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Synchronized changes in shallow water carbonate production during the Carnian Pluvial Episode (Late Triassic) throughout Tethys

Xin Jin^{a,b,c}, Piero Gianolla^d, Zhiqiang Shi^{a,*}, Marco Franceschi^b, Marcello Caggiati^d, Yixing Du^b, Nereo Preto^b

^a State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu, Sichuan 610059, China

^b Department of Geosciences, Università degli Studi di Padova, Via G. Gradenigo 6, 35131 Padova, Italy

^c State Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China

^d Department of Physics and Earth Sciences, Università degli Studi di Ferrara, Via Saragat, 1, Ferrara 44100, Italy

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ABSTRACT

Quantitative petrologic analysis on carbonates was carried out on stratigraphic sections encompassing the Carnian Pluvial Episode from northwestern Sichuan Basin, South China and eastern Southern Alps. The Carnian Pluvial Episode, or CPE, is a period of climate change that occurred between the early Carnian and the beginning of the late Carnian (Late Triassic) and coincides with multiple, sharp negative excursions in the record of $\delta^{13}\text{C}$ that are thought to be evidence of perturbations of the global carbon cycle. During the CPE, relevant environmental modifications and biological turnovers occurred in the marine realm. In particular, microbial carbonate platforms, that were dominant in northwestern Sichuan Basin and throughout Tethys, underwent widespread demise and the microbial component in shelf carbonate sediments sharply decreased and was replaced by ooid- and skeletal grains. Our results show a Tethys-wide coincidence between this change in the carbonate factory. Most notably, both in eastern and western Tethys microbial carbonate production recovered in the late Tuvanian, and the timing of recovery was not influenced by differences of basin evolution and geodynamic setting that characterize such distant domains.

1. Introduction

The Carnian Pluvial Episode or CPE (sensu Simms and Ruffell, 1989; Dal Corso et al., 2018a) is the most distinctive biotic crisis within the Triassic (Preto et al., 2010). It was first reported in the Northern Calcareous Alps (NCA), Austria, and initially referred to as “Reingrabener Wende” (Schlager and Schöllnberger, 1974). Subsequently, it has been widely documented in many regions of the Triassic Tethys (Fig. 1A). Its onset was dated to the Carnian, around the boundary between Julian 1 and Julian 2, i.e., between the *Trachyceras aonoides* and the *Austrotrachyceras austriacum* ammonoid zones (e.g., Hornung and Brandner, 2005; Hornung et al., 2007a, 2007c; Breda et al., 2009; Dal Corso et al., 2015, 2018b; Sun et al., 2016). Lukeneder et al. (2012) reported a crisis and drowning of a Carnian carbonate platform during the CPE on the equatorial Cimmerian terrane in Turkey, and proposed that they occurred near the boundary between Julian and Tuvanian, i.e., later than in other localities of Tethys.

The CPE is mainly characterized by continental siliciclastic input and by a crisis of shallow-water carbonate production in the margins of

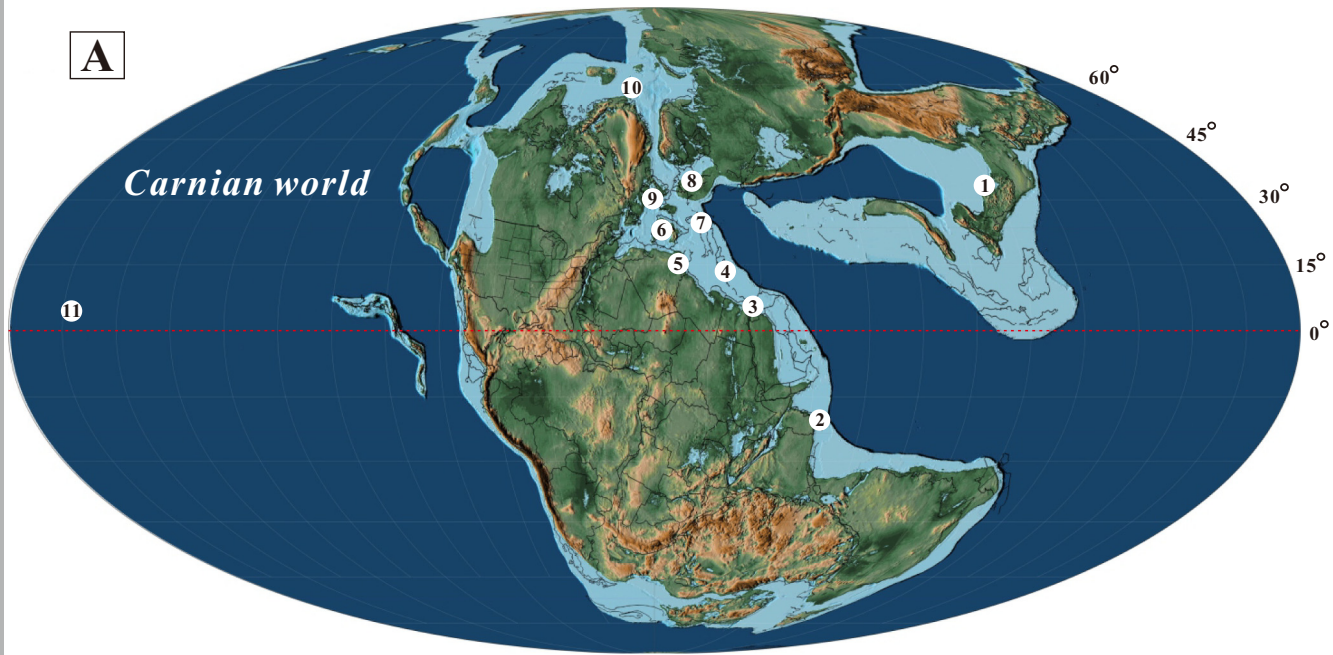
Tethys (Schlager and Schöllnberger, 1974; De Zanche et al., 2000; Keim et al., 2001, 2006; Berra and Jadoul, 2002; Hornung and Brandner, 2005; Hornung, 2007; Hornung et al., 2007a, 2007c; Breda et al., 2009; Roghi et al., 2010; Stefani et al., 2010; Sýkora et al., 2011; Haas et al., 2012; Bialik et al., 2013; Souza, 2014; Dal Corso et al., 2015, 2018b; Gattolin et al., 2015; Mueller et al., 2016; Sun et al., 2016). The carbonate sedimentation crisis and siliciclastic input can also be observed in hemipelagic and pelagic settings (Hornung et al., 2007b; Rigo et al., 2007; Rostási et al., 2011; Preto et al., 2013; Nakada et al., 2014). In continental areas, evaporitic playa-lake deposits were temporarily substituted by fluvial sandy deposits, and river systems occupied vast surfaces (Simms and Ruffell, 1989; Olsen and Kent, 1996; Colombi and Parrish, 2008; Kozur and Bachmann, 2010; Arche and López-Gómez, 2014; López-Gómez et al., 2017; Miller et al., 2017; Barrenechea et al., 2018).

This major lithological transition is thought to be related to increased rainfall and runoff, since a humid climate has been also recognized by a change from xerophytic toward more hygrophytic palynological assemblages (Hochuli and Frank, 2000; Roghi, 2004; Roghi

* Corresponding author.

E-mail address: szqcdut@163.com (Z. Shi).

A



B

Locations CPE signals	①	②	③	④	⑤	⑥	⑦				⑧	⑨	⑩	⑪
	South China	Indian	Israel	Turkey	Tunisia	Iberia	Slovenia	Italy	Hungary	Austria	Germany	UK	Norway	Japan
Carbonate platform crisis	●	●		●			●	●	●	●				
Terrigenous clastic input		●		●		●	●	●	●	●	●	●	●	●
Humid and warm climate	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Sea level drop and karst	●					●		●	●	●	●			
Marine anoxia	●	●			●			●		●				
CIEs	●							●	●	●		●	●	
CCD rise								●						
Marine extinction	●			●				●	●	●				

Fig. 1. A). General paleogeographic map of Carnian (Late Triassic) (Scotese, 2014) and some locations where the Carnian Pluvial Event (CPE) was recognized. B). Details of the documented geological record of the CPE. 1- South China: Nanpanjiang Basin (Lehrmann et al., 2005; Sun et al., 2016, 2018; Zhang et al., 2018), Sichuan Basin (Shi et al., 2019; Jin et al., 2019) and Qiangtang Basin (Wang et al., 2017). 2- Spiti Himalaya, India (Hornung et al., 2007b). 3- Levant margin, Southern Israel (Bialik et al., 2013). 4- Taurus mountains, Turkey (Lukeneder et al., 2012). 5- Atlas mountains, Tunisia (Soua, 2014). 6- Iberia, Spain (summarized in Arche and López-Gómez, 2014; López-Gómez et al., 2017; Barrenechea et al., 2018). 7- Locations in the Alpine area: Northern Calcareous Alps (NCA), Austria (Schlager and Schöllnberger, 1974; Hornung and Brandner, 2005; Hornung, 2007; Hornung et al., 2007a, 2007c; Roghi et al., 2010; Dal Corso et al., 2015; Mueller et al., 2016), Southern Alps and Northern Karawanken, Slovenia (Celarc and Kolar- Jurkovec, 2008; Roghi et al., 2010; Sýkora et al., 2011), Transdanubian Range, Hungary (Rostási et al., 2011; Haas et al., 2012; Dal Corso et al., 2015, 2018b; Baranyi et al., 2019b); Southern Alps, Northern Italy (Julian Alps: De Zanche et al., 2000; Gianolla et al., 2003; Roghi, 2004; Dal Corso et al., 2018b. Dolomites: De Zanche et al., 1993; Gianolla et al., 1998; Preto and Hinnov, 2003; Breda et al., 2009; Stefani et al., 2010; Dal Corso et al., 2012, 2015; Gattolin et al., 2015. Lombardy: Berra and Jadoul, 2002); Lagonegro Basin, Southern Italy (Furin et al., 2006; Rigo et al., 2007; Preto et al., 2013). 8- Germanic Basin (Kozur and Bachmann, 2010). 9- Southern UK (Simms and Ruffell, 1989; Miller et al., 2017; Baranyi et al., 2019a). 10- Barents Sea, Norway (Mueller et al., 2015). 11- Japan (Nakada et al., 2014). “CIEs” = carbon isotopic excursions, “CCD” = carbonate compensation depth.

et al., 2010; Mueller et al., 2015, 2016; Baranyi et al., 2019b) and by the episodic presence of coal beds and elevated kaolinite content in siliciclastic intervals (Simms and Ruffell, 1989, 1990; Simms et al., 1995; Rostási et al., 2011; Baranyi et al., 2019b). Salinity fluctuations, low oxygen conditions, relative sea-level changes and extremely humid climate associated with increase in terrestrially derived nutrients and/or organic matter during the CPE (Fig. 1B), are among the causes that have been invoked to explain the crisis and demise of carbonate platforms in the Dolomites of northern Italy (De Zanche et al., 1993; Gianolla et al., 1998; Keim et al., 2001, 2006; Bosellini et al., 2003). Preto et al. (2013) found that terrigenous supply did not directly affect the development of high-relief carbonate platforms in the Dolomites before the CPE, but rather seems to have had an influence on carbonate grain associations.

The coincidence of the onset of the CPE with a sharp negative shift of $\delta^{13}\text{C}$ recorded by bulk organic matter and n-alkanes has been documented in many locations (e.g., Dal Corso et al., 2012, 2015, 2018b; Mueller et al., 2016; Sun et al., 2016; Shi et al., 2019). It was shown that multiple carbon isotopic excursions occurred during the CPE, both in terrestrial and marine successions (Miller et al., 2017; Dal Corso et al., 2018b; Sun et al., 2018; Baranyi et al., 2019a). These major carbon isotope excursions are interpreted to be related to the injection of isotopically light carbon into the atmosphere-ocean system, possibly by intense volcanism related to the emplacement of the Wrangellia Large Igneous Province (Furin et al., 2006; Dal Corso et al., 2012, 2015, 2018b; Xu et al., 2014; Mueller et al., 2016; Sun et al., 2016, 2018).

The CPE was early identified as having had a significant impact on carbonate depositional systems (e.g., Preto and Hinnov, 2003; Hornung et al., 2007b, 2007c; Stefani et al., 2010; Breda and Preto, 2011; Haas et al., 2014). More recently, it was highlighted that changes in carbonate production mode seem to have occurred across the CPE. In the carbonate platforms of the Dolomites, Western Tethys (Northern Italy in Fig. 1A), prolific microbial carbonate production came to an end at the onset of the CPE, and was replaced by skeletal carbonate production (Dal Corso et al., 2015; Gattolin et al., 2015). This evidence seems to contradict the more established belief that microbialites represent crisis facies testifying to the opportunistic proliferation of bacteria after crises of reef building organisms (Schubert and Bottjer, 1992; Martini et al., 2004; Hornung and Brandner, 2005; Lukeneder et al., 2012; Haas et al., 2014; Peybernes et al., 2015). In the Southern Alps, microbial carbonate production recovered in the middle-late Tuvanian (late Carnian) to Norian as seen in high-relief carbonate platforms (e.g., Caggiati et al., 2018).

Whether the drop in microbial production at the CPE observed in the Southern Alps region was only a local feature confined to the western Tethys or not, is still unclear. Further investigations are needed in order to assess if the impact on microbial producers can be considered a distinctive feature of the CPE. To reach this goal, quantitative petrologic investigations on carbonates in the northwestern Sichuan Basin (eastern Tethys) are here shown and discussed. In addition, we present additional petrographic data from the Southern Alps to capture in better detail changes of microbial carbonate production that in the poorly-studied European sections of the late Carnian, and contrast/compare them to the new data from China.

2. Geological setting and stratigraphy of NW Sichuan Basin

2.1. Northwestern Sichuan Basin, South China

The Sichuan Basin is a portion of the larger tectonic plate known as South China Block. It is surrounded by the Songpan Ganzi Terrane and Longmen Shan thrust belt to the west, Micang-Daba paleo-land to the north, Kangdian paleo-land to the southwest, and the Xuefeng paleo-land to the east (Fig. 2B, Meng et al., 2005; Li et al., 2014). The Sichuan Basin hosted extensive carbonate platforms from the Late Precambrian to the Middle-Late Triassic (T_{3m}), whereas younger units are mostly

terrigenous (Chen et al., 1995). During the Triassic, the South China Block was located in eastern Tethys, the Sichuan Basin occupying its western margin. At the end of the Middle Triassic, the onset of collision between North China and South China plates resulted in the formation of a forebulge unconformity (Zhang et al., 1996; Li et al., 2003, 2011b), which brought about extensive erosion of the Middle Triassic Tianshan Formation in many parts of the Sichuan Basin (Li et al., 2003, 2011b). This unconformity marks the transition from Paleozoic-Middle Triassic passive continental margin to the Sichuan Foreland Basin (Li et al., 2011b). The lower portion of the overlying Ma'antang Formation (Carnian, Late Triassic) is missing in Hanwang area (Fig. 2A). During the early Carnian, the Longmen Shan thrust belt was a shallow submarine chain separating the western Sichuan Basin and Ganzi deep basin (Deng et al., 1982; Wu, 1984, 1989). An early Carnian transgression flooded the western Sichuan Basin, forming a semi-enclosed bay (Fig. 2B, Deng et al., 1982; Wu, 1984, 1989) and allowed the onset of a carbonate ramp system (Wu, 2009; Li et al., 2011a, 2014; Jin et al., 2018). The relative sea level was rising until the late Carnian (Li et al., 2011a, 2014), as a result of flexural deformation of the western margin of the South China Block, associated with the accelerated loading of Longmen Shan orogenic wedge. Coupled with the contemporary paleoclimate change, this triggered the drowning of carbonate platforms in the Sichuan Basin (Li et al., 2011a, 2014; Jin et al., 2018).

2.2. Ma'antang Formation in western Sichuan Basin

Petrological and facies studies have been carried out by many researchers in the Carnian of the Sichuan Basin (Wu, 2009; Wang et al., 2015; Jin et al., 2015, 2018; Shi et al., 2017). The Ma'antang Formation in Hanwang area consists of oolitic-bioclastic limestone, microbial-sponge boundstones locally forming mounds, followed by fossil-rich mudstones (Fig. 2A). In Ma'antang area, it is mainly composed of bioclastic limestones, and the typical microbial-sponge bioconstructions are absent (Shi et al., 2019). Wu (2009) proposed a carbonate ramp depositional environment for this unit in Hanwang, an interpretation that was confirmed by Jin et al. (2018). Based on a diverse fossil association, the Ma'antang Formation has been attributed to the Carnian (Wendt et al., 1989; Wendt, 2001; Wu, 1989; Wang, 1992 and particularly Jin et al., 2018; Shi et al., 2019). Jin et al. (2019) pinpointed the Carnian/Norian boundary in the upper part of the Ma'antang Formation at Qingyangou (HWQ) section based on comprehensive biostratigraphy. At its top, the Ma'antang Formation has a sharp transition to terrigenous lithologies (Fig. 2A). Shi et al. (2017) and Jiang et al. (2019) attributed the arrival of terrigenous sediments to the onset of the CPE, based on the magnetostratigraphy of Zhang et al. (2015) and conodont biostratigraphy, pointing to an early Carnian age. However, the carbon isotopes from bulk organic matter and wood from Qingyangou (HWQ) and Guanyinya (HWG) sections do not show the typical negative shift of the CPE; conversely, they exhibit a long positive trend which was attributed to the end of the CPE in Hanwang area (Fig. 2A). Ammonoid, conodont and bivalve biostratigraphy confirmed that the CPE is not documented in Hanwang (Jin et al., 2018, 2019).

3. Geological setting and stratigraphy of Southern Alps

3.1. Northern Italy

The Dolomites and Julian Alps belong to the western Tethyan realm (Fig. 3B) and are located in Northern Italy and Western Slovenia. During the Middle-Late Triassic, they were part of the western Tethys passive margin and were affected by different tectonic pulses with differential subsidence originating horst and graben structures (Fig. 3B), and they often associated with volcano-magmatic stages, followed by a relatively more stable setting characterizing the Upper Triassic (Doglioni, 1987; De Zanche et al., 1993; Gianolla et al., 1998; Preto et al., 2011; Lustrino et al., 2019). During this time-span, several

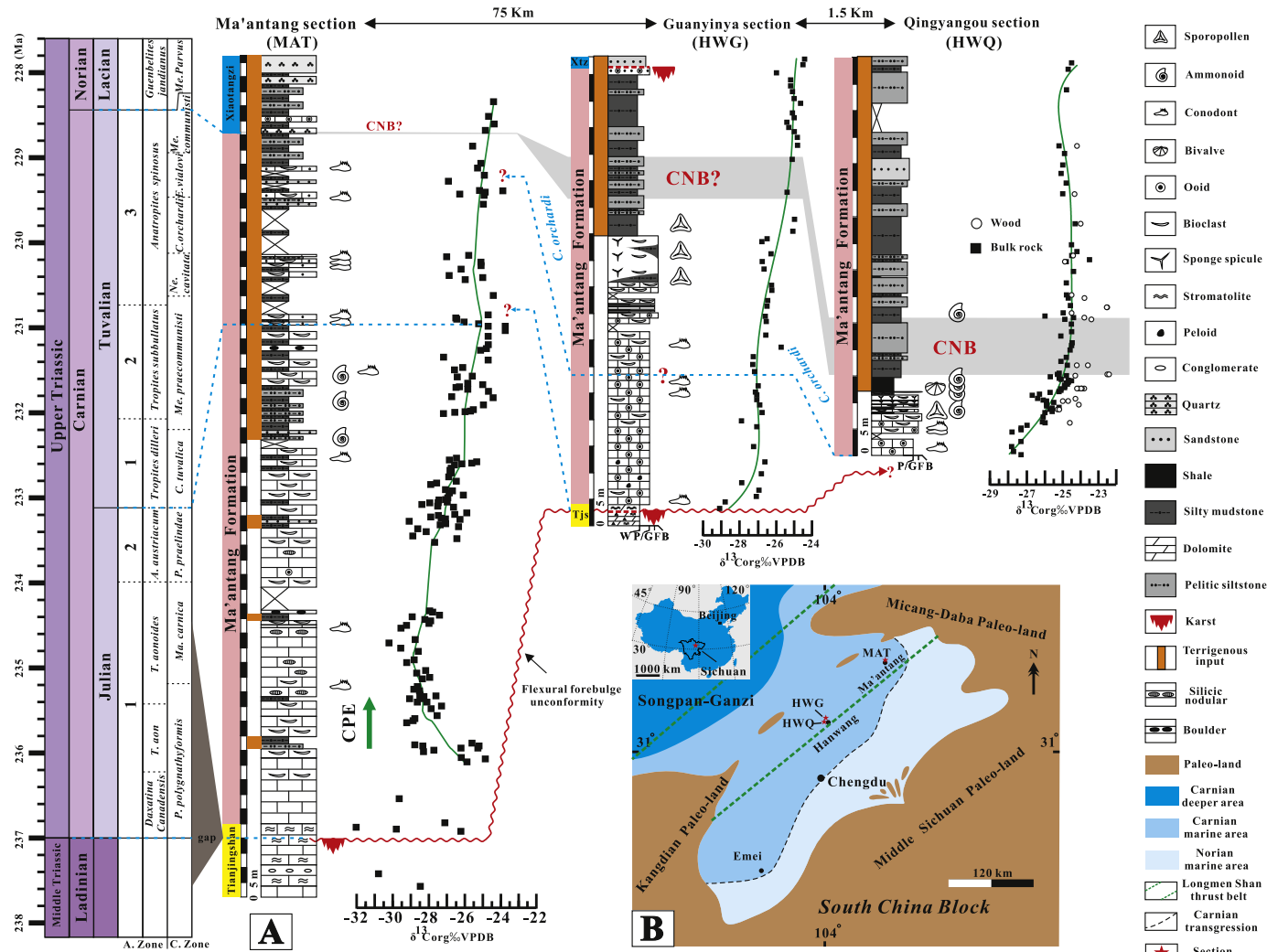


Fig. 2. A) Bulk organic carbon isotope records and biostratigraphic correlation of the MAT, HWG, and HWQ sections from northwestern Sichuan. The biostratigraphy and isotopic geochronology of the MAT section follows Shi et al. (2019). The time missing for karst dissolution is uncertain, because of the scarcity of biostratigraphic constraints in the basal Ma'antang Fm. The biostratigraphy and isotopic geochronology of the HWG and HWQ sections are based on Jin et al. (2018, 2019). B). Carnian paleogeography of western Sichuan Basin and locations of studied sections (simplified from Wu, 1989). Time scale as in Bernardi et al. (2018). The ammonoid zonation (A. zone) of the Carnian follows Gallet et al. (1994) and Broglio et al. (1999). The conodont zonation (C. zone) of the Carnian follows Rigo et al. (2018). "CNB" = Carnian/Norian boundary, "CPE" = Carnian Pluvial Episode, "W" = wackestone, "P/G" = packstone-grainstone, "F" = floatstone, "B" = boundstone, "Tjs" = Tianjingshan Formation, "Xtz" = Xiaotangzi Formation.

generations of high-relief carbonate platforms grew in the Southern Alps (Bosellini et al., 2003; Stefani et al., 2010; Preto et al., 2017). Toward the end of the early Carnian, a sharp input of siliciclastics coupled with a sea-level drop and change of carbonate production (Keim et al., 2001; Bosellini et al., 2003; Gattolin et al., 2013). Moreover, high-relief carbonate platforms suddenly changed to low-relief carbonate ramps (e.g., Heiligkreuz Fm.; Preto and Hinnov, 2003), often laterally passing to shallow water mixed systems (Heiligkreuz Fm., Rio del Lago, Cenzen and Tor Fm.; De Zanche et al., 2000; Preto et al., 2005; Breda et al., 2009; Dal Corso et al., 2018b) connected to a southern and western terrigenous shoreline (Brusca et al., 1981; Jadoul et al., 2004). From the Late Carnian (Upper Tuvalian), a depositional system characterized by a northward transition of alluvial-plain, flood-basin and shallow-lagoon dominated the Eastern Southern Alps (Travenanzes Fm., Breda and Preto, 2011) and was connected north-eastward to a carbonate platform margin-slope system (Gianolla et al., 2003, 2010; Caggiati et al., 2018). From the northern part of the Southern Alps, the carbonate platforms expanded landward on the former flood basin during the late Carnian to Norian, and prograded northeastward (basinward) for a few kilometres, generating huge

peritidal successions in northern Italy and western Slovenia (Dolomia Principale and Dachstein Limestone; e.g., Bosellini and Hardie, 1985; Ciarapica and Passeri, 1990; Celarc and Kolar-Jurkovšek, 2008; Gale et al., 2015).

3.2. Stratigraphy in the eastern Southern Alps

The late Early Carnian in the Dolomites is commonly documented by the transition from Cassian Dolomite and the heteropic San Cassiano Formation, representing high-relief carbonate platforms and the adjacent basinal carbonate-siliciclastic sediments, to the Heiligkreuz Fm., related to deposition in a carbonate ramp setting (Bosellini et al., 2003). In the Cortina area (Dibona-Milieres sections, "D" in Fig. 3B), the transition from the San Cassiano Fm. and the Heiligkreuz Fm. is characterized by the progressive shallowing of the basin, coupled with a strong increase in sandstones and the occurrence of subtidal carbonate mounds (Gattolin et al., 2015). This transition, constrained by biostratigraphy (ammonoids, conodonts) and palynomorphs to the base of Julian 2, is preceded by a strong shift in the organic carbon isotopic ratio (Dal Corso et al., 2015). At least two other isotopic shifts have

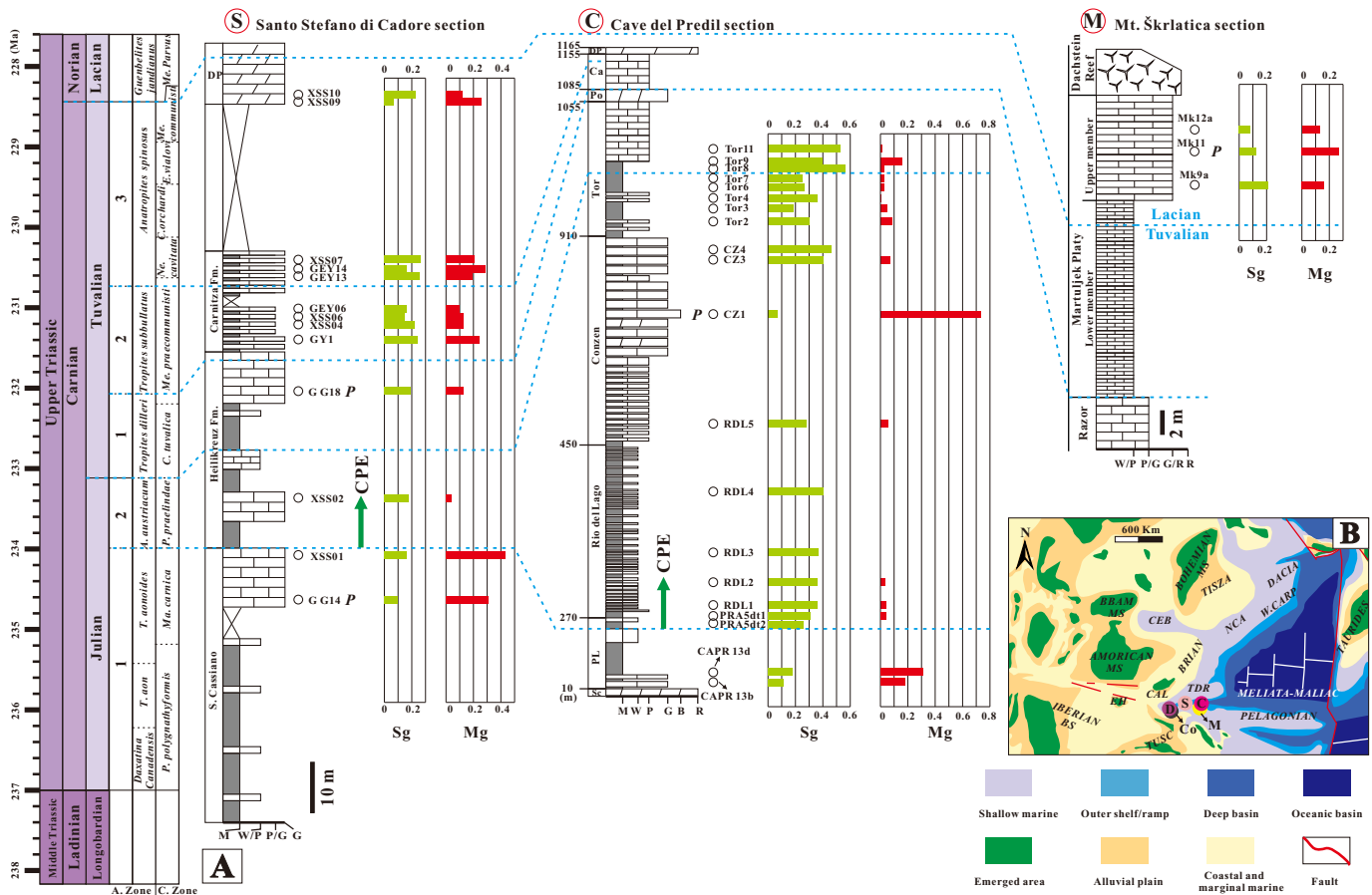


Fig. 3. A). Modal abundance of skeletal grains and microbial grains from Santo Stefano di Cadore section (Dolomites, Northern Italy), Cave del Predil section (Julian Alps, Northern Italy) and Mt. Škrlatica section (Julian Alps, NW Slovenia). The Mt. Škrlatica section was simplified from [Celarc and Kolar-Jurkovšek \(2008\)](#). “Sc” = Sciliar Fm., “PL” = Predil Limestone, “Po” = Portella Dolomite, “Tor” = Tor Fm., “Ca” = Carnizza Fm., “DP” = Dolomia Principale; “M” = marl, “W/P” = wackestone-packstone, “P/G” = packstone-grainstone, “R” = rudstone, “Sg” = skeletal grain, “Mg” = microbial grain, “P” shows the positions of described thin sections. B). Carnian palaeogeographic map of western Europe and locations of studied sections (simplified from [Bernardi et al., 2018](#)). The biochronology follows [De Zanche et al. \(2000\)](#) and [Dal Corso et al. \(2018b\)](#). “D” = Dibona-Milieres sections, “Co” = Costamoling section, “S” = Santo Stefano di Cadore section, “C” = Cave del Predil section, “M” = Mt. Škrlatica section, “BS” = Basin, “MS” = Massif, “TDR” = Transdanubian Range, “CAL” = Calabria, “TUSC” = Tuscany, “EH” = Ebro High, “CEB” = Central European Basin, “NCA” = Northern Calcareous Alps, “BRIAN” = Briançonnais.

been detected in the overlying part of carbonate ramp succession, followed by similar increases in siliciclastic input ([Dal Corso et al., 2018b](#)). Transgressive alluvial and mud-flat facies associations of Tuvalian age (Travenanzes Fm.) unconformably overlie the Heiligkreuz Fm. and are in turn overlain by carbonate peritidal cycles of the Dolomia Principale ([Breda and Preto, 2011](#)).

The area south of Santo Stefano di Cadore (“S” in [Fig. 3B](#)) lies in a relatively complex shear zone, dominated by high-angle faults originated during the Alpine orogeny, and it was likely located north-eastward of the Dolomites in the Triassic. The sedimentary succession is similar to the Dolomites, but dominated by basinal units deposited during the Early to Late Carnian ([Geyer, 1900](#); [Gianolla et al., 2010](#)). The transition from the San Cassiano Fm. to the overlying unit is gradual, marked first by an increase of terrigenous sandstones and then by the occurrence of almost regular carbonate-siliciclastic alternations, and eventually by shallow-water limestones. The latter are suddenly overlaid by an upper Tuvalian pelagic succession (*subbullatus* to *spinus* ammonoid zones), dominated by marls and calciturbidite intercalations until the toe of slope of the prograding Dolomia Principale carbonate platform is developed ([Fig. 3A](#)).

In the Cave del Predil (Raibl) area (Julian Alps) (“C” in [Fig. 3B](#)), the Carnian succession is nearly 1000 m-thick ([Assereto et al., 1968](#); [Schulz, 1970](#); [Liebermann, 1978](#); [De Zanche et al., 2000](#); [Gianolla et al., 2003](#); [Dal Corso et al., 2018b](#)). Here, the terrigenous input related to

the CPE is manifest as the superposition of the Rio del Lago Fm. ([Fig. 3A](#)), consisting of shales, siltstones and limestones alternations deposited in an outer ramp setting, on the basinal micrites of Predil Limestone, with an organic carbon-isotope shift located in the basal barren beds of the Rio del Lago Formation ([Dal Corso et al., 2018b](#)). This unit is characterized by a shallowing upward trend, with transition to the Conzen Limestones, and constrained to the *austriacum* ammonoids zone ([De Zanche et al., 2000](#); [Roghi, 2004](#); [Dal Corso et al., 2018b](#)). Sedimentation in ramp environments continued until the early Late Carnian (lower Tuvalian: Tor Fm. and Portella Dolomite; [De Zanche et al., 2000](#); [Preto et al., 2005](#)) but subsequently, drowning of the platform led to the emplacement of a pelagic setting, on which a new epicontinental carbonate platform prograded ([Gianolla et al., 2003](#); [Caggiati et al., 2018](#)). Recently, the multi-phase character of the isotopic signal and of humid pulses has been highlighted also in this area ([Dal Corso et al., 2018b](#)).

The Mt. Škrlatica section is located in the Julian Alps (NW Slovenia) (“M” in [Fig. 3B](#)), but in a different tectonic nappe with respect to the Cave del Predil area, and it was probably placed in a slightly north-eastward position during the Upper Triassic. The base of the section is composed of Razor bedded limestones, for which [Ramovš \(1987\)](#) proposed an early Carnian age. The Razor Formation bedded limestones represent cyclic peritidal sedimentation: thick-bedded packstone and grainstone with diverse skeletal grains formed in subtidal environments

and alternated with intertidal-supratidal and laminated grainstones and horizontal microbial laminites (Celarc and Kolar- Jurkovšek, 2008). They are followed by the Martuljek Formation platy limestones, upper Tuvalian to lower Norian in age according to conodonts and ammonoids (Ramovš, 1987; Celarc and Kolar- Jurkovšek, 2008). Two members of Martuljek platy limestones are observed (Celarc and Kolar- Jurkovšek, 2008). The lower member is characterized by reddish bioclastic wackestone to packstone, the upper member is made of light grey to white platy and thin-bedded, grainstones and rudstones (Fig. 3A). On these deep water micritic limestones, a carbonate platform prograded in the early Norian (Dachstein Limestone: Celarc and Kolar- Jurkovšek, 2008).

4. Methods

Thirty-six samples were selected from a large (up to 200) collection sampled in three distinct localities of the eastern Southern Alps: thirteen samples from Santo Stefano di Cadore (N46°32'49.05"/E12°34'59.15"; Dolomites), three samples from Mt. Škrlatica (N46°24'54.27"/E13°48'2.96"; eastern Julian Alps) and twenty samples from Cave del Predil (E46°26'21.05"/E13°35'59.35"; western Julian Alps). Standard, 30 µm thick thin sections were prepared at the Department of Physics and Earth Sciences, Ferrara University and at the Department of Geosciences, University of Padova. Forty-five samples were collected from three localities in northwestern Sichuan Basin: Ma'antang (MAT) (N32°11'22.14"/E105°13'50.35"), Guanyinya (HWG) (N31°28'18.4"/E104°08'50.4") and Qingyangou (HWQ) (N31°27'46.85"/E104°09'35.40"). Thin sections from the Sichuan Basin were made at the Institute of Sedimentary Geology, Chengdu University of Technology (China). All thin sections were studied and photographed with a polarizing microscope at the Department of Geosciences, Padova University.

The detailed methods and principles of point-counting follow Flügel (2010) and was carried out on photographs of thin sections. A regular two-dimensional grid was used and each component (including non-carbonate particles and vein fillings that are included in this study) which falls under a grid point was counted according to the "grain-bulk measurements" principle (Flügel, 2010). The nuclei of coated grains or ooids were counted as specific grains (i.e., whatever bioclasts or other sediments constitute the nuclei). A total of 300 points per thin section were counted with the help of the software JMicroVision 1.2.7. The point-counting of some thin sections was repeated with a graduated stage under a binocular microscope, but the results were comparable. Complete point counting data are shown in Appendix A Supplementary data.

For a more comprehensive interpretation of the evolution of carbonate systems across the CPE, the original data produced during this work were integrated and compared with those of Preto (2012) and Dal Corso et al. (2015), which were acquired with similar methods.

5. Results

In this study, we distinguished terrigenous components (clay and quartz), skeletal grains (including siliceous sponge spicules, bivalves, gastropods, brachiopods, foraminifers, calcareous sponges, echinoderms, ostracods, corals, stromatoporoids, bryozoans, and other undetermined skeletal grains), microbial grains (including clotted peloidal micrite, thrombolites, oncoids, calcimicrobes, *Tubiphytes*, agglutinated worm tubes, and pure leiolites), ooids and peloids. Agglutinated worm tubes in these samples are cf. *Terebella* sp., which walls have clotted peloidal fabric. The origin of carbonate in these tubes was interpreted as microbial because of their fabric.

5.1. Ma'antang section

The lowest part of Ma'antang section (MAT), of earliest Julian in

age, is dominated by stromatolites (Figs. 4A, 5), and is not suitable for point-counting. Above (M1), carbonate grains are mainly shells of aragonitic bivalves, substituted by calcite, which make up nearly 40 % of the total (Figs. 4B and 5). Microbial grains are rare, and small oncoids are found. Calcimicrobes (*Girvanella* sp.) are present (Fig. 4C) but are less than 5 % (Fig. 5). In the following Julian (lower Carnian) portion of the section, the skeletal grains are less abundant, generally ≤ 25 % excluding siliceous sponge spicules (Fig. 5), but microbial grains are scarce as well. Carbonate microfacies in the interval (M6-M9) that coincides with the negative shift in $\delta^{13}\text{C}$ of organic matter, are dominated by interstitial micrite or microsparite and scarce metazoans, which are mainly brachiopods, foraminifera, bivalves, and fewer ostracods (Figs. 4D, 5). In one sample (M13), siliceous sponge spicules reach 20 % of the rock volume (Figs. 4E, 5). Small oncoids, peloids, and fragments of bioclasts are found (Fig. 4E). In the interval after the main carbon isotopic excursion, which is uppermost Julian to Tuvalian in age, the skeletal grain content increases at the expense of interstitial components, and the rock type changes from prevailing wackestone to packstone-grainstone. In sample M17 (Fig. 4F), bioclasts are diverse, with echinoderms contributing up to 25 % of the whole rock volume. Brachiopods, foraminifera, bivalves, ostracods, bryozoans, and gastropods are present as well. Microbial grains rarely occur and are mainly small thrombolite fragments and oncoids. Calcimicrobes are found throughout the Tuvalian of the MAT section (Fig. 5). Most of these calcimicrobes are fragments of *Girvanella* sp. Generally, their abundance is less than 10 %. The terrigenous component is abundant in the upper part, ≥ 50 % at the top of the MAT section. Ooids are scarce and only occur in samples M20 and 21 (Fig. 5).

5.2. Guanyinya section

The Guanyinya section (HWG) has been studied by Jin et al. (2015, 2018, 2019) and Shi et al. (2017). The age of the HWG section is still debated, but conodonts roughly constrain it to the Tuvalian (Jin et al., 2018, 2019). The carbonates of the HWG section record oolitic-bioclastic shoals and sponge reef mounds. Towards the base of the section, oolites interfinger with bioclastic grainstones and packstones (Fig. 6). In sample G7 within this interval, bioclasts are made of bivalves, brachiopods, foraminifera, echinoderms and gastropods (Fig. 7A). Micrite ooids are also present. Carbonate mud may be found in interstices between bioclasts and ooids (Fig. 7A). Ooids are dominant in the middle of the section, and their content can be up to 60 % (Fig. 6). In sample G10, the majority of ooids are radial and concentric (Fig. 7B), with many exhibiting bioclasts at their nuclei (e.g., foraminifera, brachiopods, echinoderms, crinoids). Interparticle spaces are filled with clotted peloidal micrite (interstitial) and cements (Fig. 7B). The microbial grains are increasing from bottom to top in this interval. Close to the sponge mound layer at the top of the section, the content of microbial carbonates is increased to 55 % (Fig. 6). At the base of the sponge mound (G14), carbonate grains are mainly intraclasts made of thrombolite (Fig. 7C), which amount to 22 %. Bioclasts have been observed, including bivalves, brachiopods, and echinoderms (Fig. 7C). The siliceous sponge spicules are prevalent in the upper part of the HWG section, while calcimicrobes are only present in the lower part (Fig. 6).

5.3. Qingyangou section

The carbonate portion of Qingyangou section (HWQ) is dated to the late Tuvalian (*Carnepigondolella orchardi* conodont zone), and thus is younger than the MAT section. The lithology of this section, which is around 1.5 km from HWG, has been described by Jin et al. (2018). At the base of the section, the composition of carbonate microfacies is nearly the same as in the coeval upper part of the HWG section (Fig. 6). The skeletal grains (excluding siliceous sponge spicules) are generally rare. The microbial grains (excluding *Tubiphytes* sp.) are much more abundant than in the MAT section, reaching up to 60 % of the total rock

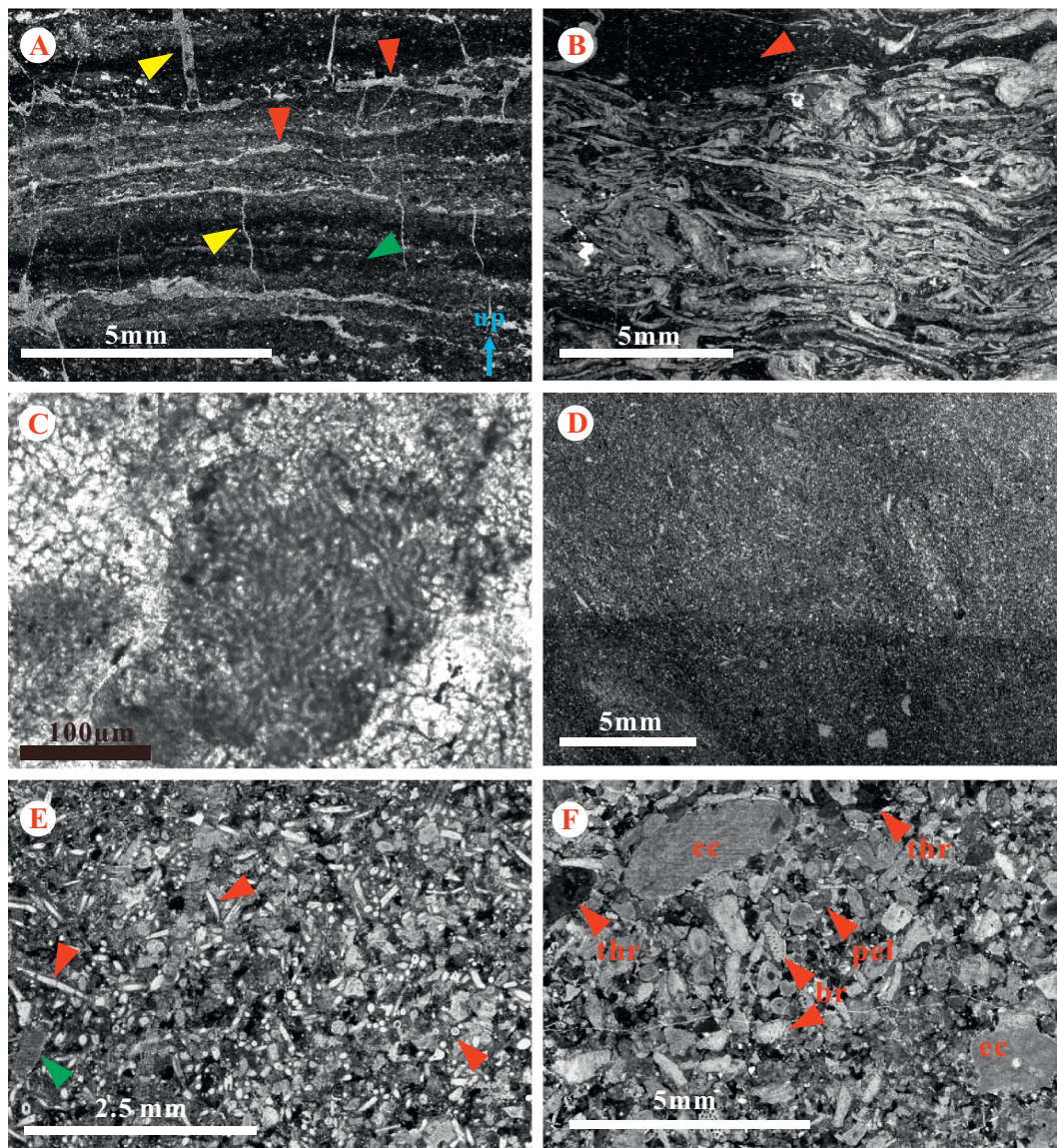


Fig. 4. Thin-section microphotographs of the Carnian successions in the MAT section, NW Sichuan Basin, South China. (A)- Stromatolitic dolomitic boundstone, from the lowest part of the MAT section. The dark stromatolitic layers (green arrow) are interbedded with fenestral structures (red arrow). They are often cut by vertical calcite veins (yellow arrow). (B)- Bioclastic packstone (sample M1). It is mainly made of aragonitic bivalves. The classification of these bivalves is impossible because their shells are substituted by late calcite cement. Intergranular spaces are filled with small peloids (red arrow). (C)- Detail of *Girvanella* sp. (from sample M11 of Fig. 5). (D)- Bioclastic wackestone, sample M7. It is mainly composed of fine carbonate mud and bioclasts. Small fragments of bivalves, brachiopods, echinoderms are visible. This mud-rich interval (M6 to M9) is coincident with the carbon isotopic negative curve (Fig. 5). (E)- Bioclastic packstone, sample M13. Siliceous sponge spicules are dominant (red arrow). Bivalves, echinoderms (green arrow) and brachiopods are also seen. Intergranular spaces are filled with micrite, peloids and fine terrigenous sediment. (F)- Bioclastic grainstone, sample M17. It is mainly made of diverse bioclasts such as bivalves, gastropods, brachiopods (br), foraminifera, echinoderms (ec). Also peloids (pel), thrombolites (thr) and terrigenous clasts are seen. Intergranular spaces are filled with blocky and microsparry cement.

volume in the upper part of the HWQ section. *Tubiphytes* sp. are found within the top sponge reef layers (Fig. 7D), but their content is often less than 10 %. Siliceous sponge spicules are common in the HWQ section. In sample Q3, microbial grains are mainly composed of big oncoids and fragments of thrombolites. Bioclasts often have oncolitic coatings (Fig. 7E), and small peloids also occur. Interparticle spaces are filled with microsparite. Upward in the section (sample Q8), the content of microbial grains reaches 40 % (Fig. 6) and is mostly composed by fragments of thrombolites (Fig. 7F). The skeletal grains are less abundant and made of bivalves and brachiopods. The sample Q9 is made of leiolites, worm tubes and fragments of siliceous sponges.

5.4. Santo Stefano di Cadore section

The Santo Stefano di Cadore section has been dated to a time-span ranging from early Julian to late Tuvalian (Geyer, 1900; Gianolla et al., 1998, 2010), which is comparable with the MAT section. The skeletal grains are diverse, their contents are around 10% to 25% (Fig. 3A). The microbial grains are dominated by thrombolites and are abundant in the lower part (Fig. 8A; sample GG14 and XSS01 in Fig. 3A), which predates the CPE. Ooids are distributed discontinuously through the section. Sample GG 18, of lower Tuvalian in age, is dominated by peloids and intraclasts (Fig. 8B); microbial grains, mostly thrombolites and oncoids, make less than 15 % of the rock volume (Fig. 3A). In sample GEY 13, microbial grains are mainly composed of small thrombolite fragments, which amount to 19 % of the rock volume. The

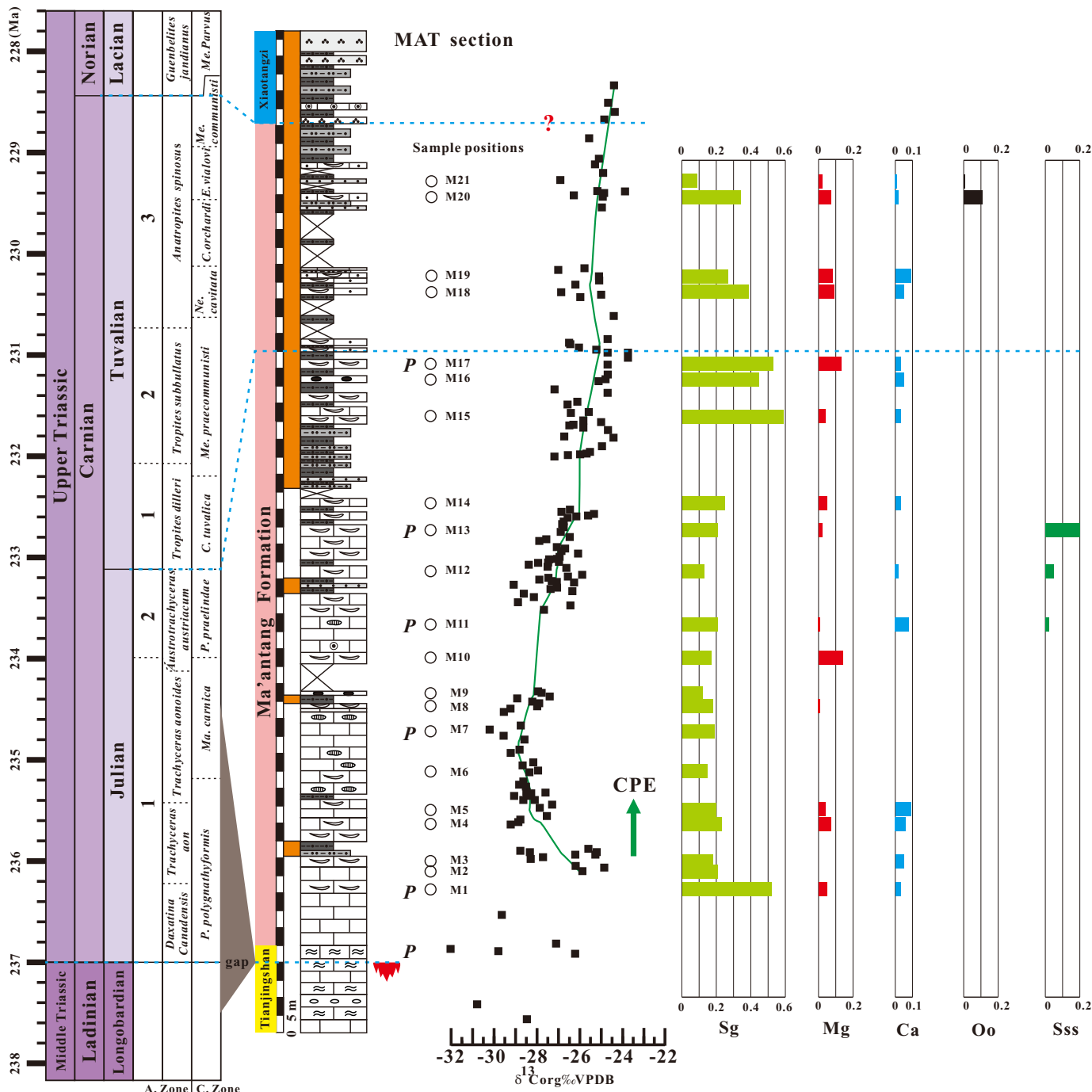


Fig. 5. Modal abundance of carbonate skeletal grains, microbial grains and calcimicrobes, ooids and siliceous sponge spicules of the MAT section. The siliceous sponge spicules were extracted from the skeletal grains to show their distribution in the MAT section. For the same purpose, calcimicrobes were extracted from microbial grains. “P” means the positions of described thin sections (see Fig. 4). The biochronology and organic carbon isotopes follow Shi et al. (2019). “CPE” = Carnian Pluvial Episode, “Sg” = skeletal grain, “Mg” = microbial grain, “Ca” = calcimicrobe, “Oo” = ooid, “Sss” = siliceous sponge spicule.

skeletal grains are made of bivalves and gastropods.

5.5. Cave del Predil section

The composite Cave del Predil section comprises a Julian to Tuvalian succession. The lithology and biostratigraphy were studied by De Zanche et al. (2000) and revised by Dal Corso et al. (2018b). The point-counting data starts in the pre-CPE interval (Fig. 3A). Skeletal grains dominate and range from 7 % to 56 % whilst microbial grains are rare. A sharp peak of microbial grain content was observed in CZ1

sample. This sample consists of thrombolites and skeletal grains are rare (Fig. 8C).

5.6. Mt. Škrlatica section

Mt. Škrlatica section is late Tuvalian to early Norian in age, analogously to the HWQ section. The contents of microbial grains are slightly higher than skeletal grains (Fig. 3A). In sample Mk11, abundant fragments of reef-builders are found, such as corals (Fig. 8D). Other bioclasts are mainly foraminifera, brachiopods and echinoderms. There is

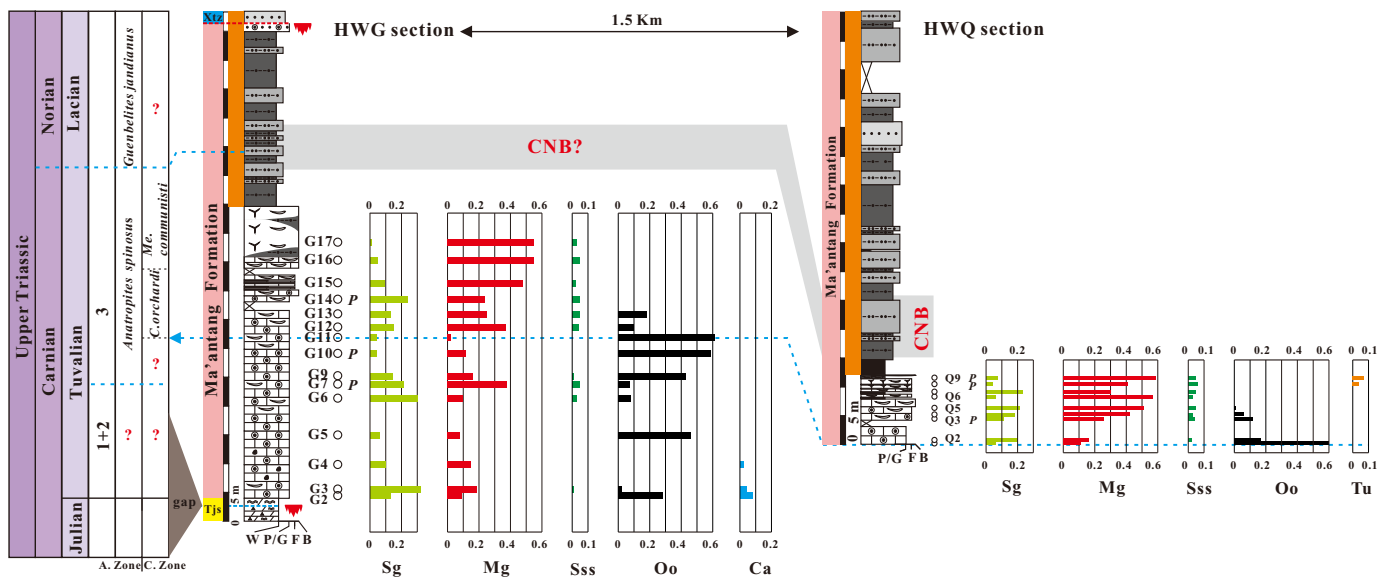


Fig. 6. Modal abundance of carbonate skeletal grains, microbial grains and calcimicrobes, ooids, siliceous sponge spicules and *Tubiphytes* of the HWG and HWQ sections. The grain compositions of the HWG and HWQ sections are nearly identical above the middle blue dashed line. The biochronology follows Jin et al. (2018, 2019). “Sg” = skeletal grain, “Mg” = microbial grain, “Ca” = calcimicrobe, “Oo” = ooid, “Sss” = siliceous sponge spicule, “Tu” = *Tubiphytes*.

interstitial clotted peloidal micrite, and the most common microbial grains are large oncoids.

6. Discussion

6.1. Carbonate platforms across the CPE

The crisis of carbonate platforms is one of the most distinctive features of the CPE (Fig. 9). In some instances, carbonate platforms came to an end (e.g., in the Lunz area, Northern Calcareous Alps), either by replacement with terrigenous deposits or by drowning, i.e., the superposition of pelagic sediments on shallow water carbonates (e.g., Schlager, 1981). This gave rise to the idea that the CPE corresponded to a Tethys-wide halt in carbonate production and its replacement by terrigenous sedimentation (e.g., Keim et al., 2006; Hornung, 2007; Hornung et al., 2007a, 2007b, 2007c; Rigo et al., 2007; Mueller et al., 2016; Sun et al., 2016, and references therein). In many cases, however, there is evidence that carbonate production continued during the CPE (Fig. 9). In the Dolomites, shallow water carbonates are mixed with terrigenous sediments (Keim et al., 2001, 2006; Preto and Hinnov, 2003; Preto et al., 2005; Breda et al., 2009, and references therein). In the Northern Calcareous Alps, a temporary interruption of carbonate platforms growth is documented in depositional environments ranging from shelf to basin (Hornung et al., 2007c). Other examples are reported from the Spiti Basin, northwestern India (Hornung et al., 2007b), the Anatolian terrane, southwestern Turkey (Lukeneder et al., 2012) and the Nanpanjiang Basin, South China (Sun et al., 2016). So, the response of Tethyan carbonate platforms to the CPE was not always a complete shut-down. Furthermore, drowning events were not always synchronous and coincident with the onset of the CPE (Fig. 9). A complex response of a carbonate platform to the CPE is documented in Turkey (Lukeneder et al., 2012). There, shallow water carbonates of the Kartoz Fm. are overlain by carbonates with deep-water faunas (ammonoids, conodonts and halobiid bivalves) of the Kasimlar Fm. This facies shift occurs within the *Austrotrachyceras austriacum* ammonoid zone, and can be interpreted as a platform drowning event. The ultimate shut-off of carbonate production occurs later, at the boundary between the *Austrotrachyceras austriacum* zone (Julian) and the *Tropites dilleri* zone (Tuvallian), and was interpreted by Lukeneder et al. (2012) as the onset of the CPE in the region. According to this interpretation

the CPE would be diachronous. In this work, the onset of the CPE is instead considered to be globally synchronous and defined by the first negative carbon isotopic excursion at the base of the *Austrotrachyceras austriacum* ammonoid zone, following Dal Corso et al. (2012, 2018b). We thus set the CPE below the drowning of the Kartoz carbonate platform, on the base of biostratigraphic correlation (Fig. 9).

In the Cave del Predil/Raibl area (Julian Alps, Italy), a change in the geometry of carbonate shelves, from high-relief platforms to mixed terrigenous-carbonate ramps, occurs at the same time of the CPE (Dal Corso et al., 2018b). Later on, in the early Tuvallian, shallow water carbonate facies of the Portella Dolomite are followed by deep water, hemipelagic cherty limestones of the Carnitza Formation (De Zanche et al., 2000; Dal Corso et al., 2018b) (Fig. 9). This drowning event thus occurred after the inception of the CPE.

In the Sichuan Basin, an abrupt lithological change from microbial-sponge boundstones, forming reef mounds, to dark grey shales with a deep water faunal association (Qingyangou section, Fig. 9, this study) is interpreted as a drowning event and is dated to Tuvallian 3 (late Carnian), i.e., much younger than the CPE (Jin et al., 2018, 2019).

In sum, evidence from various stratigraphic settings throughout the Tethys compose a complex picture, characterized by a variety in the evolution of carbonate systems and a diachroneity in the drowning of carbonate platforms in the late Carnian (Fig. 9). This means that there is not an unequivocal connection between the drowning of carbonate platforms and the climate changes associated to the CPE: drowning events occurred before, during and after the CPE, and shallow water carbonate production continued during the CPE in many localities. A link between the CPE and the crisis of shallow water carbonate producers does exist, but it is not necessarily testified by a sharp interruption of carbonate production and consequent platform drowning.

6.2. Sea level variations did not cause carbonate platform crisis and drowning during the CPE

In several instances, drowning of carbonate platforms is observed within the time span of the CPE (Fig. 9). For example, in the Cave del Predil/Raibl area of Italy and Slovenia (De Zanche et al., 2000); in the Northern Calcareous Alps of Austria, with the temporary drowning of the Wetterstein carbonate platform (Schlager and Schöllnberger, 1974; Hornung et al., 2007c); in the Taurus mountains of Turkey (Lukeneder

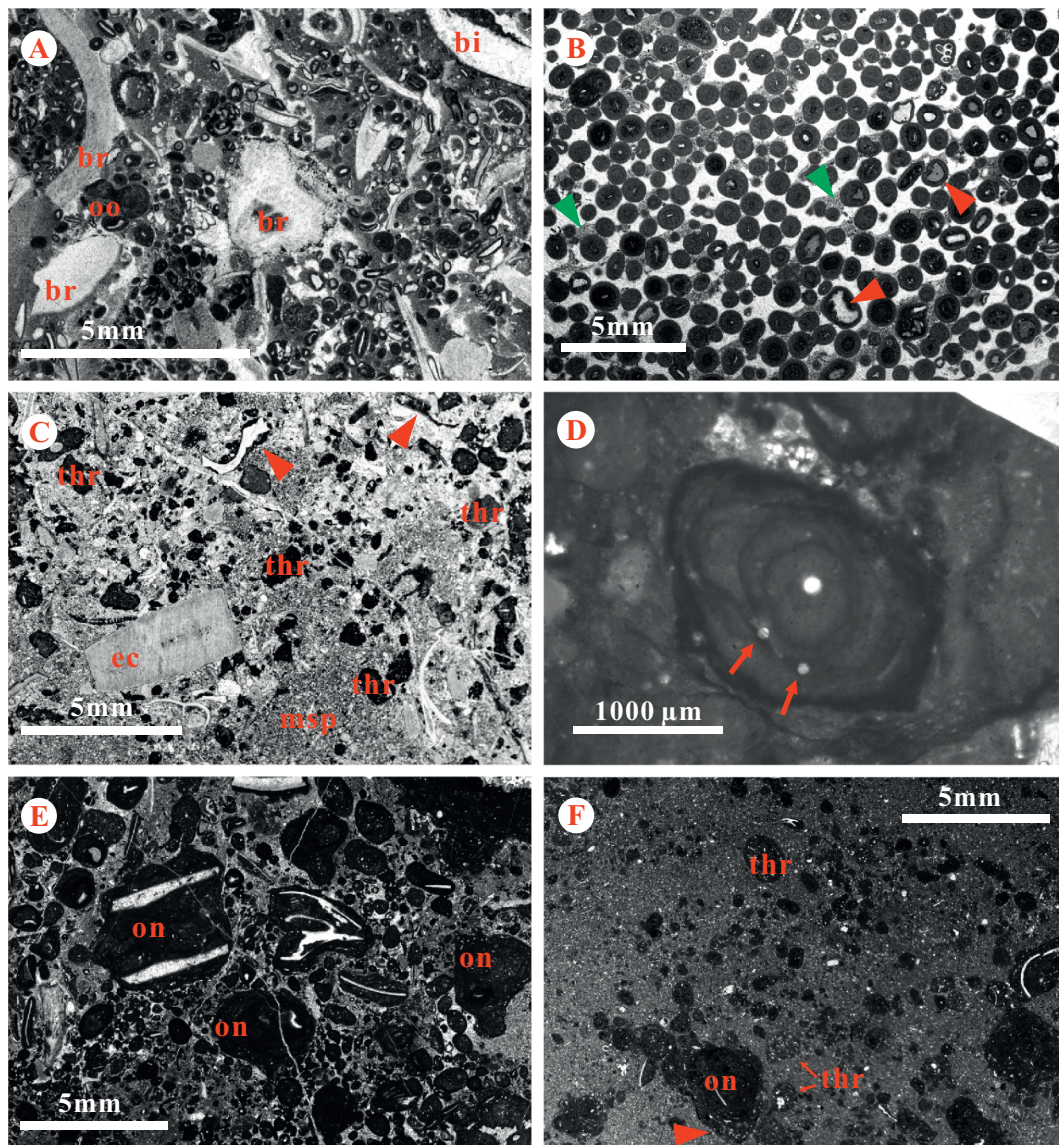


Fig. 7. Thin-section microphotographs of the Carnian successions in the HWG and HWQ sections, NW Sichuan Basin, South China. HWG section: (A)- Bioclastic-oolitic packstone, sample G7. Bioclasts and ooids (oo) are dominant. The fragments of brachiopods (br) and bivalves (bi) are seen. Some of ooids have bioclastic nuclei. Intergranular spaces are filled with micrite, or microsparry cement. (B)- Oolitic grainstone, sample G10. Some of the ooids have bioclastic nuclei such as echinoderms and bivalves (red arrow). Interstitial clotted peloidal micrite (green arrow) is commonly present in the intergranular spaces. The cements are blocky calcites. (C)- Bioclastic- thrombolitic packstone, sample G14. Fragments of echinoderms (ec), thrombolites (thr) foraminifera, bivalves and brachiopods are present. Some of them have oncolitic-microbial coating (red arrow). Dominant are fragments of thrombolite (thr), and the pore space is filled with microsparry cement (msp) and fine mud. HWQ section: (D)- Detail of *Tubiphytes* sp. (from sample Q9). The red arrows are the traces of in situ laser ablation. (E)- Bioclastic and intraclastic floatstone, sample Q3. It is mainly composed of fragments of bioclasts which often have oncolitic-microbial coating (on) with irregular shape. Locally, the soft parts of reworked siliceous sponges are substituted with clotted peloidal micrite. Microbial grains with thrombolite fabric, ooids and peloids are seen. Intergranular spaces are filled by microsparry cement. (F)- Bioclastic and intraclastic floatstone, sample Q8. It is mainly composed of fragments of thrombolites, bioclasts and intraclasts. Allochthonous thrombolites (thr, intraclast) are more common and identified because they are worn and mildly rounded. Oncoids (on) have bioclastic nuclei and are encrusted by sessile foraminifera (red arrow), which display an irregular shape. Fine terrigenous sediments and peloids are found in interstices between bioclasts.

et al., 2012); in the Nanpanjiang Basin and Sichuan Basin in South China (e.g., Sun et al., 2016; Jin et al., 2018; Shi et al., 2019). In all these instances, it may be hypothesized that the crisis of carbonate platforms, and specifically their drowning, was related to abrupt and/or large relative sea-level rise. It is shown here that sea-level rise cannot be invoked as a common cause for drowning events during the CPE, by comparing the different histories of sea-level change in the western Tethys and Sichuan Basin.

In the Sichuan Basin, a large-scale transgression related to the onset of foreland basin sedimentation in the Carnian is observed (Deng et al., 1982; Wu, 1984; Zhang et al., 1996; Li et al., 2003). The different

timeframe of drowning in South China Block (Fig. 9), early Carnian in Nanpanjiang Basin (Minzoni et al., 2015, and references therein) and late Carnian in Sichuan Basin (Jin et al., 2018) may be related to the different local structural arrangements and distances from the Indosinian orogeny. In western-central Tethys, some platforms drowned too (e.g., in the Cave del Predil/Raibl area, Northern Calcareous Alps and Taurus mountains) but the drowning events were not synchronous (Fig. 9). We thus suggest that the environmental change associated to the CPE may have favored drownings, but their exact timing was determined by local relative sea level rise due to tectonics.

Across the CPE, there is also evidence of sea level fall. In the

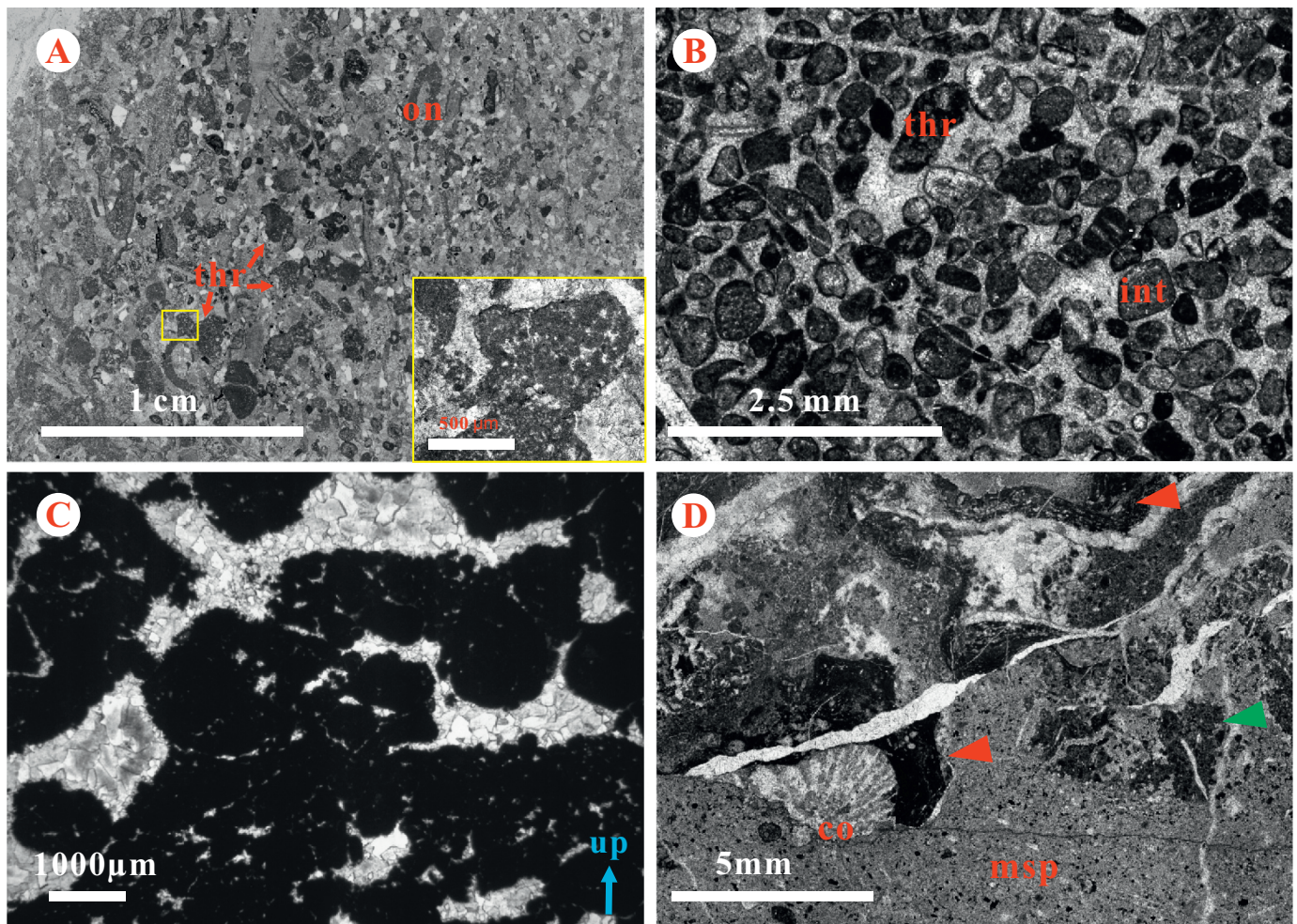


Fig. 8. Thin-section microphotographs of the Carnian successions from eastern Southern Alps. Santo Stefano di Cadore section: (A)- Thrombolitic grainstone, GG14. It is dominated by thrombolites (thr, details in the yellow square are shown in the bottom right corner), and Oncoids (on) and fragments of bioclasts are seen. Intergranular spaces are filled by microsparry and blocky cements. (B)- Bioclastic- intraclastic grainstone, GG18. It is mainly composed of intraclasts and bioclasts. Intraclasts (int) are mainly made of carbonate mud and have round shape. Bioclasts are mainly foraminifera and bivalves, with fewer brachiopods and echinoderms. Oncoids, peloids and thrombolites (thr) are seen. Intergranular spaces are filled with blocky cement. Cave del Predil section: (C)- sample CZ1, consists of thrombolites, the intergranular spaces are filled with blocky cement, and bioclasts are rare. Mt. Škrlatica section: (D)- Bioclastic and intraclastic rudstone, sample Mk11. Reef builders are common, such as corals (co), often encrusted by oncolitic-microbial coatings (red arrow). Interstitial clotted peloidal micrite (green arrow) and fragments of thrombolites are visible.

Dolomites (Fig. 9), the crisis of microbial factories was nearly synchronous with a sea level drop, the onset of a more humid climate, terrigenous input and the first occurrence of multiple carbon isotopic excursions (Gattolin et al., 2015; Dal Corso et al., 2015, 2018b, and references therein). The regression and consequent subaerial exposure of the platform, and the input of siliciclastics, were previously suggested as the main reasons of the carbonate platform crisis (e.g., De Zanche et al., 1993; Gianolla et al., 1998; Bosellini et al., 2003).

However, more recent data from the Dolomites show that the crisis of high-relief carbonate platforms began before the sea-level fall and the increase in terrigenous input (Gattolin et al., 2015). Overall, shallow water carbonate depositional systems across Tethys did experience severe changes, including drowning in some localities, at the CPE. However, there is no systematic relationship between drowning, or the crisis of carbonate systems at the CPE, and sea level rise. Instead, a crisis of shallow water carbonate production has been documented even for localities where, at the CPE, the local sea level was steady or falling. We thus exclude relative sea-level rise as a cause of carbonate platform drowning in the Carnian Tethys.

6.3. A global change in the mode of carbonate production: crisis and recovery of the microbial factory

Modal analysis on thin sections from carbonate platforms in the Southern Alps (Dal Corso et al., 2015; Gattolin et al., 2015) quantitatively showed that carbonate sedimentation continued across the CPE, but carbonates changed sharply in their nature. A drop in the relative abundance of microbial carbonates is observed, paralleled by an increase in ooids and skeletal grains that became the dominant carbonate components during the CPE (Fig. 10A).

Modal analysis of the Chinese and Italian sections examined in this study, and the correlation of the stratigraphic successions from the Sichuan Basin and the Western Tethys, highlight a common evolution in which microbial carbonate production before the CPE was replaced during the episode by skeletal components (Fig. 10A).

Quantitative carbonate petrography is available so far only from the Southern Alps and for the Sichuan Basin (Fig. 10A); however, a crisis of the microbial factory and its substitution by skeletal-dominated carbonate depositional systems can be inferred for other localities of Tethys as well. The growth of the Wetterstein carbonate platform of the Northern Calcareous Alps, which was nearly continuous from the

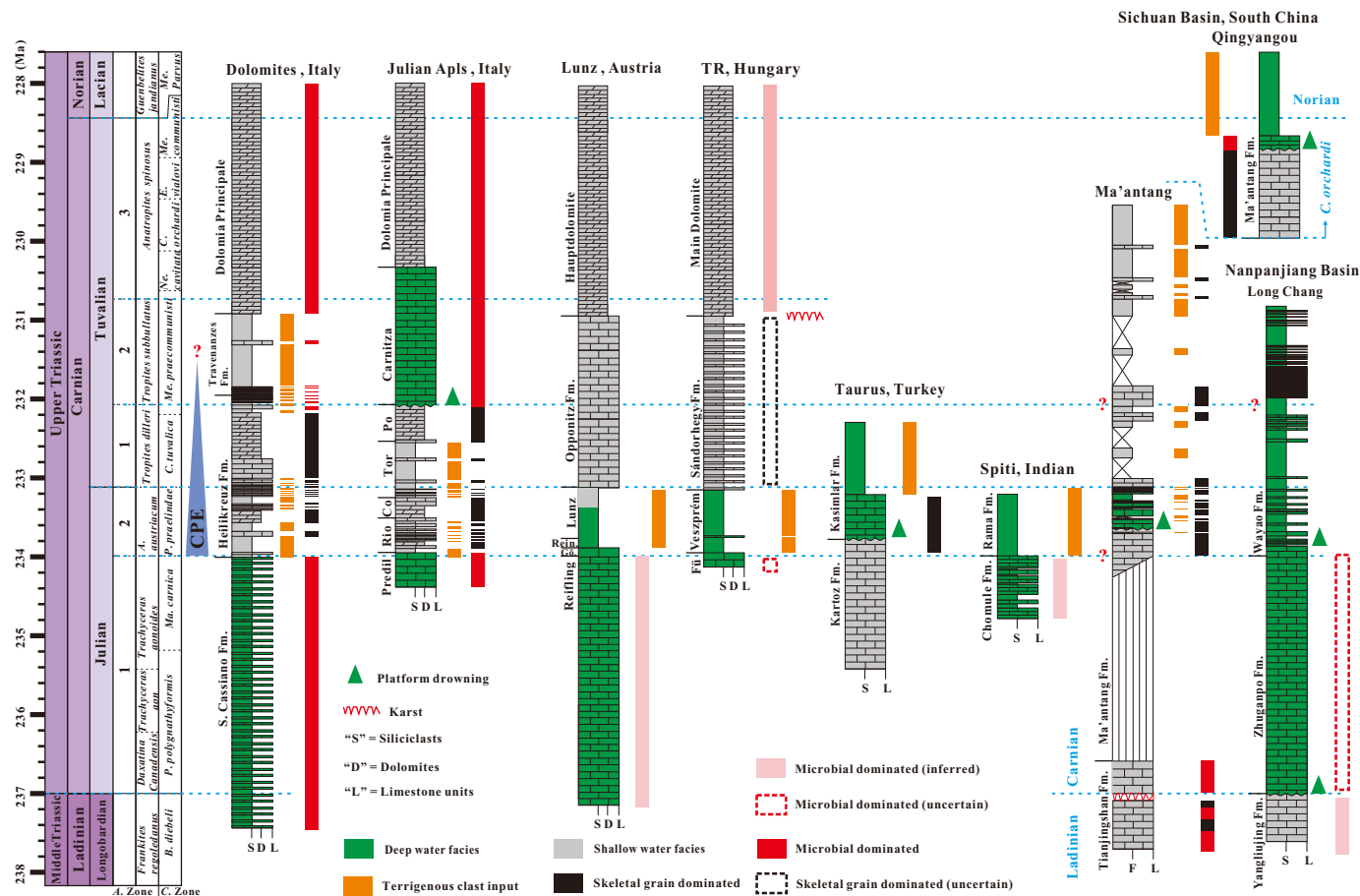


Fig. 9. Major changes of in Carnian carbonate factory and evidence of increased terrigenous input during the CPE in the Tethys. The Carnian sections (Dolomites, Julian Alps, Lunz and Transdanubian Range) from Alpine region follow Haas and Budai, 1999 Roghi et al. (2010), Preto (2012), Dal Corso et al. (2015, 2018b). The Taurus section (Turkey) follows Lukeneder et al. (2012). The Spiti section (Indian) follows Hornung et al. (2007b), and its biostratigraphy was later corrected by Mueller et al. (2016). The Ma'antang section follows Shi et al. (2019). The Qingyangou section follows Jin et al. (2018, 2019). The Long Chang section from Nanpanjiang Basin follows Sun et al. (2016). “Predil” = Predil Limestone, “Rio” = Rio del Lago Formation, “Co” = Conzen Formation, “Tor” = Tor Formation, “Po” = Portella Limestone, “Fü” = Füred Formation, “Gö” = Göstling Formation, “Rein.” = Reingraben Formation, “TR” = Transdanubian Range.

Anisian to the early Carnian, was interrupted abruptly by the CPE (Schlager and Schöllnberger, 1974). Although studies on the microbial nature of this platform are missing, the facies of the Carnian Wetterstein Formation typically include carbonates with stromatolitic or clotted peloidal fabric and abundant marine cements (e.g., Lein et al., 2012). Rüffer and Zamparelli (1997) also illustrated several microbialites and calcimicrobes from the Ladinian and Carnian Wetterstein Formation.

This evidence indicates that, while drowning events were isolated and diachronous in the Carnian, the decline in microbial production associated to the early stages of the CPE was instead a large-scale phenomenon that synchronously affected shallow-water Tethyan carbonate platforms. Notably, a similar evolution in carbonate platforms coincident with a global negative perturbation of the carbon isotopic record is reported for the Early Jurassic: across the Sinemurian-Pliensbachian (S-P) boundary Event, carbonate production on the Trento Platform, in the Western Tethys switched from microbial-dominated to skeletal-dominated (Franceschi et al., 2019). This suggests that through geologic history there might be a connection between the demise of microbial producers in shallow water carbonate systems and global events testified by carbon cycle perturbations.

Microbial carbonate platforms in the western Tethyan regions recovered in late Carnian to early Norian (Caggiati et al., 2018 and Fig. 10A). Results from the Qingyangou section show that in the Sichuan Basin (eastern Tethys) microbial content increases at late Tuvalian (Fig. 6 and 10A). Although caution has to be taken in drawing

correlations, due to the differences in biostratigraphic resolution between the two areas, this timing seems in good agreement and suggests that at least one million of years passed before microbial carbonate production could recover from the CPE crisis. The resumption of microbial carbonate factories might have been due to a Tethys-wide re-establishment of seawater conditions suitable to the development of microbialites after the CPE.

6.4. Possible causes of the synchronous changes in carbonate production across the CPE

Carbonate factory transitions are widely reported for the ‘big five’ mass extinctions, such as the Late Devonian biotic crisis and the end-Permian extinct event. However, in an opposite way respect to the CPE, microbial carbonates substituted carbonate skeletal associations in these cases (e.g., Baud et al., 1997; Wood, 2000; Riding, 2006; Kershaw et al., 2007; Mata and Bottjer, 2012; Luo et al., 2014; Ibarra et al., 2016; Fang et al., 2017). Competition from metazoa has been considered a possible factor significantly influencing the changes of microbial carbonate abundance (Riding and Liang, 2005; Riding, 2006). Schubert and Bottjer (1992) proposed that bioturbation and grazing activity were barriers to microbialite formation during the Phanerozoic.

The change of carbonate factory may be related to the chemistry of seawater, i.e., to changes in saturation with respect to carbonate minerals. Franceschi et al. (2016) explained the high carbonate

Fig. 10. A). Comparison of modal abundance of skeletal and microbial grains (excluded other components) in carbonates from Ladinian to Norian in Alpine regions (western Tethys) and Sichuan Basin (eastern Tethys). The published data from Stuores Wiesen section (Preto, 2012) and Milieres and Costamoling section (Dal Corso et al., 2015) are merged with the new results of this study. The point-counting data of studied sections were selectively illustrated here according to their comparable biochronology. The sharp decrease of abundance in microbial grains coinciding with the negative CIE is observed in both the Alpine region and Sichuan Basin, as well as the recovery of microbial grains is in late Carnian to earlier Norian. $\delta^{13}\text{C}_{\text{org}}$ record of Alpine regions are from Dal Corso et al. (2018b) and of Sichuan Basin are from Shi et al. (2019). **B).** Locations of Southern Alps and Sichuan Basin during the Carnian, paleogeographic map of Carnian from Scotese (2014).

production of microbialites on the Middle Triassic Latemar platform with a high saturation state of seawater. Other works discuss that a high saturation state is needed for the production of abundant biotically-induced carbonates (Grotzinger and Knoll, 1995; Riding and Liang, 2005). This may suggest that the microbial carbonate factory switched to skeletal grain dominated factories during the CPE because of a drop in the seawater saturation state, and consequently precipitation rates were lower during the CPE.

A mechanism able to impact on the saturation state of seawater is ocean acidification. Rigo et al. (2007) described a rise in the Carbonate Compensation Depth in the Lagonegro Basin of Southern Italy at the time of the CPE. This could accord with an ocean acidification scenario. However, no definitive proof has been provided so far that the pH of seawater was reduced during the CPE. Moreover, the duration of the microbial carbonate factory crisis, which apparently lasted for > 1 Myrs from the late Julian to the early Tuvanian (Fig. 10A), seems not compatible with the average duration of an ocean acidification event that should not exceed 100 kyrs (Hönisch et al., 2012). It should be considered, however, that the CPE encompasses multiple pulses of environmental change (e.g., Hornung et al., 2007c; Roghi et al., 2010) which are coupled with multiple carbon isotopic excursions (Dal Corso et al., 2018b). It could be therefore hypothesized that repeated, short episodes of ocean acidification occurred, which effects on shallow water carbonate production could not be adequately recorded at the sampling resolution of this study.

7. Conclusions

The Carnian Pluvial Event coincided with widespread modifications in carbonate platforms throughout the Tethys. Modal analysis carried out on carbonate grains of series in Sichuan Basin (eastern Tethys) and in the Southern Alps (western Tethys) showed that carbonate production switched from microbial-dominated to bioclastic-oolitic-dominated at the onset of the CPE. The recovery of microbial carbonate factory occurred in the late Tuvanian/early Norian in both the Southern Alps and Sichuan Basin. Thus, a synchronicity of crisis and recovery of microbial carbonate factories is observed at the scale of the entire Tethys and irrespective of the different local environmental conditions. Hence, the crisis of microbial shallow water carbonates points to changes in climate, oceanographic or seawater chemistry related to the CPE as the drivers of the observed global scale modifications in shallow water carbonate systems. A maintained lowering of seawater saturation state with respect to carbonate minerals is a likely explanation for the observed Tethys-wide crisis of microbial carbonates.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2019.103035>.

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