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Eocene-Oligocene sedimentation in the external areas of the Moldavide Basin (Marginal Folds Nappe, Eastern Carpathians, Romania): sedimentological, paleontological and petrographic approaches

CRINA MICLĂUŞ[1], FRANCESCO LOIACONO[2], DIEGO PUGLISI[3] and DORIN SORIN BACIU[1]

[1]Department of Geology, "Al. I. Cuza" University of Iaşi, Carol I Boulevard 20A, 700505 Iaşi, Romania; crina_miclaus@yahoo.co.uk; dsbaciu@clicknet.ro
[2]Dipartimento di Geologia e Geofisica, University of Bari, Via E. Orabona 4, 70125 Bari, Italy; loiacono@geo.uniba.it
[3]Dipartimento di Scienze Geologiche, University of Catania, Corso Italia 55, 95129 Catania, Italy; dpuglisi@unict.it

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Abstract: The Marginal Folds Nappe is one of the most external tectonic units of the Moldavide Nappe System (Eastern Carpathians), formed by Cretaceous to Tertiary flysch and molasse deposits, piled up during the Miocene closure of the East Carpathian Flysch basin, cropping out in several tectonic half-windows, the Bistriţa half-window being one of them. The deposits of this tectonic unit were accumulated in anoxic-oxic-anoxic conditions, in a forebulge depozone (*sensu* DeCelles & Giles 1996), and consist of a pelitic background sporadically interrupted by coarse-grained events. During the Late Eocene the sedimentation registered a transition from calcareous (Doamna Limestones) to pelitic (Bisericani Beds) grading to Globigerina Marls at the Eocene-Oligocene boundary, and upward during the Oligocene in deposits rich in organic matter (Lower Menilites, Bituminous Marls, Lower and Upper Dysodilic Shales) with coarse-grained interlayers. Seven facies associations were recognized, and interpreted as depositional systems of shallow to deeper water on a ramp-type margin. Two mixed depositional systems of turbidite-like facies association separated by a thick pelitic interval (Bituminous Marls) have been recognized. They were supplied by a "green schists" source area of Central Dobrogea type. The petrography of the sandstone beds shows an excellent compositional uniformity (quartzarenite-like rocks), probably representing a first cycle detritus derived from low rank metamorphic sources, connected with the forebulge relief developed on such a basement. The sedimentation was controlled mainly by different subsidence of blocks created by extensional tectonic affecting the ramp-type margin of the forebulge depozone.

Key words: Eocene–Oligocene, Eastern Carpathians, Romania, Moldavide Basin, Marginal Folds Nappe, paleogeography, petrography, sedimentology.

Introduction and objectives

In Central Europe, the Carpathian Mountains join the Alps with the Balkan and Rhodopean Chains, including remnants of Tethyan oceanic crust and of its continental margins, namely the internal Austro-Bihorean and the external European ones. Both were strongly deformed by Cretaceous and Miocene tectonic events (Săndulescu 1988).

Two important sectors can be recognized in the Eastern Carpathians according to their compressional periods: the Dacides (Median and External, respectively) deformed in Cretaceous tectogeneses, and the Moldavide Nappe System deformed in Miocene tectogeneses (Săndulescu 1984, 1988). The Median Dacides are formed by crystalline basement nappes with their Mesozoic sedimentary cover, whereas the External Dacides are formed by nappes originating from a marginal trough within European margin, and mainly consisting of Jurassic to Cretaceous flysch deposits with some basic and ultrabasic volcanic rocks (Săndulescu 1975, 1980, 1984). These latter rocks prove that the External Dacides represent the second ophiolitic suture of Carpathians of intraplate type, besides the main Tethyan suture known in the Romanian Carpathians as the Transylvanides (Săndulescu 1980, 1984).

The Moldavide Nappe System mainly consists of Cretaceous to Tertiary flysch and molasse nappes (Bancilă 1958; Ionesi 1971; Săndulescu 1975, 1980, 1984; Ştefănescu et al. 1979; Debelmas et al. 1980; Grasu et al. 1988).

As a consequence of tectonic loading related to Early-Late Cretaceous shortenings of the Median Dacides and the internal part of the External Dacides, a first forebulge, the so-called Perimoldavian Cordillera, was developed (Bădescu 2005). The Moldavidian Realm was located in the backbulge depozone of the foreland basin system. By the end of the Cretaceous the External Dacides were completely deformed, their nappes being overthrusted over the Moldavidian Realm internal margin (Bădescu 2005). Consequently, the entire East Carpathian foreland basin systems migrated outward. This stage of development was called by Grasu et al. (1999) "the old foreland basin" of the Eastern Carpathians. The Moldavide Nappe System is linked to the Miocene tectogeneses and to the closure of the Moldavide Basin when the East Carpathian foreland basin systems achieved their present configuration, called by Grasu et al. (1999) "the new foreland basin".

In the Eastern Carpathians, the Moldavide Nappe System includes an inner group of units represented by the Convolute Flysch (or Teleajen) Nappe, Macla and Audia Nappes consisting mainly of Cretaceous flysch (Săndulescu 1975, 1984; Grasu et al. 1988). The outer group is represented by the Tarcău Nappe and the Marginal Folds Nappe (or Vrancea Nappe), consisting of Cretaceous to earliest Miocene flysch deposits, and the Subcarpathian Nappe, comprising Paleogene flysch but mainly Early to Middle Miocene molasse successions (Săndulescu 1975, 1984, 1994; Grasu et al. 1988).

The Marginal Folds Nappe, object of this study, is structurally interposed between the Tarcău and Subcarpathian Nappes which are placed inward and outward, respectively. The sedimentary succession of this tectonic unit at the Eocene-Oligocene boundary is mainly characterized by a

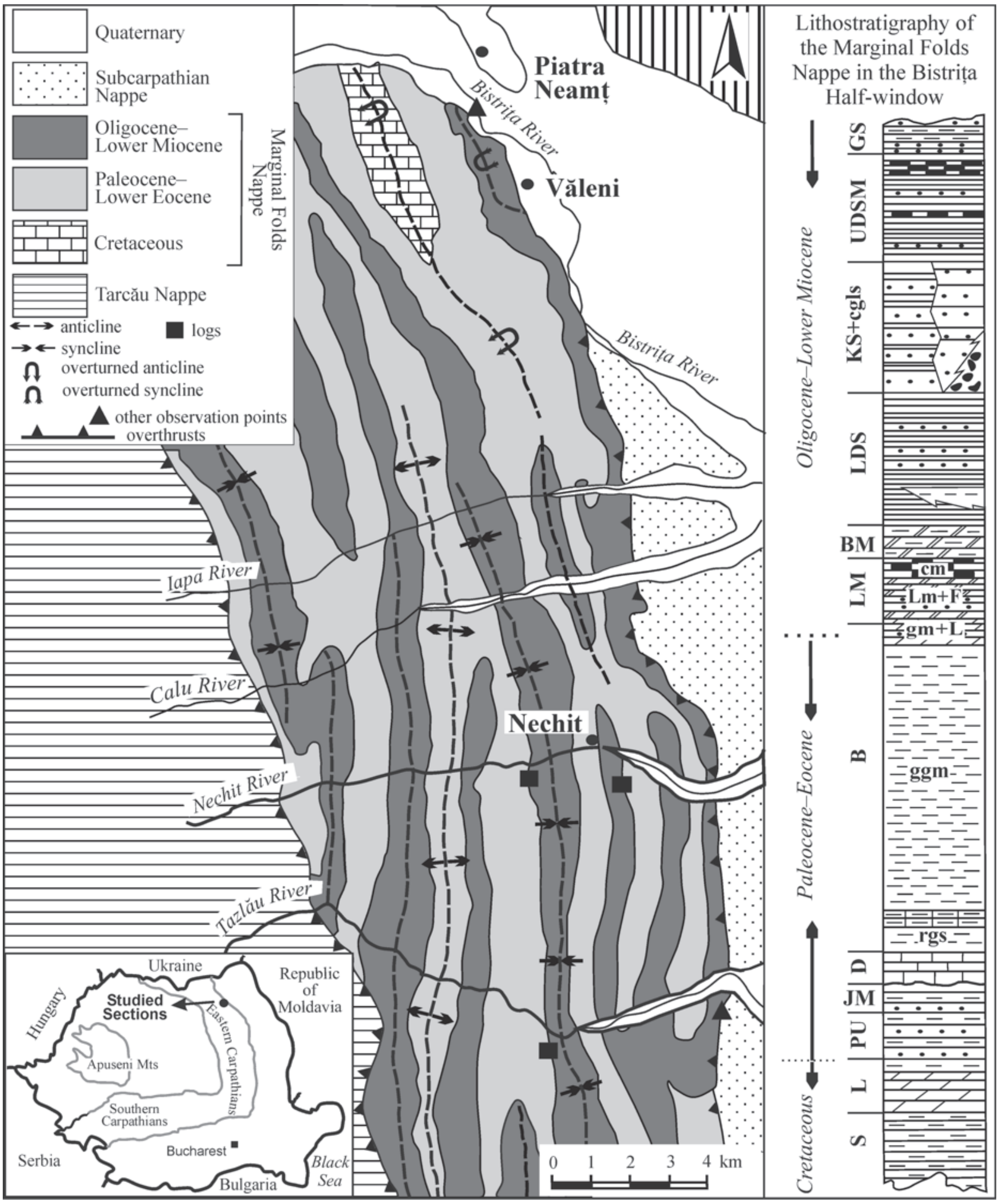

Fig. 1. Geological sketch map of the Bistrița half-window with the location of the studied logs and lithostratigraphic column of the Marginal Folds Nappe between the Bistrița and Tazlău Rivers (based on Micu 1976, 1983, and Grasu et al. 1988): **S** — Sărata Beds; **L** — Lepșa Beds; **PU** — Piatra Uscată Beds; **JM** — Jgheabu Mare Beds; **D** — Doamna Limestones; **B** — Bisericani Beds (where **rgs** = red and green shales, **ggm** = greenish-grey mudstones, and **gm+L** = Globigerina Marls and Lucăcești Sandstones); **LM** — Lower Menilites (**Lm+F+cm** = Lingurești Marls, Fierăstrău Sandstones and compact Menilites); **BM** — Bituminous Marls; **LDS** — Lower Dysodiles; **GK** — Kliwa Sandstones; **UDSM** — Upper Dysodiles and Menilites; **GS** — Gura Șoimului Beds; **f** — faults.

thick pelitic succession (Bisericani Beds), grading upward into deposits known in the Romanian geological literature as the Lower Menilites and Bituminous Marls, followed by Lower Dysodiles (Dumitrescu 1952; Băncilă 1958; Ionesi 1971; Grasu et al. 1988; Săndulescu & Micu 1989; Grasu et al. 2007), locally interlayered with arenaceous beds (Lucăceşti, Fierăstrău and Kliwa Sandstones; Fig. 1).

The stratigraphic succession sampled and logged in the Bistriţa half-window (*sensu* Băncilă 1958), near the town of Piatra Neamţ (Fig. 1), shows the entire sedimentary succession of the Marginal Folds Nappe with an excellent exposure of the middle to upper portions, where it is possible to observe the transition to the Lower Menilites.

Above these "menilite facies", the section shows a mainly pelitic interval (Bituminous Marls) evolving into the Lower Dysodilic Shales. These include the Kliwa Sandstones which due to their small thickness, less than 15 m, cannot be distinguished as a formation like in the Tarcău Nappe, where they reach hundreds of meters. At the top, the Upper Dysodilic Shales and the Upper Menilites close the flysch sedimentation, while the Gura Şoimului Beds seem to mark the beginning of the molassic deposition.

Equivalent successions have recently been studied in the more internal Tarcău Nappe from the sedimentological and petrographic points of view (Gigliuto et al. 2004; Puglisi et al. 2006; Miclăuş et al. 2007) in order to determine the paleogeographic context of the deposition of the arenaceous turbidites mainly associated with the Lower Oligocene Lower Menilite Formation and the overlying Bituminous Marls.

Thus, the aim of this paper is to collect new interdisciplinary stratigraphic and petrographic data in a more external sector of the Moldavide Basin (Marginal Folds Nappe) in order to (1) characterize the sedimentary facies and the clastic provenance and (2) to hypothesize a paleogeographic scenario for this portion of the basin, also supported by the comparison with the more internal successions.

Finally, accordingly to previous authors (Săndulescu 1972, 1984, 1988), the Paleocene-Oligocene flysch deposits have been compared within the Ukrainian and Romanian Carpathians, emphasizing a close similarity among the Skiba/Boryslav-Pokuttya Nappes (Ukraine) and the Tarcău/Marginal Folds Nappes (Romania).

So, the results of this study might also improve the knowledge of the external areas of the Moldavide Basin and they can probably also provide useful information for a more extensive paleogeographic reconstruction.

Stratigraphic setting

The Nechit River 1, 2 and Şoimu Sections were logged in the Bistriţa half-window, belonging to the Marginal Folds Nappe, the outermost tectonic flysch unit of the Moldavide Nappe System. The deposits which crop out in this area are mainly Eocene–Early Miocene in age and correspond, from the bottom to the top, to the following formations, according to the Romanian geological literature: Jgheabu Mare Beds, Doamna Limestone, Bisericani Beds, Globigerina Marls, Lower Menilites, Bituminous Marls, Lower Dysodilic Shales and Kliwa Sandstones, Upper Dysodilic Shales and Menilites, Gura Şoimului Beds (Fig. 1).

The flysch deposits involved in Moldavide units were accumulated in a foreland-type basin system (*sensu* DeCelles & Giles 1996). The Marginal Folds Nappe sedimentation area was located on the cratonic side of this basin, probably on the internal part of the forebulge depozone.

The physiography of such a basin margin is usually of ramp type, without significant change in water depth from shallow to much deeper water (Van Wagoner et al. 1990). Local fault-controlled uplifts and depocentres, rather than a smooth flexural profile, might develop on the forebulge in foreland basin systems. Extensional fault systems are common on potential forebulge uplifting area, both related to tensional stresses caused by forebulge migration, and to older structure reactivation (references in DeCelles & Giles 1996). The forebulge of the foreland basin system might be both an important source area of sediment, and a site of sediment accumulation.

Our paper concerns the deposits extending from the Bisericani Beds to the Upper Dysodilic Shales and Menilites.

Facies analysis

Facies analyses have been carried out in the field, collecting data on lithology, grain size, sedimentary structures, sand : mud ratio, bed thickness, fining and thinning upward (FThU) and coarsening and thickening upward (CTkU) cycles in three different sections (Figs. 2, 4, 5). Seven facies associations (FA) have been distinguished and interpreted in terms of sedimentary environments, parts of depositional systems, according to criteria and models proposed by Mutti & Ricci Lucchi (1972, 1975), Pickering et al. (1989), Mutti (1992), Mutti et al. (1996, 2000, 2003, 2007).

1. Greenish-grey pelites with slumps facies association of mud-rich slope apron system corresponds, according to Ionesi (1971), to the middle part of the Bisericani Beds, and consists of around 300 m of greenish-grey mudstones, mainly unstructured, with sporadic thin- to medium-bedded sandstones (10 to 40 cm thick), locally strongly deformed in antiforms (10 m high) or flat lying folds (Fig. 3b) and cut by sandstone injections (Fig. 3a). Some pebbly mudstones and block-bearing mud flows can be also found. Some bioturbated levels (*Chondrites*) were also noticed, especially in the Şoimu Section.

The lithologic uniformity and the absence of sedimentary structures can be considered a result of the high frequency of slumps, enhanced by some folded sandstone interlayers as can be noticed in the Nechit River 1 Section. These, mainly derived by rotational slumps, can be related to the $\mathbf{F_{2.1}}$ facies of Pickering et al. (1989) and their abundance might testify the slope instability.

The significant thickness of this facies association (about 300 m) might prove that these deposits were sedimented on upper slope where the influence of sediment plumes carried by hypo- and mesopycnal currents is usually considered very important (Galloway 1998) and induces slope active progradation and aggradation (Fig. 4).

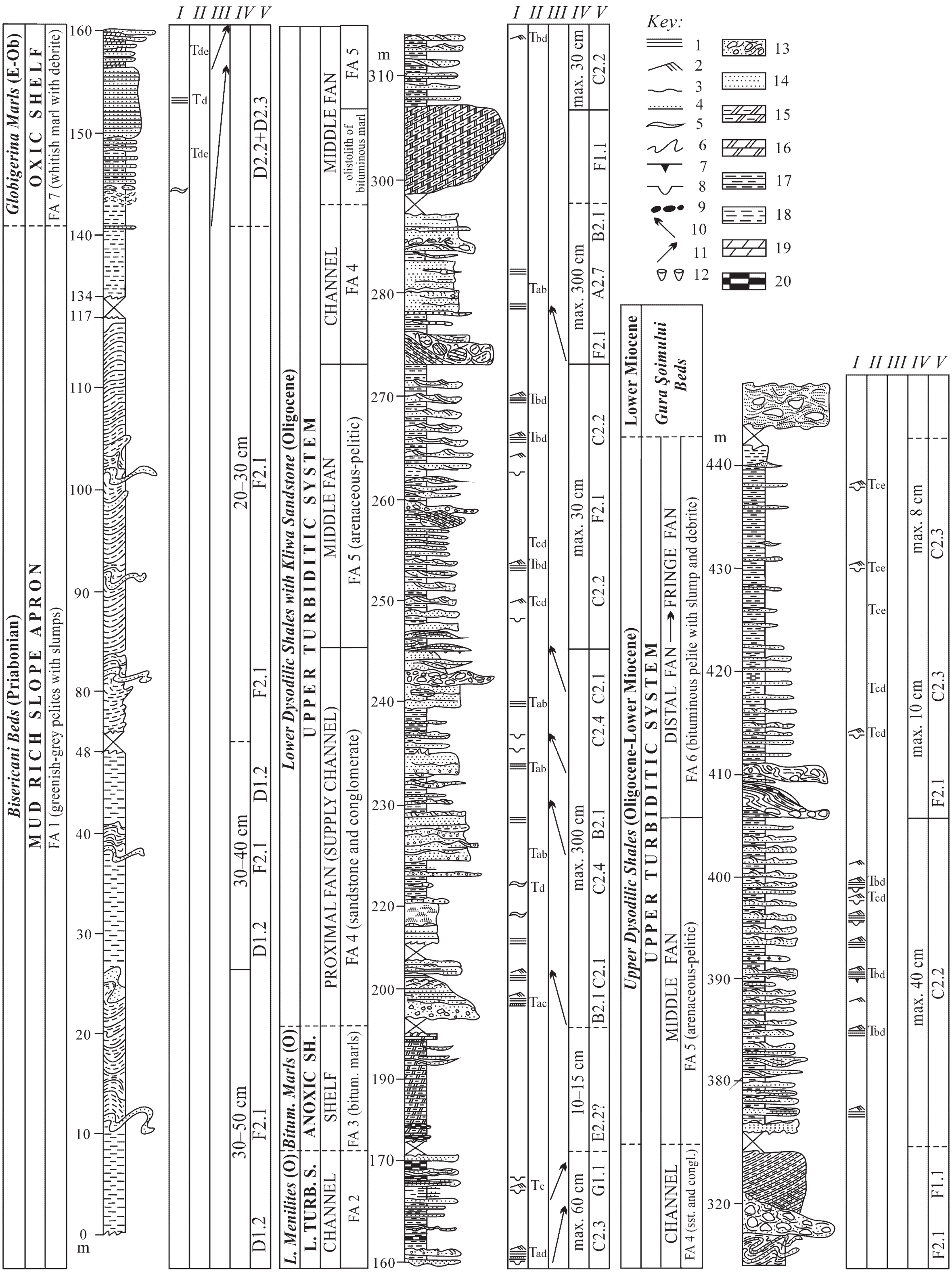

Fig. 2. Nechit River 1 Section: facies associations and environmental interpretation (Late Eocene–Early Miocene). The legend shown is also the legend for Figs. 4, and 5. **I** — sedimentary structures; **II** — Bouma sequences; **III** — ThU and TkU sequences; **IV** — sandstone bed thicknesses; **V** — Pickering et al. (1989) facies. **1** — plan parallel lamination; **2** — cross-lamination; **3** — undulated lamination; **4** — normal grading; **5** — lenticular bedding; **6** — convolute lamination; **7** — flute and tool casts; **8** — load casts; **9** — mud intraclasts; **10** — thinning upward sequences; **11** — thickening upward sequences; **12** — bioturbation; **13** — debrites; **14** — Kliwa + Kliwa-type sandstones; **15** — bituminous marls; **16** — brown marls; **17** — black shales (dysodilic shales); **18** — greenish-grey mudstone; **19** — whitish marls; **20** — black cherts and shales; **E–O b** — Eocene-Oligocene boundary; **O** — Oligocene.

Greenish-grey pelites with slump facies association including Facies $\mathbf{D_{1.2}}$; $\mathbf{D_{2.2}}$; $\mathbf{D_{2.3}}$; $\mathbf{F_{2.1}}$ in Pickering et al. (1989) terminology, are attributed to distal turbidites and hemipelagites in an underfed system of mud rich slope apron environment (on the basis of the sand : pelite ratio and vertical trend). The mud rich slope apron environment is also indicated by very frequent slump deposits. In the uppermost part of the FA a progradational trend indicated by CTkU cycles can be noticed. It is important to underline that this slope had to be rather a local feature of the bed topography controlled by the extensional faults associated with the forebulge depozone.

2. Black shales with bedded cherts and sandstones facies association of shallow channels, corresponding to Lower Menilites, consists of alternating quartz-rich sandstones (about 40 % in the association column), black shales, brown marls and siltstones, greenish-grey pelites and thin-bedded menilite s.s. (black cherts; 15–16 % in the column). Sandstones, usually thick-bedded and/or amalgamated, (0.02–0.6 m), with flute/tool or load casts on sole, wavy tops and internal structures such as plane-parallel and cross-laminations, are organized in two fining- and thinning-upward sequences (ThU) in the Nechit River 1 Section. The same sequences can be recognized in the Şoimu River Section, where the sandstone beds (Fierăstrău Sandstone) are up to 2 m thick, and in the Nechit River 2 Section (Fig. 5).

The menilite s.s. beds are mm–cm thick, very finely laminated and, locally, inter-bedded with brown marls and grey pelites. This facies association, very diversified in lithology, characterizes only the Nechit River 1 and 2 Sections but is absent in the Şoimu River Section, and corresponds to the Lower Menilites.

The facies association is referred to **C**, **D**, **E** (channel, inter-channel or levee) and to **G** (pelagites, organic and chemogenic sediments) facies of Pickering et al. (1989). This FA suggests an increase of clastic input due to a progradational trend (such as that noticed in all three logs), contemporaneous to a significant supply of pelagic sediments (mainly Nechit River 1 and 2 Sections).

The fining- and thinning-upward sequences (FU/ThU), are frequently interpreted as channel deposits, but in this specific case, due to their small thickness, seem to be linked to some distal and shallow channels.

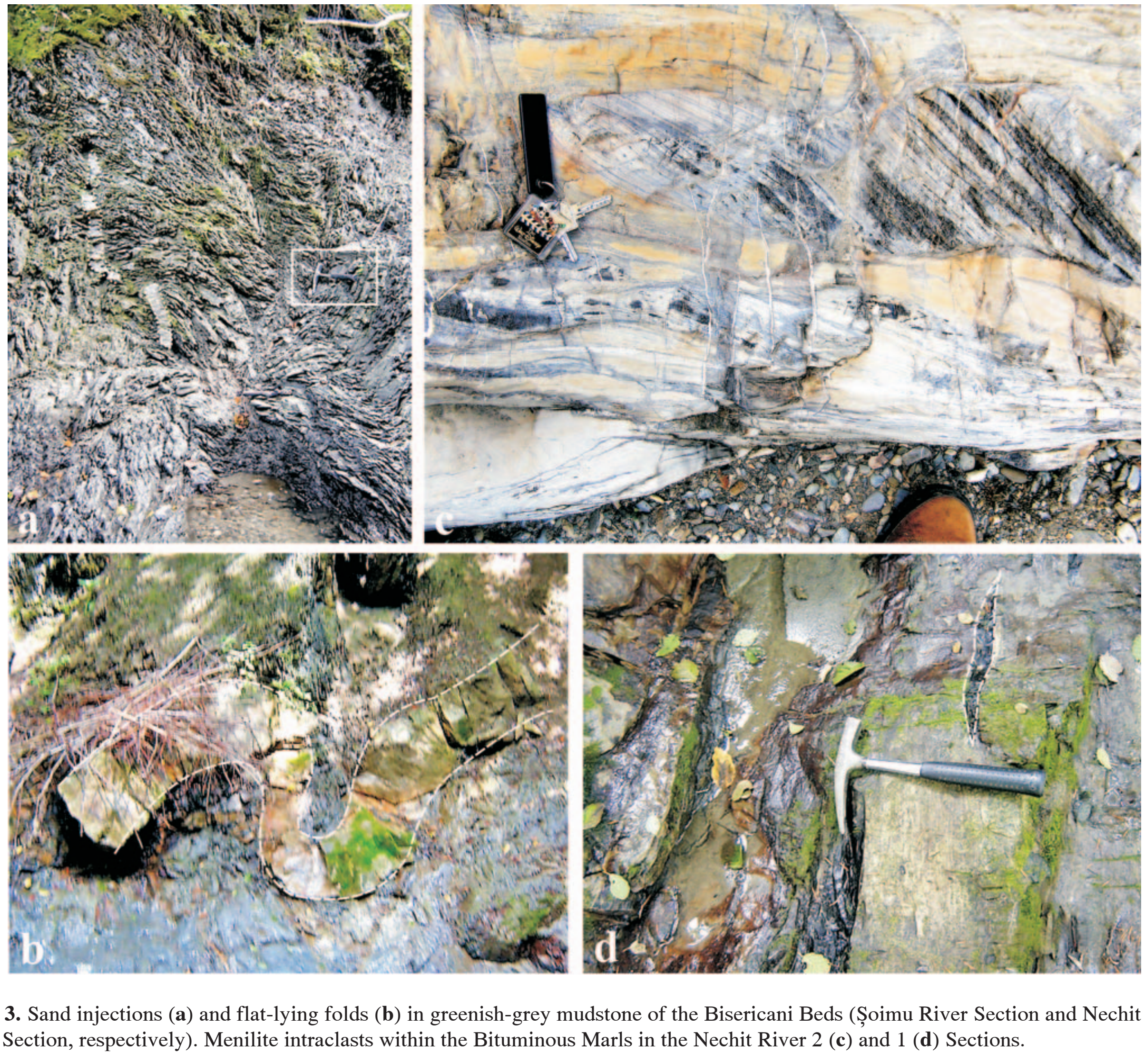

Fig. 3. Sand injections (**a**) and flat-lying folds (**b**) in greenish-grey mudstone of the Bisericani Beds (Şoimu River Section and Nechit River 1 Section, respectively). Menilite intraclasts within the Bituminous Marls in the Nechit River 2 (**c**) and 1 (**d**) Sections.

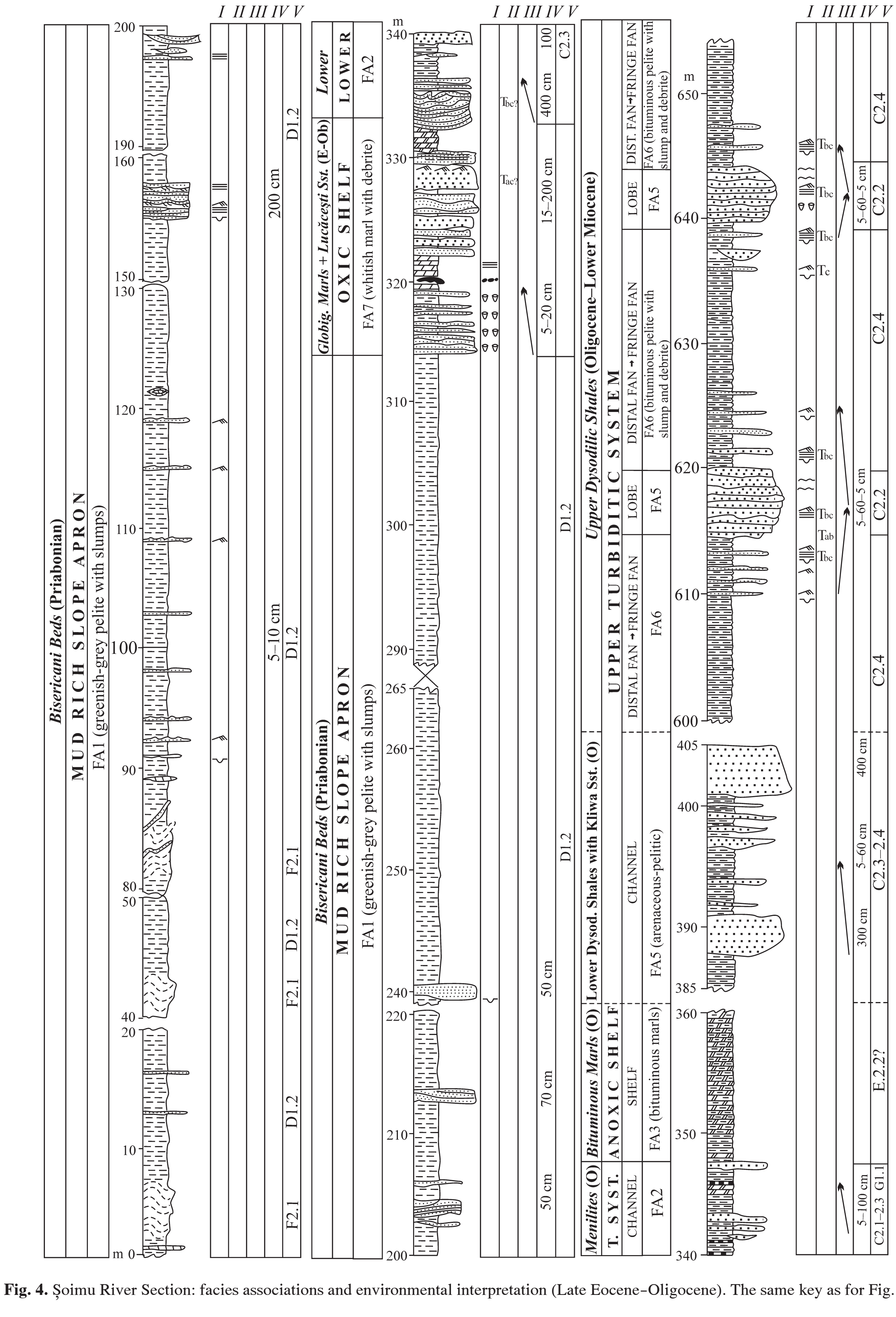

Fig. 4. Şoimu River Section: facies associations and environmental interpretation (Late Eocene–Oligocene). The same key as for Fig. 2.

3. Bituminous marls facies association of anoxic shelf, ranges in thickness from about 10 m (Nechit River 1 and Șoimu Sections) to 50 m (Nechit River 2 Section, Tazlău River, near the homonymous village, and Văleni village on the Bistrița River; Fig. 1), and consists of very fine laminated limy clays and marls, rich in organic matter (TOC = 3.54–10.04 % after Grasu et al. 1988), with cross-laminated thin interlayers (mm to dm; Figs. 6b, 7a, and 7b) of sandstones. At the bottom, large intraclasts of menilite s.s. lying parallel to the stratification can be noticed (Figs. 3c,d, and 6a).

In this facies association, sedimentary structures very similar to swaley and hummocky cross-stratification (SCS and HCS; Fig. 8a), together with parallel and low angle cross-bedding, and wavy (Fig. 7a) and lenticular (Fig. 6b) bedding are recognized. Some sandy injections as dykes, sills and ptygmatic structures of decimetric dimensions are sporadically present (Nechit River 2 Section; Fig. 8b).

This facies association, which corresponds to the Bituminous Marls, is deposited from two different processes: fallout from suspension, as their fine lamination proves, and on this background, cyclical deposition of coarse material. The fine sandstone interlayers (like those in Tazlău or Nechit 2 Section; Figs. 1, 7) can be attributed to storms or floods which developed hyperpycnal flows or turbidite currents moving downslope.

The HCS-like structures (Fig. 8a), which seems to be of scour-drape type, together with swaley cross-stratification are usually interpreted as indicating storm conditions in shelf environment above the storm wave base (Cheel & Leckie 1993). Anyway such hummocky morphology can also be developed by hyperpycnal flows as “flood-generated delta front lobes” (Mutti et al. 2000). At the Tazlău observation point (Figs. 1, 7) within the Bituminous Marls, centimetric interlayers of sandstones showing wave ripple cross-lamination, have also been noticed (Fig. 7b).

The bituminous marls facies association shows the features of a distal shelf, either fed during storms or fed by hyperpycnal flows from shoreline sources during possible floods. The shallow sedimentation conditions are also proved by the existence of very well preserved flatfish like *Scophthalmus* which will be described later in the paper.

4. Sandstone and conglomerate facies association of channels with levee, mainly consists of sandstones, matrix- and clast-supported conglomerates, and, subordinately, of bituminous pelites of dysodilic shale-type. It corresponds more or less to the coarser lower part of the Lower Dysodilic Shales with Kliwa Sandstones.

Clast-supported thick-bedded conglomerates (up to 4 m thick; Fig. 9a), mainly composed of “green schist” clasts (up to 0.8 m in diameter), subrounded and rounded white limestone, and intraclasts of dysodilic shales (Fig. 9b), show a large scale (meters to tens of meters wide) lenticular geometry with erosive bases, locally with large sole casts. These conglomerates are frequently associated with slided blocks, consisting of dysodilic shales and thin-bedded Kliwa-type sandstones.

The matrix-supported conglomerates show finer “green schist” clasts (3–5 cm diameter) floating in a Kliwa-type arenaceous sandstone matrix or sandy dysodilic shale matrix.

Sandstones of this association show different characteristics: (a) thick and composite beds (up to 4 m thick), crudely

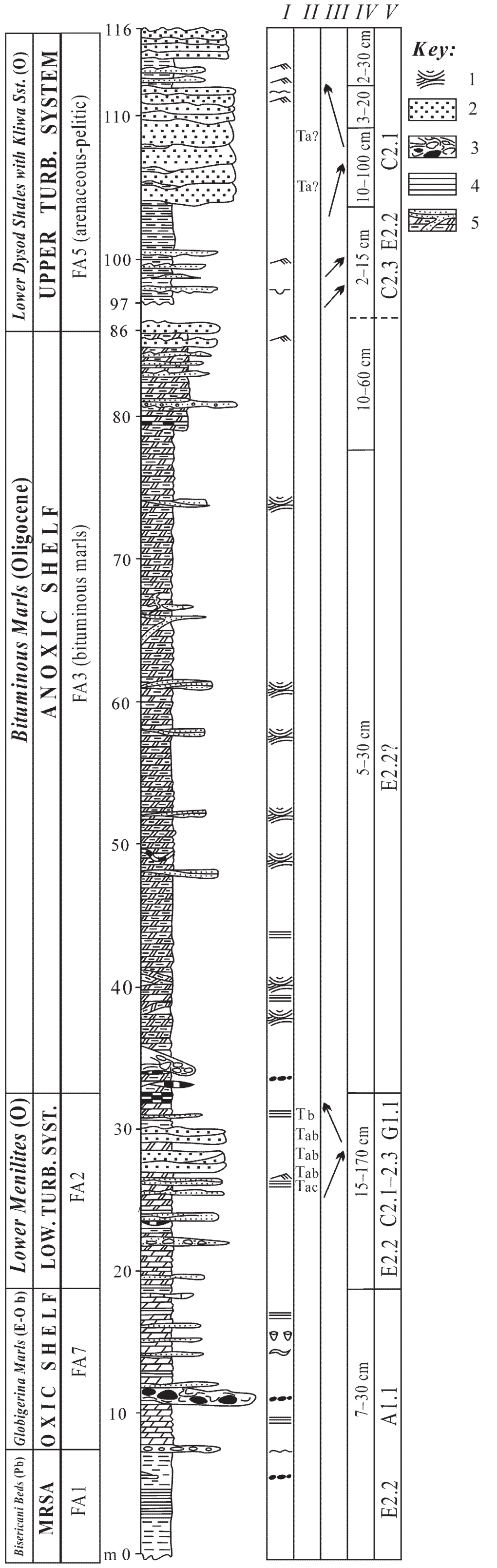

Fig. 5. Nechit River 2 Section: facies associations and environmental interpretation (Late Eocene–Oligocene). The same key as for Fig. 2. **1** — hummocky and swaley like cross-stratification; **2** — sandstones (Kliwa and Kliwa like); **3** — debrite with mud intraclastst and/or green schist clasts; **4** — dark grey pelite; **5** — sand injections; **MRSA** — mud-rich slope apron; **Pb** — Priabonian.

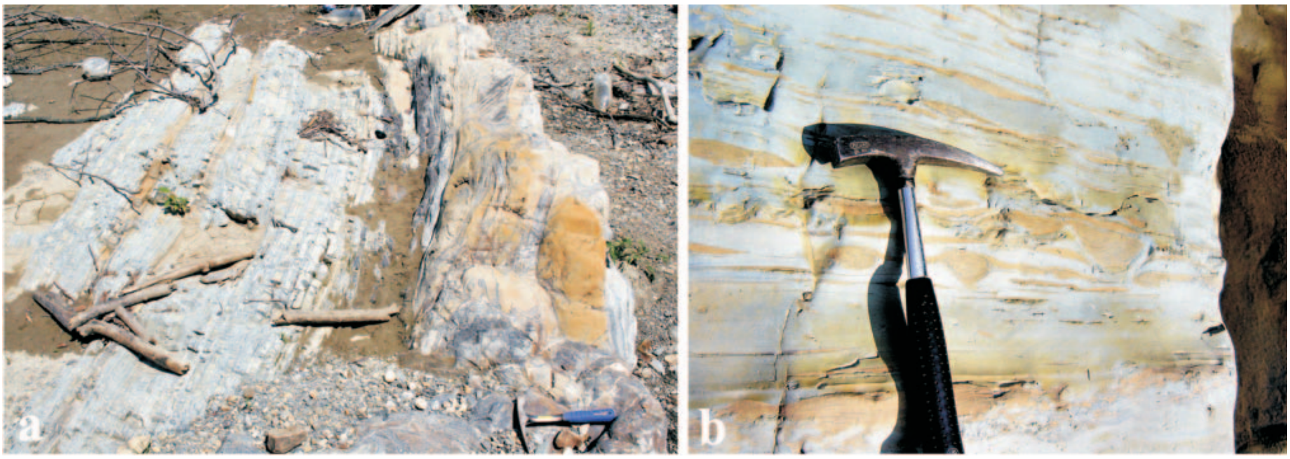

Fig. 6. a — Contact between menilites and Bituminous Marls (Nechit River 2 Section). **b** — Cross-laminated sandstones with load casts and flame (mm to cm thick) interlayered in Bituminous Marls, proving the rapid influx of coarse materials.

Fig. 7. a — Sandstones with wavy and lenticular bedding interlayered within the Bituminous Marls at Tazlău. **b** — Detail of the internal structure of sandstone beds (wave ripple cross-lamination) in white rectangle.

Fig. 8. a — Hummocky- and swaley-like cross-stratification (HCS and SCS, respectively) in bituminous marls at the Nechit River 2 Section. **b** — Dyke (*d*), sill (*s*) and ptygmatic structures (*p*) within the Bituminous Marls in the Nechit River 2 Section.

Fig. 9. Clast-supported conglomerates and thick-bedded sandstones (**a**), locally with "green schist" and limestone clasts (**b**) cut in dysodilic shales in the Nechit River 1 Section. (**c**) Sharp contact between parallel laminated sandstones with water escape structures and massive sandstones (Nechit River 1 Section), (**d**, **f**) simple flat base and wavy top sandstone beds interlayers in the Dysodilic Shales (Nechit River 1 and 2 Sections), and **(e)** thick and composite sandstone beds (Nechit River 1 Section).

graded, with large undulated amalgamation surfaces, sometimes with thin plane-parallel stratified and cross-laminated tops, locally associated with conglomerates with "green schist" clasts (Fig. 9e); (b) simple centimetre- to decimetre-sized beds, parallel flat-based or slightly undulated with tool casts, wavy tops with parallel to low angle cross-laminations (Fig. 9d); (c) simple, very thin-bedded and lenticular strata; (d) thick-bedded, laminated sandstones with water escape structures (Fig. 9c); and (e) thick sandstone beds crudely horizontal laminated with small floating clasts (Fig. 9c) resting on sandstone with convolute laminae.

This facies association re-groups all Walker's (1992) "facies" belonging to the turbidite family (i.e. massive sandstones, classical turbidites, pebbly sandstones and conglomerates). According to Pickering et al. (1989) the $F_{2.1}$, $C_{2.1}$, $C_{2.2}$, $C_{2.4}$, $A_{1.4}$ and $A_{2.7}$ facies can be distinguished. FThU sequences are also frequent and this may justify the interpretation of these deposits as channel fills. This facies association indicates the proximal part of a turbiditic system (facies **A**, **B**, **C** and intercalated **D**) composed of coarse bodies, up to 10 m thick, organized in FThU sequences, attributed to debris or sandy cyclic flows more or less channelized (Nechit River 1 Section).

The thick, composite sandstone beds might also be interpreted as type-A mixed system of Mutti et al. (2003). As the latter authors showed, the mixed systems might be difficult to distinguish from the basinal turbidites if the sediments are not framed in their stratigraphic and structural setting.

The source area of the above described coarse deposits was a "green schist" basement and its sedimentary cover of limestone probably of platform type containing nummulites. Such "exotic" clasts were described by many authors in Cretaceous to Late Miocene flysch and molasse deposits of external nappes of Moldavides since the early years of 20th century (Zuber 1902; Simionescu 1909; Mrazec 1910; Murgoci 1929; Băncilă 1958; and later by Ionesi 1971; Anastasiu 1984, 1986; Săndulescu 1984; Grasu et al. 1988, 1999, 2002, 2007). Their source area is considered to be Central Dobrogea although there are not many papers concerning the petrographic-mineralogical comparison of source area rocks and the resedimented "green schist" clasts except Simionescu (1908) and Anastasiu (1984, 1986). Central Dobrogea is an uplifted block of East Moesia located in south-east Romania.

The dominance of FThU sequences may indicate a deepening basin which also explains the episodic character of the gravity flows deriving from an unstable margin of the basin. This is a clue for the subsident trend of the basin, the main extensional tectonics (normal faults, growth faults) of the basin margin, and collapsing processes. A very important proof of extensional tectonics is the presence of a large bituminous marl olistolith (in Nechit River 1 Section; Fig. 2) in the facies association column. The active tectonic subsidence began, in fact earlier, since the bituminous marl sedimentation. This is proved by important differences of thicknesses from proximal (around 50 m thick in Nechit River 2 Section, and Tazlău or Văleni observation points) to distal (15–20 m thick in the Nechit 1, and Şoimu Sections) studied sections. In order to explain this, we can suppose a marginal block delimited by normal faults producing adjacent areas with active syn-sedimentary uplift or subsidence.

5. Arenaceous-pelitic facies association of depositional lobes partly corresponds to the upper part of the Lower Dysodilic Shales with Kliwa Sandstones (Figs. 10a,b) and partly to the Upper Dysodilic Shales. Sandstone beds show irregular scoured bases (Fig. 10a), locally with sole casts and wavy tops

Fig. 10. a — Sandstones with irregular base and wavy top with black shale interlayers. **b** — Arenaceous-pelitic facies association (depositional lobe) within the Upper Dysodilic Shales (bituminous pelitic facies association) in the Şoimu River Section. **c** — Deformed deposits (slump) of bituminous pelitic facies association in the Nechit River 1 Section. **d** — Thin intelayers of bentonitic shale in bituminous pelitic facies association (Nechit River 1 Section).

with decimeter-sized current ripple. Parallel- and cross-laminations, normal grading and weakly undulated amalgamation surfaces are the most frequent internal structures. This facies association always follows channel fill deposits (sandstone and conglomerate facies association). It consists of T_{ac}, T_{bc} turbidites or $\mathbf{C_{2.2}}$ facies of Pickering et al. (1989).

Facies belonging to this association can be interpreted as depositional lobes due to the absence of significant erosive surfaces at the base of sandstone layers. The sand : mud ratio ≈ 1 might suggest that this facies association can be referred to the intermediate part of a turbiditic system.

6. Bituminous pelites with slumps and debrites facies association of fringe fans, corresponds with the upper part of the Upper Dysodilic Shales, and mainly consists of decimeter- to meter-thick pelites of dysodilic shale-type, very rich in organic matter. These deposits, frequently deformed (Nechit River 1 Section; Fig. 10c), are associated with paraconglomerates with "green schist" clasts and, locally, to thin beds of bentonitic

Fig. 11. a — Bioturbated sandstones (*Thalassinoides*) of whitish marl with debrite facies association in Şoimu River. **b** — Highly bioturbated pelitic interlayers replaced by burrow fills (*Thalassinoides*) in whitish marl with debrite facies association in the Şoimu River. **c** — Debrite with brown marl intraclasts and green schist clasts in Globigerina Marls s.s. in Şoimu River. **d** — Thick lamination in Globigerina Marls s.s. in the Şoimu River.

shales (up to 1 cm; Fig. 10d) and to thin-bedded sandstones with planar to weakly erosive bases (with sole casts). The thin sandstone layers show wavy tops, plane-parallel and cross-laminations. They might have sheet or lenticular (0.5–1 m wide) geometry, and tend to disappear upward in succession.

The facies belonging to this association may represent a distal turbiditic system, and show a deepening upwards trend of the whole facies succession. They were sedimented into a subsident basin. Sandstone beds show the characteristics of T_{bd} and T_{cd} or of $\mathbf{C_{2.3}}$ facies. The small amount of sandstones upwards in the column might be the result either of supplying channel avulsion, or of a decreasing supply of coarse material. The deformed deposits are slump type which involves a slope of the basin floor. Based on these facts we can suppose that the deposits were sedimented on the distal turbiditic system but located at the base of a local slope.

7. Whitish marl with debrite facies association of oxic shelf, recognized in Şoimu River, Nechit River 2, and Nechit 1 River Sections. In this facies association the well known Globigerina Marls are included.

It consists of (1) decimetric, highly bioturbated sandstone beds (Fig. 11a), intelayered with pelites almost entirely replaced by horizontal to sub-horizontal anastomosed sandy filled burrows of *Thalassinoides* (Fig. 11b); (2) whitish, thick-laminated and also bioturbated (e.g. *Chondrites*) Globigerina Marls s.s. (representing the upper part of the Bisericani Beds according to Ionesi 1971; Figs. 11c,d, 12a), showing sub-vertical and horizontal sand-filled burrows (possible *Skolithos*); (3) debrites (> 1 m thick; Figs. 11d, 12c) with brown mud intraclasts and "green schist" clasts; (4) thick-bedded Kliwa-type quartzarenites (i.e. Lucăceşti Sandstones) with sharp bases and thin parallel laminated tops; (5) grey quartzarenites; and (6) brown marls.

Some differences can be noticed in the Nechit River 1 Section, where this facies association consists mainly of whitish mudstone thin (1–5 cm) or lenticular bedded, with plane-parallel lamination enhanced by an alternation of light and brown laminae. The feature difference might be the result of proximal (Nechit River 2 Section) to distal (Nechit River 1 Section) facies variation.

The prevalence of horizontal–sub-horizontal burrows indicate intervals of low energy levels associated with pelites sedimentation, well oxygenated basin bottom and abundance of deposited food (MacEarchen et al. 2007). The sandstone interlayers are also intensely bioturbated by postdepositional animal activities proving their periodic sedimentation on a background of low energy conditions. Upwards in facies association column, the sedimentation becomes muddier, and characterized mainly by whitish marls with *Chondrites*

Fig. 12. Horizontal (**a**) and vertical (**b**) burrow fills (*Skolithos*?) in Globigerina Marls s.s. in the Nechit River 2 Section; sharp contact between debrite with brown marl intraclasts and whitish marls (Globigerina Marl s.s.) in the Nechit River 2 Section (**c**); debrite with brown marl intraclasts and green schist clasts in muddy matrix in the Nechit River 2 Section (**d**).

which might announce a decrease of oxygenation levels before the establishment of anoxia condition.

The above described characteristics seem to indicate shallow-water conditions, where the proximal debrites (Nechit 2 Section) can prove the instability of sediment sources. The highly bioturbated sandstones possibly supplied by a sandy coast system might also indicate a proximal offshore above the storm wave base.

Depositional systems and sedimentary evolution

The study of the logs (Figs. 2, 4, and 5) based on the sedimentary facies analysis, points out the vertical organization of the FA and the lateral correlations in the context of an area belonging to the external flysch basin of the Eastern Carpathians, during the Eocene–Oligocene time. Based on above described and interpreted facies association we recognized 5 depositional systems.

1. Mud rich slope apron — Both in the Nechit River 1 and Şoimu Sections the very thick greenish-grey mudstones (corresponding to Bisericani Beds) suggest a mud-rich slope apron system, characterized by hemipelagites and thin turbidite sandstones of facies **D**. This slope apron might be rather a local feature of the forebulge depozone (Fig. 13b). The frequent slump deposits indicate an unstable slope most likely controlled by the extensional marginal faults and the consequent subsidence trend in the adjacent sub-basins. Facies characters suggest a mud dominated sedimentation. Upwards in the visible stratigraphic intervals (between 0–19 m, 145–170 m, and 315–330 m in the Nechit River 2, Nechit River, and Şoimu Sections, respectively) an enrichment in sand can be noticed, together with significant changes in grain size, and increasing of the sand : mud ratio. All these characters suggest a more proximal sandy system proved also by the observed ichnofauna of the whitish marl with debrite facies association (Şoimu and Nechit River 2 Sections; Figs. 4, 5).

2. Oxic shelf depositional system — The upward increase of sands in the column, which is better manifested in the Şoimu Section, suggests a shallowing upward trend of the system. As we have shown above, the features of whitish marl with debrite facies association (corresponding to Globigerina Marls and Lucăceşti Sandstone) indicate a shallow-water depositional system (Fig. 13a), while the sharp contact between greenish-grey mudstone and the bioturbated sandstones, visible especially in the Şoimu Section, seem to prove a regression.

3. Lower turbiditic system — In all three analysed logs, an important change of the sedimentation background is registered, from pelite deposited in oxic conditions (greenish-grey pelite and whitish marls) to pelite deposited in anoxic conditions (black-shale like deposits such as dysodilic shales, black cherts, brown and bituminous marls). On this background, an increasing sand input also occurred (black shale with bedded cherts and sandstone facies association). Some authors (Ionesi 1971, 1981; Dicea & Dicea 1980; Ionesi & Florea 1981, 1982; Ionesi & Meszaros 1989) consider that the Eocene-Oligocene boundary is placed in this stratigraphic interval, based on NP21–NP22 taxa, while others

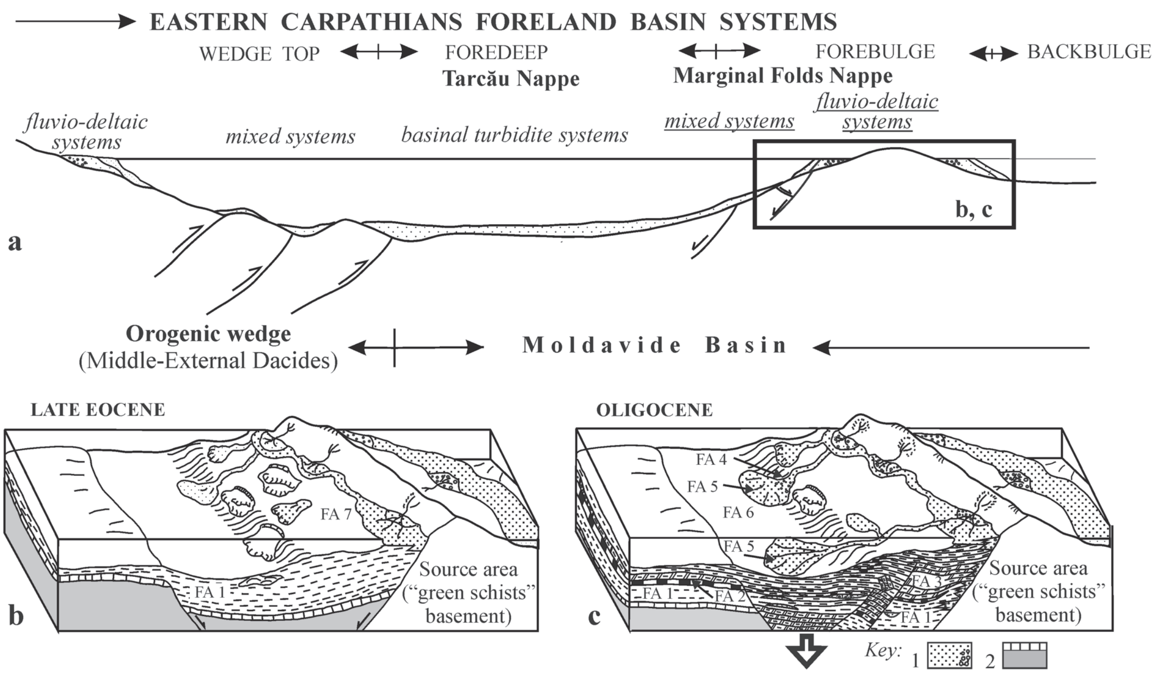

Fig. 13. A rough 3D paleogeographic interpretation of the Late Eocene-Oligocene depositional systems of studied sections within the Bistriţa half-window (Marginal Folds Nappe — Eastern Carpathians). **a** — The position of the studied area in the foreland basin systems (the italics indicate the depositional systems defined by Mutti et al. (2003) for foreland basins; the underlined italics are their equivalents on forebulge depozone). **b** — The position of Late Eocene facies associations in a sub-basin of the forebulge depozone. **c** — The position of Oligocene facies associations in a subsident sub-basin of the forebulge depozone; 1 — deposits of foreland basin systems; 2 — deposits older than Late Eocene.

(Martini & Lebenzon 1971; Lebenzon 1973; Dicea & Dicea 1976; Micu & Gheţa 1986) consider that it is inside the well-known Globigerina Marls belonging to what we have called whitish marl with debrite facies association. According to Belayouni et al. (2009) some levels in Lucăceşti Sandstones contain latest Rupelian foraminifers belonging to N1/P20 Zone of Blow (1969). The anoxia may be a result of increasing sediment supply which consequently increased the preservation of organic matter. Anoxic conditions may also have been favoured by increasing biological productivity linked to changes in the physical and chemical conditions of the sea water (C-organic and CO_2 content). This event, in turn, may be explained by controls such as: *1)* the geographical isolation of the Paratethys basin from the Mediterranean one after the collision between Africa and Eurasia plates during the Oligocene (Rögl 1999); *2)* the global climatic changes which began in the Middle Eocene (Pomerol & Premoli-Silva 1986; Soták et al. 2002); *3)* the relative sea-level fluctuations of different amplitude, tectonically controlled. Channelized sandy deposits occurring in the studied sections (black shale with bedded cherts and sandstone facies association) might be related to a rich sand shoreface and/or deltaic system drowned because of tectonic controlled sub-basin subsidence (Fig. 13b).

4. Anoxic shelf depositional system — corresponds to an important stratigraphic marker recognized in all the studied sections — the Bituminous Marls. Its lower boundary is sharp and erosional in the sections where it is exposed (Nechit River 1, and Nechit River 2 Sections). The corresponding deposits are much thicker (> 50 m) in proximal section (Nechit River 2 Section) than in distal one (around 10 m in the Nechit River 1 Section). This different thicknesses might be the result of sedimentation on different blocks, some supporting active subsidence controlled by gravitational faults (such is Nechit River 2 Section; Fig. 13c), others being uplifted (Nechit River 1, and Şoimu Sections; Fig. 13c). Such a vicinity of subsiding and uplifting blocks caused the instability of unconsolidated deposits proved by menilite intraclasts inside the bituminous marls or the shear plane at the base of the bituminous marl facies association (Fig. 3c,d).

These sedimentary features indicate a basin margin affected by tectonic deformations and consequent gravitational collapses, which may have produced a source of coarse material, which sometimes supplied the muddy shelf system via storm induced hyperpycnal flows or turbiditic currents induced by floods or storms. The shallow sedimentation conditions are also suggested by the existence of the extremely well preserved flatfish as we have shown above. The sandy dykes present in the marls may prove both the fast mud deposition and the mobility of quicksands during bottom shocks.

5. Upper turbiditic system — The contact of FA 4 with FA 3 is sharp in the Nechit River 1 Section, the only section where it is exposed. The facies associations 4, 5 and 6 indicate a deepening trend in the basin evolution in the Nechit River 1 Section. A gradual deepening and distal characters of the turbidite system can also be noticed in the Şoimu Section, and this is testified by the vertical succession of sandstone lobes, fringe fan, and black shale deposits referred to basin plain although the proximal part of this system is not exposed. This deepening might be tectonically controlled by the local subsidence of the block which hosted the analysed area (Fig. 13b). An important proof of this is the presence of the bituminous marl (identical with FA 3 of anoxic shelf) olistolith re-sedimented within deposits of upper turbiditic system. In Săndulescu & Micu's (1989) opinion the Lower Dysodilic Shales and Kliwa Sandstones (our FA 4, and 5) together with the Bituminous Marls were sedimented in deep water conditions, while the Upper Dysodilic Shale (our FA 6) were sedimented on a shelf (Dysodilic Marginal Shelf) bypassed by submarine channels which fed the Tarcău Realm with coarse materials (Upper Kliwa Sandstones).

According to Mutti et al. (1996, 2000, 2003), such a coarse type of turbidites, usually associated with debrites, may be the products of hyperpycnal flows formed in delta systems during catastrophic flood events, and able to carry sand or gravel over tens of kilometers, depositing them as marginal turbidites. These authors have introduced the concept of "mixed depositional systems" made up of turbidite-like facies and facies associations formed at relatively shallow depths (seaward edges of flood-dominated deltaic systems), but it is still difficult to identify processes, environment and water depth (Mutti et al. 2003) based only on limited exposures such are those analysed here. A possible argument for the relatively shallow-water condition of the upper turbiditic system is the presence of ichnofauna of *Thalassinoides* in the lobes of the Şoimu Section (Fig. 5). The instability of the channels in this system is proved by their recurrence in the sedimentary successions (FA 4) in alternation with the lobes (FA 5) occurring in the proximal part. Upwards in the succession of the upper turbiditic system the sand : mud ratio decreases, proving the deepening of the basin. Such a deepening was possibly controlled by extensional tectonics affecting the forebulge depozone which was retreating.

Mutti et al. (2003) recognized the "mixed depositional systems" in wedge-top basins, actively fed by deltaic systems. We consider that such systems may also develop on forebulge depozone of foreland basin systems especially during their underfilled stage of development (Crampton & Allen 1995) when the forebulge may have a prominent relief drained by rivers. This had to be the case of the Moldavidian Basin forebulge if we take into consideration the continuous supply of "exotic" clasts from the Early Cretaceous to the Early Miocene climax. For the Early Miocene Grasu et al. (1999) described a fan-delta characterized by very coarse to coarse deposits (Almaşu Conglomerates and Sandstones on Cuejdiu River northward of Piatra Neamţ), consisting mainly of "green schist", white limestone, and even some pegmatite, which prograded in shallow-waters. The clasts can have meters in diameter suggesting a short transport from their source area. Their main sedimentation processes were non-cohesive and cohesive debris flows and high-density turbiditic currents. Such fan-deltaic systems could also have fed the forebulge marginal basin during the Eocene–Oligocene.

All these elements suggest a ramp-type basin margin characterized by collapsed or uplifted blocks controlled by normal faults where both source area and depocentres with rapid basinward transition to deeper water system (subsident regime) evolved (Fig. 13).

Petrography and provenance

Petrographic study of the Eocene-Oligocene arenaceous samples associated with the Lower Menilites in the Şoimu River Section is focused on recognizing the gross composition of the sandstones, the textural characters of the grains and detecting the provenance of the detrital supply.

This study has been carried out by means of modal point counting in thin section, performed according to the criteria suggested by Gazzi (1966), Dickinson (1970) and by Gazzi et al. (1973), in order to minimize the dependence of the rock composition on grain size.

The detrital framework of the analysed rocks is characterized by a dominant non-carbonate extrabasinal fraction, made up of abundant quartz, low percentages of feldspars and traces of lithic fragments, mixed with a conspicuous presence of a non-carbonate intrabasinal fraction, mainly represented by glauconite grains (14.5 % maximum) and by a very low content of opaque minerals.

Quartz is undoubtedly the most abundant mineral in all the analysed sandstones. According to the Basu's et al. (1975) criteria, modified by Basu (1985), the detrital quartz has been distinguished into monocrystalline and polycrystalline quartz grains, each of them subdivided into two populations: monocrystalline quartz grains of low and high undulosity (≤5° or >5° apparent angle of extinction, measured with a flat-stage) and polycrystalline quartz grains with few or many subgrains (≤4 or >4, number of crystal units contained within each grain)[1].

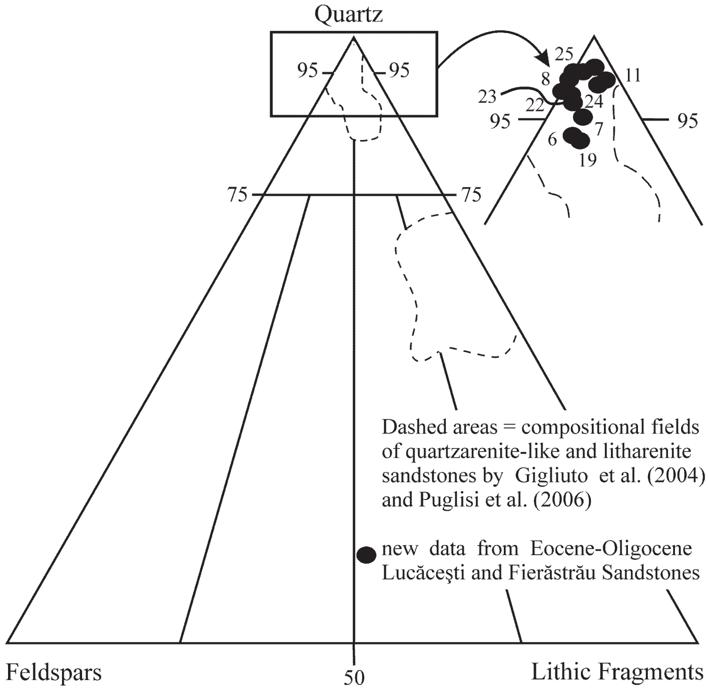

Fig. 14. Quartz-Feldspars-Lithic Fragments ternary plot showing the composition of the Lucăceşti and Fierăstrău Sandstones and other arenites associated with the Lower Menilite Formation.

Monocrystalline quartz grains are more abundant than the polycrystalline varieties and, in particular, the monocrystalline grains with high undulosity and the polycrystalline quartz grains with many subgrains (**Qm''** and **Qp''** in Table 1, respectively) are the more representative varieties.

These kinds of quartz (**Qm''** and **Qp''**) are indicative of low-grade metamorphic sources and, usually, they show a very low stability pointing to selective destruction by mechanical agencies during prolonged transport and, of course, during successive sedimentary cycles (Blatt & Christie 1963; Basu 1985).

Thus, the abundance of **Qm''** and **Qp''** and the scarcity of feldspar grains should be indicative of sediment sources predominantly composed of low-grade metamorphic rocks and, in any case, they point to exclusion of conspicuous contributions from plutonic and/or high grade metamorphic source (Fig. 14).

The presence of locally abundant epimetamorphic clasts in several stratigraphic horizons of the analysed Eocene–Oligocene sedimentary succession (Lucăceşti and Fierăstrău Sandstones, Bituminous Marls, Lower Dysodilic Shales with Kliwa Sandstones interlayered), mixed with predominant subangular-to-subrounded quartz grains, seems to support this type of provenance (Fig. 15a).

In addition, this hypothesis of provenance seems to be in agreement with Suttner's et al. (1981) model, which suggests that such kind of rocks are the only sources able to produce high amounts of quartz grains as first cycle detritus under "a unique combination of extreme conditions of climate, relief and sedimentation". Such conditions of climate, in particular, seem to be realized during Oligocene times, just after the Eocene–Oligocene transition global cooling, as documented by the values of paleotemperature and precipitation which point to a subtropical- and paratropical-like climate recorded at the Rupelian/Chattian boundary (mean annual temperature/precipitation ranging between 13–20 °C and 1.353–2.760 mm, respectively; Givulescu 1997). Anastasiu (1986) also suggested a rather chemical weathered material as source for the quartzarenites of Kliwa Sandstone and not an eolian deposit from the cratonic area as Săndulescu & Micu (1989).

Finally, the presence of glauconite as the most representative mineral of a locally abundant non-carbonate intrabasinal fraction must be noticed (Fig. 15b).

This mineral is usually supposed to be authigenic in origin and formed in marine environments under reducing to slightly oxidizing conditions on the continental shelf (Folk 1974; Pettijhon 1975; Odin 1985; Kelly & Webb 1999; Hesselbo & Huggett 2001). In the analysed rocks, it shows good roundness and grain size very similar to other detrital clasts. Roundness is an important textural characteristic indicative of highly turbulent environments or also of prolonged transports and, in

[1] The analysed sandstones are usually medium- to fine-grained, thus respecting the conventional criteria to collect the data concerning the undulatory extinction and the polycrystallinity of the detrital quartz grains mainly from the medium sand-size fraction (0.25–0.50 mm; Basu et al. 1975; Young 1976).

Table 1: Modal point counts of the Şoimu River Section sandstones compared with the Kliwa Formation and the "Moldoviţa lithofacies" quartzarenite-like sandstones of the Tarcău Nappe.

	RO 6	RO 7	RO 8	RO 11	RO 19	RO 22	RO 24	RO 23	RO 25	RO 28	RO 26	RO 27	x	σ	x'	σ'	Kliwa Sandstones*	
Q_m'	12.7	11.9	11.3	20.1	13.7	19.6	15.7	23.8	21.8	24.9	24.7	15.8	18.0	5.10	10.3	3.04		
Q_m''	47.9	48.4	53.3	59.7	52.4	47.9	53.1	55.5	60.8	55.1	52.2	54.2	53.4	4.16	30.0	6.62		
Q_p'	1.9	1.8	2.9	1.3	1.3	0.9	1.0	1.9	1.6	0.9	3.4	1.1	1.7	0.82	12.1	4.31	**Q**	80÷90
Q_p''	1.9	2.8	3.4	4.2	5.3	9.8	3.0	6.8	5.2	3.4	6.2	1.8	4.7	2.72	19.3	5.45		
Qr	–	–	–	–	–	–	–	–	–	–	–	–	–		0.1	0.30		
Ch	0.5	0.7	0.7	0.3	0.9	0.5	0.4	0.2	–	–	–	–	0.4	0.32	0.8	1.29		
Ps	2.4	2.2	0.8	0.6	2.9	1.4	1.1	1.1	1.2	1.2	1.2	2.0	1.5	0.70	1.7	0.80		
Pr	–	–	–	–	–	–	–	–	–	–	–	–	–		0.1	0.11	**F**	5÷10
Ks	0.6	0.7	0.3	–	0.3	0.5	0.4	0.6	–	–	0.8	0.7	0.4	0.31	1.2	0.48		
Lv	–	–	–	–	–	–	–	–	–	–	–	–	–		0.4	0.59		
Lc	–	–	–	–	–	–	–	–	–	–	–	–	–		0.7	0.77		
Ls	0.2	0.2	–	0.3	0.3	–	0.3	0.5	0.3	–	0.5	0.2	0.2	0.20	–		**L**	–
Lm	0.3	0.2	–	0.6	0.2	–	0.1	–	–	–	–	–	0.1	0.21	1.2	0.50		
Fo	–	–	–	–	0.6	–	–	–	–	–	–	–	**tr**		1.3	1.89		
Ms	3.7	2.8	1.3	1.9	0.6	1.9	1.7	0.3	0.9	1.0	0.7	0.8	1.7	1.11	5.8	2.43	**Gl**	3÷10
Gl	13.4	13.1	14.5	6.3	11.6	10.6	10.7	3.0	3.9	3.0	4.3	0.9	7.9	4.8	7.5	3.41		
Op	1.9	2.1	1.5	0.9	–	1.5	1.4	0.3	–	0.7	0.5	1.0	1.1	0.7	0.3	0.42	**M + Al**	**Sp**
Al	0.9	1.7	0.3	0.2	–	1.4	0.7	1.1	0.5	0.3	1.3	0.7	0.9	0.53	0.6	0.58		
Mt	2.8	2.7	1.9	0.7	1.7	3.5	1.5	4.9	3.4	9.5	4.2	9.2	3.8	2.81	3.2	196	* Mean framework modes from Grasu et al. (1988)	
Cm	8.9	8.7	7.8	2.9	8.2	0.5	8.9	–	0.4	–	–	2.6	4.2	4.02	2.4	1.21		
	100.0	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**		**100.0**			
Q	94.9	95.3	98.4	98.3	94.5	97.6	97.5	97.5	98.4	98.6	97.2	96.6	97.1	1.44	91.8	4.99	**x** and **σ** = average and standard deviation of the analysed samples	
F	4.4	4.2	1.6	0.7	4.1	2.4	2.0	1.9	1.3	1.4	2.2	3.2	2.4	1.24	3.7	1.83		
L	0.7	0.5	–	1.0	1.4	–	0.5	0.6	0.3	–	0.6	0.2	0.5	0.43	4.5	3.32		
	100.0	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**		**100.0**			
Q_m	88.6	87.5	88.8	97.9	84.9	83.6	91.6	87.7	90.9	93.6	86.5	93.1	89.6	4.05	51.7	7.52	**x'** and **σ'** = average and standard deviation of the "Moldoviţa Lithofacies" quartzarenites from Gigliuto et al. (2004); Puglisi et al. (2006)	
F	4.4	4.2	1.6	0.7	4.1	2.4	2.0	1.9	1.3	1.4	2.2	3.2	2.4	1.24	3.7	1.83		
L_t	7.0	8.3	9.6	1.4	11.0	14.0	6.4	10.4	7.8	5.0	11.3	3.7	8.0	3.55	44.6	8.00		
	100.0	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**		**100.0**			

Symbols of the parameters adopted for the modal analysis

Q = **Q_m** + **Q_p**, where: **Q** = total quartzose grains including **Q_m** = monocrystalline quartzose grains subdivided into **Q_m'** = of low undulosity (≤ 5°) and **Q_m''** = of high undulosity (> 5°) and **Q_r** = quartz in coarse-grained rock fragments (i.e. > 0.06 mm), **Q_p** = polycrystalline quartzose grains (including **Ch** = chert) which have been subdivided into **Q_p'** = with few subgrains (≤ 4 crystalline units per grain) and **Q_p''** = with many subgrains (> 4 crystalline units per grain). **Q_m', Q_m'', Q_p'** and **Q_p''** have been determined according to the criteria suggested by Basu et al. (1975) and Basu (1985);

F = **P** + **K**, where: **F** = total feldspar grains, **P** and **K** = plagioclase and potassium feldspar single grains (**Ps** and **Ks**) or in coarse-grained rock fragments (exclusively **Pr**);

L = **Lv** + **Lc** + **Lm**, where: **L** = unstable fine-grained rock fragments (< 0.06 mm, including: **Lv** = volcanic, **Ls** = sedimentary, **Lc** = carbonate, **Lm** = epimetamorphic lithic fragments and **Fo** = fossils);

Lt = **L** + **Q_p**, where: **Lt** = total lithic fragments (both unstable and quartzose);

M = micas and/or chlorites, in single grains (**Ms**);

Gl = glauconite grains, **Al** = other mineral grains, **Mt** = siliciclastic matrix; **Cm** = carbonate cement; **Sp** = sporadic occurrence, **tr** = traces.

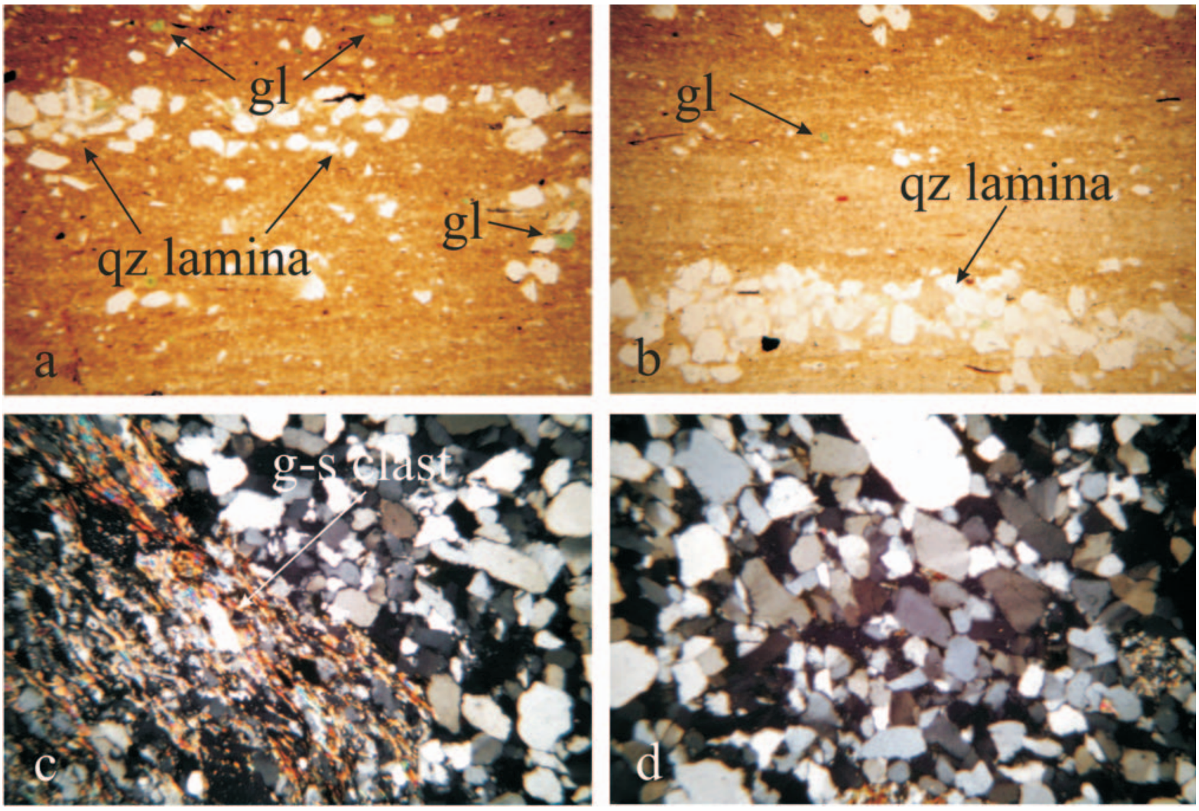

Fig. 15. Thin sedimentary laminae mainly made up of subrounded quartzose grains (*qz lamina*), rare opaque minerals and occasional glauconite (*gl*) within the Bituminous Marls (**a**, and **b**). Green schist clast (*g–s clast*) in the Fierăstrău Sandstone (**c**) and typical quartzarenites-like products characterizing the Lucăceşti Sandstones (**d**).

this case, on the basis of the above mentioned sedimentological conjuncture, it appears to be closely related to the high hydrodynamism of a shallow marine-like environment.

The source area of these lithic fragments might be the same type as the "green schist" clasts re-sedimented in all the external deposits of the former Moldavide Basin beginning with Early Cretaceous, as we have shown above. Zuber (1902) imagined this source area as an extension of the Central Dobrogea chain to the Przemyśl region (Poland) which apart the Flysch Basin from Podolian Continent (East European Platform). Since then most geologists referred the source area of "exotic" clasts to Central Dobrogea. According to Oaie et al. (2005) they were supplied by an external cratonic source area considered to be a belt of Neoproterozoic–Lower Cambrian turbidites lying on the western margin of the East European Craton which is now almost completely covered by East Carpathian nappes (Oaie et al. 2005). The only places where these turbidites outcrop are in Central Dobrogea, an uplifted block of the Moesian Platform, and the Malopolska Massif (in Poland). Anyway as we have shown above, the "exotic" clasts supplied by the "green schists" source area (Fig. 13) also include metamorphics and pegmatites, proving its rather complex constitution from the petrographic point of view (Anastasiu 1984, 1986; Grasu et al. 1999). Mirăuţă (1964) showed that the "green elements" re-sedimented within flysch and molasses deposits are characterized by higher metamorphic rank than the rocks considered their source area from Central Dobrogea. A possible explanation for the petrographic variety of the "exotic" clasts would be a deeper erosion of Central Dobrogea along the segment which played the role of forebulge for the Moldavide Basin.

Paleontology and paleoecological implications

Fish, as fossils, are almost exclusively autochthonous and thus best suited as direct indicators of aquatic vertebrate life and vertebrate biodiversity in the past.

A significant Oligocene fish fauna has been collected from the Piatra Neamţ area, located in the Bistriţa half-window. Most of the type specimens as well as numerous additional materials from this area have been collected from the Lower Dysodilic Shales and are nowadays deposited in the paleontological collection of the Natural Sciences Museum of Piatra Neamţ.

These fish are well preserved and the Lower Oligocene collections contain specimens of more than 50 species representing about 20 families. The most important species include sardinas (*Clupeidae*), bristlemouth (*Gonostomatidae*), hachetfish (*Sternoptychidae*), lightfish (*Photichthyidae*), lanternfish (*Myctophidae*), codlets (*Bregmacerotidae*), squirrelfish (*Holocentridae*), dories (*Zeidae*), boarfishes (*Caproidae*), shrimpfish (*Centriscidae*), bigeyes (*Priacanthidae*), sharksuckers (*Echeneidae*), jaks and pomparos (*Carangidae*), pomfrets (*Bramidae*), snake mackerels (*Gempylidae*), cutlassfish (*Trichiuridae*), mackerels and tunas (*Scombridae*), driftfish (*Nomeidae*), lefteye fluoders (*Bothidae*), triplespines (*Triacanthidae*).

During geological investigations in 2005–2006 an outcrop was discovered on Pietricica Mountain, Piatra Neamţ, situated in the second level of the Bituminous Marls, considered by Ionesi & Grasu (1993) to be an olistolith. Some interesting fish fossils specimens, listed and described below, were collected from Bituminous Marls cropping out near Piatra Neamţ al Văleni (Fig. 1), and also from the above mentioned olistolith.

Order: **Myctophiformes**
Family: **Myctophidae**

Genus: *Oligophus* Ružena Gregorová, 1997

Oligophus moravicus (Paucă, 1931)

The most abundant fossil specimens from Bituminous Marls (more than 10 very well preserved specimens, Fig. 16a) belong to *Oligophus moravicus* (Paucă, 1931).

Typically, the recent species of myctophids are pelagic fish of the open ocean. Most species are found in the upper 1000 m of the water column (mesopelagic). A few species live deeper than 1000 m (bathypelagic). Some species are associated with continental and island slopes (pseudoceanic).

Daily vertical migrations from about 400 to 1000 m during the day into the upper 200 m at night are common; some species reach the surface (Craddock & Hartel 2002).

Order: **Gadiformes**
Family: **Merluccidae**

Genus: *Palaeogadus* Rath, 1859

Palaeogadus sp.

In the olistolith of Bituminous Marls only one specimen, incomplete of *Palaeogadus* sp. (Fig. 16b) has been discovered. The recent species of the family Merluccidae are benthopelagic fish living on the shelf and upper continental slope, from shallow coastal waters to more than 1000 m; most species, if not all, migrate vertically at night to feed; seasonal onshore-offshore migrations have also been documented (Iwamoto & Cohen 2002).

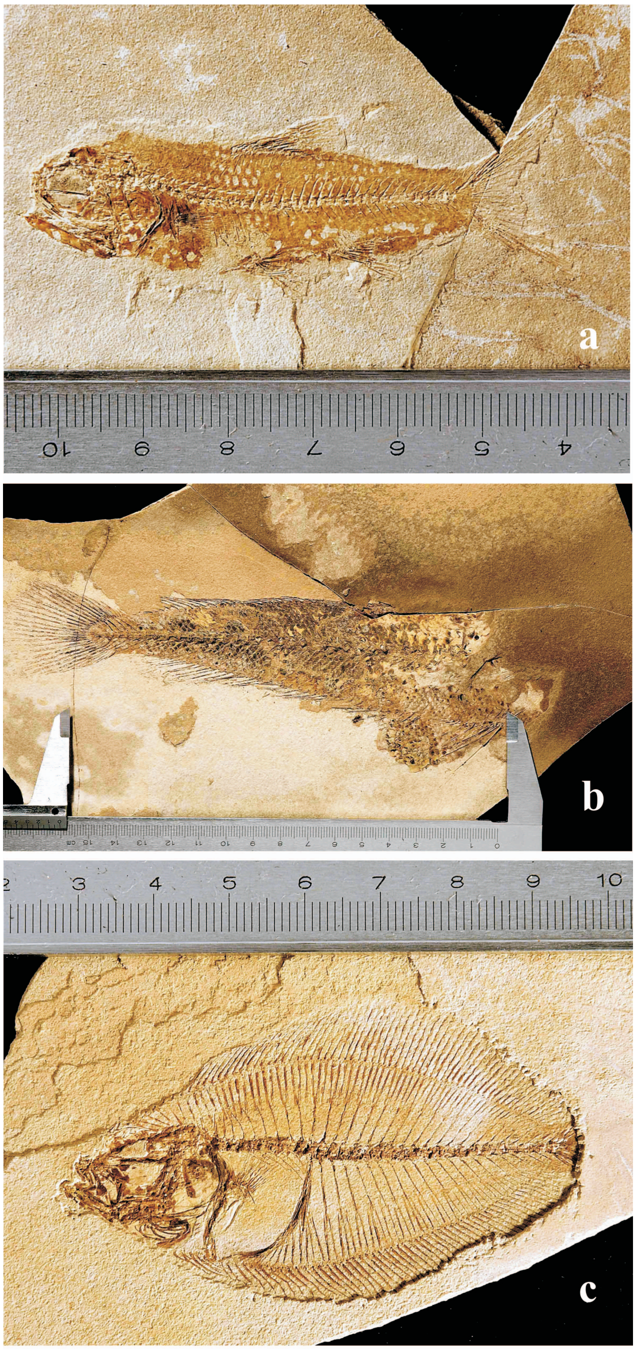

Fig. 16. a — *Oligophus moravicus* (Paucă, 1931). **b** — *Palaeogadus* sp. **c** — *Scophthalmus stamatini* (Paucă, 1931).

Order: **Pleuronectiformes**
Family: **Scophthalmidae**

Genus: *Scophthalmus* Rafinesque, 1810

Scophthalmus stamatini (Paucă, 1931)

Flatfish fossils are very rarely discovered. Baciu & Chanet (2002) described the oldest known scophthalmid, *Scophthalmus stamatini* (Paucă, 1931), from the Bituminous Marls (Lower Oligocene, Pietricica Mountain near Văleni; point V on Fig. 1). Five specimens from the Bituminous Marls and one from the olistolith of the Bituminous Marls resedimented in Lower Dysodilic Shales in Pietricica Mountain exposures, very well preserved, complete and undistorted of *Scophthalmus stamatini* (Paucă, 1931), has been discovered (Fig. 16c).

In the recent fauna, this family is represented by five genera with about 18 species, distributed in the northern Atlantic, Mediterranean and Black seas (Nelson 1994). Generally these species inhabit sand to sand/silt or mud sediments in relatively shallow-waters (less than 110 m); most abundant from 1–2 m to, usually, less than 56 m (Munroe 2002).

Most of the fish fossil specimens from the Bituminous Marls are undistorted and complete, proving the absence of transport of the specimens over long distances. Gaudant (1979) considers that it is possible to interpolate the ecological characters between recent and fossil fish fauna until the level of the family, so the presence of merluccids and scophthalmids indicate that the depth of marine basin, at the level of the Bituminous Marls had to be about 100 to 200 m.

Conclusions

The flysch deposits involved in the Moldavide units were accumulated in a foreland-type basin system (Fig. 13a). The Marginal Folds Nappe sedimentation area was located on the internal part of the forebulge depozone.

The forebulge resulted after the tectonic loading of the cratonic margin, possible of Moesian type as the "exotic" clasts would indicate, as a consequence of the Late Cretaceous closure of the External Dacide trough, and overthrusting of its nappes. Its outward migration could cause reactivation of older faults and/or tensional stresses which, in turn, could determine a fragmentation of the basin margin in uplifted and subsident blocks, hosting sub-basins. The forebulge was partly emerged during the Oligocene and later when increasing quantities of "green schists" clasts (meters in diameter) were supplied into the marginal basin (Grasu et al. 1999).

A small area of the Marginal Folds Nappe exposed in the Bistrița half-window (Eastern Carpathians) was analysed based on three successions logged on the Nechit River 1, Nechit River 2, and Șoimu River Sections. Seven facies associations were recognized in Upper Eocene-Oligocene deposits (Bisericani Beds, Globigerina Marls, Lucăcești Sandstone, Lower Menilites with Fierăstrău Sandstone, Bituminous Marls, Lower Dysodilic Shales with Kliwa Sandstone, Upper Dysodilic Shales) based on lithology, sedimentary structures, and paleontological content. They were interpreted as representing — mud-rich slope deposits, oxic shelf, shallow channels, anoxic shelf, channel-levee, depositional lobes, and fringe fans (Fig. 13b,c) belonging to five depositional systems: 1) mud-rich slope apron, 2) oxic shelf, 3) lower turbiditic system, 4) anoxic shelf, and 5) upper turbiditic system.

The different behaviour of these blocks might be the result of the observed shallowing or deepening upward sedimentary trends. The sedimentation in shallow-water is proved firstly by the coarseness of turbidites which are interpreted as "mixed depositional system" according to Mutti et al. (2003) terminology. We have shown that these mixed depositional systems may appear not only on the active margin of the foreland basin system, but also on its forebulge, when this represents an important source of coarse material, on one hand, and is affected by deformations and collapses, which define local sub-basins connected to coarse material source, probably of fan-delta type, on the other.

The presence of the two shelf depositional systems, one oxic, and other anoxic, with highly bioturbated sandstones and flatfish (*Scophthalmus stamatini* Paucă, 1931) prove again the sedimentation rather in shallow-water conditions.

The source area was located entirely on the cratonic side of the foreland basin as is proved by very frequent "green schists" clasts, and by quartzarenite-type of sandstones (Lucăcești, Fierăstrău, and Kliwa Sandstones). The source area for "green schists" clasts is considered to be a Central Dobrogea-type basement, and its sedimentary cover, which played the forebulge role. The quartzarenite petrographic characteristics prove a provenance from low-grade metamorphic rocks as green schists. Their high maturity might be a result of deep chemical weathering in a subtropical- and paratropical-like climate as was the case during the Oligocene time in the studied area.

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