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The response of two Tethyan carbonate platforms to the early Toarcian (Jurassic) oceanic anoxic event: environmental change and differential subsidence

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ABSTRACT

Chemostratigraphic analyses (^{87}Sr/^{86}Sr, $\delta^{13}C_{carb}$) of limestones from two Jurassic platform-carbonate sequences in Italy (Trento and Campania–Lucania Platforms) illustrate previously established trends found in pelagic sediments and skeletal carbonates from biostratigraphically well-calibrated sections elsewhere in Europe. Chemostratigraphic correlations between the platform-carbonate successions and appropriate intervals from well-dated reference sections allow the application of high-resolution stratigraphy to these shallow-water peritidal carbonates and, furthermore, elucidate the facies response to the Early Toarcian Oceanic Anoxic Event (OAE). Lower Jurassic (Toarcian) levels of the western Trento Platform (Southern Alps, Northern Italy) contain spiculitic cherts that appear where rising carbon-isotope values characterize the onset of the OAE: a palaeoceanographic phenomenon interpreted as driven by increased nutrient levels in near-surface waters. There is a facies change to more clay-rich facies at the level of the abrupt negative carbon-isotope excursion, also characteristic of the OAE, higher in the section. The Campania–Lucania Platform (Southern Apennines, Southern Italy) records a change to more clay-rich facies where carbon-isotope values begin to rise at the beginning of the OAE but the negative excursion, higher in the section, occurs within oolitic facies. Although, in both examples, the Early Toarcian OAE can be recognized by a change to more clay-rich lithologies, this facies development is diachronous and in neither case did the platform drown. Although the Trento Platform, in the south-west sector studied here, was adversely affected by the OAE, it did not drown definitively until Late Aalenian time; the Campania–Lucania Platform persisted throughout the Jurassic and Cretaceous. Differential subsidence rates, which can be calculated using comparative chemostratigraphy, are identified as a crucial factor in the divergent behaviour of these two carbonate platforms: relatively fast in the case of the Trento Platform; relatively slow in the case of the Campania–Lucania Platform. It is proposed that where water depths remained as shallow as a few metres during the OAE (Campania–Lucania Platform), dissolved oxygen levels remained high, nutrient levels relatively low and conditions for carbonate secretion and precipitation remained relatively favourable, whereas more poorly ventilated and/or more nutrient-rich waters (Trento Platform) adversely

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influenced platform growth where depths were in the tens of metres range. The stage was thus set for drowning on the more rapidly subsiding western margin of the Trento Plateau and a pulse of oolite deposition post-dating the OAE was insufficient to revitalize the carbonate factory.

Keywords Carbonate platform, Italy, OAE, Toarcian.

INTRODUCTION

This study primarily investigates the impact of global environmental change on two Tethyan carbonate platforms during the Early Toarcian Oceanic Anoxic Event (OAE). Initial recognition of this major palaeoceanographic phenomenon was based on the global distribution of apparently coeval lower Toarcian organic-rich shales from epicontinental and deep-marine settings, with examples known from northern and southern Europe, North Africa, Madagascar, North and South America, Australia and across Asia (Jenkyns, 1985, 1988; Jenkyns *et al.*, 2002). Because burial of excess relatively ^{12}C-enriched organic carbon would have caused an increase in the δ^{13}C value of global sea water, the accompanying positive excursion documented in pelagic and epicontinental carbonates is as predicted (Jenkyns & Clayton, 1986, 1997). However, as initially noted by Küspert (1982), within the black shales themselves an abrupt negative excursion can be recognized that subsequent studies have shown to take place in several distinct steps (Jenkyns *et al.*, 2001, 2002; Jenkyns, 2003; Kemp *et al.*, 2005; Hesselbo *et al.*, 2007). This negative excursion, locally registered in organic-poor pelagic carbonate and terrestrial wood, as well as marine organic matter, is commonly interpreted as being due to an influx of isotopically light methane from dissociation of gas hydrates and/or metamorphism of Gondwanan coals, although some authors have viewed it as a local oceanographic phenomenon (Hesselbo *et al.*, 2000a; McElwain *et al.*, 2005; van de Schootbrugge *et al.*, 2005a). The level of abrupt fall in carbon-isotope ratios essentially divides the broad positive excursion into lower and upper segments. In complete sedimentary sequences, there is thus a very diagnostic carbon-isotope signature for recognition of the lower ammonite zones of the Toarcian stage (Fig. 1). In terms of global environmental change, the beginning of the OAE is clearly registered by an increase in regional sedimentary organic-carbon values and an accompanying rise in δ^{13}C values in the boreal *tenuicostatum* Zone; the acme of the OAE – as identified by regional total organic carbon (TOC) maxima – lay in the boreal mid-*exaratum* Subzone in the core of the negative δ^{13}C excursion (Jenkyns *et al.*, 2001, 2002; Jenkyns, 2003). The level corresponding to the end of the OAE may be

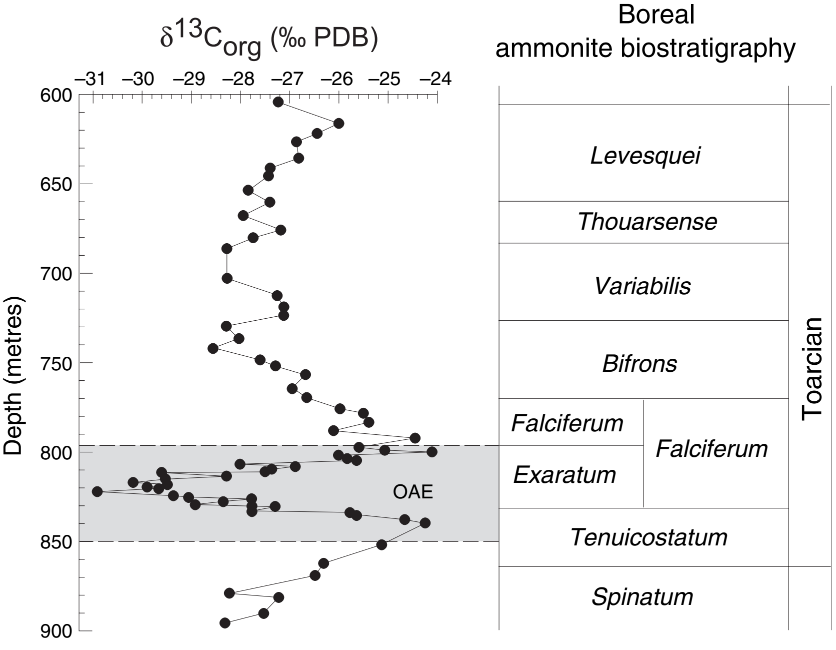

Fig. 1. Carbon-isotope data ($\delta^{13}C_{org}$) across the Pliensbachian/Toarcian boundary from the Mochras Borehole, Gwynedd, Wales (Jenkyns *et al.*, 2002), taken here as a reference section. The biostratigraphy is well-constrained by ammonites. Note the broad positive excursion interrupted by an abrupt negative shift. This pattern is also seen in terrestrial organic matter and carbonate (Hesselbo *et al.*, 2000a, 2007). Data are unsmoothed.

fixed by the maximum carbon-isotope values achieved at the level of the stratigraphically higher positive excursion, essentially at the *exaratum–falciferum* Subzone boundary (Fig. 1).

Other geochemical and palaeontological anomalies characterizing the Early Toarcian OAE include a nitrogen-isotope (δ^{15}N) positive excursion, a shift in strontium-isotope (^{87}Sr/^{86}Sr) and osmium-isotope (^{187}Os/^{188}Os) ratios to more radiogenic values and globally significant mass extinction (Hallam, 1986; Little & Benton, 1995; Aberhan & Fürsich, 1996; McArthur *et al.*, 2000; Jenkyns *et al.*, 2001, 2002; Jones & Jenkyns, 2001; Aberhan & Baumiller, 2003; Cohen *et al.*, 2004). In this study, the strontium-isotope profile is used, in conjunction with carbon-isotope curves, as a tool for correlation and dating between reference sections and Tethyan platform carbonates. These distinctive sedimentary and geochemical signatures allow accurate chemostratigraphic correlation between well-dated reference sections and carbonate-platform sequences that generally lack biostratigraphically useful fossils. Consequently, the impact of the Early Toarcian OAE on shallow-water carbonate systems can be investigated.

GEOLOGICAL SETTING

The Southern Alps of Northern Italy (Fig. 2) have been interpreted as part of a passive Tethyan continental margin subjected to major extensional movements in the Early Jurassic, the result of which was an east–west-trending half-graben submarine topography formed as the Ligurian Ocean was created to the west (Winterer & Bosellini, 1981; Sarti *et al.*, 1992). The Trento Platform is generally interpreted as an offshore, Bahamian-type platform bordered to the east and west by the pelagic Belluno Trough and Lombardian Basin, respectively. Typical facies include micritic limestones, skeletal sparites (remains of calcareous algae, benthonic foraminifera, brachiopods, corals, gastropods, echinoids and sponges), oolites and beds rich in the thick-shelled bivalve *Lithiotis*: inferred environments include tidal flats, oolitic sand bars and tidally aligned *Lithiotis* banks (Bosellini, 1972; Gaetani, 1975; Clari & Marelli, 1983; Barbujani *et al.*, 1986; Krautter, 1987; Masetti, 1998). Regional flooding of the platform, dated as Tethyan *tenuicostatum* Zone, Early Toarcian by nannoflora and ammonite biostratigraphy (Geyer *et al.*, 1986; Picotti & Cobianchi, 1996), is associated with a depositional transition from typical peritidal shallow-water carbonate facies to calcareous shales with spiculitic cherts (Castellarin, 1972; Barbujani *et al.*, 1986). However, the western sector of the Trento Platform survived this flooding event and persisted, with the development of crinoid-rich oolitic sediments, until it underwent definitive drowning in the Aalenian. At this stage, the platform became a pelagic plateau that was covered locally with cross-bedded ammonite–brachiopod–crinoid lenses (*Posidonia alpina* Beds) and subsequently with stratigraphically condensed red nodular limestones, the Rosso Ammonitico (Sturani, 1964, 1971; Zempolich, 1993).

The sections studied on the Trento Platform are found close to the western margin of the structure (now along the eastern margin of Lake Garda), and are called Madonna della Corona (MDC), Colma di Malcesine (CDM) and Sega d'Ala (SDA) (Figs 2 and 3). The MDC section is over 730 m thick and is the most complete and extensive section through the platform carbonates (Fig. 4). Samples from MDC, taken along the pilgrim's path, that leads to the sanctuary from points both above and below, were analysed for bulk-rock carbon-isotope and strontium-isotope ratios; carbon-isotope data only are presented from the other two sections. Both the CDM and SDA sections clearly expose the more clay-rich facies, locally (at the former locality) overlain by chert-bearing limestone, all interpreted as deposited during the Early Toarcian flooding event on the Trento Platform. These clay-rich intervals, being more easily weathered, do not crop out in the MDC section, although cherty facies are well-developed in strata above and below the unexposed interval (Barbujani *et al.*, 1986; Picotti & Cobianchi, 1996).

The Southern Apennines Platform is depicted as two units separated by the Lagonegro Basin (remnants of which are now found in the southern Southern Apennines region: Wood, 1981): the internal Campania–Lucania Platform (sometimes referred to as the Latium–Campania–Lucania Platform) and the more external Abruzzi–Campania Platform (Fig. 2). The Campania–Lucania Platform is described as a Bahamian-type epioceanic carbonate platform that persisted throughout the Jurassic and Cretaceous (D'Argenio *et al.*, 1971, D'Argenio, 1974). The Molise Basin (remnants of which are now found in the northern Southern Apennines region) developed during the intense rifting characteristic of the Tethyan Jurassic and eventually completely separated the Abruzzi–Campania Platform from the Apulia Platform

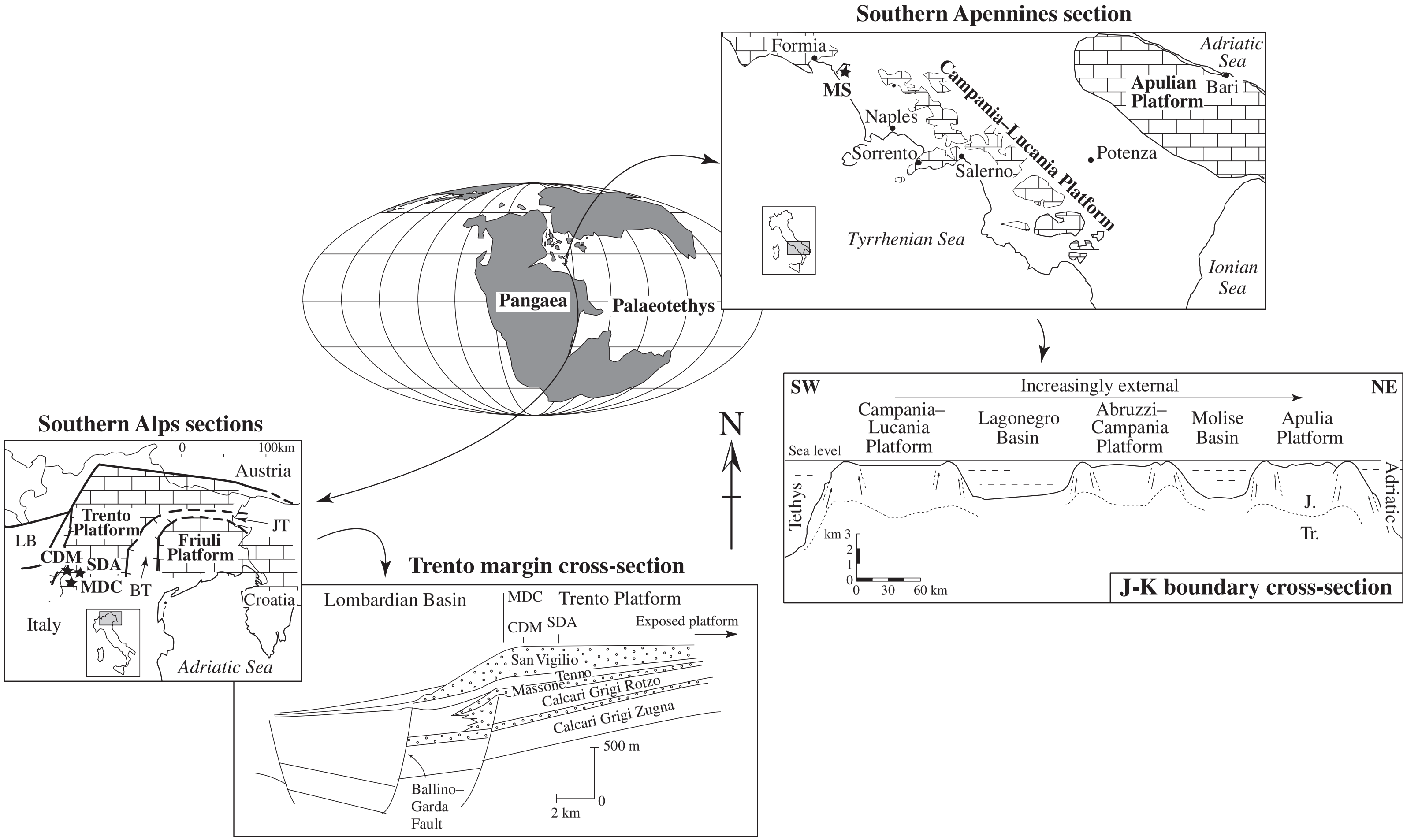

Fig. 2. Tethyan palaeogeography during the Toarcian (Smith *et al.*, 1994), illustrating the present-day locations of Madonna della Corona (MDC), Colma di Malcesine (CDM) and Sega d'Ala (SDA) on the Trento Platform, and Monte Sorgenza (MS) on the Campania–Lucania Platform. Also shown are cross-sections through the Trento and Campania–Lucania Platforms, illustrating the proposed tectonic setting and the approximate locations of the studied sequences on the platforms. LB, Lombardian Basin; BT, Belluno Trough; JT, Julian Trough. After D'Argenio (1974), Gaetani (1975), Cobianchi & Picotti (2001) and Catalano *et al.* (1976).

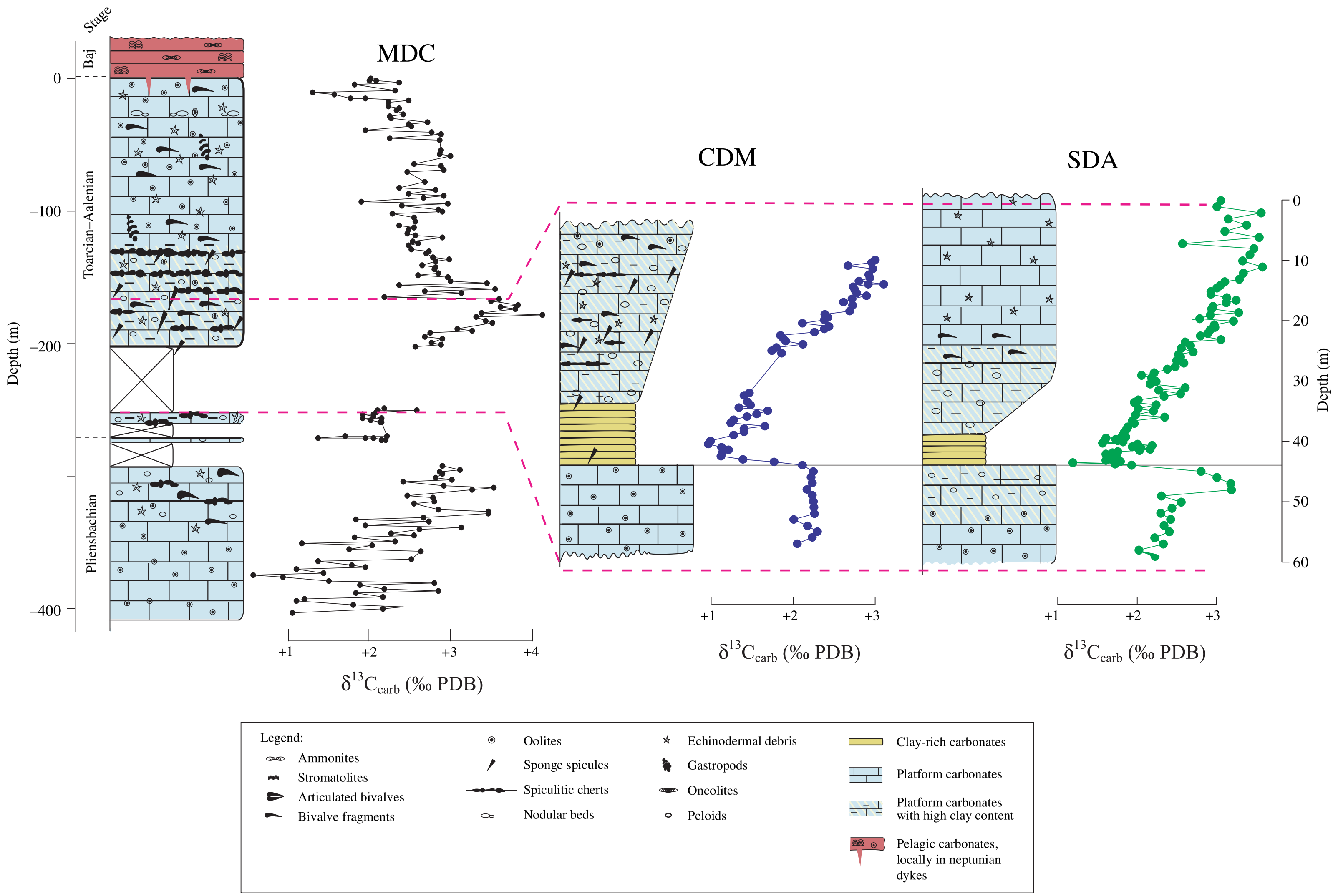

Fig. 3. Comparative carbon-isotope stratigraphy of three Lower Jurassic sections from the western sector of the Trento Platform: Madonna della Corona (MDC), Colma di Malcesine (CDM) and the Sega d'Ala (SDA). Note the difference in vertical scale between the first section and the other two sections. Tentative correlation lines are also shown, although incomplete exposure in the MDC section precludes identification of the characteristic negative carbon-isotope excursion. Data are unsmoothed.

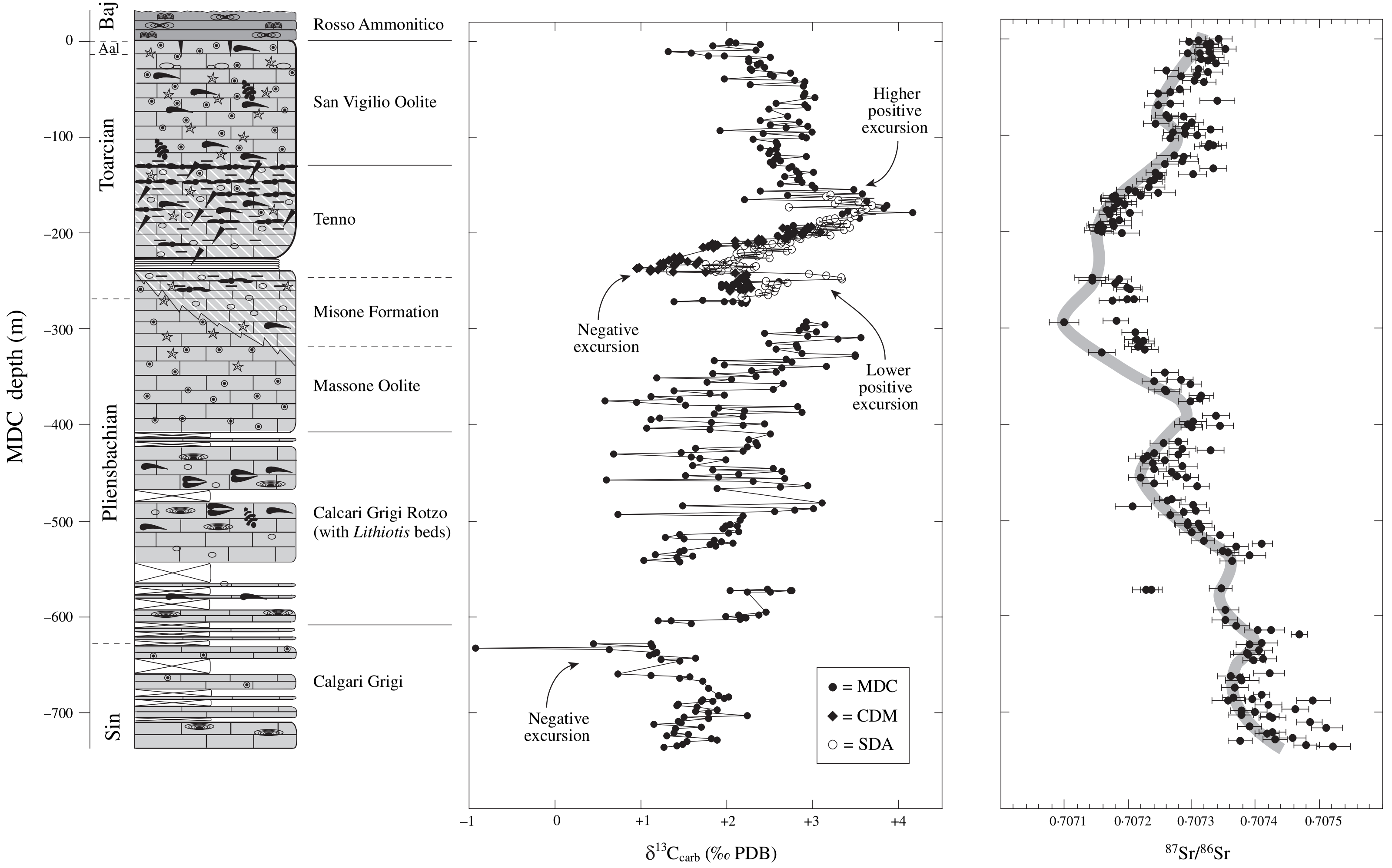

Fig. 4. Composite carbon-isotope profile of the Trento Platform, strontium-isotope profile of the Madonna della Corona (MDC) section and composite graphic log of the Trento Platform (with relevant formation names). Of significance is the lower positive, followed by pronounced negative, followed by positive $\delta^{13}C_{carb}$ excursion and a minimum in the strontium-isotope profile. Because diagenesis generally elevates marine $^{87}Sr/^{86}Sr$ ratios in carbonate, the best-estimate curve is drawn along the lower limits of the data (Burke *et al.*, 1982). Over the interval of these carbon-isotope excursions, rhythmically bedded limestones with spiculitic cherts and calcareous shales are developed. The depths are taken from the MDC section with carbon-isotope data from Colma di Malcesine (CDM) and the Sega d'Ala (SDA) fitted against this to match the pattern of overall values. Data are unsmoothed. Legend as in Fig. 3.

further to the east (Fig. 2; Catalano *et al.*, 1976; Channell *et al.*, 1979; Buonocunto *et al.*, 2002). Because this elongate zone of carbonate platforms, separated by relatively deeper-water basins, has also been recognized in Bahamian facies of the same age, it has been suggested that a semi-continuous carbonate belt stretched thousands of kilometres along the Atlantic–Tethyan margins (D'Argenio, 1974; D'Argenio *et al.*, 1975; Jenkyns, 1991). The Adriatic Plate has since been rotated and compressed by Alpine tectonics, whereas the Bahamas were pulled away from Europe by sea floor spreading in the Atlantic (Bosellini, 1989).

There is relatively little information in the literature regarding the Jurassic shallow-water carbonates of the Campania–Lucania Platform. Generally speaking, however, the Campania–Lucania Platform made the transition from a Triassic intra-continental carbonate platform with widespread supratidal facies to a Jurassic epioceanic carbonate platform (Channell *et al.*, 1979), with deposition of a more varied facies dominated by skeletal calcite (algae, benthonic foraminifera, gastropods, brachiopods, echinoids, sponges and solitary corals). This change followed a transition from aragonite-favouring to calcite-favouring deposition at the Triassic–Jurassic boundary (Sandberg, 1983; Stanley & Hardie, 1998). These Lower Jurassic facies and faunal assemblages have been interpreted as representing deposits of sub-tidal back-reef lagoons (Channell *et al.*, 1979; Violante, 2000). As in the Southern Alps, there is a distinctive *Lithiotis*-rich interval (Calcari a *Lithiotis*) believed to be Late Liassic in age (*Palaeodasycladus mediterraneous* Zone) based on the available biostratigraphy (Sartoni & Crescenti, 1962; Bosellini & Broglio Loriga, 1971; Channell *et al.*, 1979; Damiani *et al.*, 1991/2a, 1991/2b; Violante, 2000). Overlying the *Lithiotis* beds, Violante (2000) documents deposition of the Calcari Oolitici and the Calcari Maculati Formations (up to Lower Bajocian in age – *Selliporella donzellii* Zone). These formations have been interpreted as reflecting restricted to open lagoonal environments with no evidence of peritidal influence on deposition. Upper Jurassic and Lower Cretaceous deposits on the Campania–Lucania Platform represent restricted-shelf settings resulting in the accumulation of sub-tidal lagoonal facies with associated ooid and/or gastropod sand shoals (D'Argenio *et al.*, 1971; Damiani *et al.*, 1991/2b). Cessation of shallow-water carbonate sedimentation finally occurred at approximately Cretaceous/Tertiary boundary time and, as with many Tethyan carbonate platforms, the Campania–Lucania Platform eventually succumbed to the influx of orogenically derived flysch (Bosellini, 1989).

Lower Jurassic levels of the Campania–Lucania Platform were studied from exposures in the Monte Sorgenza (MS) section, located in the Aurunci Mountains immediately north-east of Formia (Figs 2 and 5). There are very few details of this section to be found in the literature, although Violante (2000) has performed lithostratigraphic correlations in an attempt to constrain approximately the age of the section.

METHODS

Powdered bulk-carbonate samples were reacted with orthophosphoric acid at 90 °C. The resulting CO_2 was analysed by a VG Isogas Series II Prism mass spectrometer [Vacuum Generators (VG), Winsford, Cheshire] and results are reported in per mil (‰) deviation from the Pee Dee Belemnite standard (PDB). Analytical reproducibility of replicate standards (Carrara Marble) for the above process was less than 0·1‰ for both carbon-isotope and oxygen-isotope analyses. Strontium was separated from bulk-carbonate samples using standard procedures (Jones *et al.*, 1994) and then loaded into a VG Isomass 54E solid-state thermal ionization mass spectrometer (TIMS). Results were normalized to an NIST SRM 987 standard value of 0·710250. The average of 54 analyses of the standard over the period of analysis was 0·710248 with a 95% confidence interval (2σ) of $2{\cdot}6 \times 10^{-6}$.

COMPLICATING FACTORS: LOCAL WATERMASS CHEMISTRY AND DIAGENESIS

Because chemostratigraphic curves are used in this account to suggest high-resolution biostratigraphic ages of carbonate-platform successions, the limitations of this methodology need to be examined. On modern carbonate platforms, water masses may become restricted in certain lagoonal environments and undergo a general depletion in ^{13}C because local effects of organic-matter oxidation dominate sea water chemistry (Patterson & Walter, 1994). Such water masses will not, therefore, necessarily match global trends in terms of their isotopic evolution (Immenhauser *et al.*, 2003). In the Cretaceous platform carbonates of Barremian–Albian age exposed in the Gavrovo

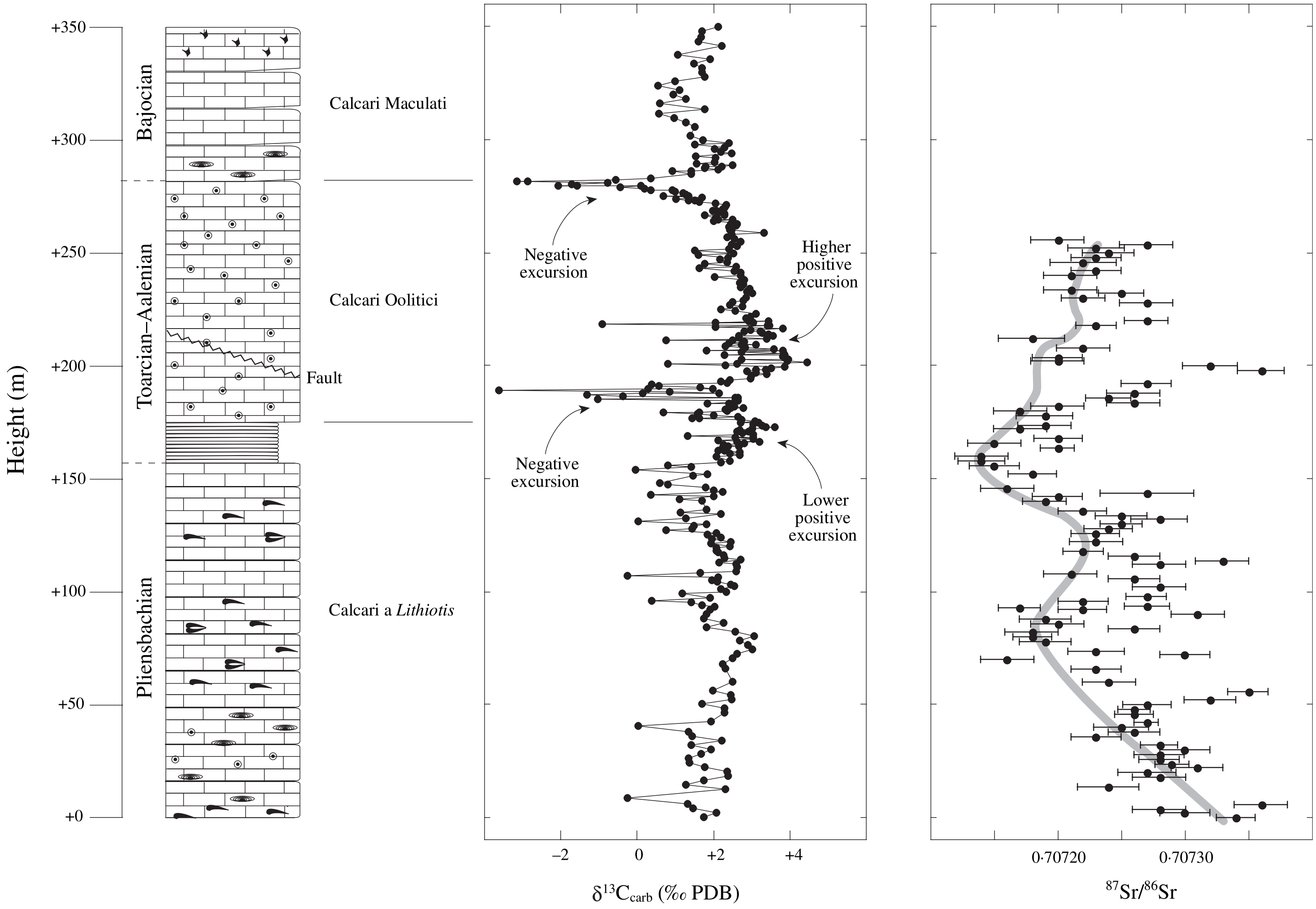

Fig. 5. Carbon-isotope and strontium-isotope profile and graphic log (with formation names) of the Monte Sorgenza section, Campania–Lucania Platform. Calcareous shales are coincident with rising $\delta^{13}C_{carb}$ values, but a negative followed by positive $\delta^{13}C_{carb}$ excursion and minimum in the strontium-isotope profile correlates with deposition of oolite. Because diagenesis generally elevates marine $^{87}Sr/^{86}Sr$ ratios in carbonate, the best-estimate curve is drawn along the lower limits of the data (Burke *et al.*, 1982). Data are unsmoothed. Legend as in Fig. 3.

Zone of western Greece, isotope trends show a $\sim 1‰$ negative offset with respect to coeval pelagic sediments but the isotopic profile is very similar (Grötsch *et al.*, 1998). Cenomanian–Turonian platform carbonates in Croatia and Southern Italy evince the same phenomenon (Davey & Jenkyns, 1999; Parente *et al.*, 2007). There is now a wealth of studies that show that long δ^{13}C time series in Cretaceous platform carbonates from the Tethyan and Pacific regions may be correlated readily with biostratigraphically well-calibrated carbon-isotope curves from pelagic sediments and that major excursions provide key intervals of correlation (Jenkyns, 1995; Vahrenkamp, 1996; Ferreri *et al.*, 1997; Grötsch *et al.*, 1998; Wilson *et al.*, 1998; Davey & Jenkyns, 1999; Jenkyns & Wilson, 1999; Masse *et al.*, 1999; Wissler *et al.*, 2003).

Diagenesis is another significant factor. As far as strontium isotopes are concerned, relatively Sr-rich fluids may be released from the breakdown products of non-carbonate minerals and these may release relatively radiogenic or, more rarely, non-radiogenic strontium into the diagenetic environment (Emery *et al.*, 1987; Banner, 1995; Gröcke *et al.*, 2007). It was to adjust for the problem of diagenetically increased Sr-isotope ratios that Burke *et al.* (1982) constructed their 'best-estimate' curve along the lower limits of their data set. Mesozoic platform carbonates, however, are relatively poor in non-carbonate detrital minerals and long time series of ^{87}Sr/^{86}Sr values show trends and absolute values that conform well to global curves generated from well-preserved skeletal carbonate deriving from belemnites and foraminifera (Jenkyns *et al.* 1995; Bralower *et al.*, 1997; Jenkyns & Wilson, 1999).

The diagenetic behaviour of carbon and oxygen isotopes in shallow-water carbonates is more 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 'Caribbean-style' diagenesis would typically introduce fluids with relatively low δ^{18}O and δ^{13}C values derived from rain water after its interaction with atmospheric carbon dioxide and humus-rich soils (e.g Hudson, 1977; Marshall, 1992; Swart & Eberli, 2005). Typically, horizons affected by such processes would have scattered and relatively low carbon-isotope and oxygen-isotope ratios compared with typical marine values and, if plotted against each other, would exhibit a clear 'mixing line' (Allan & Matthews, 1982; Grötsch *et al.*, 1998). However, in the Jurassic and Cretaceous 'greenhouse' world, for which the evidence of significant ice-caps is ambiguous at best (Crowell, 1982; Schlanger, 1986; Frakes *et al.*, 1992; Hallam, 1992; Jenkyns *et al.*, 2004; Immenhauser, 2005; Moriya *et al.*, 2007), eustatic sea-level change would have been of lesser amplitude than that caused by Tertiary glaciation–deglaciation cycles (Schlager, 1981; Dewey & Pitman, 1998): intensive meteoric-water diagenesis should hence have been less significant. Other possible causes for deviation of isotopic values from primary signals include the effect of skeletal grains that may exhibit non-equilibrium isotopic fractionation, the presence of void-filling secondary calcite (for example in inter/supratidal facies such as birdseye limestones), or diagenetic alteration of originally aragonitic material (Grötsch *et al.*, 1998; Davey & Jenkyns, 1999).

When used in conjunction with available biostratigraphy (chiefly calcareous algae and benthonic foraminifera in Jurassic–Cretaceous platform carbonates), strontium-isotope and carbon-isotope curves provide an invaluable means of high-resolution correlation in sequences that are otherwise difficult to date accurately but which were deposited in a water depth shallow enough to be affected by sea-level change but locally deep enough to feel the impact of major oceanographic perturbations.

CHEMOSTRATIGRAPHY OF THE CARBONATE-PLATFORM SECTIONS

The carbon-isotope profiles from the three sections on the western Trento Platform – MDC, CDM and SDA – are broadly comparable (Fig. 3), with the caveat that the pronounced negative excursion is not displayed at MDC because of exposure failure. Where developed, the negative shift is abrupt with a more gradual return to higher values passing up-section, an apparently characteristic feature of this excursion in all sequences examined to date (Jenkyns *et al.*, 2001, 2002; Jenkyns, 2003; Kemp *et al.*, 2005; Hesselbo *et al.*, 2007). The data from CDM and SDA are combined with those from MDC by taking the higher positive excursion as a series of common reference points, allowing assembly of a composite chemostratigraphic section for the Trento Platform (Fig. 4). Correlation may be inexact, close to the level of the lower positive excursion and complicated by the fact that a small-scale negative excursion is known to be present immediately above the Pliensbachian/

Toarcian boundary in some European sections (Jenkyns & Clayton, 1997; Hesselbo *et al.*, 2007).

In the lower part of the section (MDC), carbon-isotope values increase from approximately +1·5‰ to +3‰ between −700 and −300 m, with the exception of a negative excursion at approximately −630 m where they fall to less than unity. This negative excursion is tentatively assigned to the Sinemurian–Pliensbachian boundary because a comparable feature is recorded in belemnite calcite from well-dated sequences in England (Jenkyns *et al.*, 2002) and in bulk pelagic sediments from Marche–Umbria, central Italy (Morettini *et al.*, 2002). The more pronounced increase in $\delta^{13}C_{carb}$ values from approximately −350 m, with some scattered lower values and an additional clear positive shift in the SDA section (Figs 3 and 4), is followed by the distinctive negative and subsequent positive shift in isotope values characteristic of the Early Toarcian OAE. In the MDC section, the negative shift in $\delta^{13}C_{carb}$ is followed by an increase in values resulting in a profile maximum of over +4‰ at approximately −175 m. This positive $\delta^{13}C_{carb}$ excursion is associated with a gradual change in facies from the clay-rich Basal Tenno Formation through rhythmically bedded limestone with clay interbeds and increasingly abundant spiculitic cherts (Upper Tenno Formation) to clean-washed oolite with echinodermal debris (San Vigilio Oolite; Castellarin, 1972; Barbujani *et al.*, 1986). At this level in the platform section (approximately −100 m), carbon-isotope data have returned to background values of +2·5‰ following the $\delta^{13}C_{carb}$ maximum.

The strontium-isotope profile of MDC is also shown in Fig. 4. Strontium-isotope values range between 0·707100 and 0·707523 and, on a broad scale, show a distinctive trough in values, reaching a minimum between −250 and −300 m. Both the decline in strontium-isotope values below this minimum and the subsequent rise are characterized by a series of steps. The data are relatively coherent and the curve conforms closely to that established for the Jurassic, based on belemnite skeletal calcite, both in terms of shape and absolute values (Jones *et al.*, 1994). For example, an $^{87}Sr/^{86}Sr$ value of ~0·7074 characterizes the Sinemurian/Pliensbachian contact in England (Hesselbo *et al.*, 2000b) and a similar value is recorded from bulk carbonate at MDC at the level picked as the stage boundary on the basis of the negative carbon-isotope excursion.

The isotopic values of the MS section (Campania–Lucania Platform) are shown in Fig. 5. Carbon-isotope data illustrate a rise in values from approximately +1·5 to +3·5‰ between 0 and +170 m where the lower positive excursion is recognized, followed by a sharp decrease in values (negative excursion). Somewhat higher, a fault in the section, with an estimated vertical offset of approximately 15 m, signifies the loss of some of the section. Data from immediately above the fault register maximum values in the $\delta^{13}C_{carb}$ profile of over +4‰ at +200 m (higher positive excursion), before they gradually decrease to background values (of +2‰) at about +270 m, following which there is another distinct and well-defined negative excursion. This negative excursion is taken to define the Aalenian/Bajocian boundary because a similar feature is discernable in $\delta^{13}C$ belemnite records and terrestrial wood from England (Jenkyns *et al.*, 2002; Hesselbo *et al.*, 2003) and is particularly well-displayed in pelagic carbonates from Italy and Spain (Morettini *et al.*, 2002; O'Dogherty *et al.*, 2006). Strontium-isotope values range from 0·707140 to 0·707360 and display a similar trend to that of the Trento Platform, in general conforming to the reference curve based on belemnite calcite, but are considerably more scattered: there is a gradual decrease toward less radiogenic values resulting in a minimum at approximately +175 m before an increasing trend to more radiogenic values over the remainder of the section.

The intervals characterized by distinctive negative and positive $\delta^{13}C_{carb}$ excursions associated with the OAE from both the Trento and Campania–Lucania Platforms can be readily correlated, potentially to zonal level, with reference isotope profiles from northern and southern Europe that have been biostratigraphically dated using ammonites aided by similarly calibrated strontium-isotope values. The minimum in strontium-isotope values is characteristic of the Upper Pliensbachian and Lower Toarcian (Jones *et al.*, 1994; McArthur *et al.*, 2000) and the trough of the negative $\delta^{13}C$ excursion between the two positive excursions corresponds with the Toarcian Lower *exaratum* Subzone in England (Fig. 1) and the Toarcian Lower *levisoni* Zone in Portugal (Jenkyns *et al.*, 2002; Hesselbo *et al.*, 2007). On the basis of rare ammonite finds and nannofossils, the basal Tenno Formation has been assigned to the Tethyan *tenuicostatum* Zone (Geyer *et al.*, 1986; Picotti & Cobianchi, 1996): an interval that has been taken to correspond, in part, with the Lower *exaratum* Subzone in England (Jenkyns *et al.*, 2002). Although there is a gap in data of the MS $\delta^{13}C_{carb}$ profile (due to the presence of a fault), correlatable trends can still be seen: in particular, a tolerably well-defined positive followed by a negative excursion immediately followed by a maximum in $\delta^{13}C_{carb}$ values, the latter being dated as higher *falciferum* or *levisoni* Zones by reference to ammonite-calibrated sections in northern and southern Europe (Jenkyns & Clayton, 1986, 1997; Hesselbo *et al.*, 2007).

In summary, trends shown in both the strontium-isotope and carbon-isotope profiles of the MS section are similar to those shown by data from the western Trento Platform. However, the facies changes are somewhat different: in MS there is a transition from proud-weathering carbonates to more clay-rich recessively weathering carbonates, but this occurs coincident with the initial rise in $\delta^{13}C_{carb}$ values (lower positive excursion) below the pronounced negative excursion that signals the change to clay-rich facies on the Trento Platform (Fig. 4). Over the stratigraphically higher interval characterized by the distinctive negative and positive $\delta^{13}C_{carb}$ excursions the stratigraphic record of Monte Sogenza (Fig. 5) registers the continuous deposition of massive oolite (Calcari Oolitici; Damiani *et al.*, 1991/2a, 1991/2b; Violante, 2000).

SEDIMENTATION RATES OF TRENTO AND CAMPANIA–LUCANIA CARBONATE PLATFORMS

Application of the new chemostratigraphic frameworks to the two Tethyan carbonate platforms allows calculation of relative accumulation (post-compaction and lithification) rates of their shallow-water carbonate without assigning particular parts of the sections to particular stages. The correlation band, given in Fig. 6, is drawn on patterns in both carbon-isotope and strontium-isotope values: specifically, the lower tie-point is taken at the level of a small relative $\delta^{13}C$ maximum in both sections and just below a relative minimum in $^{87}Sr/^{86}Sr$ values and the higher tie-point is taken at the greatest $\delta^{13}C$ values in both sections. This chemostratigraphic correlation indicates that the Trento Platform, over a period of time encompassing parts of the Pliensbachian and Toarcian stages, was accumulating sediment at a rate approximately twice that of the Campanian–Lucania Platform, implying much greater subsidence in this sector of the Southern Alps than in the Southern Apennines, assuming that the platforms always remained relatively close to sea-level. The only stages that can be distinguished relatively unambiguously on both platforms are the Toarcian and Aalenian combined. Using the recent time scale of Pàlfy *et al.* (2000) and Gradstein *et al.* (2004) yields approximate accumulation rates of 23 to 28 and 12 to 15 m Myr^{-1} for the western Trento Platform and Campania–Lucania Platform, respectively, over this interval. The approximate subsidence values for the Trento Platform were 45 to 55 m Myr^{-1} during the Pliensbachian and 33 to 45 m Myr^{-1} during the Toarcian, implying a dramatic slow down during the Aalenian. These accumulation rates are relatively low when compared with the Phanerozoic norm (Bosscher & Schlager, 1993). Significant observations would seem to be a transient change to more clay-rich and cherty facies during the Early Toarcian on the western Trento Platform and the fact that drowning took place around Aalenian/Bajocian boundary time when accommodation space apparently decreased. Hence, the divergence in behaviour of the Trento and Campania–Lucania Platforms – invasion of pelagic conditions in the case of the former, continuance of the carbonate factory in the case of the latter – underscores the complexity of the 'drowning paradox' of reefs and carbonate platforms (Schlager, 1981, 1989, 1999).

The proposed stratigraphic correlation between the Trento and Campania–Lucania platforms, based on chemostratigraphy, is shown in Fig. 7. The Calcari a *Lithiotis* Formation of the Campania–Lucania Platform is broadly equivalent to the Calcari Grigi of the Trento Platform, and the upper shaly horizon of the Calcari a *Lithiotis* is coeval with the base of the rhythmically bedded Misone Formation at MDC on the Trento Platform (i.e. coincident with $\delta^{13}C$ values rising into a relative profile maximum, probably that of the *tenuicostatum* Zone of the basal Toarcian). The shaly, cherty Tenno Formation of the Trento Platform has its equivalent in oolitic deposits on the Campania–Lucania Platform and such facies are represented in both areas in the uppermost Toarcian.

THE IMPACT OF THE EARLY TOARCIAN OCEANIC ANOXIC EVENT ON THE WESTERN SECTOR OF THE TRENTO CARBONATE PLATFORM

Possible effects of the Early Toarcian OAE on Tethyan carbonate platforms can be effectively divided into two categories: temperature rise and deterioration of water quality. Maximum devastation of carbonate producers on the Trento Platform occurred synchronously with the $\delta^{13}C_{carb}/\delta^{13}C_{org}$ negative excursion, which began

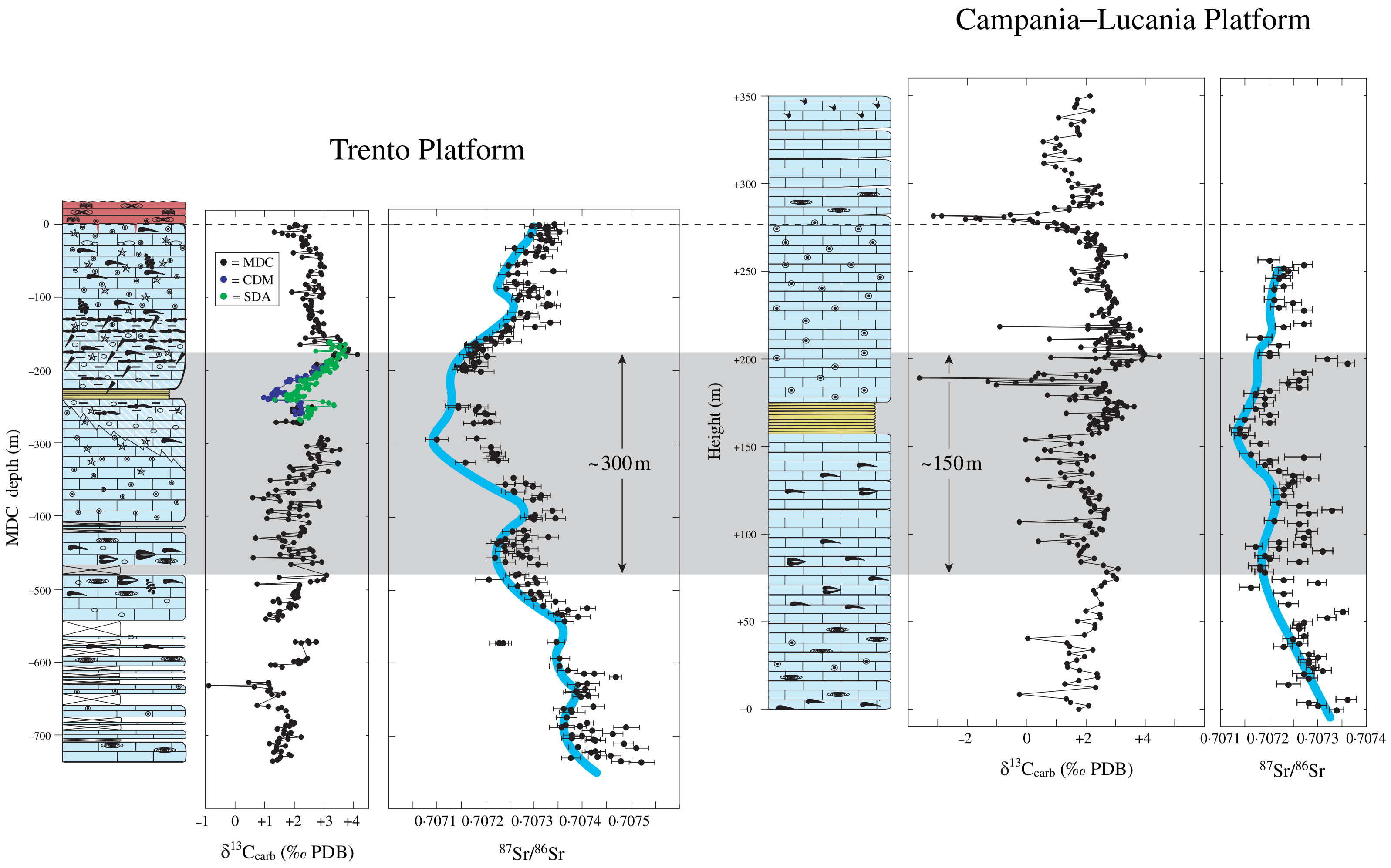

Fig. 6. Correlation between the Trento Platform and Campania–Lucania Platform (fault omitted) on the basis of comparative carbon-isotope and strontium-isotope stratigraphy. Data are unsmoothed. The correlation band represents stratigraphically unresolved portions of the Pliensbachian and Toarcian stages and indicates that, during this interval, the accumulation rate of carbonate on the Trento Platform was more than twice that of the Campania–Lucania Platform, implying greater subsidence of the former and hence greater propensity for drowning.

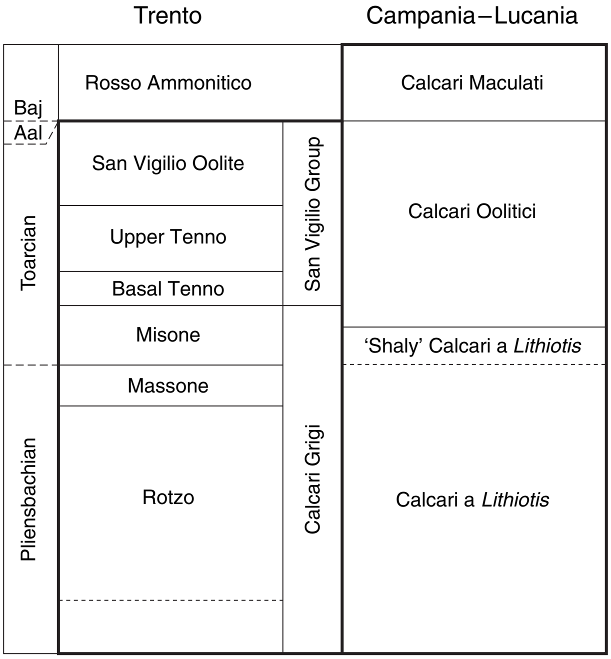

Fig. 7. Correlation of formations between the Trento and Campania–Lucania carbonate platforms based on chemostratigraphy.

in the latest *tenuicostatum* Zone and reached its nadir in the mid-*exaratum* Subzone of the *falciferum* Zone in northern and southern Europe. This abrupt negative excursion, which punctuates the rising $\delta^{13}C_{carb}$ isotope trend of the Trento and Campania–Lucania Platforms, has been attributed to the dissociation of gas hydrates (releasing methane, $\delta^{13}C$ approx. −60‰) and/or metamorphism of coals (releasing methane, $\delta^{13}C$ approx. −35 to −50‰) culminating in a sharp global temperature increase: a consequence of the greenhouse effect following the rapid oxidation of methane to carbon dioxide (Hesselbo *et al.*, 2000a,b; Jenkyns *et al.*, 2002; Jenkyns, 2003; McElwain *et al.*, 2005). However, mass input of CO_2 into the atmosphere from Karoo–Ferrar igneous activity is an alternative (or additional) mechanism for global warming (Pàlfy & Smith, 2000). If methane dissociation were ultimately responsible for the $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ negative excursions, evidence of associated pCO_2 and temperature increases would be expected. Evidence for pCO_2 increases derive from stomatal-index data from Danish fossil leaves (McElwain *et al.*, 2005; Hesselbo *et al.*, 2007). Evidence for temperature rise, based on high-resolution oxygen-isotope and Mg:Ca ratios in belemnites, is available from England, Germany and Spain. Taken together, these proxies indicate a temperature rise beginning in the latest *tenuicostatum* Zone and reaching a maximum in the Early to mid-*exaratum* Subzone and its stratigraphic equivalents (Bailey *et al.*, 2003; Jenkyns, 2003; Rosales *et al.*, 2004; van de Schootbrugge *et al.*, 2005b).

Previous authors have proposed that temperature increase has caused recent and ancient carbonate-platform crises (Jenkyns & Wilson, 1999; Glynn, 2000), and increased input of CO_2 into the ocean-atmosphere system may also be detrimental to shallow-marine carbonate factories because of an increase in the acidity of the ocean (Kleypas *et al.*, 1999; Gattuso & Buddemeier, 2000). Significantly, however, even with evidence of rises both in water temperature and nutrient levels during the OAE, the western sector of the platform did not drown, even though the facies changes suggest local deepening. Whether this deepening was related to a reduction in carbonate accumulation rates or reflects a regional, possibly eustatic, signal is not established, although an Early Toarcian transgression in many parts of Europe and elsewhere is well-documented (Hallam, 1981; Hesselbo & Jenkyns, 1998). In the eastern sector of the Trento Platform, however, the succession is somewhat different with shallow-water oolitic platform carbonates locally overlain by organic-rich black shales of Early Toarcian age that formed during the OAE (Dal Piaz, 1907; Della Bruna & Martire, 1985; Jenkyns *et al.*, 1985; Jenkyns, 1988). The overall succession, with the black shales passing laterally and vertically upwards into ammonite-bearing pelagic carbonates indicates that drowning took place close to Pliensbachian/Toarcian boundary time and may have been influenced by the OAE.

Additional factors, characteristic of the Early Toarcian OAE, may also have been significant in governing platform response. Geochemical proxies, such as Sr-isotope and Os-isotope ratios, show excursions to more radiogenic values, indicating an increase in continental weathering over the interval of the negative carbon-isotope excursion (Jenkyns, 2003; Cohen *et al.*, 2004). Accelerated fluvial flux would have carried increased nutrient loads to the oceans and stimulated organic productivity, as witnessed by deposition of the Lower Toarcian black shales in the Lombardian Basin and Belluno Trough lying to the west and east of the Trento Platform (Fig. 2; Jenkyns, 1988). Nitrogen-isotope data from the black shales in the Belluno Trough indicate nitrate reduction, suggesting that oxidation of falling organic matter locally depleted the water masses of oxygen (Jenkyns *et al.*, 2001); organic geochemical evidence indicates that at times this process advanced to sulphate reduction, liberating free hydrogen sulphide in the illuminated levels of the water column (Pancost *et al.*, 2004). Most probably, upwelling of nutrients was the proximate cause of the increased productivity that drove these chemical changes in the water column (Jenkyns *et al.*, 2001): nutrients that could have also impacted the carbonate platform in all but the shallowest (top few metres) levels of the water column.

There is a marked symmetry in the sequence of facies changes in the Toarcian section of the western Trento Platform from: (i) shallow-water oolitic carbonate; to (ii) thin-bedded cherty limestone; to (iii) calcareous shale; to (iv) thin-bedded cherty limestone; and back to (v) massive-bedded oolite (Fig. 4). This sequence of facies is mirrored in the $\delta^{13}C_{carb}$ record by (using inferred north European boreal zonation: Fig. 1) an initial (*tenuicostatum* Zone) increase, followed by a sharp decrease (*tenuicostatum–falciferum* Zone boundary) to reach a minimum in the mid-*exaratum* Subzone with a subsequent increase (Late *exaratum* Subzone) before a return to background carbon-isotope values. The initial rise in $\delta^{13}C_{carb}$ values over the latest *tenuicostatum* Zone of the Early Toarcian, seen regionally across Europe (Jenkyns & Clayton, 1997; Jenkyns *et al.*, 2001, 2002) and recording the onset of the OAE, is coincident with a change in facies, in the continuous exposure of the CDM section, from well-washed oolite to clay-rich limestone and limestone with sponge-derived cherts, recording an increase in abundance of filter-feeders reflecting mesotrophic–eutrophic shallow-marine conditions (Föllmi *et al.*, 1994). Following the pronounced negative $\delta^{13}C_{carb}$ excursion, the re-established increase in isotope values rising into the profile maximum is registered in the Trento Platform by a return to thin-bedded limestone with sponge-derived chert, signifying less extreme but still mesotrophic conditions. Given the evidence for increased nutrient availability during the Toarcian OAE in the basins lying either side of the Trento Platform, the development of mesotrophic and eutrophic conditions in shallow–water areas is not unexpected and must be one of the factors inhibiting biological carbonate secretion at this time (Hallock & Schlager, 1986; Hallock, 1988). Such effects were not confined to shallow-water environments: more open-marine sections record a 'crisis' in nannofossil abundance, linked to an increase in nutrient availability and dissolved carbon dioxide during the interval characterized by the negative carbon-isotope excursion (Erba, 2004; Tremolada *et al.*, 2005). By the latest *falciferum* Zone of the Toarcian, when temperature and nutrient levels had dropped to pre-excursion levels, the development of oolitic facies over much of the Trento Platform is interpreted as signifying oligotrophic conditions (Föllmi *et al.*, 1994). However, the fact that this oolitic facies (San Vigilio Oolite) is rich in crinoidal remains and locally contains nannofossil-bearing pelagic ooliths in its rose-coloured stratigraphically higher levels, as well as iron-manganese oxyhydroxide-encrusted hardgrounds, indicates a distinct open-marine influence and incipient drowning (Sturani, 1964; Jenkyns, 1971, 1972; Zempolich, 1993). Similar associations to these are documented between Cretaceous platform-carbonate and pelagic facies in many parts of the Alpine-Mediterranean domain (Weissert *et al.*, 1998; Graziano, 1999; Wissler *et al.*, 2003; Föllmi *et al.*, 2006).

THE IMPACT OF THE EARLY TOARCIAN OCEANIC ANOXIC EVENT ON THE CAMPANIA–LUCANIA CARBONATE PLATFORM

The facies changes coincident with the major Toarcian isotopic shifts were less dramatic on the Campania–Lucania Platform, at least as sampled in the section at MS: deposition of thinner bedded more clay-rich facies occurred in concert with rising $\delta^{13}C$ values that reflect increased global carbon burial at the onset of the OAE when nutrient levels probably began to increase (Jenkyns, 2003). Unlike the Trento Platform, however, this change preceded the abrupt negative carbon-isotope excursion (Fig. 5). Throughout the interval characterized by the pronounced negative followed by positive $\delta^{13}C$ excursions, oolite was continuously deposited, probably signifying oligotrophic conditions on the Campania–Lucania Platform at this time. Therefore, it appears that the Campania–Lucania Platform suffered few adverse consequences as a result of the Early Toarcian OAE and all of the global environmental stresses with which it was associated. A significant factor here may have been the relatively low subsidence rates, ensuring that depths remained so shallow throughout the duration of the OAE that inimical (i.e. nutrient-rich) waters could not encroach across the carbonate banks and oxygen levels remained high. Oceanic nutrient profiles generally increase abruptly below a surface minimum where organic productivity is the highest (Sverdrup *et al.*, 1942). If this interpretation is correct, it underscores the importance of subsidence rate as a key variable, in addition to palaeoceanographic change, in controlling the fate of carbonate platforms. Many Tethyan carbonate platforms disintegrated and drowned around Pliensbachian/Toarcian time and faulting and rapid subsidence commonly have been assumed to be major factors behind this regional phenomenon (Bernoulli & Jenkyns, 1974).

CONCLUSIONS

Detailed chemostratigraphic studies of two Jurassic Tethyan carbonate platforms in Italy illustrate contrasting behaviour during the Early Toarcian Oceanic Anoxic Event (OAE). The western sector of the Trento Platform in the Southern Alps of Northern Italy shows evidence for deepening and the development of more clay-rich cherty facies, suggestive of eutrophic conditions due to increased nutrient availability. There is also regional evidence for an increase in temperature over this interval that may also have proved inimical for certain skeletal carbonate producers. Although the platform recovered to some extent and did not drown definitely until Aalenian/Bajocian time, the oolitic and crinoidal facies that developed indicate a certain open-marine influence. By contrast, the carbonate platform in the Southern Apennines shows only minor facies changes recording the Early Toarcian OAE and these were registered only at its onset: during most of the OAE shallow-water oolitic sediments were deposited. A major difference in the two platforms is the reconstructed rate of subsidence during the Toarcian/Aalenian interval: 23 to 28 m Myr^{-1} for the Trento Platform versus 12 to 15 m Myr^{-1} for the Campania–Lucania Platform. The lesser subsidence rate in the case of the latter may have helped maintain environments as shallow as a few metres throughout the period of the OAE, hence shielding it from certain environmental factors that adversely affected the Trento Platform that ultimately led to its definitive drowning during the Aalenian.

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REFERENCES

Aberhan, M. and **Baumiller, T.K.** (2003) Selective extinction among Early Jurassic bivalves: a consequence of anoxia. *Geology*, **31,** 1077–1080.

Aberhan, M. and **Fürsich, F.T.** (1996) Diversity analysis of Lower Jurassic bivalves of the Andean Basin and Pliensbachian–Toarcian mass extinction. *Lethaia*, **29,** 181–195.

Allan, J.R. and **Matthews, R.K.** (1982) Isotope signatures associated with early meteoric diagenesis. *Sedimentology*, **29,** 797–817.

Bailey, T.R., Rosenthal, Y., McArthur, J.M., van de Schootbrugge, B. and **Thirlwall, M.F.** (2003) Paleoceanographic changes of the Late Pliensbachian–Early Toarcian interval: a possible link to the genesis of an Oceanic Anoxic Event. *Earth Planet. Sci. Lett.*, **212,** 307–320.

Banner, J.L. (1995) Application of the trace element and isotope geochemistry of strontium to studies of carbonate diagenesis. *Sedimentology*, **42,** 805–824.

Barbujani, C., Bosellini, A. and **Sarti, M.** (1986) L'oolite di San Vigilio nel Monte Baldo (Giurassico, Prealpi Venete). *Ann. Univ. Ferrara*, Sez. IX, **9,** 20–47.

Bernoulli, D. and **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* (Eds R.H. Dott and R.H. Shaver), *SEPM Spec. Publ.*, **19,** 129–160.

Bosellini, A. (1972) Paleoecologia dei Calcari a 'Lithiotis' (Giurassico inferiore, Prealpi Venete). *Riv. Ital. Paleontol. Stratigr.*, **78,** 441–466.

Bosellini, A. (1989) Dynamics of Tethyan carbonate platforms. In: *Controls on Carbonate Platform and Basin Development* (Eds P.D. Crevello, J.L. Wilson, J.F. Sarg and J.F. Read), *SEPM Spec. Publ.*, **44,** 3–13.

Bosellini, A. and **Broglio Loriga, C.** (1971) I 'Calcari Grigi' di Rotzo (Giurassico inferiore, Altopiano d'Asiago) e loro inquadramento nella paleogeografia e nella evoluzione tettono-sedimentaria delle Prealpi Venete. *Ann. Univ. Ferrara*, Sez. IX, **5,** 1–61.

Bosscher, H. and **Schlager, W.** (1993) Accumulation rates of carbonate platforms. *J. Geol.*, **101,** 345–355.

Bralower, T.J., Fullagar, P.D., Paull, C.K., Dwyer, G.S. and **Leckie, R.M.** (1997) Mid-Cretaceous strontium-isotope stratigraphy of deep-sea sections. *Geol. Soc. Am. Bull.*, **109,** 1421–1442.

Buonocunto, F.P., Sprovieri, M., Bellanca, A., D'Argenio, B., Ferreri, V., Neri, R. and **Ferruzza, G.** (2002) Cyclostratigraphy and high-frequency carbon isotope fluctuations in Upper Cretaceous shallow-water carbonates, southern Italy. *Sedimentology*, **49,** 1321–1337.

Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F. and **Otto, J.B.** (1982) Variation of seawater $\text{Sr}^{87}/\text{Sr}^{86}$ throughout Phanerozoic time. *Geology*, **10,** 516–519.

Castellarin, A. (1972) Evoluzione paleotettonica sinsedimentaria del limite tra 'Piattaforma Veneta' e 'Bacino Lombardo', a nord di Riva del Garda. *Giorn. Geol.*, ser. 2a, **38,** 11–212.

Catalano, R., **Channell, J.E.T.**, **D'Argenio, B.** and **Napoleone, G.** (1976) Mesozoic palaeogeography of the Southern Apennines and Sicily. *Mem. Soc. Geol. Ital.*, **15,** 95–118.

Channell, J.E.T., **D'Argenio, B.** and **Horváth, F.** (1979) Adria, the African Promontory, in Mesozoic Mediterranean palaeogeography. *Earth-Sci. Rev.*, **15,** 213–292.

Clari, P. and **Marelli, C.** (1983) I calcari oolitici di S. Vigilio nei Lessini settentrionali (Prov. Di Verona). *Riv. Ital. Paleontol. Stratigr.*, **88,** 443–476.

Cobianchi, M. and **Picotti, V.** (2001) Sedimentary and biological response to sea-level and palaeoceanographic changes of a Lower–Middle Jurassic Tethyan platform margin (Southern Alps, Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **169,** 219–244.

Cohen, A.S., **Coe, A.L.**, **Harding, S.M.** and **Schwark, L.** (2004) Osmium isotope evidence for the regulation of atmospheric CO_2 by continental weathering. *Geology*, **32,** 157–160.

Crowell, J.C. (1982) Continental glaciation through geologic time. In: *Climate in Earth History*, pp. 77–82. National Academy Press, Washington, DC.

D'Argenio, B. (1974) Le piattaforme carbonatiche periadriatiche. Una rassegna di problemi nel quadro geodinamico mesozoico dell'area mediterranea. *Mem. Soc. Geol. Ital.*, **13** (Suppl. 2), 137–159 (1977).

D'Argenio, B., **Radoičić, R.** and **Sgrosso, I.** (1971) A paleogeographic section through the Italo-Dinaric external zones during Jurassic and Cretaceous times. *Nafta, Zagreb*, **22,** 195–207.

D'Argenio, B., **De Castro, P.**, **Emiliani, C.** and **Simone, L.** (1975) Bahamian and Apenninic limestones of identical lithofacies and age. *AAPG Bull.*, **59,** 524–530.

Dal Piaz, G. (1907) Le Alpi Feltrine. *Mem. Reale. Ist. Veneto Sci. Lett. Arti*, **27/9,** 176 pp.

Damiani, A.V., **Catenacci, V.**, **Molinari, V.** and **Pichezzi, R.M.** (1991/2a) Lito-biofacies del Triassico Superiore-Dogger nei Monti Simbruini e nei Monti Ernici (Lazio). *Studi Geologici Camerti, vol. spec., Studi preliminari all acquisizione dati del profilo CROP 11*, 181–186.

Damiani, A.V., **Chiocchini, M.**, **Colacicchi, R.**, **Mariotti, G.**, **Parotto, M.**, **Passeri, L.** and **Praturlon, A.** (1991/2b) Elementi litostratigrafici per una sintesi delle facies carbonatiche Meso–Cenozoiche dell'Appennino Centrale. *Studi Geologici Camerti, vol. spec., Studi preliminari all acquisizione dati del profilo CROP 11*, 187–213.

Davey, S.D. and **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 Geol. Helv.*, **92,** 163–170.

Della Bruna, G. and **Martire, L.** (1985) La successione giurassica (Pliensbachiano–Kimmeridgiano) delle Alpi Feltrine (Belluno). *Riv. Ital. Paleontol. Stratigr.*, **91,** 15–61.

Dewey, J.F. and **Pitman, J.F.** (1998) Sea-level changes: mechanisms, magnitudes and rates. In: *Paleogeographic Evolution and Non-Glacial Eustasy, Northern South America* (Eds J.L. Pindell and C. Drake), *SEPM Spec. Publ.*, **58,** 1–16.

Emery, D., **Dickson, J.A.D.** and **Smalley, P.C.** (1987) The strontium isotopic composition and origin of burial cements in the Lincolnshire Limestone (Bajocian) of central Lincolnshire, England. *Sedimentology*, **34,** 795–806.

Erba, E. (2004) Calcareous nannofossils and Mesozoic oceanic anoxic events. *Mar. Micropaleontol.*, **52,** 85–106.

Ferreri, V., **Weissert, H.**, **D'Argenio, B.** and **Buonocunto, F.P.** (1997) Carbon isotope stratigraphy: a tool for basin to carbonate platform correlation. *Terra Nova*, **9,** 57–61.

Föllmi, K.B., **Weissert, H.**, **Bisping, M.** and **Funk, H.** (1994) Phosphogenesis, carbon-isotope stratigraphy, and carbonate-platform evolution along the Lower Cretaceous northern Tethyan margin. *Geol. Soc. Am. Bull.*, **106,** 729–746.

Föllmi, K.B., **Godet, A.**, **Bodin, S.** and **Linder, P.** (2006) Interactions between environmental change and shallow water carbonate buildup along the northern Tethyan margin and their impact on the Early Cretaceous carbon isotope record. *Paleoceanography*, **21,** doi: 10.1029/2006PA001313.

Frakes, L.A., **Francis, J.E.** and **Syktus, J.I.** (1992) *Climate Modes of the Phanerozoic*. Cambridge University Press, Cambridge, 274 pp.

Gaetani, M. (1975) Jurassic stratigraphy of the Southern Alps; a review. In: *Geology of Italy, I* (Ed. C.H. Squyres), pp. 377–402. Earth Sciences Society of the Libyan Arab Republic, Tripoli, Libya.

Gattuso, J.P. and **Buddemeier, R.W.** (2000) Ocean biogeochemistry: calcification and CO_2. *Nature*, **407,** 311–313.

Geyer, O.F., **Gohner, D.** and **Krautter, M.** (1986) Die obertriassiche bis alttertiäre Schichtfolge der Trento–Schwelle (Südalpen) unter besonderer Berücksichtigung jurassicher Formationen (Exkursion H am 4. und 5. April 1986). *Jber. Mitt. Oberrhein. geol. Ver., N. F.*, **68,** 129–176.

Glynn, P.W. (2000) El Niño-Southern Oscillation mass mortalities of reef corals: a model of high temperature marine extinctions. In: *Carbonate Platform Systems: Components and Interactions* (Eds E. Insalaco, P.W. Skelton and T.J. Palmer), *Geol. Soc. London Spec. Publ.*, **178,** 117–133.

Gradstein, F.M., **Ogg, J.G.** and **Smith, A.G.** (Eds) (2004) *A Geologic Time Scale 2004*. Cambridge University Press, Cambridge, 589 pp.

Graziano, R. (1999) The Early Cretaceous drowning unconformities of the Apulia carbonate platform (Gargano Promontory, southern Italy): local fingerprints of global palaeoceanographic events. *Terra Nova*, **11,** 245–250.

Gröcke, D., **Hesselbo, S.P.** and **Findlay, D.J.** (2007) Atypical diagenetic effects on strontium-isotope composition of Early Jurassic belemnites, Queen Charlotte Islands, British Columbia, Canada. *Can. J. Earth Sci.*, **44,** 181–197.

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

Hallam, A. (1981) A revised sea-level curve for the Early Jurassic. *J. Geol. Soc. London*, **138,** 735–743.

Hallam, A. (1986) The Pliensbachian and Tithonian extinction events. *Nature*, **308,** 686–687.

Hallam, A. (1992) *Phanerozoic Sea-Level Changes*. Columbia University Press, New York, 266 pp.

Hallock, P. (1988) The role of nutrient availability in bioerosion: consequences to carbonate buildups. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **63,** 275–291.

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

Hesselbo, S.P. and **Jenkyns, H.C.** (1998) British Lower Jurassic sequence stratigraphy. In: *Mesozoic–Cenozoic Sequence Stratigraphy of European Basins* (Eds P.-C. de Graciansky, J. Hardenbol, T. Jacquin, M. Farley and P.R. Vail), *SEPM Spec. Publ.*, **60,** 561–581.

Hesselbo, S.P., **Gröcke, D.R.**, **Jenkyns, H.C.**, **Bjerrum, C.J.**, **Farrimond, P.**, **Morgans Bell, H.S.** and **Green, O.R.** (2000a) Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event. *Nature*, **406,** 392–395.

Hesselbo, S.P., Meister, C. and **Gröcke, D.R.** (2000b) A potential global stratotype for the Sinemurian–Pliensbachian boundary (Lower Jurassic), Robin Hood's Bay, UK: ammonite faunas and isotope stratigraphy. *Geol. Mag.*, **137**, 601–607.

Hesselbo, S.P., Morgans Bell, H.S., McElwain, J.C., Rees, P.M., Robinson, S. and **Ross, C.E.** (2003) Carbon-cycle perturbation in the Middle Jurassic and accompanying changes in the terrestrial paleoenvironment. *J. Geol.*, **111**, 259–276.

Hesselbo, S.P., Jenkyns, H.C., Duarte, L.V. and **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 Planet. Sci. Lett.*, **253**, 455–470.

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

Immenhauser, A. (2005) High-rate sea-level change during the Mesozoic: new approaches to an old problem. *Sed. Geol.*, **175**, 277–296.

Immenhauser, A., della Porta, G., Kenter, J.A.M. and **Bahamonde, J.R.** (2003) An alternative model for positive shifts in shallow-marine carbonate δ^{13}C and δ^{18}O. *Sedimentology*, **50**, 953–959.

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

Jenkyns, H.C. (1972) Pelagic 'oolites' from the Tethyan Jurassic. *J. Geol.*, **80**, 21–33.

Jenkyns, H.C. (1985) The Early Toarcian and Cenomanian–Turonian anoxic events in Europe: comparisons and contrasts. *Geol. Rundschau*, **74**, 505–518.

Jenkyns, H.C. (1988) The early Toarcian (Jurassic) anoxic event: stratigraphic, sedimentary, and geochemical evidence. *Am. J. Sci.*, **288**, 101–151.

Jenkyns, H.C. (1991) Impact of Cretaceous sea-level rise and anoxic events on the Mesozoic carbonate platform of Yugoslavia. *AAPG Bull.*, **75**, 1007–1017.

Jenkyns, H.C. (1995) Carbon-isotope stratigraphy and paleoceanographic significance of the Lower Cretaceous shallow-water carbonates of Resolution Guyot, Mid-Pacific Mountains. In: *Proceedings of the Ocean Drilling Program, Scientific Results* (Eds E.L. Winterer, W.W. Sager, J.V. Firth and J.M. Sinton), College Station, Texas, **143**, 99–104.

Jenkyns, H.C. (2003) Evidence for rapid climate change in the Mesozoic–Palaeogene greenhouse world. *Phil. Trans. Roy. Soc. London, Ser. A*, **361**, 1885–1916.

Jenkyns, H.C. and **Clayton, C.J.** (1986) Black shales and carbon isotopes in pelagic sediments from the Tethyan Lower Jurassic. *Sedimentology*, **33**, 87–106.

Jenkyns, H.C. and **Clayton, C.J.** (1997) Lower Jurassic epicontinental carbonates and mudstones from England and Wales: chemostratigraphic signals and the early Toarcian anoxic event. *Sedimentology*, **44**, 687–706.

Jenkyns, H.C. and **Wilson, P.A.** (1999) Stratigraphy, paleoceanography, and evolution of Cretaceous Pacific guyots: relics from a greenhouse earth. *Am. J. Sci.*, **299**, 341–392.

Jenkyns, H.C., Sarti, M., Masetti, D. and **Howarth, M.K.** (1985) Ammonites and stratigraphy of lower Jurassic black shales and pelagic limestones from the Belluno Trough, Southern Alps, Italy. *Eclogae Geol. Helv.*, **78**, 299–311.

Jenkyns, H.C., Paull, C.K., Cummins, D. and **Fullagar, P.D.** (1995) Strontium-isotope stratigraphy of Cretaceous atoll carbonates in the Mid-Pacific Mountains. In: *Proceedings of the Ocean Drilling Program, Scientific Results* (Eds E.L. Winterer, W.W. Sager, J.V. Firth and J.M Sinton), College Station, Texas, **143**, 89–97.

Jenkyns, H.C., Gröcke, D.R. and **Hesselbo, S.P.** (2001) Nitrogen isotope evidence for water mass denitrification during the early Toarcian (Jurassic) oceanic anoxic event. *Paleoceanography*, **16**, 1–11.

Jenkyns, H.C., Jones, C.E., Gröcke, D.R., Hesselbo, S.P. and **Parkinson, D.N.** (2002) Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. *J. Geol. Soc. London*, **159**, 351–378.

Jenkyns, H.C., Forster, A., Schouten, S. and **Sinninghe Damsté, J.S.** (2004) High temperatures in the Late Cretaceous Arctic Ocean. *Nature*, **432**, 888–892.

Jones, C.E. and **Jenkyns, H.C.** (2001) Seawater strontium isotopes, oceanic anoxic events, and seafloor hydrothermal activity in the Jurassic and Cretaceous. *Am. J. Sci.*, **301**, 112–149.

Jones, C.E., Jenkyns, H.C. and **Hesselbo, S.P.** (1994) Strontium isotopes in early Jurassic seawater. *Geochim. Cosmochim. Acta*, **58**, 1285–1301.

Kemp, D.B., Coe, A.L., Cohen, A.S. and **Schwark, L.** (2005) Astronomical pacing of methane release in the Early Jurassic period. *Nature*, **437**, 396–399.

Kleypas, J.A., Buddemmeier, R.W., Archer, D., Gattuso, J.-P., Langdon, C. and **Opdyke, B.N.** (1999) Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science*, **284**, 118–120.

Krautter, M. (1987) 'Massone-Oolith' und 'Giallo di Mori' im Unterjura der Trento-Plattform (Südalpen). *Neues Jb. Geol. Paläontol. Monat.*, **1987**, 204–212.

Küspert, W. (1982) Environmental changes during oil shale deposition as deduced from stable-isotope ratios. In: *Cyclic and Event Stratification* (Eds G. Einsele and A. Seilacher), pp. 482–501. Springer-Verlag, Berlin/Heidelberg.

Little, C.T.S. and **Benton, M.J.** (1995) Early Jurassic mass extinction: a global long-term event. *Geology*, **23**, 495–498.

Marshall, J.D. (1992) Climatic and oceanographic signals from the carbonate rock record and their preservation. *Geol. Mag.*, **129**, 143–160.

Masetti, D. (1998) I Calcari Grigi della Piattaforma di Trento (Lias Inferiore e medio, Prealpi venete). *Atti. Ticinesi Sci. Terra*, **40**, 139–183.

Masse, J.P., El Albani, A. and **Erlenkeuser, H.** (1999) Isotope stratigraphy (δ^{13}C) of the lower Aptian from Provence (SE France): application to platform/basin correlations. *Eclogae Geol. Helv.*, **92**, 259–263.

McArthur, J.M., Donovan, D.T., Thirlwall, M.F., Fouke, B.W. and **Mattey, D.** (2000) Strontium isotope profile of the early Toarcian (Jurassic) oceanic anoxic event, the duration of ammonite biozones, and belemnite palaeotemperatures. *Earth Planet. Sci. Lett.*, **179**, 269–285.

McElwain, J.C., Wade-Murphy, J. and **Hesselbo, S.P.** (2005) Changes in carbon dioxide during an oceanic anoxic event linked to intrusion into Gondwana coals. *Nature*, **435**, 479–482.

Morettini, E., Santantonio, M., Bartolini, A., Cecca, F., Baumgartner, P.O. and **Hunziger, J.C.** (2002) Carbon isotope stratigraphy and carbonate production during the Early–Middle Jurassic: examples from the Umbria–Marche–Sabina Apennines (central Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **184**, 251–273.

Moriya, K., Wilson, P.A., Friedrich, O., Erbacher, J. and **Kawahata, H.** (2007) Testing for ice sheets during the mid-Cretaceous greenhouse using glassy foraminiferal calcite from the mid-Cenomanian tropics on Demerera Rise. *Geology*, **35**, 615–618.

O'Dogherty, L., **Sandoval, J.**, **Bartolini, A.**, **Bruchez, S.**, **Bill, M.** and **Guex, J.** (2006) Carbon-isotope stratigraphy and ammonite faunal turnover for the Middle Jurassic in the Southern Iberian palaeomargin. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **239,** 311–333.

Pàlfy, J. and **Smith, P.L.** (2000) Synchrony between Early Jurassic extinction, oceanic anoxic event, and the Karoo–Ferrar flood basalt volcanism. *Geology*, **28,** 747–750.

Pàlfy, J., **Smith, P.L.** and **Mortensen, J.K.** (2000) A U–Pb and ^{40}Ar/^{39}Ar time scale for the Jurassic. *Can. J. Earth Sci.*, **37,** 923–944.

Pancost, R.D., **Crawford, N.**, **Magness, S.**, **Turner, A.**, **Jenkyns, H.C.** and **Maxwell, J.R.** (2004) Further evidence for the development of photic-zone euxinic conditions during Mesozoic Oceanic Anoxic Events. *J. Geol. Soc. London*, **161,** 353–364.

Parente, M., **Frijia, G.** and **di Lucia, M.** (2007) Carbon-isotope stratigraphy of Cenomanian–Turonian platform carbonates from the Southern Apennines (Italy): a chemostratigraphic approach to the problem of correlation between shallow-water and deep-water successions. *J. Geol. Soc. London*, **164,** 353–364.

Patterson, W.P. and **Walter, L.M.** (1994) Depletion of ^{13}C in seawater ΣCO_2 on modern carbonate platforms: significance for the carbon isotopic record of carbonates. *Geology*, **22,** 885–888.

Picotti, V. and **Cobianchi, M.** (1996) Jurassic periplatform sequences of the eastern Lombardian Basin (Southern Alps): the deep-sea record of the tectonic evolution, growth and demise history of a carbonate platform. *Mem. Sci. Geol., Padova*, **48,** 171–219.

Rosales, I., **Robles, S.** and **Quesada, S.** (2004) Elemental and oxygen isotope composition of early Jurassic belemnites: salinity vs. temperature signals. *J. Sed. Res.*, **74,** 342–354.

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

Sarti, M., **Bosellini, A.** and **Winterer, E.L.** (1992) Basin geometry and architecture of a Tethyan passive margin, Southern Alps, Italy: implications for rifting mechanisms. In: *Geology and Geophysics of Continental Margins* (Ed. J.S. Watkins, F. Zhiqiang and K.T. McMillen), *AAPG Mem.*, **53,** 241–258.

Sartoni, S. and **Crescenti, U.** (1962) Ricerche biostratigrafiche nel Mesozoico dell'Appennino meridionale. *Giornale di Geologia*, ser. 2a, **29,** 161–302.

Schlager, W. (1981) The paradox of drowned reefs and carbonate platforms. *Geol Soc. Am. Bull.*, **92,** 1197–1211.

Schlager, W. (1989) Drowning unconformities on carbonate platforms. In: *Controls on Carbonate Platform and Basin Development* (Ed. P.D. Crevello), *SEPM Spec. Publ.*, **44,** 15–25.

Schlager, W. (1999) Scaling of sedimentation rates and drowning of reefs and carbonate platforms. *Geology*, **27,** 183–186.

Schlanger, S.O. (1986) High frequency sea-level fluctuations in Cretaceous time: an emerging geophysical problem. In: *Mesozoic and Cenozoic Oceans* (Ed. K.J. Hsü), *Am. Geophys. Union/Geol. Soc. Am. Geodynam. Ser.*, **15,** 61–74.

van de Schootbrugge, B., **McArthur, J.M.**, **Bailey, T.R.**, **Rosenthal, Y.**, **Wright, J.D.** and **Miller, K.G.** (2005a) Toarcian oceanic anoxic event: an assessment of global causes using belemnite C isotope records. *Paleoceanography*, **20,** PA3008, doi: 10.1029/2004PA001102.

van de Schootbrugge, B., **McArthur, J.M.**, **Bailey, T.R.**, **Rosenthal, Y.**, **Katz, M.**, **Wright, J.D.**, **Miller, K.G.**, **Feist-Burkhardt, S.** and **Falkowski, P.G.** (2005b) Early Jurassic climate change and the radiation of organic-walled phytoplankton in the Tethys Ocean. *Paleobiology*, **31,** 73–97.

Smith, A.G., **Smith, D.G.** and **Funnell, B.M.** (1994) *Atlas of Mesozoic and Cenozoic Coastlines*. Cambridge University Press, Cambridge, 99 pp.

Stanley, S.M. and **Hardie, L.A.** (1998) Secular oscillations in the carbonate mineralogy of reef-building and sediment-producing organisms driven by tectonically forced shifts in seawater chemistry. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **144,** 3–19.

Sturani, C. (1964) La successione delle fauna ad ammoniti nelle formazioni mediogiurassiche delle Prealpi Venete Occidentali. *Mem. Ist. Geol. Min. Univ. Padova*, **24,** 1–63.

Sturani, C. (1971) Ammonites and stratigraphy of the 'Posidonia alpina' beds of the Venetian Alps. *Mem. Ist. Geol. Min. Univ. Padova*, **28,** 1–188.

Sverdrup, H.U., **Johnson, M.W.** and **Fleming, R.H.** (1942) *The Oceans: Their Physics, Chemistry, and General Biology*. Prentice Hall, Englewood Cliffs, NJ, 1087 pp.

Swart, P.K. and **Eberli, G.** (2005) The nature of the δ^{13}C of periplatform sediments: Implications for stratigraphy and the global carbon cycle. *Sed. Geol.*, **175,** 115–129.

Tremolada, F., **van de Schootbrugge, B.** and **Erba, E.** (2005) Early Jurassic schizosphaerellid crisis in Cantabria, Spain: implications for calcification rates and phytoplankton evolution across the Toarcian oceanic anoxic event. *Paleoceanography*, **20,** PA2011, doi: 10.1029/2004PA001120.

Vahrenkamp, V.C. (1996) Carbon isotope stratigraphy of the Upper Kharaib and Shaiba Formations: implications for the Early Cretaceous evolution of the Arabian Gulf region. *AAPG Bull.*, **80,** 647–662.

Violante, C. (2000) Flooding unconformities at Lias–Dogger boundary in carbonate platform deposits. Aurunci Mountains, Central Apennines (Italy). In: *Riassunti delle Comunicazioni orali e dei poster* (Eds G.B. Carulli and G. Longo Salvador), pp. 464–466. 80^{a} Reunione estiva della Società Geologica Italiana, Trieste.

Weissert, H., **Lini, A.**, **Föllmi, K.B.** and **Kuhn, O.** (1998) Correlation of Early Cretaceous carbon isotope stratigraphy and platform drowning events: a possible link? *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **137,** 189–203.

Wilson, P.A., **Jenkyns, H.C.**, **Elderfield, H.** and **Larson, R.L.** (1998) The paradox of drowned carbonate platforms and the origin of Cretaceous Pacific Guyots. *Nature*, **392,** 889–894.

Winterer, E.L. and **Bosellini, A.** (1981) Subsidence and sedimentation on Jurassic passive continental margin, Southern Alps, Italy. *AAPG Bull.*, **65,** 394–421.

Wissler, L., **Funk, H.** and **Weissert, H.** (2003) Response of Early Cretaceous carbonate platforms to changes in atmospheric carbon dioxide levels. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **200,** 187–205.

Wood, A.W. (1981) Extensional tectonics and the birth of the Lagonegro Basin (southern Italian Apennines). *Neues Jb. Geol. Paläont., Abh.*, **161,** 93–131.

Zempolich, W.G. (1993) The drowning succession in Jurassic carbonates of the Venetian Alps, Italy: a record of supercontinent breakup, gradual eustatic rise, and eutrophication of shallow-water environments. In: *Carbonate Sequence Stratigraphy – Recent Developments and Applications* (Eds R.G. Loucks and J.F. Sarg), *AAPG Mem.*, **57,** 63–105.

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