unit

Based on the textural analysis of 30 samples (10 for each series)

structures due to loading are common in the lower parts of the channels (Fig. 5B). The youngest Krasiejów bone-rich horizon lies within the massive claystone capping the upper channel (Fig. 1C).

INTERPRETATION OF THE SEDIMENTARY ENVIRONMENTS

LOWER UNIT

The lower unit was deposited in a low-energy fluvial system, typically consisting of suspended-load channels, where the majority of the grains were deposited from uniform or graded suspension (Fig. 6B). The channel lithology parameter (i.e. the content of silt and clay in the bed and banks of a channel) is estimated to be 90%, whereas the ratio between the width and depth (*w*/*d*) of the channels ranges from 27 to 60.

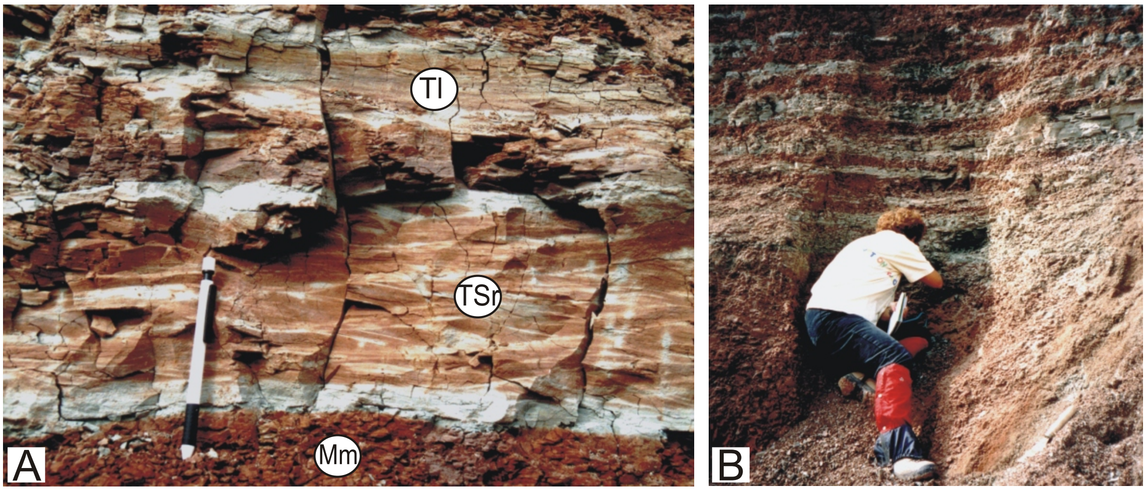


Fig. 7. Detail of the lower alluvial unit

A — graded couplet of ripple cross-laminated sandy siltstone overlain by horizontally laminated siltstone; **B** — rhythmic alternation of layers from red/dark brown to silver/grey in the top part of a palaeochannel infill; the colours do not correspond to the shapes of the sedimentary structures

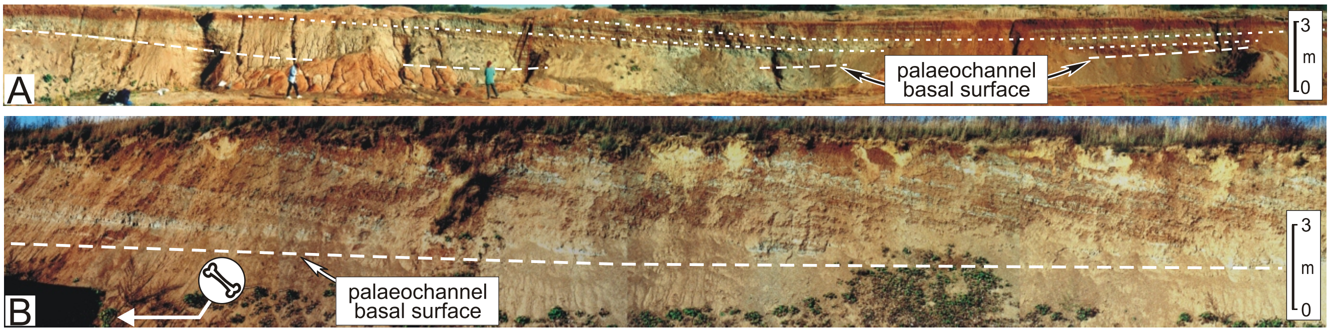


Fig. 8. Shape and characteristic features of the infilling of the channels

A — lower unit: the bed boundaries are nearly parallel to the erosional base of the palaeochannel; **B** — upper unit: almost flat base of a large palaeochannel-fill with distinctly inclined beds

The value obtained for channel sinuosity is *sn* = 1.27, which puts the environment of the unit into the class of moderately sinuous, although not yet meandering rivers (Teisseyre, 1985; Bluck, 1987).

The most important point regarding precise interpretation of the alluvial environment is the arrangement of the beds within the channels. Arrangements of the beds that follow the palaeochannel bases excludes the presence of point bars as the primary channel forms. Therefore vertical and not lateral accretion must have been the main depositional process within the alluvial channels. The lack of erosional surfaces between the beds within the channel bodies shows that the channels were relatively quickly infilled with sediment. This indicates that the channels of the lower unit had an aggradational character.

The lithofacies of the channel-fills indicates that low-energy bedload deposition in the form of rippled beds (the origin of the ripple cross-laminated sandy siltstones TSr) alternated with settling from suspension (the origin of the massive claystones Mm). The sandy siltstones with climbing ripples TSrc indicate a high concentration of fine-grained suspension load in the channels. Considering these lithofacies, the deposits analysed are similar to channel alluvium of the lowest reach of the Yellow River, a classic suspended-load river (Van Gelder *et al.*, 1994). In our opinion, the Krasiejów channels had even lower energy than the Yellow River, which resulted in a smaller number of fine-grained sandstone intercalations and an absence of ribbons built of fining-upwards successions.

The channel flows that deposited the coarse-grained siltstones, TSr and TSrc, were characterized by very low stream power, close to $\omega = 1\ \mathrm{W\ m^{-2}}$. An average flow velocity was $v \cong 0.1\ \mathrm{m\ s^{-1}}$. It must be noted, however, that the calculated parameters characterize the flood-flow conditions, which even more clearly stresses the extremely low energy level of this fluvial environment. The lack of any kind of depositional forms larger than ripples supports this palaeohydraulic analysis. The characteristic alternation of siltstone and claystone beds most probably reflects a specific climatic feature: the rhythm of humid and dry seasons. During the dry seasons, the channel flows un-

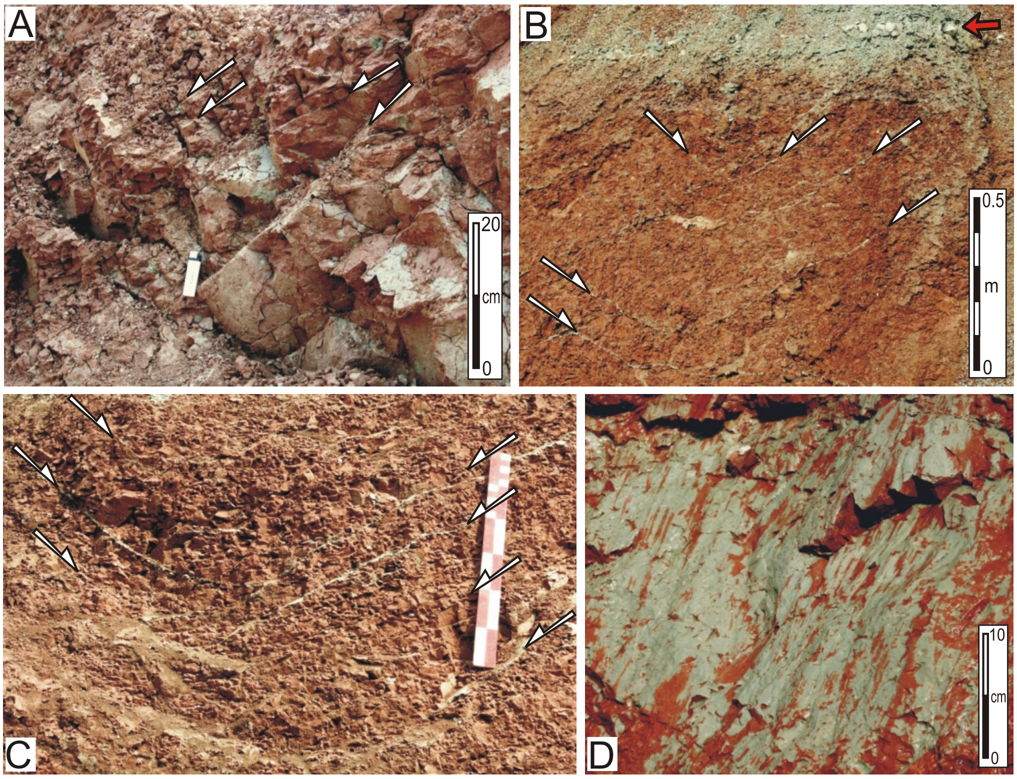


Fig. 9. Pedogenesis-related structures in claystones of the middle series

A — one side of a slickenside set with microfault planes dipping towards the axis of the structure; **B** — horizon of calcic nodules marked by an arrow above the system of slickensides; **C** — typical complementary set of slickensides indicated by silver/grey clay; scale bar is 0.6 m; **D** — shear striae (grooves) along a well-developed slickenside surface

doubtedly decayed. The alternation of colours from red/dark brown to silver/grey in the uppermost parts of the ribbons indicates that the bed of shallow, almost completely sediment-choked channels emerged periodically and was subjected to oxidation (the red/dark brown colour), whereas the underlying, still wet stratum was permanently under gley reduction conditions (silver/grey colour) (see Daniels *et al*., 1971). Additionally, the presence of mud cracks (Wojewoda, pers. comm.) supports the assumption that the channels became completely dried-up during hot and dry seasons.

The characteristics of this lower alluvial unit are in many respects consistent with those of anastomosing-river deposits. The presence of numerous channel-fills in a relatively small area of the exposed sedimentary succession suggests that the fluvial system was of an anabranching type. The channels were rapidly filled with sediment, which must have resulted in frequent avulsions. The semi-concentric channel-fills indicate an absence of lateral migration. Sedimentation was not controlled by the development of side bars (such as accretionary benches, point benches or point bars), but was predominantly vertical, with a slight lateral component only. The channels were stable elements within the fluvial sedimentary environment. Lateral stability was certainly also due to the presence of clayey, cohesive banks, which were resistant to erosion by the weak currents.

Similar channel-fills, lacking laterally accreted bars, are described by Smith and Smith (1980), Rust and Legun (1983), and Makaske (1998) as characteristic of anastomosing systems. However, these "classical" channel deposits are represented mainly by sandstones. The much finer-grained character of the Krasiejów series supports the idea of an extremely low-energy fluvial system. Analogous siltstone-dominated facies of anastomosing channels with a scarcity of sand beds were noted by Eberth and Miall (1991) in the Permian Cutler Formation (New Mexico, USA).

In some studies, typical anastomosing channels have been described as highly sinuous (*sn* > 1.5) (Schumm, 1968; Rust, 1978, 1981; McCarthy *et al*., 1991; Smith *et al*., 1997; Gibling *et al*., 1998). On the other hand, Smith and Smith (1980), King and Martini (1984), Smith (1983), Makaske (1998, 2001), and Gradziński *et al*. (2000) considered anastomosing rivers as moderately sinuous (*sn* < 1.5). In this sense, the sinuosity of the Krasiejów channels (*sn* = 1.27) can be interpreted as in agreement with the characteristics of an anastomosing system. It must be emphasized, however, that the sinuosity of channels is only an additional, though not the most essential criterion for identification of the river pattern (*cf*. Knighton and Nanson, 1993; Makaske, 2001).

The alluvial plain represented by the lower unit at the Krasiejów site had undoubtedly a very low slope. Low stream power ($\omega \cong 1$ W m^{-2}) is consistent the hydrologic data recognised as typical of anastomosing rivers ($\omega < 8$ W m^{-2}) (Nanson and Knighton, 1996). The dominance of siltstones and claystones allows a reconstruction of the sedimentary environ-

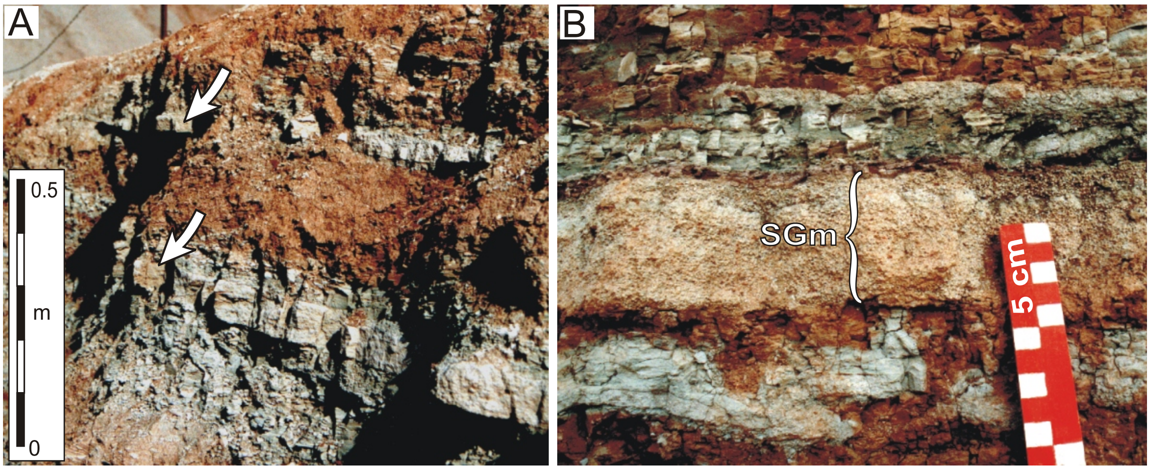


Fig. 10. Upper unit — lower part of the palaeochannel-fills

A — two (arrows) coarse-grained sandy lithofacies intercalated with layers of massive siltstones and claystones; **B** — thick layer of massive sandy conglomerate among massive and laminated siltstones and claystones

ment of the Krasiejów lower unit as a mud-dominated class of the anabranching river group in Nanson and Knighton (1996) classification. Such low-energy anastomosing rivers (such as the Diamantina River or Cooper Creek) are typical of semi-arid lowlands of Australia (see Rust and Nanson, 1986; Nanson *et al*., 1988). This analogy is appropriate as the Late Triassic climate of Polish and German area is commonly interpreted as semi-arid (Deczkowski *et al*., 1997; Mader, 1997; Reinhardt and Ricken, 2000; Hornung and Aigner, 2002*b*).

Notwithstanding the above evidence, strongly suggesting an origin of these deposits in anastomosing channels, there are also some lithological features which cannot be considered as typical of commonly used models of anastomosing fluvial systems. Within the overbank deposits, no record of natural levees or crevasse splays has been found, although these elements are considered as characteristic of the anastomosing system (Smith and Smith, 1980; Schumm *et al*., 1996; Gibling *et al*., 1998; Wende and Nanson, 1998; Makaske, 2001). On the other hand, it is usually emphasised that rivers in semi-arid areas tend to have their own characteristics, including a common lack of crevasses and crevasse splay deposits (Rust and Legun, 1983; Nanson and Croke, 1992; Törnqvist *et al*., 1993).

The second important difference lies in the cross-sectional geometry of the channels. It is commonly accepted that the channels of anastomosing rivers tend to be deep and narrow. The width to depth ratio of typical anastomosing channels often falls within the range $5 < w/d < 35$ (Miall, 1977; Smith and Smith, 1980; Smith, 1986; Makaske, 1998; Tooth and Nanson, 1999). The same parameter has values of 27–60 for the Krasiejów palaeochannels. We think that the Krasiejów channels were wide and shallow, because the channel bed erosion during avulsion was very limited due to low flow energy, a resistant clayey substrate, and a high concentration of suspended load.

MIDDLE UNIT

Sedimentation of the middle unit took place entirely from suspension settling in standing water (Fig. 6B). No evidence of ephemeral current activity has been found. The hydrological conditions were stable. A standing water body, probably a lake, must therefore be assumed to have been the sedimentary environment. The presence of siltstone intercalations in the upper part of the lacustrine succession indicates that the basin eventually became shallower. Considering the depositional ratio in basins fed by suspended-load rivers (Anderson, 1996; Basilici, 1997; Mulder *et al*., 1998), the timespan covering the sedimentation from suspension settling could be some 10 ka.

After the basin had been in filled with sediment, soil processes took place. The slickenside structures result from periodic shrink and swell processes due to evident changes of ground moisture. Such structures can form rapidly; this needs only some 200 years (Yaalon and Kalmer, 1978), and therefore their presence cannot be used to establish the entire timespan during which the soil processes were active. The calcic nodules are a much better indicator of soil maturity; their formation needs a few thousands to hundreds of thousands of years (Gustavson, 1991; Retallack, 1994; Mack *et al*., 2003). Considering the relative scarceness of the nodules it must be assumed that they formed during a relatively short timespan of some thousands of years. The genesis of the calcic nodules is related to the mechanism responsible for slickenside origin, i.e. the alternation of wet and dry intervals. The concretions grew under conditions of restricted migration of dissolved calcium carbonate in the near-surface zone. They are commonly considered to reflect a semi-arid climate (e.g. Hornung and Aigner, 2002*b*), although similar concretions can originate also under humid and sub-humid conditions (Gustavson, 1991). The bluish colour of the soil horizon is an effect of gley in a reducing, wet environment. Daniels *et al*. (1971) estimated that the development of a gley horizon requires soil saturation for at least 1/4–1/2 of each year.

To sum up, all structures in the middle unit are typical of vertisols. Most probably this soil developed in a subtropical and warm climate, in which the ground undoubtedly underwent seasonal alternations of wetting and drying. Analogous soils have been found in the Keuper of Germany (Mader, 1997;

Hornung and Aigner, 2002*b*). The main bone-bearing horizon of the Krasiejów site is directly above the vertisol. Such a superposition of both horizons is logical and proves that the vertebrates favoured the wet areas, corresponding to the topographic lows, in a semi-tropical warm climate, that seasonally became more arid (*cf.* Behrensmeyer, 1987; Therrien and Fastovsky, 2000).

UPPER UNIT

The upper unit originated in a river system with a slightly higher energy than that of the lower unit. It is clear from the shape of the cumulative grain-size curves and the Passega diagram, that traction and saltation were significant modes of transport and deposition, while settling from suspension load was much less important (Fig. 6), although still significant in the alluvial channels. The channel lithology parameter is estimated to be M = 85%, whereas the sinuosity is calculated to have been sn = 2.04. The highly sinuous channels were characterized by intensive lateral migration, which resulted in extensive sheet-like bodies. Calculation of the width/depth ratio was therefore impossible. The palaeochannel-fills are characterized by large-scale epsilon cross-stratification ECS, termed also inclined heterolithic stratification IHS (Fig. 11A), which is commonly considered as evidence of point bars. The point bars were simple forms, i.e. consisting exclusively of bar platforms. Such simple point bars are typical of low-energy meandering rivers (Miall, 1996). Secondary currents oriented perpendicular to the channel axis must have been common above the bars (Fig. 11B). The resulting silty-sandy ripples climbed up the barform slopes towards the inner channel banks. Ripple cross-lamination, oriented counter to the direction of the ECS bed dip, supports the high sinuosity of the alluvial channels. Secondary currents must have been active during floods. Deposition from suspension dominated during average and low discharge stages, so that clayey silt and clay were deposited on the bar slopes as draped laminae. Occasionally small-scale erosion was active on bar slopes, and deposition of thin coarse-grained sandy conglomerate could also take place. Megaripples, usually common in sand-bed meandering channels, are completely absent from the Krasiejów channels.

The deposits closely resemble those from the Cretaceous Wealden Group of Southern England described by Stewart (1983), who interpreted this deposit as formed in a suspended-load river of high sinuosity. Deposits of the upper Krasiejów Unit are also very similar to the 7th type of river in the classification of Miall (1985), which is considered as a river that is typical of an estuarine environment. Hornung and Aigner (1999) found alluvial channel-fills dominated by claystones in the Keuper Stubensandstein of SW Germany. In general, the successions of the German and Polish Keuper have much in common, but the Württemberg alluvium shows many sandy ribbons, which are absent from the Krasiejów quarry. The Upper Triassic Chinle Formation in Arizona, where numerous theropods have been found (Therrien and Fastovsky, 2000) is another analogue of the Krasiejów deposits because its channels are also filled with siltstones with ECS structures. There are many more examples of low-energy meandering rivers dominated by deposition of silt from suspension (see, among others: Edwards *et al.*, 1983; Kraus and Middleton, 1987; Wood, 1989; Mack *et al.*, 2003). Notwithstanding the close similarities between all these successions and the Krasiejów alluvium, they are all characterized by a higher energy level, as shown by the higher frequency of sand beds, and the presence of cross-stratification derived from dunes and scroll bars. On the basis of comparisons with all these deposits, the fluvial environment of the Krasiejów upper unit is interpreted as a meandering river of low energy.

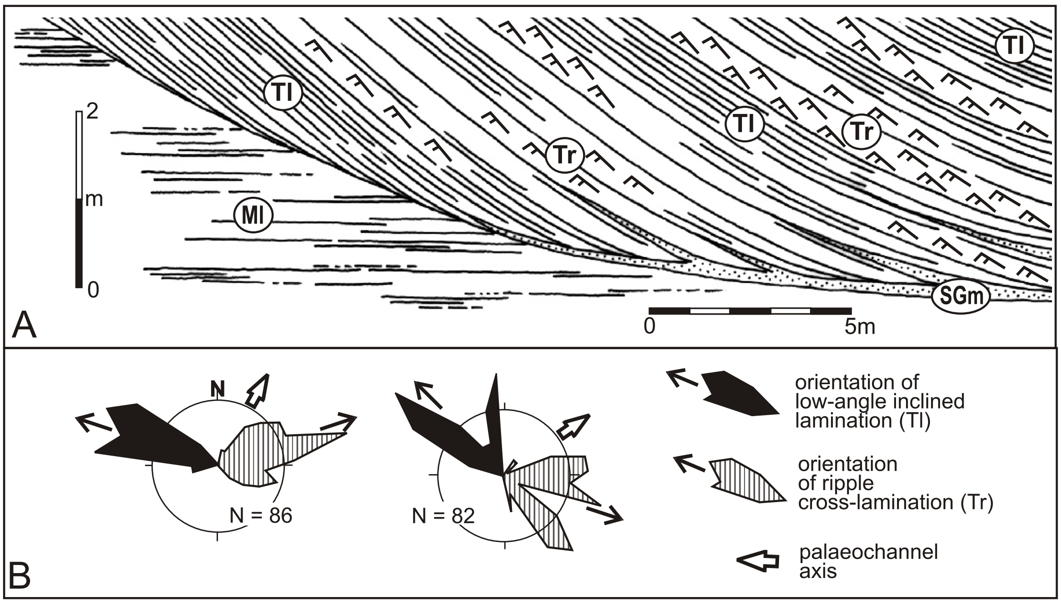


Fig. 11A — Upper unit — marginal zone of palaeochannel incised in overbank claystones (Ml); channel-fill large-scale epsilon cross-stratification (ECS) containing inclined beds with a rhythmic alternation of laminated siltstone (Tl) and rippled siltstone (Tr); B — opposite orientations of Tl and Tr laminations within ECS structure, indicating a point bar origin; N — number of measurements

PALAEOGEOGRAPHIC DEVELOPMENT

The results of our study show that the whole Krasiejów succession was formed under continental conditions. Our results are not consistent the hypothesis put forward by Zatoń *et al*. (2005) of saline water, based on a charophyte decline above the middle bone-bearing horizon. We incline rather to the second possibility mentioned by Zatoń *et al*. (2005) that stranger ocurrents may have been responsible for palaeoecological changes, when the meandering pattern was established.

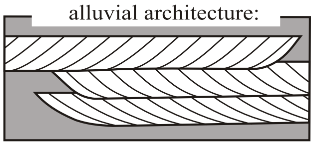
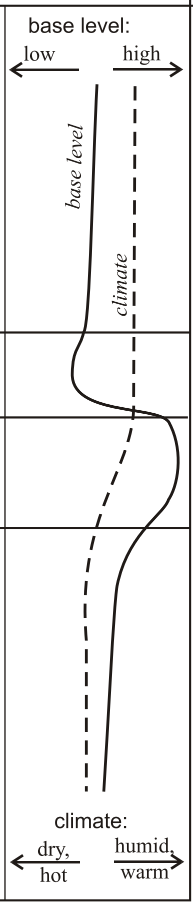
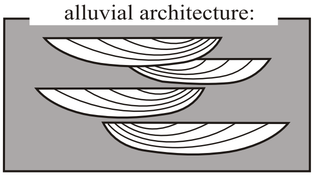
Two unit of the Krasiejów succession were formed by extremely low-energy rivers flowing over a plain at a great distance from higher ground. Our interpretation is in contrast to the opinion of Szulc (2005). His analysis of the Krasiejów succession concluded that the main sedimentary factors were sheetfloods and debris-flow events. Such depositional processes need steeper gradiends, typical of the immature topography of tectonically active regions. This is confusing, as Szulc did not exclude a fluvial origin for the deposits, but did not describe any of the alluvial channels that we found to be abundant in the Krasiejów succession. In contrast to Szulc (2005) we consider that the style of fluvial deposition, during the formation of both the lower and the upper units, was controlled by downstream factors, mainly base-level fluctuations.

The influence of downstream factors on the pattern of the fluvial channel system is particularly clear in the lower alluvial unit. The anastomosing character of the river, the high aggradation ratio, and the lack of lateral accretion support a constant rise in base level (see Woodyer *et al*., 1979; Smith and Putnam, 1980; Smith, 1986; McMarthy, 1993; Morozova and Smith, 1999; Makaske, 2001). Törnqvist *et al*. (1993) showed that an anastomosing fluvial system can evolve if the base level rises annually by at least 1.5 mm. In our opinion, sedimentation of the lower alluvial unit proceeded under conditions of a constant local base-level rise, most probably controlled by subsidence (Table 1).

The Keuper alluvial channel pattern studied may have depended only slightly on climate. This conclusion is supported by the fact that anastomosing river systems are well known from different climates: humid temperate, continental temperate, semi-arid, and polar (*cf*. Smith and Putnam, 1980; Smith, 1986; McMarthy, 1993; Nanson and Knighton, 1996; Gibling *et al*., 1998; Makaske, 1998; Jones and Schumm, 1999). The anastomosing river ran towards the NE at Krasiejów (Fig. 12A), which is consistent with the interpretation of the Late Triassic palaeogeography in this part of Europe (*cf*. Deczkowski *et al*., 1997; Mader, 1997).

Table 1

Lithology and environmental interpretation of the three unit studied

Series	Lithology	Sedimentary environment	
Upper alluvial series	siltstone (Tm, Tl, Tr); mudstone (Mm); sandstone (Sm); gravelly sandstone (SGm); sheet-like storeys paved with thin conglomerate beds, filled by ECS structures with some erosional surfaces; lack of repetetive successions within channel infills alluvial architecture: 	channel belt of meandering fluvial system: suspended-load palaeochannels (up to 3 m deep, of high sinuosity *sn* = 2.04) predominated by lateral accretion; point bars with abundant parasitic ripples formed by transverse secondary flows in sharply-curved bends; lack of megaripples due to very low energy level; erosion phases connected with cyclic avulsion; slight increase of annual river discharge in comparison with the previous fluvial system — presumably resulted from increasing humidity of climate	
Hiatus	clayey vertisol horizon approx. 1 m thick: common slickensides with shear striae, the level of calcareous nodules atop	emergence and development of extensive soil horizon in semi-tropical climate with dry and wet seasons	
Middle lacustrine series	claystone and silty mudstone (Mm); lack of erosional surfaces and grain-size successions; silty claystone frequency increases to the top	large lake: pelagic settling in open standing water; lack of bottom currents; progressive weak shoaling tendency	
Lower alluvial series	siltstone (Tm, Tl, Tr); mudstone (Mm); sandy siltstone (TSr, TSrc, TSh); gravelly sandstone (SGm); ribbons filled with concave-up, assymetrical beds arranged concordantly to channel bases; local rhythms TSr→Mm 20–30 cm thick; erosional contacts very rare alluvial architecture: 	channel belt of anastomosing fluvial system: suspended-load palaeochannels (up to 4.5 m deep, of moderate sinuosity *sn* = 1.27) predominated by vertical accretion; small bedforms (ripples) were abundant, barforms were absent; frequent avulsion due to high in-channel deposition rate; channel depositional rhythm: weak current activity during wet season followed by standing water phase during dry season and finished with emergence of channel bed; extremely low energy level (stream power approx. 1 W m^{-2})	

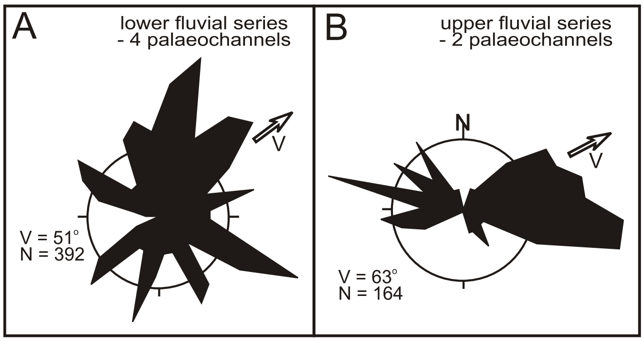


Fig. 12. Directional distribution of cross-stratification in lower (A) and upper (B) fluvial units

General directions of the channels are arrowed; V — mean azimuth, N — number of readings

The sedimentary conditions of the middle lacustrine unit might be interpreted in two ways. The first possible interpretation is that the aggradation of the river did not keep up with the regional subsidence, so that the study area became a lake. The second possibility is that the channel belt of the anastomosing river shifted towards another part of alluvial plain, while an inter-channel standing water body (i.e. a lake) developed in the Krasiejów area.

After the lake had been entirely infilled with sediment, subaerial soil processes took place. Subsidence was restrained, and aggradation and erosion were nearly in balance. The soil characteristics are generally in agreement with what is known about the climate in Poland and Germany during the Keuper. It was warm, with distinct seasonal changes from arid to humid (see, among others, Deczkowski *et al*., 1997; Mader, 1997; Reinhardt and Ricken, 2000; Hornung and Aigner, 2002*b*).

A new phase of increased subsidence is suggested by the accumulation of the upper alluvial unit. The base level was rising slower than during the accumulation of the lower alluvial unit (Table 1). The alluvial plain was not so extremely flat as during the development of the anastomosing fluvial system, so that the river acquired a meandering pattern. Vertical accretion of the channel belt was restricted, while lateral accretion of point bars developed. The channel-belt aggradation rate was limited due to channel migration across the alluvial plain.

The same river reaction can be related to the influence of climate on the hydrologic conditions. A more humid climate must have resulted in some changes of fluvial transport character. The sediments were transported and deposited as bedload, while clayey suspended load diminished. This is why the upper alluvial unit is mainly represented by point-bar facies within the palaeochannels. The current directions of the lower anastomosing and the upper meandering systems remained the same, as the meandering river also flowed towards the NE (Fig. 12B).

CONCLUSIONS

Although the Krasiejów succession has a fairly uniform lithology, consisting mainly of siltstones and claystones, it was possible to distinguish three sedimentary units: two alluvial units separated by a lacustrine one. Vertebrate bone horizons are present in each of these unit. Both alluvial units are characterized by well-developed palaeochannels, mostly filled with siltstones. The lacustrine unit contains predominantly massive claystones. The most important clues to the interpretation of the sedimentary environments are summarized here.

1. Both alluvial units represent low-energy, silt-bed river systems. It seems that this part of Europe formed a fairly well-developed extensive lowland during the Late Triassic.

2. The lower alluvial unit is interpreted as representing an anastomosing river system because of the numerous ribbons reflecting an anabranching channel pattern, the moderately sinuous character of the channels ($sn \cong 1.27$), the high value of the channel lithology parameter (M = 90%), the extremely low power of flood flows ($\omega \cong 1$ W m^{-2}), the slightly asymmetric concentric fills of the palaeochannels due to vertical accretion as the most common sedimentary process, the lack of side bars resulting from high channel stability.

The anastomosing river system was controlled mainly by tectonically induced base-level rise (i.e. permanent subsidence), whereas climatic factors were of less importance. The hypothesis of an anastomosing character of the Late Triassic rivers in Central Europe has been put forward earlier (*cf*. Mader, 1997), but the present contribution is the first that, on the basis of a sedimentological analysis, supports this postulate.

The upper alluvial unit is interpreted as having formed in a meandering river system because the channels were inferred to have been highly sinuous (sn = 2.04) and the channel lithology parameter was high (M = 85%), the palaeochannel-fills with abundant ECS/IHS structures indicating point bars formed by transverse secondary currents within meanders.

3. The rivers of both systems flowed in the same NE direction.

4. The middle, clayey lacustrine unit records an extensive lake where suspension settling was not disturbed by any currents. Progressive shallowing resulted in final emergence. The lacustrine deposits were then affected by soil processes, and a vertisol developed in a subtropical warm climate with an evident arid-to-wet seasonal rhythm.

5. Base level changed during sedimentation from a lower to a higher position, and later changed a lower position again. This enabled evolution of environments from an anastomosing river system in the lower base level position, through lake development during the highest base level, to a meandering system when the base level was lowest. However, these base level fluctuations were not great enough to change the grain-size of deposits greatly.

6. Seasonal aridity of the climate meant that the Late Triassic vertebrates preferred specified wet habitats. Presumably, these were depressions in the gently undulating alluvial plain and residual ponds after the lake had dried.

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