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The Early to Middle Triassic continental–marine transition of NW Bulgaria: sedimentology, palynology and sequence stratigraphy

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Abstract: Sedimentary facies and cycles of the Triassic continental–marine transition of NW Bulgaria are documented in detail from reference sections along the Iskar river gorge between the villages of Tserovo and Opletnya. The depositional environments evolved from anastomosing and meandering river systems in the Petrohan Terrigenous Group to mixed fluvial and tidal settings in the Svidol Formation, and to peritidal and shallow-marine conditions in the Opletnya Member of the Mogila Formation. For the first time, the palynostratigraphic data presented here allow for dating the transitional interval and for the precise identification of a major sequence boundary between the Petrohan Terrigenous Group and the Svidol Formation (Iskar Carbonate Group). This boundary most probably corresponds to the major sequence boundary Ol4 occurring in the upper Olenekian of the Tethyan realm and thus enables interregional correlation. The identification of regionally traceable sequence boundaries based on biostratigraphic age control is a first step towards a more accurate stratigraphic correlation and palaeogeographic interpretation of the Early to early Middle Triassic in NW Bulgaria.

Keywords: Lithofacies, sedimentary cycles, palynology, continental–marine transition, sequence stratigraphy, Triassic, NW Bulgaria.

Introduction

Among the prominent features of the Triassic continental–marine transition in NW Bulgaria is the pronounced cyclic character of its sedimentation, recorded at different hierarchical scales. Although this stratigraphic interval has been the focus of many previous lithological and lithofacies studies (Tronkov 1983; Mader & Čatalov 1992; Ajdanlijsky 2002, 2010a, b; El-Ghali et al. 2006, 2009; Stefanov & Chatalov 2015; Chatalov et al. 2015; Chatalov 2018), the lack of biostratigraphic dating hampers the genetic interpretation of the deposits and their time range.

The good exposure and only minor tectonic disturbance of the Lower–Middle Triassic succession along the central and northern parts of the Iskar river gorge provide excellent conditions for detailed lithological and stratigraphical studies. The study area includes the Iskar river valley between the villages of Tserovo and Opletnya (Fig. 1) where the complete Triassic succession is well exposed and where some of the reference sections of the Lower and Middle Triassic series in Western Bulgaria are located. The current study covers the transitional interval from the upper parts of the entirely continental facies to the lowermost shallow-marine parts of the succession. The here presented sections were selected on the basis of stratigraphic significance, number of lithological and lithofacies studies previously done, and last but not least the accessibility allowing for the establishment of regional reference sections.

The new palynological data, combined with the well-recognizable lithological levels and surfaces and the characterization of sedimentary cyclicity of different orders are a good basis for developing an improved, high-resolution stratigraphic scheme and better regional correlations of this stratigraphic interval.

Geological setting

The study area belongs to the central-eastern part of the alpine Western Balkan Tectonic zone (Western Balkanides) of Ivanov (1998). The Triassic succession forms the base of its Mesozoic cover and lies over pre-Mesozoic basement, including high-grade metamorphosed lower Palaeozoic sedimentary and igneous rocks and upper Palaeozoic sedimentary, igneous and volcanic rocks (Fig. 1). Here, the Triassic succession is referred to as "Balkanide type" (Ganev 1974; Zagorchev & Budurov 2009) and is subdivided into three parts. The lower part is dominated by continental terrigenous red beds representing mainly fluvial and rare alluvial deposits that lithostratigraphically are referred to as Petrohan Terrigenous Group (Tronkov 1981). The middle part consists of carbonate and mixed siliciclastic-carbonate rocks of the Iskar Carbonate

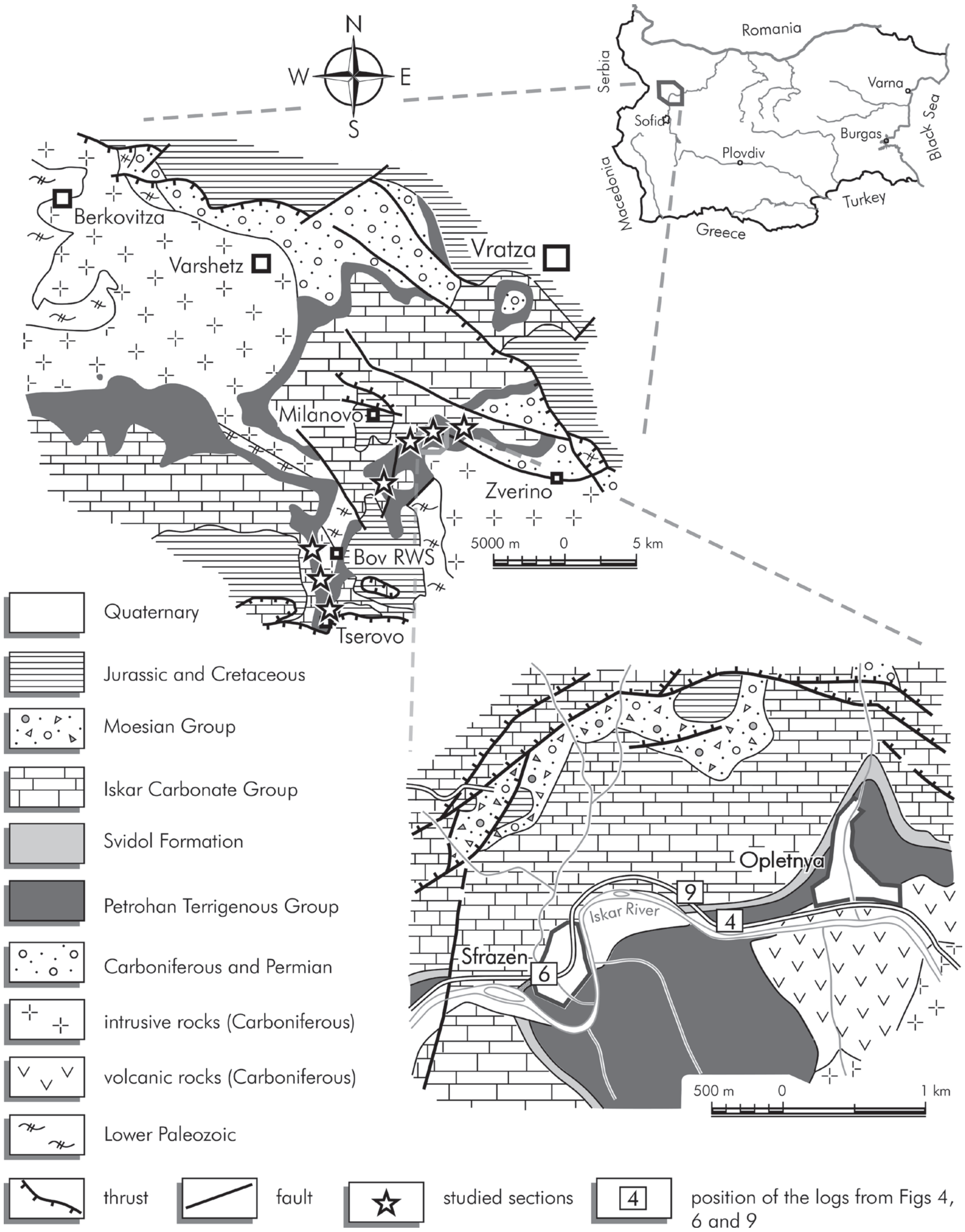

Fig. 1. Geological map of the Berkovitza unit and the study area in NW Bulgaria with position of the studied and palynologically sampled sections.

Group (Tronkov 1981; Fig. 2), and the upper part is represented by terrigenous-carbonate and carbonate rocks of the Moesian Group (Chemberski et al. 1974). In the study area the Petrohan Terrigenous Group and the lowermost part of the Iskar Carbonate Group show a pronounced cyclic character (Fig. 3).

Previous studies

According to the published data (Tronkov 1968, 1983; Čatalov 1974, 1975; Assereto et al. 1983; Tronkov & Ajdanlijsky 1998a, b; Ajdanlijsky et al. 2004), the Petrohan Terrigenous Group and the lowermost part of the Iskar Carbonate Group (Svidol Formation and lower part of the Mogila Formation) were deposited during the Early Triassic (Fig. 2). During that time the study area was located between 30° and 40° palaeolatitude as a part of the Eurasian passive margin of the Tethys Ocean (Philip et al. 1996), with overall semi-arid to arid climatic conditions (Nachev 1980; Tronkov 1983; Mader & Čatalov 1992; Chatalov 1994, 1997a, b, 1998, 2005a, b, 2006; Ajdanlijsky 2002, 2005).

The Petrohan Terrigenous Group is composed of sandstones, siltstones and mudstones, which were deposited in braided, anastomosing and high-sinuosity (i.e., meandering)

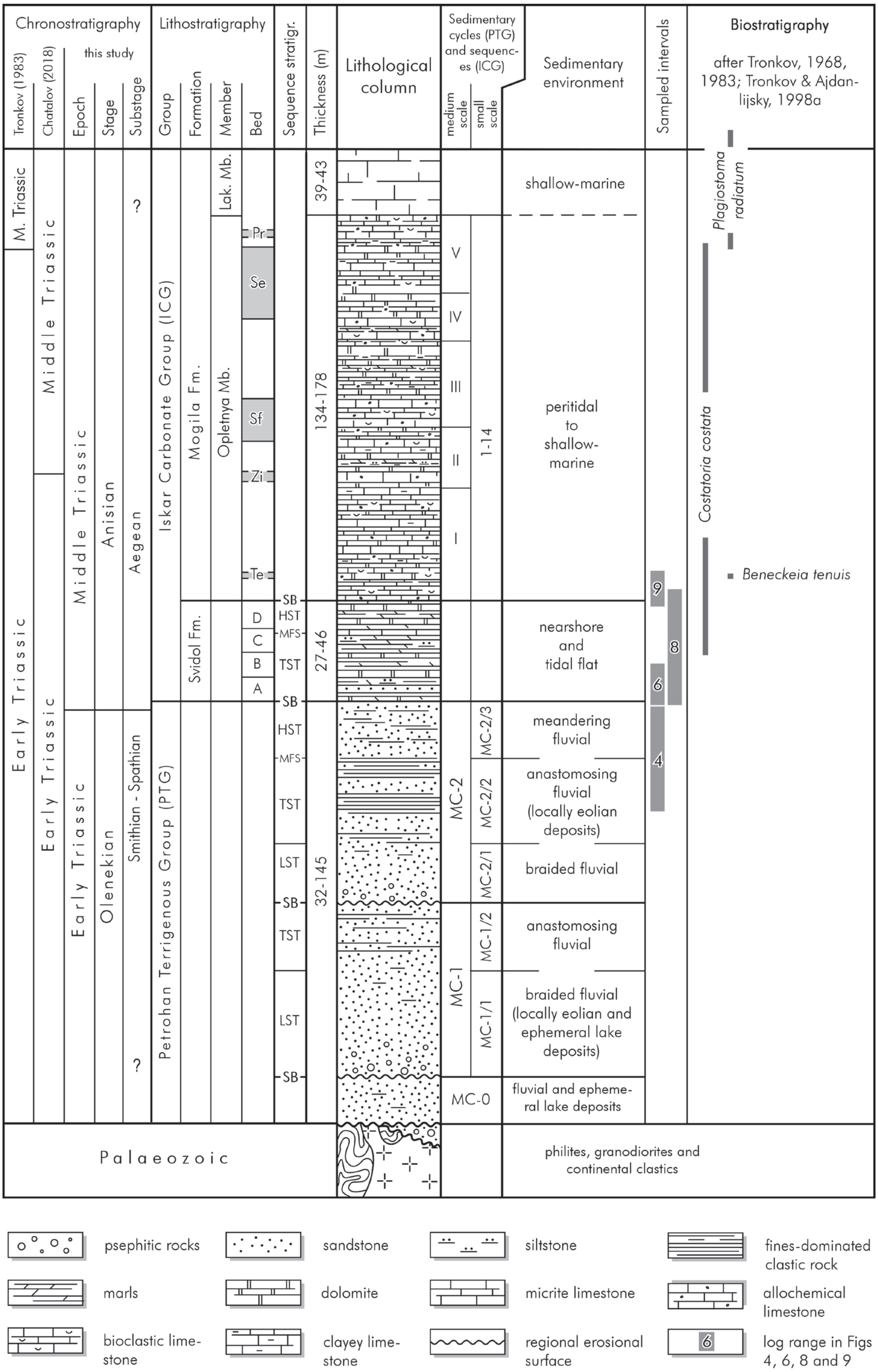

Fig. 2. Stratigraphic column of the lower part of the Triassic sequence exposed in outcrops of the Iskar river gorge, NW Bulgaria, with range of the studied sections shown in Figures 4, 6 and 9. Sequence-stratigraphic interpretation according to El-Ghali et al. (2006, 2009) and sedimentary cyclicity according to Ajdanlijsky et al. (2004) and Ajdanlijsky (2005, 2010a). Abbreviations used: SB — sequence boundary; LST — lowstand systems tract; TST — transgressive systems tract; MFS — maximum-flooding surface; HST — highstand systems tract; Te — Tenuis Bed; Zi — Zhitolub Bed; Sf — Sfrazen Bed; Se — Sedmochislenitzi Bed; Pr — Prebointitza Bed.

fluvial systems (Ajdanlijsky 2001a, 2005, 2009; Ajdanlijsky et al. 2004). Because of the very irregular terrain on which the Petrohan Terrigenous Group rests in some parts of the Iskar river gorge (Tronkov 1960, 1963; Rashkov 1962; Tronkov et al. 1965; Ajdanlijsky 2010a) its thickness varies from 32 to over 145 m, but most of the sections measured reveal a range from 90 to 110 m (Ajdanlijsky 2005).

Tronkov (1995) proposed a lithostratigraphic subdivision of the Petrohan Terrigenous Group distinguishing three units: a lower conglomerate, a middle sandstone, and an upper sandstone–siltstone unit. Along with Tronkov's subdivision of the continental Lower Triassic red beds, a complex stratigraphic subdivision of sequences was proposed by Mader & Čatalov (1992). They established in the section named by them the "Buntsandstein in Bulgaria" four informal units that formed during two tectonic and palaeoenvironmental megacycles. Later, based on well-developed, regional bounding surfaces with erosional amplitudes of 30–35 m, lithofacies architecture, changes in regional pattern of fluvial palaeotransport and the degree of development and the position of the palaeosol levels, Ajdanlijsky (2005, 2010a) subdivided the clastic succession of the Petrohan Terrigenous Group into three main units (MC-0, MC-1, MC-2; Fig. 2). Within these units, representing medium-scale sedimentary cycles, Ajdanlijsky (2005) recognized small-scale cyclic patterns, thus introducing a hierarchic nomenclature of cyclicity: elementary fluvial cycles (EFC) representing the basic building blocks of mesocycles (MC), correspond to the third-order cycles (sequences) of Miall (1997, 2010) and Wright & Marriott (1993). Based on similarity in lithofacies of the elementary fluvial cycles, the second and third mesocycle of the Petrohan Terrigenous Group are subdivided into sub-mesocycles, reflecting the stages of development of the alluvial system from the erosional base-level change to the re-establishment of the river equilibrium profile. Later, El-Ghali et al. (2009) interpreted these mesocycles as sequence units and the sub-mesocycles as sequence systems tracts.

The lowermost part of the Iskar Carbonate Group is represented by a transitional continental to marine, mixed siliciclastic–carbonate, tide-dominated succession referred to as Svidol Formation (Čatalov 1974) that is overlain by the shallow-marine Mogila Formation (Assereto & Čatalov 1983; Assereto et al. 1983). The unit is comprised of sandstones, silt- and mudstones, dolomitic to clayey limestones and dolomites. According to Čatalov (1975) its origin is connected with sedimentation in a low-relief coastal sandy to silty plain, a supratidal evaporite clayey-carbonate setting and an intertidal to shallow subtidal carbonate flat. Its thickness ranges from 27 m in the southern part to 46 m in the northern part of the study area. Based on bivalve, gastropod and ammonoid findings, Tronkov (1968, 1976, 1995) placed the Svidol Formation in the Spathian.

The Opletnya Member of the Mogila Formation, showing thickness ranges from 134 m to over 180 m, is dominated by micritic and clayey limestones and dolostones that form a well-pronounced cyclicity described by Tronkov (1983) as uniform hemirhythms, bounded by transgressive surfaces. Another feature of the lower part of the Opletnya Member is the occurrence of hardgrounds in parts of the Western Balkanides. In the Iskar river gorge section and the Vratza Mountains, the same author distinguished four beds that can be traced over a long distance: the Tenuis, Zhitolub, Sfrazen and Sedmochislenitzi beds (Fig. 2). Additionally, Asseretto & Čatalov (1983) defined the Prebointitza Bed. Later, Tronkov (1993) recognized this bed as part of the Sedmochislenitzi Bed. Ajdanlijsky et al. (2004) subdivided the Opletnya Member into five medium-scale sedimentary cycles (I–V; Fig. 2). These medium-scale cycles are subdivided into small-scale cycles (1–14; Fig. 2), which in turn are subdivided into elementary cycles (or parasequences) bounded by transgressive surfaces. The palaeogeography of the study area during the deposition of the Opletnya Member is interpreted as part of a carbonate platform (Chatalov 1998, 2000a) or ramp (Čatalov 1988; Chatalov 2002, 2007, 2011) that Tronkov (1993) named as Opletnya Carbonate Ramp and Chatalov (2013) defined as homoclinal ramp.

Materials and methods

The sections studied, situated along the Iskar river gorge between the villages Tserovo and Opletnya (Fig. 1; Opletnya: N 43°06'01" E 23°25'42", Sfrazen: N 43°05'39" E 23°25'32", Tserovo: N 43°00'19" E 23°21'26"), are among the most representative for the Triassic continental–marine transition of NW Bulgaria and provide continuous vertical and satisfactory lateral exposure.

The lithological characteristics of the uppermost part of the Petrohan Terrigenous Group are documented in nine detailed logged sections. The section description is based on lithofacies logging following the scheme of Miall (1977, 1978, 2006), adapted and modified to the features of the study area (Ajdanlijsky 2012, 2013a,b) and developed for the needs of carbonate and mixed clastic-carbonate systems. A total of 216 samples and 141 thin-sections has been analyzed for this Group. The fluvial style is interpreted on the base of architectural-element analysis (Ajdanlijsky 2014, 2015a,b) and measurement of the sedimentary palaeotransport indicators (Ajdanlijsky 2009).

Lithofacies documentation of the Svidol Formation is based on seven sections (Fig. 1), all of them sampled and studied in detail (142 samples and 92 thin-sections). Lithology and facies studies of the Opletnya Member of the Mogila Formation were performed in three complete sections near Tserovo and Oletnya villages and north of the Lakatnik railway station (406 samples and 138 thin-sections).

The sequence-stratigraphic nomenclature follows that of Catuneanu et al. (2011). The high-resolution sequence-stratigraphic analysis is based on the concepts of Strasser et al. (1999). Parasequences are defined as being limited by flooding surfaces (van Wagoner et al. 1990). However, the sequence-stratigraphic nomenclature discussed by Schlager

Fig. 3. Cyclic architecture of deposits of the Triassic continental–marine transition exposed in outcrop sections along the Iskar river: **a** — lower part of the Svidol Formation near Sfrazen hamlet (the bush to the left of the picture is about 1.8 m high); **b** — Petrohan Terrigenous Group east of Tserovo village (the cliff is about 87 m high); **c** – lower part of the Mogila Formation (Opletnya Member) near Zitolub spring, north-west of the Lakatnik railway station (the lowermost cycle shown is 4.4 m thick). Lines and arrows mark the base of elementary fluvial cycles (b) and sequence boundaries of elementary sequences (c), respectively. Abbreviations used: SB — sequence boundary; PTG — Petrohan Terrigenous Group; SvF — Svidol Formation.

(2004, 2010) introducing a scale-invariant sequence model might overcome the challenge of future basin-wide correlation of sequences and systems tracts, once major third-order flooding surfaces and sequence boundaries have been defined.

Palynological samples from siltstones and limestones of the Opletnya and Sfrazen sections span the upper fluvial interval of the Petrohan Terrigenous Group, the Svidol Formation (transitional interval) and the lowermost part of the shallow-marine Opletnya Member of the Mogila Formation (Fig. 2). The 8 samples were prepared using standard palynological processing techniques, including HCl (33 %) and HF (73 %) treatment for dissolution of carbonates and silicates, and saturated $ZnCl_2$ solution (D≈2.2 g/ml) for density separation. Residues were sieved at 15 µm mesh size. Slides have been mounted in Eukitt, a commercial, resin-based mounting medium. Sedimentary organic matter was studied under a Leica DM2000 transmitted light microscope.

Results

Sedimentology and facies

The uppermost 50–55 m of the Petrohan Terrigenous Group are composed of fluvial channel and near-channel sandstone bodies and overbank fines. The sandstones are medium- to fine-, rare coarse-grained, poorly to moderately sorted quartz arenites, sublitharenites and subarkoses. Detrital monocrystalline quartz grains are dominant (average over 50 %), with polycrystalline quartz being present (average 6 %). Detrital feldspar occurs in small amounts, mainly presented by potassium feldspar. The lithic fragments are mainly volcanic (average 2.5 %), and plutonic fragments are present as single grains. Mica is mainly muscovite with biotite being present. Mud intraclasts are very rare.

In the lower 25–35 m of this part of the Petrohan Terrigenous Group sandstones show trough, planar and low-angle cross-bedding and ripple cross-lamination (Fig. 4) forming downstream accretion and rarely lateral accretion bodies (Fig. 5c). They are overlain by a package of massive, low-angle cross-bedded sandstones with ripple cross-lamination and massive to laminated sandy and silty mudstones. Small-scale load cast structures and local erosional features can be observed at the base of the sandstone bodies. Carbonate pedogenic features, mainly powder calcrete levels (Figs. 4, 5e), occur mainly in overbank deposits. Rarely and weakly developed, they can be found in near-channel deposits. The thickness of the elementary fluvial cycles varies from 9.7 to 11.1 m.

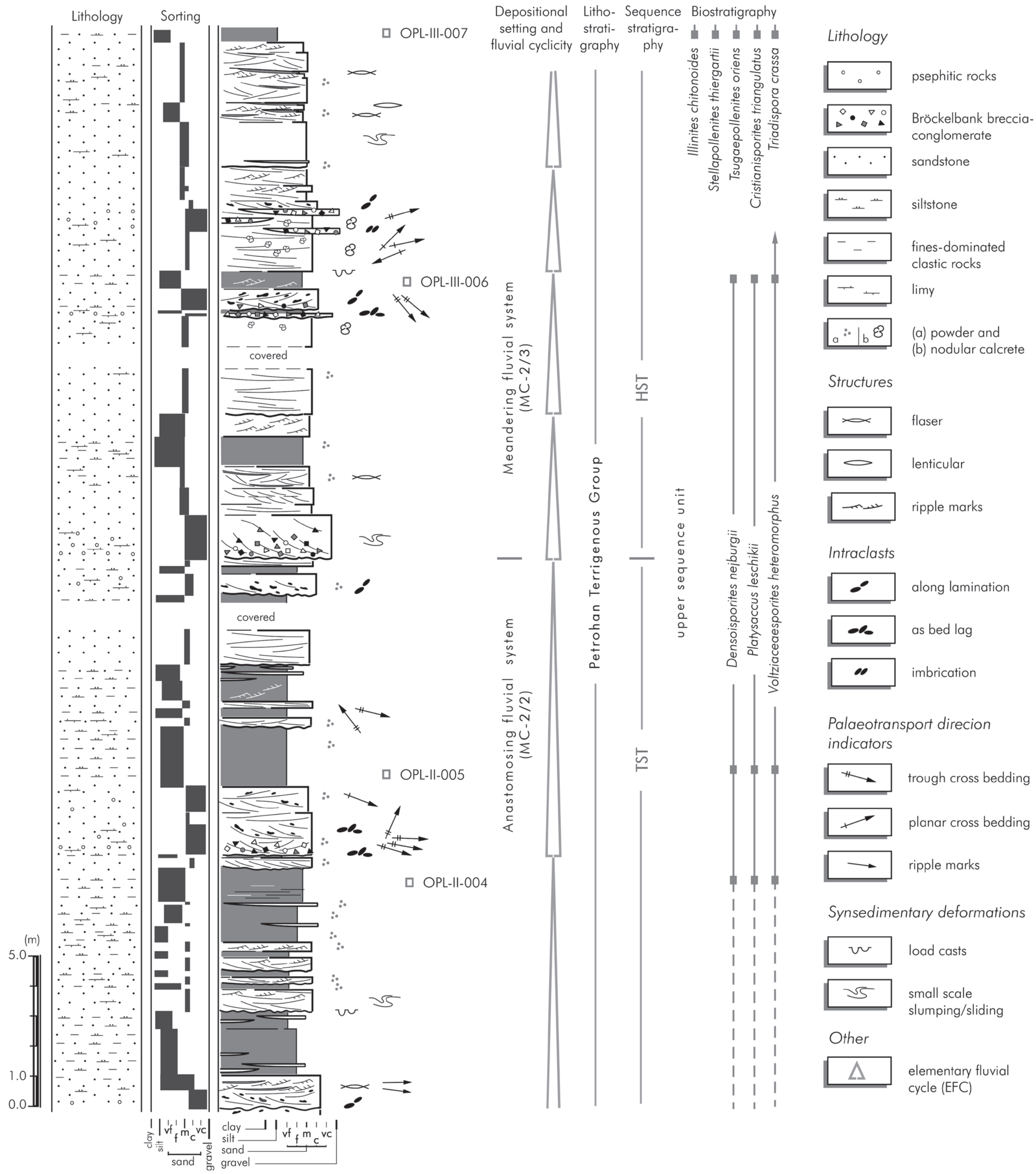

Fig. 4. Lithological column, depositional setting and stratigraphy of the upper part of the Petrohan Terrigenous Group exposed west of Opletnya village. The fluvial cyclicity is presented by elementary fluvial cycles (EFC). A marked change in palynological key taxa is documented in the uppermost Petrohan Terrigenous Group (sample OPL-III-007). Abbreviations used: TST — transgressive deposits; HST — highstand deposits. Palynological samples: OPL-II-004, OPL-II-005, OPL-III-006, OPL-III-007.

Fig. 5. Petrohan Terrigenous Group: **a** — upper part of elementary fluvial cycle (EFC) with near-channel fines (marked by hammers) preserved, covered by cross-bedded channel sandstones of the next EFC with muddy intraclast lags (arrows); braided river part (MC-1/1) of mesocycle MC-1, Opletnya section; **b** — upper part of thick overbank fines (sample OPL-II-004) intercalated by a set of crevasse-splay sandstone beds (between arrows) and their boundary (dashed line) with the overlying channel sands of the upper part of the anastomosing fluvial interval of MC-2 (MC-2/2), Opletnya section; **c** — lateral accretion sandy point bar bed with erosional base (arrows) that forms the base of an elementary fluvial cycle within the anastomosing fluvial interval of mesocycle MC-2 (MC-2/2), Tserovo section; **d** — synsedimentary deformation (slumping) in the upper part of the point bar rich in reworked palaeosol materials; lower part of an elementary fluvial cycle within the meandering fluvial part of mesocycle MC-2 (MC-2/3), Opletnya section; **e** — small powder concretions in palaeosol profile formed in overbank fines, upper part of the Tserovo section; **f** — allochthones reworked as cross-bedded lag lenses (Bröckelbank breccia lithofacies; Bbr) and autochthones (dense clarets; Pc) with palaeopedogenetic products at the base and within a crevasse-splay body from the uppermost part of the Petrohan Terrigenous Group (PTG); (MC-2/3), Sfrazen section. The boundary with the overlying Svidol Formation (SvF) is marked by solid line.

In the uppermost 15 to 25 m of the Petrohan Terrigenous Group the thickness of the elementary fluvial cycles decreases more than twice ranging from 3.2 to 5.4 m (Fig. 4). The lateral distribution of the overbank fines is much more restricted as well as their portion within a cycle. Multiple erosional surfaces are typical for the channel part of the cycles. Often the lag deposits contain much more reworked calcrete nodules than muddy intraclasts (Fig. 5f). Flaser and lenticular bedding as well as climbing ripple cross-lamination are common in the upper parts of the elementary fluvial cycles (Fig. 4). Synsedimentary deformations occur some meters to tens of meters laterally apart of similar erosional surfaces (Fig. 5d).

Based on the facies and the sedimentary structures described above, the lower part of the Petrohan Terrigenous Group is interpreted as belonging to an anastomosing fluvial system, while the upper part characterizes a meandering system (Fig. 4).

The Svidol Formation shows a large variety of siliciclastic terrigenous, siliciclastic-carbonate and carbonate rocks. Its basal part is represented by an 8 to over 10 m thick interval (unit A of Tronkov & Ajdanlijsky 1998b) of alternating tidal- and fluvial-influenced deposits showing a distinct cyclic pattern (Figs. 6, 7a,b). The base of the small-scale sedimentary cycles is characterized by sharp-based sandstone beds with tidal ripples that periodically overlie claystones or siltstones (Fig. 8). In places, this surface is developed as a shallow scour (Fig. 6). Mainly vertical bioturbation and small-scale synsedimentary deformation features such as sliding and convolute lamination are observed in the lower parts of the cycles (Figs. 6, 7c, 8). Upsection, sandstones become thinner and finer, claystones predominate, and thin beds of marly dolostones appear (Fig. 7e), often with evidence of prolonged subaerial exposure resulting in intrabasinal mud- and doloclast redeposition (Figs. 6, 7f). An increase of sand content together with carbonate pedogenic features such as powder spots and small nodular calcretes and cluster-like aggregates of calcite or dolomite composition as well as desiccation cracks are observed (Figs. 6, 8).

Upsection, the small-scale cycles show a reduction in thickness. The sandy siliciclastic lithofacies are still prevailing, but the carbonate content of the rocks is increasing. This 9 to 12 m thick interval (unit B of Tronkov & Ajdanlijsky 1998b) is characterized by bi-directional small-scale cross-lamination (ripple marks), the gradual disappearance of carbonate palaeopedogenic features (here represented only by powder spots), the shift of bioturbated intervals to the middle part of the cycles as well as occurrence of mica in the sediments (Figs. 6, 8). Wavy, flaser, lenticular and nodular bedding are common. The red colors are gradually replaced by ochre and whitish-beige ones. Cycles form coarsening-upward successions, built up predominantly of marls, dolomarls and argillaceous dolomites. Limestones with single and poorly preserved fragments of brachiopods and bivalves are also present. The trend of cycle thickness reduction is maintained.

The following interval (unit C of Tronkov & Ajdanlijsky 1998b) is characterized by intertidal grey limy sandstones, beige-grey marls, and limy siltstones with intercalated micritic limestones (Fig. 8) rich in brachiopods and bivalves. Evidence of erosion is rarely observed and mainly associated with small-scale scour-and-fill structures.

The uppermost part of the Svidol Formation (unit D of Tronkov & Ajdanlijsky 1998b) consists of cycles built up by carbonates and marls with supratidal dolomites and dolomarls prevailing upsection (Fig. 8). Fragments of marine bivalves and crinoids are common. The top of this unit is marked by an erosional and transgressive surface. The depositional environment of the Svidol Formation thus reflects alternating fluvial and tidal influences (Fig. 6).

The lowermost part of the Mogila Formation (Opletnya Member) is dominated by carbonates displaying a great facies variety. Detrital quartz and clay still occur but are limited to discrete and thin levels. Grainstones and rudstones containing ooids and bioclasts (Figs. 9, 10b) are most prominent, with well-developed cross-bedding (Fig. 10d) and absence of micritic matrix. Grain- and packstones can also contain a high amount of peloids and mudstone lithoclasts. They are commonly strongly bioturbated and may show overpacking.

Wackestones are often bioturbated and contain benthic foraminifera and ostracods. Mudstones, often laminated and comprising pyrite, some of them bioturbated as well, are also common in the lowermost part of the member. In some mudstone beds solitary fragments or thin lenses of gagate are observed (Fig. 10g). Birdseyes occur occasionally both in wackestones and mudstones. Wackestones as well as mudstones may be dolomitized (Fig. 10e). Small-scale synsedimentary deformation, some of it with sigmoidal texture, is also observed in several levels (Figs. 9, 10f).

Dolomites commonly are associated with tepees and flat pebbles that form local lags (Fig. 10b) and/or lenses with chaotic orientation of the clasts. Some of them exhibit also imbrication structures, or the clasts form short bands lying on the foreset lamina in cross-stratified levels. On top of distinct dolomite beds, hardgrounds are developed (Fig. 10c). The facies and sedimentary structures of the Opletnya Member point to a peritidal to shallow-marine environment (Fig. 9).

Palynology

Sedimentary organic matter is poorly preserved in the lower part of the studied interval within the Petrohan Terrigenous Group (samples OPL-II-004 and OPL-II-005 from MC-2/2, and OPL-III-006 from MC-2/3; Fig. 4). Samples from the uppermost Petrohan Terrigenous Group (sample OPL-III-007; MC-2/3; Fig. 4), from the Svidol Formation (transitional interval, samples SFR-IV-008, SFR-IV-009, and SFR-IV-010; Fig. 6) and from the lowermost shallow-marine Mogila Formation (lower Opletnya Member, sample SFR-013 (TST); Fig. 9) show well-preserved organic particles.

A palynomorph assemblage dominated by *Densoisporites nejburgii*, *Platysaccus leschikii* and *Voltziaceaesporites heteromorphus* places the lower part of the studied fluvial Petrohan Terrigenous Group (samples OPL-II-004, OPL-II-005, OPL-III-006; MC-2/2-3) in the Early Triassic (Olenekian). An early Anisian (Aegean) palynomorph assemblage is identified from the uppermost fluvial Petrohan Terrigenous Group (sample OPL-III-007; MC-2/3), the Svidol Formation (transitional interval, samples SFR-IV-008, SFR-IV-009, and SFR-IV-010) and the lowermost shallow-marine Mogila Formation (lower Opletnya Member, sample SFR-013), including Anisian index taxa such as *Illinites chitonoides*, *Stellapollenites thiergartii*, *Tsugaepollenites oriens*, *Cristianisporites triangulatus*, and *Triadispora crassa* (Fig. 11). Therefore, the studied interval is stratigraphically placed at the Early–Middle Triassic boundary. Marine acritarchs (*Micrhystridium* spp.) were identified about 6 m above the onset of shallow-marine limestones (sample SFR-013; Fig. 9) in the basal part of the Opletnya Member of the Mogila Formation.

Palynofacies is dominated by opaque phytoclasts of different size and shape (equidimensional and needle-shaped),

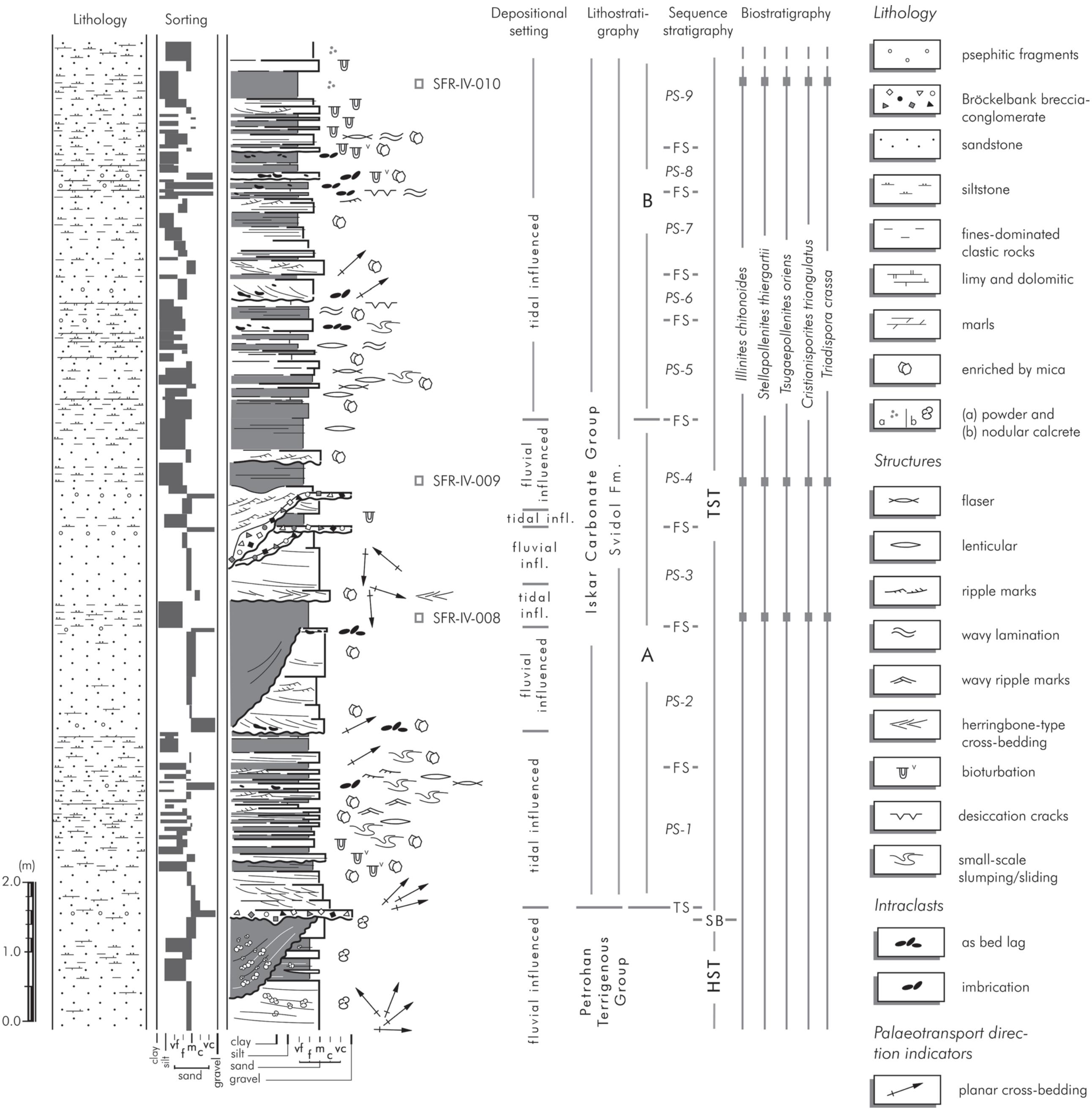

Fig. 6. Lithological column, depositional setting and stratigraphy of the lower part of the continental–marine transitional interval exposed west of Sfrazen hamlet. Abbreviations used: TST — transgressive deposits; HST — highstand deposits; SB — third-order sequence boundary; TS — transgressive surface; FS — flooding surface; PS — parasequence. A–B — units according to Tronkov and Ajdanlijsky (1998b). Palynological samples: SFR-IV-008, SFR-IV-009, SFR-IV-010.

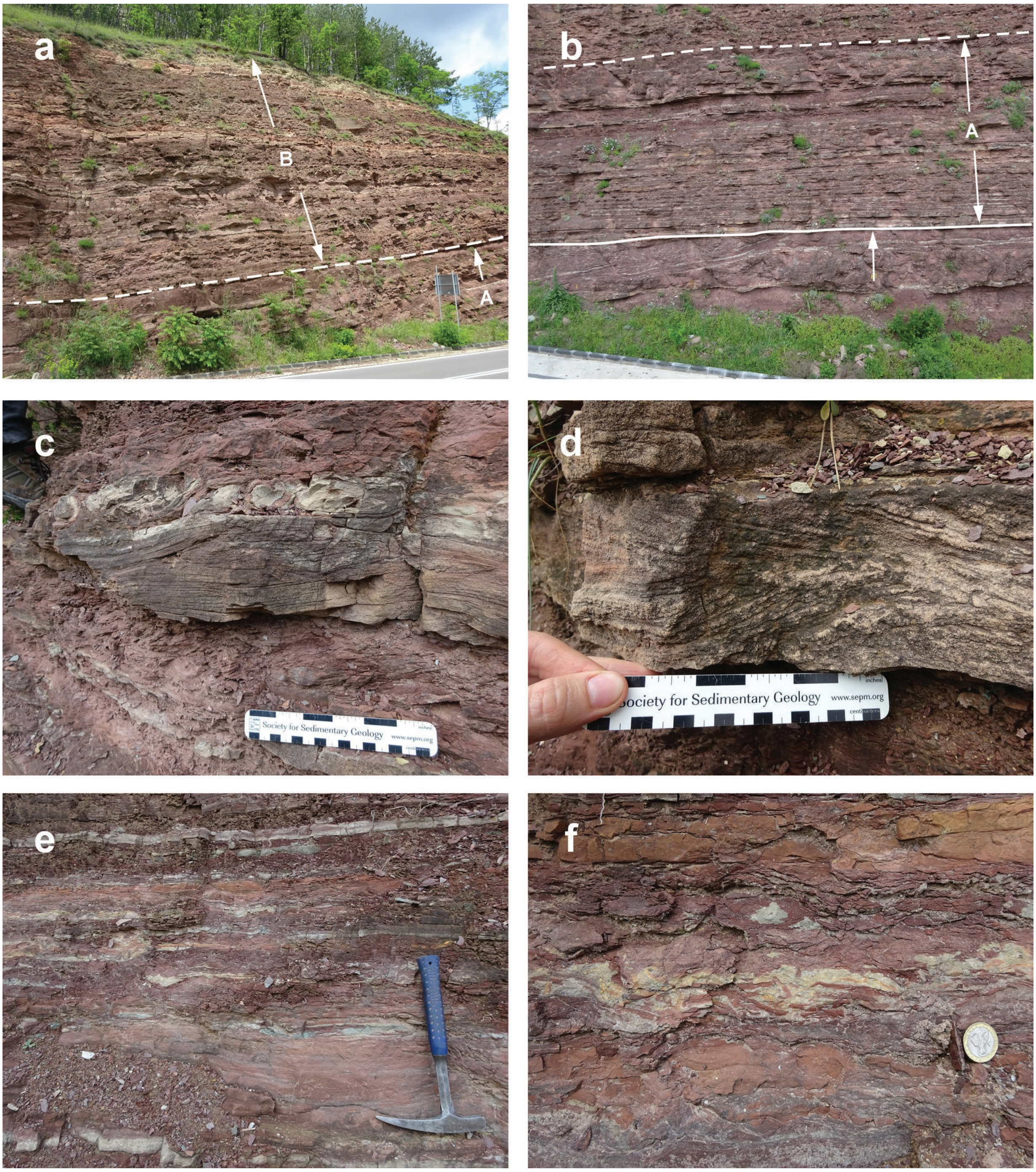

Fig. 7. Svidol Formation: **a** — units A and B (Tronkov and Ajdanlijsky, 1998b) exposed at Sfrazen hamlet; **b** — lower part of the Sfrazen hamlet section showing the boundary between the Petrohan Terrigenous Group and the Svidol Formation (solid line), and between units A and B of the Svidol Formtion (dashed line); **c** — convolute structure as result of synsedimentary small-scale sliding during cut-and-fill channel processes; **d** — herringbone cross-stratification in the middle part of unit A; **e** — supratidal terrigenous-carbonate alternation in the lower part of unit B; **f** — intraformational clasts as result of re-deposition of desiccation-cracked and re-deposited supratidal carbonate and terrigenous materials in the lower part of unit B.

translucent particles being present. Degraded organic matter consists mainly of pollen grains, the dominant palynomorph group; spores are rare. The change in fluvial style from anastomosing to meandering is reflected in the sorting and preservation of sedimentary organic matter (Fig. 12). A higher variety of phytoclast sizes and shapes as well as a high amount of degraded organic matter occurs in samples from fluvial deposits representing anastomosing rivers (samples OPL-II-004, OPL-II-005; Fig. 12a). In contrast, samples from meandering river systems (samples OPL-III-006, OPL-III-007; Fig. 12b) show a high amount of small, equidimensional opaque phytoclasts, a higher amount of translucent particles, and a better preservation of palynomorphs. The palynofacies of tidal-flat deposits (sample SFR-IV-010; Fig. 6) is dominated by opaque phytoclasts. The onset of the transgressive phase within the basal Mogila Formation is documented by an acritarch peak (sample SFR-013; Fig. 9).

So far, the studied succession was interpreted as Lower Triassic deposits (cf. Tronkov 1981; Mader & Čatalov 1992). The here presented new palynological data reveal an early Middle Triassic age for the uppermost Petrohan Terrigenous Group, and the Early–Middle Triassic boundary is placed within the late highstand of the MC-2 sequence, about 1 m below the base of the Svidol Formation (basal Iskar Carbonate Group). The marine plankton peak in the basal Mogila Formation may represent a first transgressive pulse of the carbonate ramp evolution during Anisian times.

Depositional sequences

In the study area, the Petrohan Terrigenous Group is composed of three mesocycles (Ajdanlijsky et al. 2004; Ajdanlijsky 2005, 2010a) that correspond to third-order cycles (*sensu* Miall 1997) or third-order sequences (*sensu* Miall 2010), the base of which are marked by distinctive erosion surfaces (Fig. 2). Only the uppermost mesocycle (MC-2) is completely developed and comprises three parts. Its base marks a regional sequence boundary incised a few to over 30 meters into the underlying fluvial sequence.

The lowermost part of mesocycle MC-2 (sub-mesocycle MC-2/1) is represented by an amalgamated braided fluvial succession representing lowstand or early transgressive deposits. They are stacked, multistory medium- to coarse-grained sandstone channel fills with a very restricted portion of near-channel or overbank deposits (Fig. 5a; Ajdanlijsky 2010a). The channel-fill deposits are dominated by sandy bedforms and show a high width/thickness ratio. The fluvial palaeotransport pattern is unidirectional (Ajdanlijsky 2005, 2009). The palaeosol products are represented mainly as reworked channel lag conglomerates.

Transgressive deposits consist of mud-rich, anastomosing isolated fluvial channels in the middle part of the sequence (sub-mesocycle MC-2/2), indicating base-level change. In this part of the sequence elementary fluvial cycles (EFC) with maximum thicknesses (over 11 m) are identified. They are formed by channel, near-channel (levee and crevasse splay) and overbank deposits (Fig. 4). The channel part, where downstream accretion sand bodies dominate over the lateral accretion ones, forms only 25 to 30–35 % of the EFC and the crevasse splay beds are separated by relatively thick overbank fines. A similar proportion leads to ribbon morphology of the channel complex. Here, in overbank intervals, silty beds and even pure claystones are present, suitable for palynological sampling. In braided and meandering fluvial settings, silt- and claystones are completely absent or relatively rare, documented as very thin isolated lenses. The palaeosol levels are in an initial stage of development, mainly in crevasse splay beds and in overbank fines, represented by powder nodules or spots.

The uppermost 15 to 25 m thick siliciclastic package of the Petrohan Terrigenous Group (sub-mesocycle MC-2/3) formed in a high-sinuosity (i.e. meandering) fluvial setting, documenting highstand deposits. An abrupt reduction of the overbank part of the EFC is observed, while maintaining the thickness of the channel and levee deposits, which in turn leads to a reduction of the EFC more than twice compared to the underlying interval (Fig. 4). Multiple erosional surfaces and palaeosols are typical for this part. Frequent channel erosion, caused by restricted accommodation space, led to the development of calcrete lags in channel and near-channel beds (Fig. 5d, f; Ajdanlijsky 2000) or caused synsedimentary slide and slump structures (Ajdanlijsky 2001b). The top of the Petrohan Terrigenous Group is marked by the next third-order sequence boundary (Fig. 6).

The Svidol Formation represents a third-order depositional sequence. Its lower part exhibits transgressive deposits (TST) with a prominent transgressive surface that closely follows the sequence boundary at the top of the Petrohan Terrigenous Group, documenting a rapid shift from terrigenous facies to a tidally influenced depositional environment (Figs. 6, 7b, 8). Lowstand deposits are absent or thin because accommodation was lacking. The siliciclastic-dominated lower part of the formation is formed during rising sea level that remobilized sands and clays. Accommodation space was created but constantly filled by sediment, thus maintaining a tidal-flat or tidally-dominated environment. High-frequency sea-level fluctuations were superimposed on this general trend and created a cyclic succession that is interpreted to be formed by elementary sequences (*sensu* Strasser et al. 1999) or parasequences (*sensu* van Wagoner et al. 1990). In Figure 6, the parasequence concept is applied, the limits of the parasequences (PS) corresponding to marine flooding surfaces (FS). The lower part of the TST records more coarsening-upward than fining-upward parasequences, each passing from tidally to fluvially influenced sedimentation. They are interpreted as corresponding to prograding bodies in a deltaic sedimentary environment. As a whole, however, the TST is built up of retrogradational parasequence sets and only in its uppermost part features of aggradational stacking are present (Fig. 6).

Upsection, the marked change from siliciclastic to carbonate deposits is interpreted as being related to maximum flooding, when reduction of clastics in the water column may have allowed the carbonate-producing organisms to proliferate, and carbonate mud accumulated in a shallow-water environment. The maximum-flooding interval (MF in PS 12; Fig. 8) is marked by a finely laminated, dark-gray, silty marl layer. The upper part of the Svidol Formation, featuring dolomitic limestones, is interpreted as highstand deposits (HST), although a shallowing-up trend is not visible. The sequence boundary is not clearly defined but must be placed below the transgressive surface of the following sequence that initiates the deposition of the carbonate-dominated Mogila Formation (Fig. 9).

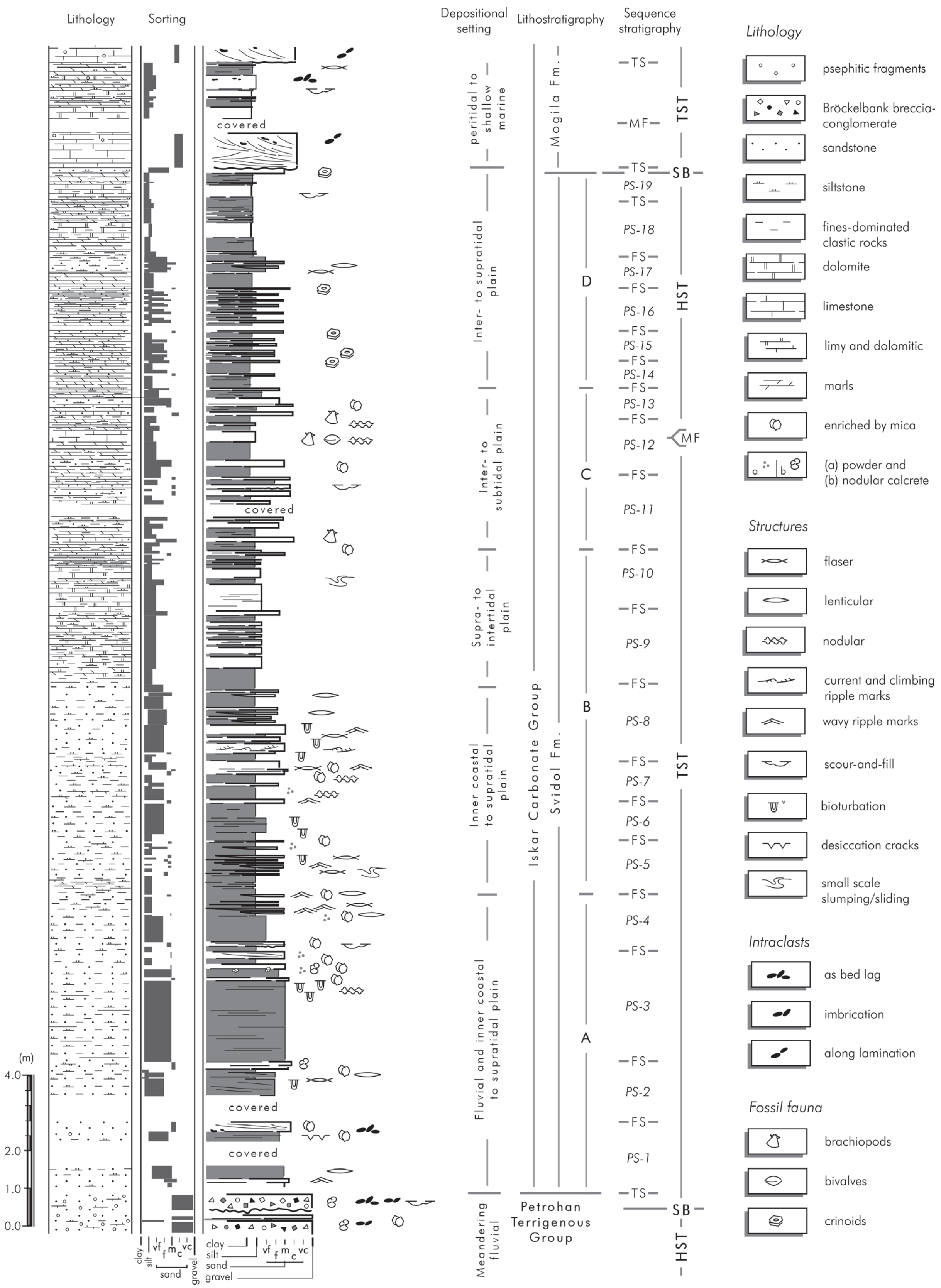

Fig. 8. Lithological column, depositional setting and stratigraphy of the Svidol Formation in the studied outcrop east of Tserovo village. Abbreviations used: SB – third-order sequence boundary; TST – transgressive deposits; HST – highstand deposits; TS – transgressive surface; FS – flooding surface; MF – third-order maximum-flooding interval; PS – parasequence; A-D – units according to Tronkov and Ajdanlijsky (1998b).

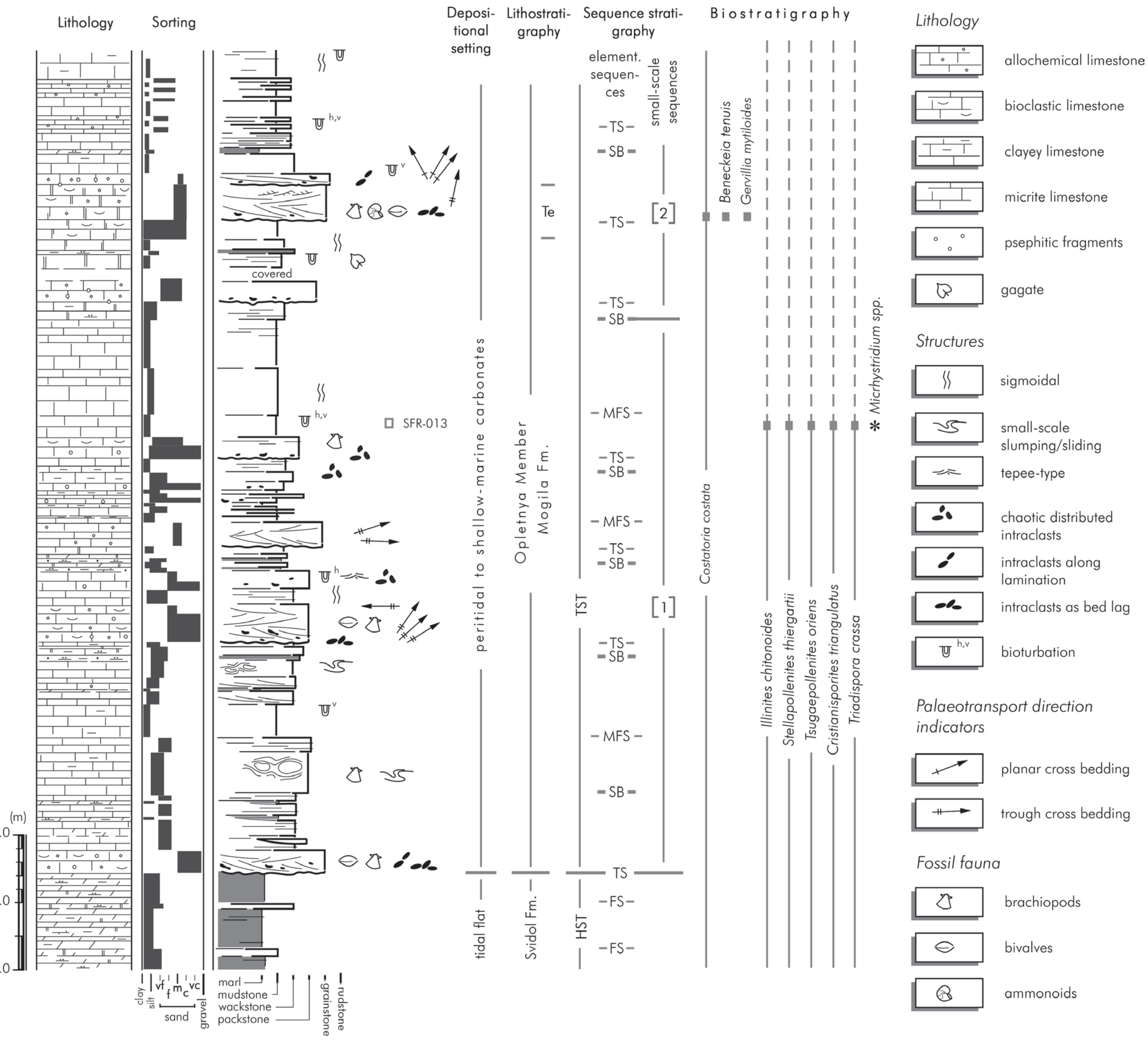

Fig. 9. Lithological column, depositional setting and stratigraphy of the lowermost part of the shallow-marine interval of the Opletnya Member (Mogila Formation) exposed between Opletnya village and Sfrazen hamlet. Fossil macrofauna distribution according to Tronkov (1968). Abbreviations used: Te — Tenius Bed; TST — transgressive deposits; HST — highstand deposits; SB — sequence boundary of elementary sequence; FS — flooding surface; TS — transgressive surface; MFS — maximum-flooding surface of elementary sequence. Palynological sample: SFR-013.

In the lowermost, carbonate-dominated part of the Opletnya Member, the depositional sequences are interpreted following the methodology of Strasser et al. (1999). Elementary sequences commonly start with high-energy facies representing tidally influenced oolitic and/or bioclastic bars formed during transgression, when the previously very shallow, intertidal or supratidal environment was flooded (Fig. 10b). The corresponding transgressive surface is well developed and commonly erodes into the underlying sediment (Fig. 9). The increased water depth and diminished current energy led to the abandonment of the high-energy bars. Low-energy wacke- and mudstones then predominate. Intense bioturbation may indicate temporarily low sedimentation rates. A rapid shift from high-energy to low-energy as well as reduced sedimentation rate are interpreted to be related to maximum flooding on the scale of an elementary sea-level cycle. Also the preservation of gagate (Figs. 9, 10g) around maximum-flooding surfaces seems to reflect a change in the hydrodynamic conditions. Highstand deposits in the elementary cycle are mud-dominated, part of them dolomitized, with evaporite pseudomorphs and/or tepees. If siliciclastics occur, they are more abundant in the late highstand. This suggests that they have been washed into the system when relative sea level dropped, contrary to the ones in the Svidol Formation that are associated to transgression. The boundaries of the elementary sequences cannot always be placed at a discrete bedding surface and rather define thin sequence-boundary zones (Strasser et al. 1999). Below the following transgressive surface, thin lowstand or

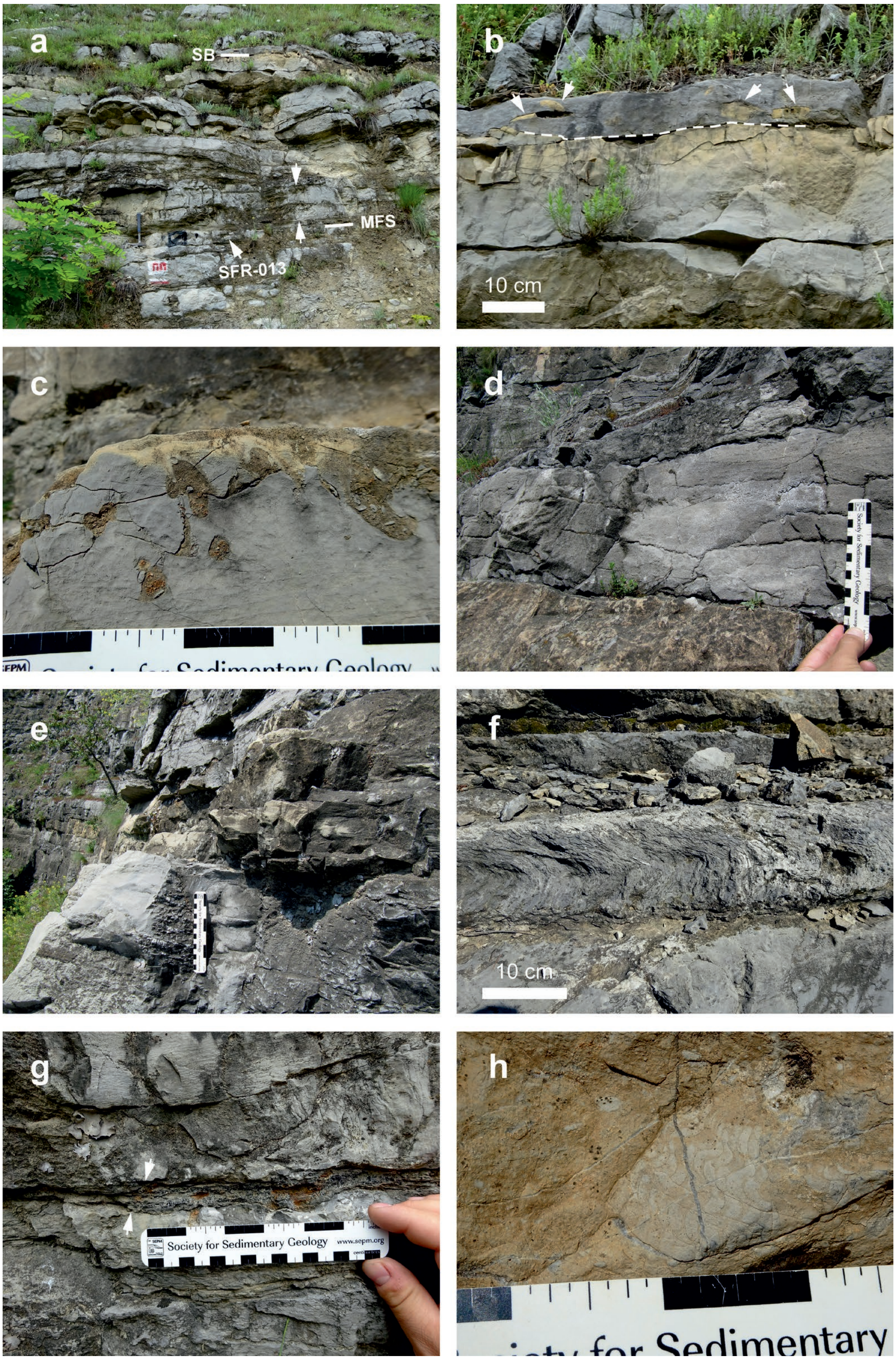

Fig. 10. Opletnya Member (Mogila Formation): **a** — elementary sequence with maximum-flooding surface (MFS) and sequence boundary (SB), and interval with sigmoidal structures (between arrows), Sfrazen section (hammer for scale); **b** — top of the elementary sequence overlain by grainstones with large, slightly rounded dolomitic intraclasts, Sfrazen section; **c** — hardground marking the top of an elementary sequence, Sfrazen section; **d** — allochemical trough cross-bedded limestone at the bottom of an elementary sequence, Lakatnik section; **e** — upwards dolomitized package of massive wacke- and mudstones that forms the top of an elementary sequence, Lakatnik section; **f** — sigmoidal structure in the upper part of an elementary sequence, interpreted as the result of small-scale synsedimentary slumping, Lakatnik section; **g** — thin gagate lenses developed in the maximum-flooding zone of the elementary sequence below the Tenius level, Lakatnik section; **h** — *Beneckeia tenuis* level, Lakatnik section.

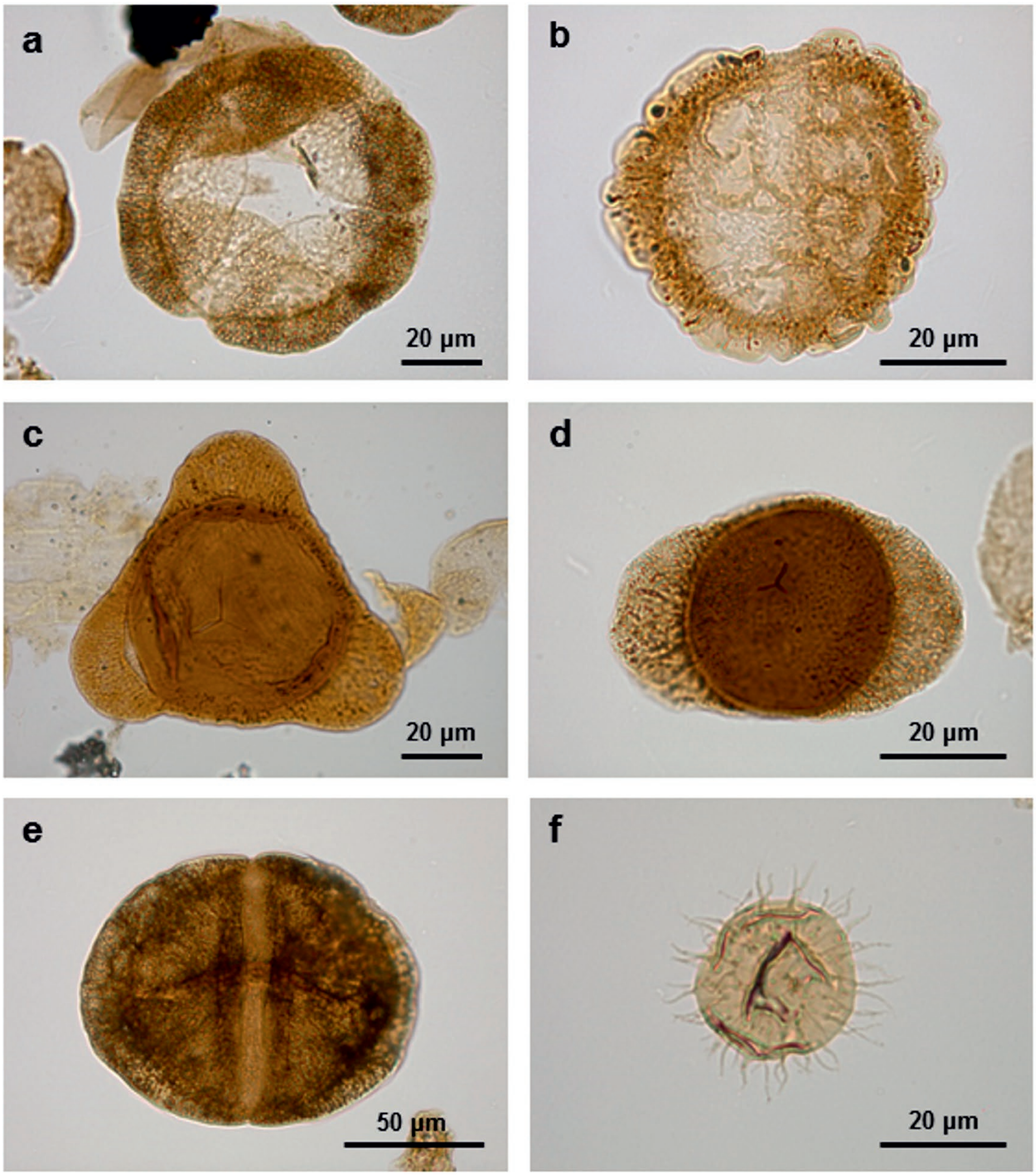

Fig. 11. Palynomorphs of the Opletnya (OPL) and Sfrazen (SFR) sections: **a** — *Stellapollenites thiergartii* (Mädler 1964) Clement-Westerhof et al. 1974 (sample SFR-IV-008); **b** — *Tsugaepollenites oriens* Klaus 1964 (sample OPL-III-007); **c** — *Cristianisporites triangulatus* Antonescu 1969 (sample SFR-IV-009); **d** — *Triadispora crassa* Klaus 1964 (sample OPL-II-005); **e** — *Illinites chitonoides* Klaus 1964 (sample SFR-IV-010); **f** — *Micrhystridium* sp. (sample SFR-013).

early transgressive deposits may occur. In some cases, however, a prominent transgressive surface directly overlies the sequence boundary, implying very low accommodation.

A striking feature of highstand deposits in elementary sequences is the development of sigmoidal and other types of small-scale synsedimentary deformation, as recorded in the lower 30 m of the Opletnya Member. In previous studies, they have been interpreted as product of periodic palaeoseismic activity (Chatalov 2001a, b), related to the onset of oblique rifting in the Palaeo-European shelf (Michalík 1997). However, the present study reveals that most of them developed during a stage of decreasing accommodation space when the weakly lithified mainly wacke- and mudstones became unstable because of shallow channel erosion and slumped over a very short distance, forming thin lens- and/or wedge-like disturbed bodies. Their repeating presence in the same level of the elementary sequences (Figs. 9, 10f) indicates a cyclic sedimentary rather than a palaeoseismic control.

Elementary sequences are composed of several beds, and facies reflect different sub-environments in the shallow-subtidal, intertidal, and supratidal realms. Autocyclic processes such as shifting mudbanks or tidal channels are common in

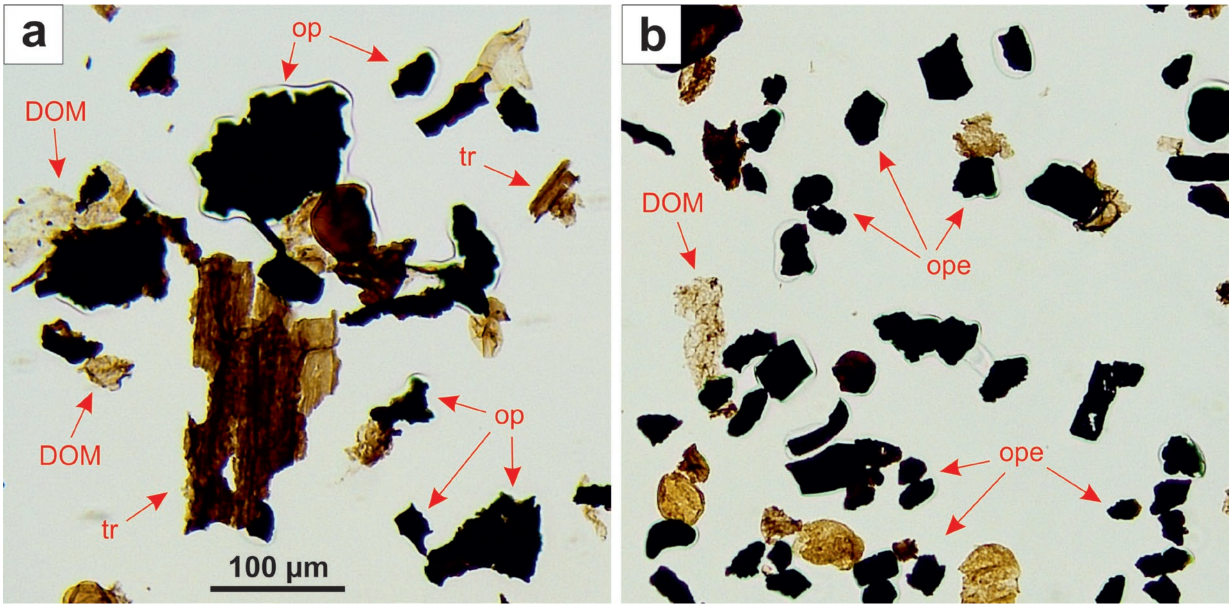

Fig. 12. Palynofacies of fluvial deposits: **a** — Anastomosing river systems (sample OPL-II-005) are characterized by a high variety of phytoclast sizes and shapes (op — opaque particles, tr — translucent particles) as well as a high proportion of degraded organic matter (DOM); **b** — meandering river systems (sample OPL-III-006) show a high percentage of small, equidimensional opaque phytoclasts (ope). Scale (100 µm) applies to (a) and (b).

such environments (e.g., Pratt & James 1986; Strasser 1991). Consequently, the unequivocal definition of an elementary sequence that is related to a sea-level cycle (i.e. that is allocyclic) is not always possible.

Elementary sequences stack into larger sequences, termed small-scale sequences that again show characteristic facies trends: many contain ooids preferentially in their lower part and muddy facies in their upper part (Fig. 9). This is interpreted as being related to the long-term transgressive-regressive sea-level evolution, over which the higher-frequency elementary cycles were superimposed.

Discussion

To date, the lack of precise age control of the studied interval, documenting the continental–marine transition within the Lower to Middle Triassic of NW Bulgaria, hampers its chronostratigraphic subdivision. Previously, the chronostratigraphic placement of the Petrohan Terrigenous Group, the Svidol Formation and the Opletnya Member of the Mogila Formation in the area of the Iskar river gorge was based on regional geological criteria and data from adjacent areas (Ganev et al. 1965, 1970; Assereto et al. 1983; Chatalov 1994, 1997a, 1999, 2000b, 2005a,b). By analogy with the German Triassic deposits, Tronkov (1968, 1983) used the bivalve *Costatoria costata* (Zenker), which in Germany indicates the *Costatoria costata–Beneckeia tenuis* zone, as an index fossil for the uppermost parts of the Lower Triassic series, and the lowermost parts of the Anisian stage were defined by the presence of *Plagiostoma radiatum* (Goldfuss). Accordingly, he placed the Lower–Middle Triassic boundary about 12 m below the boundary between the Opletnya Member and the dolomites of the upper member of the Mogila Formation (Lakatnik Member) (Fig. 2). Some authors (Tronkov & Ajdanlijsky 1998 a,b; Chatalov & Stanimirova 2001; Ajdanlijsky et al. 2004) accept and use these biostratigraphic index fossils, while others place the boundary in the middle (Chatalov 2000a) or even lower parts of the Opletnya Member (Chatalov 2005a, 2007, 2013, 2018), sometimes quite arbitrarily and without giving biostratigraphic evidence.

On the other hand, independent local studies of different researchers within the continental, transitional and marine intervals of the Lower–Middle Triassic led to the introduction of different terminologies in the literature, using cyclostratigraphic or sequence-stratigraphic terms.

Scale, composition, lateral extent and nature of the bounding surfaces of the three mesocycles within the Petrohan Terrigenous Group (Ajdanlijsky 2005, 2009) correspond with the third-order sequences *sensu* Miall (2010). However, the identification of systems tracts of third-order sequences following the non-marine sequence model of Wright & Marriot (1993), Shanley & McCabe (1994), and Gibling & Bird (1994) is still hampered by the lack of studies on a basin scale.

Based on the here presented palynostratigraphic data, the boundary between the uppermost mesocycle MC-2 of the Petrohan Terrigenous Group and the base of the Svidol Formation (Iskar Carbonate Group) is dated and correlated with a major sequence boundary Ol4 in the upper Olenekian (Hardenbol et al. 1998; Ogg 2012) of the Tethyan realm. Using this boundary as a time line, the three mesocycles of the Petrohan Terrigenous Group (MC-0, MC-1, MC-2; Fig. 2) may be interpreted as medium-scale sequences within the Olenekian Stage, bounded by the Ol3 and Ol2 sequence boundaries. On the other hand, this boundary may also be correlated with the S2/An1 and An1/An2 sequence boundary in the late Olenekian of the Peri-Tethys realm and the southern Alpine basins (Rüffer & Zühlke 1995; Szulc 2000; Feist-Burkhardt et al. 2008).

The new palynological data obtained from the Triassic continental–marine transitional interval allow redefinition of the age range of both the Petrohan Terrigenous Group and the Iskar Carbonate Group (Fig. 2), which is important not only for the intrabasinal correlation but also for the application of sequence- and cyclostratigraphy for precise stratigraphic subdivision and interregional correlation. Previously, the Petrohan Terrigenous Group and the continental–marine transitional succession of the basal Iskar Carbonate Group (Svidol Formation and the lowermost Mogila Formation) were placed in the Early Triassic (Tronkov 1983; Chatalov 2018; Fig. 2). The new biostratigraphic data indicate an Anisian age for the uppermost Petrohan Terrigenous Group, the Svidol Formation and the lowermost Mogila Formation.

Refinement of the early Anisian age range of the Triassic continental–marine transition interval also serves to interpret the palaeogeography of the area studied. Recently published data on the benthic foraminifera association of Triassic sections along an east–west transect of the Western Balkanides (Chatalov et al. 2016; Ivanova et al. 2016) provided an Aegean/Bithynian age for the transitional interval. This confirms a significant E–W surface leveling at the end of the Early Triassic in NW Bulgaria as documented in sub-mesocycle MC 2/3 (highstand deposits) of the Petrohan Terrigenous Group (Ajdanlijsky 2005, 2010b), which led to a meandering fluvial sedimentation style. Later, during the continental–marine transition interval, the relatively flat palaeotopography enabled preservation of minor fluctuations in sea level with high-frequency transgressions and regressions, generating parasequences and elementary sequences with significant lateral extent. Such conditions continued during the initial stage of accumulation of the sediments of the Opletnya Member.

The end-Spathian (Early Triassic) surface leveling determined the development of the boundary between the Petrohan Terrigenous Group and the Svidol Formation and the sedimentary record of the early Anisian continental–marine transition. The lower part of the Svidol Formation documents the initial transgression with alternating tidal and fluvial packages, limited terrigenous supply and gradual development of shallow-marine environments recorded in small-scale sequences (Figs. 6, 8). This gradual development of shallow-marine environments is also reflected in the palaeontological record. In the lowermost part of the Mogila Formation, Tronkov (1983) reports well-preserved single specimens of *Beneckeia tenuis* (Seebach) in the Tenuis Bed (Fig. 2), situated about 9.5 m above the boundary with the Svidol Formation. Later, the same author (unpublished data) reports on the presence of *Beneckeia tenuis* in various stratigraphic horizons in the Mogila Formation exposed along the Iskar River and to the north, in the Vratza region, within the Svidol Formation. Assuming that these horizons are synchronous, the difference in their position relative to the transitional interval along a south-north transect in the eastern part of the Western Balkanides could be interpreted as evidence of a northwards marine transgression. However, additional biostratigraphic control, e.g. conodont data, has to validate the use of the existing sparse information for further interpretation.

The stratigraphic subdivision of the lower Iskar Carbonate Group based on lithofacies as well as on the nature and scale of the cyclicity has also been discussed in previous studies. Čatalov (1974) subdivided the Svidol Formation into two cycles: a lower symmetrical transgressive-regressive cycle, and an upper one represented only by its transgressive part. Later, Mader & Čatalov (1992) established the informal stratigraphical interval "Terminal Mudstones" that corresponds to the Svidol Formation (see also Chatalov 2006). Based on characteristic parasequence sets (*sensu* van Wagoner et al. 1988, 1990), Tronkov & Ajdanlijsky (1998b) subdivided the Svidol Formation into four sets (sets A–D; Fig. 2), forming the transgressive systems tract (sets A–C) and highstand systems tract (set D) of a third-order depositional sequence (*sensu* Miall 2010). Later, El-Ghali et al. (2006) interpreted the transgressive systems tract as generated in tide-dominated deltaic settings and the highstand systems tract representing a tidal-flat environment. In the lower part of the Opletnya Member, Chatalov (1998, 2000a) identified peritidal hemicycles, as well as several well correlatable oolitic levels along the Iskar river gorge (Chatalov 2005a), some of them partially or completely matching with the beds introduced by Tronkov (1983). The same author (Chatalov 2005b) described two specific oolitic levels, one in the lowermost part of the Opletnya Member and another one in the uppermost part of the Svidol Formation, that he proposes as well correlatable in the study area. However, because of the lack of precise biostratigraphic dating of the section, the time range of the different orders of cyclicity has not been defined yet. Undoubtedly, the identification of regionally traceable cycle boundaries based on biostratigraphic age control is a first step towards more accurate basin-wide correlation and palaeogeographic interpretation of the Triassic successions in NW Bulgaria. However, a high-resolution palynostratigraphic zonation scheme is needed to further refine the existing stratigraphic framework by integrating sequence stratigraphy and cyclostratigraphy. Ongoing research aims at providing high-resolution biostratigraphic data to perform regional and interregional correlations.

Conclusions

The detailed analysis of facies and sedimentary structures of Triassic sections in the Iskar river gorge in NW Bulgaria reveals that the depositional environments evolved from anastomosing and meandering river systems (Petrohan Terrigenous Group) to alternating fluvial and tidal influences (Svidol Formation) and then to peritidal and shallow-marine conditions (Opletnya Member of the Mogila Formation). New palynostratigraphic data from these Triassic continental–marine transitional deposits allow for a precise stratigraphic placement of a prominent sequence boundary between the fluvially dominated continental red beds of the Petrohan Terrigenous Group and the shallow-marine deposits of the Iskar Carbonate Group. This boundary may correlate with the major sequence boundary Ol4 occurring in the upper Olenekian of the Tethyan realm and the S2/An1 sequence boundary of the northern Peri-Tethys Basin, thus enabling interregional correlation and refined palaeogeographic interpretation of the Early to early Middle Triassic in NW Bulgaria. Furthermore, the pronounced cyclic character of the transitional sedimentary succession, recorded at different hierarchical scales, and its biostratigraphic age control enable pinpointing the first marine pulse during the early Anisian and reconstructing the evolution of depositional environments across the Early/Middle Triassic boundary.

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