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THE CRUZIANA ICHNOFACIES IN THE LOWER MEMBER OF THE BISERICANI FORMATION (EASTERN CARPATHIANS, ROMANIA)

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Abstract A 7 m sedimentary succession of the lower member of the Bisericani Formation from the Vrancea Nappe (Bistrița Half-window) was studied by means of sedimentary facies analysis and ichnological methods. The peculiar heterolithic deposits were accumulated by gravity flows, traction, and pelagic and hemipelagic fallout. They contain mainly hypichnial, endichnial, and rarely epichnial trace fossils, several of them being identified at ichnogenus or ichnospecies levels, such as: *Chondrites*, *Avetoichnus luisae*, *Planolites*, *Lockeia*, *Thalassinoides, and Rhizocorallium commune*. Ethologically, they can be included in fodinichnia, domichnia, and supposedly agrichnia (*Avetoichnus luisae*) categories, representing a part of the *Cruziana* ichnofacies. Based on combined sedimentary facies and ichnologic analysis, the depositional system of the studied section is interpreted as an offshore-transition one characterized by tempestites, favorable for the *Cruziana* ichnofacies development.

Keywords: *Cruziana* ichnofacies, offshore-transition, Priabonian, Bisericani Formation, Eastern Carpathians

INTRODUCTION

Some intervals of the Cretaceous-Early Miocene sedimentary succession of the Romanian Outer Carpathians Flysch are characterized by rich trace fossils which were scarcely studied by ichnofacies point of view (Alexandrescu & Brustur, 1981; Brustur & Alexandrescu, 1993; Buatois et al., 2001). This is especially true for one of the outermost nappe of the Moldavide Nappe System (*sensu* Săndulescu, 1984), namely the Vrancea Nappe. The sedimentary succession of the latter unit, between Bistrița and Tazlău Rivers (in the Bistrita Half-window), consists of deposits belonging to the Lower Cretaceous Sărata Formation (Băncilă, 1955) followed by the lowermost Upper Cretaceous variegated shale (Grasu et al., 1988), and by the Upper Cretaceous Lepșa Formation (Dumitrescu, 1952). The Paleocene-Eocene interval is characterized by the Putna (Micu, 1980), Piatra Uscată (Micu, 1976a), Jgheabu Mare (Olteanu, 1953), Doamna Limestone (Athanasiu et al., 1927), and Bisericani (Athanasiu, 1921 in Athanasiu et al., 1927) Formations. The Oligocene-Lower Miocene sedimentary succession consists of informal lithostratigraphic units, such as: the lower menilites, bituminous marls, dysodilic shales with Kliwa Sandstone (Mirăuță & Mirăuță, 1964), and Gura Șoimului Formation (Stoica, 1953).

Previously, a wide variety of ichnofossils were described in many lithostratigraphic units belonging to the more internal Carpathian nappes (Alexandrescu & Brustur, 1980, 1981, 1982, 1987, 1990; Brustur, 1995a; Brustur & Alexandrescu, 1993; Brustur & Stoica, 1993). Brustur (1995a) reported 32 ichnospecies from Podu Secu, Plopu, and Bisericani Formations (which are considered lateral equivalents), representing over 50% of the total known ichnospecies from the Paleogene deposits of the Tarcău and Vrancea Nappes. According to Alexandrescu & Brustur (1980, 1982, 1987) the majority of the ichnospecies were reported from the Tarcău Nappe, the number of those from Vrancea Nappe deposits being much smaller. Very few are described from the Bistrița Half-window.

Trace fossil communities are used by many decades in paleoenvironmental interpretation (Seilacher, 1964, 1967, 1978; Rhoads, 1975; Frey, 1978; Ekdale et al., 1984 and many others) but for Romanian Carpathians studies of this type are scarce (Alexandrescu & Brustur, 1981; Brustur & Alexandrescu, 1993; Buatois et al., 2001). Nor the sedimentologic studies are better represented; the few which exist (Grasu et al., 1999, 2007; Anastasiu et al., 2007; Miclăuș et al., 2007, 2009; Sylvester, 2007) refer to individual lithostratigraphic units, although the interpretation of the depositional environments should be based on them. Instead, the sedimentary succession of the former Moldavide Basin (MB), generally described as "flysch", continue to be interpreted as deep water deposits although there are many lithostratigraphic units which do not have the "flysch" (turbidite) features. Recently, the Cretaceous variegated and black shales from the more internal Audia Nappe were interpreted as deep sea deposits (Melinte-Dobrinescu et al., 2015), but no such studies exist for their equivalent units belonging to the Vrancea Nappe in Bistrița Half-window.

It is the purpose of this paper to present an ichnological and sedimentological analysis of an informal lithostratigraphic unit characterizing the sedimentary succession of the Vrancea Nappe, namely the red and green shale member of the Bisericani Formation.

The Bisericani Formation was divided into three informal members (Ionesi, 1971): the red and green shale, the greenish-gray mudstone, and the "Globigerina Marls". The age of the Bisericani Formation is largely considered Late Eocene (Ionesi, 1971; Bombiță, 1986; Micu & Gheța, 1986). The lower member of the Bisericani Formation in the Vrancea Nappe cropping out in the Bistrița Half-window consists mainly of red shale in its lower part, going upward in red and green shales, then mainly in green shale with sandstone interlayers, and rare lenticular beds of microconglomerate with green schist clasts and sideritic limestone (Grasu et al., 1988).

For a better understanding of the depositional paleoenvironment of the red and green shales, we conducted a sedimentological and ichnological

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investigation in Piatra Neamț area, on the Runcu Brook, a right-hand tributary of the Cuejdi River. By sedimentary facies analysis we determined the processes involved in the deposits accumulation while by ichnological analysis we identified some ichnogenera and also their ichnofacies affiliation.

GEOLOGICAL SETTING

The studied deposits were accumulated in the internal forebulge of the Carpathian foreland basin system (Miclăuș et al., 2009), the latter known as the Moldavide Basin - MB (Săndulescu, 1984, 1988) whose deposits were deformed and build up in tectonic nappes during Miocene tectonic events (Săndulescu, 1984; Guerrera et al., 2012 and references within). In the Vrancea Nappe sedimentation area of MB, from Cretaceous to Early Oligocene, the sediments of the following litostratigraphic units were accumulated: Sărata Fm., variegated shales considered an equivalent of the Cîrnu Formation, Lepșa Formation, Putna and Piatra Uscată Formations, Jgheabu Mare Formation, Doamna Limestone Formation, Bisericani Formation. They are followed by the bituminous Oligocene-Lower Miocene deposits divided in informal units, which Grasu et al. (1988) assigned the rank of formation: lower menilites, bituminous marls, and dysodilic shale with Kliwa Sandstone. The sedimentary succession ends with Gura Șoimului Formation. In the studied area, the ages of some of the above mentioned units were established by biostratigraphic analyses, while others were assumed by their position in the sedimentary succession. For Sărata Fm., based on macrofauna, Joja et al. (1970) indicated an Albian age. The variegated shale would be lowermost Upper Cretaceous if it is equivalent with Cîrnu Formation dated by Cosma (in Mirăuță & Mirăuță, 1964) based on some fragments of *Rotalipora*. The deposits considered here as belonging to Lepșa Formation were assigned to two lithostratigraphic units, namely Lepșa and Cuejdiu Beds, by Ion et al. (1982) and dated based on foraminifers as Senonian-Paleocene. Putna Formation was dated by Ionesi (1971), which call it Izvor Formation, in Tarcău Nappe based on agglutinated and large foraminifers as Paleocene. Piatra Uscată Formation was dated by Bratu (1975) and Ion et al. (1982) based on foraminifers as Upper Paleocene. The age of Doamna Limestone is accepted as Middle Eocene (Mirăuță & Mirăuță, 1964; Ionesi, 1971 among many others) and was recently confirmed by a poor foraminifer assemblage (Guerrera et al., 2012). The Bisericani Formation with its three members is considered Priabonian in age by Ionesi (1971), while Micu & Gheța (1986), based on nannplankton analysis, established the Eocene-Oligocene boundary within Globigerina Marls. A Lower Oligocene (Rupelian) age was also proved for the "Globigerina Marls" based on foraminifers (Amadori et al., 2012; Guerrera et al., 2012) in the studied area. The younger deposits, rich in organic matter, are assigned to Oligocene-Lower Miocene interval, while the Gura Șoimului Formation was dated on nannoplakton basis as Lower Burdigalian (Popescu, 2005).

The geological evolution of this area was recently presented by Guerrera et al. (2012) based on an integrated study of tectonic-activity markers and dating results. Heterogeneousness is the common characteristics of many units of the Vrancea Nappe, but in this paper we refer to the upper part of the red and green shale member of the Bisericani Formation exposed on Runcu Brook (46º59′39.01″N/26º16′6.90″E; Fig. 1), mainly consisting of greenish-gray heterolithics, weathered whitish-yellowish-gray mudstone with greenish sandstone interlayers. The unit does not expose its entire succession because it is involved in small-size faulted folds.

MATERIAL AND METHODS

In order to reveal some paleoenvironmental characteristics we integrated ichnological and sedimentary facies analyses.

Ichnological analysis follows the morphological attributes (size, geometry), ethology (regarding the behavior of the tracemakers) and toponomy (the positions of the trace fossils relative to a reference deposit), the infilling types compared with the hosting sediment, the presence or absence of burrow wall ornamentation or lining of the trace fossils in conjunction with the characteristics of the host deposit. On top of that, the analysis seeks the density of the ichnofossils and cross-cutting relationships. In order to establish the ethology, we used the summarized classification of Ekdale et al. (1984), for toponomical characterization, Martinsson's terminology (Frey, 1973), while for morphological attributes we used the extended classification proposed by Knaust (2012). We also made the deformation evaluation, calculating, when it was possible, the cross section a:b ratio of the galleries/tubes with infillings similar with the host sediment to establish the substrate consistency at the bioturbation time (Wetzel & Aigner, 1986; Schieber, 2003).

The sedimentary facies analysis is already a classic method involving: identification and description of sedimentary facies, grouping the genetically related sedimentary facies in associations, and establishing the successions of facies associations. These steps are used to interpret the sedimentary processes and their links with the specific depositional sub-domains which evolved under different controls, contributing to sedimentary basin fill.

Being "primary sedimentary structures" of the substrate in which they formed, trace fossils viewed in conjunction with physical sedimentary structures offer clues to a reliable interpretation of the ancient sedimentary environments (Howard, 1975). Both analyses are based on bed by bed macroscopic observation of the studied section consisting of 7 m column; no ichnofossils were collected.

RESULTS

The studied outcrop may be lithologically described as a "classic flysch" consisting of alternation of sandstone and mudstone, where sandstones are characterized by sharp lower bounding surfaces with "hieroglyphs". At a closer look, several other lithologic types can be recognized: paraconglomerate (pebbly mudstone), sedimentary breccia, and even rare limestones (Fig. 2). The description of the sedimentary succession was made in a

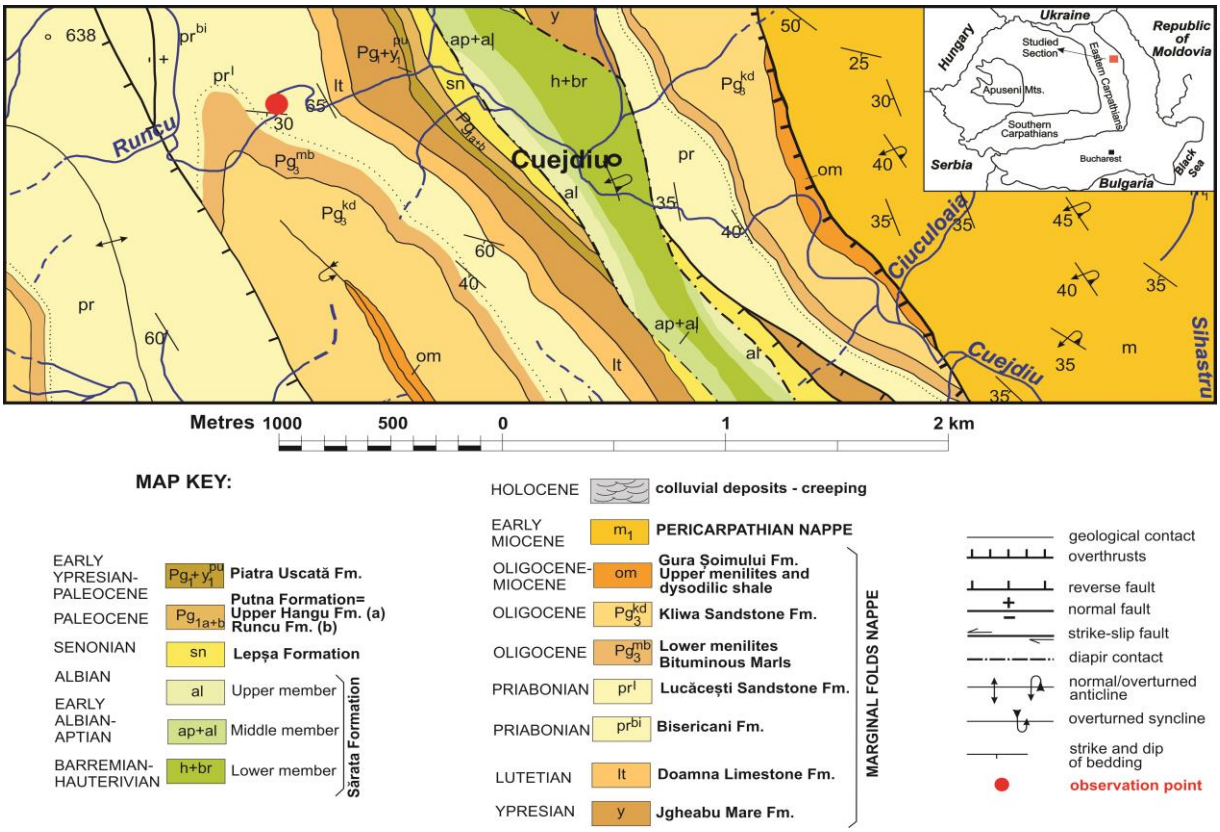

Fig. 1 Geological map showing the studied section (after Micu, 1976b, Piatra Neamț Geological Map 48b, 1:50000)

sequence of 25 intervals named after Runcu Brooks and labeled from 1 to 25"R" (Fig. 2).

SEDIMENTARY FACIES. DESCRIPTION AND INTERPRETATION

Eight sedimentary facies were defined (Fig. 3a-h): 1) G_{ms} – pebbly mudstone; 2) G_m – clast supported sedimentary breccia; 3) S_{pp} – plan-parallel laminated sandstones; 4) S_{rcl} – ripple cross laminated sandstones and small scale hummocky cross lamination S_{hcs}; 5) S_{tcl} – trough cross laminated sandstones; 6) Si_{pp} – blackish plan-parallel siltstones; 7) Si_{rcl} – dark cross laminated siltstones; 8) M_l - greenish-gray laminated mudstones.

Facies **G_{ms}** (pebbly mudstone) consists of a grayish mudstone with subrounded-rounded pebble-size clasts of green schists. Slabs of sandstone (up to 25 cm) lying at different levels can also be seen. Some of them contain green schist clasts, while others may show cross lamination. The grayish mudstone matrix shows a crude stratification (Fig. 3a).

The unit is over 50 cm thick and occurs only once at the base of the logged section. The characteristics of this unit suggest a cohesive debris flow in Lowe's (1979, 1982) terminology. The crude stratification of the matrix might be the result of internal shearing of the plastic flow during which some unlithified sandstone beds were dismembered but still preserving their inner structures and their positions in the flow. The presence of sandstone slabs suggests either that the source sediment was another pebbly mudstone with sandstone interlayers or that the debris flow involved some still unlithified sandstone on its way. Facies **G_m** (clast supported sedimentary breccia) consists of a lenticular bed (about 4 to 5 m wide) of breccia with green schist and gray limestone clasts in a coarse sandy matrix with no grading or other structures (Fig. 3b). The unit has an erosive lower bounding surface, while to its top passes sharply into a coarse to medium sandstone with mid-scale trough cross lamination (S_{tcs}). The sedimentary breccia is 10 to 20 cm thick and together with S_{tcs} reaches 0.5 m.

The erosive base of this unit suggests a constrained flow with some turbulence which cut a small channel into the underlying G_{ms}, followed by clasts' sedimentation. The ungraded clasts and the disorganized fabric are important characteristics of debris flow deposits, while the clast-supported texture indicates its non-cohesive nature (Nemec & Steel, 1984) where the clay component of the matrix may act as a lubricant of the clasts.

The facies **S_{tcs}** on top of the G_m indicate a tractive fluidal flow, probably evolved by dilution of debris flow, which was able to develop three-dimensional dunes restricted to the same scoured channel.

Facies **S_{pp}** (plan-parallel laminated very fine to fine sandstones) is one of the commonest facies in the studied section. It occurs in beds of centimeters thick (Fig. 3c) which in places pass upward into thin, undulated or cross-laminated sandstone beds, while in other cases is sharply covered by plane-parallel laminated siltstones or mudstones. Isolated, we observed endichnia trace fossils with elliptical cross section (long diameter a=6 mm, short diameter b=3 mm). The beds with sharp lower bounding surfaces are characterized by hypichnia. Some beds with plane-parallel lamination grade upward into bioturbated mudstones.

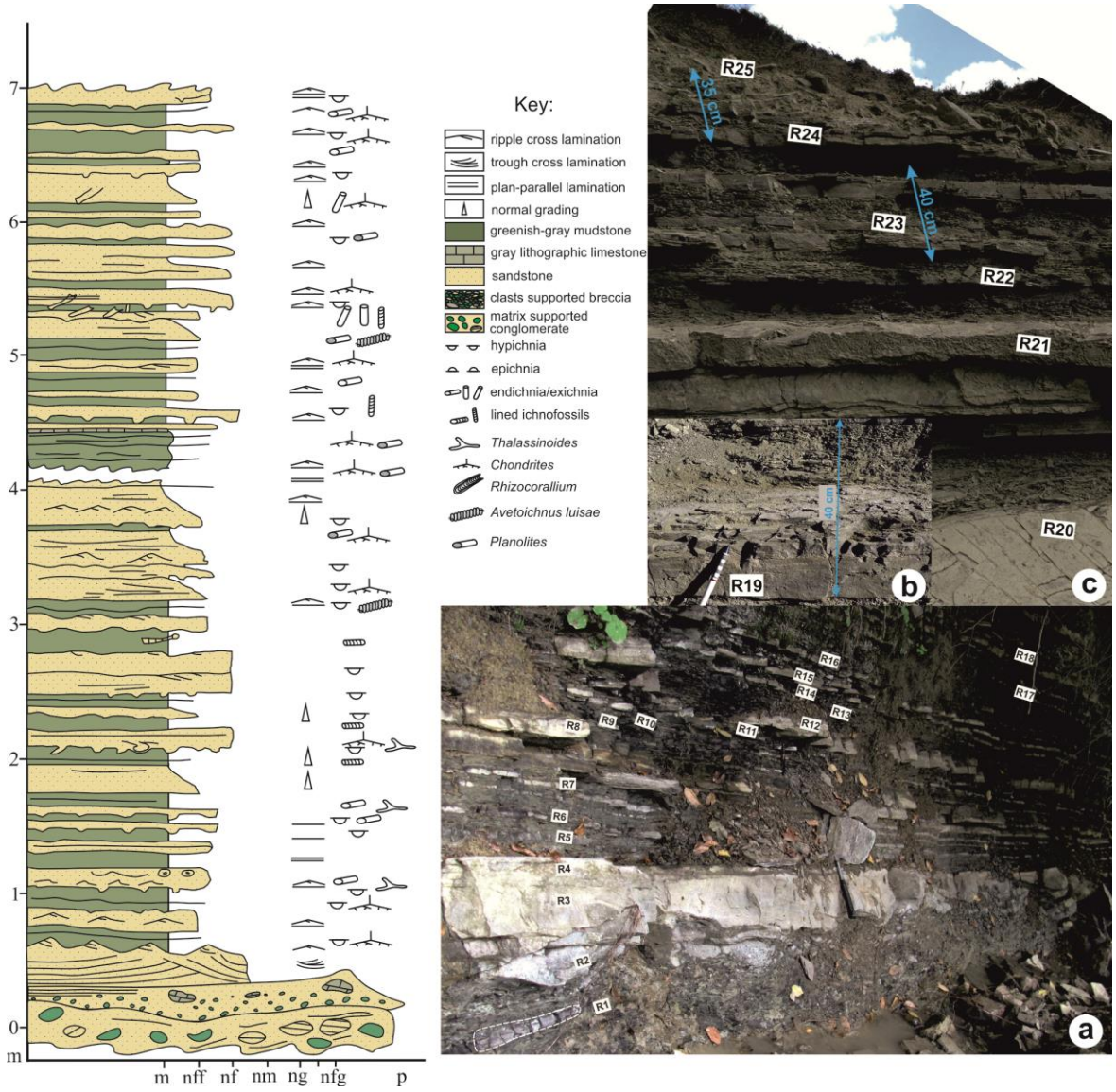

Fig. 2 Upper part of the red and green shale member of the Bisericani Formation (Runcu Brook log) with the labeled intervals "R". **a** the lower part of the section; **b** the middle part of the section; **c** the upper part of the section

This sedimentary facies represents the result of tractive currents which might be either turbidity or storm induced currents. If we consider it to be part of a turbidite, then plane-parallel laminated sandstones (S_{pp}) would represent the T_b subdivision of the Bouma sequence which is interpreted as a result of upper flow regime (Midleton & Hampton, 1976; Walker, 1978). No bed of this type in the studied outcrop is associated with normal graded underlying sandstone, an indicator of sedimentation from suspension, typical for the T_a turbidite subdivision. According to Shanmugam (2002), a sedimentary unit without graded bed subdivision (T_a) is not a turbidite at all. The lack of this element and the numerous cases where S_{pp} passes upward in S_{rcl} limits the S_{pp} interpretation towards possible tractive currents in upper flow regime passing in lower flow regime. The turbidite beds which begin with the division B or C represent the result of deposition from progressive slower flows which can be related to increasing distance across the basin (Walker, 1978; Lowe, 1982). On the other hand, Snedden & Nummedal (1991) showed that sandstone beds with plane-parallel lamination with sharp lower bounding surfaces represent the most common facies on storm-dominated shelf of Texas.

The facies **S_{rcl}** (ripple cross laminated sandstone) recurs in the section, more than 20 times, as simple or composite beds, following the S_{pp}. The beds are 5 to 10 cm thick, fine to medium grained sandstones, usually with undulated tops and gradational base when overlay S_{pp}. Toward the upper part of the column, the top on one bed (R21) shows symmetric, rounded-crest ripples in cross section. Circular to oval convex-up areas (up to 35 cm in diameter) separated by concave-up areas, both resembling very much with hummocks and swales (Fig. 3h) occur on the bed top. The hummocks show convex lamination (**S_{hcs}**). Some sharp based beds are also noticed, their soles being characterized by hypichnia and having gradational contacts with the overlying laminated siltstones. We often observed straight vertical-to-subvertical endichnia of 3-4 mm wide and 5-7 cm long, commonly cross-cutting each

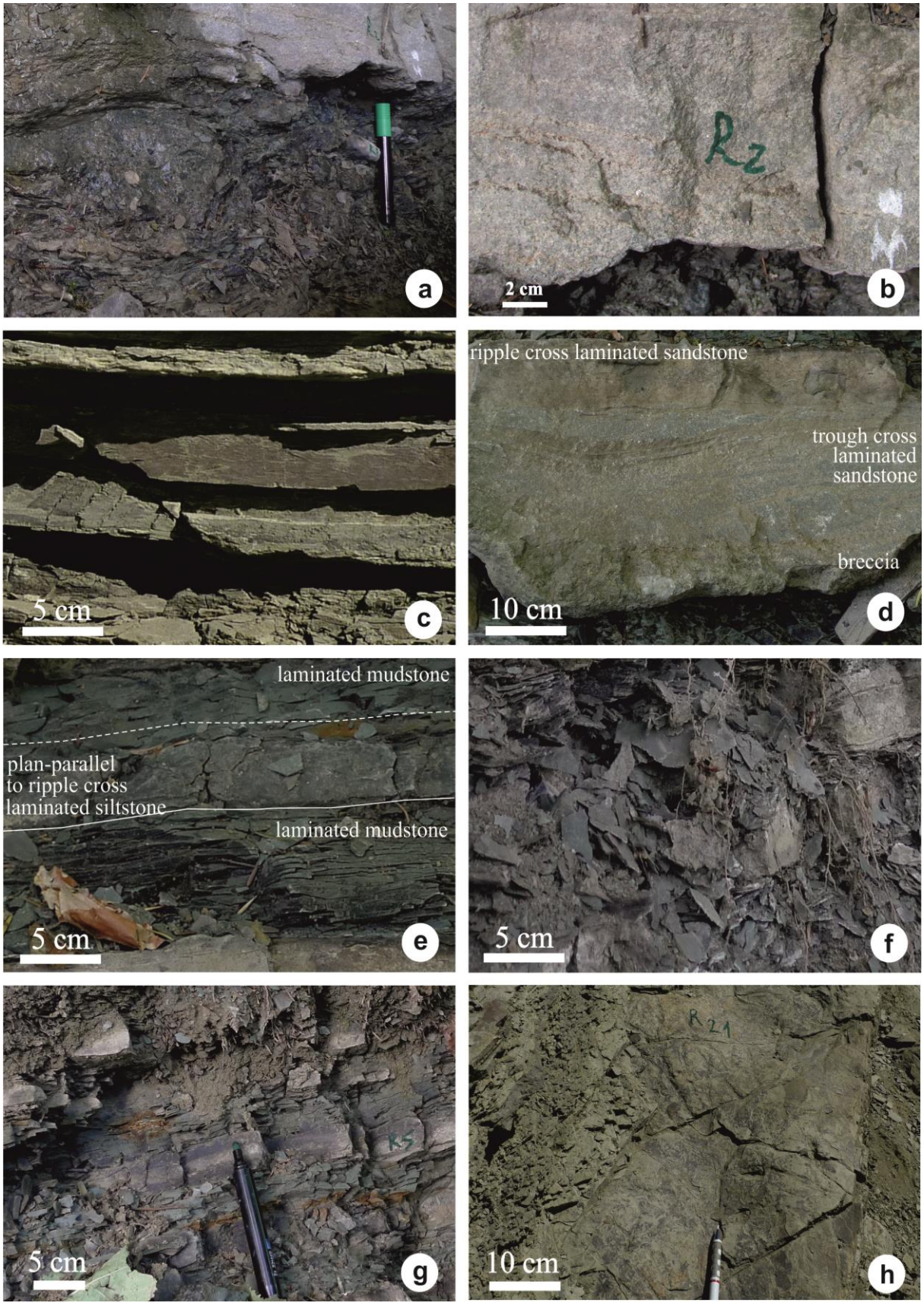

Fig. 3 Sedimentary facies: **a** pebbly mudstone (G_{ms}); **b** clast supported sedimentary breccia (G_m); **c** plan-parallel laminated sandstones (S_{pp}); **d** ripple cross laminated sandstones (S_{rcl}); **e** plan-parallel to cross laminated siltstones (Si_{pp}-Si_{rcl}); **f, g** greenish-gray laminated mudstone (M_l); **h** hummocky cross stratification (S_{hcs})

other (Fig. 3d and 6 for details).
The S_{rcl} sedimentary facies is also the result of tractive currents in lower flow regime, able to buildup ripples. When it follows after S_{pp} it might be considered as the T_c division of a possible Bouma sequence lacking the T_a division, as the model of changing the turbidite internal organization with travel distance suggests (Walker, 1978; Lowe, 1982). However, as Sanders (1965) shows, one of the diagnostic sedimentary structure developed during the deposition of sand from a turbulent suspension would be the "ripple drift with deposition from above" or climbing ripples. No such situation was observed in the studied sedimentary succession. When composite beds occur, they are rather the result of different sedimentation events as it is proved by their undulated amalgamation surfaces containing ichnofossils (Anistoroae & Miclăuș, 2014). Instead, couplets of sandstone beds with plane-parallel lamination followed by cross lamination and passing gradationally upward in bioturbated fines are described as distal storm beds on modern shelves (Snedden & Nummedal, 1991). The presence of hummocks on top of one the above mentioned beds would be an argument for such an interpretation. Hummocky cross stratification is considered by most of sedimentologists to be the most important sedimentary structure of tempestites. Since it was defined (Harms et al., 1975), its significance was a matter of debates. A purely oscillatory flow, a unidirectional-dominated combined flow or an oscillatory dominated combined flow were proposed as responsible process for such structures (Harms et al., 1975; Dott & Bourgeois, 1982; Duke et al., 1991; Arnott & Southard, 1990; Cheel & Leckie, 1993). Experimental works (Arnott & Southard, 1990; Myrow & Southard, 1991; Dumas & Arnott, 2006) showed that the stronger the unidirectional component is, the more anisotropic the hummocky stratification is. The hummocks here seem to be more isotropic suggesting they were rather the product of oscillatory flow.
The beds of **Si_{pp}** and **Si_{rcl}** facies (plan-parallel and cross laminated siltstones) are few centimeters thick and show sharp bases and gradational tops passing into greenish mudstone (Fig. 3e). Some of these beds reveal concave hypichnia, which are a few millimeters wide and centimeters in length. The thickest bed (over 20 cm) is amalgamated, having on its set bounding surfaces small *Chondrites*, circular hypichnia (5-6 mm in diameter), and *Planolites* infilled with ferruginous sediment.
As the sharp, erosive lower bounding surfaces associated with hypichnia indicate, this facies is the result of tractive currents. They can be either turbidity currents or storm induced currents as it was mentioned above. For the fine-grained turbidite, Stow & Shanmugam (1980) proposed a sequence model with nine divisions which are more or less equivalent with the T_d and T_e components of the Bouma sequence. Such a turbidite is supposed to be deposited from low density turbidity currents transporting mainly silts and clays by traction and fallout. Characteristics of the above mentioned siltstones are interpreted by Myrow (1992) as distal tempestites. It is known that distal turbidites and distal tempestites may show similar physical sedimentary structures (Seilacher, 1982; Einsele & Seilacher, 1991), the only way to discriminate between them being the trace fossil analysis.
The **M_l** facies (laminated mudstone) consists of various color (green, greenish-olive, blackish, grayish or whitish) laminated mudstones, centimeters to decimeters thick beds, mostly bioturbated (Fig. 3f-g). The mudstones with alternating red and green colors from the upper part of the column give the name of the studied unit. Some reddish-beige-whitish surfaces are the result of weathering. On them, well defined epichnial *Chondrites* and *Planolites* (Fig. 3h) may be seen.
Lacking more information than the macroscopic ones, the mudstone facies can be seen as the "background" sediment, usually interpreted as a result of pelagic to hemipelagic fallout, associated either with turbidites or storm induced tempestites which may be considered event beds. In the last years an increasing number of papers show that the mudstone can be deposited by tractive currents in the same manner as sands or silts are (Schieber et al., 2007, 2010 and references within), consequently we do not exclude such a situation.
Three main sedimentary processes were involved in the sedimentation of the red and green member of Bisericani Formation: non-cohesive and cohesive debris flow, tractive currents (either unidirectional or oscillatory), and pelagic-hemipelagic fallouts. Although the coarse grained beds display sedimentary structures common both to distal turbidites and distal tempestites, they lack some features considered as diagnostic for turbidites such as: well defined "ripple drift with deposition from above" as well as the clear normal graded units, tool or flute casts which although are known in both type of event beds are more common in turbidites. Instead, they show a dominance of the S_{pp} facies and have at least one bed with hummocky top. These elements would rather suggest that coarse beds are tempestites.
If there is no doubt that the debrites may be part of any turbiditic system, there are also examples in the literature of similar deposits associated with tempestites (Myrow & Hiscott, 1991) or with sandstones with hummocky cross stratification (Wiley & Moore, 1983), the latter supplied by a possible prograding fan delta.
It is obvious that based only on sedimentary facies analysis we cannot unequivocally interpret the depositional setting. For this reason the ichnologic study methods can add important data related by sediment-organism relationships which further will help to better define the sedimentary environment.

TRACE FOSSILS ANALYSIS

Many sandstone beds from this section are characterized by hypichnial, epichnial or both types trace fossils. The siltstone and mudstone beds contain endichnial and exichnial trace fossils. Overall, the heterolithics of red and green shale member of the Bisericani Formation from the analyzed section accumulated in favorable conditions for production and preservation of trace fossils.
Some of the observed trace fossils are described and identified at the ichnogenus and ichnospecies level (Figs. 4a-k, 5a-h). Many others of unknown affiliation occur and are mentioned only with their toponomic and, sometimes, ethologic attributes (Fig. 6a-d). The description of the ichnofossils is arranged according to

their abundance in the analyzed log, starting with the most abundant.

Ichnogenus *Chondrites* Sternberg, 1833
Chondrites targionii (Brongniart, 1828)
Material: numerous specimens encountered in siltstone and mudstone beds, throughout the entire sedimentary succession, but mainly in its upper part (from R17 to R 25, Fig. 2a-c), were observed in the field.
Description: plantlike (Fig. 4a) or featherlike (Fig. 4b) branched-pattern of small cylindrical tunnels system; some branches are very long (up to 7 cm; right-upper part of Fig. 4a) and largely curved. The third order branches are rather short (up to 2 cm) with uniform diameter (no more than 3 mm). Overall the system is from 5 to 12 cm wide. The tunnels fill consist of light-colored mud which contrast with the surrounding dark-colored mudstone.
Remarks: this trace fossils were produced by deep infaunal wormlike tracemakers that may have populated different types of sediment accumulated from littoral to abyssal environment (Seilacher, 2007).
Chondrites intricatus (Brongniart, 1823)
Material: Several larger specimens in two mudstone beds of R17 and R20 intervals (Fig. 4c, d); many smaller specimens throughout the entire analyzed log (Fig. 4e, f).
Description: radial system with straight to slightly curved branches at a maximum 20º angle between them, generally looking like an inverted tree. The relative constant diameter of the branches is no more than 1.5 mm. The entire system is around 7 cm wide (Fig. 4c). The tunnels fills show dark-colored contrast with the surrounding rock, but also light-colored fills are present (Fig. 4c, d, e, f).
Remarks: *Chondrites intricatus* and *Ch. targionni* are ethologically diagnosed as deep tier wormlike fodinichnia (Häntzschel, 1962, 1975; Savrda & Bottjer, 1991), Bromley (1996) suggesting chemichnia as special feeding behavior. They occur in different types of sediments (mudstone and siltstone in the examined section), even those accumulated in low-oxygen conditions, showing a post-depositional character (Bromley, 1996; Uchman et al., 2012). They are described from littoral to abyssal environments and usually represent the last and the deepest tier in a given bioturbated sequence (Ekdale et al., 1984; Bromley & Ekdale, 1984; Martin, 2004), although *Thalassinoides* cross-cutting *Chondrites* was reported (Rodríguez-Tovar and Uchman, 2006).

Ichnogenus *Planolites* Nicholson, 1873
Planolites isp.
Material: Many specimens observed in the background mudstone beds as full reliefs (Fig. 4g); few specimens on the lower surface of plan-parallel laminated or ripple cross laminated sandstone beds as positive hyporeliefs (R6, Fig. 4h).
Description: subcylindrical unbranched burrow, horizontal to subhorizontal, straight to slightly curved, occasionally overlapping one another (Fig. 4h). The infilling contrasts with the surrounding matrix by color, texture, and composition. In some cases it reveals rusty (Fig. 4i) or black (Fig. 4j) infill color. The unbranched cylinder is less than 1.5 cm, rarely 2 cm in diameter (Fig. 4j), while the length does not exceed 15 cm. In several whitish-gray mudstone beds *Chondrites* co-occurs with and horizontal flattened galleries of *Planolites* isp., which are largely curved, 0.7 cm wide and 8 cm long, darker than the host deposit (Fig. 4f).
Remarks: *Planolites* is most likely a tunnel produced by deposit feeding worms, which actively back-filled with biologically processed sediment Häntzschel (1975). The author noticed that *Planolites* is quite easily confused with *Palaeophycus* due to striking external morphological resemblance, the difference being based on the type of filling. The rusty infilling of a *Planolites* is a good example of color contrast which might result either from the limonitization of sediment bypassed trough the tracemaker gut or from sediment sorting resulted from selective feeding (Pemberton & Frey, 1982). The transversal fine ornamentation noted on some specimens (Fig. 4k) would demonstrate the back-filling activity (Häntzschel, 1975). The flattened endichnial *Planolites* is the result of compaction. Calculating a:b ratio (a = 0.7 cm; b = 0.2 cm), the obtained 3.5 value suggests a fluid to soft substrate consistency at colonization time (Wetzel & Aigner, 1986, Schieber, 2003).

Ichnogenus *Thalassinoides* Ehrenberg, 1944
Thalassinoides isp.
Material: several positive hyporeliefs in plan-parallel and ripple cross laminated sandstone beds (R12, R15, and R23).
Description: cylindrical burrows, at least 7 to 12 cm long and 1.5-2.5 cm in diameter, showing Y- shaped bifurcations and slightly swellings at branching points (Fig. 5a), or elsewhere (e.g. at terminal part of the tube: Fig. 5b). The tubes are smooth, without ornamentation or lining. On some surface, circular sections are noticed (R23 interval: Fig. 5c).
Remarks: Some of the specimens from the analyzed section do not have the peculiar Y- or T-shape, but this situation may be explained by the lack of exposed surfaces. The circular sections may be interpreted as transversal cross sections of vertical shafts of the *Thalassinoides* burrow system.
This ichnogenus is a facies-crossing trace fossil produced by crustaceans (Frey et al., 1990) and is considered a typical fodinichnia-domichnia trace fossil for shallow-marine environment (Ekdale et al., 1984). Occasionally, it was described in modern (Wetzel, 1983) and ancient deep-marine environments (Vaziri & Fürsich, 2007). It is also described by Wetzel & Uchman (1998) in the Polish Carpathian flysch which was interpreted as deep-sea deposit.

Ichnogenus *Lockeia* James, 1879
Lockeia isp.
Material: several hypichnial positive reliefs on lower surfaces of sandstone beds from the middle part of the analyzed section.
Description: Small, smooth almond-shaped oblong bodies, from 4 to 10 mm long and up to 3 mm high, tapered at one end and obtusely pointed or rounded at the other; rather scattered than oriented (Fig. 5d).
Remarks: When first described it was interpreted as algae, later on as "ovarian capsules" of graptolites (Häntzschel, 1975), but now is consider to be a resting

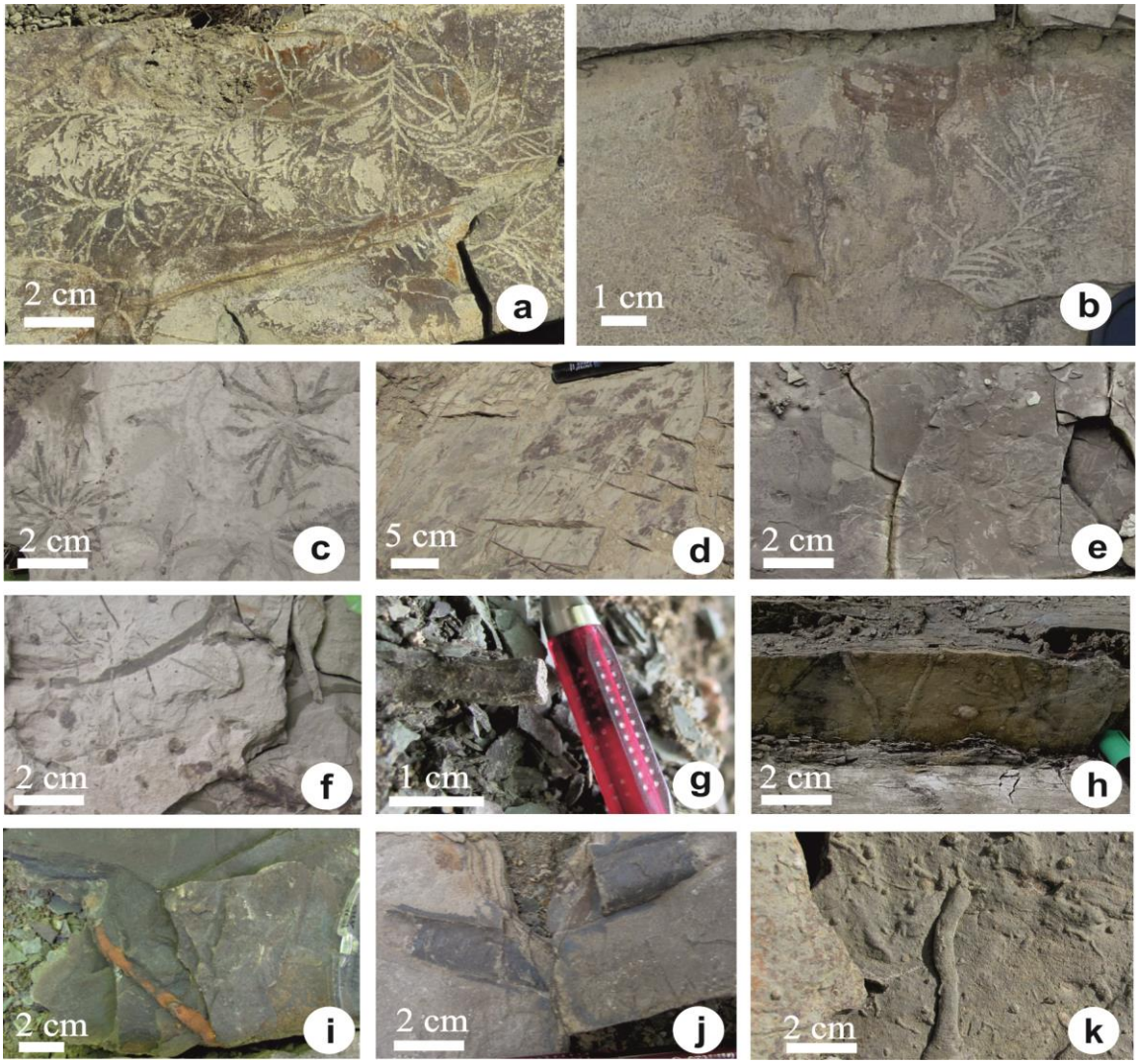

Fig. 4 Trace fossils: **a** plantlike *Chondrites targionii*; **b** featherlike *Chondrites targionii*; **c, d** large specimens of *Chondrites intricatus*; **e, f** small specimens of *Chondrites intricatus*; **g** *Planolites* in the background mudstone - full relief; **h** *Planolites* – positive hyporeliefs; **i** *Planolites* with rusty material infill; **j** *Planolites* with dark material infill; **k** *Planolites* with transversal fine ornamentation.

trace of a semi-sessile pelecypods (Seilacher & Seilacher, 1994). This ichnofossil may occur in any aquatic environment where bivalves can be found (from shallow marine through brackish water to fluvial and lacustrine freshwater facies).

Ichnogenus *Rhizocorallium* Zenker, 1836
Rhizocorallium commune Schmid, 1876
Material: several epichnial specimens on top of sandstone beds from the R21 interval, but also positive hypichnia right below the mentioned level (Fig. 5e).
Description: U-shape horizontal-subhorizontal tongue-like structures of 6-8 cm long, with up to 1.5 cm individual tunnel diameter (Fig. 5f). Usually the tubes are covered by striae. The distance between the limbs of U is up to 2.5 cm. One specimen reveals protrusive spreiten (Fig. 5g).
Remarks: *Rhizocorallium* is considered a burrow of deposit – feeding polychaete worm or a dwelling burrows of filter feeders (Knaust, 2013). According to Seilacher (2007), *Rhizocorallium* is ethologically interpreted as fodinichnia but without a behavioral genealogy. Gingras et al. (2009) noted that it is the result of a complex ethology of relatively deep tier tracemakers that systematically feed both with suspension and accumulated sediment. The *Rhizocorallium* from the analyzed section shows horizontal spreiten which normally represent deposit feeding of the subsurface strip-mining type (Bromley, 1996). While feeding, the animal builds up the burrow for housing. The presence of striae is a clue for some deposit consistency at bioturbation time. They are usually found in littoral to neritic environment, the specimens older than Cretaceous being described exclusively in shallow waters (Knaust, 2013). Rarely, it can be found in the deep water, indicating increasing oxygenation and depth of the redox boundary in sediment (Kotlarczyk & Uchman, 2012). According to Buatois & Mángano (2011), this ichnospecies characterizes lower shoreface to the lower offshore environment.

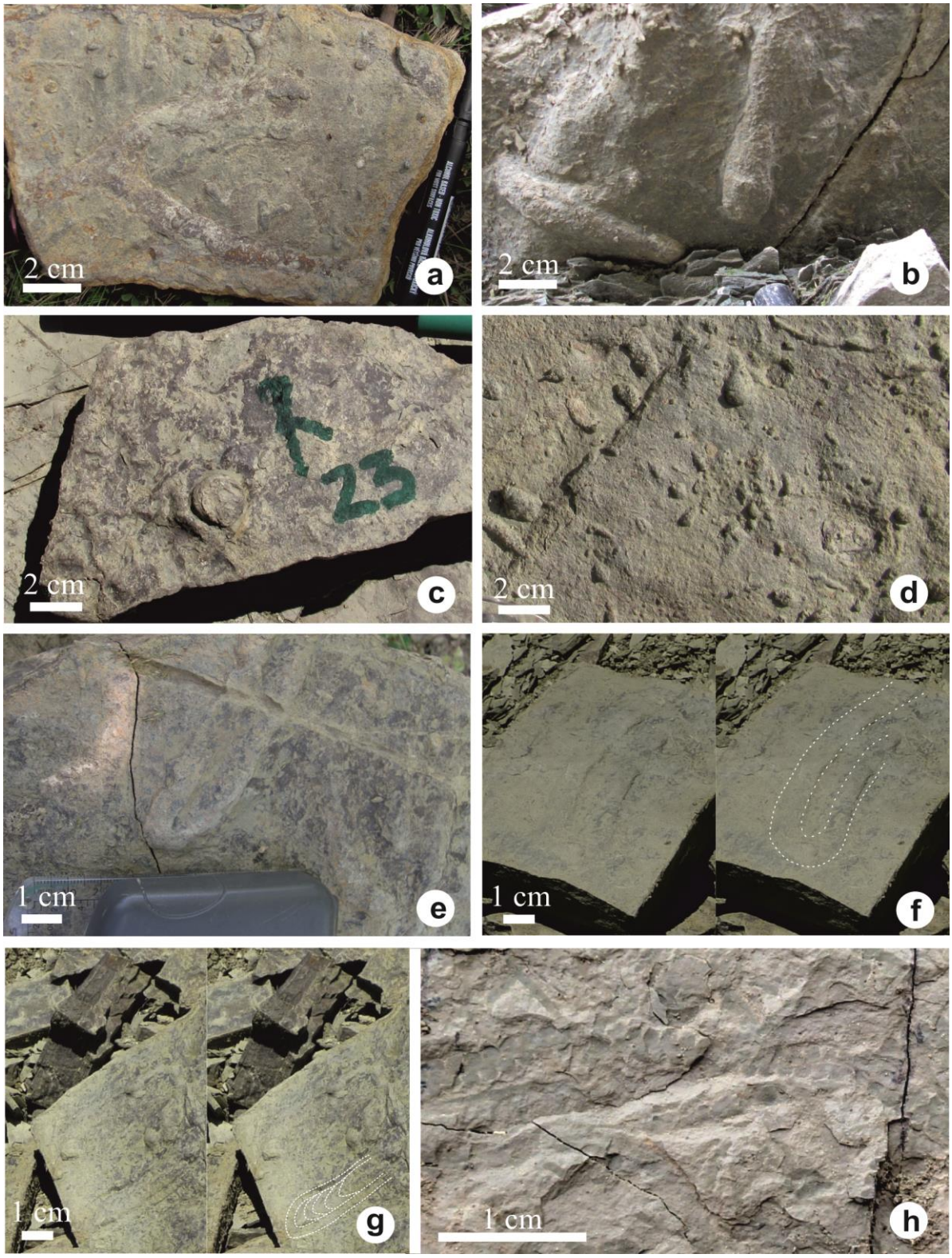

Fig. 5 Trace fossils: **a** *Thalassinoides* swelled at branching point; **b** *Thalassinoides* swelled at terminal part of the tube; **c** *Thalassinoides* circular section in R23 interval; **d** *Lockeia*; **e, f** *Rhizocorallium*; **g** *Rhizocorallium* with protrusive spreiten; **h** *Avetoichnus luisae*

Ichnogenus *Avetoichnus* Uchman & Rattazzi, 2011
Avetoichnus luisae Uchman & Rattazzi, 2011
Material: around 50 endichnia specimens in two levels of whitish-gray mudstone from the levels R7 to R 17.
Description: dark-colored horizontal to slightly curved zip-like trace fossils. Specimens are up to 45 mm long and over 3 mm wide and appear as two rows of dots arranged along a central axis. Zip-like shape is the result of a "beheaded" helical spiral, each whorl of the spiral being preserved as a pair of dots (Fig. 5h).
Remarks: the ethology of the ichnospecies is debatable. According to Uchman & Rattazzi (2011), this complex trace fossil is an agrichnion of a non-graphoglyptide tracemaker which stashed the nutrients rich sediment in

its central tubular axis for starting a bacteria farm. It was described as populating deep marine environment, but based on its co-occurrence especially with *Rhizocorallium* it seems that this species is rather a cross-facies one and its ethology may be more complicated than the original proposed one (Anistoroae & Miclăuș, 2014).

Aside from the described ichnotaxa, many other trace fossils occur in the logged sedimentary succession, but systematic feeding traces of graphogliptides lack. They are generally three-dimensional, horizontal, and subhorizontal, some of them being in co-occurrence, while others are isolated. The plan-parallel or ripple cross laminated coarser beds are dominated by hypichnia, rare epichnia, while endichnia are well developed in the "background" laminated mudstone beds.

ICHNOFACIES AND DEPOSITIONAL ENVIRONMENT

The described ichnofossils as well as the undetermined forms are associated with sedimentary facies, as follows:

1) the S_{pp} facies beds show very rich trace fossils, especially on their lower surfaces, almost at each lithological contact. They are different size positive hypichnia, as follows: horizontal and subhorizontal tunnels (*Thalassinoides*, R12: Fig. 5b) and *Cruziana*-like ichnofossils (Fig. 6a), large bulbous forms with circular profiles (R8: Fig. 6b) as well as smaller with less marked profiles (R18: Fig. 6c), superimposed galleries (*Planolites*, R17: Fig. 4h), circular cross sections, possible of vertical shafts (R23: Fig. 5c), and other undetermined ichnofossils of variable shapes and sizes (R24: Figs. 4k, 5d);

2) the S_{rcl} facies displays a comparable variety of traces as the S_{pp} facies. Both hypichnia and epichnia occur and often vertical and subvertical (R2: Fig. 3d; R21: Fig. 6d), but also horizontal (Fig. 4i), endichnia can be observed. From R18 interval upward, *Lockeia* and straight hypichnia (*Planolites*) are frequent on the lower bounding surfaces of coarse grained beds. On an upper surface bounding surface of one S_{rcl} bed in R21 interval, *Rhizocorallium commune* occurs (Fig. 5e, f, g);

3) the Si_{pp}-Si_{rcl} facies show mainly hypichnia on the amalgamation surfaces of composite beds. R6 (Fig. 4i), for example, displays circular convex hypichnia, 5-6 mm in diameter, *Chondrites intricatus*, *Planolites* with ferruginous infilling, high profile *Lockeia* or *Lockeia*-like traces (Fig. 6d). On some surfaces we noticed populations of small (Fig. 4e) and large *Chondrites intricatus* (R20: Fig. 4c, d) and *Ch. targionii* (R17: Fig. 4a, b);

4) the M_l facies houses many endichnia of different oriented detachable *Planolites* (R16: Fig. 4g), abundant *Chondrites intricatus* (Fig. 4e, f), and *Avetoichnus luisae* (R17: Fig. 5h).

The ichnofossils in the analyzed section are mainly the result of complex feeding strategies and sediment feeding behavior of the tracemakers that populated different levels of the nutrient rich mud, the abundant hypichnia from sandstone and siltstone bed soles reflecting the biotic activities from the underlying mudstones (Ekdale et al., 1984; Bromley & Ekdale, 1984; Bromley, 1996; Martin, 2004). Except for *Lockeia*, which is a resting trace or cubichnia (Seilacher & Seilacher, 1994), all the described ichnofossils reflect feeding strategies of the subsurface trace makers. Ethologically, *Thalassinoides* and *Rhizocorallium* were interpreted as composite fodinichnia-domichnia (Ekdale et al., 1984; Knaust, 2013).

For some of the deep-tier trace fossils, such as *Chondrites*, a chemosymbiotic behavior was suggested (Bromley, 1996), while complicated systems, such as *Avetoichnus*, were interpreted as the result of gardening activity (Uchman & Rattazzi, 2011).

Some structures are more durable than others due to the specific behavior (e.g. domichnia) and to the chances of their preservation increasing with the depth of bioturbation beneath the depositional surface (e.g. *Chondrites*). The deepest infauna activity is the best preserved, while the shallowest one may never be recorded, especially if the basin is characterized by episodic high-energy events able to remove any surficial effect of bioturbation (Ekdale & Bromley, 1991; McIlroy, 2004; Bromley, 1996). This was the case in the sedimentation area whose sedimentary record is here discussed where either turbidites, or tempestites are considered to be event beds.

When fine ornamentation is preserved, some substrate consistency can be considered (Figs. 4k, 6a). Furthermore, the pronounced profiles of some hypichnial trace fossils preserved on the S_{pp} or S_{rcl} soles indicate a certain stiffness of the bioturbated background deposit whose soupy to soft levels were partially washed out by the more or less erosive events. Where flattened trace fossils (*Planolites*) occur, one may consider the host deposit was almost fluid at bioturbation time and later, through compaction, the burrows were deformed from original circular to elliptical profiles. In Figure 4f they are found at the same level with *Chondrites*, suggesting that they were not coeval.

If normal oxygenation at water-sediment surface is considered, the shallowest tier is *Planolites* of soft sediment (later flattened), while *Chondrites* represents deeper tier in stiffer, oxygen depleted deposit (Ekdale et al., 1984; Bromley, 1996). As the sea floor aggradates, the *Chondrites* tracemakers move upward in search for the same life style, reaching at some point the *Planolites* already colonized levels. Such a scenario was presented by Anistoroae & Miclăuș (2014) taking into consideration three tier levels: *Planolites*, *Avetoichnus*, and *Chondrites*.

The ichnogenera described above characterize wider or narrower areas of a sedimentary basin as well as special conditions: 1) *Chondrites* – marine environment, common in reduced-oxygen deposits (Bromley & Ekdale, 1984); 2) *Planolites* – eurybathic trace makers of well oxygenated bottom waters (Pemberton & Frey, 1982); 3) *Thalassinoides* – common in shallow waters but not limited to them (Ekdale et al., 1984); 4) *Lockeia* – any aquatic environment (Seilacher & Seilacher, 1994); 5) *Rhizocorallium* – shallow marine waters, rarely deep waters (Knaust, 2013); 6) *Avetoichnus* – low-energy sedimentary environment with low nutrients content, described in flysch interpreted as deep-sea deposits (Uchman & Rattazzi, 2011; Monaco et al.,2012; Rodrígues-Tovar & Uchman, 2012) but also in shallow water deposits (Anistoroae & Miclăuș, 2014).

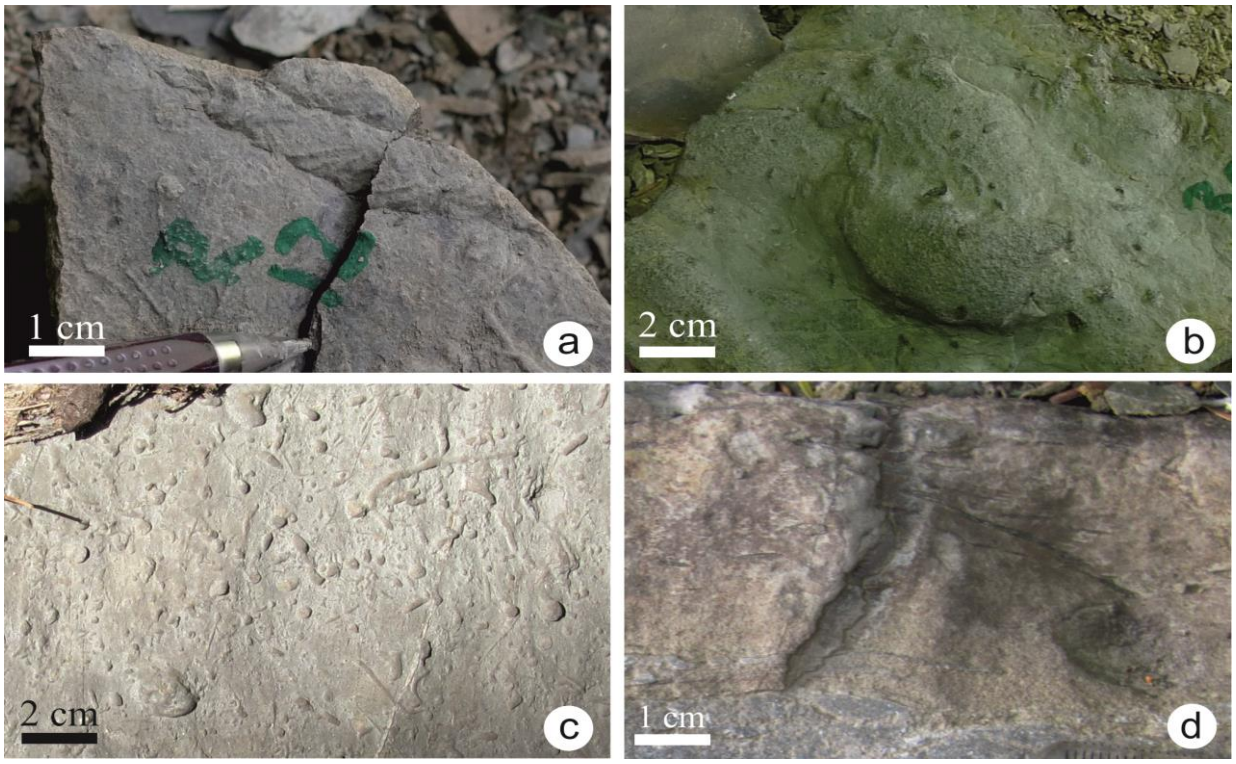

Fig.6 Ichnofossils without taxonomic assignments: **a** *Cruziana*-like trace fossil; **b** large circular forms with marked (bulbous) profiles; **c** small circular forms with less marked profiles; **d** vertical-subvertical endichnia

The ichnofossil content of the sedimentary succession described in this paper may be characterized, as follows:
1) showing a moderate diversity of the trace fossils; 2) dominated by horizontal and subhorizontal trace fossils on the event bed soles; 3) dominated by three-dimensional trace fossils in the "background" deposits due to their higher chances of preservation; 4) having a wide variety of ethological categories dominated by sediment feeding trace fossils of mobile infauna preserved in the event beds and by systematic feeding or chemosymbiotic behavior in the "background" deposit; no grazing trace fossils were found; 4) containing rare permanent domiciles; 5) indicating different consistency of the sediment during bioturbation, proved by a:b ratio calculated and interpreted according to Schieber (2003)'s model; 6) showing some beds of the "background" mudstone with established tiers (Anistoroae & Miclăuș, 2014); 7) showing sharp transition from background endichnia to event bed hypichnia controlled by preservation chances and lithological preferences; 8) poor colonization of the event beds (e.g. few epichnia in S_{rcl}).
An enormous number of study cases using integrated sedimentologic-ichnologic analysis contributed to the elaboration of robust ichnofacies models for different depositional environments (Seilacher, 1967, 2007; Frey, 1975; Bromley, 1996; Buatois & Mángano, 2011; Pemberton et al., 2012 to mention only some). According to them, the *Cruziana* ichnofacies is characterized by: dominance of horizontal and subhorizontal trace fossils, almost all ethological types, dominance of deposit and detritus feeding traces of mobile animals, high ichnodiversity, high abundance, extremely variety of

tracemakers and, most relevant, deep and shallow tiers in a wide variety of substrates. Most of these features are similar with the ones we mentioned for the studied section.
Environmentally, this ichnofacies occurs in a basin zone ranging from lower shoreface to the lower offshore, from closely above the fair-weather wave base to the extreme storm wave base. Together with the results from the sedimentary facies analysis, the transition-offshore is a plausible sedimentation setting.
Although *Paleodictyon* was previously mentioned in the Bisericani Formation (Brustur, 1995a, 1995b: table 1) neither its stratigraphic position within the section, nor information about its co-occurences are known. *Paleodictyon* is a diagnostic trace fossil of the *Nereites* ichnofacies, but scattered records of it from shallower sedimentary basin areas have been mentioned by Fürsich et al. (2007). The latter authors emphasize the restriction of this trace fossil to event beds from environments characterized by high sedimentation rate, also cautioning in using a single ichnotaxa for bathymetric interpretations.

CONCLUSIONS

A sedimentary unit usually included in the Romanian Carpathian "flysch" in geologic traditional literature was analyzed using sedimentologic and ichnologic methods. The unit represents the informal lower member of the Bisericani Formation, known as the red and green shales, Priabonian, possibly Rupelian, in age. By sedimentologic analysis, nine sedimentary facies were defined which were interpreted as products of gravity flows, tractive (unidirectional and oscillatory) currents, and hemipelagic-pelagic fallout processes. The sedimentary facies bear both turbidite, and tempestite features (sharp based coarse beds with "hieroglyphs", plane-parallel to

cross lamination) which make difficult their unequivocal interpretation. Other features (hummocks on one bed top, lack of tool and flute casts, lack of graded beds) would indicate rather tempestites. In order to overpass this ambiguity, the ichnological methods were used. The coarse units are mostly characterized by sharp lower bounding surfaces with different size hypichnia and some epichnia on tops, while the fine sedimentary facies contain endichnia with different degrees of deformation. The sharp contacts between "background" mudstone with endichnia and coarse beds with hypichnia indicate the event nature of the latter. The better the relief and ornamentation of hypichnial forms are, the stiffer the burrowed sediment was. This means that possible multiple erosion events washed out the soupy-soft surficial sediment, exposing deeper and deeper sediment to bioturbation. The coarse bed soles indicate that the background sediment was bioturbated in its shallow top. The largest, well defined trace fossils (*Planolites*, *Thalassinoides*, *Rhizocoralium*, and *Lockeia*) were described in these situations. In some fine beds, tiers could be recognized (*Planolites*, *Avetoichnus*, and *Chondrites*) based on known divergent colonization requirements of the trace makers, from shallow (*Planolites*), intermediate (*Avetocihnus*), and deep (*Chondrites*) levels. This proves that time spans between the recorded erosive events were long enough for them to colonize the preferred levels. The longer term aggradation of sea floor made possible the co-occurrences of trace fossils characterizing different tiers (*Planolites* - *Chondrites*; *Planolites* – *Avetoichnus* - *Chondrites*).

Ethologically, the chemosymbiotic and sediment feeding behaviors dominate, although there are also domichnia and even agrichnia. Taxonomically, seven ichnogenera were recognized. Three ichnotaxa were determined at the ichnospecies level.

The diversity and dominance of horizontal and subhorizontal trace fossils on the event bed soles, the abundance of the deep tiered *Chondrites* in the "background" mudstone due to its higher preservation chances, the ethological variety and abundance of fodinichnia, the wide consistency range of the substrate at colonization moment and the tiers presence in the background sediment are reliable attributes for the *Cruziana* ichnofacies accepted by most as part of lower shoreface to lower offshore setting. These, together with some physical attributes of the event beds, suggest the offshore transition zone with tempestites as a plausible interpretation for the red and green shale member of the Bisericani Formation in the studied section.

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