Acta Geologica Polonica, Vol. 63 (2013), No. 2, pp. 175–199
DOI: 10.2478/agp-2013-0007

Sedimentology of the Early Jurassic terrestrial Steierdorf Formation in Anina, Colonia Cehă Quarry, South Carpathians, Romania

ARTUR KĘDZIOR[1] AND MIHAI E. POPA[2]

[1] *Polish Academy of Sciences, Institute of Geological Sciences, Krakow Research Centre, Senacka 1 str; PL-31-002, Kraków, Poland. E-mail: ndkedzio@cyf-kr.edu.pl*
[2] *University of Bucharest, Faculty of Geology and Geophysics, Laboratory of Palaeontology, 1, N. Bălcescu Ave., R-010041, Bucharest, Romania. E-mail: mihai@mepopa.com*

ABSTRACT:

Kędzior, A. and Popa, E.M. 2013. Sedimentology of the Early Jurassic terrestrial Steierdorf Formation in Anina, Colonia Cehă Quarry, South Carpathians, Romania. *Acta Geologica Polonica*, **63** (2), 175–199. Warszawa.

The continental, coal bearing Steierdorf Formation, Hettangian – Sinemurian in age, is included in the Mesozoic cover of the Reşiţa Basin, Getic Nappe, South Carpathians, Romania. The Steierdorf Formation can be studied in Anina, a coal mining center and an exceptional locality for Early Jurassic flora and fauna, occurring in the middle of the Reşiţa Basin. This paper presents the results of sedimentological, stratigraphical and paleobotanical researches undertaken in Colonia Cehă open cast mine in Anina, where the Steierdorf Formation outcrops widely. Several sedimentary facies associations have been described, these associations permitting the reconstruction of various depositional systems such as alluvial fans, braided and meandering river systems, as well as lacustrine and coal generating marsh systems of the Steierdorf Formation. The sedimentary associations recorded within the Steierdorf Formation show a gradual fining upward trend, pointing to a rising marine water table and a decreasing relief within the source area.

Keywords: Sedimentology; Hettangian – Sinemurian; Alluvial and fluvial systems; Fossil flora and fauna; Steierdorf Formation; South Carpathians; Romania.

INTRODUCTION

The Reşiţa Basin, also known as the Reşiţa-Moldova Nouă sedimentary zone, is the largest Paleozoic and Mesozoic sedimentary basin of the Getic Nappe (Text-fig. 1A), an important tectonic unit of the South Carpathians (Murgoci 1905). The Reşiţa Basin occurs south of the town of Reşiţa, and has a north-south orientation, reaching the Danube (Text-fig. 1B). The Getic Nappe belongs to the Median Dacides (Săndulescu 1984), and includes both the crystalline basement and the sedimentary cover. The Mesozoic sedimentary cycle of the Reşiţa Basin begins with the detritic, continental deposits of the Steierdorf Formation (Bucur 1991, 1997; Popa and Kędzior 2008), followed by the black, bituminous shales (Text-fig. 2) of the Uteriş Formation (Bucur 1991, 1997), and it continues with carbonate marine formations deposited during all of Middle and Late Jurassic times, and ending during Early Cretaceous (Aptian) times.

For the Hettangian–Sinemurian time interval, the term Reşiţa Basin can be used in a sedimentological sense, as it functioned as a well-defined trough-shaped, depositional area, with its own depocenter, source areas and sedimentary influx. The basin was surrounded by crystalline (Sebeş-Lotru Group) or Variscan (Westphalian – Autunian formations) heights which provided the clastic sources for the Steierdorf Formation. Therefore, a series of lateral facies were recorded (Bucur 1997), with alluvial, coarse features near the margin of the basin and finer, fluviatile and lacustrine features towards the center of the basin, in the Anina area.

Since 1792, both the Steierdorf and the Uteriş formations had a high economic significance related to coal, clay and bituminous shales extraction, therefore important mining centers were established along the median axis of the Reşiţa Basin, in Anina (formerly known as Steierdorf) and Doman, south of the Reşiţa town, where these formations reach their greatest thickness and lateral development, previously described by Bucur (1997) as the Anina subfacies of the Steierdorf Formation.

Anina (Steierdorf) is the most important coal mining center of the Reşiţa Basin, occurring 35 km south of Reşiţa. Mining began in 1792, when the first coal seam was discovered, and continued without interruption until today, although the last major pit of the town was closed in 2006, after a tragic accident. Coal mining was undertaken both in underground mines, which reached as deep as 1300 m and open cast mines. Popa (2000a, 2009) and Popa and Meller (2009) showed the dense complex of mining works in Anina, associated with the coalfields and local boundaries. Anina had several important coalfields such as Anina, Kübeck, Uteriş, Miniş, Sigismund, etc., where pits and intricate, deep underground galleries were dug. The most important open cast mines occur along the western flank of the Anina Anticline, the major structure in the middle part of the Reşiţa Basin. These quarries are the Ponor, Colonia Cehă and Hildegard open cast mines, and they were opened mainly for the extraction of bituminous shales and refractory clays.

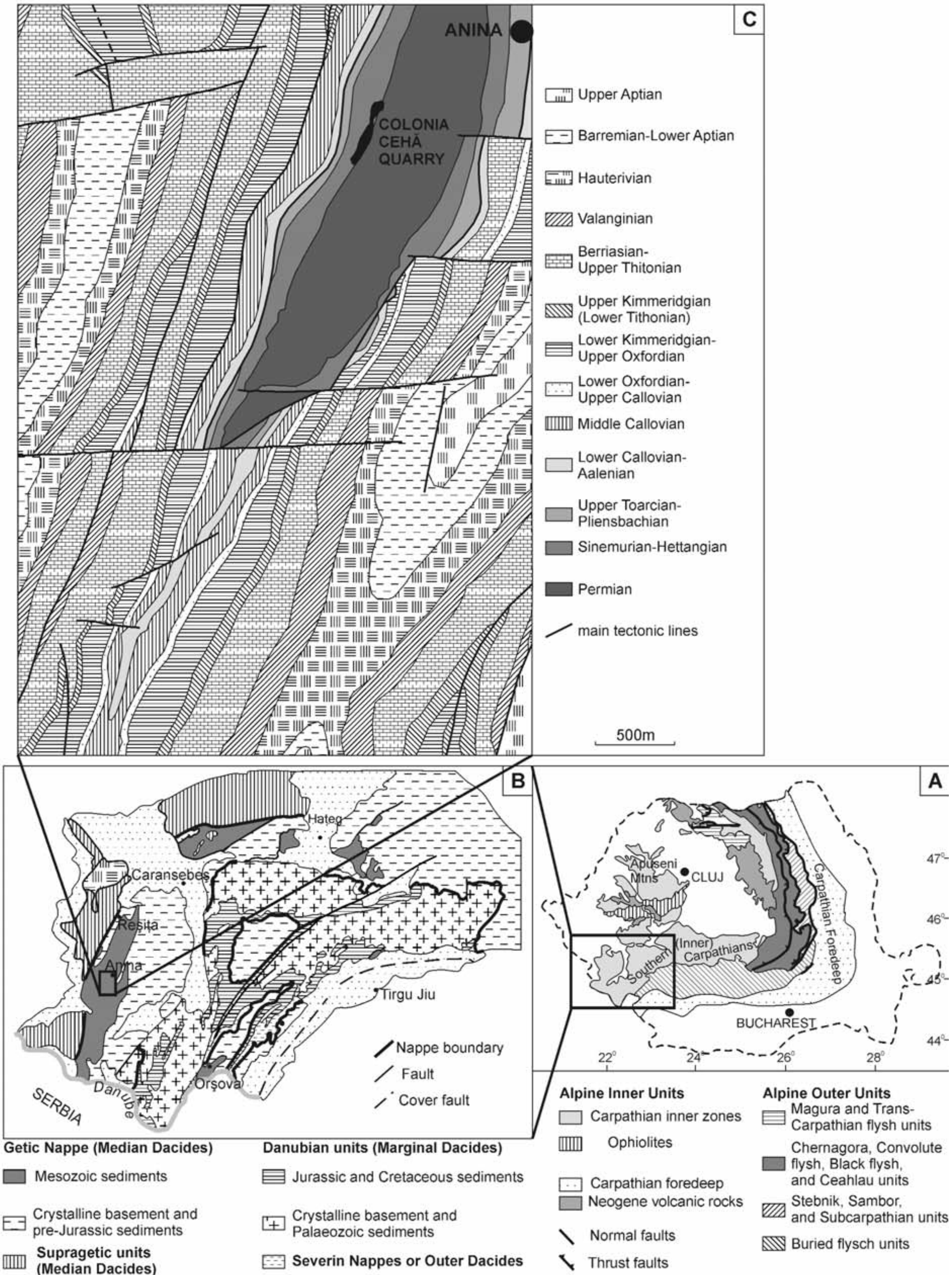
Such significant, complex and long lasting mining works in all of the coalfields of Anina have permitted a detailed, three dimensionally study of the Steierdorf Formation, a unique opportunity for obtaining a deep understanding of this formation, with all its lateral and vertical lithological and depositional variations.

The local structure is dominated by the main Anina Anticline, with Lower Jurassic coal-measures along both of its flanks (Text-fig. 1C). The eastern flank was exploited extensively during the 19th and the first half of the 20th centuries, while the western flank was exploited even longer, until today. The Anina Anticline is separated by a complex set of longitudinal faults from the Brădet Syncline, occurring to the west. The western flank of the Anina Anticline is fragmented by transverse faults into a series of small structural blocks which also define different coalfields.

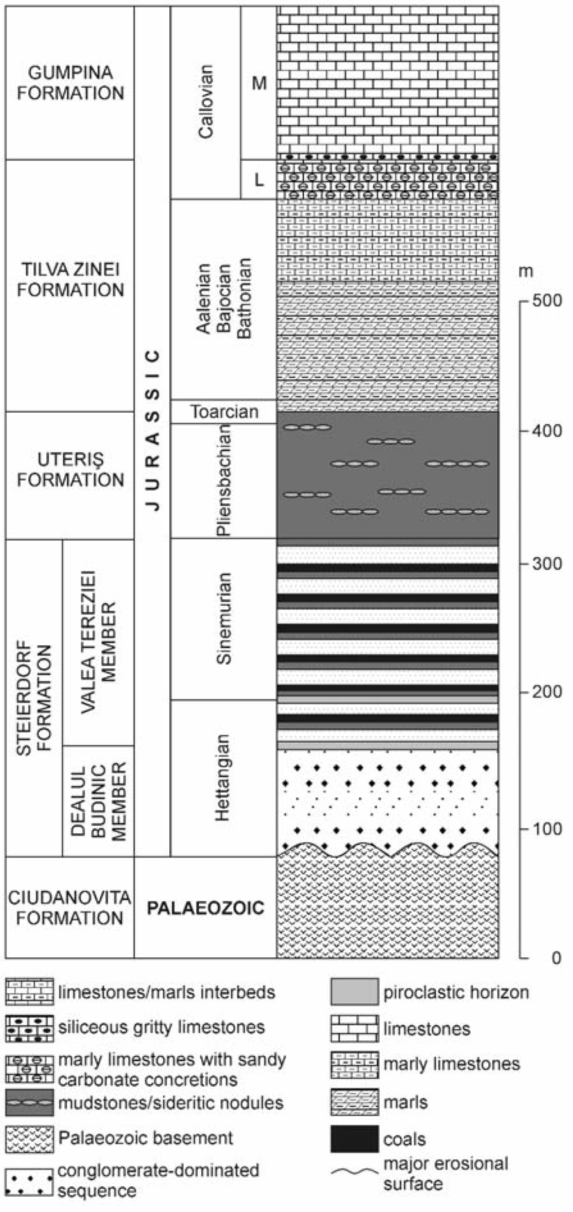
The Early Jurassic flora of Anina is well known and is represented by bryophytes (Hepaticatae), pteridophytes (Sphenopsids, Lycopsids, Filicopsids) and gymnosperms (Pteridosperms, Ginkgopsids, Cycadopsids, Coniferopsids). The flora of Anina was first cited by Foetterle (1850), followed by the classic monographs of Ettingshausen (1852, 1855). Recent monographs include those of Semaka (1962), Givulescu (1998) and Popa (2000a). It is a compression flora with a significant coal generating character; it is a highly diverse flora and its preservation is excellent. Preliminary results regarding the faunal remains of the Steierdorf Formation include tetrapod tracks (Popa 2000c), vertebrate tunnels (Popa and Kędzior 2006), and sauropod dinosaur tracks (Pieńkowski *et al*. 2009), together with very diverse invertebrate traces, but the real ichnological potential of this formation still has to be unveiled. Plant-animal interactions are also very diverse (Popa 2000a, 2009). Such features make Anina an exceptional locality, from both diversity and preservation perspectives. Moreover, the extensive mining in the area has permitted the collecting of plant material throughout the whole volume of the Steierdorf Formation (Popa 2000a, 2009), with a stratigraphic, paleoecological and lateral depositional control of the flora and of its sedimentological and depositional context (Popa and Kędzior 2008).

The phytostratigraphy of the Steierdorf Formation (Popa 2000b) includes two marker zones. The first is a basal association marked by the *Thaumatopteris brauniana* taxon range Zone, indicating the Hettangian, and occurring through the Dealul Budinic Member and the basal sequences of the Valea Tereziei Member. The second is the acme zone with *Nilssonia* cf. *orientalis*, marking the Sinemurian Stage, and occurs through the median and topmost sequences of the Valea Tereziei Member, up to the first occurrence of the black shales belonging to the Uteriş Formation (Text-fig. 2). The floral zones marking the Hettangian and the Sinemurian stages change vertically next to the pyroclastic (fireclay) layer recorded in the Valea Tereziei Member, this layer occurring in a lacustrine sequence which can be well recorded laterally.

No detailed sedimentological studies have been carried out on the Steierdorf Formation. Several opinions



Text-fig. 1. Romanian segment of the Carpathian Chain (A), Geology South Carpathians (B) and Anina Anticline (C); after Pop *et al.* 1997; Năstăseanu and Savu 1970



Text-fig. 2. Late Palaeozoic to Middle Jurassic stratigraphy of the Reşiţa-Moldova Nouă zone, after Bucur 1997

have been expressed but without any proof that the deposits of the Steierdorf Formation have been accumulated under continental to lagoonal conditions (see Mutihac 1958; Bucur 1997). Bucur (1997) interpreted the Steierdorf Formation as having formed in an intramontane depression with several sub-environments typical for such a setting.

The main goal of this paper is a description of the sedimentary environments and basin evolution during Hettangian-Sinemurian time. This description has been made on the basis of detailed sedimentological analysis, supported by palaeobotanical data.

GEOLOGICAL SETTING

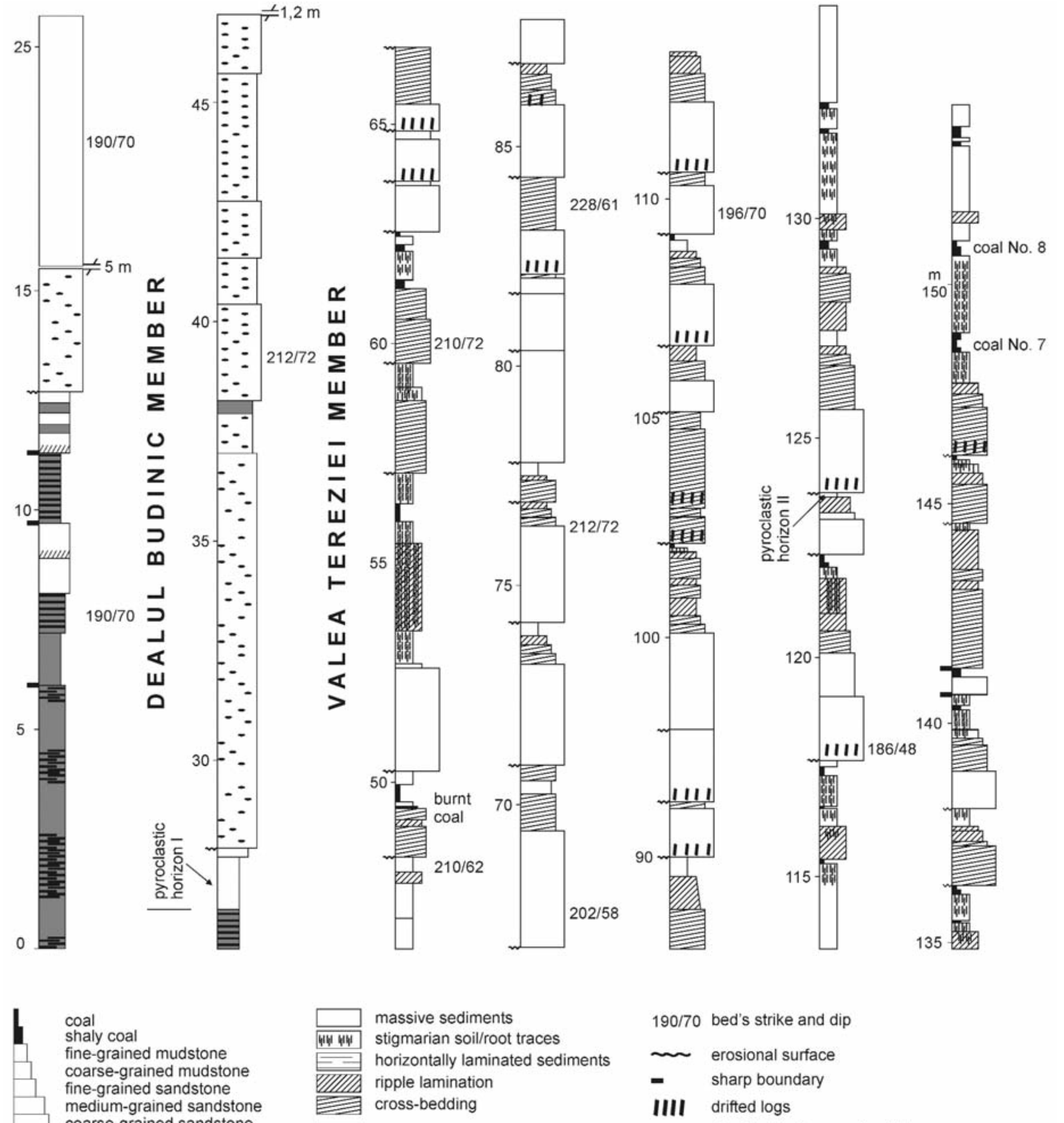
The Steierdorf Formation is a continental formation unconformably overlaying the Late Paleozoic formations of the Reşiţa Basin or the crystalline basement represented by the Sebeş-Lotru Group. The age of the Steierdorf Formation is Early Jurassic, more precisely Hettangian–Sinemurian (Bucur 1991, 1997; Popa and Kędzior 2008). This formation is conformably overlain by the Uteriş Formation, which is Pliensbachian–Middle Toarcian in age (Bucur 1991, 1997; Popa and Kędzior 2008). The Steierdorf Formation yields two members, the Dealul Budinic Member (Bucur 1991, 1997), Hettangian in age, and the Valea Tereziei Member, Hettangian–Sinemurian in age (Text-fig. 2).

The geology of the Steierdorf Formation was touched on in papers dealing with the general geology and stratigraphy of the Reşiţa Basin by Kudernatsch (1855, 1857) and Schreter (1912). Later, the contributions of Codarcea (1940), Răileanu (1957), Răileanu *et al.* (1957), Mutihac (1958), Năstăseanu (1964, 1984), Năstăseanu *et al.* (1981) detailed the geological knowledge on the Mesozoic formations of the Reşiţa Basin, including the Steierdorf Formation. Mateescu (1932) published the first work on the coal petrography of the Jurassic coal measures, adding stratigraphical and paleobotanical results. This paper was followed by the coal geology treatises of Răileanu *et al.* (1963), Petrescu *et al.* (1987) and Preda (1994), all detailing the geology of the Jurassic coal measures from Anina. Bucur (1991, 1997) defined the formal stratigraphy of the Reşiţa Basin, followed by Popa and Kędzior (2008) who separated the Uteriş Formation from the Steierdorf Formation, as the former was initially considered as a member of the Steierdorf Formation. Bucur (1997) described lateral variations of the Steierdorf Formation within the Reşiţa Basin as various continental depositional subfacies, naming them the Anina (central area of the basin), Brădet, Doman, Ranchina-Secu, Predilcova, Beu Sec and Pleşiva subfacies. Stănoiu *et al.* (1997) and Popa (2009) detailed the stratigraphy of the continental sequences in Anina.

During field work, animal trace fossils have been found in the Colonia Cehă Quarry, within the Steierdorf Formation. The majority of traces were produced by invertebrates, such as fresh-water molluscs, probably gastropods and crayfish. The most spectacular findings were described by Popa (2000c), Popa and Kędzior (2006) and Pieńkowski *et al.* (2009) as vertebrate traces from the uppermost part of the Dealul Budinic and the lower part of the Valea Tereziei members. The Dealul Budinic Member yields linear cast structures. The former spiral shape casts described by Popa and Kędzior

(2006) with a diameter of several dozens of centimetres, are surrounded by a ferro-oxide crust against the contact with the neighbouring deposits, and should be regarded as dissolved or destroyed siderite nodules. The linear trace fossils have been found within red coloured mudstones, directly below the lower pyroclastic layer, regarded here as shallow lake deposits. These mudstones represent the place of coalescence of individual lobes of an alluvial fan, or a depression developed on the fan surface. The linear casts are strongly elongated up to 700 cm long, 40 cm wide and sometimes they are dichotomously divided. They are considered as evidence for digging undertaken by vertebrates. The burrows could have been used as hiding places against insolation, as recent crocodiles do, digging burrows in the rivers' banks. In one place, a chamber with striated walls was recorded, suggesting digging with claws (Popa and Kędzior 2006).

With the lowermost part of the Valea Tereziei Member, a few meters above the older pyroclastic layer, occurs another type of trace fossils. They were left by sauropods and they are represented by tracks



Text-fig. 3. Synthetic log of the Steierdorf Formation in the Colonia Cehă Quarry

Lithofacies	Abbreviation	Text-figure
Matrix supported conglomerate	CGm	Fig. 4
Clast supported conglomerate	CGc	Fig. 5
Very coarse-grained sandstone	VC	Fig. 6
Massive coarse-grained sandstones	SCm	Fig. 7
Large scale cross-bedded sandstones	SLx	Fig. 8
Ripple laminated sandstone	SR	Fig. 9
Horizontally laminated sandstones	SH	Fig. 10
Root reworked sandstones	Srr	Fig. 11
Massive fine-grained deposits	FM	Fig. 12
Horizontally laminated mudstones	FH	Fig. 13
Coal, carbonaceous shales	C	Fig. 14
Pyroclastics	T	Fig. 15

Table 1. Lithofacies types distinguished in the studied succession

and trackways. The features described by Pieńkowski *et al*. (2009) are indicative for heteropodous animals with a gravipodal posture typical for Eusauropoda. The footprints size belonged to cf. *Parabrontopodus* isp., and they are indistinguishable from coeval types from Poland or Italy and they do not show insular dwarfism. This feature does not support the recently published paleogeographic reconstruction made by Blackley (2009) showing the Moesian Plate as an isolated island.

MATERIALS AND METHODS

The data have been gathered during several field seasons in the Anina area, in the Ponor Quarry, along the western flank of the Anina Anticline, where the Steierdorf Formation outcrops. The data include eleven profiles of various sizes, from several meters up to 110 m thick (Text-fig. 3), and comprise more than 360 m of stratigraphical logs.

The main method of this study is faces analysis, with two basic steps. The first step leads towards a lithofacies description and comprises observations of grain-size variations; clast size, shape, roundness, composition, and clast/matrix relationships; type of individual layer contacts; sedimentary structures; macrofossils, fossilization type and their orientation with respect to stratification and lithofacies-layer thickness. The lithofacies coding with their full names is shown in Table 1. This set of information was used for interpretation of the deposition mechanisms. The second step established the lithofacies associations. During this second stage of study, the vertical lithofacies sequences have been analysed, distinguishing sets of connected lithofacies with depositional processes interpretation responsible for sequences set up. Finally, on the basis of genetically related lithofacies associations, the individual subenvironments have been described.

LITHOFACIES DESCRIPTION

Matrix supported conglomerate (CGm)

This is a typical lithofacies for the Dealul Budinic Member. Clasts are poorly sorted, usually angular or weakly rounded of variable size up to 15 cm in diameter (Text-fig. 4). The clast inventory shows the predominance of resistant pebbles, mostly quartz, subordinate gneisses and amphibolites, and rare other lithic grains (quartzites, mudstones) and granites. The matrix/clast ratio is variable, optically ranging half and half, with no distinction between diamictite and matrix supported conglomerates. The pebbles are dispersed through the whole bed. Layer thickness varies from 0.35 m to up to 3.7 m. In the Valea Tereziei Member, this lithofacies appears subordinately where it is characterized by smaller clast sizes up to 9 cm, but more usually not larger than 3 cm. The clast inventory is similar to the Dealul Budinic Member, but lithic grains are fewer. The layer thickness rarely exceeds 2 m, the most common being about 1 m. In both members, the CGm lithofacies seems to be massive, without clearly visible sedimentary structures. The lower boundaries of this lithofacies are rather sharp, instead of erosional.

Clast supported conglomerate (CGc)

This lithofacies includes sorted, angular clasts up to 7 cm in diameter, usually not exceeding 3 cm (Text-fig. 5), and is absent from the Dealul Budinic Member. The in-

Text-fig. 4. Matrix-supported conglomerate (CGm)

ventory of clasts records mostly quartz with minor amounts of lithic grains, but gneiss and amphibolite, and only sporadically intraclasts of sandstone and mudstone have been seen. The sediments typically show no clearly marked structures, only occasionally clast imbrications and large scale cross-bedding. The thickness of the layers is variable, ranging from a few dozens of centimeters up to 6 m, however as a rule the thickest packages of this lithofacies are observed in the lower part of the Valea Tereziei Member. The lower boundaries are usually erosional, only a few cases sharp or gradational.

Text-fig. 5. Clast-supported conglomerate (CGc)

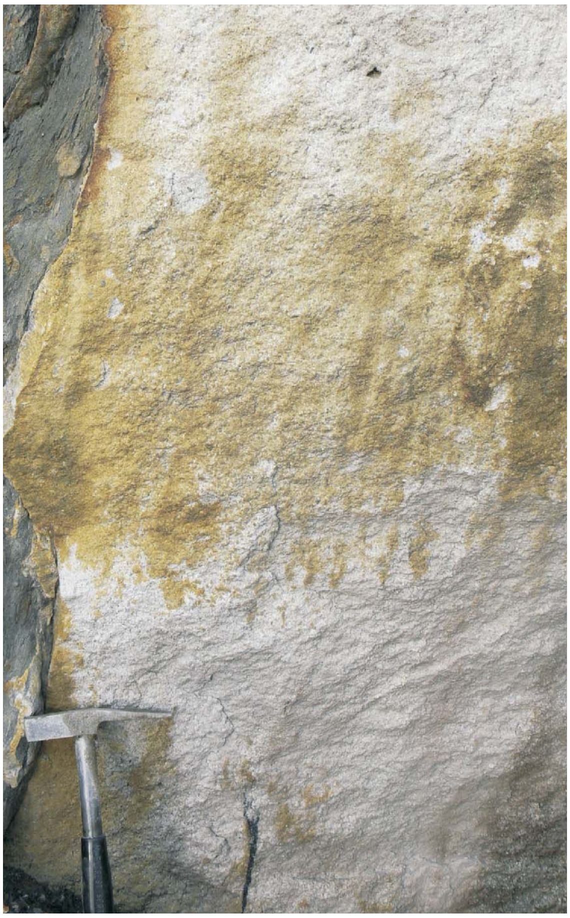
Very coarse-grained sandstone (VC)

This lithofacies is transitional between CGm and SCm (massive coarse-grained sandstone) lithofacies. It includes massive and large scale cross-bedded (the latter being typical only for the Valea Tereziei Member) (Text-fig. 6) and it occurs in the lower part of the Member. In the Dealul Budinic Member it contains dispersed clasts up to 2–3 cm, of the same composition as in the CGm and CGc lithofacies, with high matrix content. The lower boundaries are often gradational, passing from underlying conglomerates. When the deposits below are finer, the boundaries are sharp or erosional. The thickness of the deposits of this lithofacies varies from 8 m to 1 m in the Dealul Budinic Member, whereas in the Valea Tereziei Member the thickness is slightly reduced and does not exceed 1 m. The color of the deposits observed in the Dealul Budinic Member is red to brown-red, sometimes yellowish; the Valea Tereziei deposits are exclusively gray to olive-gray.

Massive coarse-grained sandstones (SCm)

In this lithofacies (Text-fig. 7), the boundaries often are arbitrarily marked due to transitional passages between coarser deposits and finer sediments. In the Dealul Budinic Member, the lithofacies is thicker, up to 8.5 m, than in the Valea Tereziei Member, where it does

Text-fig. 6. Very coarse-grained sandstone (VC) not exceed 1 m, and is often 20–30 cm. The thickness in many cases was reduced due to synsedimentary erosion. In a few cases, when the erosional surfaces on the top are present, followed by a conglomeratic layer, the thickness is less than 15 cm and the coarse-grained sandstones appear to be massive. However, it cannot be excluded that originally these beds were cross-bedded, especially if the thickness has been reduced up to a few centimeters due to erosion preceding deposition of the next portion of sediments. Sometimes in this lithofacies casts of drifted gymnosperm logs occur embedded in their basal parts. In a few layers within the Dealul Budinic Member, towards the top, a polygonal network of the oval blocks up to 40 cm in size with a secondary ferro-oxide crust can be visible.



Text-fig. 7. Massive coarse-grained sandstones (SCm)

Large scale cross-bedded sandstones (SLx)

The characteristic feature of this lithofacies is the presence of originally inclined sets of laminae at various angles, not exceeding 20°–25°. The cross-bedding is emphasized by a subtle change in grain size or the occurrence of drifted plant fossils. However, the scale of exposures is not sufficient to identify the type of cross-bedding in the whole succession; the visible structures allow only defining them as trough-shaped (Text-fig. 8). The thickness of the individual lamina sets varies from a few centimeters to a few dozens of centimetres. The lithofacies is represented by coarse-grained as well as medium-grained sandstones, but it is significant that the thickness of the medium-grained sandstones of this lithofacies is distinctively smaller than of the coarse-grained. The thickness of the deposits ascribed to the SLx lithofacies varies from almost a few centimeters up to almost 2 m. Towards the upper part of the whole depositional sequence, upwards thinning has been observed. The smallest thickness of this lithofacies is linked to the occurrence of erosional surfaces, followed in most cases by the deposition of conglomeratic layers. The lower boundaries are either erosional or gradational. The erosional boundaries were noted when the coarse-grained material was laid down on the fine-grained (or phytogenic) substratum. The upper boundaries of this lithofacies, in the lower part of the Valea Tereziei Member, are erosional. Upwards, more frequently they have gradational features, passing into ripple laminated sandstones (SR lithofacies). In the basal parts, especially if the lithofacies is composed of coarse-grained sandstones, there are often drifted logs up to 1.5 m long and 30 cm in diameter.

Text-fig. 8. Large scale cross-bedded sandstones (SLx)

Text-fig. 9. Ripple laminated sandstone (SR), northern end of the Colonia Cehă Quarry.

Ripple laminated sandstone (SR)

This lithofacies is composed of both medium- and fine-grained sandstones, but it is significant that the medium grained-sandstones have been observed only occasionally. The thickness of this lithofacies is highly variable, from several centimeters up to 1.5 m (Text-fig. 9). The rippled lamination is in the most cases pointed out by the presence of plant remains or finer material. The upper boundaries of the lithofacies are mainly gradational passing into mudstones; the lower boundaries are sometimes sharp if the sandstones were deposited directly on the phytogenic material. When the coarse-grained sediments overlay this lithofacies, usually an erosional surface has been observed.

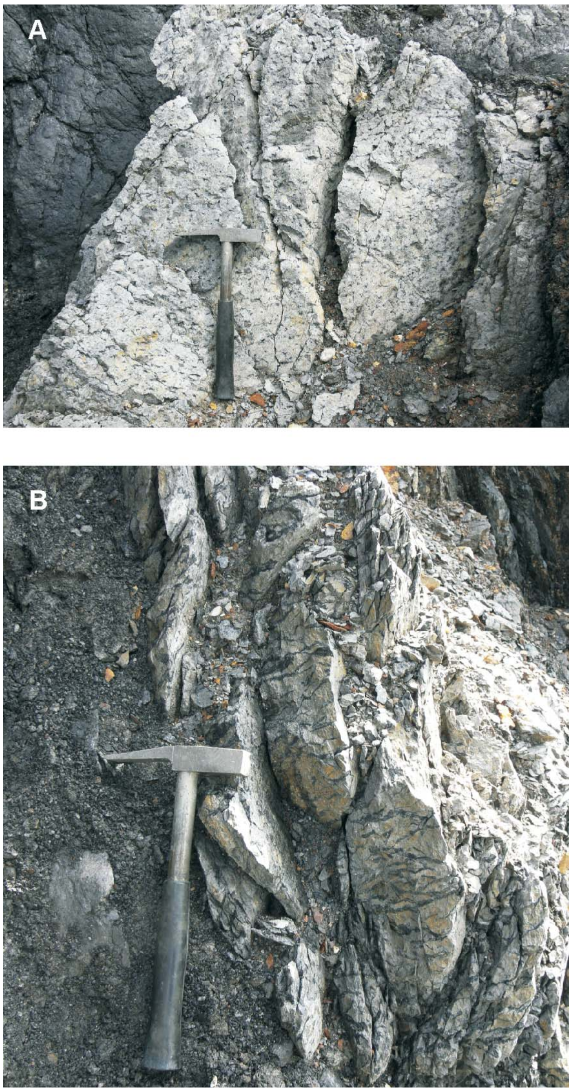
Horizontally laminated sandstones (SH)

This lithofacies is composed of fine- to medium grained sandstones. The lamination is marked by color variations from red-brown to yellow. The boundaries of this lithofacies are usually sharp and the thickness does not exceed 1 m, but sometimes may reach up to 6 m (Text-fig. 10).

Text-fig. 10. Horizontally laminated sandstones (SH)

Root reworked sandstones (Srr)

This lithofacies occurs only in the Valea Tereziei Member. The thickness of Srr depends on the root penetration level, reaching in some cases more than 1m, but the average thickness does not exceed 30–40 cm (Text-fig. 11). The root penetration affected both medium- and fine grained sandstones, with the latter being more frequent. Only when fine-grained sandstone layers are thin, have root traces been found within coarser sediments. The primary sedimentary structures have been largely erased but sometimes blurred remnants of ripple lamination can be visible. This lithofacies is always connected with overlying mudstones and phytogenic sediments. Sometimes, towards the top of such a layer occurs an accumulation of preserved compressed plant fossils, in layers a few millimeters thick.



Text-fig. 11. Root reworked sandstones (Srr). A) bedding surface view; B) perpendicular view

Massive fine-grained deposits (FM)

This lithofacies includes both mudstones and claystones. The macroscopic observation does not reveal any distinctive sedimentary structures. In the most cases, the FM lithofacies rests on the Srr lithofacies and it is followed by phytogenic sediments. Sometimes it is also overlain by coals or carbonaceous shale (Text-fig. 12), therefore the boundaries are usually gradational. Only when the coarsest sediments occur towards the top of the sequence are the boundaries erosional or sharp. The thickness of this lithofacies is variable, but only in a few parts of the sequence it reach more than 1 m, and usually it does not exceed 50 cm. A significant increase upwards in the number and thickness of this lithofacies has been observed. Along the bedding surfaces, numerous well preserved coalified, compressed leaves and other plant organs, as well as roots, have been recorded.

Horizontally laminated mudstones (FH)

This lithofacies is represented in both members. In the Dealul Budinic Member, red to brown-red deposits with thicknesses of several dozens of centimeters are dominant. The lamination is emphasized by the color change to yellow. In the Valea Tereziei Member there are only grey to dark grey deposits (Text-fig. 13), which usually contain fine and coalified plant remnants. Usually, the lamination is poorly visible due to dense root traces, in many cases very similar to the FM lithofacies. The lower boundaries are always gradational, passing from Srr lithofacies, while upper boundaries can be also sharp or erosional. Gradational boundaries are observed if the FH lithofacies is followed by coals or carbonaceous shales. Sharp and erosional boundaries are connected with the rapid lithological change into sandstones or conglomerates.

Coal, carbonaceous shales (C)

This lithofacies has phytogenic deposits and in all cases they do not exceed 50 cm in thickness. The phytogenic material is composed of mostly bright, bituminous coals and by an alternation of coals with clayey-muddy laminas very rich in organic matter. Additionally, burnt coal seams have been found, represented as thin layers of thermally altered organic matter covering the surrounding deposits. The lower boundaries are always gradational, passing from mudstones or claystones, whereas upper ones can be also erosional or sharp (Text-fig. 14). In those cases, the phytogenic material is overlain by conglomerates

Text-fig. 12. Massive fine-grained deposits (FM) and underlying lithofacies (C and Srr)

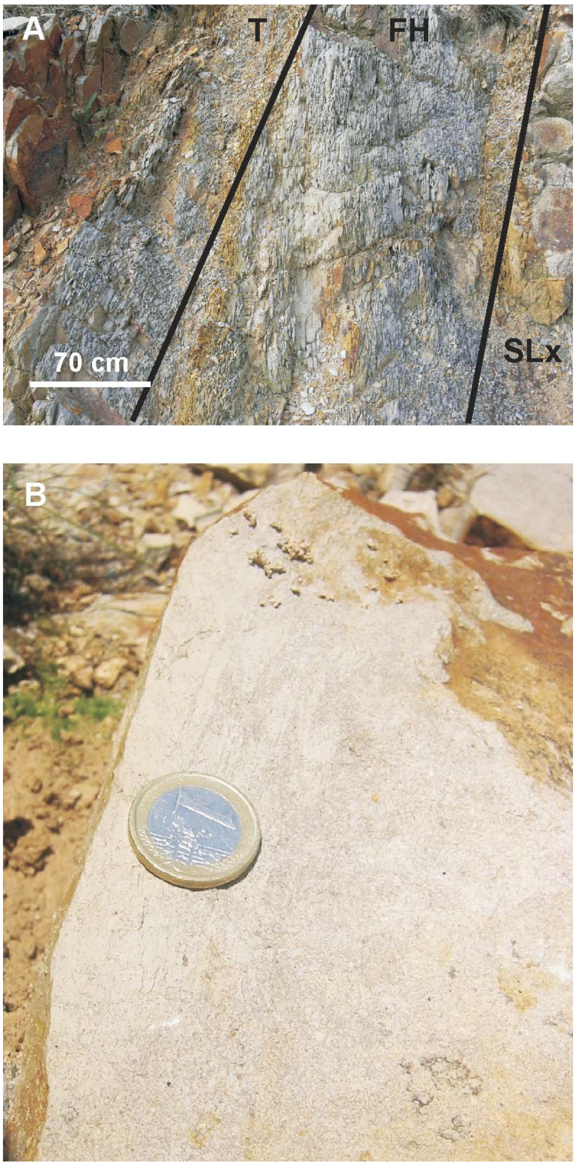
Text-fig. 13. Horizontally laminated mudstones (FH)

Text-fig. 14. Coal, carbonaceous shale (C)

(CGc) and various types of sandstones (SLx, SCm, VC). If a sharp boundary is observed, the C lithofacies is followed by a thin layer of ripple and horizontally laminated sandstones (SR and SH respectively).

Pyroclastics (T)

Two layers of pyroclastic deposits have been found within the succession. The first one, treated here as the boundary between the Dealul Budinic and Valea Tereziei members, is a 60–70 cm thick layer composed mostly of kaolin (up 95%), quartz and traces of feldspars, characterized by an average degree of order (Hinckley index=0.96). The lower part of the layer is usually massive, whereas the upper part shows poorly preserved ripple lamination (Text-fig. 15). The second pyroclastic layer is regarded as the boundary between the Hettangian and Sinemurian stages, and it is included within the Valea Tereziei Member. This second layer is currently not visible due to intensive extraction.



Text-fig. 15. Pyroclastics (T). Associated lithofacies (FH and SLx); B) subtle horizontal lamination

LITHOFACIES ASSOCIATIONS

Two main lithofacies associations can be distinguished within the depositional succession. The first, composed of coarse-grained sediments, and the second comprising clastic fines and phytogenic material. Additionally, due to the differences between the two units, i.e. Dealul Budinic and Valea Tereziei members, the associations are treated separately.

The coarse-grained association of the Dealul Budinic Member

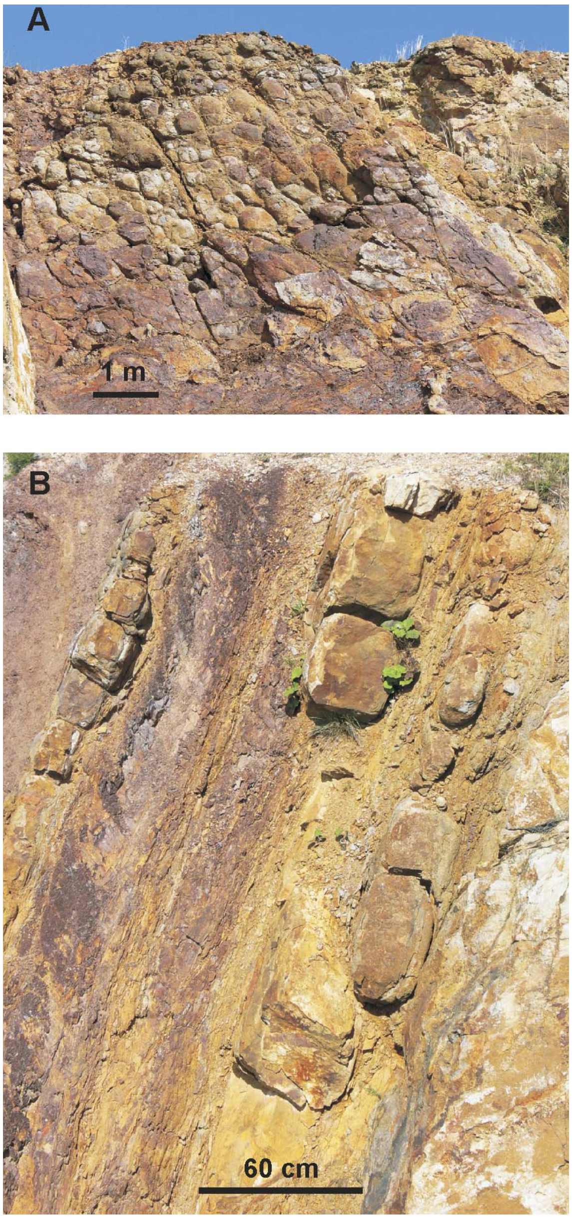
The coarse grained sediments are arranged into sequences up to 20 m thick. The packages can be divided into two groups of different thickness. The first group has a thickness exceeding 14 m and the second is characterized by a thickness less than 7 m. No differences in the lithofacies composition have been observed that can be related to sequence thickness. Both groups include in various proportions the following lithofacies: CGm, VC and SCm, but also lithofacies such as CGc, SLx and SH. The typical sequence observed within this association starts with conglomerates, whose deposition was sometimes preceded by clearly visible erosional surfaces. The conglomerates (mostly CGm) are covered by VC and then by SCm or SLx. Fully developed sequences of the type CGm-VC-SCm-SLx (SH) are rarely observed. Usually they miss finer members, generating composite accumulations separated by erosional surfaces or marked by sharp lithological change. The sharp or erosional surfaces can occur at any level, even just after the deposition of the coarsest fraction and just above one conglomeratic layer. Some sequences end with layers of the SCm facies, when oval blocks of 30–40 cm in diameter with secondary ferro-oxide crusts are present. The coarse-grained association lacks any plant or animal fossils; only faunal trace fossils within the sandstone's bedding surfaces have been found, in places where the medium to coarse-grained sandstones are followed by clastic fines. The deposits' coloration seems to be a secondary feature due to the patchy occurrence of red to red-brown sediments within yellowish, light grey and slightly greenish sediments.

Interpretation

The occurrence of poorly sorted deposits, the lack of sedimentary structures or the crude bedding characterized by a chaotic fabric (lithofacies GGm, VC) indicates rapid deposition by competent high energy flows. The transportation of the sediments took place as a viscous flow that carried clay together with clasts of variable size and resulted in a poorly organized mass. The deposits contain angular to sub-angular clasts up to 15cm in diameter, composed mostly of resistant pebbles, chaotically dispersed over whole beds, with gradational contacts or characteristic, weakly expressed erosional surfaces for debris flow operated on alluvial fans (Bull 1972; Nemec and Steel 1984; Levson and Rutter 2000). The deposits, which are characterized by crude cross bedding (the lithofacies CGc and SLx) and horizontal lamination (the lithofacies SH) occur subsequently within this association. They can be indicative of sedimentation within braided channels existing to the middle or the distal reach of the alluvial fan (Neves *et al*. 2005). It cannot be excluded that some parts of the coarse-grained association might be linked with hyper concentrated flood flows, which is transitional flow between fluvial and debris flow processes. The occurrence of gradational contacts between sandy and gravel beds, outsized clasts and rare grade bedding are typical features for hyper concentrated flood flow deposits, and support such a hypothesis. The accumulation took place on the proximal part of the fan surface, where both types are the main factors responsible for transportation and deposition of the sediments (Levson and Rutter 2000). The third group comprises SCm and SH lithofacies fine- to coarse-grained sediments in fining upward cycles with gradational transitions into clastic fines. These deposits can be interpreted as a sheet flow formed during flooding periods, with decreasing flow velocity in the middle part of the alluvial fan, with lesser gradient of slope or in joining places between fans (Neves *et al.* 2005).

The alluvial fan environments are found in all latitudes (Wasson 1975) and are not restricted to specific climate zones; they occur wherever the sediment is available and appropriate conditions prevail (Rachocki 1981), but mainly in dry or semi-dry climate. The accumulation of sediments in the alluvial fan environment needs the following specific conditions: a difference in topography between a steep valley and a relatively flat area into which the water-course is entering; periodical and efficient climatic factors (heavy rainfalls causing extreme runoff and washing down available weathered material) and a lack of dense vegetal cover, which eventually can protect the surface against erosion.

Some suggestions about the climate can be inferred based on the occurrence of oval blocks on the top surface of the sandstone bodies. Individual blocks are separated by crack systems filled later by ferro-oxide minerals, generating around them a few millimeters thick coat. Their distribution and size are similar to desiccation cracks (Text-fig. 16). It is not excluded that those features are related to recent weathering (spheroidal type), developed along joint sets. It is also possible that the desiccation crack system existed and guided the formation of joint sets, which later broke up and weathered (M.R. Gibling, personal information). The desic-



Text-fig. 16. Oval blocks showing possible features of the desiccation cracks within Dealul Budinic Member. A – Bedding surface view; B – Perpendicular view. (photos taken in two different places) cation cracks are typical for subaerially exposed clay-rich sediments, and it is indicative of water-table fluctuations. Such conditions can be linked with monsoonal conditions, as it was postulated for the Reşiţa Basin during Early Jurassic times (Mateescu 1958; Pieńkowski *et al.* 2009). This area was located between 20° and 30° North (Popa and Van Konijnenburg-Van Cittert 2006). The red color of the deposits is indicative of oxidizing conditions, connected with deposition of detritic hematite under a warm moist climate with seasonally distributed rainfalls (Van Houten 1961). The absence of plant remains can be explained by the high oxidation level, which does not allow the preservation of plant tissues and quickly destroys them, or by steep slopes subjected to periodic and heavy rainfalls. On the alluvial fan surface, the plants without well developed root systems cannot stabilize themselves under high water discharge.

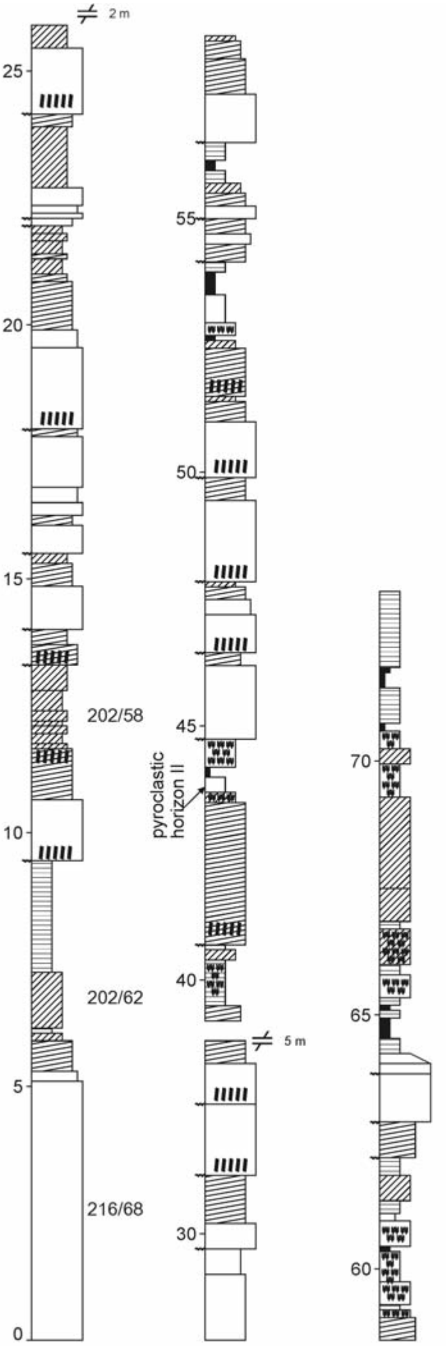
The fine-grained association of the Dealul Budinic Member

The fine-grained sediments of this association are exclusively red in color. They are composed of the lithofacies FM and FH, to which pyroclastics are added. The lower boundaries of this association are always gradational, passing quickly from massive or horizontally laminated sandstones (lithofacies SCm and SH respectively). The upper boundaries are usually sharp with a prominent increase of the deposits' fraction, or they are erosional, that erosion preceding deposition of conglomerates or of very coarse-grained sandstones (CGm and VC lithofacies). The thickness of the fine-grained association is less than the coarse-grained association and it reaches up to 1.8m directly below the first layer of the pyroclastics. The total content of the fine-grained sediments varies from 30% to 15% and it decreases eastwards at a distance of several hundreds of meters.

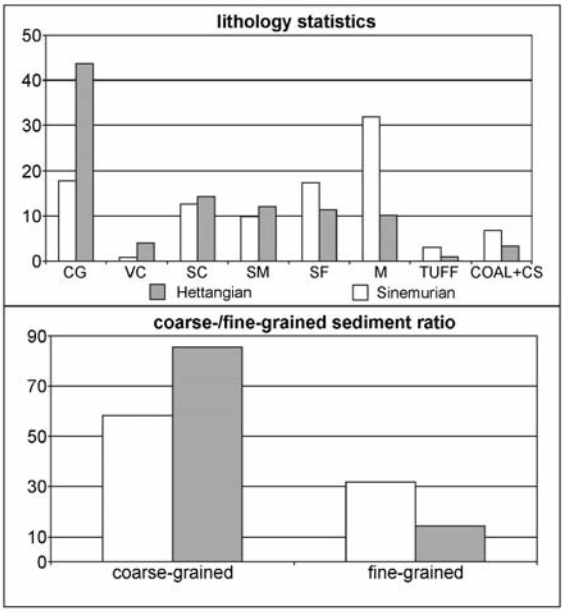
This association might be related to the formation of water bodies, where the deposition of clastic fines can occur. The typical areas for this association are common in places of coalescence of individual lobes (Neves *et al.* 2005) or within depressions created on the top of the alluvial fans (Rachocki 1981). The deposition of the mud may occur also after heavy rainfall, when the fan surface can be covered by a mud layer almost simultaneously with sand and gravel (Rachocki 1981).

The coarse-grained association of the Valea Tereziei Member

The sediments of the coarse-grained association are represented by various types of sandstones (lithofacies SLx and SCm) and subordinately by clast-supported conglomerates (CGc) and ripple laminated sandstones (SR). Very coarse-grained sandstones and matrix supported conglomerates (CGm and VC lithofacies) have been found only occasionally in the lowermost part of the unit, between the bounding pyroclastic layer and first coal seam. The succession of this association starts usually with an erosional surface, followed by the deposition of conglomerates or of coarse-grained sandstones, overlain by medium- to fine-grained sandstones.



Text-fig. 17. Valea Tereziei deposits at the northern end of the Colonia Cehă Quarry. For explanation see Text-fig. 3

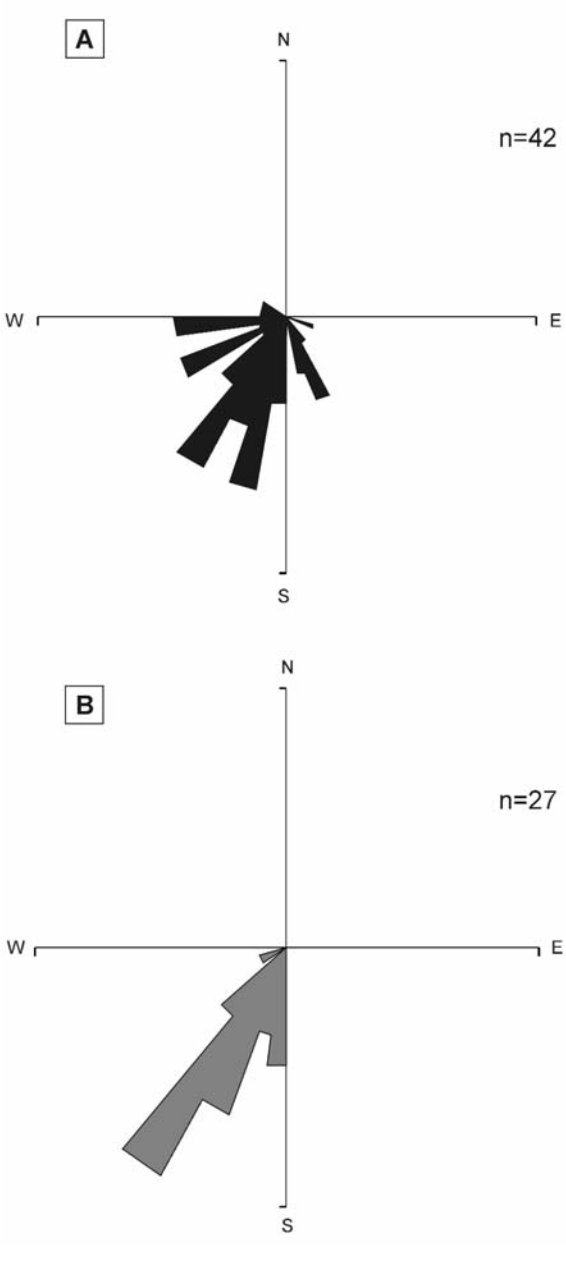


Text-fig. 18. Sediments thickness distribution of the Steierdorf Formation with no respect to lithofacies. CG – conglomerates, VC – very coarse-grained sandstone, SC – coarse-grained sandstone, SM – medium grained sandstone, SF – fine-grained sandstone

Medium-grained sandstones are represented as well as the lithofacies SLx and SR. Such sequences continuing to decrease in grain size are not common, and the majority of them is restricted to the two, the coarsest members i.e. conglomerates/coarse-grained sandstones and coarse-/medium-grained sandstones respectively. The thickness of this association varies from more than 22 m to 1.3 m (Text-fig. 17).

The coarse-grained packages can be divided into three main groups related to their thickness. The first has a thickness varying between 1 and 3 m, the second has a thickness between 4 and 6 m, while the third group has a thickness exceeding 12 m. The latter is observed only sporadically. The most commonly recorded packages vary in thickness between 4–6 m. A simple statistical analysis has been applied to the main lithological group. The thickness of the individual layers of the sandstones and conglomerates regardless of the lithofacies is shown on Text-fig. 18. Within conglomerates, the layers with thickness of 0.6–1.5 m predominate, subordinately the thinnest and the thickest beds occur, whereas in the case of sandstones, mostly the thinnest layers occur, with a thickness rarely exceeding 0.6 m. Two types of sequence have been recognized. The first, characterized by a normal gradation of fining upward features, from conglomerates or coarse-grained sandstones to fine-grained sandstones; and a second type, with a coarsening upward or pensymmetrical distribution of the layers (see Text-fig. 3). Usually the fining upward sequences are not fully developed and they contain internal erosional surfaces at various levels within the sequence. In those cases, where the fining upward sequence is complete, its thickness is markedly smaller (up to 3 m) in comparison with sequences with complex internal structure.

On the basis of observations of deposits which cover particular coarse-grained association and possible presence internal erosional surfaces, two types bodies have been recognized. First, fining upward sequences, which usually start with conglomerates and end with ripple laminated fine-grained sandstones with no internal erosional surfaces; such associations refer



Text-fig. 19. Drifted wood orientation (A) in respect to beds' strike (B) to simple channel bodies. The second type is characterized by not fully developed fining upward sequences, interrupted by episodes of erosion, visible in the sections as erosional surfaces. This type refers to multistorey channel bodies.

Within the coarse-grained association, numerous drifted, gymnosperm logs have been recorded. Their size is highly variable, from small fragments a few centimeters in length and width, to large size log fragments up to 3 m long and 30 cm in diameter. The large drifted floral remains are found in various positions, but the majority of them are embedded in the basal part of the coarse-grained lithosomes. In a few cases, they do not occur within the first coarse-grained body, if it is composed of conglomerates, but they occur only in the overlying one, separated by an erosional surface. The measured orientation of the longer axis of the drifted wood shows a direction parallel to the beds' strike of the whole unit (Text-fig. 19).

Interpretation of the coarse grained association

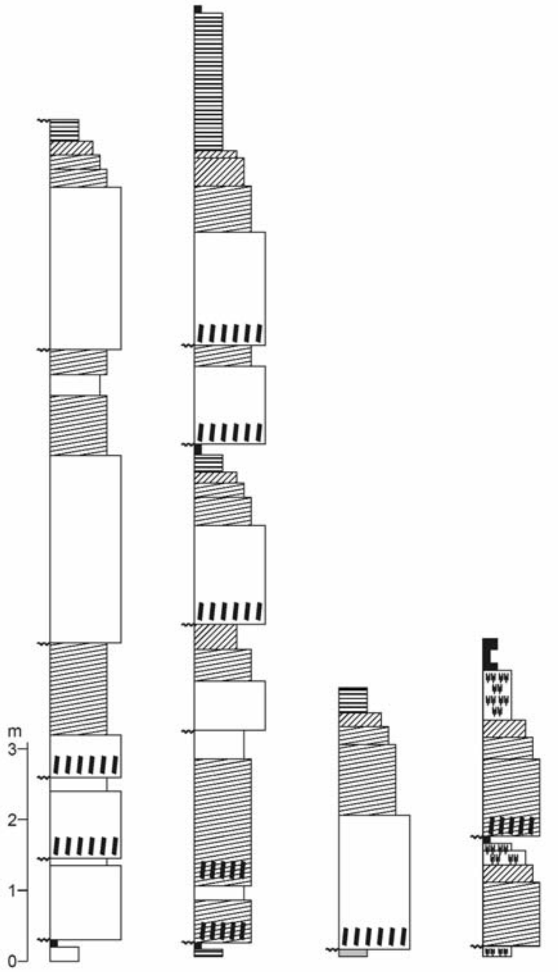
The lower part of the Valea Tereziei Member differs significantly from its upper part. This observation was made possible by recording the coarse-grained/fine grained content ratio of the association. The boundary between the two parts was recorded along the second pyroclastic layer, this layer being also the Hettangian/Sinemurian boundary (Popa 2000; Popa and Kędzior 2008). The overall sedimentary features of the coarse-grained association in the lower part of the unit, observed along vertically and horizontally fragmented exposures, allowed the packages to be assessed as being deposited within river channels, where the clastic material was carried mainly in traction. The predominance of sandy material with relatively low conglomerate content and with only a subordinate amount of clastic fines, suggest a deposition within tracts system constructed by a braided river. A comparison with existing models allows us to recognize a high-energy, sand-bed braided system similar to that described by Miall (1977, 1996). The limited size of exposures due to strong tectonic disruption expressed as small (dozens to several tens of meters) tilted blocks, and the present state of the abandoned open cast mines, do not allow us to observe in detail any type of large scale cross-bedding, therefore the precise identification of bedform types must be doubtful. The observed sedimentary structures have been recognized as through cross-bedding type, and they are interpreted here as a result of downstream migration of large bedforms or of lateral accretion of large bars (Miall, 1996). According to Miall (1977, 1985, 1996) and Cowan (1991), this fluvial style is characterized by an abundance of low-angle cross-bedding, as well as plane lamination (rare in Valea Tereziei Member), suggesting deposition during high-energy, possibly shallow discharge events.

The sequences which start with erosional surfaces followed by conglomerates and coarse-grained sediments, and showing fining upward features are interpreted as in-channel deposits. The depth of a channel was relatively small, taking into account the thickness of the fully developed in-channel sequences, which are not exceeding 3–4 m (Text-fig. 20). Such sequences are interpreted as single depositional events. In those cases, where the internal erosional surfaces are observed within coarse-grained associations, several repeating episodes of erosion and deposition took place. The occurrence of these two groups of in-channel sequences might reflect their various positions within channel-tracts or variation in water discharge. The simple channel bodies could occur on the flanks of channel tracts, whereas complex bodies could represent the axial zone of a tract. The exact width of the individual channel fills is hard to identify due to the above mentioned reasons. Only one site gives the possibility to have an insight into the lateral variability. The observed basal conglomeratic member wedging out along a distance of about 15 m permits the total width of the channel to be estimated as not less than 15m and probably not wider than 30 m.

The sedimentary features of the upper part of the Valea Tereziei Member such as the coarse-fine-grained deposits ratio, lithofacies sequences and their thickness, allow us to recognize a meandering system, where the sandstone packages with minor conglomerate content were deposited within active channels. A typical in-channel sequence is composed of SLx (CGc)/SR/Srr lithofacies and it shows normal gradation. The basal members usually are separated from underlying deposits by an erosional surface. The sandstones are coarse-grained and they pass gradually into medium- and fine-grained sandstones and finally into mudstones. Usually, the sequences do not contain internal erosional surfaces and they can be interpreted as single depositional events. The thickness of the in-channel sequences does not exceed 3.5 m in total channel depth. The lateral extent of the channel bodies is unknown, but in such an environment, significant extensions should be expected. The comparison with other coal basins showing fossil meandering systems points to a thickness varying between several dozens and up to several hundreds of meters (cf. Doktor and Gradziński 1985; Kędzior 2001; 2008). The formation of in-channel sequences is explained according to Doktor and Gradziński (1985) as following: the erosional surface beneath the initial sequence is the remains of an erosional river bottom. The conglomeratic layers (CGc lithofacies) deposited over this surface, can be interpreted as a channel lag or lower parts of bedforms.

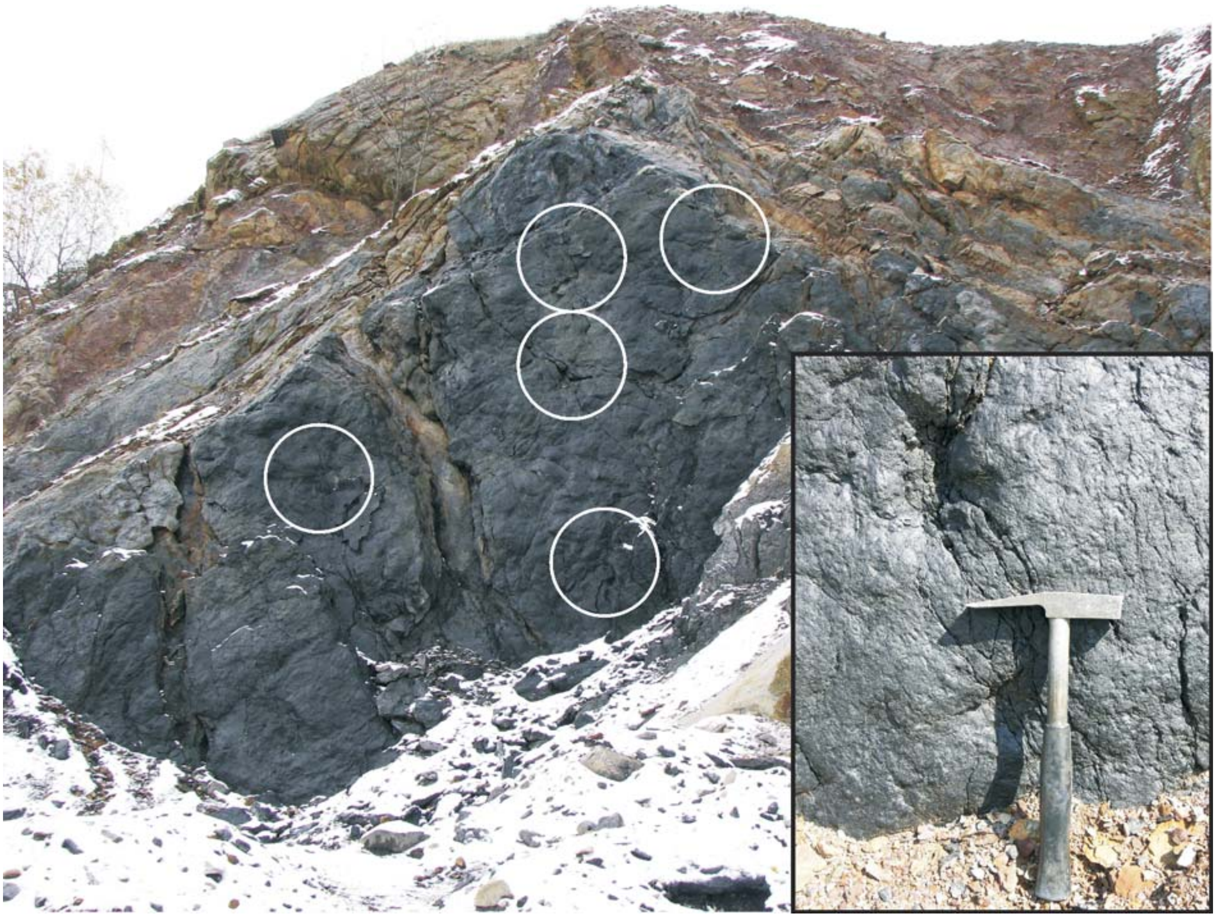
The coarsest deposits are sedimented in the deepest parts of the fluvial channel (Allen 1965a; Levey 1978; Jackson 1981). The channel lag deposits are overlain by sandstones, marked by predominantly large-scale cross bedding, a typical feature for in-channel deposits of almost all larger meandering systems. These deposits can be related to multistage development and lateral accretion of point bars (Allen 1965b; Gradziński 1970; Puidgefabregas and van Vliet 1978). The topmost parts of the point bars were covered by fine-grained sandstones and mudstones (lithofacies SR and MP respectively) and could probably have been aerially exposed during times when the water table was lower.

The basal parts of the channel fills in many cases contain drifted gymnosperm wood logs up to 1.5 m long and 0.3 m wide, preserved as coalified compressed fragments (Text-fig. 21). The arrangement of large plant remains is parallel to the beds' strike. The orientation of the longer axis of drifted wood sometimes is used as a paleocurrent indicator (MacDonald and Jefferson 1985; Retallack 1995; Gastaldo and Degges 2007; Riera *et al.* 2010), but in almost all cases without confirmation from direction of sedimentary structures, the paleocurrent indication can be treated only as a suggestion. Riera *et al.* (2010) briefly described the necessary conditions which favor plant orientation, pointing out that during deposition, the orientation of logs depends on the flow strength, and that elongated fragments are easily orientated by the flow direction, while more isometric remains display a wide range of orientation. The stem fragments which where found within in-channel deposits of the Valea Tereziei Member mostly are strongly elongated (only in a few cases almost isometric), a fact that can favor their orientation parallel to the main flow direction. If it can be assumed that the transitional to upper flow regime is typical for high energy in sand-bed braided rivers (Cowan 1991; Miall 1996), the flow direction could operate here along a N-S direction, but it should be noted that this is only a speculative conclusion. In addition to the drifted wood fragments, in some places traces of upright stems have been found. The traces are preserved as small-sized holes (up to 5cm in diameter) observed in the topmost part of charcoal layer (Text-fig. 22). The holes sometimes are filled up with sandy deposits of the layer overlying the coal seam. The plants rooted in the ancient peat were suddenly buried by sand introduced into the peatland area. The stems were crushed by pressure forces of flowing water and finally they were filled by the transported clastic material. Unfortunately, the primary height is not known due to the extraction of the overlying deposits. The mechanisms of burying stems in growth position were broadly described by Doktor and Gradziński (1985), and Gradziński and Doktor (1995), and authors pointed out the importance of fast sedimen-



Text-fig. 20. In-channel sequences of the Valea Tereziei Member. For explanation see Text-fig. 3.

Text-fig. 21. Drifted woods within in-channel sequences at the top of bedding surface of the massive coarse-grained sandstone (SCm)



Text-fig. 22. Upright, in situ stems preserved at the top of the burnt coal layer. Encircled areas show position of the stems' remains

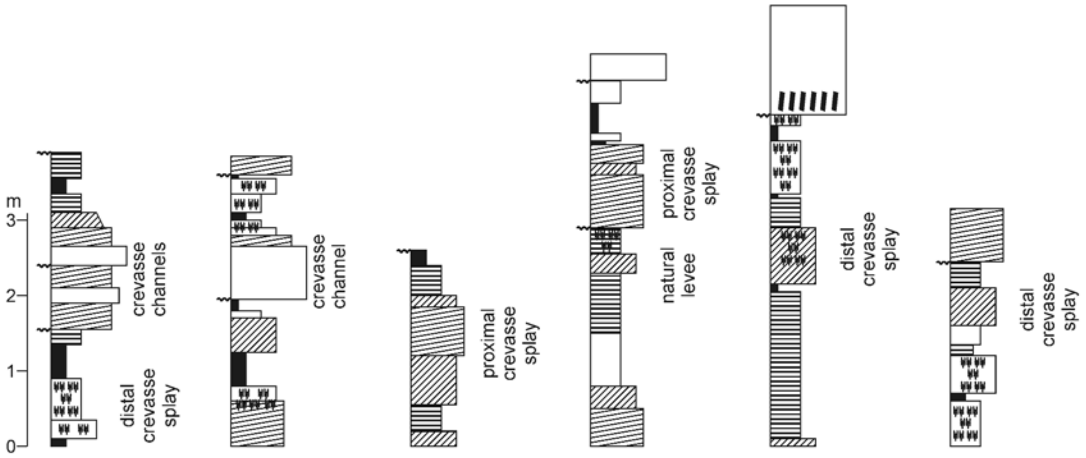
tation rates, as well as of forced and substantial fresh peat compaction under sediment load.

Description of the fine-grained association of the Valea Tereziei Member

The fine-grained association consists mainly of mudstones together with a subordinate amount of sandstones and phytogenic sediments represented by coals and carbonaceous clay. The thickness of the fine-grained packages is usually much smaller than the coarse-grained sequences, and in many cases they represent only thin interbeds within the coarse grained sediments (Text-fig. 23), except for the upper part of the Valea Tereziei Member. In the lower part of this member, between two pyroclastic layers, the thickness of this association usually does not exceed 2.5 m, whereas the upper part contains packages up to 7 m in thickness. The topmost part is characterized by a decrease of coarse-grained sediments content, while the mudstones, together with fine-grained sandstones, predominate. The total content of the fine-grained association in the lower part of the unit reaches up to 19%, while in the upper part it is half and half with coarse-grained sediments.

The mudstones are both massive and horizontally laminated (lithofacies FM and FH respectively), sometimes with primary sedimentary structures having been destroyed by roots. The majority of the mudstone is coarse-grained, pointing to a silt admixture, and only clastic fines underlying coals and carbonaceous shales can be regarded as fine-grained or claystones.

Within the fine-grained association are also embedded coarser sediments, such as medium- and fine-grained sandstones. The typical sedimentary structures comprise large-scale cross bedding as well as ripple lamination and root reworked deposits. The thickness of these layers is definitely smaller than that observed within the coarse-grained association, rarely exceeding 1m. The sandstone packages show both fining and coarsening upward features.



Text-fig. 23. Overbank deposits of the Valea Tereziei Member and interpretation of the their sedimentary sub-environments. For explanation see Text-fig. 3

The phytogenic sediments represent less than 4% of the total thickness of the whole succession. This type of deposit is composed of coals and coaly shales. Almost half of the coaly layers do not exceed 15 cm and two-thirds are thinner than 25 cm. In almost all cases, the phytogenic sediments are embedded within clastic fines, usually massive mudstones and claystones, and only in a few places are they overlain by coarse-grained deposits, separated by erosional surfaces.

Interpretation of the fine grained association

The deposits of the fine-grained association accumulated in overbank environments constructed by both types of fluvial systems, i.e. braided and meandering systems. Here they are regarded as flood plains such as those referred to by Reinfels and Nanson (1993), generally extended and flat areas of alluvial plains situated next to active fluvial channels and temporarily subjected to flooding. The deposition is undertaken by both traction and suspension processes. The size-grain variability of the fine-grained deposits can be explained as a result of decrease in flow velocity and load capacity, within increased distances from an active channel. Several subenvironments have been recognized.

The occurrence of thin layers of sandstones within fine-grained association is interpreted as crevasse splays and crevasse channel deposits. The difference between these two groups was made possible on the basis of lithofacies thickness and their grain-size. The crevasse channels are characterized by the occurrence of medium-grained sandstones belonging to the lithofacies SLx, followed by fine-grained sandstones with ripple lamination. The grain-size is only slightly finer than observed in in-channel deposits, when the deposition is preceded by erosion (Text-fig. 22). The thickness of such packages does not exceed 1.5 m. The crevasse channels distributed clastic material from the main channel during floods onto the flood plain areas (Gradziński *et al.* 1986) and with increasing distance from the main channel, a decrease in grain-size is the rule, as sediments pass into crevasse splays. The deposits accumulated in crevasse splay areas are represented by fine- and medium-grained sandstones of SR lithofacies. The thickness of theses layers does not exceed dozens of centimeters. The boundaries are always gradational and are encompassed within mudstones. The crevasse channels as well as crevasse splays are one of the most characteristic subenvironments for alluvial plains formed by suspended load rivers (Doktor and Gradziński 1985), however, they have also been described from braided systems (Gradziński *et al.* 1995; Doktor 2007). These subenvironments are developed along active channels and they are usually separated by natural levees. The breakups created during flood stages (crevasse channels) are the main routes of flow of the waters from the main channel and they carry out a part of the clastic material transported by the river. Some typical features of crevasse channels and splays in modern and fossil river systems were listed by Doktor and Gradziński (1985). As the most important features, they recorded grain-size, which is finer than in in-channel deposits; the sandstone packages are characteristically less thick in comparison with those deposited within main channels; the crevasse deposits have embedded within them clastic fines and phytogenic material; the great variety in thickness and lithological features; and ripple lamination is prevalent as a type of sedimentary structure. The reverse gradation of the crevasse deposits is a characteristic feature for crevasse channels or for the most proximal parts of crevasse splays (Horne *et al.* 1978; Gersib and McCabe 1981; Doktor and Gradziński 1985).

The small thickness of crevasse deposits can be explained by a regionally controlled small subsidence ratio, when the thickness of the packages cannot exceed the height difference between the top of natural levees and flood plains (Obernyer 1978). The repeated association of thin sandstone layers and mudstones characterized by the occurrence of the dense coalified root systems are interpreted as natural levees deposits. The ripple lamination, currently blurred or destroyed by vegetation, can be indicative of a low flow regime. The bioturbation by roots is typical for hot and humid regions. The sedimentary structures are usually better and longer preserved than within the clastic fines (Hudson 2008).

Massive mudstones predominate within clastic fines, while horizontally laminated mudstones occur subordinately. Some layers can be identified as stigmarian-like soils (seat earth), due to their high concentration of root traces (see Text-fig. 11). All features observed in the fine-grained deposits are indicative mainly for deposition from suspension in the flood plain areas. The characteristic feature for these deposits is the abundance of roots and rootlets. Their occurrence within thick packages suggests that the deposits were sedimented in the areas overgrown by tree-like plants and simultaneously excluding the possibility of deposition in the bottom of water basins with a depth making impossible the growth of such plants. The deposition took place mainly during floods, but it is not be excluded that some deposition was also partially related to flood basins, where the thin water cover could exist even after retreat of the flooding water bodies. Excepting the clastic fines of the flood plain, thin layers of sandstones were introduced during flooding. These layers were related to distal parts of crevasse splays. The flow strength decreased with increasing distance from the main channel, additionally slackened by the vegetal cover.

All the coal seams of the Valea Tereziei Member are humic in nature and they are underlain by stigmarian-like soils. Usually they are embedded within clastic fines, except in those places where in-channel deposits have been observed over the coal seams. In such cases, the deposition of the coarsest sediments was preceded by erosion. These features are sufficient to recognize coals as autochthonous. The most suitable conditions for peat accumulation and the consequential development of peatlands is on poorly drained areas. The several additional set of conditions was controlled by: (1) the flourishing vegetation, yielding the necessary amount of primary plant material; (2) lack or only limited clastic input on the peatland areas; (3) suitable relationships between the water table and the depositional surface of the phytogenic material (see Stach *et al.* 1975). The deposits underlying the coal seams show fining upward sequences, characteristic for the decrease of the current's strength, for the decrease of sediment supply in terms of amount and grain-size, hence the first possibility of the necessary conditions. The root concentration is linked not only to dense vegetation cover, but also to the sediment acting as a net, causing the decrease of sedimentation rate on the flood plain (Kulczyński 1952; Brzyski *et al.* 1976). The coal seams of the Valea Tereziei Member are rarely thicker than several dozens of centimeters, pointing out to the loss of balance between the peat accretion rate and the aggradation rate of the channels (cf. Gradziński *et. al.* 2000, 2003). This disequilibrium could be caused by the high aggradation rate of the channels, leading to the production of a critical relief and finally to avulsion (Allen 1978; Leeder 1978; Bridge and Leeder 1979; Bryant *et al*. 1995; Heller and Paola 1996).

The coal seams are covered by both types of sediments, fine and coarse-grained, thus the cessation of the peatland development may be related to two different processes. In the first case, when the coals are covered by clastic fines bioturbated by roots, they contain coalified roots and drifted wood fragments. Their occurrence allows us to assume that the peatlands were not drowned by flooding waters for long periods of time, and that they were rather buried by sediments introduced onto these areas (Doktor and Gradziński 1985). When the coals are overlain by coarse-grained deposits, the erosional surface occurs directly below the base of the package. This can be interpreted as an entrance of an active channel into the area occupied by the peatland. During flooding, the weakest parts of the natural levees can be broken or when the channel's accommodation was exceeded, the water flowed out into the floodplain areas. A part of the coarse-grained packages represents crevasse channels, while another part is linked to the action of the main channel. The creation of the new channel position can be explained in two ways: the crevasse channel has been converted into a main channel, e.g. under long term flooding; or it is related to a meander bend cut-off. In all cases, the basic requirements have been implemented, such as the creation of the suitable height difference between the water tables in the channel and in the depositional surface of the floodplain areas. For avulsion, a critical relief is necessary and under such conditions, the main flow could be directed into the lowest parts of the alluvial plain (Smith *et al.* 1989; Jones and Schumm 1999).

The pyroclastic deposits are represented by thin layers embedded within coarse-grained sediments. In recent outcrops, only the lower layer is visible and it is regarded as an isochronous boundary between the Dealul Budinic and Valea Tereziei members. Its characteristic feature is a very subtle lamination, and this horizon is interpreted as a volcanic ash washed down from other areas and deposited by flowing waters within a shallow lake. During the 1980s and 90s this pyroclastic horizon had been extensively extracted as "fireclay", but in recent outcrops it cannot be reached. This horizon has been previously interpreted as shallow lake deposits. Popa (2000b) used this horizon for marking the Hettangian – Sinemurian boundary within the Valea Tereziei Member.

DISCUSSION AND INTERPRETATION

The Hettangian-Sinemurian deposits of the Colonia Cehă open cast mine are generally interpreted as continental in origin. This sequence accumulated within alluvial and fluvial systems composed of alluvial fans, braided and meandering systems.

The Anina Anticline depositional area during Early Jurassic times was probably an intramontane basin (Bucur 1997, fig. 42), confined at least to the east by a fault. The hypothetic reconstruction made by Bucur (1997) includes no faults, although they are assumed for reconstructions of later Jurassic and Cretaceous intervals. According to the stratigraphic sequences known from the western flank of the Anina Anticline, deposits older than Norian?/Hettangian have been recognized, such as the Permian strata in the Anina area, which are separated from the Mesozoic formations by a stratigraphic gap (Bucur 1997; Bucur *et al.* 2009). That hiatus indicates that the basin development was initiated not earlier than towards the end of the Triassic by a tectonically created accommodation space along the major eastern fault. The activity of this eastern fault produced local sinking of the depositional surface along a hanging wall, thus generating the lowermost part of the alluvial valley, favouring clastics accumulation. Another possible scenario is related to the uplift of the source area along the eastern fault, while the new accommodation space was generated next to the fault scarp. The third possibility concerns climate induced changes or tectonic changes within the source areas, generating an increased discharge or/and clastic input (Shanley and McCabe 1994). In the case of the Hettangian Anina Anticline area, the uplift of the source area is stressed in this paper as the most probable factor responsible for the alluvial fan initiation.

The upward decrease in coarse-grained sediment content of the whole continental sequence suggests two possible explanations. The first explanation is related to a transgression of marine waters. The reconstruction made by Bucur (1997, fig. 40) assumes that due to the transgression and progradation of marine facies from purely continental during the Hettangian, to deep water carbonates of the Oxfordian-Kimmeridgian (Brădet and Valea Aninei formations), the base level had risen through Jurassic times. Bucur (1997) located the alluvial valley of the Anina Anticline relatively close to the sea shore. Under such conditions a continuous fining upward succession should be expected. However an influence of the base level changes can control aggradation/degradation of the channels only for a certain distance from seashore. Upstream of this point, aggradation/degradation undergoes influences from climatic and tectonic changes. For the modern Mississippi River more than 200 km (Fisk 1944) is the limit, and probably the river system of the Anina Anticline was much smaller. Even if the same scale of tides could be assumed, the distance from the sea shore should have been shorter.

The second explanation does not demand a base level rise and it is connected to a reduction in elevation of the source area; discharge decreasing or sediment supply. Hot and wet climate during Early Jurassic times for the Anina Anticline area (Popa and Van Konijnenbrug-Van Cittert 2006) was controlled by seasonal, monsoonal type heavy rainfall, thus the high erosion and efficient runoff. All these factors are enough to reduce differences in the elevation between the source area and the basin, washing down all weathered material, exposing fresh rocks and the contemporary depositing of that material within the basin. The interpretation could involve aspects of both explanations, including continuous sea level rise combined with the degradation of the relief of the source area.

CONCLUSIONS

The Lower Jurassic strata of the Steierdorf Formation observed in the Colonia Cehă Quarry are interpreted as purely continental deposits. The lower part of the succession represented by Dealul Budinic Member is characterized by alluvial fan environments. The coarsest sediments were deposited by high energy, high viscosity flows, while hyper concentrated flood flows within braided channels existed at the top of the alluvial fans. The fine-grained sediments were deposited on places of coalescence between individual lobes or within depressions developed on the alluvial fan.

The middle part of the Steierdorf Formation, belonging to both Dealul Budinic and Valea Tereziei members, was deposited by a braided river system, recognized as a sand-bed braided system. The coarse-grained sediments are related to channel fills, and the fine-grained sediments are related to overbank areas which occurred along the flanks of the alluvial valley.

The upper part, included in the Valea Tereziei Member, is represented by sediments deposited by a meandering system, with well developed floodplain areas. The thickest sandstone/conglomeratic sequences represent in-channel deposits, the thinner and finer deposits are related to deposition within crevasse channels, crevasse splays and natural levees. The fine-grained strata, together with phytogenic sediments, were accumulated on the overbank areas.

The channel aggradation was not balanced by accretion of the overbank areas, relatively often resulting in avulsions and breakups of the natural levees leading to flooding of the extrachannel areas.

The fining upward of the whole continental succession from alluvial fan to meandering river system can be explained by a continuous sea level rise during Hettangian – Sinemurian times and to contemporary degradation of the relief in the source area.

Acknowledgements

This paper is a result of the CNCSIS (NURC) research grant 978 (436/1.10.2007) to one of the authors (MEP). The authors thank Prof. Ryszard Gradziński and Prof. Martin R. Gibling for very effective discussions and Dr. hab. Anna Wysocka and an anonymous reviewer for help in improving our manuscript. The authors also want to thank Dr. Christopher J. Cleal (Cardiff) for his help in improving the English of the manuscript.

REFERENCES

Allen, J.R.L. 1965a. A review of the origin and characteristics of recent alluvial sediments. *Sedimentology*, **5**, 89–191.

Allen, J.R.L. 1965b. The sedimentation and palaeogeography of the Old Red Sandstone of Anglesey, North Wales. *Proceedings of Yorkshire Geological Society*, **35**, 139–185.

Allen, J.R.L. 1978. Studies in fluviatile sedimentation: an exploratory quantitative model for the architecture of avulsion-controlled alluvial sites. *Sedimentary Petrology*, **21**, 129–147.

Andrae, C. 1855. Beitrage zur kenntniss der fossilen Flora Siebenburgens und des Banates. *Abhandlungen der Kaiserische und Koenigichle geologischen Reichsanstalt*, **3,** 1–48.

Bridge, J.S. and Leeder, M.R. 1979. A simulation model of alluvial stratigraphy. *Sedimentology*, **26**, 617–644.

Bryant, M., Falk, P. and Paola, C. 1995. Experimental study of avulsion frequency and rate of deposition. *Geology*, **23**, 365–368.

Brzyski, B., Gradziński, R. and Krzanowska, R. 1976. Upright Calamite stems from Brynów and conditions of their burial. *Rocznik Polskiego Towarzystwa Geologicznego*, **46**, 159–182. [In Polish with English summary]

Bucur, I.I. 1991. Proposition pour une nomenclature formelle des depots paleozoiques et mesozoiques de la zone de Reşiţa-Moldova Nouă (Carpathes Meridionales, Roumanie). *Studia Universitatis Babeş-Bolyai, seria Geologie*, **36**, 3–14.

Bucur, I.I. 1997. Formaţiunile mesozoice din zona Reşiţa-Moldova Nouă, Cluj-Napoca, 214 pp.

Bucur, I.I., Popa, M.E., Kędzior, A. and Vişan, M. 2009. Field trip stops: Descriptions. In: Abstracts and Field Guide, 8th Symposium of IGCP 506 “Marine and Nonmarine Jurassic”. pp. 51–91 Bucharest; Romania.

Bull, W.B. 1972. Recognition of alluvial-fan deposits in the stratigraphic record. In: J.K. Rigby and W.K. Thamblin (Eds), Recognition of ancient sedimentary environments. *SEPM Special Publications*, **16**, 63–83.

Codarcea, A. 1940. Vues nouvelles sur la tectonique du Banat meridional et du Plateau de Mehedinţi. *Dări de Seamă ale Institutului Geologic al României*, **20**, 1–74.

Cowan, E.J. 1991. The large-scale architecture of the fluvial Westwater Canyon Member, Morrison Formation (Jurassic), San Juan Basin, New Mexico. In: A.D. Miall and N.Tyler (Eds), The Three-dimensional Facies Architecture of Terrigenous Clastic Sediments, and its Implication for Hydrocarbon Discovery and Recovery. *SEPM Concepts in Sedimentology and Paleontology*, **3**, 80–93.

Doktor, M. 2007. Conditions of accumulation and sedimentary architecture of the upper Westphalian Cracow Sandstone Series (Upper Silesia Coal Basin, Poland). *Annales Societatis Geologorum Poloniae*, **77**, 219–268.

Doktor, M. and Gradziński, R. 1985. Alluvial depositional environment of coal-bearing “mudstone series” (Upper Carboniferous, Upper Silesian Coal Basin. *Studia Geologica Polonica*, **82**, 5-67. [In Polish with English summary]

Ettingshausen, C. 1852. Über die fossilen Pflanzen von Steierdorf in Banat. *Jahrbuch der kaiserlich-koniglichen geologische Reichsanstalt* **3**, 194 pp.

Fisk, H.N. 1944. Geologic investigations of the alluvial valley of the lower Mississippi River: Vicksburg, Mississippi, pp. 1–170. U.S. Army Corp of Engineers, Mississippi River Commission.

Foetterle, F. 1850. Verzeichniss der an die K.K. geologische Reichsanstalt gelangten Eisendungen von Mineralien, Petrefacten Gebirgsarten u.s.w. *Jahrbuch der kaiserich-koniglichen geologische Reichsanstalt*, **1** (2), 350–358.

Gastaldo, R.A. and Degges, C.W. 2007. Sedimentology and paleontology of a Carboniferous log jam. *International Journal of Coal Geology*, **69**, 103–118.

Gersib, G.A. and McCabe, D.J. 1981. Continental coal-bearing sediments of the Port Hood Formation (Carboniferous). Cape Linzee, Nove Scotia, Canada. In: F.G. Ethridge and R.M. Flores, (Eds), Recent and ancient nonmarine depositional environments: models for exploration. *SEPM Special Publications*, **31**, 95–108.

Givulescu, R. 1998. Flora fosilă a Jurasicului inferior de la Anina, 90 pp. Editura Academiei Române; Bucureşti.

Gradziński, R. 1970. Sedimentation of dinosaur-bearing Upper Cretaceous deposits of the Nemegt Basin, Gobi Desert, Mongolia. *Palaeontologia Polonica*, **21**, 147–232.

Gradziński, R. and Doktor, M. 1995. Upright stems and their burial conditions in the coal-bearing Mudstone Series (Upper Carboniferous), Upper Silesia Coal Basin, Poland. *Studia Geologica Polonica*, **108**, 129–147.

Gradziński, R., Kostecka, A., Radomski, A. and Unrug, R. 1986. Zarys sedymentologii, pp. 1–628. Wydawnictwa Geologiczne; Warszawa.

Gradziński, R., Doktor, M. and Słomka, T. 1995. Depositional environments of the coal-bearing Cracow Sandstone andies (Upper Westphalian), Upper Silesia, Poland. *Studia Geologica Polonica*, **108**, 149–170.

Gradziński, R., Baryła, J., Danowski, W., Doktor, M., Gmur, D., Gradziński, M., Kędzior, A., Paszkowski, M., Soja, R., Zieliński, T. and Żurek, S. 2000. Anastomosing system of the Upper Narew River, NE Poland. *Annales Societatis Geologorum Poloniae*, **70**, 219–229.

Gradziński, R., Baryła, J., Doktor, M., Gmur, D., Gradziński, M., Kędzior, A., Paszkowski, M., Soja, R., Zieliński, T. and Żurek, S. 2003. In-channel accretionary macroforms in the modern anastomosing system of the upper Narew River, NE Poland. *Annales Societatis Geologorum Poloniae*, **73**, 35–53.

Heller, P.L. and Paola, C. 1996. Downstream changes in alluvial architecture: an exploration of controls on channel-stacking patterns. *Journal of Sedimentary Research*, **66**, 297–306.

Horne, J.C., Frem J.C., Caruccio, F.T. and Baganz, B.P. 1978. Depositional models in coal exploration and mine planning in Appalachian region. *AAPG Bulletin*, **62**, 2379–2411.

Hudson, P.F. 2008. Natural levees. In: S.W. Trimble, B.A. Stewart and T.A. Howell (Eds), Encyclopedia of Water Science, pp. 1–1586. CRC Press.

Jackson, R.G. II. 1981. Preliminary evaluation of the lithofacies models for meandering alluvial streams. In: A.D. Miall (Ed.), Fluvial Sedimentology. *Canadian Society of Petroleum Geologists, Memoir*, **5**, 543–576.

Jones L.S. and Schumm S.A. 1999. Causes of avulsion: an overview. In: N.D. Smith and J. Rogers (Eds), Fluvial Sedimentology VI. *IAS Special Publication*, **28**, 171–178.

Kędzior, A. 2001. Identification of the fluvial-channel tracts based on thickness analysis: Zabrze Beds (Namurian B) in the Main Anticline and Bytom-Dąbrowa trough of Upper Silesia Coal Basin, Poland. *Annales Societatis Geologorum Poloniae*, **71**, 21–34.

Kędzior, A. 2008. Depositional architecture of the Zabrze Beds (Namurian B) within the Main Anticline of the Upper Silesia Coal Basin, Poland. S*tudia Geologica Polonica*, **129**, 131–156.

Kudernatsch, J. 1855. Beitrage zur geologischen kenntnis des Banater Gebirgzuges. *Jahresbuch der kaiserlich-koniglichen geologische Reichsanstalt*, **6** (2), 219–254.

Kudernatsch, J. 1857. Geologie der Banater gebirgszuges, *Sitzungsbericht der Akademie der Wissenschaft*, **23**, 1–39.

Kulczyński, S. 1952. Geneza karbońskich złóż węglowych. *Prace Wrocławskiego Towarzystwa Naukowego, Seria B*, **64**, 1–67

Leeder, M.R. 1978. A quantitative stratigraphic model for alluvium with special reference to channel deposits density and interconnectedness. In: A.D. Miall (Ed.), Fluvial Sedimentology. *Canadian Society of Petroleum Geologists, Memoir*, **5**, 587–596.

Levey, R.A. 1978. Bedform distribution and internal stratification of coarse-grained point bars, upper Congaree River. In: A.D. Miall (Ed.), Fluvial Sedimentology. *Canadian Society of Petroleum Geologists, Memoir*, **5**, 105–127.

Levson, V.M. and Rutter, N.W. 2000. Influence of bedrock geology on sedimentation in Pre-Late Wisconsinan alluvial fans in the Canadian Rocky Mountains. *Quaternary International*, **68-71**, 133–146.

MacDonald, D.I.M. and Jefferson, T.H. 1985. Orientation studies of waterlogged wood; a paleocurrent indicator? *Journal of Sedimentary Research*, **55**, 235–239

Mateescu, I. 1932. Petrographische Untersuchungen der Kohlenfloze des liassischen Steinkohlenlagers von Anina-Steierdorf im Banat (Rumanien). *Mitteilung aus dem Institut für Brennstoffgeologie an der Bergakademie Freiberg*. PhD thesis, 106 pp.

Mateescu, I. 1958. Studiul petrografic al cărbunilor de la Rudăria (Svinecea Mare). *Anuarul Comitetului Geologic*, **31**, 5–49.

Miall, A.D. 1977. A review of the braided-river depositional environment. *Earth-Science Reviews*, **13**, 1–62.

Miall, A. D. 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews*, **22**, 261–308.

Miall, A.D. 1996. The geology of fluvial deposits: sedimentary facies, basin analysis and petroleum geology, pp. 1–582. Springer-Verlag; Berlin–Heidelberg–New York.

Mutihac, V. 1958. Studii geologice în partea mediană a zonei Reşiţa-Moldova Nouă (Banat), 1 ed. Editura Academiei Romîne; Bucureşti, 106 pp.

Năstăseanu, S. 1964. Prezentarea hărţii geologice a zonei Reşiţa-Moldova Nouă. *Anuarul Comitetului Geologic*, **33**, 291–342.

Năstăseanu, S. 1984. Geology of the Main Coal Basins in Romania. *Anuarul Institului de Geologie şi Geofizică*, **64**, 195–204.

Năstăseanu, S. and Savu, H. 1970. Geological Map of Romania, 1:50 000 scale, Reşiţa sheet. Geological Institute of Romania; Bucharest.

Năstăseanu, S., Bercia, I., Iancu, V., Vlad and Hârtopanu, I. 1981. The structure of the South Carpathians (Mehedinţi – Banat Area). Guidebooks series, 22, 3–100 pp. IGR, Bucureşti.

Nemec, W. and Steel, R.J. 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits. In: E.H. Koster and R.J. Steel (Eds), Sedimentology of Gravels and Conglomerates. *Canadian Society of Petroleum Geologists, Memoir*, **10**, 1–30.

Neves, M.A., Morales, N. and Saad A.R. 2005. Facies analysis of tertiary alluvial fan deposits in the Jundiaı' region, São Paulo, southeastern Brazil. *Journal of South American Earth Sciences*, **19**, 513–524.

Obernyer, S. 1978. Stratigraphy of the Fort Union and Wasatch Formations (Tertiary) in the Buffalo-Lake De Smet area, Johnson County, Wyoming. In: H.E. Hodgson (Ed.), Proceedings of the 2-nd Symposium on the Geology of Rocky Mountain coal, pp. 49–65. Denver.

Petrescu, I., Nicorici, E., Biţoianu, C., Ţicleanu, N., Todros, C., Ionescu, M., Mărgărit, G., Nicorici, M., Duşa, A., Pătruţoiu, I., Munteanu, A. and Buda, A. 1987. Geologia zăcămintelor de cărbuni. 2. Zăcăminte din România, 2, 386 pp. Editura Tehnică; Bucharest.

Pieńkowski, G., Popa, M.E. and Kędzior, A. 2009. Early Jurassic sauropod footprints of the Southern Carpathians, Romania: palaeobiological and palaeogeographical significance. *Geological Quarterly*, **53**, 461–470.

Pop, G., Mărunţiu, M., Iancu, V., Seghedi, A. and Berza, T. 1997. Geology of the South Carpathians in the Danube Gorges, 1–28 pp. IGR, Bucharest.

Popa, E., Năstăseanu, S. and Antonescu, E. 1976. Nouvelles donnees concernant la biostratigraphie du Jurassique inferieur de la zone de Sirinia (Banat). *Dări de seamă ale şedinţelor*, **63**, 7–24.

Popa, M.E. 2000a. Early Jurassic land flora of the Getic Nappe, University of Bucharest, PhD thesis, Bucharest, 258 pp.

Popa, M.E. 2000b. Aspects of Romanian Early Jurassic palaeobotany and palynology. Part III. Phytostratigraphy of the Getic Nappe. *Acta Palaeontologica Romaniae*, **2**, 377–386.

Popa, M.E. 2000c. First find of Mesozoic tetrapod tracks in Romania. *Acta Palaeontologica Romaniae*, **2**, 387–390.

Popa, M.E. 2009. Late Palaeozoic and Early Mesozoic continental formations of the Reşiţa Basin, 197 pp. Editura Universităţii din Bucureşti; Bucharest.

Popa, M.E. and Kędzior, A. 2006. Preliminary ichnological results on the Steierdorf Formation in Anina, Romania. In: Z. Csiki (Ed.), Mesozoic and Cenozoic vertebrates and paleoenvironments, pp. 197–201. Bucureşti.

Popa, M.E. and Kędzior, A. 2008. High resolution paleobotany and sedimentology of the Steierdorf Formation, Reşiţa Basin. In: I.I. Bucur and S. Filipescu (Ed.), Annual scientific session "Ion Popescu Voiteşti", pp. 57–59. Cluj University Press; Cluj-Napoca.

Popa, M.E. and Meller, B. 2009. Review of Jurassic plants from the Anina (Steierdorf) coal mining area, South Carpathians, in the collections of the Geological Survey of Austria. *Jahrbuch der Geologischen Bundesanstalt*, **149**, 487–498.

Popa, M.E. and Van Konijnenburg-Van Cittert, J.H.A. 2006. Aspects of Romanian Early – Middle Jurassic palaeobotany and palynology. Part VII. Successions and floras. *Progress in Natural Sciences*, **16**, 203–212.

Preda, I., Turculeţ, I., Bădăluţă, A., Barus, T. and Androhovici, A. 1994. Geologia zăcămintelor de cărbuni. Partea a II-a. Răspândirea zăcămintelor de cărbuni, 2, 392 pp. Editura Universităţii din Bucureşti; Bucureşti.

Puigdefabregas, C. and Van Vliet, A. 1978. Meandering stream deposits from the Tertiary of the southern Pyrenees. In: A.D. Miall (Ed.), Fluvial Sedimentology. *Canadian Society of Petroleum Geologists, Memoir*, **5**, 469–485.

Rachocki, A. 1981. Alluvial Fans. An attempt at an empirical approach, pp 1–161. John Wiley

Răileanu, G. 1957. Consideraţii generale asupra geologiei Banatului de Vest. *Analele Romăno Sovietice*, **4** (33), 5–18.

Răileanu, G., Grigoraş, N., Onescu, N. and Plişcă, T. 1963. Geologia zăcămintelor de carbuni, cu privire specială asupra teritoriului RPR, 344 pp. Bucureşti.

Răileanu, G., Năstăseanu, A. and Mutihac, V. 1957. Cercetări geologice în regiunea Anina – Doman (zona Reşiţa – Moldova Nouă – Banat). *Buletin ştiintific, Secţia de Geologie şi Geografie*, **2,** 289–310.

Reinfels, I. and Nanson, G. 1993. Formation of braided river floodplains, Namakiri River, New Zeland. *Sedimentology*, **40**, 1113–1127.

Retallack, G.J. 1995. Permian and Triassic driftwood from the Allan Hills, Antarctica. *Antarctic Journal of the United States*, **30**, 37–39.

Riera, V., Marmi, J., Oms, O. and Gomez, B. 2010. Orientated plant fragments revealing tidal palaeocurrents in the Fumanya mudflat (Maastrichtian, southern Pyrenees): Insights in palaeogeographic reconstructions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **288**, 82–92.

Roca, E., Bessereau G., Jawor E., Kotarba M. and Roure, F. 1995. Pre-Neogene evolution of the Western Carpathians: Constraints from the Bochnia-Tatra Mountains section (Polish Western Carpathians), *Tectonics*, **14**, 855–873.

Săndulescu, M. 1984. Geotectonica României, 336 pp. Editura Tehnică; Bucureşti.

Schreter, Z. 1912. Adatok a nyugat-Krassószörenyi mészkőhegység déli részének hegyszerkezetéhez. *Magyar királyi Földtani Intézet*, pp. 124–158.

Semaka, A. 1962. Flora Liasică de la Anina (Banat). *Anuarul Comitetului Geologic*, **32**, 527–569.

Shanley K.W. and McCabe, P.J. 1994. Perspectives on the sequence Stratigraphy of continental strata. *AAPG Bulletin*, **78**, 541–568.

Smith, N.D., Cross, T.A., Dufficy, J.P. and Clough, S.R. 1989. Anatomy of an avulsion. *Sedimentology*, **36**, 1–23.

Stach, E., Mackowsky, M-Th., Teichmuller, M., Taylor, G.H., Chandra, G. and Teichmuller, R. 1975. Stach's textbook of coal petrology (2nd edition) pp 1–428. Gebrüder Borntraeger; Berlin.

Stănoiu, I., Popa, M.E., Diaconiţă, D., Ţicleanu, M., Dinulescu, C. and Balabaş, T. 1997. The Liassic from Reşiţa and Sirinia Basins. In: A. Grubic, Berza, T. (Eds), Geology of the Danube Gorges, International Symposium, pp. 249–254. Belgrade Institute of Geology; Milanovac–Orşova.

Van Houten, F.B. 1961. Climatic significance of redbeds. In: A.E.M. Nairn (Ed.), Descriptive Paleoclimatology, pp. 89–139. Interscience; New York.

Manuscript submitted: 20th July 2010
Revised version accepted: 15th March 2013