CARBON-ISOTOPE ANOMALIES AND DEMISE OF CARBONATE PLATFORMS IN THE SINEMURIAN (EARLY JURASSIC) OF THE TETHYAN REGION: EVIDENCE FROM THE SOUTHERN ALPS (NORTHERN ITALY)

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Abstract

Despite its global impact on ecosystems, the T/J boundary event had only a modest effect on the carbonate depositional systems of the Southern Alps, whereas a fundamental reorganization of the same palaeogeographic area took place during the Sinemurian Stage. This paper investigates whether or not the well-documented demise of Sinemurian carbonate platforms in the Tethyan region was a response to a global event by examination of carbon-isotope anomalies in successions of different facies that record this interval of time. A chemostratigraphic transect from the Garda Lake up to the eastern Italian border is illustrated by four stratigraphic sections; high-resolution (20 cm over key intervals) chemostratigraphic sampling allowed detection of a major negative δ^{13}C anomaly of ~ 1.5 ‰, preceded by a positive excursion, both in shallow- and deep-water successions, over the stratigraphical range of the ammonite genus *Arnioceras*. A comparison with sections from the UK suggests that the positive excursion belongs to the *turneri* Zone and the succeeding negative excursion falls within the *obtusum* Zone. In the deep-water Belluno Basin, the negative anomaly occurs in a biogenic chert-rich unit

recording the onset of mesotrophic conditions in the basin. In the platform-carbonate successions, this major negative carbon-isotope excursion is developed within a calcarenitic unit corresponding to the lowest occurrence of the foraminifer *Paleomayncina termieri*. This evidence for deepening and trangression across the carbonate platform suggests pre-conditioning for drowning. Hence, rather than tectonic subsidence alone, environmental factors may have aided the demise of Tethyan carbonate platforms during the Early Jurassic Sinemurian Stage.

1. Introduction: The demise of carbonate platforms in the Sinemurian of the tethyan area.

Global episodes of environmental change represent major turning points in the history of the Earth. Among these, the Triassic/Jurassic boundary (T/J) is characterized not only by a major extinction but also by disturbances in the carbon-isotope reservoir of the oceans and atmosphere. Despite its global impact, the T/J event had only a modest effect on the palaeogeographic configuration of the Southern Alps as exposed in northern Italy. The palaeogeography of the Southern Alps at the beginning of the Jurassic was characterized by the widespread development of shallow-water carbonate platforms (Corna, Monte Zugna Formation), representing the continuation of late Triassic peritidal sedimentation, and stretching from Lombardy to Slovenia, only interrupted by the deep Belluno Basin (Gaetani, 1975; Winterer and Bosellini 1981; Masetti *et al.*, 2012). Similar shallow-water environments also existed elsewhere, for example in the Umbria–Marche Apennines of central Italy (Calcare Massiccio Formation), and in the Southern Limestone Apennines (Calcare a Paleodasycladus Formation: D'Argenio *et al.*, 1973).

Although the T/J event had negligible effect on the Jurassic depositional systems of the Southern Alps and Apennines, a fundamental reorganization of the carbonate systems took place during Sinemurian time (Masetti *et al.*, 2012). In Lombardy, the Corna Platform was locally capped by open-marine crinoidal calcarenites (encrinites) of Sinemurian age (Schirolli, 1997; Meister *et al.* 2009); across much of the Trento Platform, the Hettangian–Sinemurian peritidal succession of the Calcari Grigi Group

(Monte Zugna Fm.) is unconformably overlain by a Sinemurian–Pliensbachian condensed succession (Fanes Piccola Encrinite, Masetti and Bottoni 1975; Masetti *et al.* 2012); in the Northern Apennines, Marino and Santantonio (2010) describe the Early Sinemurian replacement of the peritidal Calcare Massiccio platform by means of deep-water deposits of the Corniola Fm. In the structural highs of the same area this event is recorded later, at the base of the *semicostatum* Zone, by the superposition of a “drowning succession” (“Calcare Massiccio B”) over the underlying, peritidal, “Calcare Massicio A”. In the Ligurian Alps, the Early Sinemurian carbonate platform ceased sediment production and was covered by deep-water deposits (Decarlis and Lualdi, 2010); in Eastern Sicily, the progradational trend of the peritidal Inici Fm. ceased at the Early/Late Sinemurian boundary, just before the drowning of the carbonate platform that occurred in the Late Sinemurian, when the deep-water Modica Fm. started to accumulate (Ronchi *et al.*, 2000). Ammonites found close to the top of the Inici Formation in western Sicily also suggest that the carbonate platform, locally at least, ceased deposition at some point in the *bucklandi* or *semicostatum* Zone of the Early Sinemurian or soon thereafter (Wendt, 1969; Jenkyns and Torrens, 1971). In the Betic Cordillera (Spain) Ruiz-Ortiz *et al.* (2004) described the Early Jurassic stratigraphic evolution of the rifted Iberian margin indicating that widespread peritidal carbonates evolved with faulting to a more open and deep marine setting. These authors refer the first dissection of the platform by extensional faults to the Early Pliensbachian, on the base of a benthic foraminiferal association. However, prior interpretations have dated the faulting as intra-Sinemurian (Ruiz-Ortiz *et al.,* 2004), so the evolution may be similar to the Italian examples. In the High Atlas (Morocco) Merino-Tomé *et al.* (2012) described in detail the break-up of the peritidal Early Jurassic carbonate platform of Djebel Bou Dahar into smaller deeper water blocks as a result of tectonic processes at the boundary between the Early and Late Sinemurian. The same authors highlight a sudden contemporaneous decrease in carbonate production leading to the generalized developing of hiatuses and the subsequent onset, in the Late Sinemurian–Pliensbachian, of sub-photic siliceous sponge microbial facies. Despite the huge increase in area affected by drowning of carbonate platforms in the Apennines and Southern Alps, the consensus to date is to view this event as regional and essentially due to increasing subsidence rate of fault-bounded blocks during extension of the Jurassic continental margin (Bernoulli and Jenkyns, 1974).

Bearing in mind the widespread demise/drowning of carbonate platforms in the Tethyan area during a poorly dated interval or intervals in the Sinemurian, and that the Southern Alps contain outcrops of a former passive Mesozoic continental affected by such phenomena, the main aims of this paper are:

1) to investigate whether or not the demise of Sinemurian carbonate platforms was the result, wholly or partially, of a chemostratigraphic/palaeoenvironmental event, by examining carbon-isotope anomalies in successions across the whole area of the eastern Southern Alps;

2) to provide high-resolution correlation between shallow-water platform carbonates and deeper water pelagic ammonite-bearing successions across the Eastern-Southern Alps by means of carbon isotopes, in order to locate the exact position/timing of any palaeoenvironmental event.

3) to ascertain the nature of carbonate-platform evolution coincident with this palaeoenvironmental event in order to highlight the potential response of the sediment-producing carbonate factory.

2. Geological Setting: the Southern Alps

Since the early seventies, the Southern Alps have been interpreted as a passive continental margin that, during Mesozoic time, experienced polyphase extensional tectonics that caused the fragmentation of the Adriatic Plate. The tectonic activity started during the Late Triassic (Norian). After relative quiescence during the Rhaetian (latest Triassic), renewed extension took place during the Early Jurassic. Extension shifted westwards to the Ligurian–Piedmont area where oceanic crust had formed by the Middle Jurassic (Bill *et al.*, 2001). From this time until the Early Cretaceous, the Southern Alps underwent post-rift thermal subsidence (Bertotti *et al.,* 1993; Fantoni and Scotti, 2003).

The Mesozoic extension resulted in the creation of N–S half-grabens, bounded by east- and west-dipping master normal faults (Fig.1). In the eastern Southern Alps three paleogeographical-structural units are recognizable. These are, from west to east (Gaetani, 1975; Winterer and Bosellini, 1981): a carbonate platform, which drowned in the Early Jurassic, evolving into a pelagic plateau with condensed pelagic sedimentation during the Late Jurassic (Trento Platform) and bordered to the west by the Lombardian Basin that accumulated pelagic clays and carbonates; a basin, with similar pelagic facies, that developed in the very Early Jurassic (Belluno Basin); and a carbonate platform that persisted from the Jurassic till the Cretaceous (Friuli Platform).

2.1. The Trento Platform

On the Trento Platform, the shallow-water sedimentation of the Early Jurassic is recorded in the thick pile of the Calcari Grigi Group, and the overlying pelagic “condensed” sedimentation recorded by the Rosso Ammonitico Veronese (Bajocian to Tithonian, Fig. 2). The Calcari Grigi Group is several hundred metres thick; its lower part corresponds to the Monte Zugna Formation, a unit representing the Jurassic continuation of the underlying, Upper Triassic, peritidal succession of the Dolomia Principale. The Loppio Oolitic Limestone and the Rotzo Formation represent, respectively, the middle and upper part of the Calcari Grigi Group; the most typical and renowned facies are those present in the Rotzo Formation, characterized by abundant plant remains and extensive banks of oyster-like “*Lithiotis”*, deposited in a dominantly subtidal environment (Masetti *et al*., 1998; Posenato and Masetti 2012; Franceschi *et al*., 2014). This subtidal environment, interpreted by previous authors as lagoonal, as the so-called “Lithiotis Lagoon” (Bosellini and Broglio Loriga, 1971), passed laterally to the western marginal oolitic complex (Massone Oolite, Figs 2 and 3). The Monte Zugna Formation and the Loppio Oolitic Limestone, lacking faunas of proved chronostratigraphic value, have been referred to a generic Hettangian–Sinemurian p.p. interval, whereas the age of Rotzo Formation is still debated and ascribed to a time interval spanning the late Sinemurian to late Pliensbachian, on the base of foraminifer bio-chronostratigraphy (Fugagnoli, 2004), or to early Pliensbachian to late Pliensbachian, on the base of ammonoid bio-chronostratigraphy (Sarti in Posenato and Masetti, 2012).

The unconformity surface capping the top of the shallow-water Calcari Grigi Group corresponds to a temporal hiatus that expands in duration eastward (Masetti *et al*., 1998; Figs 2 and 3). Based on the hiatus at the top of the Calcari Grigi Group and the lateral variations displayed by the Pliensbachian units, Masetti *et al*. (2012) proposed a further subdivision of the Trento Platform into a central-western area (with the Pliensbachian Rotzo Formation) and in a north-eastern area (without the Rotzo Formation). The approximate spatial distribution of these areas is shown in Figure 2; Figure 3 illustrates the Hettangian–Sinemurian Monte Zugna Formation crossing the entire Trento Platform from west to east with little variation in facies and thickness (Masetti *et al.,* 1998), whereas the classic Calcari Grigi succession with its well-known “*Lithiotis”* beds (Rotzo Formation) is present only in the central-western sector of the Trento Platform passing westward to plane-bedded facies interpreted as marginal shoals (Massone Oolite; Beccarelli-Bauck, 1988).

The north-eastern sector of the Trento Platform (Figs 2 and 3) is characterized by a widespread hiatus corresponding to the Pliensbachian units, replaced by a thin veneer of red cross-bedded crinoidal sand bodies corresponding to the Fanes Piccola Encrinite: where this unit is missing, the Rosso Ammonitico rests directly on the Monte Zugna Formation (Masetti *et al*., 2012).

2.2. The Belluno Basin*.*

The birth of the Belluno Basin was linked to Early Jurassic rifting that led to a roughly N–S oriented fault system (Masetti and Bianchin, 1987); during Hettangian–Pliensbachian time, this basin was filled by dark cherty, basinal micrites (Soverzene Formation, Figs 2, 3). On the base of data coming from the Verzegnis section, where sediments are free from heavy dolomitization, Masetti *et al.* (2012) suggested that the birth of the Belluno Basin can be referred to the Triassic–Jurassic boundary interval or even to the latest Triassic. Above the Soverzene Formation, the Early Toarcian oceanic anoxic event (Jenkyns, 1988) is recorded by discontinuous levels of black shales and manganoan carbonates, contained within the Igne Formation, which consists of decimetric rhythms of grey marls and marly mudstones (Jenkyns *et al*., 1985; Claps et. al., 1995; Bellanca *et al*., 1999). This last unit is covered by the Vajont Limestone, composed of oolitic sands and biogenic skeletal debris redeposited by means of gravity-flow processes that transferred oolitic sands from the western edge of the Friuli Platform into slope and basin environments (Bosellini and Masetti, 1972; Bosellini *et al*., 1981). The age of the Vajont Limestone has been revised by Cobianchi (2002), by means of nannofossil biostratigraphy performed on several sections, and can be ascribed to the late Bajocian–Bathonian interval. The Fonzaso Formation (Callovian to Lower Kimmeridgian) overlies the Vajont Limestone and consists of pelagic cherty mudstones and skeletal-rich turbidites and debris-flow deposits. The Fonzaso Formation grades upwards into nodular, micritic red limestones very similar to the Rosso Ammonitico Veronese (Upper Member, Upper Kimmeridgian to Lower Tithonian; Martire, 2007).

2.3. The Friuli Platform

In a similar way to the Trento Platform, Masetti *et al*. (2012) proposed a further subdivision of the Friuli Platform into a northern and a southern area (Figs 2 and 3). The northern area is characterized by a stratigraphic evolution similar to that experienced by the eastern and northern sector of the Trento Platform, in which the shallow-water Rotzo Formation is missing and the Monte Zugna Formation is overlain by the Fanes Piccola Encrinite. On top of this last unit lies a deep-water, Middle and Upper Jurassic succession, typical of the Belluno Basin (Vajont Limestone and Fonzaso Formation). To the south, the classic persistent carbonate platform is exemplified by the section cropping out along the Valcellina Valley, located at the southern edge of the Friuli Prealps, in which the exposed shallow-water succession spans the interval from the Oxfordian through the whole of the Cretaceous (Cuvillier *et al*., 1968).

Bearing in mind the above-mentioned stratigraphic setting shown in Fig. 2, four stratigraphic sections have been selected, each being representative of the different sectors in which Masetti et al. (2012) subdivided the main palaeogeographic units of the Eastern Southern Alps. These sections allowed the generation of a chemostratigraphic transect across the whole domain of the Eastern Southern Alps, from the Garda Lake up to the eastern Italian border (Fig. 2).

3. Chemostratigraphic transect across the Eastern Southern Alps

The stratigraphic sections selected are, from east to west (Figs 2 and 3): Monte Verzegnis, located in the Belluno Basin; Monte Cumieli, located in the northern sector of the Friuli Platform; Foza, in which the Rotzo Formation is missing and the Middle Jurassic Rosso Ammonitico rests directly on top of the Monte Zugna Formation; and Chizzola, representative of the central-western area of the Trento Platform (with the Pliensbachian Rotzo Formation). In all these sections, chemostratigraphic sampling has been concentrated just below the unconformity surface at the top of the shallow-water succession where distinctive carbon-isotope anomalies were predicted to be present (Fig. 3).

3.1 Chemostratigraphic sampling and analyses

Analytical techniques

Chemostratigraphic sampling was performed on the selected stratigraphic sections at a resolution of 20 cm, wherever allowed by the exposure conditions; powdered samples were obtained directly by means of a drill powered by a generator with micritic matrix being preferentially sampled and skeletal fragments and veins being avoided, on the assumption that these components would be more prone to vital effects and diagenesis. The high-resolution sampling preceded lower resolution sampling (a sample every 2 metres) in order to identify the main isotopic anomalies occurring in the section. The total thickness of the stratigraphic succession, corresponding to the 4 sections presented here, on which this high-resolution sampling has been performed, exceeds 570 m. For isotopic analysis, the samples were analysed isotopically for $\delta^{13}C$ and $\delta^{18}O$ using a VG Isogas Prism II mass spectrometer with an on-line VG Isocarb common acid bath preparation system. Samples were cleaned with hydrogen peroxide (H_2O_2) and acetone [$(CH_3)_2CO$] and dried at 60°C for at least 30 minutes. In the instrument they were reacted with purified phosphoric acid (H_3PO_4) at 90°C. Calibration to PDB standard via NBS-19 was made daily using the Oxford in-house (NOCZ) Carrara marble standard. Reproducibility of replicated standards was typically better than 0.1‰ for both $\delta^{13}C$ and $\delta^{18}O$. For strontium-isotope analyses, approximately 50 mg carbonate per sample were dissolved in 6 ml of $2HNO_3$ for both $^{87}Sr/^{86}Sr$ and trace-metal analyses. A 1.5-mL aliquot of the dissolved solution was taken to perform strontium purification for the $^{87}Sr/^{86}Sr$ measurements, and the remaining solution was diluted and measured for Sr, Mn and Fe concentrations. Strontium was separated by a standard chromatography method using Eichrom Sr resin, and the purified solution was dried at 100°C and re-dissolved in 2% HNO_3 prior to the isotopic analysis. The total blank was < 2 ng Sr. The $^{87}Sr/^{86}Sr$ measurements were performed on a Nu Plasma multi-collector inductively coupled plasma mass spectrometer (Plasma 1), and the trace-metal abundances were measured on a Thermo-Finnigan inductively coupled plasma mass spectrometer (Element II) at the University of Oxford. Both instruments were coupled with a membrane desolvating system (Aridus, Cetac) to achieve high signal sensitivity and stability. For $^{87}Sr/^{86}Sr$ measurements, all isotopes (^{88}Sr, ^{87}Sr, ^{86}Sr, ^{85}Rb, ^{84}Sr and ^{83}Kr) were measured in static mode. To achieve maximum precision and accuracy, the ^{88}Sr signal was kept between 13 and 16 V, and a minimum of 40 isotope ratios were collected with 20-second integration time per ratio. 83Kr was monitored to correct for the interference of ^{86}Kr on ^{86}Sr, and likewise ^{85}Rb was monitored for ^{87}Rb correction on ^{87}Sr. ^{83}Kr intensity was generally consistent and below 0.2 mV, and ^{85}Rb varied between samples but was generally lower than 2 mV. Samples were measured using a standard bracketing method with the NIST SRM 987 standard. The instrument mass fractionation was corrected internally using $^{86}Sr/^{88}Sr = 0.1194$. The external reproducibility of $^{87}Sr/^{86}Sr$ in SRM 987 showed a value of 0.710258 ± 0.000049 (2 S.D.) from August to September, 2013.

Diagenesis versus palaeoceanography

The diagenetic behaviour of carbon and oxygen isotopes in shallow-water carbonates is problematic because such materials are particularly susceptible to meteoric-water diagenesis. Such facies accumulate close to sea level, small changes in which can lead to periodic emergence. The resultant diagenesis would typically introduce fluids with relatively low $\delta^{18}O$ and $\delta^{13}C$ values derived from rainwater after its interaction with atmospheric carbon dioxide and humus-rich soils (Hudson, 1977; Marshall, 1992). Typically, horizons affected by such processes would have scattered and relatively low carbon- and oxygen-isotope ratios compared to typical marine values. Other possible causes for deviation of isotopic values from primary signals include variable quantities of skeletal grains exhibiting non-equilibrium fractionation, different quantities of aragonite and calcite in the original sediment

(Swart, 2008), and the presence of void-filling secondary, low-Mg calcite in cavities opened in the supratidal environment (e.g. Grötsch *et al.*, 1998; Davey and Jenkyns, 1999). Despite the possible modification of shallow-water carbonates introduced by meteoric-water diagenesis, the primary isotopic signal of carbon should not change substantially because the amount of carbon in diagenetic fluids is low, unlike the case with oxygen, whose primary isotopic signal can also be deeply modified during burial with recrystallization at relatively high temperatures (Scholle and Arthur, 1980). If chemostratigraphic analysis is simultaneously performed on the same stratigraphic interval in both shallow- and deep-water Jurassic successions, in conjunction with available biostratigraphy (calcareous algae and benthonic foraminifera in platform carbonates and ammonites in deep-marine carbonates), the presence of similar carbon-isotope anomalies in all sections proves the primary nature of these major oceanographic and carbon-cycle perturbations (Woodfine *et al.*, 2008; Trecalli *et al.*, 2012; Sabatino *et al.*, 2013).

3.2 The Monte Verzegnis section

This section, 260 m thick (Fig. 4), has been measured and sampled in the homonymous mountain group located in the Carnian Alps, not far from the small town of Tolmezzo. The section contains little dolomite. From the palaeogeographic point of view, it belongs to the north-eastern sector of the Belluno Basin (Fig. 2).

Lithostratigraphy.

The Lower Jurassic fill of the Belluno Basin is made of thin-bedded, cherty mudstones and wackestones with peloids, radiolarians and sponge spicules representing the Soverzene Formation (Fig. 4). This unit has been interpreted as peri-platform ooze (cf., Schlager and James, 1978) in which pelagic material falling through the water column has mixed with the carbonate mud supplied from adjacent carbonate platforms (Zanferrari *et al.* 2013). The Soverzene Fm. is about 200 m thick and lies atop the peritidal deposits of the Dachstein Limestone containing Upper Triassic megalodontids and the foraminifer *Triasina hantkeni,* thus allowing the time of the initial development of the Belluno Basin to be fixed as close to the Triassic–Jurassic boundary. In its uppermost portion, corresponding to a thickness of 16 m (Fig. 4), the Soverzene Fm. is enriched in white chert that forms thick bands (up to 40 cm) interbedded with thinner limestones. The rise in the silica content corresponds to an increase of the proportion of sponge spicules in the rock, likely indicative of the onset of mesotrophic conditions in the Belluno Basin (cf., Föllmi *et al.*, 1994).

The Soverzene Fm. passes upward, through an unconformable boundary, to a bi-directional cross-bedded calcarenitic unit, 20 m thick, present at the top of this Formation in the whole area of the Carnian and Julian Prealps. This unit is composed of grainstones with small superficial ooids in which radiolarians and sponge spicules are mixed with benthic foraminifera and crinoidal fragments, recording an ephemeral shallowing-upward evolution experienced during this time by the Carnian Prealps area of the Belluno Basin (Zanferrari *et al.*, 2013). This calcarenitic unit of the Soverzene Fm. is truncated by a hardground surface coated with Fe-Mn oxyhydroxide crusts, on top of which lies the Mount Verzegnis Encrinite, a condensed unit, about 20 m thick, characterized by the intercalation of cross-bedded, red crinoidal calcarenites and red nodular limestones in facies of the Lower Rosso Ammonitico, commonly showing peculiar stromatolitic/thrombolitic structures similar to those described by Jenkyns (1971) from western Sicily and Massari (1981) from the Trento Plateau. Further upward, this unit passes into the Vajont Limestone, largely constituted by redeposited oolitic grainstones, recording a return to basinal conditions on top of the underlying shallower water deposits.

Biostratigraphy

The Soverzene Fm. is referred in the literature to the Hettangian–Pliensbachian (Zanferrari *et al.* 2013). During the measuring of the section, a specimen of an ammonite, which has been identified by F. Venturi (Perugia University) as pertaining to the genus *Arnioceras*, was discovered in a debris cone fed from a small cliff located about forty metres below the top of the Soverzene Fm. The *Arnioceras* genus has a distribution that embraces the *semicostatum*, *turneri*, *obtusum* and, possibly, *oxynotum* ammonite zones (transition from the early to the late Sinemurian; Dommergues *et al.*, 1994, Fig. 5), here informally called “Arnioceras time”. The finding of the *Arnioceras* 20 metres below the top of the unit indicates deposition of the main part of the Soverzene Formation, at least in this part of the Belluno

Basin, during the Hettangian–Sinemurian interval. The crinoid-rich calcarenitic unit at the top of the Soverzene Fm. is devoid of ammonites and nannofossils (Erba, 2011, personal communication); a $^{87}Sr/^{86}Sr$ ratio from a belemnite rostrum collected a few centimetres below its upper boundary gave a value of 0.707196 ± 0.000042 (normalized against a value of 0.710250 for the NBS-987 standard) suggesting an age interval either spanning the mid-Pliensbachian to the Early Toarcian or the Early Bajocian (reference curve in Jones *et al.* 1994; Jenkyns *et al*., 2002). This evidence suggests that this unit could be considered the more open-marine counterpart of the mid-upper portion of the Rotzo Fm. in the Venetian Prealps and could be ascribed to the Pliensbachian p.p. (Masetti *et al.* 1998; Posenato and Masetti, 2012).

In the Monte Verzegnis Encrinite, referred in the literature to the Toarcian p.p.–Bajocian p.p. (Piano and Carulli, 2002) some ammonite specimens have been collected in the lower part of the formation. Among these, G. Pavia (Turin University) determined *Teloceras cf. triptolemus* (Buckman) and *Holophilloceras sp*. ammonites, both referable to the Early Bajocian. A $^{87}Sr/^{86}Sr$ determination of a belemnite collected in the lowermost part of the Verzegnis Encrinite, gave a value of 0.707062 ± 0.000042 (normalized against a value of 0.710250 for the NBS-987 standard) indicating either the Pliensbachian–Toarcian boundary or a time interval spanning from the Early Bajocian to the Early Bathonian. Taken together, the data confirm an Early Bajocian age of the lower portion of the unit. No ammonites have been found in the upper part of the Monte Verzegnis Encrinite and, by analogy with the similar Rosso Ammonitico cropping out in other areas of the eastern Southern Alps (Martire, 2007), it likely corresponds to the Bathonian–Early Callovian.

In summary, the original biostratigraphic data suggest:

- in the Verzegnis section, the deep-water micritic unit of Soverzene Fm., chert-rich unit included, corresponds to peri-platform ooze delivered to the basin during Hettangian–Sinemurian p.p. time, up to and including the so-called “Arnioceras time”;

- $^{87}Sr/^{86}Sr$ data suggest that the calcarenitic unit at the top of the Soverzene Fm. belongs to the mid–Late Pliensbachian, and it corresponds to the mid-upper portion of the Rotzo Fm. in the Venetian

Prealps, overlying the lower part of the same formation with a hiatus corresponding to the Late Sinemurian–Early Pliensbachian; and the Verzegnis Encrinite was deposited during the Early Bajocian–Early Callovian and lies unconformably on top of the Soverzene Formation with a hiatus corresponding to the Toarcian– Aalenian interval.

The $\delta^{13}C$ curve

444 samples have been analyzed coming from a stratigraphic section 261-m thick (Fig. 4). The high-resolution interval (20 cm/sample) goes from 146 to 240 m. The remaining under- and overlying segments have been sampled with lower resolution (2 m/sample). Through the entire section, the carbon-isotope values mostly fluctuate between ~ 1.5‰ and ~ 3.5‰. In the lowest 60 m, the curve mostly ranges between ~ 2‰ and ~ 2.7‰: the relatively low resolution of the profile prevents reliable identification of the negative peaks located at the T/J boundary. Stratigraphically higher, between 60 and 80 metres, including an unexposed interval of ~11 m, the curve shifts towards consistent values around 2.5‰. Up to about 160 m, the curve fluctuates around a value of 2.5‰, with a pronounced positive shift (to ~3‰ around 114 m). A small (0.5‰) negative followed by a small (0.5‰) positive excursion characterizes the interval 140–160m. From here on up, the profile describes a symmetrical oscillation that arrives at a minimum of ~ 1.4‰ at ~ 196 m then rises up to ~ 3.6‰ at ~ 236 m. This spectacular and symmetric oscillation of the carbon-isotope curve corresponds to about 60 m of section and is completely contained within the Soverzene Formation. The lowest value is located close to the cliff where the *Arnioceras* specimen was found, just at the base of the chert-rich unit located at the top of the typical micritic facies of the Soverzene Fm. At ~ 237–238 m the carbon-isotope curve moves relatively abruptly to lower values (~ 2.6‰) just below the unconformable boundary between the calcarenitic unit of the Soverzene Fm. and the Monte Verzegnis Encrinite before rising to >3.5‰ at the base of this latter unit.

3.3 The Monte Cumieli section

The Monte Cumieli section (Fig. 4) crops out in the Carnian Prealps, not far from the small town of Gemona, is 126 m thick, and exemplifies the Jurassic succession of the northern sector of the Friuli

Platform, characterized by the early demise of the Early Jurassic carbonate platform of the Monte Zugna Formation (Fig. 2) and by the lack of shallow-water carbonates younger than Sinemurian (Zanferrari *et al.*, 2013).

Lithostratigraphy.

The Monte Zugna Formation is further subdivided, as illustrated in Fig. 4, into a lower peritidal and an upper calcarenitic unit. The lower unit is 87 m thick and is composed of peritidal cycles representing the Jurassic continuation of the depositional theme of the underlying, Upper Triassic Dolomia Principale. The calcarenitic unit is 33 m thick and comprises metre-scale beds of oolitic grainstones that become progressively richer upwards in echinoderm debris suggesting increasing open-marine influence (e.g., Jenkyns, 1971). This calcarenitic body is interpreted as a subtidal shoal largely controlled by storm waves whose activity is recorded by plane parallel lamination. Throughout the entire unit, the ooids exhibit some degree of concentric structure; however, in the lower part of the unit, the cortex is dominantly micritic, in some cases with outer thinly laminated tangential oriented crystals (Fig. 6a). These micritic ooids are associated with oncoids, dasyclad algae (*Palaedasycladus mediterraneus*, *Palaeodasycladus gracilis*), and foraminifers (*Aeolisaccus dunningtoni*, *Siphovalvulina* spp., *Everticyclammina praevirguliana*). The micritic ooids are replaced up-section by radial-fibrous ooids whose structure is interrupted by dark microborings (Fig. 6b). The palaeontological assemblage associated with these radial-fibrous ooids is characterized by foraminifera with a complex wall structure *(Palaeomayncina termieri*, *Tersella genotii*, *Rectocyclammina* sp.), locally acting as nuclei for the oolitic cortex (*Everticyclammina praevirguliana*, Fig. 6b).

The Monte Zugna Formation is truncated by a disconformity surface on top of which lie the cross-bedded crinoidal calcarenites of the Fanes Encrinite interpreted as sand-waves (Zanferrari *et al.*, 2013). Resedimented deposits of the Vajont Limestone represent the youngest unit cropping out in the Monte Cumieli Section and record a deepening-upward evolution of the northern sector of the Friuli Platform which, during the Middle Jurassic, foundered to become effectively part of the Belluno Basin where it received oolitic turbidites derived from the southern portion of the same platform that persisted as a productive shallow-water carbonate source (Masetti *et al.* 2012; Zanferrari *et al.*, 2013).

Biostratigraphy

The shallow-water assemblage recorded in the Monte Cumieli section accords with the classic successions of the Alpine-mediterranean Tethys as documented in the Central Apennines and Southern Apennines by De Castro (1991), Chiocchini *et al.*, 1994, 2008), Western Croatia (Velić, 2007) and Morocco (Septfontaine 1984; 1985). Barattolo and Romano (2005) recognize the following four shallow-water carbonate-platform assemblages as pertaining to the Upper Triassic–Lower Jurassic:

1) Algal and foraminiferal Triassic assemblage (TA assemblage, uppermost Rhaetian) characterized by the occurrence of dasycladaleans, *Griphoporella curvata* (Gümbel) and *Gyroporella vesiculifera* Gümbel, involutinid foraminifera (essentially *Aulotortus* and *Triasina*) and oncoids. Macrofauna is composed of the large shells of megalodontid bivalves. Foraminifera and megalodontids become more common up-section, whereas dasycladaleans become rare or are missing altogether.

2) *Thaumatoporella* and *Aeolisaccus dunningtoni* assemblage (LA assemblage, lowermost Hettangian–upper Hettangian) characterized by the exclusive occurrence of *Thaumatoporella* and *Aeolisaccus dunningtoni* Elliott, mainly in the lower part of its range. Small siphonous valvulinid foraminifera are rather rare, but up-section they become more common. Rare gastropods, bivalves and corals may also occur. Oncolitic coatings on grains are common.

3) Lower Jurassic dasycladalean assemblage (LB assemblage, upper Hettangian–upper Sinemurian) characterized by the occurrence of a variety of Liassic species of dasycladaleans. The most representative genera are *Palaeodasycladus*, *Fanesella*, *Sestrosphera* and *Tersella*. Taxa of the previous LA assemblage continue into the base of the LB assemblage, which can be subdivided into lower (LB1) and upper (LB2) sub-assemblages. In LB1, Liassic dasycladaleans are not abundant and LA microfossils are still important. In LB2, dasycladaleans become dominant and large foraminifera appear (e.g. *Paleomayncina*).

4) Large foraminifer assemblage (LC assemblage, upper Sinemurian–Upper Pliensbachian) marked by a dominance of dasycladaleans, but with a relatively low diversity. Larger foraminifera with a complex internal skeleton are abundant, the most widespread genera being *Orbitopsella*, *Lituosepta*, *Amijiella* and *Haurania*. The background fauna is always composed of an LA assemblage.

The Monte Zugna Formation in the Monte Cumieli section is dominated by foraminifers (*Aeolisaccus dunningtoni, Siphovalvulina* spp.*, Meandrovoluta asiagoensis*, *Everticyclammina praevirguliana)* and algae (*Thaumatoporella parvovesciculifera, Palaeodasycladus mediterraneus, Palaeodasycladus gracilis, Tersella genotii* and *Cayeuxia*-like briopsidales*);* the calcarenitic unit records the first occurrence of *Paleomayncina termieri* and an enrichment of foraminifera with a complex wall structure. According to Zanferrari *et al.* (2013), the Monte Zugna Formation has been assigned a generic Hettangian–Sinemurian age; the micropalaeontological content of the section corresponds to the upper part of the LB1 and the lower part of the LB2 assemblages *sensu* Barattolo & Romano (2005). The palaeontological assemblage of the overlying Fanes Piccola Encrinite is characterized by the dominance of foraminifers (*Involutina liassica*, *Agerella martana*, *Lenticulina*, Frondicularia, *Ophtalmididae* e *Nodosaridae)* of little reliable stratigraphic significance. Zanferrari *et al.* (2013) interpreted this unit as the result of discrete, and virtually instantaneous, deposition of sand-waves bounded by long-lasting periods of non-deposition that overall occurred between the age of the earliest (“Arnioceras time”) and the age (Bajocian–Bathonian), of the base of the overlying Vajont Limestone).

The δ^{13}C curve of the Monte Cumieli section

274 samples have been analyzed from a 137-m-thick stratigraphic section (Fig. 4). The first segment of the section, 55 m thick, has been sampled at relatively low resolution (2 m/sample), the second, 47.5 m thick, extending up to the top, at higher resolution (one sample every 20 cm). Within the section, the carbon-isotope values fluctuate between ~ 2.9‰ (90 m) and ~ 0.4‰ (107 m). Up to 43 m from the base, within the peritidal unit of the Monte Zugna Formation, the profile evolves vertically with symmetric oscillations centred around a value of 2‰. Higher in the stratigraphy, extending up to about 90 m, the

curve moves to generally more positive values (maximum value in the section: 3‰) with a trend interrupted by a couple of negative shifts (at 67 m and 84 m). This positive fluctuation of the curve corresponds, on the base of the chemostratigraphic correlation (Figs 7, 8), to the upper part of the peritidal unit and to the first few metres of the calcarenitic unit of the Monte Zugna Fm., recorded by a thin intercalation of micritic deposits corresponding to the *Gervillia* beds of the Foza and Chizzola sections. The calcarenitic unit, starting from the first occurrence of *Paleomayncina termieri*, records a clear negative excursion in which values shift from ~ 2.9‰ (at ~ 90 m) to ~ 0.4‰ (at ~ 107 m); higher in the section, the curve returns towards more positive values (~ 1.7‰) up to ~ 120 m, at the level of the unconformity between the Monte Zugna Fm. and the Fanes Piccola Encrinite.

3.4 The Foza section

The Foza section (Fig. 7) is located in the eastern sector of the Asiago Plateau (Venetian Prealps), is 73 m thick, and has been sampled along the road connecting the small towns of Valstagna, located in Valsugana, to Foza, just below this last village. The Foza section exemplifies the Jurassic succession of the north-eastern area of the Trento Plaform, characterized by the lack of Pliensbachian shallow-water carbonates (Rotzo Formation) and hence early demise of the Early Jurassic carbonate platform of the Monte Zugna Formation (Fig. 2 and 3).

Lithostratigraphy. The Foza section has been entirely sampled inside the Monte Zugna Fm, up to its upper boundary with the Lower Rosso Ammonitico; in the shallow-water carbonates of the Monte Zugna Fm. the peritidal features are less marked than elsewhere, but the depositional environment may be interpreted as the internal, slack-water and muddy sector of the carbonate platform (Romano *et al.* 2005). As with the Monte Cumieli section, a calcarenitic unit, 33 m thick, is superimposed on the lower, mainly micritic unit of the formation (Fig. 7); this granular unit is split into two parts by intercalated fine-grained deposits of lagoonal character containing the bivalve *Gervillia buchi* (Fig. 7). Here the ooids also exhibit a stratigraphic evolution in which the micrite-coated grains with thinly laminated tangential cortices (Fig. 6a), present at the base, are replaced up-section by radial-fibrous ooids (Fig. 6b).

Biostratigraphy

The micropalaeontological content is similar to that present in the Monte Cumieli section. The micritic unit is characterized by dasycladaleans (*Palaeodasycladus mediterraneus, Sestrosphaera liasina and Eodasycladus* sp.) and the foraminifer *Everticyclammina praevirguliana*. In addition to this, the calcarenitic unit contains *Palaomayncina termieri*, *Terquemella* sp (dasycladalean calcified reproductive organs) and the coprolite *Favreina* sp. The first occurrence of *Paleomayncina termieri* falls in the middle of the calcarenitic unit, about 20m below the unconformity. The Monte Zugna Formation has been assigned to the Hettangian–Sinemurian interval (Romano *et al.*, 2005). The micropalaeontological assemblage of the Foza section, like that of the Monte Cumieli section, corresponds to the upper part of the LB1 and the lower part of the LB2 assemblages *sensu* Barattolo & Romano (2005). The unconformity surface is covered by the Rosso Ammonitico Inferiore whose stratigraphical extent in the Trento Plateau is referred to the upper Bajocian–Lower Callovian (Martire, 2007).

The $\delta^{13}C$ curve of the Foza section

324 samples have been analyzed coming from a 70-m-thick stratigraphic section (Fig. 7). The $\delta^{13}C$ values, which are highly scattered, mostly fall between -2 and 2‰. Overall, the curve can be split into three minor negative excursions separated by positive rebounds. The stratigraphically lowest negative excursion corresponds to the 0–16 m segment of the section, reaches a minimum value of ~ -0.9‰ (at 10.6 m) and returns to a value of ~ 2‰ (at 15.8 m); the second reaches ~ –2.40‰ at 32 m from the base (not shown in figure) then moves rather abruptly in a positive sense toward a value of 2.45‰ at the level of a bivalve bed (*Gervillia*) located at about 40m from the base of the section, close to the lower boundary of the calcarenitic unit of the Monte Zugna Formation. The third, relatively broad negative excursion starts from a value of ~ 2.5‰ (highest value in the section: 42.5 m), then falls abruptly, following the calcarenitic unit and the stratigraphical distribution of *Paleomayncina termieri*, to reach a minimum of ~ -1.4‰ (56 m) and returns to ~ 2.5‰ at the boundary with the Rosso Ammonitico,

3.5. The Chizzola section

This section (Fig. 7) represents the central-western areas of the Trento Platform (Fig. 2) in which the Pliensbachian shallow-water unit (Rotzo Fm.) lies on top of the Monte Zugna Formation. Located in the Adige Valley, the Chizzola section has been sampled along the road connecting the villages of Chizzola and Mori. The top of the section, corresponding to the upper half of the Loppio Oolitic Limestone, has been measured near Nomi village.

Lithostratigraphy

The Chizzola section exposes the upper portion of the Monte Zugna Formation (92 m) and the whole thickness of the Loppio Oolitic Limestone (32 m). The first unit is further subdivided into a peritidal calcarenitic unit (25 m) in which the peritidal cycles are made of cross-bedded, subtidal oolitic calcarenites passing upwards in the cycle to inter–supratidal stromatolites, locally with dinosaur tracks (Avanzini *et al.* 1997), and an upper, subtidal, nodular unit (67 m) cut by a neptunian dyke filled with oolites derived from the overlying Loppio Oolitic Limestone. The occurrence of peritidal facies in the calcarenitic unit of the Monte Zugna Formation is a peculiar feature of the Adige Valley, and the sediments have been interpreted by Masetti *et al.* (1998) as deposited inside small tidal flats, developed behind marginal shoals, that were retrograding towards the inner part of the Trento Platform during a transgressive phase. The nodular subtidal units are interpreted as representing a deepening phase of the topmost portion of the Monte Zugna Fm., which is missing in the other sections; the Loppio Oolitic Limestone is an oolitic body interposed between the Monte Zugna Fm. and the Rotzo Fm. that spread across the main portion of the underlying unit during a sea-level rise that pushed the marginal oolitic bars composing this unit from west to east across the Trento Platform (Fig. 3; Masetti *et al.* 1998).

Biostratigraphy

The micropalaeontological content of the Monte Zugna Fm. is similar to that described in the two previous sections. As regards the Loppio Oolitic Limestone, the lack of fauna of significant value precludes reliable stratigraphic attribution and it is generically referred to the Sinemurian stage. The stratigraphic setting of the Rotzo Formation is still matter of debate: either from the upper Sinemurian to the upper Pliensbachian, if assigned on the base of foraminiferal biostratigraphy (Fugagnoli, 2004), or from the lower Pliensbachian to the upper Pliensbachian, on the base of ammonite biostratigraphy (Posenato and Masetti, 2012). The sharp bounding surface between the Loppio Oolitic Limestone and the Rotzo Formation, locally encrusted with red ferruginous coatings, suggests that the contact between these two units represents a regionally extensive unconformity.

The $\delta^{13}C$ curve of the Chizzola section

508 samples have been analyzed from a 118-m-thick stratigraphic section (Fig. 7) with a sampling resolution of 20 cm. The entire carbon-isotope curve fluctuates between values of ~ -1.6‰ (~4.5 m) and ~ 2.4‰ (~ 25 m), with values being particularly scattered in the basal 20m. The curve illustrates a positive excursion (~ 2.4‰) at 7.5 m, declining abruptly to a relative minimum at 13 m, before moving again to more positive values that reach a maximum value of ~ 2.4‰ at 25 m. These positive–negative oscillations are entirely contained within the calcarenitic unit of the Monte Zugna Fm., here characterized by peritidal features. Above these excursions and extending for about 60 m up to ~ 84 m, within the upper portion of the Monte Zugna Fm. in which peritidal structures are missing, the profile displays another broad negative excursion, centred around the neptunian dyke and reaching the lowest value of ~ 0.1‰ at about 53 m: positive indentations are present around 35 m and 44 m. The top of the subtidal, mainly micritic unit of the Monte Zugna Fm., from 84 to 92 m (~ 1.6‰), corresponds to a third negative excursion (minimum value of ~ 0.8‰ at 89 m) between two positive excursions. The curve becomes more stable in the remaining part of the unit, fluctuating around an average value of about 1.3 ‰, with a minor positive excursion around 114 m.

3.6 Correlations of $\delta^{13}C$ curve across the Eastern Southern Alps and their comparison with coeval anomalies

The proposed correlation of the above-described anomalies of the $\delta^{13}C$ curves across the entire Eastern Southern Alps, from the Garda Lake to the eastern Italian border, is illustrated by the grey band in Figure 8. The excellent matching between the single curves allows recognition, both in the shallow-and deep–water units, of a distinct abrupt positive followed by broader negative carbon-isotope excursion (CIE) located just below an unconformity surface (Fig. 3). The primary origin of these excursions is supported by the following observations: all the coeval segments sampled in different sections exhibit the same carbon-isotope excursions with similar geometry and extending over similar stratigraphic thicknesses; all the curves are characterized by well-defined trends and not by single peaks that might represent diagenetic artifacts; the curves conform with the stratigraphic occurrence of key faunal datum levels; the curves conform with similar facies developments.

In the basinal Monte Verzegnis section, the carbon-isotope excursion spans a stratigraphic thickness of about 60–70 m (depending on chosen baseline), referable, thanks to the finding of a specimen of *Arnioceras*, to a time interval ranging from the base of the *semicostatum,* through the *turneri* to the top of the *obtusum* Zones (Dommergues *et al.*, 1994, Fig. 5) and thus likely corresponding to an interval of 2–3 Ma (Gradstein *et al.*, 2012). The same negative CIE is clearly recognizable, with a similar geometry, in the two palaeogeographic domains situated either side of the Belluno Basin, namely in the Monte Cumieli section (Friuli Platform) and the Foza Section (northern sector of the Trento Platform). Although values are scattered, this negative CIE signal, which is entirely contained within the calcarenitic unit at the top of the Monte Zugna Formation (thickness around 30 m), is not only preceded by a positive excursion but also interrupted by positive indentations. Significantly, the positive to negative shift at the base of the major negative CIE correlates with the first occurrence of the *Paleomayncina termieri* foraminifer in both the Foza and Monte Cumieli sections. The isotopic correlation with strata containing *Arnioceras* allows this foraminifer, once attributed to a poorly defined Sinemurian age, to be linked to the transition from the lower to the upper part of the stage. In the Chizzola section, located on the other side of the Trento Platform, this negative CIE is contained within the ~25 m-thick calcarenitic unit of the Monte Zugna Formation.

Most Jurassic chemostratigraphical studies to date have been mainly focused on the Pliensbachian–Toarcian interval; other stages are less well defined. In the Hettangian–Sinemurian interval, Jenkyns *et al.* (2002) recorded carbon-isotope ratios from belemnites and oyster shells from Portugal and England indicating a positive excursion in the Lower Sinemurian followed by a negative excursion at the Sinemurian–Pliensbachian boundary. More detail is given by Jenkyns and Weedon (2013), who illustrate a high-resolution organic-carbon isotope curve from Sinemurian black shales cropping out in the Wessex Basin (Dorset, UK). These data show a negative excursion likely centred around the boundary of the *semicostatum* and *turneri* Zones, a positive excursion extending through the upper *turneri* Zone before a fall at the close of that zone into the lower part of the *obtusum* Zone, followed by a rise before the continuity of the section is interrupted by a hiatus (Fig. 8). This positive *turneri*-Zone excursion has been recorded also by Porter *et al.* (2014) in marine sediments from North America (British Columbia, Canada) and manifestly represents a global marine carbon-isotope signature. Riding *et al.* (2012) studied a section from a borehole in eastern England and documented a marked negative excursion in a δ^{13}C curve from wood and palynomorphs centred in the *oxynotum* Zone (lower part of the Upper Sinemurian, Fig. 5), an interval that is missing in the Dorset profile. This negative excursion, registered in both marine and terrestrial carbon (thereby indicating a response in both atmosphere and oceans) was coupled with an increase in abundance of the thermophilic pollen *Classopollis classoides* (Fig. 9), suggesting the occurrence of a warming event.

In Morocco, carbonate isotopic data from Lower Jurassic peritidal platform carbonates show a well-defined negative excursion attributed to the early Sinemurian and a positive excursion in overlying open-marine sediments whose basal levels contain the ammonite *Arnioceras* and are placed in the late Sinemurian (Wilmsen and Neuweiler, 2008). In England and other parts of northern Europe, *Arnioceras* ranges from the *bucklandi* Zone of the basal Sinemurian into the *obtusum* Zone (Page, 2010), in good correspondence with the distribution proposed by Dommergues *et al.* (2004; Fig. 5). If we take the high-resolution data from all these sections as a guide (Figs 4, 6, 7), it seems that there are two possible negative excursions over the likely stratigraphical range of *Arnioceras.* If we concentrate on positive excursions, the most pronounced of which in the Dorset profile is in the upper part of the *turneri* Zone (Fig. 9), then the suggested zonal equivalence in the Verzegnis profile is as suggested in Figure 8. A negative trend covers the interval attributed to the *semicostatum* and possibly some of the *turneri*

Zone, whose defining feature, however, is a positive excursion, albeit relatively small in the Verzegnis profile. Following the *turneri*-Zone positive excursion, there is a well-defined negative excursion in the *obtusum* Zone, likely extending into the *oxynotum* Zone, followed by near-symmetrical recovery to higher values: a pattern matching that in the borehole material in eastern England (Fig. 9). In the platform-carbonate sections, the abrupt positive excursions seen in Chizzola, Foza and Monte Cumieli can thus be referred to the *turneri* Zone and the ensuing negative excursion to the *obtusum* and *oxynotum* Zones.

4.0 Possible causes of the "*Arnioceras* Time" negative δ^{13}C excursion

The "*Arnioceras* time" broad negative δ^{13}C excursion of ~1.0 ‰ recorded in the Soverzene Formation of the Monte Verzegnis section is well defined and extends over a thickness of ~60 m. Unlike the negative excursion that characterizes the early Toarcian interval, which is abrupt with a clear stepped profile in all sections (Hesselbo *et al.*, 2007; Kemp *et al.*, 2005; Hermoso *et al.*, 2012; Jenkyns *et al.*, 2002; Sabatino *et al.*, 2009), the excursion at Monte Verzegnis appears more gradual with values dropping from ~ 2.5‰ to ~ 1.5‰. If values of ~ 2.5‰, which characterize the lower parts of the section, are taken as background, the negative shift may record introduction of isotopically light carbon into the ocean–atmosphere through oxidation of a formerly buried reservoir such as sub-seafloor clathrates or organic-rich sediments. Alternatively, a reduction in the amount of global biomass or organic carbon buried in response to environmental change could have caused movement to lower carbon-isotope values. LIP volcanism cannot be invoked, because there are no known provinces of this age (Courtillot and Renne, 2003): the main activity phase of the Central Atlantic Magmatic Province (CAMP) occurred around 200 Ma and terminated during Hettangian time (Marzoli *et al.*, 1999).

If isotopically light CO_2 were to have been introduced into the atmosphere, resultant global warming would have likely led in turn to acceleration of the hydrological cycle and to the increase of global weathering rates. Increased quantities of nutrients and fine-grained continental sediments delivered to oceans would have favoured both increased organic productivity and formation of salinity-stratified water bodies leading to the onset of eutrophic conditions and deposition of organic-rich clays and clay-rich limestones. No such markers of wet and humid conditions during the CIE have been so far identified in the Southern Alps during "*Arnioceras* Time", but a coeval warming event has been recognized in Southern England by Riding *et al.* (2012), based on palynological data and extending over the *obtusum* and *oxynotum* Zones (Fig. 9). A possible important role in the release of the isotopically light ^{12}C into the atmosphere could have been played by syn-sedimentary tectonics that caused fracturing and leakage of gas-hydrate reservoirs (cf., Jenkyns, 2010). The negative excursion of "Arnioceras time" occurred coincidently with the reactivation of the rifting activity that affected large sectors of the Tethyan areas from the Southern Alps, Apennines and Sicily to the Betic Cordillera (Spain) and Moroccan High Atlas (Masetti *et al.*, 1998; Marino and Santantonio, 2010; Ruiz Ortiz *et al.*, 2004; Merino Tomé et al; 2012). This coincidence in timing could explain why many authors have ascribed local to regional drowning of carbonate platforms primarily to tectonic causes affecting subsidence rate rather than climatic influence on the sediment factory itself.

5.0 IMPACT OF THE "*ARNIOCERAS* TIME" NEGATIVE δ^{13}C EXCURSION ON CARBONATE SEDIMENTATION

The inferred position of the "*Arnioceras* Time" negative δ^{13}C excursion within the Lower Jurassic succession along the transect crossing the Eastern Southern Alps is shown in Figures 3 and 8. In the Belluno Basin, the negative carbon-isotope anomaly corresponds with the upper part of the lower micritic unit of the Soverzene Fm., with the lowest values located just below the base of the chert-rich unit at the top of the same formation (Figs 4, 7 and 8). In the shallow-water carbonates, both in the Trento and Friuli platforms, the anomaly begins at the top of the lower, peritidal unit of the Monte Zugna Fm., is interrupted by a short positive □^{13}C pulse, and culminates in the calcarenitic unit at the top of the same Formation.

The chert-rich unit of the Belluno Basin (Fig. 4, 16 m thick) correlates with an appreciable increase in the sponge-spicule content, likely reflecting a more nutrient-rich mesotrophic environment. Such mesotrophic conditions could have been related to an accelerated hydrological cycle linked to introduction of isotopically light CO_2 into the atmosphere and subsequent global warming. The deleterious effects of nutrient excess on shallow-water carbonate production by reducing water transparency, and encouraging bioeroding organisms is well documented (Hallock and Schlager, 1986, Schlager, 2005). Consequently, the hiatus in the Verzegnis section between the chert-rich and calcarenitic units in the upper part of the Soverzene Fm., supposedly representing the Late Sinemurian–Early Pliensbachian interval, could in part be related to the postulated coeval drop in the carbonate production on the neighbouring carbonate platforms. Since the lower portion of Soverzene Fm. represents peri-platform oozes in which pelagic material, falling through the water column, has been mixed with carbonate mud supplied by the adjacent platforms ('peri-platform ooze' of Schlager and James, 1978), the drop of the carbonate precipitation and secretion in the shallow-water feeder areas, acting together with the Sinemurian/Pliensbachian carbon-cycle boundary event recognized on the Trento platform by Franceschi *et al.* (2014), could have produced the basinal starvation that caused this hiatus.

The onset of the calcarenitic unit at the top of the Monte Zugna Fm. in many localities represents a fundamental reorganization of the palaeogeography during the interval of the major negative CIE: tidal flat areas across much of the Tethyan area were replaced by subtidal, wave-controlled, oolitic shoals, in which peritidal facies are missing. The only exception in the Southern Alps is the Adige Valley (Chizzola section, Fig. 7) where Masetti *et al.* (1998) interpreted these remnants of the former peritidal system as small tidal flats developed behind the western marginal shoals of the Trento Platform. The calcarenitic unit at the top of the Monte Zugna Formation, like the overlying Loppio Oolitic Limestone, has been interpreted as due to the retrogradation of the marginal carbonate sand bars located at the western margin of the Trento Platform during a relative sea-level rise (Masetti *et al.*, 1998). At its most extreme, this deepening and transgressive phase in the eastern Southern Alps coincided with the definitive loss/drowning of Early–Late Sinemurian peritidal platforms, inherited from the Late Triassic, which were located in many other areas around the Mediterranean (e.g. western Southern Alps, Ligurian Alps, Northern Apennines, western and eastern Sicily, and High Atlas).

Previous authors have postulated an interaction between tectonic and eustatic processes as the most viable mechanism able to explain the transgressive phase that occurred at the boundary between the Early and Late Sinemurian stages. Tectonic and/or eustatic processes were probably important, given the significant rise in the *turneri* Zone of the putative eustatic sea-level curve of Haq *et al.* (1988) and the north European relative sea-level curve of Hesselbo and Jenkyns (1998). However, taking in account the coeval carbon-isotope excursion described herein, this relative sea-level rise in the Southern Alps and elsewhere in the Tethyan region could be interpreted not as purely eustatic but as the consequence of a simultaneous decrease in carbonate production in shallow-water platforms caused by introduction into the atmosphere-ocean system of isotopically light carbon that led to increased introduction of terrestrially derived nutrients and ocean acidification, hence suppressing carbonate production and deposition (cf., Trecalli *et al.*, 2012)..

This climatic event, acting together with a reactivation of the syn-sedimentary extensional tectonics that reduced the productive areas of the carbonate platforms, would have ensured that the top of the carbonate platforms could no longer be readily maintained at sea level. Such a proposed decrease in carbonate production is also suggested by a fall in the sedimentation rate: the thickness of the calcarenitic units, in both the Friuli and Trento Platforms is about 30 m (Foza and Monte Cumieli sections) and a little thinner (about 20 m) in the Chizzola section, likely corresponding to the *turneri*, *obtusum* and *oxynotum* Zones (~ 10m/Ma sedimentation rate). Assuming a thickness of about 100 m for the lower peritidal unit of the Monte Zugna Formation (Masetti *et al.* 1998) and referring it to the remaining part of the Early Sinemurian (*semicostatum* and *bucklandi* zones) and to the Hettangian, the corresponding time span could be estimated as about 4 Ma according to the time scale of Gradstein *et al.* (2012): that is, a sedimentation rate (~ 25 m/Ma) more than twice that of the calcarenitic unit.

The development of oolitic limestones in the run-up to the demise of the carbonate factory is a widespread feature in many platforms of the Tethys (Trecalli *et al.* 2012 and references therein).

Recently, Trecalli *et al.* (2012) proposed for the early Toarcian oceanic anoxic event, recorded in the Apennine carbonate platform, a model involving ocean water acidification, forced by CO_2 release at the beginning of the event, followed by a calcification overshoot, driven by the recovery of ocean alkalinity. According to this model, the negative CIE occurred over a short time interval during a biocalcification crisis followed by a rebound of the $\delta^{13}C$ curve towards more positive values corresponding to the deposition of the oolitic units.

Obvious evidence for the mesotrophic environments recorded by the chert-rich unit of the Verzegnis section in the Belluno Basin is apparently missing in the palaeontological assemblage in the shallow-water calcarenitic units at the top of the Monte Zugna Fm. On the contrary, the first appearance of the *Paleomayncina termieri* and, more generally, an enrichment of foraminifera with a complex wall structure, seem to be related to an amelioration of the environment and to a shift towards an oligotrophic regime as proposed, for example, by Fugagnoli (2004) for the overlying Rotzo Fm. This anomaly could be explained assuming that trophic conditions are not the main parameter controlling the development of these foraminifera. Analysing in detail the behaviour of the carbonate factory with respect to the isotopic excursions in all the three shallow-water sections suggests that the first negative CIE, centred around the boundary of the *semicostatum* and *turneri* Zones (Fig. 8), coincides with the stratigraphic level recording the loss of peritidal sediments; and their replacement by subtidal shoals coincides with the interval of transition between negative and positive excursions of the isotopic curve. These shoals are composed of ooids with a dense micritic ultrastructure (Fig. 6a), typically associated with oncoids and dasycladaleans (*Palaeodasycladus mediterraneus*, *Palaeodasycladus gracilis*). The recovery of the platform during the positive *turneri*-Zone CIE caused its progradation outwards and the deposition of the fine-grained lagoonal *Gervillia buchi* beds on top of the marginal oolitic deposits of the Chizzola and Foza sections, respectively at the western and eastern margin of the Trento Platform. In the Friuli Platform (Cumieli section) the *Gervillia* beds are not recorded and are replaced by micritic deposits lacking obvious macrofossils.

The negative *obtusum–oxynotum* Zone excursion, which may be interpreted as due to a further introduction of isotopically light carbon into the ocean–atmosphere system, can similarly be linked to a reduction in carbonate production and a new transgression, recorded everywhere in the upper portion of calcarenitic unit of the Monte Zugna Fm. Being similar in bed organization and sedimentary structures to the lower part of calcarenitic unit, this upper portion shows a vertical evolution in which micritic ooids and dasycladaleans are replaced upward by radial-fibrous ooids and foraminifera with a calcitic wall structure (Fig. 6b). The degree of water turbulence and velocity, as denoted by sedimentary structures, apparently changed little during deposition of the unit, ruling out physical environmental factors as controlling ooidal ultrastructure. Notably, the micritic ooids are associated with aragonitic dasycladaleans and correlate with transitions between positive and negative excursions of the CIE, whereas the radial-fibrous ooids are associated with foraminifera with calcitic walls during the acme of the CIE. These associations point to seawater pH, in turn forced by CO_2 release, as a leading factor controlling both fossil occurrence and ooidal structure by promoting short-term changes in the dominant mineralogy (aragonite *vs* calcite) of the carbonate factory (e.g., Sandberg, 1983; Wilkinson and Given, 1986; Zhuraviev and Wood, 2009). Following Strasser's (1986) study of Lower Cretaceous limestones in France and Switzerland (1986), the micritic ooids are interpreted as originally aragonitic which, after inversion to calcite, preserved some degree of original concentric structure, whereas the radial-fibrous ooids, formed in waters of relatively low pH, preserved the original calcitic composition and crystallographic orientation. Because a negative pulse of the carbon-isotope curve corresponds with a transgressive trend of the sedimentary succession, and the positive excursion records the contrary, the seawater pH may have directly controlled the whole production of the carbonate platform and hence sedimentary accumulation rate and relative sea level.

In the mid–Late Pliensbachian, the carbonate factory moved laterally from the top of the platform into the neighbouring Belluno Basin, incorporating the portion of the basin corresponding to the Monte Verzegnis area into a shallow-water domain where the cross-bedded calcarenitic unit at the top of the Soverzene Fm. (interpreted as subtidal shoals) started to accumulate (Fig. 4; Zanferrari *et al.*, 2013). During the same interval, a lack of accommodation space is assumed to have prevented deposition of shallow-water deposits in the adjacent Friuli Platform (Monte Cumieli section; Zanferrari *et al.*, 2013). The calcarenitic unit at the top of the Soverzene Fm. is in turn truncated by a hard-ground surface intervening between its upper boundary and the Verzegnis Encrinites. Since this latter unit corresponds to the Early Bajocian to Early Callovian interval, the hard-ground surface is equivalent to a time span extending from the Toarcian to the Aalenian, a hiatus equivalent to that separating the top of the Rotzo Fm. from the Lower Rosso Ammonitico in the central-western sector of the Trento Platform (see above and Masetti *et al.* 1998).

After the postulated Sinemurian event, the Pliensbachian recolonization seems to have been largely controlled by an extensional tectonic phase that led to the first differentiation of the central-western and northern-eastern sector of the Trento Platform in which accommodation space regulated the thickness of the shallow-water succession. In the more subsident central-western sector of the Trento Platform, the available accommodation space allowed the onset of a new type of carbonate factory characterized, at the beginning, by eutrophic deposits with abundant marls and lenses of black shales, followed by the development of the "*Lithiotis*" beds (Rotzo Fm.; Masetti *et al.* 1998; Bassi *et al.*1999; Posenato and Masetti 2012). This Early Pliensbachian environmental deterioration could be also ascribed to the climatic events that occurred at the Sinemurian/Pliensbachian boundary (Hesselbo and Korte, 2012; Franceschi *et al.* 2014) or, more likely, to the cumulative effects of both the preceding "*Arnioceras* time" and the S/P boundary events. According to Posenato & Masetti (2012), it is likely that the Rotzo Fm., overlying the Monte Zugna Fm., is separated by a depositional hiatus referable to part of the Early Pliensbachian. Other evidence of mesotrophic conditions during "*Arnioceras* time" comes from the Umbro–Marchean Apennines where peritidal deposits of the Calcare Massiccio pass upward into a deeper water succession characterized by the prevalence of sponges and other filter-feeding organisms ("Calcare Massiccio B", from *semicostatum* (Lower Sinemurian) to *jamesoni* Zones (Lower Pliensbachian) following Marino and Santantonio (2010).

In the north-eastern portion of the Trento Platform and in the northern edge of the Friuli Platform, where no accommodation space was available, the top of the Monte Zugna Fm. is truncated by an unconformity surface corresponding to the gap embracing the Pliensbachian, Toarcian and Aalenian stages (about 20 Ma, Gradstein *et al.* 2012), sporadically interrupted by the emplacement of the crinoidal sand waves of the Fanes Piccola Encrinite (Masetti *et al.* 1998, Zanferrari *et al.*, 2013). The lithostratigraphic relationships depicted in Figure 3 suggest that this huge hiatus could be related to the interplay between negligible accomodation space, with the top of the Trento Platform fixed at sea-level for more than 20 Ma, and the deleterious effects on the carbonate factory of at least four climatic events: that of the "*Arnioceras* time" described here, the Sinemurian/Pliensbachian boundary event, the mid–Pliensbachian warming event and the Toarcian OAE.

6.0 Summary and conclusions

Starting from the documented demise and/or drowning of several Tethyan carbonate platforms at some point during the Sinemurian Stage, a chemostratigraphic transect through this interval has been performed across the whole domain of the Eastern Southern Alps to investigate the response of both shallow- and deep-water domains during this time interval. Investigation has concentrated on carbonate-platform successions, locally underlying open-marine and/or pelagic cover, and one basinal peri-platform succession. An abrupt positive followed by a broader negative carbon-isotope excursion, typically in the range of 0.5–1.0 ‰, has been detected in all 4 stratigraphic sections over the likely stratigraphical extent of the ammonite *Arnioceras* that is recorded from the deep-water basinal succession. The positive excursion is attributed to the *turneri* Zone and the following negative excursion likely centred in the *obtusum* Zone (Figs 5, 8).

In the Belluno Basin, filled by peri-platform oozes (Monte Verzegnis section: deep-water Soverzene Fm.), the negative CIE spans a stratigraphic thickness of about 60 m and its lowest value is located immediately below the base of a chert-rich unit corresponding to an increase in the sponge content of the sediment. The hiatus between the chert-rich and calcarenitic units in the upper part of the Soverzene Fm. is considered to embrace the Late Sinemurian–Early Pliensbachian, an interval missing in both the shallow-water Monte Cumieli and Foza sections, and could be related to the coeval postulated drop in the sediment production of the feeder carbonate platforms.

In the shallow-water carbonate succession of the Monte Zugna Formation (Monte Cumieli, Foza, Chizzola sections), the correlative major carbon-isotope negative excursion is mainly developed within the calcarenitic unit at its top, which is divided into two parts (*semicostatum–turneri* Zones and *obtusum* Zone, respectively, for the lower and upper parts) by the lagoonal *Gervillia buchi* beds, indicating an apparent rapid recovery of the platform (*turneri* Zone, Figs 4, 7 and 8). The different ooidal structures and fossil assemblages characterizing the two calcarenitic units (Fig. 6) could have been a result of changes in pH that, operating on a scale of few thousands of years, favoured first 'aragonitic' and then 'calcite seas'. The virtual lack of fine-grained carbonate in the succession during the negative excursion may thus be explained if the switch to calcite seas also controlled the production of aragonitic mud, whether inorganically precipitated or derived from biological sources. These considerations, coupled with a fall in sedimentation rate to half the value of the preceding peritidal platforms, suggests that the transgression recorded by the calcarenitic unit that came to overlie the lower peritidal unit of the Monte Zugna Fm. and well documented by sea-level curves reconstructed for the Early/Late Sinemurian interval, could be the consequence, not of a purely eustatic oscillation, but also a decrease in carbonate production. The lateral spread of this calcarenitic unit represents a potential first step first step towards the demise and ultimate drowning of the platforms.

The re-colonization of the Trento Platform after the "Arnioceras time" climatic event was controlled by extensional tectonics governing the availability of accommodation space: where such space was negligible, the top of the Monte Zugna Fm. is truncated by a huge unconformity surface corresponding to a hiatus spanning the Late Sinemurian to the Early Bajocian (about 20 Ma); in the more subsident central-western sector, the available accomodation space allowed the onset of a new type of subtidal carbonate factory characterized by the Pliensbachian "Lithiotis facies".

The negative $\delta^{13}C$ excursion may be attributed to a reduction of global biomass and/or burial of organic matter and/or introduction of ^{13}C-depleted CO_2 into the atmosphere–ocean system from a buried source of isotopically light carbon. A coeval negative excursion in $\delta^{13}C$, described from southern England, is accompanied by palynological evidence suggesting the onset of a major warming event. The data presented here demonstrate that the major negative CIE of “Arnioceras time” is represented across the entire eastern Southern Alps, invariably associated with environmental reorganization of carbonate platforms and regional deepening. Taking in account also the widespread occurrence of definitive demise and drowning during the Sinemurian Stage in many parts of the Tethyan area, the negative CIE likely represents a global climatic event that pre-conditioned many carbonate platforms for demise and drowning.

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References

AVANZINI, M., FRISIA, S., KEPPENS, E. & VAN DEN DRIESSCHE, K.,1997. A dinosaur tracksite in an Early Jurassic tidal flat in Northen Italy: palaeoenvironmental reconstruction from sedimentology and geochemistry. *Palaio*s **12**, 538–551.

Beccarelli-Bauck, L., 1988. Unter-bismitteljurassische Karbonatformationen am Westrand der Trento-Platform (Südalpen, Norditalien). *Münchner Geowissenschaftliche Abhandlung* **13**, 1–86.

Barattolo F. & Romano R., 2005. Shallow carbonate platform bioevents during the Upper Triassic–Lower Jurassic: an evolutive interpretation. *Bollettino della Società Geologica Italiana* **124**, 123–142.

Bassi, D., Boomer, I., Fugagnoli, A., Loriga, C., Posenato R. & Whatley, R. C., 1999. Faunal assemblages and palaeoenvironment of shallow water black shales in the Tonezza area (Calcari Grigi, Early Jurassic, Southern Alps). *Annali dell'Università degli Studi di Ferrara, Sezione di Scienze della Terra* **8**,1–16.

Bellanca, A., Masetti, D., Neri, R. & Venezia, F., 1999. Geochemical and sedimentological evidence of productivity cycles recorded in Toarcian black shales from the Belluno Basin, Southern Alps, northern Italy. *Journal of Sedimentary Research* **69**, 466–476.

Bernoulli, D. & Jenkyns, H. C., 1974. Alpine, Mediterranean and central Atlantic Mesozoic facies in relation to the early evolution of the Tethys. In Modern and Ancient Geosynclinal Sedimentation, Edited by R. H. Dott, Jr and R. H. Shaver, *SEPM Special Publication* ***19***, 129–160.

Bertotti, G., Picotti, V., Bernoulli, D. & Castellarin, A., 1993. From rifting to drifting: tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. *Sedimentary Geology* **86,** 53–76.

Bill, M., O' Dogherty L., Guex J., Baumgartner P. O. & Masson H., 2001. Radiolarite ages in Alpine–Mediterranean ophiolites: constraints on the oceanic spreading and the Tethys–Atlantic connection. *Geological Society of America Bulletin* **113**, 129–143.

Bosellini, A. & Broglio Loriga, C., 1971. I "Calcari Grigi"di Rotzo (Giurassico inferiore, Altopiano di Asiago) e loro inquadramento nella paleo-geografia e nella evoluzione tettonico-sedimentaria delle

Prealpi venete. *Annali dell'Università di Ferrara (Sezione Scienze Geologiche e Paleontologiche)* **5**, 1–61.

Bosellini, A. & Masetti, D., 1972. Ambiente e dinamica deposizionale del Calcare del Vajont (Giurassico medio, Prealpi Bellunesi e Friulane. Annali dell'Università di Ferrara *(Sezione Scienze Geologiche e Paleontologiche)* **5**, 87–100.

Bosellini, A., Masetti, D. & Sarti, M., 1981. A jurassic "Tongue of the Ocean" infilled with oolitic sands: the Belluno Trough, venetian Alps, Italy. *Marine Geology* **44**, 55–95.

Chiocchini M., Farinacci A., Mancinelli A., Molinari V. & Potetti M., 1994, Biostratigrafia a foraminiferi, dasicladali e calpionelle delle successioni carbonatiche mesozoiche dell'Appennino centrale (Italia). *Studi Geologici Camerti*, Camerino, volume speciale "Biostratigrafia dell'Italia centrale" p. 9–128.

Chiocchini, M., Chiocchini, R. A., Didaskalou, P. & Potetti, M. (2008): Ricerche micropaleontologiche e biostratigrafiche sul Mesozoico della piattaforma carbonatica laziale-abruzzese (Italia centrale). *Memorie descrittive Carta Geologica Italiana* **84**, 5–170.

Claps M., Erba, E., Masetti D. & Melchiorri F., 1995 - Milankovitch-type cycles recorded in Toarcian black-shales from the Belluno Trough (Southern Alps, Italy*). Memorie Scienze Geologiche Padova* **47**, 179–188

Cobianchi, M., 2002. I nannofossili calcarei del Giurassico medio e superiore del Bacino di Belluno (Alpi Meridionali). *Atti Ticinensi di Scienze della Terra* **43**, 3–24.

Cuvillier, J., Foury, G. & Pignatti Morano, A., 1968. Foraminiferes noveaux du Jurassique superieur du Val Cellina (Frioul Occidental, Italie). *Geologica Romana* **7,** 141–155.

Courtillot, V.E. & Renne, P.R., 2003. On the ages of flood basalt events. Sur l'ages des trappes basaltiques. *C.R. Geosciences* **335**, 113–140.

D'Argenio, B., Pescatore, T. & Scandone, P.,1973. *Schema geologico dell'Appennino meridionale (Campania e Lucania). Quaderni Accademia Nazionale dei Lincei, Convegno sul tema: Moderne vedute sulla geologia dell'Appennino* **183**, 49–82.

Davey, S. D. & Jenkyns, H. C., 1999. Carbon-isotope stratigraphy of shallow-water limestones and implications for the timing of Late Cretaceous sea-level rise and anoxic events (Cenomanian-Turonian of the peri-Adriatic carbonate platform, Croatia). *Eclogae Geologicae Helvetiae* **92**, 163–170.

Decarlis, A. & Lualdi, A., 2010. Synrift sedimentation on the northern Tethys margin: an example from the Ligurian Alps (Upper Triassic to Lower Cretaceous, Prepiedmont domain, Italy). *International Journal of Earth Sciences* **100**, 1589–1604.

De Castro P., 1991. Jurassic. In: *5th International Symposium on Fossil Algae. Capri. 7–12 april 1991. Field-Trip Guide book*.

Dommergues, J. L., Ferretti, A. & Meister, C., 1994. Les faunes d'ammonites du Sinémurien de l'Apennin Central (Marches et Toscane, Italie). *Bollettino della Società Paleontologica Italiana* **33(1),** 13–42.

Fantoni, R. & Scotti, P., 2003. Thermal record of the Mesozoic extensional tectonics in the Southern Alps: *Atti Ticinensi Scienze della Terra* **9**, 96–101..

Föllmi, K. B., Weissert, H., Bisping, M. & Funk, H., 1994. Phosphogenesis, carbon-isotope stratigraphy, and carbonate-platform evolution along the Lower Cretaceous northern Tethyan margin. *Geological Society of American Bulletin* **106**, 729–746.

Franceschi, M., Dal Corso, J., Posenato, R., Roghi, G., Masetti, D. & Jenkyns, H. C., 2014. Early Pliensbachian (Early Jurassic) C-isotope perturbation and the diffusion of the *Lithiotis* Fauna: Insights from the western Tethys. *Palaeogeography, Palaeoclimatology, Palaeoecology* **410**, 255–263.

Fugagnoli, A. (2004). Trophic regimes of benthic foraminiferal assemblages in Lower Jurassic shallow water carbonates from northeastern Italy (Calcari Grigi, Trento Platform, Venetian Prealps). *Palaeogeography, Palaeoclimatology, Palaeoecology* **205 (1–2)**, 111–130.

Gaetani, M.,1975. Jurassic stratigraphy of the Southern Alps: a review. In C. Squyres, ed., *Geology of Italy; Libyan Arab Republic Earth Sci. Soc* 377–402.

Gradstein, F. M, Ogg, J. G. & Schmitz, M. D. Eds, 2012. *The Geologic Time Scale, 2012.*

Boston, USA, Elsevier.

Grötsch, J., Billing, I. & Vahrenkamp, V.C.,1998. Carbon isotope stratigraphy in shallow-water carbonates: implications for Cretaceous black-shale deposition. *Sedimentology* **45**, 623–634.

Haq, B. U., Hardenbol, J. & Vail, P. R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus, C. K., Hastings, B. S. & Kendall, C. G. St. C., Posamentier, H. W., Ross C.A. Van Wagoner, J. C. (eds.), *Sea-Level Changes: An Integrated Approach. SEPM Special Publication* **42**, 71–108.

Hallock, P. & Schlager, W., 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. *Palaios* **1**, 389–398.

Hermoso, M., Minoletti, F., Rickaby, R. E. M., Hesselbo, S. P., Baudin, F. & Jenkyns, H. C., 2012. Dynamics of a stepped carbon-isotope excursion: ultra high-resolution study of Early Toarcian environmental change. *Earth and Planetary Science Letters* **319–320**, 45–54.

Hesselbo, S. P. & Jenkyns, H. C., 1998. Sequence stratigraphy of the Lower Jurassic of the British Isles. In: de Graciansky, P. C., Hardenbol, J., Jaquin, T., Vail, P. R. & Farley, M.B. (Eds), *Mesozoic and Cenozoic Sequence Stratigraphy of Europe, Special Publication of the Society of Economic Paleontologists and Mineralogists* **60**, 561–581.

Hesselbo, S. P., Jenkyns, H. C., Duarte, L. V. & Oliveira, L. C. V., 2007. Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin,Portugal). *Earth and Planetary Science Letters* **253**, 455–470.

Hudson, J. D., 1977. Stable isotopes and limestone lithification. *J. Geol. Soc. London*, **133**, 637–660.

Jenkyns, H. C. 1971. Speculations on the genesis of crinoidal limestones in the Tethyan Jurassic. *Geologische Rundschau* **60**, 471–488.

Jenkyns, H. C., 1988. The early Toarcian (Jurassic) anoxic event: stratigraphic, sedimentary, and geochemical evidence. *American Journal of Sciences* **288**, 101–151.

943 JENKYNS, H. C., 2003. Evidence for rapid climate change in the Mesozoic–Palaeogene greenhouse world. *Philosophical Transactions of the Royal Society of London, Series A* **361**, 1885–1916.

945 JENKYNS, H. C. & TORRENS H. S., 1971. Palaeogeographic evolution of Jurassic seamounts in Western Sicily. In: Colloque du Jurassique méditerranéen, Edited by E. Végh-Neubrandt, *Annales Instituti Geologici Publici Hungarici* **54/2**, 91–104.

948 JENKYNS, H. C., SARTI, M., MASETTI, D. & HOWARTH, M. K. 1985. Ammonites and stratigraphy of Lower Jurassic black shales and pelagic limestones from the Belluno Trough, Southern Alps, Italy. *Eclogae Geologicae Helveticae* **78**, 299–311.

951 JENKYNS, H. C., JONES, C. E., GRÖCKE, D. R., HESSELBO, S. P. & PARKINSON, D. N., 2002. Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. *Journal of the Geological Society* **159**, 351–378.

954 JENKYNS, H.C. & WEEDON, G.P., 2013. Chemostratigraphy ($CaCO_3$, TOC, $\delta^{13}C_{org}$) of Sinemurian (Lower Jurassic) black shales from the Wessex Basin, Dorset and palaeoenvironmental implications. *Newsletters on Stratigraphy* **46**, 1–21.

957 JONES, C. E., JENKYNS, H. C. & HESSELBO, S. P., 1994. Strontium isotopes in Early Jurassic seawater. *Geochimica Cosmochimica* Acta **58**, 1285–1301.

959 KEMP, D. B., COE, A. L., COHEN, A. S. & SCHWARK, L., 2005. Astronomical pacing of methane release in the Early Jurassic period. *Nature* **437**, 396–399.

961 KORTE, C. & HESSELBO, S.P., 2011. Shallow marine carbon and oxygen isotope and elemental records indicate icehouse-greenhouse cycles during Early Jurassic. *Paleoceanography* **26**, PA4219, doi: 10.1029/2011PA002160.

964 MARINO, M. & SANTANTONIO, M. (2010). Understanding the geological record of carbonate platform drowning across rifted Tethyan margins: examples from the Lower Jurassic of the Apennines and Sicily (Italy). *Sedimentary Geology* **225,** 116–137.

967 MARSHALL, J. D., 1992. Climatic and oceanographic isotopic signals from the carbonate rock record and their preservation. *Geological Magazine* **129**, 143–160.

Martire, L. (2007). Rosso Ammonitico Veronese. In: Cita, M. B., Abbate, E., Balini, M., Conti, M. A., Falorni, P., Germani, D., Groppelli, G., Manetti, P. & Petti, F. M. (eds.), Carta Geologica d'Italia 1:50.000. Catalogo delle Formazioni, Unità tradizionali (1). APAT, Dipartimento Difesa del Suolo, Servizio Geologico d'Italia, Quaderni del Servizio Geologico d'Italia **Serie III, 7 (VI),** 98-100.

Marzoli, A., Renne, P. R., Piccirillo, E. M., Ernesto, M., Bellieni, G. & De Min, A., 1999. Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. *Science* **284,** 616–618.

Masetti D. & Bottoni, A., 1975. L'Encrinite di Fanes e suo inquadramento nella paleogeografia giurassica delle Dolomiti centro-occidentali*. Rivista Italiana di Paleontologia e Strat*igrafia **84**, 169-186.

Masetti, D. & Bianchin, G., 1987. Geologia del Gruppo dello Schiara (Dolomiti Bellunesi): suo inquadramento nell'evoluzione giurassica del margine orientale della piattaforma di Trento. *Memorie di Scienze Geologiche Padova* **39,** 187–212.

Masetti, D., Claps, M., Giacometti, A., Lodi, P. & Pignatti, P., 1998. I Calcari Grigi della Piattaforma di Trento (Lias inferiore e medio, Prealpi Venete). *Atti Ticinensi di Scienze della Terra* **40**, 139-183.

Masetti, D., Fantoni, R., Romano, R., Sartorio, D. & Trevisani, E., 2012. Tectonostratigraphic evolution of the Jurassic extensional basins of the eastern Southern Alps and Adriatic foreland based on an integrated study of surface and subsurface data. *American Association of Petroleum Geologists Bulletin* **96**, 2065–2089.

Massari F., 1981. Cryptalgal fabrics in the Rosso Ammonitico sequences in the Venetian Alps. In: Farinacci, A. and Elmi, S., Eds., *Rosso Ammonitico Symposium Proceedings*, Edizioni Tecnoscienza, Rome, 453–469.

Merino-Tomé, O., Della Porta, G., Kenter, J. A. M., Verwerk, K., Harris, P. M., Adams, E. W., Playton, T. & Corrochano, D., 2012. Sequence development in an isolated carbonate platform (Lower Jurassic, Djebel Bou Dahar, High Atlas, Morocco): influence of tectonics, eustacy and carbonate production. *Sedimentology* **59**, 118–155.

Meister, C., Schirolli, P.,Dommergues, J. L., 2009. Sinemurian to lowermost Toarcian ammonites of the Brescian Prealps (Southern Alps, Italy): preliminary biostratigraphical framework and correlations. *Volumina Jurassica* **7**, 9–18.

Page A., 2010. Stratigraphic framework. In: Lord, R. & Davis, P.G. (Eds), *Fossils from the Lower Lias of the Dorset Coast, Palaeontological Association Field Guides to Fossils* **13**, 33–53.

Piano, C. & Carulli, G. B. 2002. Sedimentazione e tettonica giurassica nella successione del gruppo del Monte Verzegnis (Prealpi Carniche nord-orientali). In: Carulli, G. B. & Ponton, M. (eds), Atti dell'80ª Riunione Estiva della Società Geologica Italiana*, Memorie della Società Geologica Italiana* **57**, 115–122.

Porter, S. J., Smith, P., Caruthers, A., Houa, P., Gröckeb, D. R. & Selbyb, D., 2014. New high resolution geochemistry of Lower Jurassic marine sections in western North America: A global positive carbon isotope excursion in the Sinemurian. *Earth and Planetary Science Letters* **397**, 19–31.

Posenato, R. & Masetti, D., 2012. Environmental control and dynamics of Lower Jurassic bivalve build-ups in the Trento Platform (Southern Alps, Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology* **361–362**, 1–13.

Riding, J. B., Leng, M. J., Kender, S., Hesselbo, S. P. & Feist-Burkhardt, S., 2012. Isotopic and palynological evidence for a new Early Jurassic environmental perturbation. *Palaeogeography, Palaeoclimatology, Palaeoecology* **374**, 16–27.

Ronchi, P., Lottaroli, F. & Ricchiuto, T., 2000. Sedimentary and diagenetic aspects of the Liassic Inici Fm. and its stratigraphic context (Sicily Channel, Italy). *Memorie della Società Geologica Italiana*, **55**, 261–269.

Romano, R., Barattolo, F. & Masetti D., 2005. Biostratigraphic evidence of the middle Liassic hiatus in the Foza Section. (Eastern sector of the Trento Platform, Calcari Grigi Formation, Venetian Prealps). *Bollettino della Società Geologica Italiana* **124**, 301–312.

Ruiz-Ortiz, P. A., Bosence, D. W. J., Rey, J., Nieto Castro, J. M., & Molina J.M., 2004. Tectonic control of facies architecture, sequence stratigraphy and drowning of a Liassic carbonate platform

(Betic Cordillera, Southern Spain). *Basin Research* **16**, 235–257.

SABATINO, N., NERI, R., BELLANCA, A., JENKYNS, H. C., BAUDIN, F., PARISI G. & MASETTI, D., 2009. Carbon-isotope records of the Early Jurassic (Toarcian) oceanic anoxic event from the Valdorbia (Umbria–Marche Apennines) and Monte Mangart (Julian Alps) sections: palaeoceanographic and stratigraphic implications. *Sedimentology* **56**, 1307–1328.

SABATINO, N., VLAHOVIĆ, I., JENKYNS, H. C., SCOPELLITI, G., NERI, R., PRTOLJAN, B. & VELIĆ, I., 2013. Carbon-isotope record and palaeoenvironmental changes during the early Toarcian anoxic event in shallow-marine carbonates of the Adriatic Carbonate Platform in Croatia. *Geological Magazine* **150,** 1085–1102.

SANDBERG, P. A., 1983. An oscillating trend in Phanerozoic non-skeletal carbonate mineralogy. *Nature* **305**, 19–22.

SCHIROLLI, P.,1997. La successione liassica nelle Prealpi Bresciane, Centro-Occidentali (Alpi Meridionali, Italia): stratigrafia, evoluzione paleogeografico-strutturale ed eventi connessi al rifting. *Atti Ticinensi di Scienze della Terra* **6**, 5–137.

SCHLAGER, W., 2005 Carbonate Sedimentology and Sequence Stratigraphy. *SEPM Concepts in Sedimentology and Paleontology No.* 8, 1–198.

SCHLAGER, W. & JAMES N. P. 1978. Low-Magnesium calcite limestone forming at the deep-sea floor, tongue of the Ocean, Bahamas. *Sedimentology* **25**, 675–702.

SCHOLLE, P. & ARTHUR, M. A. 1980. Carbon isotope fluctuations in Cretaceous pelagic limestones: potential stratigraphic and petroleum exploration tool*. American Association of Petroleum Geologists Bulletin* **64,** 67–87.

SEPTFONTAINE M., 1984. Biozonation (à l'aide des Foraminifères imperforés) de la plate-forme interne carbonatée liasique du Haut Atlas (Maroc*). Revue de Micropaléontologie* **27**, 209–229.

SEPTFONTAINE M., 1985. Milieux de dépôts et Foraminifères (Lituolidés) de la plate-forme carbonatée du Lias moyen au Maroc. *Revue de Micropaléontologie* **28**, 265–289.

STRASSER, A.,1986. Ooids in Purbeck limestones (lowermost Cretaceous) of the Swiss and French

1047 Jura. *Sedimentology* **33**, 711–728.

1048 SWART, P.K., 2008, Global synchronous changes in the carbon isotopic composition of carbonate
1049 sediments unrelated to changes in the global carbon cycle. *Proceeding of the National Academy of*
1050 *Sciences* **105**, 13741–13745.

1051 TRECALLI, A., SPANGENBERG, J., ADATTE, T., FOLLMI, K. B. & PARENTE, M., 2012. Carbonate platform
1052 evidence of ocean acidification at the onset of the early Toarcian oceanic anoxic event. *Earth and*
1053 *Planetary Science Letters* **357–358**, 214–225.

1054 WENDT, J. 1969. Die stratigraphisch-paläogeographische Entwicklung des Jura in Westsizilien.
1055 Geologische Rundschau **58**, 735–755.

1056 WILKINSON, B.H. & GIVEN, R.K., 1986. Secular variation in abiotic marine carbonates: constraints on
1057 Phanerozoic atmospheric carbon dioxide contents and oceanic Mg/Ca ratios. *Journal of Geology* **94**,
1058 321–333.

1059 WILMSEN, M. & NEUWEILER, F., 2008. Biosedimentology of the Early Jurassic post-extinction carbonate
1060 depositional system, central High Atlas rift basin, Morocco. *Sedimentology* **55**, 773–807.

1061 WINTERER, E. L. & BOSELLINI, A., 1981. Subsidence and Sedimentation on Jurassic Passive
1062 Continental Margin, Southern Alps, Italy. *American Association of Petroleum Geologists Bulletin* **65**,
1063 394–421.

1064 WOODFINE, R. G., JENKYNS, H. C., SARTI, M., BARONCINI, F. & VIOLANTE C., 2008. The response of two
1065 Tethyan carbonate platforms to the early Toarcian (Jurassic) oceanic anoxic event: environmental
1066 change and differential subsidence. *Sedimentology* **55**, 1011–1028.

1067 VELIĆ I., 2007, Stratigraphy and Palaeobiogeography of Mesozoic benthic foraminifera of the Karst
1068 Dinarides (SE Europe). *Geologia Croatica* **60**, 1–113.

1069 ZANFERRARI, A., MASETTI, D., MONEGATO, G. & POLI, M. E., 2013. Geological map and explanatory
1070 notes of the Italian Geological Map at the scale 1:50.000: Sheet 049 “Gemona del Friuli”. ISPRA -
1071 *Servizio Geologico d’Italia-Regione Autonoma Friuli Venezia Giulia*, 262
1072 pp.http://www.isprambiente.gov.it/Med.

ZHURAVLEV, A. Y. & WOOD, R.A., 2009. Controls on carbonate mineralogy: Global CO_2 evolution and mass extinctions. *Geology* **37**, 1123–1126.

FIGURE CAPTIONS

Fig. 1: A: Mesozoic structural domain of the Southern Alps. The dotted line indicates the section in Fig. 1B. B: Section across the Southern Alps showing the extensional Mesozoic architecture of the Southern Alps at the end of Early Cretaceous time. After Masetti *et al.* (2012).

Fig. 2: The chemostratigraphic transect across different types of Jurassic successions inside the main palaeogeographic units of the eastern Southern Alps and location of the sections presented here. In the map, 1 and 2 represent, respectively, the areal distribution of central-western and the north-eastern areas of the Trento Platform; 3 represents the Belluno Basin; 4 and 5 represent, respectively, the northern and southern areas of the Friuli Platform. ZG = Monte Zugna Formation; OL = Loppio Oolitic Limestone; RZ = Rotzo Formation; CG = Undifferentiated Calcari Grigi; OM = Massone Oolite; ENF = Fanes Piccola Encrinite; OSV = San Vigilio Oolite + Tenno Formation; SOV = Soverzene Formation; IGNE = Igne Formation; ARV = Rosso Ammonitico Veronese ; VJ = Vajont Limestone; CEL = Cellina Limestone. Modified from Masetti *et al.* 2012.

Fig. 3: Lithostratigraphic relationships of the Jurassic units across the entire Trento Platform–Plateau from the Lombardian Basin in the west, to the Belluno Basin in the east. Red spots highlight the location of the negative CIE described in the text. Modified from Masetti *et al.* (2012).

Fig. 4: Monte Verzegnis and Monte Cumieli sections. In the upper part of the deep-water Monte Verzegnis section there is an abrupt positive carbon-isotope excursion followed by a broad negative excursion over the likely stratigraphical range of *Arnioceras*. In the shallow-water Monte Cumieli section, the same two negative excursions are tentatively recognizable, the first just above the top of

1098 the peritidal unit of the Monte Zugna Formation and the second in the calcarenitic unit of the same formation, separated by a thin micritic intercalation corresponding to a positive CIE. LO *Paleomayncina termieri* indicates its lowest occurrence identified in the section.

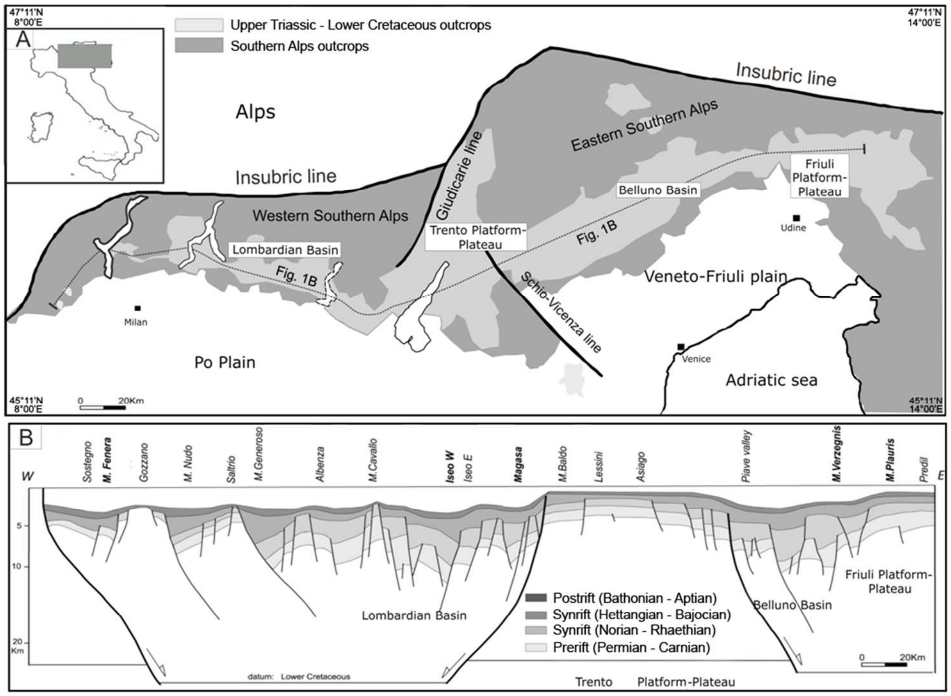
1101 Fig. 5: Ammonite stratigraphy of the Sinemurian Stage. Modified from Dommergues *et al.*, 1994.

1102 Fig. 6: Microfacies from Foza and Cumieli sections. a) micritic ooids showing thinly laminated outer tangential cortices, associated with *Palaeodasycladus mediterraneus*, visible in a transversal section in the lower part of the thin-section. Lower part of the calcarenitic unit of the Monte Zugna Fm., Foza section, scale bar = 1 mm; b) radial-fibrous ooids in which crystalline cortices are penetrated by dark microborings. *Everticyclammina praevirguliana* at the nucleus of the largest ooid. Upper part of the calcarenitic unit of the Monte Zugna Fm., Cumieli section, scale bar = 1mm.

1108 Fig. 7: Foza and Chizzola sections. In the Foza section the same two negative excursions described in the Mount Verzegnis section are readily discernible**.** The stratigraphically lowest negative excursion is present just above the base of the calcarenitic unit of the Monte Zugna Formation where the *Gervillia* bed crops out, and the stratigraphically higher negative excursion in the calcarenitic unit of the same formation. In the Chizzola section, the same isotopic pattern is repeated with the positive excursion coincident with the Gervillia bed, but outcrop failure does not allow generation of data from stratigraphically lower strata.

1115 Fig. 8: Chemostratigraphic transect through the Eastern Southern Alps with pertinent biostratigraphic data. The figure illustrates the correlation of the above-described anomalies of the $\delta^{13}C$ curves across the entire Eastern Southern Alps, from the Garda Lake to the eastern Italian border. The excellent matching between the single curves allows recognition, both in the shallow- and deep–water units, of the abrupt positive followed by broader negative carbon-isotope excursion described in the text. The correlation belt, coloured grey in the figure, defines the major negative excursion and its lower boundary (abrupt positive excursion) can be correlated with the peak of the excursion to heavier values in the *turneri* Zone: this level records the first appearance of the foraminifera *Paleomayncina termieri*. Recognition and proposed zonal attribution of key carbon-isotope excursions in Monte Verzegnis derives from data from well-dated Sinemurian mudstones and shales from the UK (Fig. 8).

Fig. 9: Left-hand diagram illustrates the Copper Hill Borehole (Eastern England) studied by Riding *et al.* (2012) and illustrating an increase of the dinoflagellate cyst *Liasidium variabile* and the thermophylic pollen grain *Classopollis classoides* in ammonite-bearing mudstones, suggesting the occurrence of a warming event coincident with a negative carbon-isotope excursion in marine and terrestrial organic matter largely corresponding to the *obtusum* and *oxynotum* Zones of the Sinemurian Stage. The presence of the negative excursion in terrestrial pollen indicates that the atmosphere as well as the ocean was affected by the disturbance in the carbon cycle. Scale in metres is depth below surface. *semicost.* = *semicostatum* Zone; *ob.* = *obtusum* Zone; *oxynot* = *oxynotum* Zone. Right-hand diagram illustrates high-resolution organic carbon-isotope stratigraphy of Sinemurian ammonite-bearing black shales from Dorset, Southern England (Weedon and Jenkyns, 2013). A positive excursion is characteristic of the *turneri* Zone followed by a negative excursion in the lower part of the *obtusum* Zone; the upper part of the *obtusum* Zone and the whole of the *oxynotum* Zone are lost to a hiatus. Grey band illustrates the position of the principal negative carbon-isotope excursion, only partly developed in Dorset. Depth is given in metres below the top of the Black Ven Marls. semi. = *semicostatum* Zone; *res.* = *resupinatum* Subzone; *obtu.* = *obtusum* Subzone; *rari.* = *raricostatoides* Subzone.



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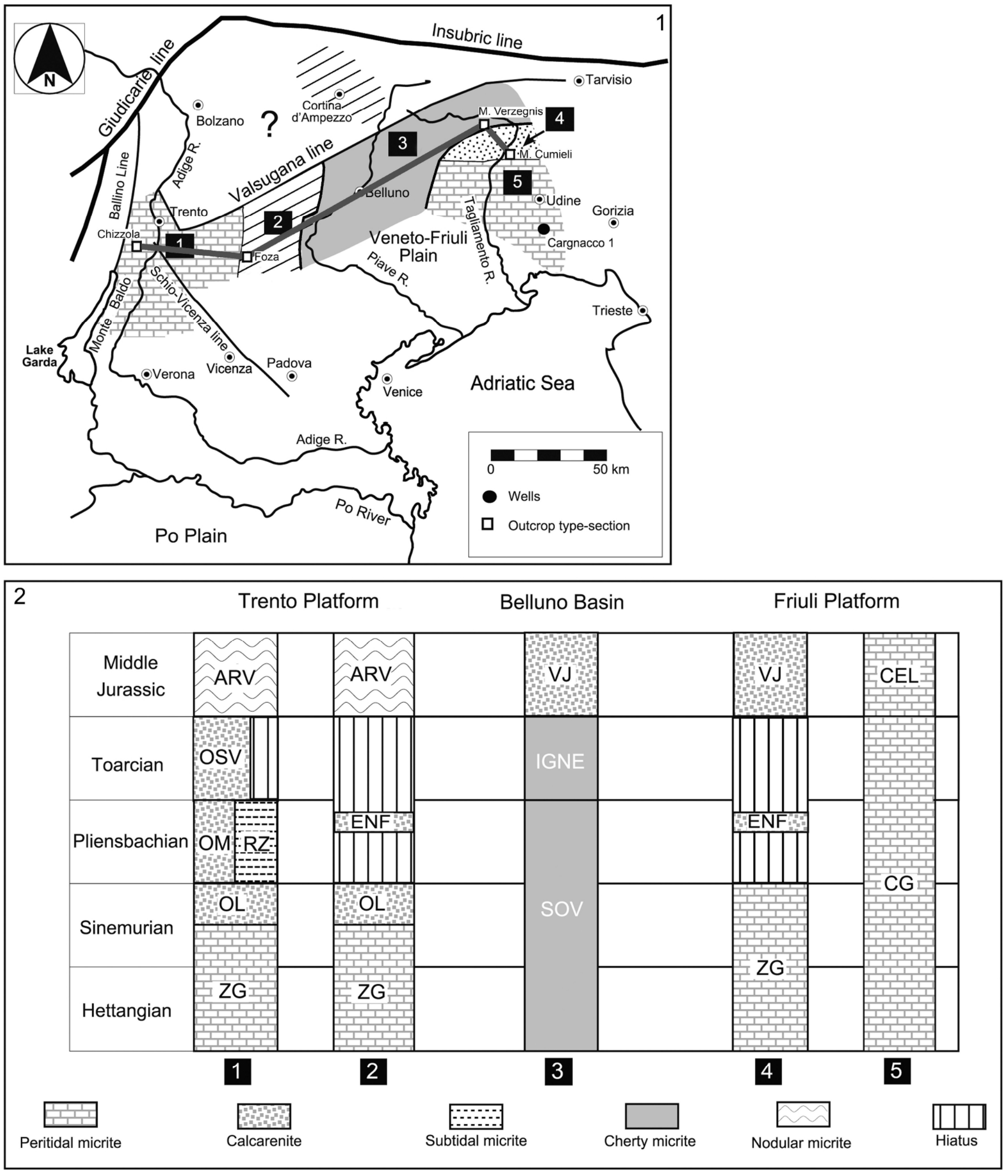

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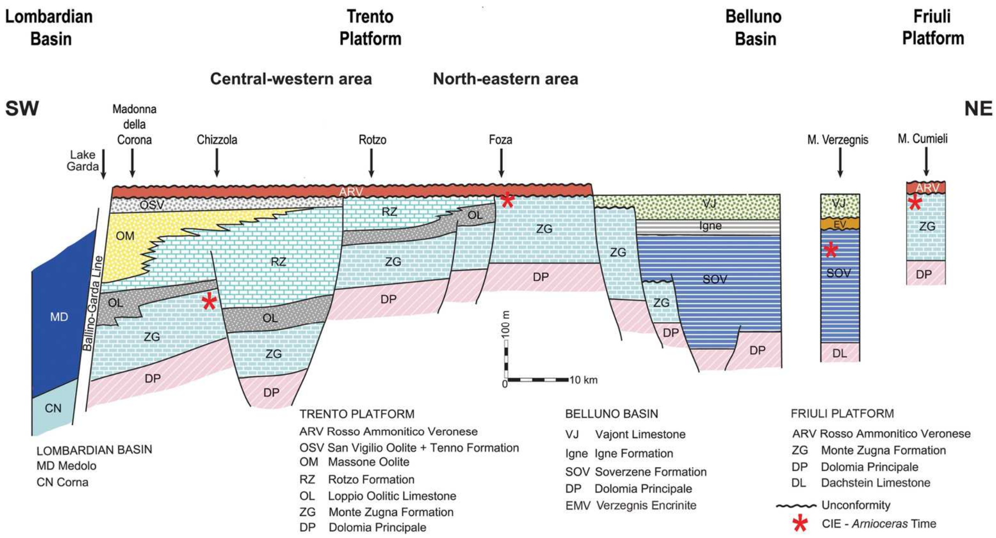

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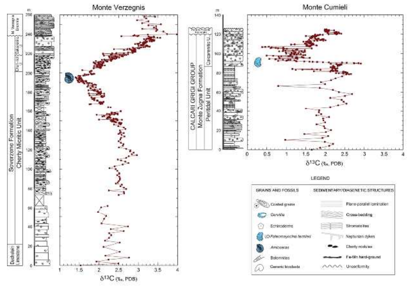

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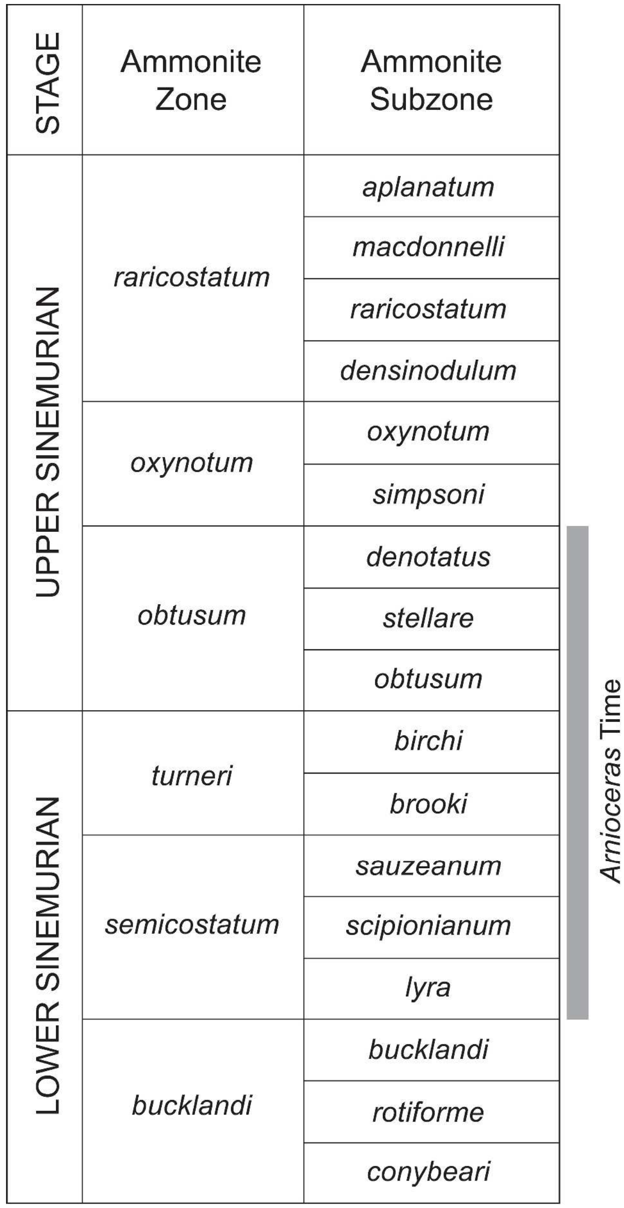

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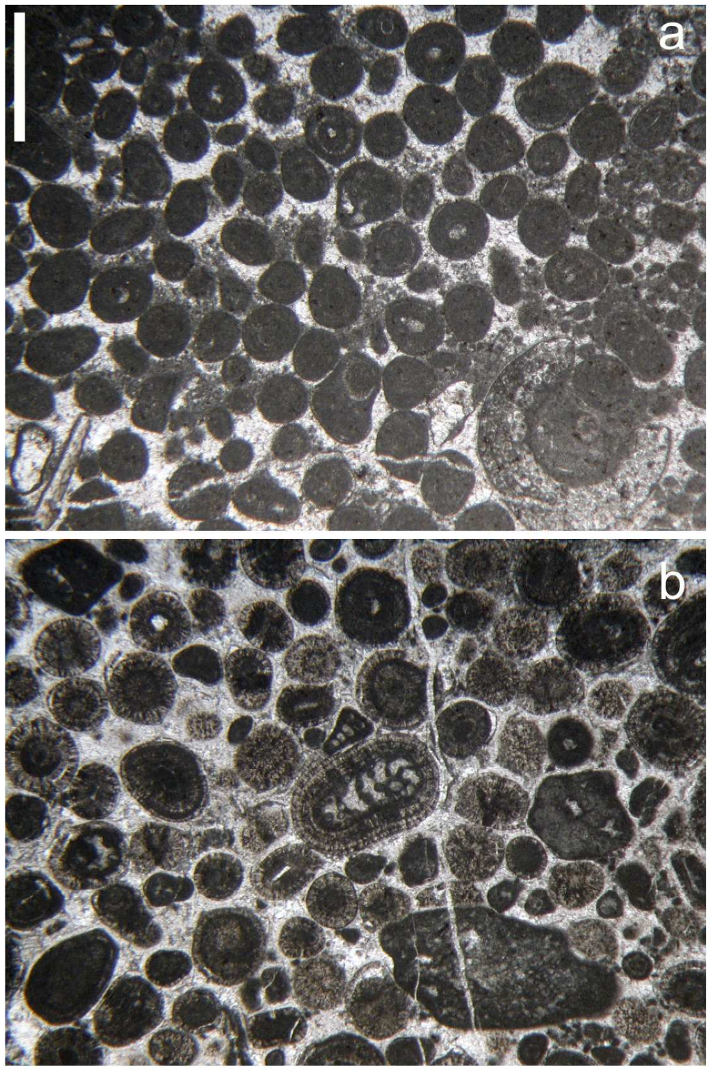

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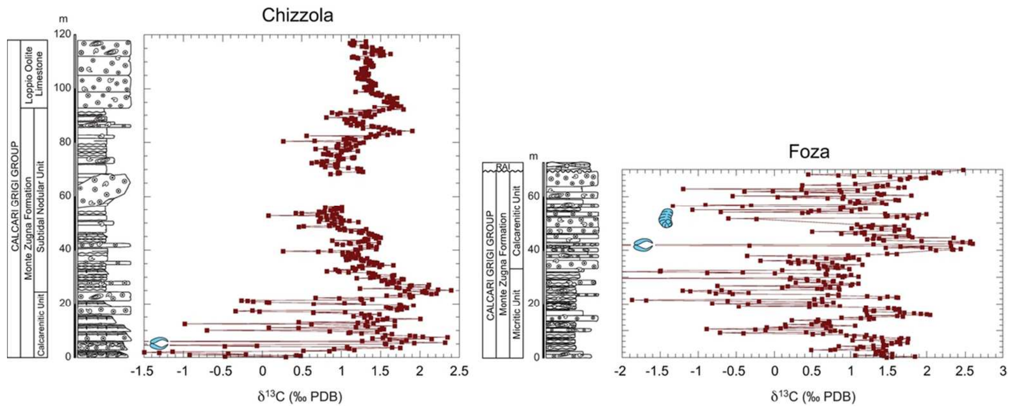

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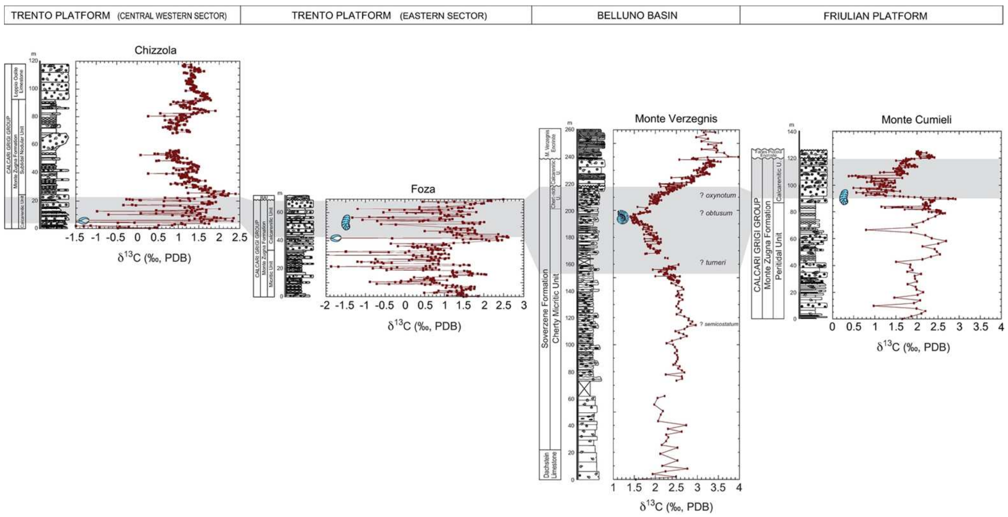

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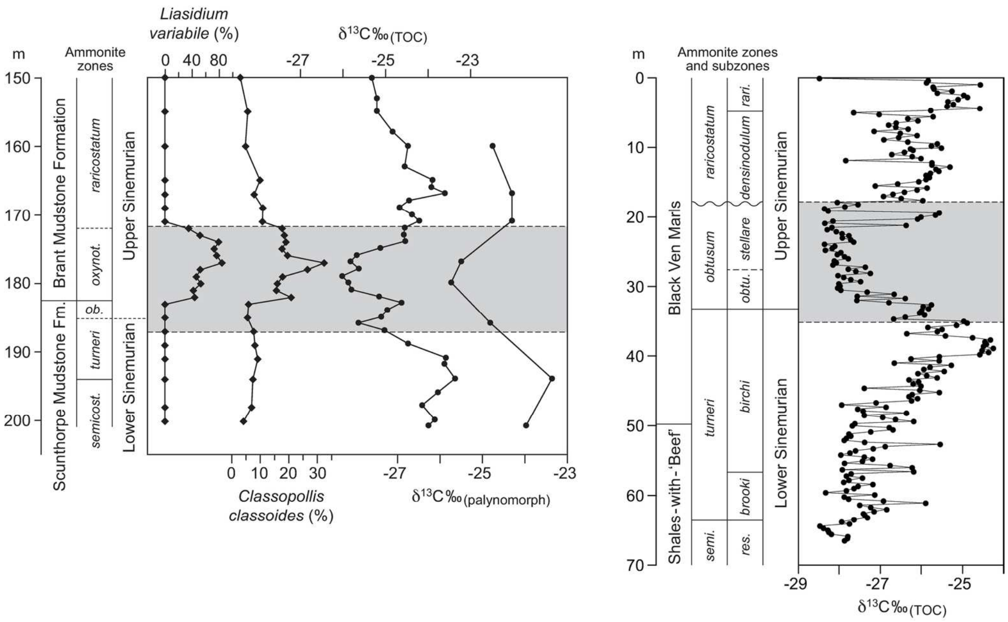

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