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# Across the end Permian "Great Extinction": from field studies to scientific results

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# Mémoires de Géologie (Lausanne)

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# Late permian / early triassic stress events and permian – triassic boundary in Croatia

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Upper Permian and Lower Triassic deposits are one of the best studied on our planet, and various scientists, by studying these deposits and by determining the Permian–Triassic Boundary (PTB), try to resolve the cause of the biggest mass extinction in the geological history. Several studies in Croatia focused on these, rarely exposed deposits. The main research areas include Velebit Mt. area and Samoborsko Gorje Hills, concerning the PTB, and Muć–Ogorje area in southern Dalmatia where changes in biota, environmental conditions and depositional patterns were studied in the aftermath of the extinction. Presented research focused on sedimentology, palaeontology and stratigraphy of the studied deposits, as well as on the positioning of the PTB using geochemical methods, including stable isotopes of carbonates ($\delta^{13}$Ccarb, δ18Ocarb) and organic matter ($\delta^{13}$Corg, δ15Norg), major, trace and rare earth element (REE) compositions and biomarkers.

Keywords: Croatia, Permian, Triassic, PTB, carbonates, clastic deposits

## Introduction

End Permian to Early Triassic interval is famous for the biggest mass extinction connected with the Permian–Triassic Boundary (PTB). Therefore, the uppermost Permian and lowermost Triassic deposits, including the PTB interval, have been studied in detail around the globe.

Upper Palaeozoic deposits in Croatia crop out in only 11 geographically restricted areas (Sremac, 2005), while Lower Triassic deposits are more common (Velić and Vlahović, 2009). Nevertheless, the contact between these units is extremely rarely exposed.

The main research area concerning the Permian and Triassic deposits in Croatia includes the inland slopes of the Velebit Mt. (1 in Fig. 1), with carbonate deposits originating from the platform that was established following several tectonically active phases and uplift during the Late Palaeozoic. Particularly well known is a more than 900 m thick Middle–Upper Permian carbonate succession, dominated by alternation of early- and late-diagenetic dolomites, with three distinct limestone zones. Although lithologically rather uniform, frequent subtidal–supratidal cycles can be revealed on the basis of sedimentological and palaeontological features (solution vugs, mud cracks, dolomitization patterns, microbialites etc.). Although biota was gradually changing, several typical microfacies patterns were common during the Middle–Late Permian. The dominant carbonate producers were calcareous algae (dasycladales, gymnocodiaceans), typical for very shallow, restricted subtidal environments, locally in association with large benthic fusulinid foraminifera. Microbial mats were typical for the low-stand episodes (Sremac, 2005). During the Late Permian, low-stand phases became more common, with a dominant regressive event recorded close below the Permian–Triassic boundary. This event finally caused a distinct change in the depositional setting, introducing again the terrestrial input to the platform. All Permian "equilibristic" biota disappeared, while only a small number of opportunistic taxa survived (Sremac, 2005 ; Fio et al., 2010).

The second research area with the Upper Permian and Lower Triassic deposits includes northern part of the Samoborsko Gorje Hills in NW Croatia (2 in Fig. 1) that belong to the Zagorje-Mid-Transdanubian Zone of the Inner Dinarides (Pamić and Tomljenović, 1998). Studied sequence is composed of Upper Permian (Lopingian) carbonates rich in calcareous algae (gymnocodiaceans and dasycladales), gastropods and small foraminifera. The middle part is characterized by the dolomitic breccia and microbreccia, known as "Transitional breccia", with common disaster forms of foraminifera, confirming the environmental crises in the shallow-marine environments and stressful and probably dysoxic environmental conditions during the transgression, followed by the gradual recovery of the biota in Early Triassic (Fio et al., 2013).

The third research area includes Lower Triassic clastic and carbonate deposits of the Muć–Ogorje area in Central Dalmatia (southern Croatia ; 3 in Fig. 1) which were studied in order to explain changes in biota, environmental conditions and depositional patterns after the PTB. Identified fossil and trace fossil associations suggested a Dienerian age for the lower, Smithian for the middle, and Spathian age for the upper part of the studied profile (Fio Firi et al., 2022).

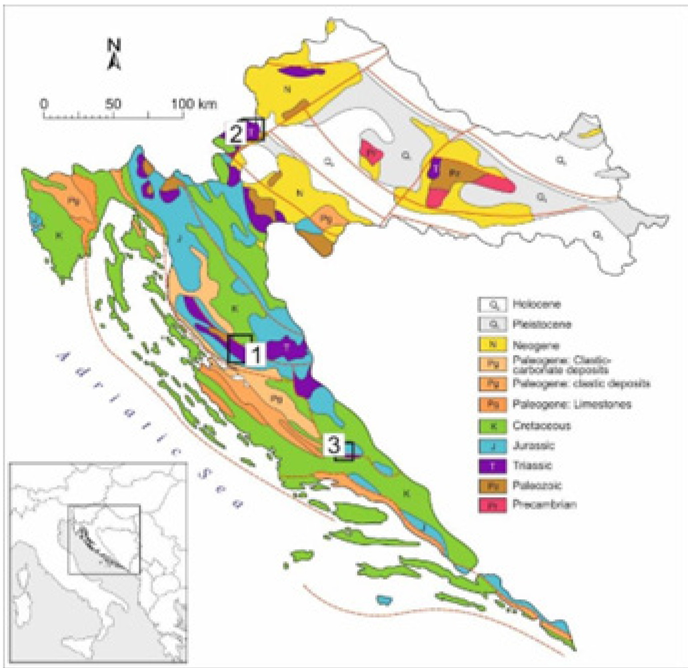


Fig. 1. Simplified geological map of Croatia (modified after Velić and Velić, 1995) with marked position of the study areas : 1) Velebit Mt. in southern Croatia, 2) Samoborsko Gorje Hills in NW Croatia, 3) Muć–Ogorje area, southern Croatia.

## Methods and materials

The Permian and Triassic deposits in Croatia were studied throughout the 20th century. We will mention : Salopek (1942, 1948), Sokač (1973), Sokač et al. (1974, 1976), Šikić et al. (1977, 1979), Herak (1983), Šćavničar and Šušnjara (1983), Kochansky-Devidé (1973, 1982), Sremac and Kochansky-

Devidé (1982), who mostly worked in aforementioned main research areas, but also Palinkaš and Sremac (1989) and Sremac and Aljinović (1997) for other areas in Croatia.

During the last 20 years, the research was more intensified through the work done by Jelaska (2003), Aljinović et al. (2003, 2006, 2008, 2018), Sremac (2005), Fio et al. (2010, 2016), Chen et al. (2021) and Fio Firi et al. (2022). Mentioned authors focused on sedimentology, palaeontology and stratigraphy of the studied deposits. The position of the PTB was determined only at two localities in the Velebit Mt. area (Rizvanuša and Brezimenjača), using geochemical methods, including stable isotopes of carbonates (δ1$^{3}$Ccarb, δ18Ocarb) and organic matter (δ1$^{3}$Corg, δ15Norg), major, trace and rare earth element (REE) compositions and biomarkers (Fio et al., 2006, 2010).

## Results and discussion

Rizvanuša and Brezimenjača sections in the Velebit Mt. area (1 in Fig. 1) consist of continuous marine carbonate rocks determined as Transitional Dolomite (TD) and Sandy Dolomite (SD). Lack of index fossils close to their contact and very clear lithological difference (Fig. 2) resulted in traditional opinion that the change in lithology corresponds to the PTB. Geochemical analyses have shown that $\delta^{13}C_{carb}$ values for the better exposed and in more detail analysed Rizvanuša section, were constant at the TD–SD lithologic boundary (~1–1.5 ‰), while the $\delta^{13}C_{org}$ revealed a decrease of up to 3 ‰. The $\delta^{15}N_{org}$ values of ~4 ‰ within the TD indicate a dominant influence of cyanobacteria, while lower values towards the TD–SD boundary indicate terrestrial material contribution. Input of terrigenous material and change from typical marine conditions was confirmed by the lowest whole-rock CaO and MgO contents, strong enrichments in most of the Major and REE, negative Ce anomaly at the TD–SD contact, and almost constant decrease of the $\delta^{18}O_{carb}$ throughout the section. Furthermore, Permian fossils have been found in the lowermost part of the overlying unit – Sandy Dolomites, and an abrupt negative excursion in $\delta^{13}C_{carb}$ was determined at both Rizvanuša and Brezimenjača sections within the Sandy Dolomites. This enabled the determination of the chemostratigraphic PTB in the Velebit Mt. area within the Sandy Dolomites unit, without recognizable facies change, 11 m above the lithological contact at Rizvanuša, and 0.2 m above at Brezimenjača section (Fio et al., 2010). Distribution of hopanes (biomarkers specific for bacteria) revealed no major change between the Upper Permian and Lower Triassic samples, but $\delta^{13}C$ of individual hydrocarbons indicated increase in primary productivity in Early Triassic (Fio et al., 2006).

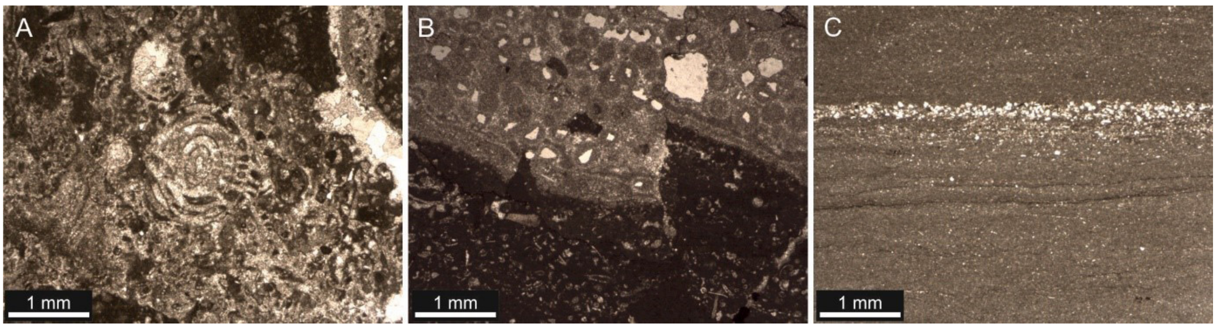


Fig. 2. Photomicrographs of the Transitional and Sandy Dolomite samples, Rizvanuša section (Velebit Mt. area). A) Shallow-marine dolobiopelmicrite with large fusulinid foraminifera within the TD, B) Erosional contact between dolomicrite of the TD and dolointrasparite of the SD, C) alternation of dolopelsparite and dolointrasparite in the SD unit.

Area between Bregana and Grdanjci villages in the northern part of the Samoborsko Gorje Hills in NW Croatia (2 in Fig. 1) contains tectonized deposits. Permian and Triassic deposits were therefore studied through six sections, to determine fossil assemblages and microfacies, and find a possible position of the PTB. Defined microfacies types indicated shallow-marine sheltered environments and shallowing-upward sequence during the Late Permian, occurrence of shallow-marine polymict breccia with rare tests of only small foraminifers in the middle part, and existence of environmentally tolerant microfossils in the upper part of the studied section, determined as Late Olenekian by the presence of foraminifera Meandrospira pusilla. Due to the stressful conditions and/or tectonic influence, transition from Permian to Triassic could only be indicated within the proposed "Transitional breccia" interval (Fio Firi et al., 2016).

Sedimentological features and fossil associations of the Lower Triassic deposits from the Muć-Ogorje area (southern Croatia; 3 in Fig. 1) enabled determination of seven facies associations, suggesting multiple changes concerning siliciclastic input and transgressive–regressive cycles from Dienerian to Spathian. Changes in sedimentology and associated biota throughout the succession revealed persistent environmental stress throughout the Early Triassic, as an aftermath of the PTB event (Fio Firi et al., 2022).

**Conclusions**

Presented research on the Upper Permian, Permian–Triassic Boundary and Lower Triassic deposits from several localities in Croatia (Velebit Mt., Samoborsko Gorje Hills, Muć–Ogorje area), confirmed several previous findings and, due to detailed sampling and geochemical analyses, provided new results on palaeontology, sedimentology and stratigraphy of these deposits. The chemostratigraphic Permian–Triassic boundary set in the Velebit Mt. area, found within succession of similar rocks and within single dolomite layers, represents the only area in Croatia where PTB is determined in detail. Partly exposed Upper Permian and Lower Triassic deposits of the Samoborsko Gorje Hills enabled palaeoenvironmental determinations, but between Permian and Triassic only "Transitional breccia" interval could be determined. Clastic and carbonate deposits from southern Croatia revealed Early Triassic environmental changes in the western Tethys epicontinental shelf area following the PTB.
Presented sections contribute to positioning of the Permian–Triassic boundary and determining the palaeoenvironmental and palaeogeographical reconstructions of this part of the Palaeo-Tethys during the Late Permian and Early Triassic, but also to understanding of the stressful conditions during the Late Permian and in the aftermath of the end Permian extinction.

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