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Depositional environments and fluvial system changes in the dinosaur-bearing Sânpetru Formation (Late Cretaceous, Romania): Post-orogenic sedimentation in an active extensional basin

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Abstract

The Sânpetru Formation (Haţeg Basin, Romania) was deposited in an active extensional basin in response to the post-orogenic collapse of the Southern Carpathians. Despite being one of the best exposed latest Cretaceous continental successions of Eastern Europe and having great potential to improve knowledge about the Mesozoic evolution of the Carpathian orogen and the latest Cretaceous terrestrial paleoenvironments of Europe, this formation has been the subject of limited sedimentologic research. Fourteen stratigraphic sections were measured in the Sânpetru Formation throughout an 860-m-thick interval exposed along the Sibişel Valley in order to conduct the most detailed stratigraphic and sedimentologic study of this formation to date.

The Sânpetru Formation is a repetitive succession of fining-upward units composed of stratified and structureless sandstones, conglomerates, and mudstones. Facies analysis reveals that the Sânpetru Formation was deposited by braided streams that flowed through a symmetrical, extensional basin. The low variability of paleocurrent direction, the sheet-like architecture of the deposits, and the paucity of channel-shaped scours indicate poorly channelized flow across a shallow, broad braidplain.

Small-scale fluctuations in sandstone/mudstone ratio and maximum grain size of channel deposits in the lower Sânpetru Formation reflect autocyclic shifts in paleochannel position. In the upper Sânpetru Formation, sandstone/mudstone ratios and maximum grain size of channel deposits increase, paleocurrent direction changes significantly, and hydromorphic paleosols become the sole type of paleosols present. These changes reflect an episode of rapid uplift of the source area and the basinward creation of accommodation space below the local water table, which resulted in the creation of extensive wetlands. The wetlands of the upper Sânpetru Formation were not an environment favorable for the formation of dinosaur bonebeds, which are found in the lower part of the formation. The apparent absence of fossils in the upper part of the formation led previous researchers to incorrectly interpret the Cretaceous–Tertiary boundary at the transition between the lower and upper Sânpetru Formation.

Keywords: Braided stream; Dinosaur extinction; Haţeg Basin; Paleoenvironmental change; Sheetflood; Southern Carpathians

1. Introduction

Continental deposits of the Upper Cretaceous Sânpetru (or Sînpetru) Formation are exposed in the Haţeg Basin, west-central Romania. Deposited in response to the post-orogenic collapse of the Southern Carpathians, the Sânpetru Formation is one of the best exposed latest Cretaceous continental successions of Eastern Europe. This formation is famous for its unique assemblage of dinosaurs, crocodilians, chelonians, squamates, fishes,

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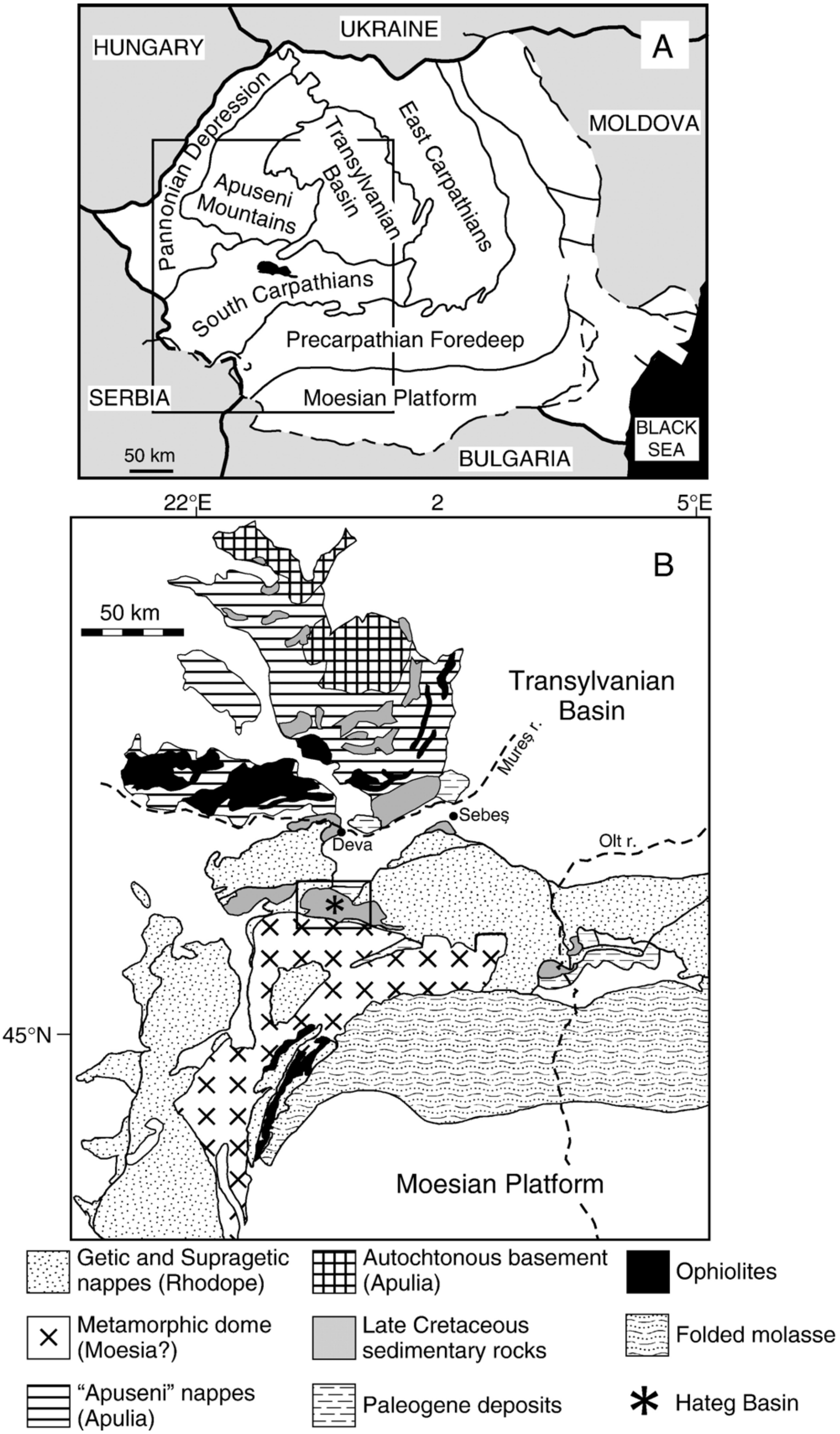

A
HUNGARY
UKRAINE
MOLDOVA
Pannonian Depression
Apuseni Mountains
Transylvanian Basin
East Carpathians
South Carpathians
Precarpathian Foredeep
Moesian Platform
SERBIA
BULGARIA
BLACK SEA
50 km
22°E
2
5°E
B
50 km
Transylvanian Basin
Mureş r.
Sebeş
Deva
Olt r.
45°N
Moesian Platform
Getic and Supragetic nappes (Rhodope)
Autochtonous basement (Apulia)
Ophiolites
Metamorphic dome (Moesia?)
Late Cretaceous sedimentary rocks
Folded molasse
“Apuseni” nappes (Apulia)
Paleogene deposits
Hateg Basin

amphibians, pterosaurs, and multituberculates, representing the best preserved and most diverse latest Cretaceous fauna of Europe (for a review, see Grigorescu and Csiki, 2002; Therrien, 2005).

Although the fossil fauna has been the subject of extensive research, the sedimentologic and paleoenvironmental aspects of the Sânpetru Formation are poorly understood. A detailed stratigraphic and sedimentologic study of this formation is warranted because it can give insight into the Mesozoic evolution of the Carpathians and, given the importance of the Sânpetru dinosaur fauna in the formulation of biogeographic and evolutionary hypotheses (e.g., Weishampel et al., 1991, 1993, 2003), can shed light on the latest Cretaceous continental paleoenvironments of Europe. Furthermore, the necessity for a detailed stratigraphic section of the Sânpetru Formation is strengthened by the long-held belief that this formation may record continuous deposition across the Cretaceous–Tertiary (K/T) boundary (Laufer, 1925; Iliescu et al., 1972; Stilla, 1985; Weishampel et al., 1991; Grigorescu, 1992).

This paper represents the most detailed stratigraphic and sedimentologic treatment of the Sânpetru Formation to date. The nature of the depositional system is discussed and the first composite stratigraphic section of the most extensive outcrops of the formation is presented. The results presented below give insight into the evolution of the fluvial system in a tectonically active extensional basin and provide a strong stratigraphic control over the fossiliferous localities and paleoenvironmental indicators found in the Sânpetru Formation. Finally, a tectonic model is developed to explain the causes of the changes in fluvial system observed throughout the formation, a model that also offers a possible explanation for the paucity of dinosaur remains in the upper Sânpetru Formation.

2. Geologic setting

2.1. The Haţeg Basin

The Haţeg Basin is an intramontane basin, approximately 45 km long (E–W) by 15 km wide (N–S), located within the Southern Carpathians of west-central Romania (Fig. 1). In this basin, Jurassic through Pleistocene strata rest unconformably on a basement of either Precambrian crystalline rocks or Permian sedimentary rocks from the Getic/Supragetic nappe complex (Willingshofer, 2000; Willingshofer et al., 2001). The sedimentary sequence of the basin records the complex tectonic history of the Southern Carpathian orogen, created by the collision of at least three microcontinents drifting though the Tethys Ocean: Apulia, Rhodope, and Moesia. From the Jurassic until the mid-Cretaceous, the Haţeg region was the site of deposition of clastic sediments and carbonates on a passive margin of Rhodope (Stilla, 1985). During the Albian, the collision between the three microplates raised the Haţeg region above sea level and transformed it into a piggy-back basin riding onto thrusted Getic/Supragetic (Rhodopean) nappes (Willingshofer, 2000; Willingshofer et al., 2001). After a brief depositional hiatus, synorogenic continental deposition occurred from the Albian through the lower Cenomanian in the form of bauxite-bearing alluvial and lacustrine deposits (Stilla, 1985; Becze-Deak, 1992; Grigorescu, 1992). Subsequently, a marine transgression deposited shallow to deep marine sediments over the region until the late Campanian, although orogenic pulses created erosional unconformities in the stratigraphic sequence (e.g., Stilla, 1985; Willingshofer, 2000; Willingshofer et al., 2001). The South Carpathian orogen collapsed during the Maastrichtian, resulting in the formation of extensional basins, exhumation of metamorphic domes, and onset of continental deposition. During the collapse, the Haţeg Basin was transformed into a post-orogenic extensional basin and sediments were deposited as fluviolacustrine systems throughout the Maastrichtian and into the Cenozoic (e.g., Stilla, 1985; Grigorescu, 1992; Schmid et al., 1998; Willingshofer, 2000; Willingshofer et al., 2001).

Paleogeographic reconstructions locate the Southern Carpathian orogen between 20° and 30° North latitude in the Mediterranean Tethys Ocean during the Maastrichtian (Patrascu and Panaiotu, 1990; Willingshofer, 2000; Panaiotu and Panaiotu, 2002). Although paleoclimatic inferences made on the basis of the Romanian paleoflora suggest a warm, tropical climate (mean annual temperature 22–24 °C) with abundant (1300–2500 mm/year) yet seasonal precipitation (Petrescu and Du°a, 1982a,b; Pop and Petrescu, 1983), a recent study of calcareous paleosols from various Maastrichtian formations of Romania has revealed that a monsoonal climate prevailed and that mean annual precipitation may have been significantly lower (<1000 mm/year) than previously believed (Therrien, 2005).

Fig. 1. Haţeg Basin, Romania. (A) Location of the Haţeg Basin (black outline) in the Southern Carpathians of western Romania. The boxed area is detailed in (B). Modified from Grigorescu (1992). (B) Geologic map of the Apuseni Mountains and Southern Carpathians. The Haţeg Basin is a post-orogenic extensional basin produced by the collapse of the Southern Carpathians during the Maastrichtian. Boxed area is presented in Fig. 2A. Modified from Burchfiel and Bleahu (1976), Schmid et al. (1998), Sanders (1998), Willingshofer (2000), and Willingshofer et al. (2001).

2.2. The Sânpetru Formation

The Maastrichtian Sânpetru Formation is exposed in the western Haţeg Basin (Fig. 2A). Although the entire stratigraphic interval of the formation is not exposed, Nopcsa (1905) estimated the Sânpetru Formation to be approximately 2500-m-thick based on the distribution of exposures in the basin. The most extensive outcrops of the Sânpetru Formation are located along the Sibişel Valley, near the village of Sânpetru (Fig. 2). Historically, the Sânpetru Formation has been divided into two members based on lithological differences visible in the Sibişel outcrops: (1) the lower member displays a mixture of gray-green and red mudstones and has been

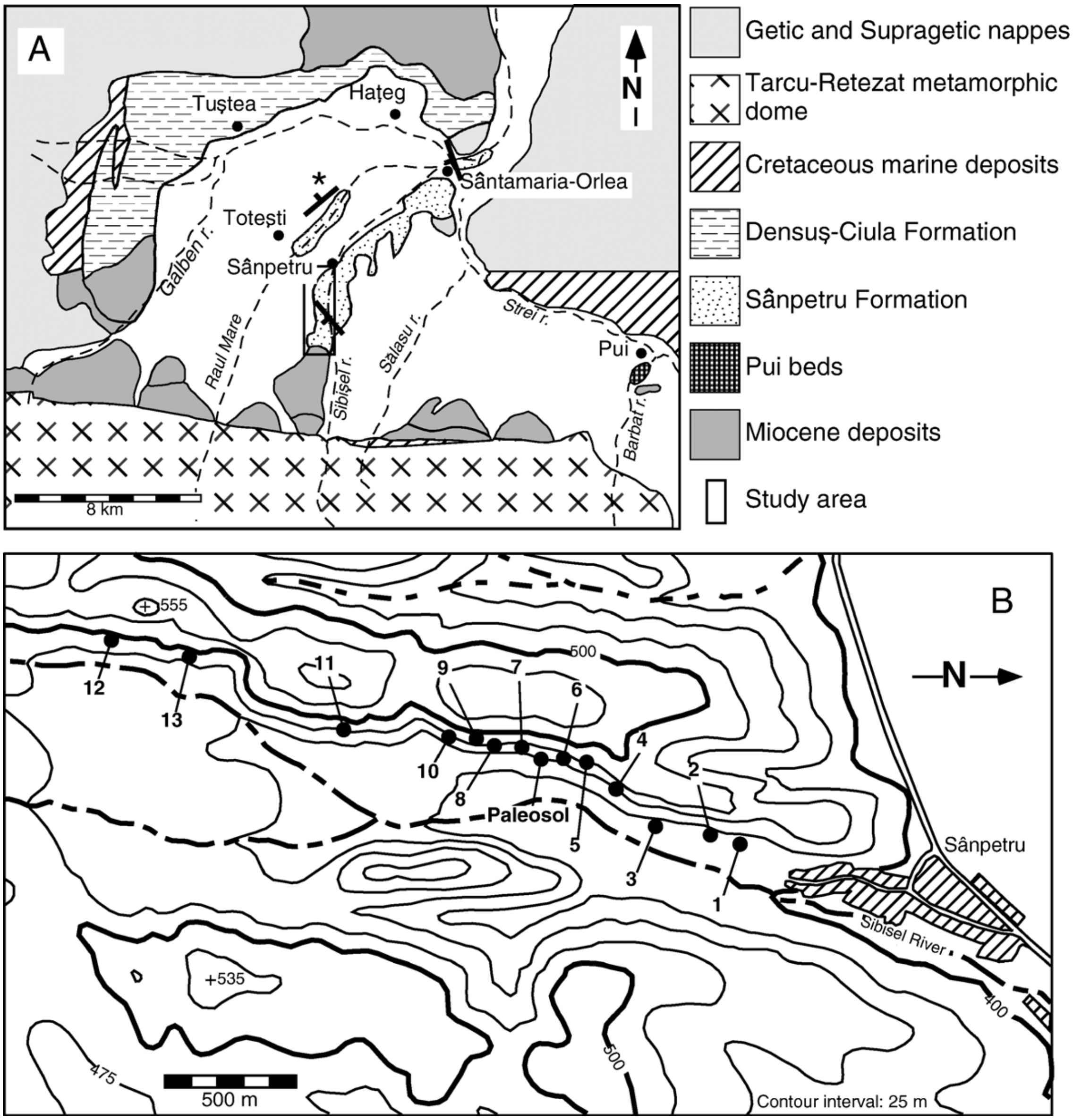


Fig. 2. Sânpetru Formation in the Haţeg Basin. (A) Geologic map of the western portion of the Haţeg Basin where the Maastrichtian Sânpetru Formation is exposed. The most extensive outcrops of the Sânpetru Formation represent an 860-m-thick sequence exposed along the Sibişel River. The attitudes of the strata (strike and dip) are reported for various rock exposures in the Haţeg Basin; all were measured by the present author except for the one indicated by an asterisk "*", which was reported by Codrea et al. (2002) and Smith et al. (2002). Strata attitude: northern exposure on the eastern bank of Raûl Mare near Haţeg (136°N, 55° to the west), along the Sibişel River (142°N, 45° to the west), and Raûl Mare deposits* (220–230°N, dip: 75–80° north). Modified from Weishampel et al. (1991). (B) Location of the 14 stratigraphic sections measured along the Sibişel Valley in order to compile the Sânpetru composite stratigraphic section.

reported to contain disseminated pyroclastic material in the matrix of mudstones and sandstones (Nopcsa, 1905; Grigorescu, 1983; Weishampel et al., 1991); and (2) the upper member is characterized by the presence of numerous conglomerate beds, the absence of red mudstones, and allegedly contains andesitic tuffites (Grigorescu, 1983, 1992; Weishampel et al., 1991). Because the Sibişel outcrops represent only a portion of the entire Sânpetru Formation (possibly the upper part given their location relative to exposures near Toteşti and Sântamaria-Orlea; Fig. 2A), the recognition of two members may not be applicable to the entire formation (see Codrea et al., 2002). Consequently, the bipartite division of the formation should be used only along the Sibişel Valley.

The Sânpetru Formation has long been considered late Maastrichtian in age based on its pollen assemblages (e.g., Antonescu et al., 1983; Weishampel et al., 1991; Grigorescu, 1992; Grigorescu and Csiki, 2002), but recent revision of the pollen assemblage and magnetostratigraphic studies revealed that the deposits might rather be of early to middle Maastrichtian age (López-Martinez

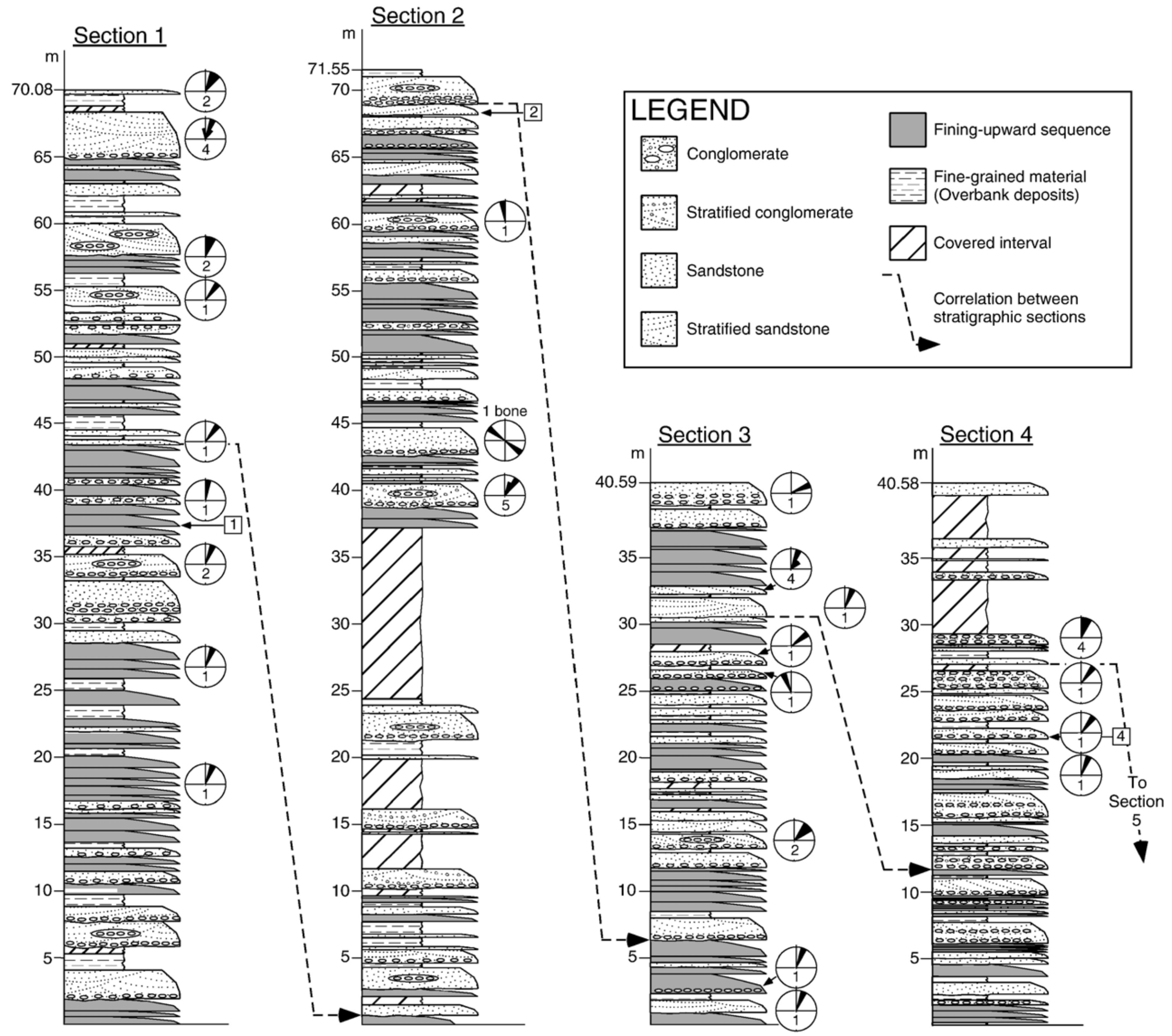


Fig. 3. Fourteen stratigraphic sections measured along the Sibişel Valley to construct the composite stratigraphic section of the Sânpetru Formation. The location of eight sandstones studied for provenance analysis is indicated by numbers in boxes. Paleocurrent direction is represented by rose diagrams next to the sandstone bed in which the sedimentary structures were observed; the number of measurement taken in a given bed is indicated by the number inside the rose diagrams.

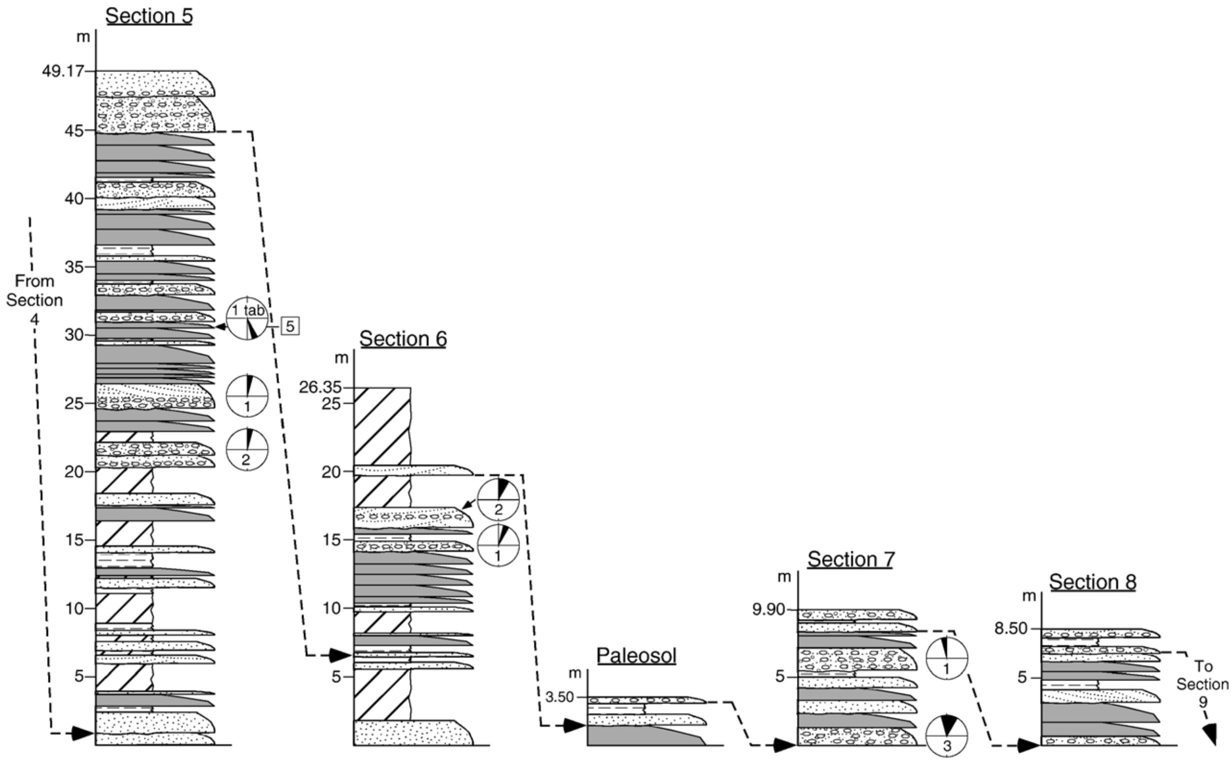


Fig. 3 (*continued*).

et al., 2001; Panaiotu and Panaiotu, 2002; Therrien, 2004; Van Itterbeeck et al., 2005).

3. Methods

Due to the strike and dip of the strata (142°N, 45° to the west), outcrops on the eastern wall of the Sibişel Valley expose nearly exclusively the upper surface of beds. For that reason, and because outcrops are more extensive on the western wall, sections were measured exclusively on the western valley wall. A total of 14 stratigraphic sections were measured to compile a composite stratigraphic section of the Sânpetru Formation (Figs. 2B and 3). The first section was measured south of the Sânpetru village (on the Vulk family property, 45°32′37N 22°54′34E), and the last section (Section 12) was measured on the last hill of the valley wall (45°31′29″N 22°54′16″E). The sections are located approximately 6.5 and 4.0 km, respectively, north of the Ţarcu–Retezat Mountains (Fig. 2A). Over the 2.5 km of valley wall, an 860-m-thick stratigraphic interval was studied, although vegetation covers nearly 50% of the section (Fig. 3); very poor outcrops located between Sections 11 and 13 were not studied. After trigonometrically correcting for the dip of the strata (assumed to be constant throughout the valley and without major vertical deformation), the last measured section (Section 12) is determined to have been located approximately 2.2 km south-southwest (sourceward) from the first section on the Maastrichtian paleolandscape.

The steep dip and vegetation cover limit lateral exposure of most sedimentary units to a maximum of 200 m. The sections were correlated by physically tracing marker beds (walking along laterally extensive sandstone ledges) between sections. When a covered interval prevented direct correlation between two sections (e.g., between Sections 10, 11, 12, and 13; see Figs. 2B and 3), the missing stratigraphic interval was calculated trigonometrically by using the distance separating the two sections (measured on a topographic map) and the orientation of the dipping strata. This method assumes that no vertical displacement (i.e., faults) occurs within the intervening covered interval. Although faults are observed within the Sânpetru Formation, vertical displacement rarely exceeds 10 m; consequently, the estimation error of the thickness of covered stratigraphic interval is presumed to be minimal.

Each lithological unit was described in terms of sedimentary and/or pedogenic features. Stratum thickness and paleocurrent direction were recorded and

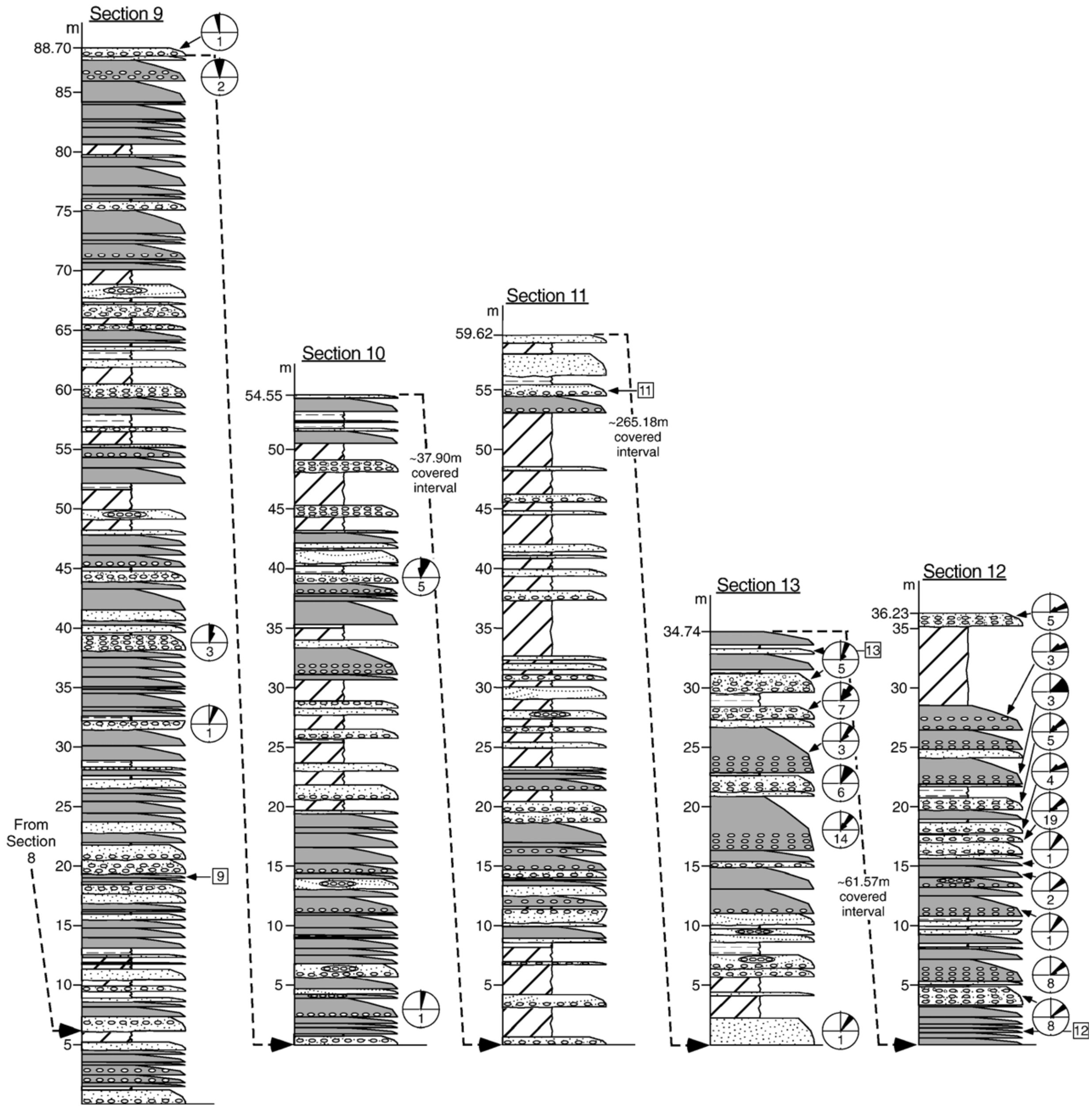


Fig. 3 (*continued*).

corrected for the inclination of the beds. Paleocurrent direction was measured from various sedimentary structures, predominantly clast imbrication and trough cross-stratification (from three-dimensional exposure) and rarely tabular cross-stratification (Fig. 3). Because paleocurrent variability proved to be low in the lower member, all paleocurrent directions were compiled into a single rose diagram; in the upper Sânpetru Formation, paleocurrent directions were compiled into rose diagrams for each individual section. No paleocurrent data were obtained for Section 11. Statistics were calculated with the software GEOrient 9.2 and SPSS 13.0.

To complete the sedimentologic study, eight sandstone beds, considered representative and occurring at various stratigraphic levels throughout the composite section (Fig. 3), were sampled for point counting analysis. All samples are medium-grained sandstones, except for sample 9, which is a fine- to very fine-grained sandstone. Mineral proportions were obtained by counting a total of at least 300 points dispersed in three of the four corners of each thin section. Minerals included within lithic fragments were counted as the type of lithoclast in which they occur rather than as their respective mineral constituents (Decker and Helmold, 1985; Johnsson et al., 1991; von Eynatten and Gaupp, 1999; Garzanti and Vezzoli, 2003; contra Gazzi-Dickinson counting method, Ingersoll et al., 1984).

4. Sedimentology of the Sânpetru Formation

Along the Sibişel Valley, the Sânpetru Formation consists of a repetitive succession of brown and gray sandstone ledges interbedded with gray to green (5G 3/1 to 10GY 2.5/1) or brown to red (2.5Y 4/2 to 10YR 4/2) muddier intervals (Fig. 4A). These beds form stacked fining-upward units (called "cyclothems" by Grigorescu, 1983): laterally extensive sandstone ledges, consisting of calcite- and silica-cemented arenites, fining upward into muddy sandstones (wackes; sandstone classification after Williams et al., 1982) and mudstones (i.e., subequal proportion of silt- and clay-sized particles) in the non-ledge-forming interval (Fig. 4B). Although the sandstone units are laterally extensive, protrusion from the ground in the form of a ledge is impersistent (Fig. 4A). Grigorescu (1983) and Bojar et al. (2005) noted that some sandstone beds graded laterally into overbank deposits over tens of meters, an observation that could potentially be related to the discontinuous protruding nature of the sandstone ledges. In the fining-upward units, the sandstone intervals (arenite + wacke) vary generally between 0.20 m and 2.00 m in thickness (up to a maximum of 4.00 m), whereas the mudstone intervals are generally less than 1.00 m thick (rarely exceeding 1.80 m; Figs. 3 and 4C); sandstone generally forms 40–80% of a fining-upward unit. Sandstone beds displaying a coarsening-upward trend occur rarely, but numerous beds exhibit alternating coarse- and fine-grained intervals, evidence of a complex depositional history.

4.1. Channel deposits

All sandstone beds form laterally extensive sheets for which the maximum lateral extent cannot be determined due to the dip of strata and the limited exposure. The majority of sandstone sheets are single storey. Multistorey sheets are limited to two storeys and occur predominantly in the upper Sânpetru Formation (Section 13).

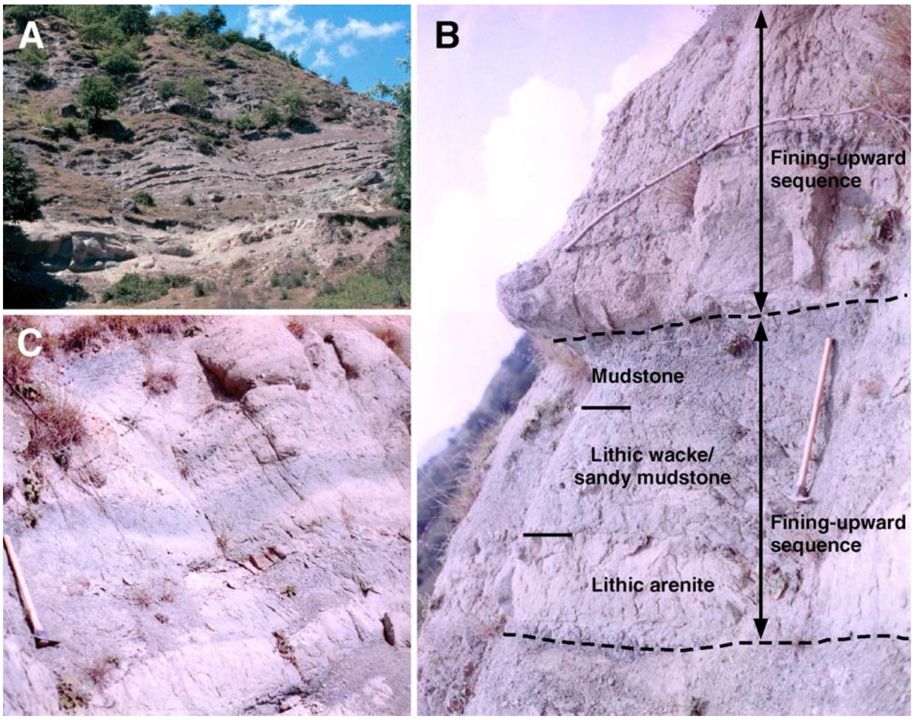


Fig. 4. Photographs of the Sânpetru deposits. (A) The Sânpetru Formation is composed of stacked fining-upward sequences composed of a basal sandstone unit overlain by mudstone. This approximately 100-m-high hill is the location of Section 1. (B) Typical fining-upward sequence: a (ledge- to non-ledge-forming) lithic arenite with a subhorizontal erosional base grading upward into a non-ledge-forming interval of lithic wacke/sandy mudstone and mudstone. This 1-m-thick sequence unconformably overlies and is unconformably overlain by fining-upward sequences. Picture taken at 19 m from the base of Section 12. Pick for scale. (C) Close-up of stacked fining-upward sequences. Picture represents 14–17-m interval of Section 12.

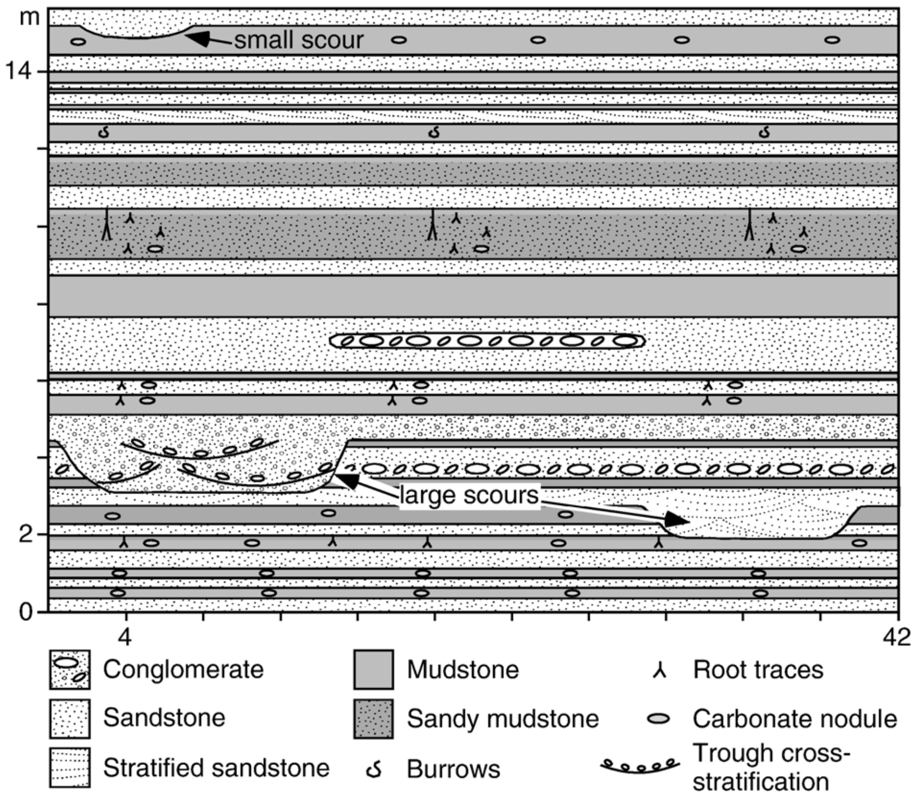


Fig. 5. Schematic representation of the sedimentologic architecture of the Sânpetru Formation, based on stratigraphic intervals present in Sections 1 and 4. The stratigraphic section consists of stacked fining-upward sequences and occasional interbedded sandstone and mudstone lacking a discernible fining-upward trend. The sandstone units possess a sheet-like architecture with a subhorizontal erosional base. Channel-shaped scours occasionally occur at the base of a sandstone sheet: the depth of a sandstone sheet is approximately 1/3 that measured at maximum scour depth. Small (<10.00 m wide and <1.50 m deep) and large channel-shaped scours (<30.00 m wide and <4.00 m deep) are observed, their width/depth ratio varying between 3 and 14. Scale in meters. Note the different scale for horizontal and vertical dimensions.

Sandstone sheets are characterized by a subhorizontal erosional base, although shallow channel-shaped scours occur locally at the base of sandstone sheets (Fig. 5). A maximum of one channel-shaped scour has been observed per sandstone sheet, but limited exposure could have prevented the recognition of more scours. Small (less than 10.00 m wide and 1.50 m deep) and rarer large (up to 30.00 m wide and 4.00 m deep) channel-shaped scours are observed, the upper margin of each extending laterally into sandstone sheets of a thickness approximately one-

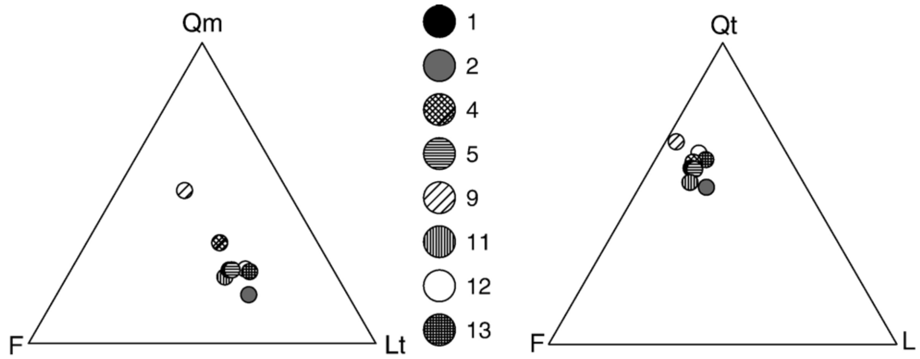


Fig. 6. Compositional ternary diagrams of eight sandstones of the Sânpetru Formation. All sandstones cluster together, indicating provenance from a unique source area. The apparent distinctive composition of sample 9 is an artifact of its finer grain size.

third the maximum depth of the scour (Fig. 5). Thickness of sandstone sheets generally decreases laterally over tens of meters away from large scours; variation in thickness away from small scours is less obvious. Large channel-shaped scours are mostly characterized by a coarser grained base and better developed sedimentary structures than their contiguous sandstone sheet, whereas no significant difference in grain size is observed between small scours and their contiguous sheet. The lateral extensions of a channel scour into thin sandstone sheets are reminiscent of the "wings" attributed to splay channels described by several authors (e.g., Smith et al., 1989; Mjøs et al., 1993; Kraus, 1996). Width–depth (w/d) ratios for 16 basal channel-shaped scours (without the "wings") range from 3 to 14 (mean = 7.05, standard deviation = 3.21), but these values represent maxima given the possibility of measuring channel width at an oblique angle to paleocurrent direction.

The sandstones of the Sânpetru Formation are very poorly to moderately sorted, lithic arenites and wackes. The framework grain composition of eight Sânpetru sandstones form clusters on the compositional ternary diagrams (Figs. 3 and 6), indicating a persistent source area over the entire stratigraphic interval studied. The average composition of the sandstones is 48% quartz, 19% K-feldspar, 10% metamorphic (gneiss and schist) lithoclasts, 10% felsic intrusive igneous (granitoid) lithoclasts, 5% phylosilicates, 4% plagioclases, 3% accessory minerals, and 1% fragments of sedimentary origin (carbonate and sandstone). No glass shards or volcanic material was observed in the matrix of the sandstones (contra Nopcsa, 1905; Grigorescu, 1983), a characteristic that distinguishes the Sânpetru Formation from contemporaneous formations within the Haţeg Basin (Van Itterbeeck et al., 2004; Therrien, 2005). One sandstone appears to have a different composition from the others (#9, Fig. 6), but this difference is attributed to the finer grain size of this sample (see Ingersoll et al., 1984; Zuffa, 1985). The compositional immaturity of the sandstones (Qt/F+L and Qp/F+L ratios varying between 1.08–1.71 and 0.68–1.04, respectively; see Suttner and Dutta, 1986) and the angularity of the framework grains throughout the stratigraphic section argue for local derivation and limited transport of the sediments.

4.2. Overbank deposits

Siltstones and mudstones cap most fining-upward sequences in the Sânpetru Formation. These facies are generally poorly sorted and contain sand and fine gravel particles. Siltstones and mudstones are black, gray, green, brown, or red in color. Most mudstones are bioturbated and contain gastropod shells. Pedogenic features, such as carbonate nodules, redoximorphic features (i.e., mottles), slickensides, and clay and iron oxide coatings, are developed to various degrees within mudstones.

The association of sedimentary structures and pedogenic features permits the recognition of two broad categories of Sânpetru overbank deposits: (1) stratified deposits and (2) paleosols (Table 1). Among paleosols, five distinct pedotypes, each characterized by a unique assemblage of pedogenic features, are identified: (1) gray or green paleosol that lacks advanced signs of pedogenesis (immature, hydromorphic); (2) gray or green paleosol with carbonate concretions (well-developed, hydromorphic); (3) gray or green paleosol with redoximorphic features (hydromorphic with fluctuating water table); (4) red paleosol with slickensides and redoximorphic features (immature, moderately drained habitat); and (5) red paleosol containing carbonate nodules and redoximorphic features (well-developed, moderately drained habitat). The first three pedotypes represent topographically low, poorly drained regions of the floodplain, whereas the latter two represent topographically higher, better drained habitats (Therrien, 2004). The association of hydromorphic and brown-red calcareous paleosols indicates that a mosaic of wetlands and moderately drained floodplains formed the Maastrichtian landscape of the Sânpetru Formation (Therrien, 2004).

4.3. Sedimentary facies and facies associations

Sedimentary structures are only locally recognizable in the sandstone beds of the Sânpetru Formation, which led Grigorescu (1983) to describe the sandstones as massive. However, many apparently "massive" sandstones preserve horizontal or curved alignment of coarse sand or gravel, belying this categorization. Nevertheless, the sedimentary structures, when recognized, are generally only faintly discernible, making it nearly impossible to document them photographically.

Seven lithofacies are recognized in the Sânpetru Formation (Table 1). These lithofacies form four distinct facies assemblages, labeled A through D. Facies assemblages A and C are the most common, whereas facies assemblages B and D are uncommon.

4.3.1. Facies assemblage A

Facies assemblage A is a fining-upward sequence, ranging from 0.30 m to 4.00 m thick (mean = 1.00 m; Fig. 7), composed of a flat-bedded or imbricated

Table 1
Lithofacies of the Sânpetru Formation

Facies	Lithofacies	Characteristics	Interpretation
1	Conglomerate	Uncommon; ≤2-m-thick flat-bedded and imbricated cobble conglomerate (upper Sânpetru Formation), ≤0.5-m-thick at base of sandstone sheets or channel-shaped scours (lower Sânpetru Formation), clast supported, granule to pebble (occasionally cobble), angular to rounded extraformational clasts.	Sheetfloods; in-channel lags
2	Horizontally laminated sandstone	Abundant; <4 m thick, occurs predominantly within sandstone sheet but occasionally forms a unit under sandstone sheet or channel-shaped scour, any grain size, local gravel, angular to rounded grains.	In-channel plane beds, sheetfloods, splays
3	Trough cross-stratified sandstone	Common; occurs as large (>0.2 m) or small (<0.05 m) sets within sandstone sheets or channel-shaped scours, any grain size, local gravel, angular to round grains.	In-channel 3-D dunes
4	Tabular cross stratified sandstone	Rare; occurs as medium to small sets (<0.45 m) in the upper half of thick (>1.50 m) sandstone sheets, paleocurrent orientation either parallel or perpendicular to that of trough cross-stratified sandstone, medium to fine sand, local gravel, angular to round grains.	In-channel bars, 2-D dunes
5	Structureless sandstone	Abundant; occurs in the uppermost part of or as discrete sandstone sheets, <0.5 m thick (mean 0.30 m), any grain size, angular to round grains, occasional burrows, root traces, iron oxide and carbonate concretions.	In-channel fills, splays
6	Horizontally laminated siltstone and mudstone	Uncommon; occurs above fining-upward or rarely within sandstone sheets, 0.1–1.0-m-thick, local sand and gravel, occasional coal fragments, gastropod and disarticulated bivalve shells, local bioturbation.	Suspension settling in poorly drained overbank environments
7	Structureless mudstone	Abundant; <1-m-thick, local sand and gravel, bioturbated, pedogenic features (carbonate nodules, slickensides, redoximorphic features, clay and iron oxide coatings) present in various associations and abundance, gastropod and disarticulated bivalve shells.	Paleosol

conglomerate (facies 1), passing upward into horizontally laminated (facies 2) and large- through small-scale trough cross-stratified sandstone (facies 3), and in turn into siltstone or mudstone (facies 6 or 7). Tabular cross-stratified sandstone (facies 4) occurs occasionally in thick sandstone sheets (mean = 1.50 m; Fig. 7). The gradation from one lithofacies to the next occurs over the entire width of the exposure. Mud drapes, reactivation surfaces, and tabular mudstone or conglomeratic intervals occur locally in this facies assemblage.

Facies assemblage A resembles the sedimentary sequence observed in many modern and ancient braided stream deposits (e.g., Collinson, 1970; Cant and Walker, 1976, 1978; Cant, 1978; Diemer, 1992; Bentham et al., 1993). The facies assemblage reflects the initial channel-scouring event followed by the migration of small-scale bedforms in the channel. Variability in the sequence of lithofacies (e.g., presence/absence of tabular cross-stratified sandstone) in this facies assemblage suggests deposition in various parts of the braid belt or channel, where different bedforms migrated. The occurrence of mud drapes, reactivation surfaces, and abrupt changes in grain size within sandstone units (e.g., conglomeratic intervals) indicates fluctuations in flow conditions during the flood (Smith, 1971; Cant and Walker, 1976, 1978; Singh, 1977; Cant, 1978; Miall, 1988). The fact that facies assemblage A is not confined generally to channel scours but occurs in laterally extensive, thick sandstone sheets suggest deposition either in very wide channels or as vast unchannelized flows. Cassiliano (1998) described similar strata and facies assemblages in the Huesos Member from the Plio-Pleistocene Palm Spring Formation of southern California, which he interpreted as having been deposited by poorly channelized flow (i.e., sheetfloods) or in shallow and wide braid belts.

4.3.2. Facies assemblage B

Facies assemblage B (Fig. 7) refers to thin (<0.30 m) or thick (>1.50 m) tabular conglomerate beds that may be normally graded (fining-upward), non-graded, or rarely coarsening-upward (facies 1). The conglomerates are clast-supported and exhibit imbrication, horizontal lamination, or rarely trough cross-stratification. These deposits are generally overlain by finely laminated or structureless mudstone (facies 6 or 7).

Facies assemblage B represents the deposits of high-energy events, such as fast-flowing, shallow rivers or proximal splays. The paucity of complex sedimentary structures in this facies assemblage is the result of high-energy flow in a shallow channel or over a broad alluvial plain. The scarcity of this facies assemblage in the Sânpetru Formation indicates that the conditions necessary for its development were uncommon. The

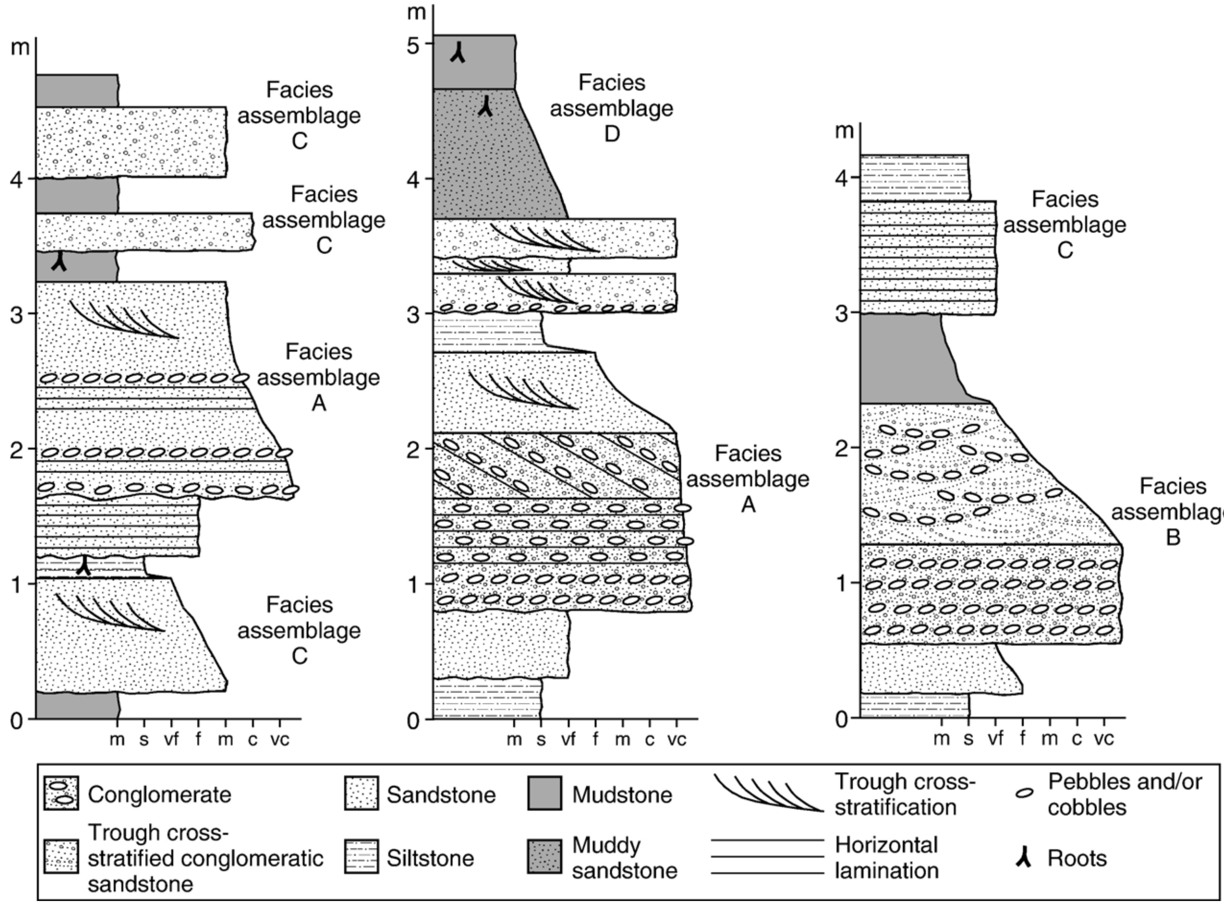


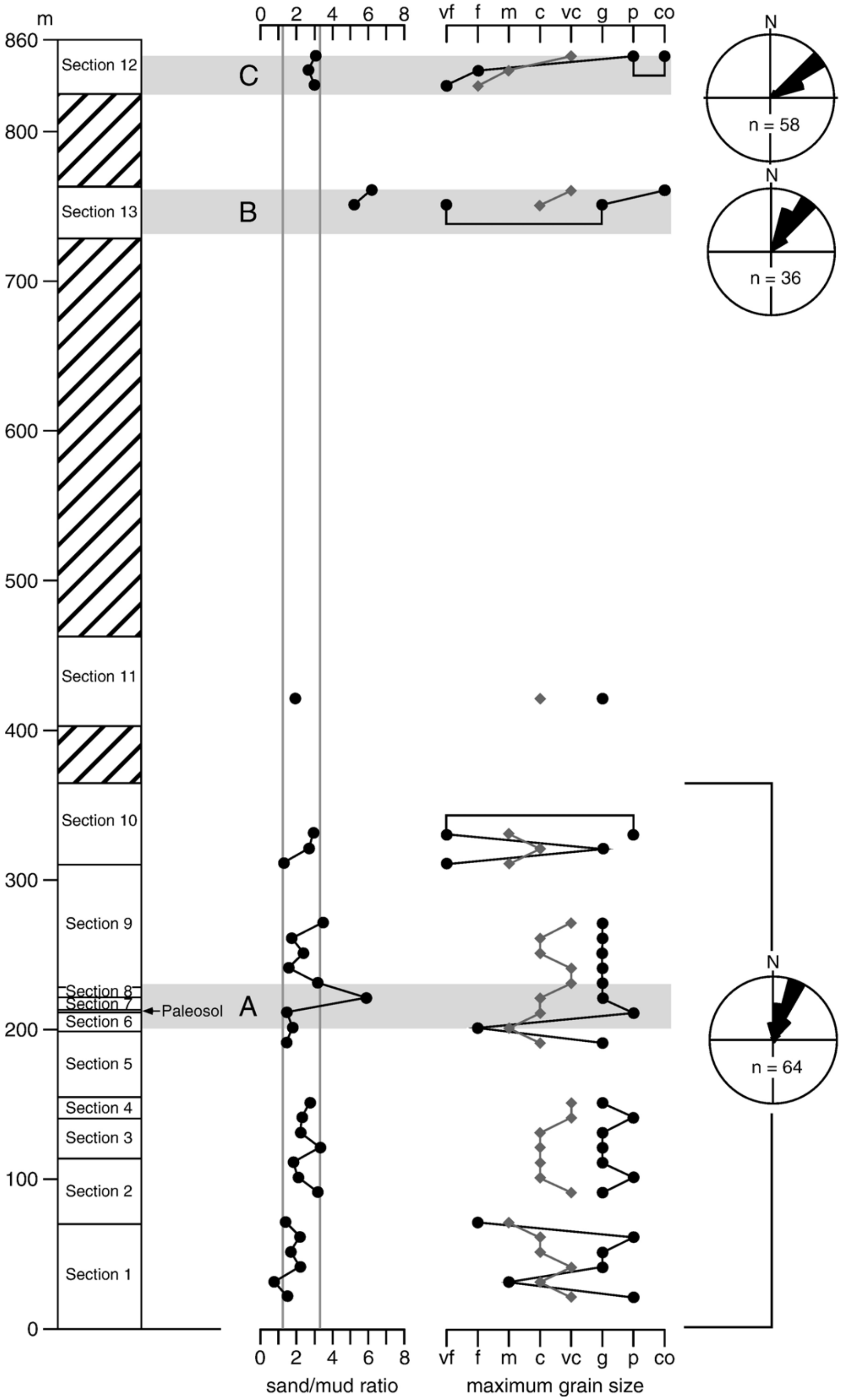
Fig. 7. Facies assemblages characteristic of the Sânpetru Formation. See text for discussion. Facies assemblages illustrated in the left section occur in the 37.5–42.0-m interval of Section 2, facies assemblages illustrated in the middle section occur in the 29.0–34.0-m interval of Section 3, and facies assemblages illustrated in the right section occur in the 5.0–9.0 m interval of Section 12.

exclusive occurrence of thick conglomerate beds in the upper Sânpetru section suggests that an important change in fluvial conditions occurred in that stratigraphic interval (see below).

4.3.3. Facies assemblage C

Facies assemblage C occurs generally as thin (<0.50 m thick), medium- to very fine-grained, non-graded or normally (rarely inversely) graded sandstone sheets that either fine upward into mudstone or are overlain by sandy mudstone without a gradational decrease in sand size (simply an increase in mud content; Fig. 7). These deposits generally lack sedimentary structures, but small-scale trough cross-stratification and horizontal lamination are locally present in the sandstone interval (facies 2, 3, and 5). The sandstone beds are characterized by a subhorizontal base with minimal erosional relief (a few cm at most), although some show shallow (<1.00 m) and

Fig. 8. Variation in sandstone/mudstone ratio, maximum grain size of channel deposits (black circle = mode, gray diamond = mean), and paleocurrent orientation throughout the Sânpetru Formation. When two modes of maximum grain size occur at a given stratigraphic level, they are connected by a bracket. The vertical gray lines in the sandstone/mudstone ratio graph represents one standard deviation on either side of the mean (mean = 2.28, σ = 1.01). The fluctuations in the sandstone/mudstone ratios and maximum grain size in the lower Sânpetru Formation (sections 1–11) reflect autocyclic changes in the position of the river channels on the alluvial plain. The higher sandstone/mudstone ratios, the increase in coarseness and thickness of channel deposits, and the change in paleocurrent direction in section 13 indicate a major phase of uplift of the source area. The return to sandstone/mudstone ratios typical of the lower formation, the scarcity of multistorey sandstones, and further change in paleocurrent direction in section 12 demonstrate that the fluvial system reached a new equilibrium with tectonic uplift. Although the presence of cobble and pebble conglomerates in the stratigraphic interval 840–860 m reveals that high-energy floods occurred, the predominance of very fine-grained sandstones indicates that low-energy flows prevailed. The shaded stratigraphic intervals (A–C) are illustrated in details in Fig. 10.



m
860
800
700
600
500
400
300
200
100
0
Section 12
Section 13
Section 11
Section 10
Section 9
Section 8
Section 7
Section 6
Paleosol
Section 5
Section 4
Section 3
Section 2
Section 1
A
B
C
0 2 4 6 8
sand/mud ratio
vf f m c vc g p co
maximum grain size
N
n = 58
N
n = 36
N
n = 64

Table 2
Differences between the lower and upper Sânpetru Formation

	Lower Sânpetru Formation	Upper Sânpetru Formation	
	Sections 1–11	Section 13	Section 12
Sandstone/mudstone ratio	Low (mean = 2.28, σ = 1.01) single-storey sandstones	High (> 5.10) multistorey sandstones	Low (mean = 2.91, σ = 0.21) single-storey sandstones
Maximum grain size of channel deposits	Fluctuations but cobbles never form mode	Very coarse, cobbles form mode	Finest of the entire formation at base of section, very coarse at top of section (cobbles form mode)
Number of sandstone beds per 10-m stratigraphic interval	8–17	8	9–12
Paleosols	Mixture of hydromorphic (67%) and brown-red (33%) paleosols	Exclusively hydromorphic paleosols (100%)	Exclusively hydromorphic paleosols (100%)
Palaeocurrent direction	21°N (n = 64)	34°N (n = 36)	59°N (n = 58)
Fossil preservation	Lenticular bonebeds, channel deposits, red paleosols	Hydromorphic paleosols	Hydromorphic paleosols

narrow (< 3.00 m) channel-shaped scours at their base (Fig. 5). Mud content of the sandstones may increase laterally, resulting in the blending of the sandstone ledge with the overlying structureless, pedogenically modified mudstones (facies 7). Bioturbation and pedogenic features locally cross the lithologic boundary and pervade the sandstone unit.

This facies assemblage is interpreted as the deposits of poorly channelized flood events, such as sheetfloods and crevasse splays. The lateral extension of sandstone sheets beyond small basal channel-shaped scours reflects the widespread flooding that followed the filling of splay or secondary channels (Smith et al., 1989; Mjøs et al., 1993; Kraus, 1996). The lateral increase in mud content of the sandstone beds indicates a decrease in flow velocity away from the active channel. The finer grained and non-graded sandstones probably reflect splay deposition in more distal reaches of the floodplain, whereas coarser and fining-upward beds represent proximal splay deposits (Smith et al., 1989; Mjøs et al., 1993).

4.3.4. Facies assemblage D

Facies assemblage D, which varies between 0.10 m and 1.70 m in thickness, is dominated by siltstones and mudstones (facies 6 and/or 7) but some intervals also contain interspersed, thin (< 0.10 m) sandstone layers (facies 5; Fig. 7). Although the overall trend is that of a fining-upward sequence, variation in grain size in some profiles testifies to a complex history of episodic depositional events. Bioturbation and pedogenic features are found in most units of this facies assemblage, although their degree of development varies greatly (see above; Therrien, 2004).

Facies assemblage D is interpreted to be the result of fine-grained overbank deposition on the floodplain. Vertical aggradation of the floodplain occurred through the incorporation of distal splay and flood deposits in the profile, as indicated by the occurrence of fine sandy layers and variations in grain size and the absence of laterally continuous sandstone sheets. After water receded, the overbank deposits were pedogenically modified.

4.4. Sedimentologic trends in the Sânpetru formation

In order to study trends in fluvial style, paleocurrent direction and grain size variation was documented through the Sânpetru Formation (Appendix A). Sandstone/mudstone ratio and maximum grain size (mean and mode) of channel deposits were calculated for each 10-m interval throughout the composite stratigraphic section (Fig. 8). Although a strict channel deposit/overbank deposit ratio can be applied to conventional fluvial systems (with well-defined channel and overbank environments), it applies poorly to the Sânpetru fluvial system, which is characterized by widespread sheetfloods. In this context, the sandstone/mudstone ratio is more appropriate as it acts as a proxy for the abundance of high-energy events within a stratigraphic interval. Stratigraphic intervals in which significant covered intervals are present (> 1.20 m) were not considered; smaller covered intervals were not included in the calculation of sandstone/mudstone ratio. Maximum grain size of channel deposits was reported semi-quantitatively in terms of grain size category (cobble, pebble, granule, very coarse sand, etc.).

Paleocurrent variability is low within the lower Sânpetru Formation (circular standard deviation = 0.4 and circular mean deviation about mean = 14°) and in the two sections of the upper Sânpetru Formation (circular standard deviation = 0.2 and circular mean deviation about mean <9°). Paleoflow in the lower Sânpetru Formation is northward but a change in paleocurrent direction occurs in the upper member of the formation, where paleoflow turns slightly more to the east (Section 13) and is oriented to the northeast (Section 12) at the top of the formation (Fig. 8, Table 2). Non-parametric, two independent samples *t*-tests indicate that the difference in paleocurrent direction between each stratigraphic interval is statistically significant ($p < 0.05$).

The variability in sandstone/mudstone ratios and maximum grain size of channel deposits through the lower Sânpetru Formation is interpreted to reflect autocyclic changes in the position of the river channels on the alluvial plain: sandier stratigraphic intervals and coarser grained

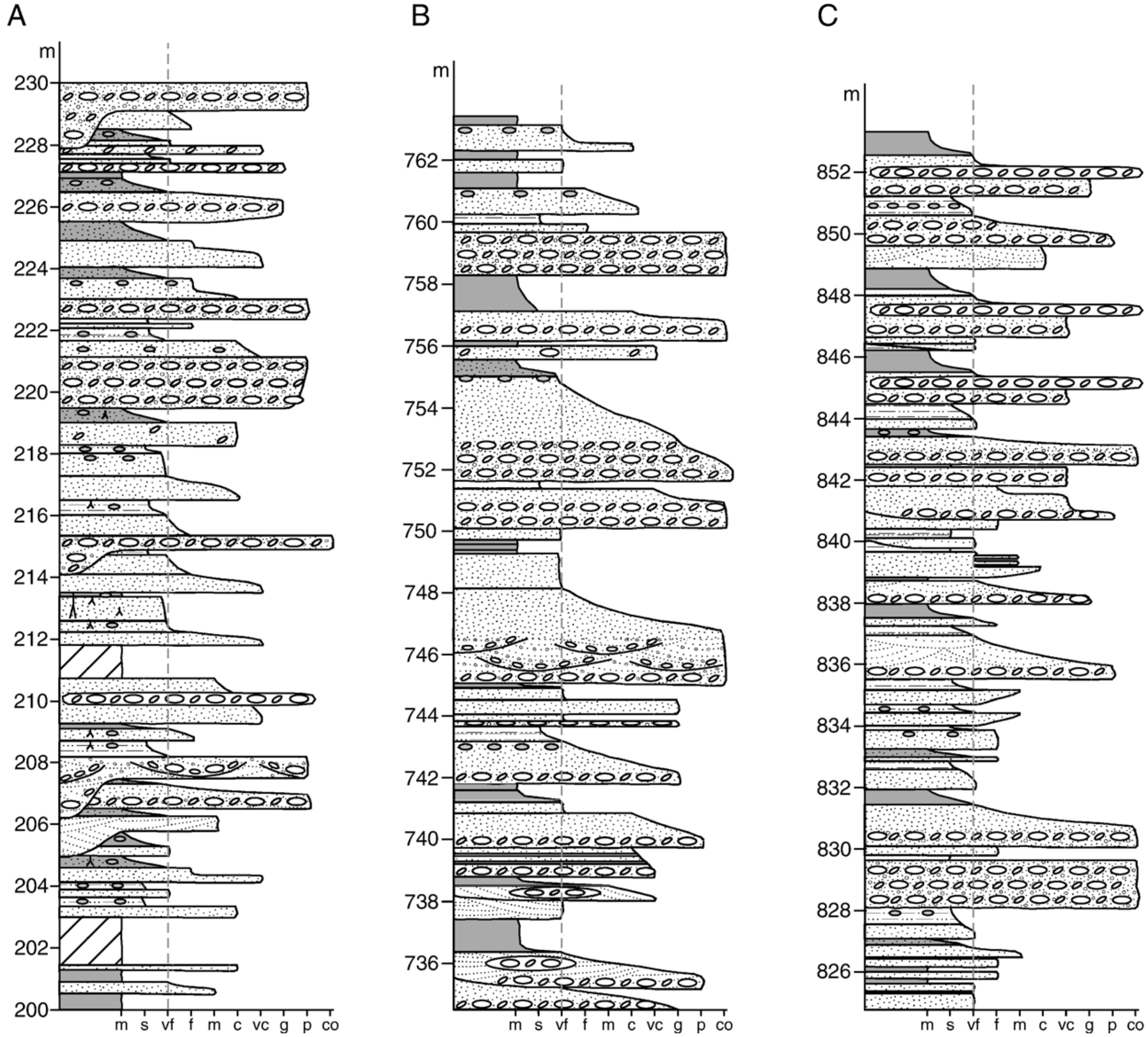
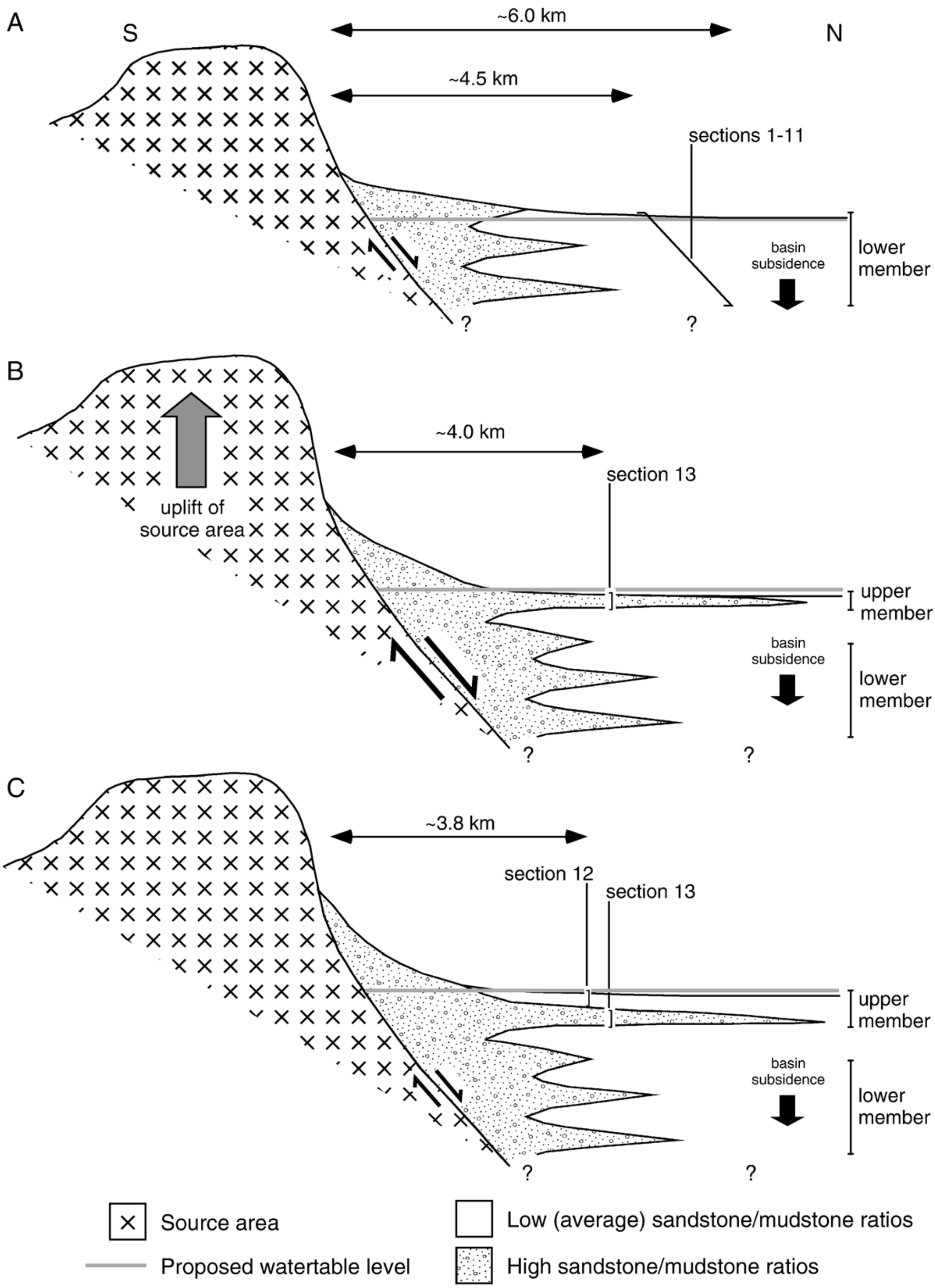


Fig. 9. Details of stratigraphic intervals characterized by peculiar sandstone/mudstone ratios and maximum grain size trends highlighted in the figure. For legend, see Figs. 4, 6, and 7). The gray dashed line represents the sandstone/mudstone grain size limit. (A) Stratigraphic interval 200–230 m. Whereas the 200–210-m and 220–230-m intervals possess sandstone/mudstone ratios within the range typical for the lower Sânpetru Formation, the 210–220-m interval is characterized by a higher ratio. This higher sandstone/mudstone ratio is due to the fact that overbank deposits consists of very fine sand, presumably reflecting deposition in proximity to major channels. (B) Stratigraphic interval 735–763 m, base of the upper member (Section 13) of the Sânpetru Formation. Sandstone/mudstone ratios and maximum grain size for the 740–760-m interval are higher than in the lower Sânpetru Formation. Thicker and coarser grained channel deposits characterize this interval. (C) Stratigraphic interval 825–853 m, top of upper member (Section 12) of the Sânpetru Formation. Sandstone/mudstone ratios for the 825–850-m interval are typical of values for the lower Sânpetru Formation. The 825–840-m interval is characterized by a predominance of fine-grained channel deposits, whereas conglomerates dominate the 840–850-m interval.


A
S
~6.0 km
N
~4.5 km
sections 1-11
basin subsidence
lower member
?
?
B
uplift of source area
~4.0 km
section 13
upper member
basin subsidence
lower member
?
?
C
~3.8 km
section 12
section 13
upper member
basin subsidence
lower member
?
?
Source area
Proposed watertable level
Low (average) sandstone/mudstone ratios
High sandstone/mudstone ratios

channel deposits occur in proximity to major channels whereas muddier stratigraphic intervals and finer grained channel deposits occur in distal settings (Fig. 8). It is worth noting that despite the presence of cobbles in the lower Sânpetru Formation, they never form the mode of maximum grain size. The sandstone/mudstone ratios reveal that coarse particles are generally twice as abundant as finer material in the lower member (Table 2). The sandstone/mudstone ratio fluctuates generally within one standard deviation of the mean throughout the lower member. The fluctuation in sandstone/mudstone ratio does not vary predictably as a function of the number of distinct channel deposits present in each 10-m stratigraphic interval, as intervals with the same number of sandstone bodies deliver differing ratios (Table 2, Appendix A). Interestingly, one interval notably rich in sand (sandstone/mudstone ratio = 5.89, 210–220 m interval; Figs. 8 and 9A) does not consist of thick sandstone sheets but rather of sandy "overbank" deposits. This observation suggests that the latter interval might represent a proximal floodplain environment, although the presence of well-developed paleosols (Therrien, 2004) indicates infrequent flooding.

The upper Sânpetru Formation, previously reported as distinct from the lower member based on the presence of conglomerates and dark gray mudstones (Weishampel et al., 1991; Grigorescu, 1992), is a non-homogeneous stratigraphic unit (Fig. 8). The base of the upper member (Section 13) is characterized by extremely high sandstone/mudstone ratios (>5.10) as well as coarse-grained channel deposits (mode in the gravel range; Table 2). This stratigraphic section is dominated by a low number of thick, coarse-grained, and occasionally multistorey sandstone sheets (Fig. 9B, Table 2). The uppermost stratigraphic interval of the formation (Section 12) is characterized by sandstone/mudstone ratios similar to those of the lower Sânpetru Formation. Despite the fact that numerous cobble conglomerates occur in this section (Fig. 9C), fine-grained sandstones are predominant. In fact, the maximum grain size of channel deposits in the first 20 m of Section 12 is the lowest in the entire formation (Figs. 8 and 9C, Table 2). In contrast, the last 10 m of the section are characterized by some of the coarsest channel deposits of the entire formation (pebbles and cobbles forming the mode at 850 m; Figs. 8 and 9C). In addition, the number of sandstone units in Section 12 returns to levels characteristic of the lower Sânpetru Formation (Table 2), indicating thinner channel deposits than in Section 13.

5. Interpretation of the Sânpetru depositional environments

Although the limited number of outcrops prevents detailed study of regional variation in fluvial architecture, the recognized facies assemblages, the abundance of high-flow horizontal lamination, the low variability of paleocurrent indicators, the sheet-like architecture of the deposits, and the paucity of channel-shaped scours indicate that the Sibişel outcrops of the Sânpetru Formation were formed by low-sinuosity fluvial systems on a poorly channelized alluvial plain (Cant and Walker, 1976, 1978; Cant, 1978; Grigorescu, 1983; Diemer, 1992; Bentham et al., 1993), supporting conclusions reached by Bojar et al. (2005). Similar facies assemblages have been described for low-sinuosity rivers flowing through symmetrical, extensional basins (i.e., grabens) (e.g., Mack and James, 1993) and for shallow, poorly channelized, bedload-dominated, braided fluvial systems (e.g., Cassiliano, 1998). The northward paleoflow, combined with the abundance of metamorphic grains in the fluvial deposits, identify the Ţarcu–Retezat Mountains, situated less than 7 km south of the study area, as the source area for the Sânpetru Formation.

The presence of channel-shaped scours of low width/depth ratio at the base of sandstone sheets (Fig. 5) indicates that, during low-flow conditions (i.e., prior to overbank flooding), flow was constrained within well-defined streams. During the initial phase of a flood, larger channels could have contained rapid flow longer than small channels before water overflowed onto the

Fig. 10. Tectonic model for the changes in depositional environments observed in the Sânpetru Formation. The distances of each section from the source area are corrected for dip and assume that the location of Section 1 has not changed during deformation (i.e., Section 1 is the reference point). (A) In the lower Sânpetru Formation, basin subsidence led to the creation of accommodation space near the water-table level, resulting in the formation of a mosaic of wetlands and better drained floodplains. (B) At the base of the upper Sânpetru Formation, a pulse of rapid source area uplift, associated with limited basin subsidence, led to an increase in sediment input, resulting in the deposition of a stratigraphic interval characterized by coarser channel deposits, multistorey sandstone sheets, and a greater sandstone/mudstone ratio (Section 13). Accommodation space was created slightly below water-table levels, leading to the exclusive development of wetlands. (C) Following the uplift pulse, the fluvial system reached equilibrium with the new conditions and returned to sandstone/mudstone ratios typical of the lower member and predominant single-storied sandstone sheets (Section 12). Although coarse-grained channel deposits are present in this stratigraphic interval, fine-grained channel deposits are predominant. Accommodation space remained slightly below the local water-table level, maintaining the development of wetlands. Note that the position of the water table in the diagrams is relative to the paleosurface at the time of deposition. The vertical elevation of the water table is exaggerated to help visualization.

floodplain. This difference could explain why coarser grained deposits and larger sedimentary structures are preferentially found within the confine of large scours and not in the laterally contiguous sandstone sheets, whereas no grain size difference is observed between small channel scours and their contiguous sand sheets. At high flood stage, active bedload deposition through migration of bedforms occurred over a vast area of the alluvial plain in the form of an unchannelized sheet flow or as a shallow and wide braidplain. The abundance of upper flow regime horizontal lamination in sandstones supports the interpretation of deposition by high energy and/or shallow flow. As flow waned, finer sand was deposited under lower flow regime before being covered by fine-grained overbank deposits. As the water receded, flow was concentrated into newly incised channels. Once aerially exposed, overbank deposits were pedogenically modified and a variety of hydromorphic and calcareous paleosols developed as a function of the local hydrologic (drainage and water table) conditions and proximity to channels (Therrien, 2004).

This interpretation of the depositional environments of the Sânpetru Formation differs from the conclusions reached by Van Itterbeeck et al. (2004) for outcrops exposed in Raûl Mare (see Fig. 2). These authors recognized lateral accretion surfaces in sandstone sheets, isolated channel-shaped sandstone bodies ("ribbon sandstone"), mud-filled channel-shaped scours, paleocurrent indicators oriented to the northwest, and other sedimentary facies that they interpreted as evidence of deposition in a meandering river system. Although the absence of these structures in the Sibişel outcrops could be an artifact of limited exposure, it is possible that their absence reflects genuine differences in fluvial systems. Two scenarios could explain the difference between the Raûl Mare and Sibişel deposits: (1) the Raûl Mare deposits could represent the distal reaches of the Sânpetru alluvial plain, where the lower paleoslope allowed for the development of a high-sinuosity fluvial system; or (2) the Raûl Mare deposits could represent a different stratigraphic interval of the Sânpetru Formation than the one represented by the Sibişel outcrops, thus indicating that changes in fluvial system occurred during deposition of the Sânpetru Formation. Due to the major structural deformation of the deposits and the extensive vegetation cover separating the Raûl Mare and Sibişel outcrops, it is unfortunately impossible to correlate the two localities directly. Future work should aim at correlating these two localities through structural and biostratigraphic studies to determine which scenario is valid as well as its implications in terms of basin evolution and paleoecology.

The documented change in paleocurrent direction observed in the upper Sânpetru Formation, which was not recognized by Grigorescu (1983, 1992), cannot be ascribed to a change in fluvial system (e.g., from braided streams to meandering rivers) because paleocurrent indicators remain tightly clustered. The change in paleocurrent direction could be the result of extrabasinal forces (e.g., tectonism, climate) acting on the fluvial system during the Maastrichtian. Although an increase in humidity is inferred to have occurred through the Sânpetru section (Bojar et al., 2005), the constancy of sandstone maturity (Qt/F + L and Qp/F + L ratios) and of the degree of weathering of feldspars throughout the formation suggests that climate probably did not play a controlling role in the fluvial changes observed (Suttner and Dutta, 1986). Rather, tectonic activity is most likely responsible. The collapse of the Carpathian orogen during the Maastrichtian led to the rapid exhumation of metamorphic basement (Willingshofer, 2000; Willingshofer et al., 2001), which modified the paleoslope of the alluvial plain and altered the orientation of rivers.

The sedimentologic trends in the upper Sânpetru Formation attest to the influence of tectonism on the creation of accommodation space and increase in sediment supply (Fig. 10). The increase in coarseness and thickness of channel deposits, the presence of multistorey sandstone sheets, the abundance of sandstone (high sandstone/mudstone ratios), and the change in paleocurrent direction at the base of the upper member (Section 13) reveal that a major phase of uplift of the source area increased sediment input and the gradient (paleoslope) of the alluvial plain (Fig. 10B). Depositional rate must have been higher than the rate of creation of accommodation space at first, explaining the presence of multistorey sandstone sheets in Section 13 (Fig. 9B). The return to sandstone/mudstone ratios typical of the lower member, the scarcity of multistorey sandstones, and further change in paleoflow direction at the top of the Sânpetru Formation (Section 12) suggest that the fluvial system reached equilibrium with tectonic uplift (Fig. 10C). Although the presence of cobble and pebble conglomerates in the 840–860-m stratigraphic interval indicates that high-energy floods occurred, the predominance of very fine-grained sandstones in Section 12 (lowest mean and mode of maximum grain size in the entire formation) shows that low-energy flows prevailed.

Paleoenvironmental changes co-occur with the changes in fluvial system observed in the upper Sânpetru Formation. Whereas the lower Sânpetru Formation is composed of a mixture of hydromorphic (67%) and brown-to-red (33%) paleosols where immature hydromorphic paleosols are common (18%), the upper

Sânpetru Formation consists exclusively of hydromorphic paleosols (100%), where immature hydromorphic paleosols are predominant (64%) (Table 2; Therrien, 2004). The exclusive occurrence of hydromorphic paleosols in the upper member of the formation reflects the development of widespread wetlands associated with the fluvial changes. Although the co-occurrence of a high-energy fluvial system with low-energy wetlands may appear paradoxical, such settings have been described for anastomosed rivers, where channelized flow is partly constrained by the surrounding wetlands (e.g., Flores and Hanley, 1984; Rust et al., 1984; Davies and Gibling, 2003). However, anastomosed fluvial systems are generally diagnosed by thick, multistorey, and laterally restricted sandstone bodies encased within overbank deposits, features that do not characterize the Sânpetru Formation. Rather, the onset of impeded drainage and high-energy flows is inferred to be related to tectonic activity. The subsidence of the Haţeg Basin and the rapid uplift of the Ţarcu–Retezat Mountains created accommodation space below local water-table levels in a part of the basin already characterized by a high or perched water table (Fig. 10B and C). In response to uplift of the source area, flood events would have been more frequent and occasionally more energetic although floodplains would have been characterized by impeded drainage due to the high water table. The high frequency of flood events would have limited the development of pedogenic features and produced predominantly immature paleosols. These conditions would have prevailed until subsidence ceased and/or vertical aggradation brought the paleosurface of the alluvial plain close to or above the water table, at which point a mosaic of wetlands and dry floodplains would have been re-established. Similar tectonically induced paleoenvironmental changes in extensional basins have been documented in the Newark rift basins of eastern North America (e.g., Schlische and Olsen, 1990; Smoot, 1991; Olsen et al., 1996) and in the Carboniferous Joggins Formation (Nova Scotia, Canada; Rust et al., 1984; Davies and Gibling, 2003).

It could be argued that the changes observed in the upper Sânpetru Formation reflect the more sourceward position of the sections: the base of the upper member (Section 13) was located approximately 500 m farther south than the last measured outcrops of the lower member (Section 11) on the Maastrichtian landscape, as reconstructed trigonometrically (Fig. 10). If this was the case, coarser sediment should characterize both channel and overbank deposits in the upper member (i.e., higher sandstone/mudstone ratios). However, the return to sandstone/mudstone ratios similar to those of the lower Sânpetru Formation at the top of the upper member, combined with the predominance of fine-grained channel deposits, does not support the hypothesis that the sedimentologic differences of the upper member can be explained strictly by a more proximal position on the paleolandscape. Rather, basin subsidence accompanied by uplift of the source area appears to have been the dominant control on the sedimentologic changes observed in the Sânpetru Formation, although the presence of coarse conglomerates in Section 12 could be related to the proximity of the source area.

6. Implications of the fluvial system changes for the absence of dinosaurs in the upper Sânpetru Formation

Although isolated bones are occasionally found in sandstones or red mudstone, the majority of fossil remains in the lower Sânpetru Formation occur as lenticular bonebeds (the "fossiliferous pockets" of Grigorescu, 1983) within gray overbank deposits (Nopcsa, 1900, 1902; Grigorescu, 1983; Grigorescu and Csiki, 2002). The size of two fossiliferous lenses was reported by Grigorescu (1983) as being 18 m wide by 3 m deep and 8 m wide by 1.5 m deep, dimensions consistent with those of channel-shaped scours at the base of sandstone sheets (Fig. 5). Because skeletal remains display evidence of disarticulation, subaerial exposure, and transport prior to burial (Grigorescu, 1983; Grigorescu and Csiki, 2002), the fossil assemblages have been interpreted as the result of hydraulic concentration of remains in channels and/or depressions on the floodplain.

The absence of dinosaurs in the upper Sânpetru Formation, a conclusion based on the lack of lenticular bonebeds and the fact that dinosaur remains had not been discovered in that stratigraphic interval until recently (Z. Csiki, personal communication, 2004), led previous researchers to postulate that the formation may record uninterrupted deposition across the K/T boundary (Grigorescu, 1983, 1992; Weishampel et al., 1991). However, dinosaur absence occurs in a stratigraphic interval characterized by significant fluvial and paleoenvironmental changes. Grigorescu (1983, 1992) and Weishampel et al. (1991) did not consider the effects of changes in depositional environments on fossil preservation potential, which could have been dramatically modified. Although a detailed study of the sedimentologic and taphonomic characteristics of the Sânpetru bonebeds is necessary to investigate this correlation, the results of this study allow for the formulation of a testable hypothesis to explain the disappearance of bonebeds in the upper Sânpetru Formation.

In the context of a dynamic mosaic of wetlands and drier floodplains, characteristic of the bonebed-bearing lower Sânpetru Formation (see above; Therrien, 2004), flowing streams and crevasse splays would have been the principal environments of bone concentration. In contrast, the upper Sânpetru Formation is characterized exclusively by poorly developed hydromorphic paleosols, indicative of impeded drainage and high water tables, revealing the prevalence of low-energy paleoenvironments. Even though high-energy flood events occurred (as indicated by the presence of conglomerates) in the upper member of the formation, low-energy floods appear to have been the norm (smallest grain size modes and means in Section 12). Wetlands generally being calm environments, such low-energy settings would not have favored the local concentration of skeletal remains by hydraulic means to form bonebeds. Rather, the parautochthonous incorporation and preservation of macro- and microfaunal elements into hydromorphic paleosol profiles (Van Itterbeeck et al., 2004; Z. Csiki, personal communication, 2004) appears to have been the principal mode of fossil preservation in the upper Sânpetru wetlands. Thus, the paucity of dinosaur remains and lenticular bonebeds in the upper Sânpetru Formation may not reflect the extinction of dinosaurs at the end of the Cretaceous, but solely a change in the preservation potential of macrofossils (Therrien, 2004).

In conclusion, until a detailed sedimentologic and taphonomic investigation of the Sânpetru bonebeds is conducted, interpretation of the disappearance of dinosaurs in the upper Sânpetru Formation as evidence of a Cretaceous–Tertiary transition should be considered with caution.

7. Summary and conclusions

The Sânpetru Formation consists of a repetitive succession of fining-upward units dominated by sandstones. Although exposure is limited due to vegetation cover and the steep dip of the strata, the sandstones appear to form laterally extensive sheets. Small and large channel-shaped scours occur at the base of some sandstone sheets, with width/depth ratios varying between 3 and 14.

Four distinct facies assemblages of stratified and structureless sandstones, conglomerates, and overbank deposits are recognized in the Sânpetru Formation. The facies assemblages are typical of low-sinuosity rivers flowing through symmetrical, extensional basins. The low variability of paleocurrent indicators, the sheet-like architecture of the deposits, and the paucity of channel-shaped scours support the interpretation that the Sânpetru Formation was deposited by poorly channelized flow or on a shallow, broad braidplain. Mineralogical composition and the paleocurrent direction of the channel deposits argue for a persistent source area in the Țarcu–Retezat Mountains, a metamorphic complex situated less than 7 km south of the study area.

A study of large-scale sedimentologic trends throughout the formation reveals small-scale fluctuations (on a 10-m scale) in sandstone/mudstone ratio and maximum grain size of channel deposits in the lower Sânpetru Formation, which are interpreted as recording autocyclic shifts in channel position on the alluvial plain. In contrast, major sedimentologic changes occur in the upper Sânpetru Formation, where sandstone/mudstone ratios and maximum grain size of channel deposits increase dramatically, and paleocurrent direction and paleosol types change significantly. The lack of evidence for climate control indicates that the changes in depositional environments reflect an episode of basin subsidence and uplift of the Țarcu–Retezat Mountains.

Although high-energy flood events occurred, the exclusive occurrence of hydromorphic paleosols in the upper Sânpetru Formation indicates that this stratigraphic interval was dominated by low-energy wetlands. Such depositional settings contrast strongly with the mosaic of wetlands and better drained floodplains of the lower Sânpetru Formation. The low-energy wetlands of the upper Sânpetru Formation presented fewer opportunities to concentrate fossil remains through hydrologic agents to form bonebeds, in contrast to the conditions in the lower member, and erroneously led previous researchers to infer the presence of the K/T boundary at the transition between the lower and upper Sânpetru Formation.

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Appendix A. Sedimentologic parameters of the Sânpetru Formation

Stratigraphic interval (m)	Sandstone/mudstone ratio	Maximum grain size of channel deposits		Number of sandstone beds
		Mode	Mean	
10–20	1.50	p	vc	17
20–30	0.77	m	c	10
30–40	2.22	g	vc	9
40–50	1.69	g	c	12
50–60	2.19	p	c	10
60–70	1.40	f	m	8
80–90	3.18	g	vc	11
90–100	2.09	p	c	14
100–110	1.84	g	c	15
110–120	3.32	g	c	12
120–130	2.24	g	c	15
130–140	2.32	p	vc	11
140–150	2.77	g	vc	13
180–190	1.44	g	c	17
190–200	1.79	f	m	10
200–210	1.47	p	c	12
210–220	5.89	g	c	10
220–230	3.17	g	vc	11
230–240	1.57	g	vc	14
240–250	2.38	g	c	14
250–260	1.77	g	c	15
260–270	3.46	g	vc	10
300–310	1.31	vf	m	12
310–320	2.60	g	c	14
320–330	2.92	vf+p	m	15
410–420	1.92	g	c	13
740–750	5.10	vf+g	c	8
750–760	6.08	co	vc	8
820–830	2.97	vf	f	9
830–840	2.67	vf	m	12
840–850	3.08	p+co	vc	11

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