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The Carnian Pluvial Episode in Italy: History of the research and perspectives

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ABSTRACT - The Carnian Pluvial Episode (CPE) was a perturbation of the Late Triassic climate that had a strong impact on marine and terrestrial ecosystems. The CPE is still a relatively neglected episode if compared to the other global ecosystem turnovers of the Mesozoic. Nevertheless, the CPE is synchronous with a major biological turnover, with both extinction among many marine and terrestrial groups and, remarkably, one of the most important evolutionary phases in the entire history of Life. The first significant radiation of dinosaurs, the spread of conifers and bennettitaleans, the first common occurrence of calcareous nannofossils, and the first reefs built by scleractinian corals all occurred during or soon after the CPE. Furthermore, the first common occurrence of amber dates to the CPE. Ammonoids and conodonts, the two most important groups for the biostratigraphy of the Triassic, were also subject to a significant turnover. Many localities in Italy had a primary role for the understanding of the CPE, and still represent benchmarks for new studies. Some of these localities are paradigmatic examples of the geological and biotic processes that were occurring during this interval of geologic time, and should be designated as geosites. While recent studies on the CPE focused on identifying the episode globally, and far from the best studied regions of Western Tethys and the European continent, the Italian CPE localities could still provide a wealth of information on this event, especially concerning the evolution of shallow marine and terrestrial groups. Indeed, the best deep-water record of the CPE (Pignola, Basilicata), the most expanded and complete shallow water successions (Raibl area, Friuli-Venezia Giulia), the most prolific amber sites and the best preserved reef associations (Dolomites, Veneto) all occur in Italy.

RIASSUNTO - [L'Evento Pluviale Carnico in Italia: storia delle ricerche e prospettive] - *L'Evento Pluviale Carnico (CPE) è stato un evento climatico e di crisi biologica che ebbe luogo a metà dell'età Carnica (tardo Triassico) e che ebbe un impatto notevole sugli ecosistemi marini e terrestri. Rispetto ad altri eventi di crisi biologica del Mesozoico, il CPE è stato finora trascurato. Eppure, si può provare come allo stesso tempo si sia verificata l'estinzione di numerosi taxa in gruppi marini e terrestri, ma soprattutto la radiazione di molteplici gruppi tassonomici, al punto che il CPE dovrebbe essere considerato uno dei passaggi evolutivi più importanti della storia della vita. Tra i gruppi che hanno avuto una importante radiazione durante o immediatamente dopo il CPE, vanno annoverati i dinosauri, le conifere e le bennettitali, i nannofossili calcarei. Anche i primi reef con un contributo significativo dei coralli Scleractinia e la prima apparizione diffusa e abbondante di ambra vanno datate al CPE. Infine, i due principali gruppi di fossili di mare aperto, che sono anche i principali strumenti biostratigrafici per il Triassico, sono stati soggetti ad un forte turnover durante il CPE. Le località italiane che contengono una documentazione del CPE sono numerose, hanno rappresentato e rappresentano tuttora degli affioramenti irrinunciabili per la comprensione e lo studio degli effetti del CPE sulla sedimentazione e sulla vita sulla Terra. Proprio per il loro ruolo nella storia della comprensione di questo evento, e per la loro importanza nel documentare il CPE, si propone che i principali siti che documentano questo evento siano riconosciuti come geositi. Gli studi più recenti sul CPE si sono concentrati nel riconoscere questo episodio di cambiamento climatico a scala globale, e in particolare lontano dalle regioni più intensamente studiate della Tetide occidentale e dell'Europa continentale. Ci si potrebbe quindi chiedere se esista ancora uno scopo nell'indagare le caratteristiche del CPE in Italia. Si osserva qui che le serie di ambiente marino profondo meglio documentate (ad esempio nel Bacino di Lagonegro della Basilicata), le successioni di mare basso più continue ed espanse (Cave del Predil in Friuli-Venezia Giulia), i giacimenti più prolifici di ambra triassica ed i reef meglio preservati (Bacino di Cortina nelle Dolomiti) sono tutti localizzati in Italia. Queste località possono ancora fornire una notevole quantità di informazioni inedite, soprattutto per quanto riguarda l'evoluzione degli organismi di mare basso e terrestri.*

INTRODUCTION

The Carnian Pluvial Episode, or CPE, is a climatic perturbation that occurred during the Carnian (Late Triassic), and is recorded globally both in continental and marine sedimentary successions (e.g., Preto et al., 2010; Dal Corso et al., 2018). It was first identified as a palaeoclimatic event by Simms & Ruffell (1989), but the tale of its discovery and acceptance was a long and complex one (Simms & Ruffell, 2018). Originally, Simms & Ruffell (1989) pointed out that the CPE roughly coincides with several extinctions and originations of marine and terrestrial taxa, but the Episode has never been listed among the largest global perturbations nor

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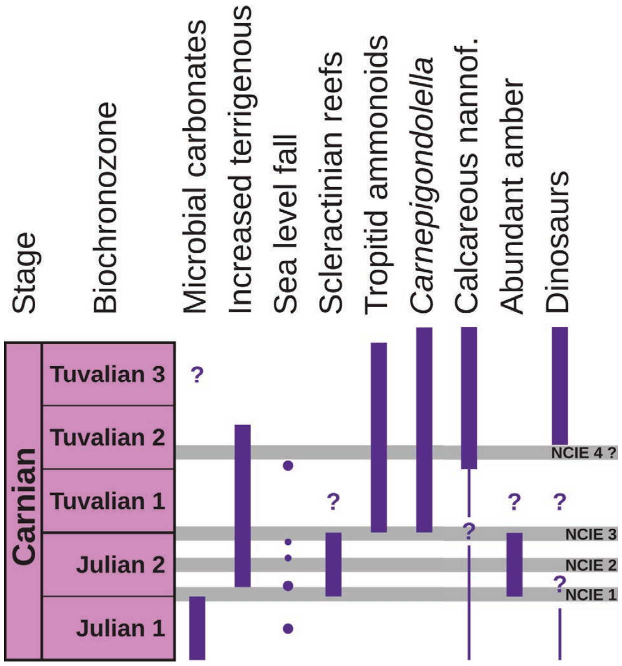


Fig. 1 - Some of the major environmental and biotic changes recorded in the Carnian of Italy: distribution of microbial carbonates from Gattolin et al. (2015); terrigenous input from Dal Corso et al. (2018) and references therein; sea level fall from Gianolla et al. (1998a) and Preto & Hinnov (2003); distribution of scleractinian reefs from Gattolin et al. (2015). Tropitid ammonoids and the conodont *Carnepigondolella* are taken here as representative for Tuvalian taxa that radiated during the CPE among ammonoids and conodonts. Distribution of calcareous nannofossils from Preto et al. (2013); amber from Seyfullah et al. (2018) and references therein; distribution of dinosaurs from Bernardi et al. (2018). NCIE: Negative Carbon Isotopic Excursion (from Dal Corso et al., 2018).

among the major biodiversity crises until very recently (Bond & Grasby, 2017). However, although all the other Phanerozoic crises have been studied with variable detail, the CPE ranks low in this league under any possible perspectives. The CPE is indeed, so far, a neglected event.

The little attention the CPE attracted is probably an unfortunate artefact of its chronological position: not only does the CPE not correspond to any major boundary (e.g., era or period) of the geological time scale, but it does not even correspond to a substage boundary (Fig. 1). This obliviousness is, however, not fully deserved. Some significant steps in evolution took place during the CPE. This time of climate change saw the dinosaurs conquering a primary role in terrestrial ecosystems (Bernardi et al., 2018), while in the shallow seas of Tethys, scleractinian corals became significant components of ecological reefs for the first time on Earth (e.g., Stanley, 2003). Calcareous nannoplankton only became abundant after the CPE (Preto et al., 2013): this began the transition to a modern carbon cycle, in which oceans contribute with a strong buffering capacity (Ridgwell, 2005).

Italian localities and fossils played a primary role in the recognition and understanding of the CPE. With this contribution, we aim to review the stratigraphic record of the CPE in Italian sites, highlighting their importance for study of the Upper Triassic, suggesting future research directions and providing advice for the popularisation and conservation of those localities that may qualify as geosites.

HISTORY OF THE RESEARCH ON THE CPE

The discovery that an episode of climate change occurred during the Carnian, and was associated with significant biotic turnover, dates back to the seminal paper of Simms & Ruffell (1989). Recently, the authors of this paper provided their insider's account of the discovery, which apparently took a certain dose of luck, as well as the brilliant intuition that Carnian crinoid extinctions and fluvial sandstone deposition were somehow related (Simms & Ruffell, 2018). The discovery, however, did not arrive completely out of the blue (Fig. 2). Previously, Schlager & Schöllnberger (1974) recognised that an event occurred in the Carnian that abruptly interrupted the growth of Tethysian carbonate platforms. This was known in the Triassic literature as the "Raibl", "Lunz", and/or "Reingraben" Event or Turnover (Schlager & Schöllnberger, 1974; Tollmann, 1976; Liebermann, 1979) and has often been correlated with the deposition of a sandstone unit, the Schilfsandstein, in the otherwise evaporitic Germanic Basin (e.g., Kozur & Bachmann, 2010). The unique characteristics of the "Reingraben" Event were known since the dawn of Alpine stratigraphy: its existence and correlation throughout Europe were roughly established since the 1800s (e.g., von Hauer, 1853; Fötterle, 1856; Wörhmann, 1889; Mojsisovics et al., 1895; Verloop, 1908; Koken, 1913; Jerz, 1966), but the climatic component was not fully understood. Furthermore, Benton (1983, 1986) noted a turnover among terrestrial vertebrates in the Carnian, but the stratigraphic constraints available at the time were insufficient to associate this turnover with the CPE.

A fundamental contribution, based on data from the Italian Dolomites, was published in 2012 at the apex of a revival of the CPE in the international scientific community (Wignall, 2017). Dal Corso et al. (2012) performed a set of carbon isotope analyses of bulk organic matter and biomarkers from the Rifugio Dibona section (Dolomites, Italy), and identified a major negative carbon-isotope excursion at the onset of the CPE. As the negative shift is recorded by both marine and terrestrial fossil molecules, this must have reflected a change in the carbon-isotope composition of the entire atmosphere-ocean system (Dal Corso et al., 2012). The most likely "smoking gun" for an injection of light carbon into the reservoirs of the global carbon-cycle was found in the eruption of the coeval Wrangellia Large Igneous Province (LIP), a connection that was earlier suggested by Furin et al. (2006). Such findings moved the CPE to the same level as other LIP-related events, attracting the interest of more and more research groups around the world (e.g., Dal Corso et al., 2015, 2018; Mueller et al., 2016a, b, 2017; Sun et al., 2016). However, as is always the case in science, the paper by Dal Corso et al. (2012) on its own did not come out of the blue, but it was instead the result of a long and established tradition of research on Carnian stratigraphy, sedimentology and palaeontology by the Italian scientific community.

A relationship between the climate episode supposed by Simms & Ruffell (1989) and the common occurrence of amber in the Dolomites and globally was suggested by Gianolla et al. (1998a). Researchers in Padova and Ferrara then studied the stratigraphic signature of the

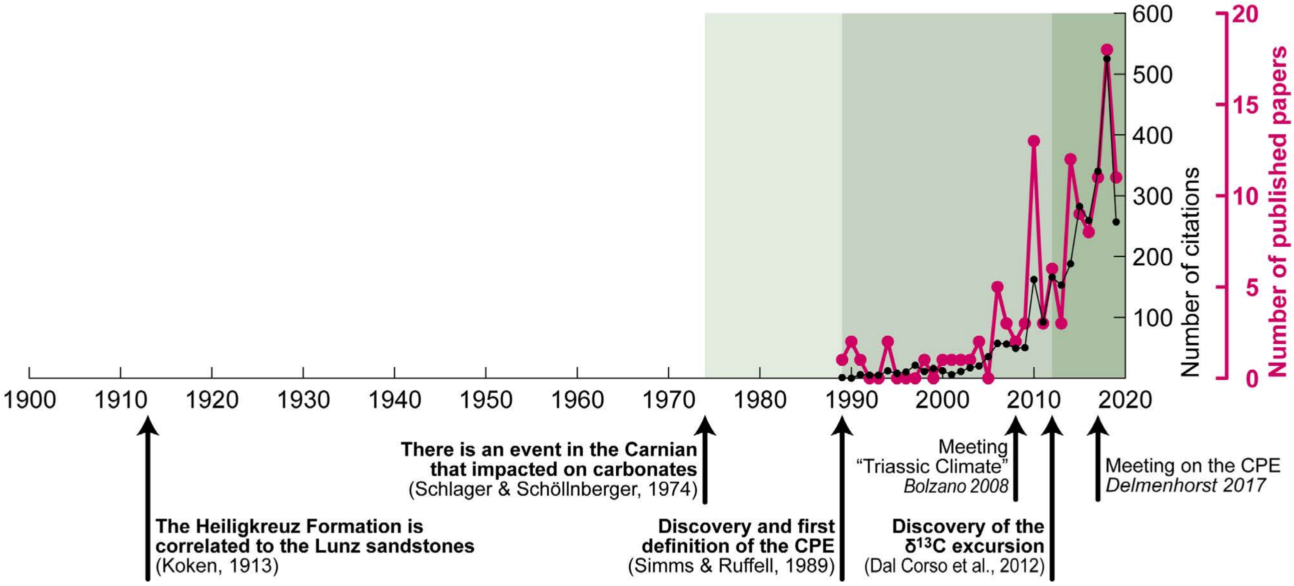


Fig. 2 - Timeline with major milestones/discoveries about the CPE, and impact on the scientific community. Citation data are obtained from Scopus © with a search for [Carnian AND pluvial] OR [Carnian AND humid] OR [Carnian AND climate], and subsequent manual cleaning of the list. All papers that make reference to climate or environmental change in the Carnian, including those with a broader focus on the Triassic or Mesozoic, where retained. Citation data for year 2019 are limited to the 15th of February. Only an arbitrary selection of discoveries and milestone research meetings is shown.

CPE, firstly in the Southern Alps (e.g., Bosellini et al., 2003; Preto & Hinnov, 2003; Stefani et al., 2010), then in the Apennines and elsewhere (Furin et al., 2006; Rigo et al., 2007, 2012; Roghi et al., 2010; Dal Corso et al., 2015, 2018). The impact of the CPE on sedimentation was also documented in Lombardy (Berra & Jadoul, 2002). Similarly, research groups based in German-speaking central Europe were also investigating the impact of the CPE on sedimentation (e.g., Hornung & Brandner, 2005; Keim et al., 2006; Hornung et al., 2007a). The crisis of high-relief carbonate platforms during the Carnian is one of the most evident effects of the CPE, and was associated with a sea level drop and consequent sudden increase of siliciclastics, noted in earlier works (e.g., Bosellini, 1984; De Zanche et al., 1993; Gianolla et al., 1998b; Neri & Stefani, 1998). Only later, did the role of climate change on the evolution of carbonate platforms became obvious (Keim et al., 2001; Bosellini et al., 2003; Hornung et al., 2007b; Neri et al., 2007; Stefani et al., 2010) and when the effects and timing of the forcing were more clearly described by Gattolin et al. (2015).

THE CPE IN ITALY: AN OVERVIEW OF MOST RELEVANT SITES

Stratigraphic sections in the Dolomites

A significant portion of present knowledge of the CPE derives from studies on stratigraphic sections of the Carnian of the Dolomites and nearby areas, where several sections that encompass the CPE have been described (e.g., Keim et al., 2001; Preto & Hinnov, 2003; Breda et al., 2009; Dal Corso et al., 2015). The stratigraphic succession between Mount Lagazuoi and the base of the Tofana di Rozes (Rifugio Dibona) is one of the most spectacular outcrops of the Dolomites and has been the subject of stratigraphic and palaeontological studies since the XIX century (e.g., Mojsisovics, 1879; Ogilvie-Gordon, 1893, 1900, 1929; Koken, 1913; Neri et al., 2007). Along this km-scale platform-basin transect, the relationships between high-relief carbonate platforms and basins, the basin infilling and levelling of the palaeotopography and then the establishment of a thick Upper Triassic continental to shallow water succession are exposed continuously. The stratigraphic succession of Rifugio Dibona (Fig. 3), on the eastern end of the transect, has been the most studied

Locality: **Rifugio Dibona**

Region:	**Veneto (Dolomites)**
Coordinates:	**46°32'2.68"N 12°4'9.31"E**
Environment:	**Shallow marine - paralic**
Notable for:	**Best record of CPE carbonates in Italy; amber**
UNESCO site:	**YES**
Geosite:	NO
Potential geosite:	**YES**
GSSP:	NO
Potential GSSP:	NO

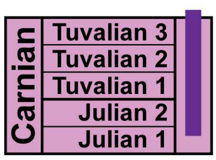


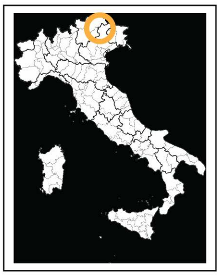
Fig. 3 - Summary of Rifugio Dibona section (in the picture), as a representative example of the stratigraphic sections in the Dolomites. For the geographic coordinates the WGS 84 system is used.

in relation to the CPE (e.g., Preto & Hinnov, 2003; Breda et al., 2009; Dal Corso et al., 2012; Gattolin et al., 2015; Maron et al., 2017), but is only one of many studied sections in the Dolomites that encompass the CPE; a correlation scheme with other locations of the Dolomites is available, e.g., in the explanatory notes of the national geological map of the area (Neri et al., 2007). Among these sections, the one near Heiligkreuz is notable because it was correlated early on with the "Lunz" Event of Austria (Koken, 1913; Fig. 2). Furthermore, the Rifugio Dibona section is known for the occurrence of abundant amber (Koken, 1913; Gianolla et al., 1998a; Roghi et al., 2006) which yielded the oldest amber inclusions of terrestrial micro-organisms and arthropods (Schmidt et al., 2006, 2012).

Carbonate platforms of the Dolomites

The Sella is one of the most famous massifs of the Dolomites. The vertical steep cliffs of this isolated massif are typically interrupted by a step, locally called "cengia del Sella", that runs continuously all around the platform and corresponds to a ca. 80 m thick succession of erodible beds (Fig. 4). The erodible succession, however, decreases towards the centre of the Sella and disappears at its nucleus (Doglioni & Goldhammer, 1998). This cliff-step-cliff morphology is the typical appearance of the CPE in the carbonate platform successions of the Dolomites, and a main architectural element of some of the most famous scenic views in the region: it corresponds to the plains at the base of the Drei Zinnen/Tre Cime di Lavaredo (e.g., Gianolla et al., 2018b), it is the basement of the Cinque Torri near Cortina d'Ampezzo, and shapes the profile of such walls as those of the Tofane and Lagazuoi on the left flank of the Falzarego Valley and the Croda da Lago massif, east of Passo Giau (e.g., Mojsisovics, 1879; Neri et al., 2007; Breda et al., 2009). It formed as clay or sand-rich sediments related to the increased runoff at the CPE, and encroached on early Carnian carbonate platforms: these sediments then formed highly erodible sandstones and marlstones, and were later overlain by the wall-forming dolomitic peritidal cycles of the late Carnian to Norian Hauptdolomit/Dolomia Principale. CPE-related morphologies are therefore one of the key features that contributed significantly to shape the unique landscape of the Dolomites, recognised as a UNESCO World natural heritage site (Gianolla et al., 2009).

Locality: **Sella platform**

Region:	**Veneto - Trentino Alto Adige**
Coordinates:	**46°30'32.01"N 11°49'42.05"E**
Environment:	**Shallow marine**
Notable for:	**Impact of the CPE on carbonate platforms and landscape**
UNESCO site:	**YES**
Geosite:	NO
Potential geosite:	**YES**
GSSP:	NO
Potential GSSP:	NO

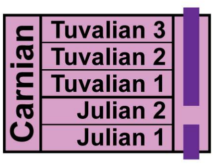


Fig. 4 - Summary of the Sella carbonate platform, as a representative example of the carbonate platforms of the Dolomites. For the geographic coordinates the WGS 84 system is used. In the picture, the "Cengia del Sella", i.e., the terrigenous interval breaking the walls that formed during the CPE, at Passo Sella.

Dinosaur footprints of the Travenanzes Formation

In the western part of the Dolomites region, along the Mendola Chain-Etschtal/Adige Valley and in the Nonstal/Val di Non, the Carnian succession is well exposed in several sections (e.g., Gennaro, 2007; D'Orazi Porchetti et al., 2008; Avanzini et al., 2012; Bernardi et al., 2013). The bases of the successions record only the younger phases and the aftermath of the CPE, represented by interbedded white-grey dolostones and reddish or greenish shales of the Travenanzes Formation (Neri et al., 2005; Avanzini et al., 2012; Kustatscher et al., 2016; Bernardi et al., 2018). The Travenanzes Formation was deposited in alluvial-plain, carbonate tidal flat and shallow-lagoon environments, and its upper portion is organised into metre-scale peritidal cycles (Avanzini et al., 2010, 2012; Breda & Preto, 2011). While in the classical central/eastern Dolomites sections the Travenanzes Formation lies on the Heiligkreuz Formation, in most of the Adige Valley it lies directly on the Schlern/Sciliar Dolomite (upper Anisian-upper Ladinian) or on volcanics (upper Ladinian), with a sharp and erosional contact (Neri et al., 2005; Avanzini et al., 2012).

The Travenanzes Formation is dated to the Tuvalian (Roghi, 2004), and, especially in the western Dolomites, yielded several well-preserved archosaur ichnoassociations (Fig. 5). Three localities have contributed most to our knowledge of the CPE event:

1. The San Gottardo outcrop (Fig. 5) in the Etschtal/Adige Valley. Here, only a few metres of Travenanzes Formation, represented by white-grey aphanitic to silty dolostones with beds of reddish or greenish shales, crop out between the Schlern/Sciliar Dolomite and the overlying Hauptdolomit/Dolomia Principale (Avanzini et al., 2012). The San Gottardo outcrop yielded one of the most diverse ichnoassociations of the whole Carnian. Dinosaur footprints were found on the same stratigraphic horizon with dinosauromorph and crurotarsan tracks (D'Orazi Porchetti et al., 2008).

2. The Mostizzolo-Faè section (Fig. 6a), located in the Nonstal/Val di Non, nearby the village of Cles (Trento Province). Here, a 70-m-long succession of white-grey dolostones intercalated with reddish or greenish shales is exposed, that belongs to the Travenanzes Formation and passes upward gradually into dolomitic peritidal cycles of the Hauptdolomit/Dolomia Principale (Avanzini et al., 2010). A mixed archosaur ichnoassociation was described by Avanzini et al. (2010) and Bernardi et al. (2010).

3. The Mt. Roen section (Fig. 6b), located along the Mendola Chain. Here the Travenanzes Formation is remarkably rich in organic matter, mainly composed of amorphous material and sporomorphs (Gennaro, 2007).

Locality: **Val d'Adige (San Gottardo)**

Region: **Trentino Alto Adige**
Coordinates: **46°13'11.55"N 11° 6'47.30"E**
Environment: **Continental to shallow marine**
Notable for: **Dinosaur footprints**

UNESCO site: NO
Geosite: NO
Potential geosite: **YES**
GSSP: NO
Potential GSSP: NO

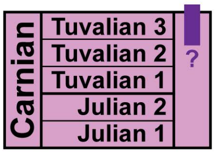


Fig. 5 - Summary of San Gottardo section (in the picture), as a representative example of the Carnian dinosaur footprint localities of the Adige Valley. For the geographic coordinates the WGS 84 system is used.

This section yielded dinosaur footprints that have been attributed to theropod dinosaur trackmakers with an estimated body length of about 5 m (Bernardi et al., 2013, 2018).

The Raibl area

The Cave del Predil area near Tarvisio (Fig. 7), formerly Raibl, has probably the most expanded Carnian succession of the entire Southern Alps (e.g., Suess, 1867; Wöhrmann, 1889; Assereto et al., 1968; Schulz, 1970; Liebermann, 1978a, b; De Zanche et al., 2000). It has been considered the type-area of the Carnian Stage for a long time (Mojsisovics, 1869; Mojsisovics et al., 1895; Liebermann, 1980). The Carnian stratigraphy of Cave del Predil is characterised by an alternation of terrigenous and carbonate units lapping on the slope of a Middle Triassic to lower Carnian carbonate platform (Schlern Dm.) and documenting the infilling of a basin and then the recovery of a new carbonate platform system, facing a deep water periplatform carbonate environment (Gianolla et al., 2003; Caggiati et al., 2018). Dal Corso et al. (2018) identified the onset of the CPE at the boundary between the dark platy limestones (Predil Limestone) and a distinct terrigenous interval made of laminated siltstone of the lower Rio del Lago Formation. The CPE has been identified on the basis of ammonoid biostratigraphy and the occurrence of a negative carbon isotopic excursion in bulk organic carbon, but the reason why the area of Cave del Predil is most important is the occurrence of multiple negative carbon isotopic excursions, which in this section could be dated and correlated to the Tethysian biochronostratigraphy with unprecedented precision (Dal Corso et al., 2018).

The Pignola 2 section and the Lagonegro Basin

The Carnian succession in the Lagonegro Basin of southern Italy (Fig. 8) is so far one of the few to document the CPE in a deep-water environment. The CPE is there represented by a ca. 6 m thick interval of green silicified clays (argillite) and green radiolarites, intercalated within a thick succession of well-bedded nodular cherty limestones with thin-shelled bivalves and radiolarians, and bearing conodonts and rare ammonoids. This interval (green clay-radiolaritic horizon in Rigo et al., 2007, after Scandone, 1967) can be found everywhere in the basin (Rigo et al., 2012), but it is best exposed in the Pignola 2 section, where the Aglianico ash bed was dated to 230.91 +/- 0.33 Ma - a crucial tie point for the Triassic time scale and the first absolute dating of the CPE in the literature (Furin et al., 2006). According to Rigo et al. (2007), the carbonate-free green clay-radiolaritic horizon testifies to a temporary rise of the Carbonate Compensation Depth (CCD) in the Lagonegro Basin during the CPE.

Pizzo Mondello (Sicily)

The superbly exposed succession of Pizzo Mondello in Sicily (Fig. 9) does not encompass the CPE, but it captures

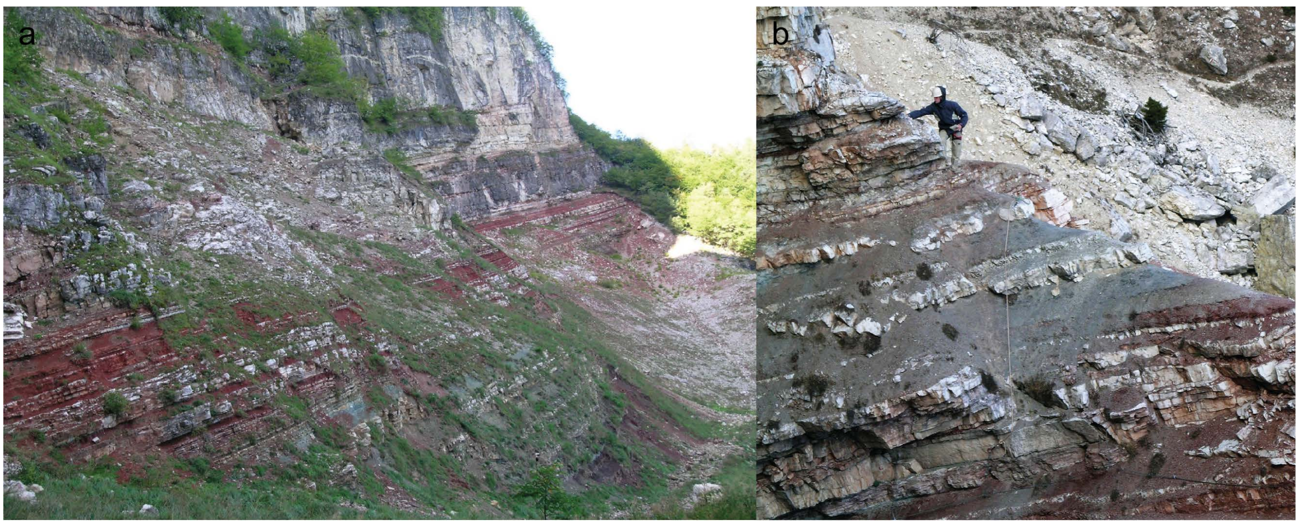


Fig. 6 - Two localities in the Travenanzes Formation that yielded dinosaur footprints. a) Mostizzolo in Non Valley. b) Monte Roen in Adige Valley. A third important locality with dinosaur footprint, i.e., San Gottardo, is illustrated in Figure 5.

Locality: **Cave del Predil (Raibl)**

Region:	**Friuli Venezia Giulia**
Coordinates:	**46°26'30.50"N 13°34'17.08"E**
Environment:	**Shallow to deep marine**
Notable for:	**Best record of multiple carbon isotopic excursions**

UNESCO site:	NO
Geosite:	YES
Potential geosite:	NO
GSSP:	NO
Potential GSSP:	NO

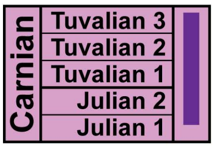


Fig. 7 - Summary of the Cave del Predil (Raibl) area. For the geographic coordinates the WGS 84 system is used. In the picture, the clinoforms of the upper Carnian to Norian Dolomia Principale dipping towards Passo della Portella, as seen from the mine of Cave del Predil.

its aftermath in a deep-water periplatform basin. Since it has been proposed as the GSSP of the Norian Stage, it has been intensively studied for its biostratigraphy (e.g., conodonts, ammonoids, bivalves: Balini et al., 2012; Levera, 2012; Mazza et al., 2012, 2018), stable isotopic stratigraphy and magnetic stratigraphy (Muttoni et al., 2004; Mazza et al., 2010). Thus, it became a "must-know" for stratigraphic studies including the late part of the CPE and the Carnian-Norian interval in general. Nearby localities of the Sicani Basin (e.g., Monte Scalpello) are much less studied, but must include the CPE at least in part, on the basis of the discussion and descriptions in Gemellaro (1902).

Monte Pora (Bergamasc Alps)

There are few localities in Italy yielding plant fossils belonging to the CPE. The most diverse plant association has been collected from Monte Pora in the Bergamasc Alps (Fig. 10; Passoni & Van Konijnenburg-van Cittert, 2003). The fossiliferous horizons belong to the Gorno Formation, assigned to the Early and early Late Carnian (Assereto & Casati, 1965). The formation consists of a succession of limestones, marly-sandy limestones and marls, deposited in a shallow, well-oxygenated lagoon with low energy, interposed between deltas and carbonate platforms (Gnaccolini & Jadoul, 1988). The fossiliferous layers are silty marls that are up to 2 m thick (Passoni & Van Konijnenburg-van Cittert, 2003). The plant fossil assemblage is composed of sphenophytes (*Equisetites*), ferns (*Danaeopsis*, *Asterotheca, Marattiopsis*, *Anomopteris*, *Phlebopteris*), cycadophytes (*Pterophyllum*, *Sphenozamites*, *Taeniopteris*, *Macrotaeniopteris*, *Zamites*), conifers ("*Yuccites*", *Brachyphyllum*, *Elatocladus*, *Aethophyllum*, *Voltzia*, *Willsiostrobus*) and incertae sedis taxa such as *Pseudodanaeopsis*.

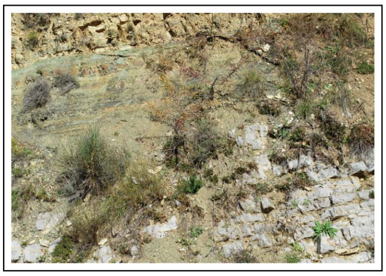
FOSSILS OF THE CPE

Biostratigraphic markers of the CPE

Ammonoids and the CPE - The Triassic timescale is traditionally based on ammonoid biostratigraphy, and the Triassic stages were initially intended as ammonoid biozones (e.g., Mojsisovics, 1879; Balini et al., 2010). Carnian biostratigraphy is no exception: ammonoids allow a fine subdivision of the Carnian Stage (e.g., Krystyn, 1978), and the two Carnian substages, Julian and Tuvalian (Fig. 1), are also defined on the basis of ammonoid occurrences: the primary marker for the GSSP of the Carnian (Mietto et al., 2012) is the first occurrence of the ammonoid *Daxatina canadensis* Whiteaves, 1889 at Stuores, which also defines the base of the Julian, while the base of the Tuvalian coincides with the first occurrence of *Tropites dilleri* Smith, 1904 and the family Tropitidae.

The onset of the CPE does not coincide with any major ammonoid turnover, being dated roughly at the boundary between the early and late Julian, with the first occurrence of *Austrotrachyceras austriacum* (von Mojsisovics, 1882) (Fig. 11) and the genus *Austrotrachyceras* (*A. austriacum* Biozone of Krystyn, 1978). This might suggest that the CPE did not have a significant impact on ammonoid evolution, and in fact a recent compilation of diversity, extinction rates and origination rates of ammonoids throughout the Permian and Triassic (Brayard et al., 2009) does not highlight the Carnian as a time of exceptional diversity loss, extinctions or originations. Nevertheless, experts on Triassic ammonoid biostratigraphy have

Locality: **Lagonegro Basin (Pignola 2)**



Region:	**Basilicata**
Coordinates:	**40°32'56.70"N 15°46'59.06"E**
Environment:	**Deep marine**
Notable for:	**Best deep water CPE section**

UNESCO site:	NO
Geosite:	NO
Potential geosite:	YES
GSSP:	NO
Potential GSSP:	NO

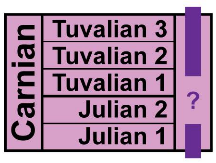
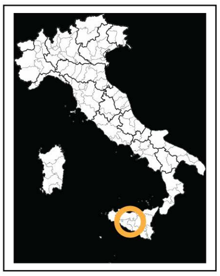


Fig. 8 - Summary of Pignola 2 section in the Lagonegro Basin, southern Italy. For the geographic coordinates the WGS 84 system is used. In the picture, the green clay-radiolaritic horizon.

Locality: **Pizzo Mondello**



Region: **Sicily**
Coordinates: **37°37'46.95"N 13°24'18.43"E**
Environment: **Deep marine**
Notable for: **Best biostratigraphic record of the Upper Carnian in Italy**

UNESCO site: **NO**
Geosite: **YES**
Potential geosite: **NO**
GSSP: **NO**
Potential GSSP: **YES**

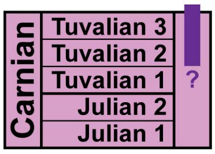


Fig. 9 - Summary of Pizzo Mondello section (picture) in Sicily. For the geographic coordinates the WGS 84 system is used.

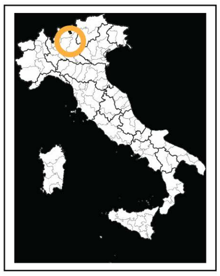
always regarded the Julian/Tuvalian boundary as a time of high turnover rates (e.g., Tozer, 1984; Jenks et al., 2015), which witnessed the near extinction of trachyceratids and the origination and rapid radiation of the juvavitids and tropitids. These three families were possibly the most characteristic and diverse of the Carnian age. Thus, while the onset of the CPE did not coincide with any notable extinction event among ammonoids, a major evolutionary step did take place during the CPE, not quite at its beginning, but still at the time of one of the three carbon isotopic excursions (Figs 1 and 11e-f).

The most probable reason why the major ammonoid turnover at the Julian/Tuvalian boundary did not appear so far in quantitative evolutionary studies is a lack of resolution. In fact, the evolution of Triassic ammonoids was so fast that all major Carnian groups (i.e., *Trachyceras* and related genera, tropitids and juvavitids) flourished for the time of a sub-age, and only left a few isolated descendants. The analysis of Brayard et al. (2009) considered just two time bins in the Carnian, i.e., the Julian and Tuvalian substages. Since the rise and fall of the main ammonoid clades only took a substage to be complete, this time resolution is insufficient to capture the evolutionary trend of Carnian ammonoids.

In Italy, ammonoids of the CPE interval are known from only a few localities. In the Dolomites, rare late Julian ammonoids were collected from the lower Heiligkreuz Formation (formerly upper Cassian Beds); the most typical representatives of this late Julian fauna are probably the diverse species of the genus *Sirenites* (e.g., Bizarrini & Braga, 1988; Bizarrini, 2000; Breda et al., 2009). Furthermore, isolated findings of *Shastites* spp. were collected from the lower Tuvalian (De Zanche et al., 2000). Another, much more diverse Tuvalian ammonoid association is described by Gemellaro (1902) and was collected at several localities of the Sicani Mountains of Sicily.

Conodont evolution during the CPE - The Late Triassic saw a continuous decline of specific diversity among Conodonta, punctuated by severe extinction-recovery pulses (Sudar et al., 1996; Martínez-Pérez et al., 2014; Rigo et al., 2018). Some lower Julian conodonts, such as *Budurovignathus* and *Mosherella*, are considered relict forms from the Middle Triassic (Sudar et al., 1996; Rigo at al., 2018). They disappeared at the end of the *Trachyceras aon* ammonoid Biozone, while paragondolellids, e.g., *Paragondolella polygnathiformis* (Budurov & Stefanov, 1965), survived much longer and even beyond the onset of the CPE. After this turnover, within the *Trachyceras aonoides* ammonoid Biozone, small platform conodonts such as *Mazzaella* and *Hayashiella* first occur (Fig. 11b) (Rigo et al., 2018). Pectiniform elements with a well-developed basal cavity (e.g., *Nicoraella*? *budaensis* Kozur, 1991) also occur, limited to shallow and/or restricted basins (Kozur & Mock, 1991; Kolar-Jurkovšek et al., 2005; Kolar-Jurkovšek & Jurkovšek, 2010; Dal Corso et al., 2018). All of these changes in the conodont associations, which took place before the CPE began, are hardly distinguishable from the normal background turnover rate of times away from biotic crises. From the compilations of literature data, no extinction occurred at the CPE among conodonts. Incidentally, this implies that that there is no clear-cut conodont biostratigraphic marker for the CPE. However, at the Julian/Tuvalian boundary most of the Julian conodonts disappear, with the only exception of *Paragondolella polygnathiformis, P. praelindae* Kozur, 1993*, P. maantangensis* (Dai & Tian, 1983) and *Nicoraella*? *budaensis* (e.g., Rigo et al., 2018). This extinction was followed by a quick recovery, with the appearance of new genera such as *Carnepigondolella*, *Metapolygnathus* and *Epigondolella* (Fig. 11a), which reached a climax during the middle-late Tuvalian. All of these new forms are characterised by a forward shifting

Locality: **M. Pora**



Region: **Lombardia**
Coordinates: **45°54'8.5"N 10° 6'46"E**
Environment: **Shallow marine - paralic**
Notable for: **Best CPE flora of Italy**

UNESCO site: **NO**
Geosite: **NO**
Potential geosite: **YES**
GSSP: **NO**
Potential GSSP: **NO**

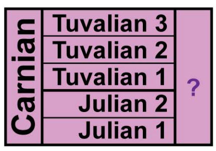


Fig. 10 - Summary of Monte Pora. For the geographic coordinates the WGS 84 system is used. In the picture, a specimen of *Pseudodanaeopsis aberi* Passoni & Van Konijnenburg-van Cittert (2003).

of the pit, platform reduction and development of tiny to strong denticles as platform ornamentation. The genus *Paragondolella* and its direct descendent *Norigondolella* still exhibit simple morphological features, without ornamentation or posterior pit (Rigo et al., 2018). Most of these new Tuvalian forms went extinct around the Carnian/Norian boundary (Mazza et al., 2018; Rigo et al., 2018).

The CPE and the origin of modern calcareous nannofossils - Calcareous nannofossils are primary biostratigraphic tools for open marine successions of Jurassic age or younger (e.g., Erba, 2006). A biostratigraphic subdivision of the Late Triassic based on calcareous nannofossils also exists (e.g., Bown, 1998), but for this time interval, conodonts, ammonoids, radiolarians or even bivalves are preferred. Although the first coccoliths only appeared in the late Norian (Gardin et al., 2012), the first abundant occurrence of calcareous nannofossils (non-coccoliths) in pelagic or hemipelagic environments dates back to the CPE. In fact, late Carnian periplatform limestones deposited at the deep bottom of the Lagonegro and Sicani basins contain abundant calcispheres with average diameter of ca. 20 µm (Preto et al., 2013; Fig. 11i). These calcispheres are almost always strongly diagenised, having a typical calcite overgrowth, which makes their taxonomical attribution difficult and uncertain. The current hypothesis is that they are calcareous dinocysts similar to *Pithonella* (Preto et al., 2013). Later on, during the Late Triassic, other forms of calcareous nannofossils would appear, which include the enigmatic spherical nannolith *Prinsiosphaera* (e.g., Bralower et al., 1991) and the earliest coccoliths. The first occurrences of these new nannofossils may be used to define a Triassic nannofossil biozonation. The first of these biozones would have its base within the CPE.

Plant fossils, palynomorphs and the CPE - The quantitative distributions of spore-pollen assemblages represent a well-developed proxy for past climatic conditions. Palynological studies of the CPE were fundamental in elucidating the environmental perturbation that occurred during the episode. Studies mainly conducted in Carnia and the Julian Alps revealed four pulses of increased abundance of hygrophytic pollen such as Filicopsida (ferns), Lycopodiales (clubmosses), Equisetopsida (horsetails) and Cycadeoidales (Roghi et al., 2010). During these pulses, xerophytic pollens are scarcer (Roghi et al., 2010). Monosaccate (*Enzonalasporites*, *Vallasporites* and *Patinasporites*) and Circumpolles are characteristic in Late Triassic Tethyan assemblages, while they are not present in the typical high-latitude assemblages characterised more by conifer pollens (*Araucarites* and *Protodiploxypinus*) (Hochuli & Vigran, 2010; Paterson & Mangerud, 2017).

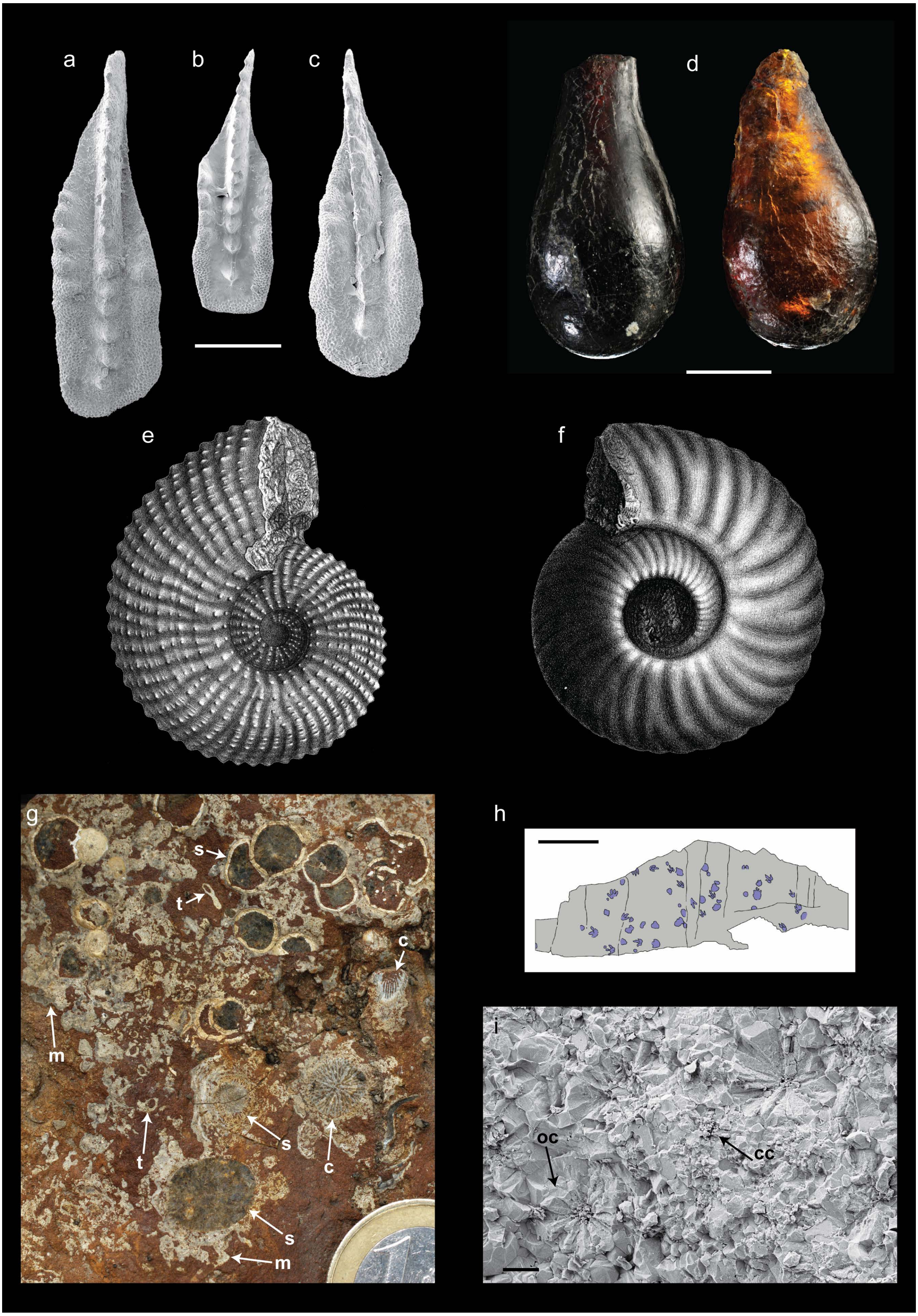
Despite these latitudinal differences, the increase of spores and the acme of pollens such as *Cycadopites* and *Aulisporites* were recognised in many Carnian successions globally (Roghi, 2004). This palynological change is thus interpreted as having climatic as well as biostratigraphic significance. Whether these pulses of hygrophytic pollen could be used for fine scale time-correlations is still unclear, despite the fact that an increase of hygrophytic forms in palynological assemblages always occurs within the time span of the CPE (e.g., Roghi et al., 2010).

The special fossils of the Italian CPE

Some rich and significant fossil sites are found within the CPE successions in Italy. We here briefly describe three of these special occurrences: the beautifully preserved microbial-metazoan reefs of the Cortina Basin, the amber deposits in the Southern Alps, and the tetrapod ichno-sites of the Dolomites and Adige Valley. We also depict briefly the unique character of floral remains during the CPE, as testified by Italian fossil plant collections.

The microbial-metazoan reefs of the Cortina Basin - Late Triassic reef facies and fossil associations from the area of Cortina d'Ampezzo are well known for their exceptional preservation: a very diverse reef biocoenosis in which corals, calcareous sponges and many other organisms (e.g., Fig. 11) are often found in life position and with their original aragonite skeletal composition preserved (e.g., Scherer, 1977; Frisia Bruni & Wenk, 1985; Russo et al., 1991; Tosti et al., 2014). These well-known fossil reefs are dated to the late Julian (e.g., Neri et al., 2005; Gattolin et al., 2015; Gianolla et al., 2018a, b), and their exceptional preservation is tightly related to the fine siliciclastic input and poor oxygenation of shallow waters below the wave base (Russo et al., 1991) that was associated with the onset of the CPE. The carbonate platforms of the Dolomites before the CPE were dominated by microbialites (e.g., Preto, 2012); according to Gattolin et al. (2015), these microbialites entered a crisis at the onset of the CPE, and so the abundance of metazoans in the Carnian reef biocoenoses of the Cortina Basin is a not yet fully understood consequence of the CPE.

Fig. 11 - Typical CPE fossils. a) *Metapolygnathus praecommunisti* Mazza, Rigo & Nicora (2011), a late Carnian platform conodont that originates in the late phases of the CPE (from Mazza et al., 2011). Scale bar: 0.2 mm. b) *Hayashiella nodosa* (Hayashi, 1968), another typical platform conodont of the late Carnian (Tuvalian) (from Mazza et al., 2011). Scale bar: 0.2 mm. c) *Paragondolella noah* Hayashi (1968), a late Carnian platform conodont that was lumped together with the early to late Carnian conodont *P. polygnathyformis* for a long time (from Mazza et al., 2011). All conodonts are from Pizzo Mondello. Scale bar: 0.2 mm. d) Amber drops from Rifugio Dibona section (from Schmidt et al., 2012), early Carnian. Scale bar: 2 mm. e) The ammonoid *Austrotrachyceras austriacum* is the marker of the austriacum ammonoid Zone and appears contemporaneously with the first isotopic excursion of the CPE. Image from Mojsisovics (1893). f) The late Carnian (Tuvalian) ammonoid *Tropites subbullatus* (Hauer, 1849) is a typical representative of the family Tropitidae, which radiated during the CPE and nearly disappeared at the end of the Carnian. Image from Mojsisovics (1893). g) A field image of an early Carnian microbial-metazoan reef facies of the Cortina Basin, with preservation of the aragonite of coral and sponge skeletons. Calcareous sponges belonging to different groups (s), corals (c) and brachiopods co-occur with microbial carbonate forming a thrombolite (m) and agglutinated tubes attributed to cf. *Macrotubus* sp. (t). h) Line drawing of a trampled bed of the late Carnian Travenanzes Formation from San Gottardo Castle. Scale bar: 1 m. i) Scanning Electron Microscope image of a fresh-cut limestone from the Pizzo Mondello section in Sicily, bearing several calcispheres, most with a thick syntaxial overgrowth (oc) and some without overgrowth (cc). Scale bar: 0.01 mm.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The amber deposits of the Southern Alps - One of the main effects of the CPE was a global hyper-production of resin (Seyfullah et al., 2018). Fossil resin, i.e., amber, from the Heiligkreuz Formation in the Dolomites is the oldest quantitatively important deposit of amber known so far at the global scale. First reported by Koken (1913) and later by Zardini (1973) and Wendt & Fürsich (1980), this amber has been extensively studied including the determination of its chemico-physical properties (Gianolla et al., 1998a). Localities in the Dolomites yielded several thousand drops (Fig. 11), associated with conifer leaves, in autochthonous or parautochthonous positions. One of the main resin-producing conifer groups were the Cheirolepidiaceae, which are also well represented in palynological associations by the abundant genus *Circumpollen* (Roghi et al., 2006). Amber drops are 2-3 mm in diameter, rounded or oval, sometimes with a little stem, and they show desiccation fractures on the surface (Fig. 11d). Inside this amber, a rich microbiological association including bacteria, fungi, algae, ciliates, testate amebae, spores, pollen and, more recently, arthropods was discovered (Schmidt et al., 2006, 2012; Sidorchuk et al., 2015).

The tetrapod ichnosites of the Dolomites and nearby areas - The role of the CPE in the evolution of dinosaurs was recently explored in two papers by Bernardi et al. (2018) and Benton et al. (2018). Bernardi et al. (2018) identified three precisely dated ichnoassemblages (A1, A2, A3) in the Late Triassic of the Southern Alps. A1, of Julian age, was described as crurotarsan-dominated and comprised ichnological data from the Val Sabbia Sandstone (Bergamo Province) and the Cassian Dolomite of the central Dolomites. Typical ichnogenera comprise *Brachychirotherium* and *Chirotherium*. A2, of early Tuvalian age, was described as a mixed Crurotarsan-Dinosauri association characterised by the co-occurrence of *Eubrontes*, *Atreipus*-like, *Evazoum* and *Brachychirotherium* ichnogenera. This is the classical ichnoassociation found in the Travenanzes Formation outcropping in the Adige and Non valleys (Figs 5-6, 11) and in the rare Heiligkreuz Formation ichnosites of Vare di Giau (Giau Pass) and Sasso della Croce in the central Dolomites. A3, of late Tuvalian-Norian age, was defined by the dominance of dinosaur-related ichnogenera (*Eubrontes*, *Grallator*) and comprised the many Hauptdolomit/Dolomia Principale ichnosites of the Dolomites and nearby areas.

The identification of these precisely dated ichnoassociations in the Southern Alps allowed Bernardi et al. (2018) to link, for the first time, the timing of the first dinosaur diversification to the CPE, when dinosaurs shifted from being nearly absent (0%, A1) to become ecologically dominant (> 90% A3).

CPE Italian fossil plant collections - Overall, the Italian Carnian successions yielded one of the most abundant and diverse macro- and microfloras of the Triassic (e.g., Fig. 10). Several families and orders make their first appearance or start at least their first radiation during this stage. This includes bennettitaleans, modern ferns (e.g., Dipteridaceae, Matoniaceae) and conifer families (Pinaceae, Araucariaceae, Cheirolepidaceae) as well as putative angiosperms (e.g., *Furcula*, *Sanmiguelia*), although angiosperm-like pollen has been described already from Middle Triassic successions (Kustatscher et al., 2018). The humid (paralic, swampy, fluvial, deltaic) environments that were widespread during the CPE permitted sphenophytes, ferns and bennettitaleans to become the most important groups in the floras, and lagoonal environments promoted the preservation of plant fossils and amber, megaspores and charcoal that are found associated with the macroremains (Kustatscher et al., 2018).

HOW POPULAR IS THE CPE? A SURVEY OF ACADEMIC AND SCIENTIFIC DATABASES

A survey on the publication record conducted in Scopus exposes quite straightforwardly how much the CPE was neglected until recently: in the 20 years after its discovery in 1989, fewer than two papers per year on average were published that mentioned a Carnian climate change in the title or abstract (Fig. 2). This history of scientific indifference towards the CPE was nicely exposed by Simms & Ruffell (2018) and is mirrored by the nearly complete absence of the topic in outreach-oriented products. To the best of our knowledge, the only popular science book dealing (also) with the CPE appeared just two years ago (Wignall, 2017). A survey of Wikipedia statistics, however, gives somehow surprising results. The "Pageviews analysis" tool (https://tools.wmflabs.org/pageviews) provides statistics of the overall and daily-average views of Wikipedia pages since July 1st, 2015. All major biotic turnovers of the Phanerozoic have a page of their own on Wikipedia, which means that a comparison of page reads within Wikipedia may be statistically robust, due to the uniformity of the sample. The CPE page attracted unprecedented interest since 2018 (Fig. 12). This can be attributed to the high media coverage of several scientific papers (e.g., Bernardi et al., 2018; Dal Corso et al., 2018a, b), which so far (February, 2019) had a lasting effect on Wikipedia reads.

This recent increased interest also had a bizarre side effect, with the CPE being cited as a proof of the biblical flood, and in creationist narratives, by antiscientific and pseudoscientific think-tanks. Given the relevance for the onset of present-day type ecosystems and the potential links with the ongoing Anthropocene crisis, the CPE may attract more and more popular interest.

PERSPECTIVES

Unanswered research questions and how Italian sites could help

The last few years saw a strong increase in publications related to the CPE, and many of these works featured localities in Italy. The question arises, thus, whether there is still something to find about the CPE in Italian localities. Yet, when compared to other major biotic events of Earth's history, the CPE is still much less understood. Some large uncertainties, such as the true global extent and regional variability of the climatic crisis associated with the CPE, cannot possibly be resolved by solely focusing on Italian locations. However, other major unknowns, in order to be solved, may require large fossil collections and high stratigraphic resolution that may be ideally found in some Italian sites. We here identify two of these major unknowns, which are particularly relevant for the broad field of palaeontology.

The biotic response to the CPE in the marine realm - Little is known, in quantitative terms, about the real magnitude of biotic turnover at the CPE. This is probably a consequence of the odd time location of the CPE, far from any major chronostratigraphic boundaries: in palaeobiological databases (as, e.g., the Paleobiology database: https://paleobiodb.org), occurrences are given in time bins, which break typically at stage boundaries. In these databases, the relevant time bin lumps together occurrences before and after the CPE, and fossil distributions thus reconstructed are not likely to capture much of the biotic turnover.

For those fossil groups that are used for high-resolution biostratigraphy, however, a better insight is possible, as the occurrences of such fossils as ammonoids and conodonts usually date themselves at a sufficient resolution to split the CPE interval into numerous biozones. It has been known for a long time among ammonoid and conodont specialists, that these open marine groups did experience a severe turnover at the CPE, although with a timing not exactly coincident with the main isotopic excursion. Was it the same for shallow water marine groups, and especially those with benthic habits? Answering this question would require a much more detailed time-binning of palaeobiology fossil databases, which will not be achieved any time soon. Meanwhile, a detailed sampling and palaeontological study of long, expanded, well dated and fossil-rich successions of the Southern Alps - such as those of the Raibl area - could provide robust data on the biotic response of marine benthic ecosystems during the development if the CPE.

The timing of the CPE - A milestone in our knowledge of the CPE was the U/Pb dating of the Aglianico ash bed in the late Carnian of the Lagonegro Basin (Furin et al., 2006). This radiometric date constrained the age of the CPE and contributed significantly to stretching the Triassic timescale into its current appearance, but could say little about its duration. Years later, the duration of the CPE and the timing of climatic perturbation and biotic change within it are still essentially unresolved. It is clear, for example, that the CPE developed over a geologically relevant time interval of > 1 m.y. and comprised several sub-events, each corresponding to a perturbation of the global $\delta^{13}C$ record (e.g., Miller et al., 2017; Dal Corso et al., 2018; see also Fig. 1). It is instead less clear how long each single carbon isotope excursion actually lasted. Relative temporal relationships were established for most of the environmental changes associated with the CPE. We know, for example, that sea level fall and terrigenous input came after the isotopic perturbations (e.g., Dal Corso et al., 2015; Gattolin et al., 2015), but how much did it take for the forcing mechanisms (assuming that the $\delta^{13}C$ perturbations faithfully recorded the timing of the forcing) to translate into actual environmental and climate change? Expanded and continuous successions are needed to try to answer these questions. Again, promising candidates for this type of work are the successions of the eastern Southern Alps (e.g., Raibl area).

The best CPE localities should be geosites

Grounding on the wealth of new data available, there is scope for a new set of outreach-oriented products to

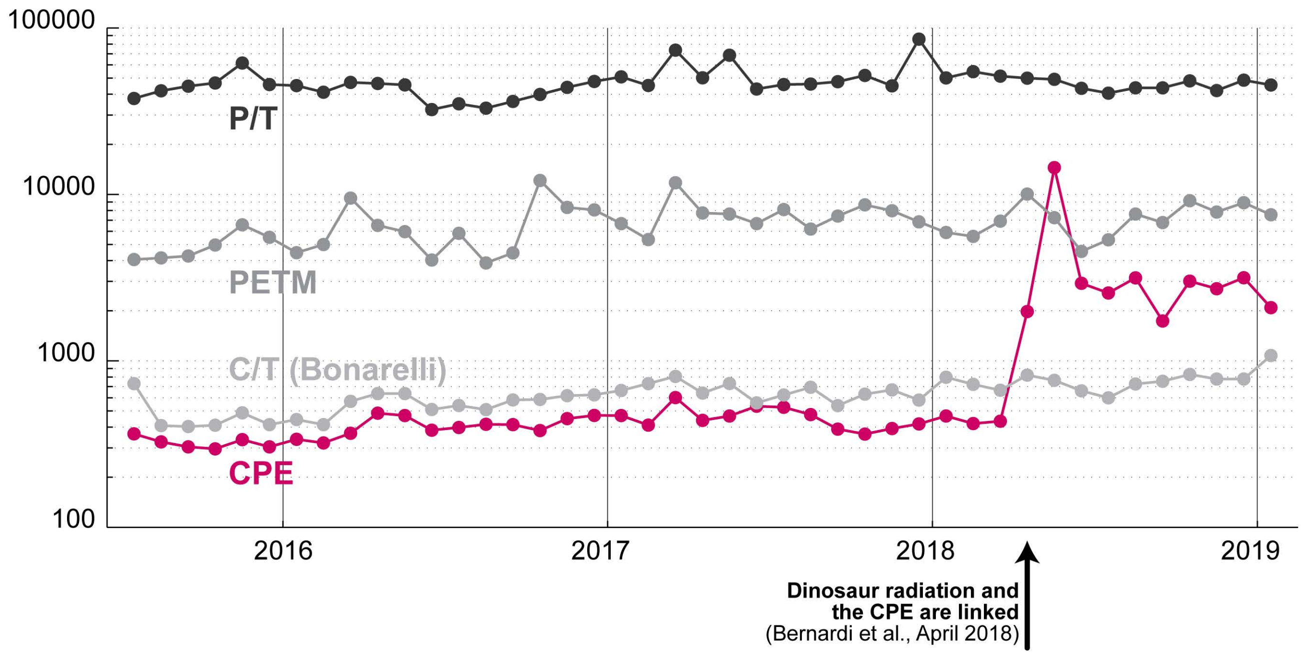

Fig. 12 - Page views on English Wikipedia from July 2015 to January 2019, plotted on a logarithmic scale. P/T: Permian-Triassic extinction event; PETM: Palaeocene-Eocene Thermal Maximum; C/T: Cenomanian-Turonian boundary event (which corresponds to the Bonarelli event in Central Italy); CPE: Carnian Pluvial Event. These names identify the main Wikipedia pages for each of the events; synonyms for these events do exist in Wikipedia, and redirect to the selected main pages. By selecting the main Wikipedia page, views via redirects are also accounted.

be developed in the next years. A first step towards the popularisation of Italian research on the CPE may be the identification of geosites related to the discovery and understanding of the CPE. Among the few localities described in this review, two (Pizzo Mondello in Sicily and the Raibl area in Friuli-Venezia Giulia) are already geosites, and two are, at least in part, within the boundaries of the Dolomites UNESCO world natural heritage site. For none of them, however, is the CPE mentioned as a reason of interest and/or need of protection.

One main point of this review was to show that knowledge that has accumulated about the CPE, and rising awareness among scientists on the relevance of this event, are in a great part a story of Italian research. Key localities in Italy are thus geodiversity elements of great scientific value - geosites, according to Brilha (2016), worth being preserved and made accessible for future studies, and should be popularised as part of the Italian geoheritage.

In Italy, the compilation of geosite inventories has been so far been allocated to administrative Regions, while the national environmental agency (ISPRA) gathered together the regional inventories. Some regional administrations, such as the Friuli-Venezia Giulia region and the Trento autonomous province, have already accomplished the task of selecting a list of the best geosites (e.g, Cucchi et al., 2009). Others, as for example the Veneto region, are in the process of filling their list. The Dolomites UNESCO Foundation is also contributing to the selection of sites to include in the geoheritage inventory. However, geosite inventories should not be static: as research progresses, localities that did not bear scientific value before may become important facets of the geodiversity of an area. This could be the effect of recent research on the CPE in Italy, which should call for a revision of geosite inventories, even for those regions that have already consolidated a list.

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