Swiss J Geosci (2016) 109:401–413
DOI 10.1007/s00015-016-0233-4

The first evidence of Permian–Triassic shallow-marine transitional deposits in northern Croatia: Samoborsko Gorje Hills

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Received: 14 January 2016 / Accepted: 2 November 2016 / Published online: 18 November 2016

Abstract Permian–Triassic successions occur throughout the world, but well-exposed transitional sequences are relatively rare. In Croatia, only two localities with continuous transition from Permian to Triassic have been described previously from its southern parts, but in northern Croatia the Permian–Triassic boundary remains undocumented. A succession of Permian and Triassic sub- to supratidal deposits is exposed in the Samoborsko Gorje Hills in N Croatia, on the northern margin of the Dinarides towards the Pannonian Basin. Oldest part of the sequence is composed of dolomudstones to dolopackstones containing an Upper Permian (Lopingian) biota: calcareous algae (gymnocodiaceans and dasycladales), gastropods and smaller foraminiferans (e.g. *Hemigordius* sp., *Glomospira* sp., *Earlandia* sp. and *Ammodiscus kalhori*). The middle part of the succession is characterized by the 'Transitional breccia'—dolomitic breccia and microbreccia, with ferroan calcite cement, probably deposited during the Late Permian regression. 'Transitional breccia' deposits contain only disaster forms (*Ammodiscus kalhori* and *Earlandia* sp.) which are often considered as survivors, but can generally be found in both Permian and Triassic deposits, confirming environmental crises in the shallow-marine environments. Gradual recovery of the biota can be traced in the upper part of the succession, with dolomudstones to dolowackestones containing peloids and sparse, smaller foraminiferans. The presence of foraminiferan *Meandrospira pusilla*, which is identified for the first time in the studied area, indicates a Late Olenekian age for the youngest part of the studied deposits. This study demonstrates that the transition from Permian to Triassic can be indicated even in stressful and/or tectonized areas lacking conodonts, and contributes to the palaeogeographical reconstructions of this part of the Paleo-Tethys.

Keywords Permian–Triassic transition · Samoborsko Gorje Hills · Northern Croatia · Biostratigraphy · Sedimentology

Editorial handling: D. Harper and D. Marty.

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1 Introduction

The end of the Palaeozoic era was characterized by the most severe biotic crisis and the greatest mass extinction in the history of the Earth. At the Permian–Triassic Boundary (PTB) up to 96% of previously existing organisms disappeared, or drastically changed their biodiversity profiles (e.g. Raup 1979; Erwin 2006; Weidlich and Bernecker 2007; Chen et al. 2013). Numerous studies are focusing on the biosedimentary records connected with the PTB and post-extinction ecosystems recovery (e.g. Bottjer et al. 2008; Algeo et al. 2011; Song et al. 2011b, 2015; Chen and Benton 2012; Hofmann et al. 2014; Wei et al. 2014).

Upper Palaeozoic deposits in Croatia can be found only locally, in 11 geographically restricted areas (Sremac 2005), while Triassic deposits are more common (for more details see Velić and Vlahović 2009). Unfortunately, exposures with continuous successions from Permian to Triassic are rarely present. Previously described PTB sections in Croatia are situated mainly in its southern part, in

Fig. 1 Geographic setting of Croatia and neighbouring countries. Position of the Samoborsko Gorje Hills is marked with *A*; *letters B–E* are marking sections with Permian–Triassic deposits in Croatia. *Numbers 1–7* are marking documented PTB sections in Slovenia, Austria, Hungary and Italy (for details see text)

the Karst (Outer or External) Dinarides area (B, C, D and E on Fig. 1).

During the recent road reconstruction between Bregana and Grdanjci village in the northern part of the Samoborsko Gorje Hills (A on Fig. 1; Fig. 2a), which belong to the Croatian part of the Inner Dinarides area, a new road section was exposed, where Upper Permian and Lower Triassic deposits crop out. The Upper Permian deposits in the northern part of the Samoborsko Gorje Hills are mostly represented by carbonates and evaporites deposited in relatively shallow, isolated environments (Šikić et al. 1979), and they were correlated based on fossil assemblages (algae, foraminiferans and rare ammonites). The Permian sequence comprising lagoonal deposits with dasycladal and gymnocodiacean algae, as well as gastropods, was already studied in this area for the purpose of the geological field-trip (Sokač, personal communication), but unfortunately this section is no longer exposed due to road reconstruction. A continuous transition into the Lower Triassic within shallow depressions was proposed, 5 km S of the studied area, dominated by clastic deposits and without any fossil remains (Šikić et al. 1979). Nevertheless, the subsequent tectonic activity in the study area was quite significant (Herak 1956), complicating the reconstruction of the studied succession and raising doubts on the continuity of the deposition.

The aim of this study was to determine the microfossil assemblages in newly opened sections, define their stratigraphic significance and microfacies, reconstruct the succession of the Upper Permian and Lower Triassic deposits and propose the approximate stratigraphic position of the Permian–Triassic Boundary. Emphasis will be given to the reconstruction of the palaeoenvironments and environmental changes, which should also help in palaeogeographic reconstruction for this, so far relatively poorly understood part of the Paleo-Tethys Ocean.

2 Geological and stratigraphical setting

Samoborsko Gorje Hills (A on Fig. 1) are situated in northwestern Croatia, near the capital Zagreb, and belongs to the Zagorje–Mid-Transdanubian Zone of the Inner Dinarides (Pamić and Tomljenović 1998). Tectonic features of the Samoborsko Gorje Hills represent a combination of two structural systems, NW–SE striking Dinaric system and NE–SW striking tectonic system (Palinkaš et al. 2010). Palaeogeographic situation of the Samoborsko Gorje Hills area within the Paleo-Tethys during the Late Palaeozoic is still not completely clear, especially due to its general orientation normal to the Dinaric strike (Sremac 2012).

The area of the Samoborsko Gorje Hills includes Palaeozoic, Mesozoic–Palaeocene and Neogene formations (Herak 1956; Šikić et al. 1979). Palaeozoic deposits are

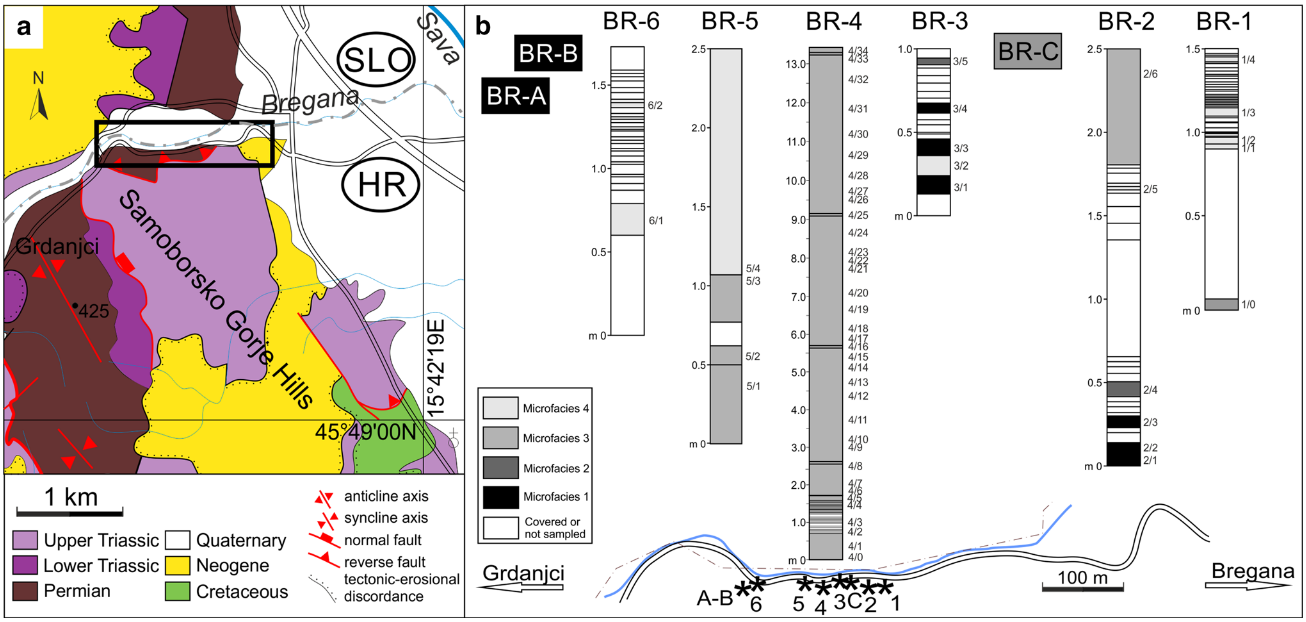

Fig. 2 **a** Geological map of the northern part of the Samoborsko Gorje Hills (modified after Šikić et al. 1977). Research area on the road between Bregana and Grdanjci village is marked with rectangle. **b** Enlarged segment of the road between Bregana and Grdanjci village with marked positions of six sampled sections (BR-1 to BR-6) and three additional outcrops (BR-A, B, C). Sections display position of the individual samples and microfacies types 1–4 (marked by *black*, *dark grey*, *grey* and *light gray*). Note different scale for the section BR-4

characterized by regressive trends, starting with Upper Carboniferous dark grey schists, shales and sandstones followed by Permian fine- to coarse-grained sandstones, interlayered with conglomerates, dolostones and evaporites. Overlying clastic–carbonate unit was deposited during the latest Permian to Early Triassic transgression (Herak 1956; Šinkovec 1971; Šikić et al. 1979). Mixed, carbonate–clastic–evaporite deposits with evidence of emersion were studied in the vicinity of Samobor (Herak 1956; Šikić et al. 1977, 1979), but the transition between Permian and Triassic has not been documented so far.

In the Karst (Outer or External) Dinarides, dominantly clastic Permian–Triassic deposits with barite ore described in Gorski Kotar (B on Fig. 1) hindered identification of the PTB due to a lack of fossils (Palinkaš and Sremac 1989; Sremac and Aljinović 1997; Aljinović et al. 2003). In the Velebit Mt. area and Lika region, the Permian–Triassic transition is characterized by carbonate deposition (e.g. Salopek 1942, 1948; Sokač et al. 1974; Ramovš and Kochansky-Devidé 1981; Sremac 2005; Vlahović et al. 2005; Fio et al. 2010, 2013), including the only documented position of the PTB in Croatia so far (Rizvanuša and Brezimenjača sections, Velebit Mt.—Fio et al. 2010; C and D on Fig. 1). A thick Upper Permian evaporite sequence of sabkha origin with volcanic and clastic intercalations is described from central part of the Karst Dinarides (E on Fig. 1; Ivanović et al. 1977, 1978; Šušnjara et al. 1992; Tišljar 1992; Kulušić and Borojević Šoštarić 2014), while the complete Permian is missing at some localities (e.g. Bruvno area; Šušnjar et al. 1973; Sokač et al. 1976a, b).

In the neighbouring Slovenia, several sections with the Permian–Triassic transitional deposits have been described. Section in the Žiri area in western Slovenia (1 on Fig. 1) is composed of the Upper Permian Bellerophon Formation (represented by the 'bellerophon limestone member' in the lower part and the 'evaporite–dolomite member' in the upper part). These deposits are continuously overlain by the Lower Triassic Lukač Formation represented by the 'streaky limestone member' and 'carbonate–clastic member' including Permian–Triassic 'transitional beds' at the base. The PTB is placed within the 'transitional beds' on the basis of the presence of conodont *Hindeodus parvus* (Kozur & Pjatakova) (Kolar-Jurkovšek et al. 2011a; Nestell et al. 2011). The Idrijca Valley section in western Slovenia (2 on Fig. 1) comprises Upper Permian black, well bedded, fossiliferous shallow-marine carbonates (Žažar Formation). The upper part of the Žažar Formation contains dark-coloured limestone layers rich in microfossils, mainly calcareous algae and foraminiferans, interbedded with black shale layers. Lower Triassic is composed of light-grey limestones and dolomites. PTB in the Idrijca Valley section was determined on the basis of the sedimentological and palynological data (Dolenec et al. 1999b), as well as palaeontological and geochemical data (Ramovš 1986; Dolenec et al. 2001; Schwab and Spangenberg 2004). In northern Slovenia (southern Karawanke

Mts., 3 on Fig. 1), Permian–Triassic boundary is characterized by continuous sedimentation, and placed on the basis of the chemostratigraphic data ($\delta^{13}C$; Dolenec et al. 1999a).

Closest areas with well-documented PTB sections are located relatively far from the Samoborsko Gorje Hills: the Velebit Mt. area (S Croatia) is ca. 145 km S (C on Fig. 1), Slovenian sections (Idrijca Valley and Žiri area; 1 and 2 on Fig. 1) are ca. 120 km WNW, and closest Hungarian section (Gárdony core in the NE part of the Transdanubian Range; 5 on Fig. 1) is located ca. 270 km NE from the study area.

3 Materials and methods

Sampling was performed in the northern part of the Samoborsko Gorje Hills, along the recently reconstructed road from Bregana to the Grdanjci village (Fig. 2a). Sedimentary rocks of Late Permian and Early Triassic age are located along the approximately 400 m long outcrop. Initial sampling was performed in 2012 at three localities with students from the Department of Geology, Faculty of Science, University of Zagreb. During this research Permian microfossils were found at the western part of the open section, which was therefore chosen for further analyses and field work. Six geological sections (BR-1 to BR-6) and three additional outcrops (BR-A, BR-B, BR-C) were sampled along the road in order to reconstruct the whole succession (GPS coordinates for sections: BR-1: 45°50′426, 15°40′332; BR-2: 45°50′431, 15°40′313; BR-3: 45°50′437, 15°40′292; BR-4: 45°50′428, 15°40′256; BR-5: 45°50′432, 15°40′237; BR-6: 45°50′430, 15°40′134; Fig. 2b). Since the area is significantly tectonized, tectonic structures—folds, joints and normal and reverse faults—were analyzed in order to reconstruct the sequence of deposits.

Thin sections were made out of 60 samples from all six sections in order to investigate the fossil assemblages, microfacies, minerals and diagenetic processes. To determine carbonate mineral types (calcite, ferroan calcite, dolomite and ferroan dolomite) samples were coloured with Alizarin Red S and potassium ferrocyanide.

After the initial micropalaeontological study, two fossiliferous Permian and two Triassic dolomite samples, ca. 2 kg each, were dissolved in formic acid for conodont retrieval.

4 Results

Estimated thickness of the sampled sections along the road from Bregana to Grdanjci village is ca. 23 m. The correlation of sections was based on sedimentological and palaeontological data, in order to recognize a potential Permian–Triassic transition within the succession.

4.1 Sedimentological data

According to their sedimentological features, the samples were grouped into four microfacies types (Figs. 2b, 3).

4.1.1 Microfacies 1: Dolowackestone to dolopackstone with calcareous algae and gastropods

Deposits of Microfacies 1 (Fig. 3a) are mainly associated with gymnocodiacean and dasycladalean algae, gastropod remains and small benthic foraminiferans (Textulariina, Miliolina, Fusulinina and Lagenina).

This microfacies, in which gymnocodiacean algae (especially *Permocalculus*) predominate, is common from the NW Caucasus to Hungary in the Upper Permian deposits above the Guadalupian–Lopingian boundary (e.g. Gaillot and Vachard 2007). It is found in the lowermost parts of sections BR-2 and BR-3, as well as in samples BR-A and BR-B (Figs. 2b, 4). Since gymnocodiacean algae are generally more abundant, most of these samples can be considered as gymnocodiacean dolowackestones (Fig. 3a). Elongated fragments of *Permocalculus* thalli are well preserved, and there is no visible preferential orientation of these elongated particles. However, sediment trapped within algal fragments or gastropod shells in some grains differs from the surrounding matrix, indicating certain transport of grains. It is noted that thin sections containing dasycladal algae exhibit less visible diagenetic overprint than those with gymnocodiaceans. This microfacies is characteristic for the shallow-marine sheltered environments (e.g. lagoons and sheltered bays).

4.1.2 Microfacies 2: Dolomudstone to dolowackestone with organic matter

Microfacies 2 contain rare and poorly preserved microfossils, mostly recrystallized algae and gastropods (Fig. 3b). The algae, mostly gymnocodiaceans, are indicative of the Late Permian. Relics of organic matter are common. This microfacies represents part of the general shallowing-upward sequence. It is present mostly in the sections BR-2 and BR-3 of the studied succession (Figs. 2b, 4).

4.1.3 Microfacies 3: Dolomitic breccia and microbreccia

Microfacies 3 is characterized by shallow-marine polymict breccia consisting of lithoclasts (mostly fragments of dolomudstones, less common dolomite crystals and

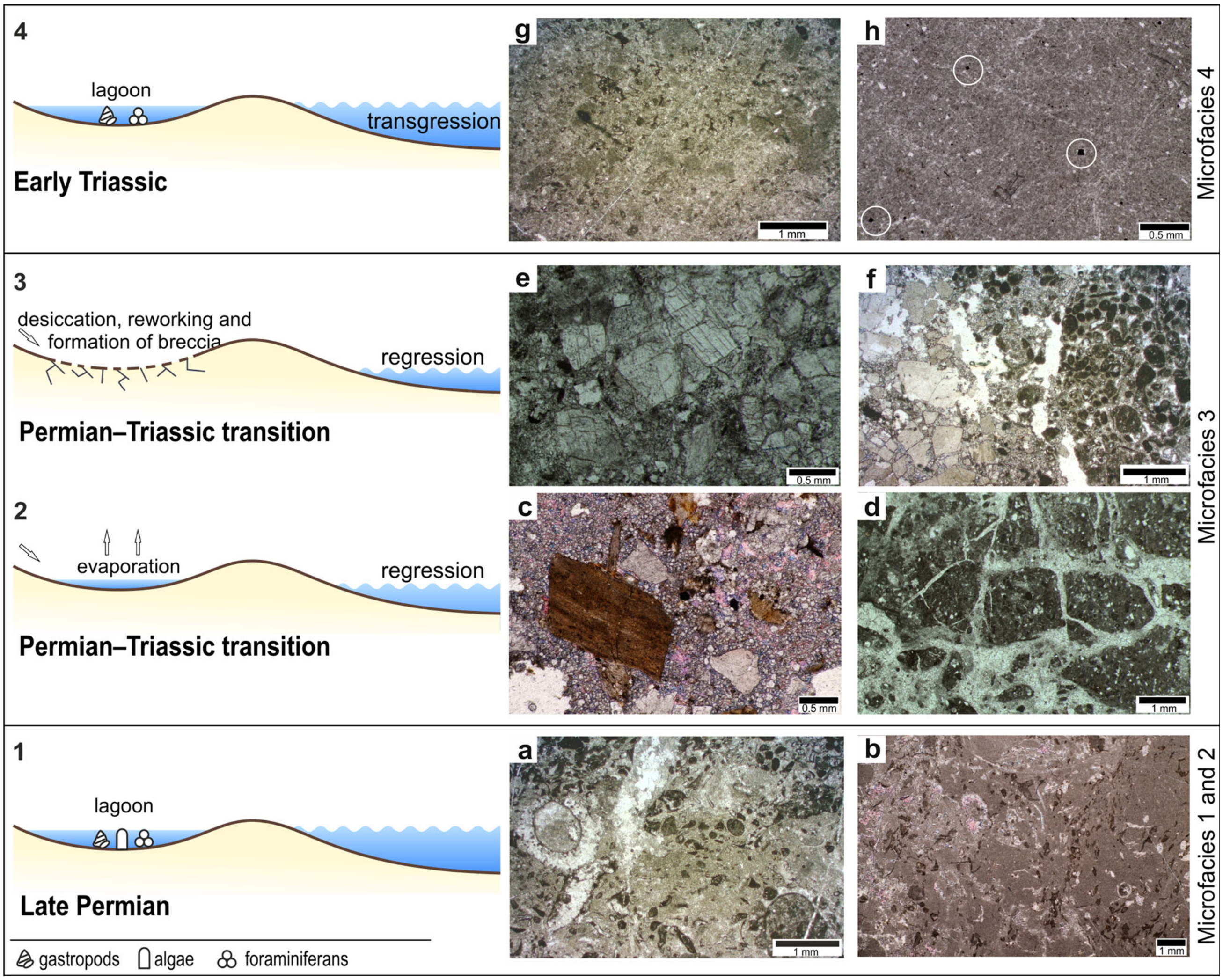

Fig. 3 Schematic reconstruction of the Late Permian to Early Triassic succession of shallow-marine lagoonal depositional environments caused by Late Permian regression and following Early Triassic transgression with typical microfacies types. *1* During the Late Permian carbonates were deposited in isolated lagoonal area with normal to slightly increased salinity, fossil assemblage includes calcareous algae, small foraminiferans and gastropods; **a** Microfacies 1 (sample BR-B)—dolowackestones to dolopackstones with calcareous algae and gastropods; **b** Microfacies 2 (sample BR-2/4), recrystallized algae and gastropod fragments, with presence of organic matter. *2* During Permian–Triassic transition evaporation salinity in the lagoonal areas was increased. The regression resulted in establishment of the 'Transitional breccia' facies; **c** common input of variable lithoclasts (sample BR-3/1); **d** common desiccation of the carbonate mud (sample BR-4/15). *3* The second phase of the Permian–Triassic transition was characterized by ongoing dolomitization, desiccation and input of lithoclasts into the shallow-marine environments, causing formation of more 'Transitional breccia' deposits; **e** dolomite crystals (sample BR-4/18); **f** breccia with different lithoclasts, e.g. dolomudstone and dolomite clasts (sample BR-1/0). *4* Transgression and re-establishment of the lagoonal settings in the Early Triassic; **g** dolowackestone with rare foraminiferans (sample BR-6/1); **h** dolomudstone with peloids and pyrite (marked by white circles) (sample BR-1/2)

evaporites, and rare shale fragments of different size; Fig. 3c–f). Throughout the middle part of the studied succession breccia and microbreccia are the most common lithofacies (Figs. 2b, 4), with variation of the predominant lithoclast types within individual samples. In some samples mica and quartz grains occur. The most common clasts exhibit several varieties of breccia/microbreccia structures: breccia/microbreccia with commonly angular fragments, mostly of dolomitic origin and with ferroan calcite cement (Fig. 3c), breccia/microbreccia with the mudstone clasts and calcite cement (Fig. 3d), breccia/microbreccia comprising large dolomitic crystals (Fig. 3e); and breccia/microbreccia with dolomudstone and dolomite particles (Fig. 3f). Microfacies type 3 coincides with the disappearance of calcareous algae. Presence of rare tests of only small foraminiferan species (Fig. 4), indicative of environmental stress, which are found both within the grains and within the matrix, indicate the ongoing biotic crisis.

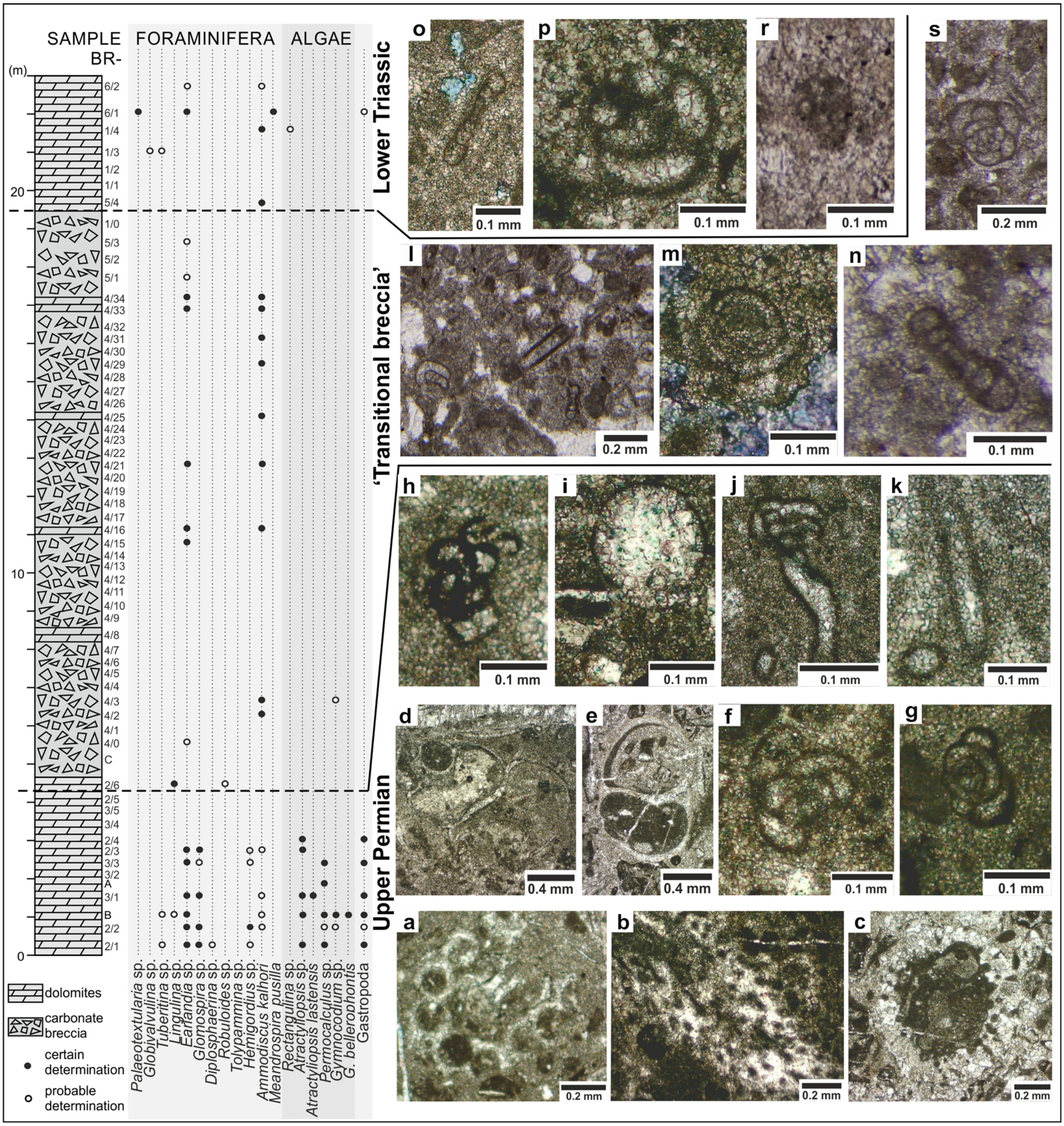

Fig. 4 Schematic reconstruction of the Upper Permian to Lower Triassic succession from the Samoborsko Gorje Hills, with estimated thickness of ca. 23 meters, and position of foraminiferans, algae and gastropods within Upper Permian, 'Transitional breccia' and Lower Triassic units. **a** Fragment of *Atractyliopsis* (BR-B); **b**, **c** *Permocalculus* sp. (sample BR-2/1, BR-B); **d–e** gastropod fragments (BR-2/1, BR-B); **f**, **g** *Glomospira* sp. (BR-2/1, BR-2/2); **h** *Hemigordius*? sp. (BR-2/2); **i** *Tuberitina*? sp. (BR-2/1); **j** *Tolypammina* sp. (BR-2/3); **k**, **l** *Earlandia* sp. (BR-2/2, BR-4/34); **m**, **n** *Ammodiscus kalhori* (BR-4/2, BR-4/34); **o** *Ammodiscus kalhori* (BR-5/4); **p** *Palaeotextularia* sp. (sample BR-6/1); **r** *Meandrospira pusilla* (BR-6/2); **s** undetermined foraminiferan (BR-4/33)

4.1.4 *Microfacies 4: Dolomudstone to dolowackestone with peloids and rare foraminiferans*

Microfacies 4 appears within different levels of the studied succession, but is more common in its younger part (Figs. 2b, 4). Dolomudstone sporadically contains rare, extremely environmentally tolerant microfossils (Fig. 3g), and their appearance commonly coincides with the onset of stressful environments (cf. Nestell et al. 2011, 2015). Occurrence of pyrite grains (marked on Fig. 3h) indicates probable dysoxic conditions.

4.2 Palaeontological data

The microfossil assemblage from the section in the northern part of the Samoborsko Gorje Hills includes cyanobacteria, red and green calcareous algae, benthic foraminiferans, ostracods and problematica, together with gastropods, bivalves and echinoderm debris. Some of the taxa have been determined only at the generic level, since the fossils are partly destroyed by diagenesis.

During the previous research a total of 13 microfossil taxa was determined from the study area (Herak and Škalec 1967; Šikić et al. 1979): calcareous algae *Gymnocodium bellerophontis* (Rothpletz 1894) Pia 1920, *Atractyliopsis lastensis* Accordi 1956, *Atractyliopsis* sp. and *Epimastopora* sp.; foraminiferans *Palaeotextularia* sp., *Earlandia* sp., *Pachyphloia reicheli* Loriga 1960, *Endothyra* sp., *Hemigordius* sp., *Hemigordius harltoni* Cushman & Waters 1928, *Ammodiscus* sp., *Glomospira* sp., and problematica *Shamovella obscura* Maslov 1956. *Atractyliopsis lastensis* Accordi 1956 as determined by Herak and Škalec (1967) was later revised as *Aciculella* sp. (Granier and Grgasović 2000).

This study confirmed previous findings and expanded the aforementioned list with several additional fossils: porostomate *Rectangulina*? sp.; dasycladacean *Atractyliopsis* sp. (Figure 4a), gymnocodiaceans *Permocalculus* sp. and *Gymnocodium* sp. (Figure 4b, c); gastropods (Fig. 4d, e); foraminifers *Glomospira* sp. (Figure 4f, g), *Hemigordius*? sp. (Figure 4h), *Tuberitina* sp. (Figure 4i), *Tolypammina* sp. (Figure 4j), *Earlandia* sp. (Figure 4k, l), *Ammodiscus kalhori* (Brönnimann, Zaninetti, and Bozorgnia), 2015 (Fig. 4l–o), *Palaeotextularia* sp. (Figure 4p), *Meandrospira pusilla* (Ho 1959) (Fig. 4r), *Globivalvulina*? sp., *Diplosphaerina*? sp., *Lingulina* sp., *Robuloides* sp., as well as one undetermined foraminiferan species (Fig. 4s).

As is commonly the case with the Upper Permian deposits, fossil assemblages at the base of the section are much more diverse (Fig. 4), while the younger deposits, close to the Permian–Triassic transition, contain fewer fossils (cf. Dolenec et al. 2001; Fio et al. 2010). The occurrence of *Meandrospira pusilla* in the uppermost part of the section is indicative of a Late Olenekian age.

The most abundant foraminiferans in the studied section, particularly common in its middle part, are *Ammodiscus kalhori* and *Earlandia* sp.

The sections were completely devoid of conodonts (J. Španiček, pers. comm.), probably due to the type of shallow-marine facies. Thus the tectonized sequence, the presence of Permian fossils and an index fossil only for the Late Olenekian, enabled only a general correlation of the succession for the studied deposits (Fig. 4).

5 Discussion

5.1 Stratigraphy

5.1.1 *Upper Permian*

Due to common fragments of calcareous algae (*Gymnocodium* sp., *Gymnocodium bellerophontis* (Rothpletz), *Permocalculus* sp. and *Atractyliopsis lastensis* Accordi 1956) typical for Late Permian shallow-marine facies, lower parts of the sections BR-2 and BR-3 and samples BR-A and BR-B are assigned to the Upper Permian. Together with the Permian foraminiferans and gastropods, they are common in Microfacies 1 (dolowackestone to dolopackstone with calcareous algae and gastropods), as well as in Microfacies 2 (dolomudstone to dolowackestone with organic matter) (Fig. 3a, b). The Permian ammonite *Paraceltites* cf. *sextensis* has also been documented in the wider area (Šikić et al. 1977). During this study, several new microfossil taxa with wider stratigraphic ranges were reported from this horizon (Fig. 4). The Upper Permian tidal bioaccumulations of gymnocodiaceans, especially *Permocalculus*, are found from the NW Caucasus to Hungary and indicate prolific carbonate production (Gaillot and Vachard 2007). According to the prevailing gymnocodiaceans, a Lopingian age is proposed for this part of the section (cf. Gaillot and Vachard 2007).

5.1.2 *Permian–Triassic transition*

The stratigraphic position of dolowackestones with sporadic fossil fragments and rare foraminiferans (*Lingulina* sp. and *Robuloides* sp.) in the uppermost part of the section BR-2 is questionable, and is therefore assigned to the transitional level (Fig. 4). The lowermost part of the section BR-1, sample BR-C, section BR-4 and lower part of the section BR-5 are marked by Microfacies 3 (Dolomitic breccia and microbreccia) containing a variety of fragments (mostly dolopelmicrites and dolomicrites), often cemented with ferroan calcite. Their exact stratigraphic position is also questionable, since only rare, small foraminiferans are present (Fig. 4), which can be found within both Permian and Triassic deposits. Prevailing angular fragments (Fig. 3c–f) were probably not transported significantly, indicating that this breccia of a synsedimentary origin was formed close to the source area. Ferroan calcite is characteristic only for this part of the succession. Occurrence of mica and quartz grains in some breccia samples may represent eroded material from the nearby land areas, supporting the scenario on accelerated rates of chemical and physical weathering connected with the PTB (Algeo and Twitchett 2010; Algeo et al. 2011). Similar input of terrigenous siliciclastic material connected with the Late Permian regression was noted in the Velebit Mt. area, where it marked a lithological transition between the Transitional and Sandy Dolomite units, situated 11 (Rizvanuša section, C on Fig. 1) and 0.2 m (Brezimenjača section, D on Fig. 1) below the PTB (Fio et al. 2010).

Micropalaeontological analyses highlighted an intermediate horizon between the Upper Permian and Lower Triassic deposits, containing low-diversity, resistant biota, which are known globally as PTB survivors (e.g. *Earlandia* and *Ammodiscus kalhori*). Foraminiferans, as the principal protist group between lower microbial and higher metazoan communities, representing important part of the food chain, can provide a good indication of the ecological collapse associated with the Permian–Triassic transition. Since the environmental conditions throughout the succession can be considered as stressful, and most of these species are thought to be ecological species (cf. Kolar-Jurkovšek et al. 2011b; Krainer and Vachard 2011; Nestell et al. 2011, 2015; Song et al. 2011a), it was practically impossible to exactly define the position of the Permian–Triassic boundary within the studied succession.

Conodont samples from the section appeared to be sterile. In sections worldwide lacking conodonts, the presence of disaster forms of foraminiferans (*Postcladella* (=*Ammodiscus*) *kalhori* and *Earlandia* sp.), and even microconchids (the annelid *Spirorbis phlyctaena*, He et al. 2013; Zatoń et al. 2013; Yang et al. 2015a, b), is commonly used to indicate the Lower Triassic (Nestell et al. 2011; Korngreen et al. 2013 and references therein). However, since those disaster forms can be found not only in Lower Triassic deposits but also in the uppermost Permian beds (Krainer and Vachard 2011), and since there is no visible facies change within the breccia deposits, we proposed the name 'Transitional breccia' for this horizon.

Transitional biotas within a relatively thick succession without any typical Upper Permian or Lower Triassic index fossils support a model of a prolonged extinction event, established at the Meishan GSSP and already proposed by several authors (e.g. Yin et al. 2007; Song et al. 2009; Chen et al. 2010; Huang et al. 2011). Many authors even proposed two pulses of extinction connected with the PTB, which are often included within 'transitional beds', since Permian survivors are commonly found in the Lower Triassic deposits (Song et al. 2007, 2011a, 2012; Yin et al. 2007).

5.1.3 Lower Triassic

The first definite Lower Triassic fossil in the studied section is the benthic foraminiferan *Meandrospira pusilla*, which is of Late Olenekian age (Popescu and Popescu 2005; Vuks 2007; Krainer and Vachard 2011; Fig. 4r) found within peloid dolomudstones in the uppermost part of the succession, together with *Paleotextularia* and *Ammodiscus*? sp. Numerous peloids are common in calm, restricted, lagoonal environments, and organic matter is quite common in this part of the succession.

The upper part of the section BR-1 consists mostly of dolomicrites with the presence of pyrite, and rare opportunistic foraminiferans (small agglutinated forms, *Eotuberitina*? and *Globivalvulina*; Fig. 4), indicating dysoxic to anoxic environments. Even though *Globivalvulina* is commonly found within Permian deposits (e.g. Gaillot and Vachard 2007), it has also been found in Lower Triassic deposits (e.g. Gaillot and Vachard 2007; Song et al. 2007, 2009, 2011a).

Such a significant facies change in the upper part of the section BR-1 suggests the possible Lower Triassic (Induan) age of these sediments, since *Ammodiscus kalhori* and *Earlandia* sp., the disaster forms found in the lowest Triassic, are considered as the survivors of the PTB crisis (cf. Krainer and Vachard 2011 and references therein). Both taxa are ecologic generalists and opportunists, which bloomed during the environmental crisis in stressful shallow-water environments (Nestell et al. 2011) when almost all hemigordiopsids and cornuspirids disappeared (see Gaillot and Vachard 2007 and references therein; Krainer and Vachard 2011). Due to synonymies, determinations of these species are often complicated. According to Krainer and Vachard (2011), *Postcladella kahlori* (Brönnimann, Zaninetti and Bozorgnia 1972) represents unique miliolid species comprising *Rectocornuspira kalhori* and *Cyclogyra* (or *Cornuspira*) *mahajeri*, which occurred during the Late Permian. Due to its tolerance to hypersalinity, poor nutrient availability and even anoxia it is considered a survivor. According to Nestell et al. (2015) foraminiferans identified as *Rectocornuspira kalhori*, *Cornuspira mahajeri*, and *Earlandia* spp., whose tests were previously considered to be calcareous, are named *Ammodiscus kalhori* and *Hyperammina deformis,* and are confirmed to be agglutinated.

Reconstruction of the Lower Triassic part of the succession with Late Olenekian *M. pusilla*, enables us to suggest that sedimentation was probably continuous from the Induan/Early Olenekian to Late Olenekian, since there is no visible change in facies or discontinuity in the upper part of the studied succession (Figs. 3g–h, 4).

5.2 Palaeoenvironments

During the Late Permian, depositional environments along the Palaeo-Tethyan inner shelves were changing from shallow subtidal environments with high biotic diversity, to intertidal (even supratidal) with low to very low biodiversity (Sremac 2005 and references therein; Fig. 3/1–3/3). The Early Triassic in marginal marine areas was characterized by the significant input of the terrestrial material which altered the mode of sedimentation along the shallow-marine areas (Sremac 2005, and references therein; Algeo and Twitchett 2010; Fig. 3/2–3/4). Shallow-marine deposition with a significant terrestrial input is characteristic also for some Lower Triassic deposits in the area of the Karst Dinarides (Fio et al. 2010 and references therein).

Considering the high values of estimated mean water temperature for the Late Permian in this part of the Paleo-Tethys, typical for the tropical areas close to the Equator (Polšak and Pezdič 1978; Fio et al. 2013), the nearshore shallows were probably quite warm and salinity might have been at least temporarily above the average marine values. These conditions can partly be compared with those in the central part of the Karst Dinarides area (E on Fig. 1) where evaporites formed (Šušnjara et al. 1992; Tišljar 1992).

Studied sections along the Bregana–Grdanjci road indicate shallow-marine environments throughout the Late Permian and the beginning of the Triassic (Fig. 3), and microfacies analyses indicated relatively low facies diversity.

Gymnocodiaceans and small benthic foraminiferans were the most diverse biota, characterized by high tolerance to environmental conditions, especially salinity fluctuations (Flügel 1991). Gymnocodiacean bioaccumulations are generally considered the main carbonate producers in the inner platform environments during the latest Permian (1 on Fig. 3), after the decline of the dasyclad algae (e.g. Flügel 1991; Gaillot and Vachard 2007). Dasycladal algae (*Aciculella*, *Atractyliopsis*) and gastropods are also present in the studied succession, but only in some layers. They were probably deposited in somewhat deeper or more open marine environments with more or less normal salinity.

The Late Permian regression (2 on Fig. 3) caused the disappearance of calcareous algae and gastropods, decrease in biodiversity and survival of only disaster taxa, which appear in dolomudstones with desiccation cracks (Fig. 3d). Most of the survivors belong to the foraminiferan groups Textulariina and Miliolina, together with small, less specialized Fusulinina.

Carbonate breccias were deposited during tectonic uplift and/or lowering of the sea-level (3 on Fig. 3), and clasts were reworked and probably at least partly redeposited from surrounding areas during the Early Triassic transgression, since mostly angular lithoclasts of different rocks indicate the increased input of the terrestrial material. These deposits represent the middle part of the succession described as 'Transitional breccia' (Fig. 3c–f).

Deposits in the Lower Triassic part of the succession are characterized by low biodiversity faunas within re-established shallow-marine environments (4 on Fig. 3). The presence of pyrite (Fig. 3h) in these deposits indicates probable dysoxic to anoxic conditions, which were common in Equatorial palaeolatitudes even in shallow-marine settings (cf. Bond and Wignall 2010). Only PTB survivors, planispirally coiled foraminiferans, peloids, and rare gastropod fragments appear in this horizon. Algal remains were not found, additionally pointing to enhanced environmental stress and the probable Lower Triassic age of the deposits, within which algae are lacking on a global scale (cf. Flügel 1991 and references therein). The most common microfossil in this part of the succession is *Ammodiscus kalhori*. Small disaster taxa in the Lower Triassic deposits are characterized by decrease of the foraminiferan test dimensions, which typically started with the first episode of the end-Permian mass extinction, and their dimensions did not recover to the pre-extinction levels until the Olenekian (Song et al. 2011a). The decrease in test dimensions probably even assisted some foraminiferans to survive the end-Permian mass extinction, since their energy consumption was decreased as a consequence (Song et al. 2011a; Rego et al. 2012). This phenomenon is connected with the extinction of large taxa and the 'Lilliput effect' in the aftermath of the PTB (Twitchett 2006, 2007; Song et al. 2011a).

Peloids and disaster foraminiferan taxa can be considered typical for very isolated environments (e.g. lagoons—4 on Fig. 3). Lagoonal dolomudstones with Olenekian foraminiferans *Palaeotextularia* sp. and *Meandrospira pusilla* have been found in the topmost part of the succession (Fig. 4p–r).

5.3 Regional correlation and palaeogeographic implications

The first systematic research on the Permian–Triassic boundary in Croatia was supported by the Swiss National Foundation SCOPES Project no. IB7320-11885 (2005–2008). Several promising areas were examined in the field but continuous deposition was noted at only two locations in the Velebit Mt. area (Rizvanuša and Brezimenjača sections, Karst Dinarides—southern Croatia, C and D on Fig. 1). The PTB based on chemostratigraphic correlation in the Velebit Mt., is clearly marked by the negative shift in $\delta^{13}C_{carb}$ and enrichment in most major and trace elements and appears above the boundary of two lithological units within a single carbonate bed, while fossil assemblages, composed mostly of small disaster taxa, mark at least two extinction phases (Fio et al. 2010). Typical stressed communities present across the whole Paleo-Tethys were recorded also at the Velebit Mt., including the genera *Earlandia*, *Ammodiscus*, *Glomospira*, *Tuberitina*, *Pachyphloia*, *Globivalvulina*, *Hemigordius* and small lagenids (Fio et al. 2010). Shallow marine, dominantly carbonate Upper Permian and Lower Triassic deposits with similar microfossils can be also found in the neighbouring countries, which belonged to the same depositional region in the Equatorial part of the western Paleo-Tethys Ocean.

Transitional Permian–Triassic beds with the disaster taxa '*Cornuspira*' *mahajeri* and '*Earlandia*' *gracilis* were recorded from Lukač section (Žiri area) in Slovenia (1 on Fig. 1). They were deposited in restricted, shallow-marine environments (Kolar-Jurkovšek et al. 2011a, b; Nestell et al. 2011). Slovenian Idrijca Valley section (2 on Fig. 1) contains rich Upper Permian fossil assemblages (e.g. *Permocalculus fragilis*, *Gymnocodium bellerophontis*, *Glomospira* sp., *Tuberitina* sp., *Pachyphloia* sp. and *Hemigordius* sp.) with the topmost part characterized by a 20-cm thick black algal packstone containing algal and foraminiferan fragments, displaying the gradual impoverishment of Upper Permian taxa towards the PTB with an abrupt disappearance at the boundary (Dolenec et al. 2001 and references therein).

The disaster fauna of the Werfen Formation in the Karawanken Mts. (southern Austria; 4 on Fig. 1) shows a similar succession to Samoborsko Gorje Hills section, with *Postcladella kalhori*, followed by *Meandrospira pusilla* (Krainer and Vachard 2011). The Permian–Triassic transition is also well documented in neighbouring Hungary (Transdanubian Range and Bükk Mts.—5 and 6 on Fig. 1; e.g. Haas et al. 2006, 2007; Hips and Haas 2009) and Southern Alps in Italy (7 on Fig. 1; e.g. Buggisch and Noé 1986; Noé 1987; Cirilli et al. 1998; Farabegoli et al. 2007).

Samoborsko Gorje Hills area can also be compared with the Upper Permian to Lower Triassic fossil assemblages and environments described from the oil-bearing Khuff Formation of the Middle East (Gaillot and Vachard 2007). Vuks (2007) described Early Triassic planispiral foraminiferans and especially the Late Olenekian foraminiferan *Meandrospira pusilla* from Western Caucasus, Eastern Precaucasus and Gorny Mangyshlak in the Caspian Sea region, which are similar to those in the Carpathian and Balkan regions, and correlative with the Samoborsko Gorje Hills succession. Identification of the Late Olenekian *Meandrospira pusilla* in the Samoborsko Gorje Hills area fills the gap in the geographical distribution of that species provided by Vuks (2007). Foraminiferan assemblages from the Samoborsko Gorje Hills can also be compared with the Permian–Triassic boreholes from the central coastal plain of Israel, where the Permian–Triassic transition with small stressed foraminiferans is marked by the presence of both Permian and Triassic foraminiferans (Korngreen et al. 2013).

At the Meishan global stratotype (GSSP) in South China, lagenids are the most abundant and diverse within the P–Tr transition bed, including the genera *Pachyphloia* and *Robuloides*, present also in the Samoborsko Gorje Hills. Additional similarities include presence of cosmopolitan ammodiscid taxa (*Ammodiscus* sp.), Globivalvulida (*Globivalvulina* sp.) and Cornuspirida, as well as the family Hemigordiidae (*Hemigordius* sp.) (Korchagin 2011). The dominance of Lagenina at the GSSP can be explained by probably deeper-water depositional environments than those in the studied succession of the Samoborsko Gorje Hills. The Samoborsko Gorje Hills succession can also be partly correlated with other South Chinese sections in Guanxi Province characterized by carbonate deposits. Some South China Lopingian sections are characterized by abundant Globivalvulinidae in semi-restricted shallow depositional settings, while Lagenida are considered indicative for inner to middle neritic environments (Gaillot et al. 2009 and references therein). The widespread *Geinitzina*, *Pachyphloia* and *Robuloides*, recorded in the sections from South China (Gaillot et al. 2009) have also been found in the Samoborsko Gorje Hills. Algal communities are also similar, with rare dasycladales and more abundant red algae, *Permocalculus* and *Gymnocodium*, pointing to similar depositional environments.

However, the studied succession from the Samoborsko Gorje Hills in the Inner Dinarides is characterized by specific facies development, especially the 'Transitional breccia' deposits which contain Permian and Triassic species whose presence commonly coincides with stressful shallow-marine environments. Although there is a significant similarity between the fossil assemblages, the succession from the Samoborsko Gorje Hills in a large part cannot be lithologically correlated with the other Permian–Triassic sections in Croatia or neighbouring countries. Therefore the succession provides new data for an under-explored part of the Paleo-Tethys but also fills an important gap in regional and global palaeogeographical reconstructions.

6 Conclusions

1. The area of the today Samoborsko Gorje Hills, during the Late Permian and Early Triassic was a part of the huge carbonate platform system extending along the shelves of the Paleo-Tethys.

2. The Late Permian (Lopingian) age of the basal part of the section is well documented within the lagoonal carbonate rocks, mostly bioclastic dolowackestones with calcareous algae, gastropods and benthic foraminiferans.
3. The Late Permian regression and sporadically emerged marginal parts influenced by desiccation, reworking, dolomitization and evaporitic processes, resulted in deposition of the carbonate breccia within probably very hostile environments. These deposits, described as 'Transitional breccia', contain various lithoclasts, together with remnants of disaster taxa, both within clasts and in matrix, which characterize Upper Permian to Lower Triassic transitional deposits.
4. Lagoonal deposition was re-established during the Early Triassic, but with clear evidence of enhanced environmental stress. Only the PTB survivors *Ammodiscus kalhori* and *Earlandia* sp. are present within this horizon. The transitional disaster fauna, present in a significant part of the succession supports the theory of prolonged, possibly multi-phase extinction.
5. Foraminiferan *Meandrospira pusilla* found in the upper part of the studied succession clearly indicates a Late Olenekian age and fills the gap in the previously known geographical distribution of that species.
6. The succession in the Samoborsko Gorje Hills is unique in having a breccia horizon in the central part of the succession, probably encompassing the PTB. Such deposition should not be uncommon during major marine regressions, characteristic for the studied interval. The identification of the 'Transitional breccia' horizon can help in future investigations of similar PTB depositional successions lacking index fossils in other Paleo-Tethyan areas.

Acknowledgments This study was supported by the Ministry of Science, Education and Sports of the Republic of Croatia (Project # 119-1951293-1162 and 195-1953068-0242). We would like to thank students of geology at the Faculty of Science in Zagreb, K. Terzić and A. Čerepinko for their help with initial field-work, as well as PhD student J. Španiček for help in the field and conodont retrieval. For the preparation of graphics we are grateful to R. Koščal. We are grateful to Dr. D. Vachard for constructive comments on an early version of the manuscript. We would like to thank D. A. Harper and D. Marty for editorial comments and language improvements, and Z. Q. Chen and an anonymous reviewer, for their constructive comments on the manuscript.

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