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Middle and Late Jurassic carbon stable-isotope stratigraphy and radiolarite sedimentation of the Umbria-Marche Basin (Central Italy)

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Key words: Middle-Late Jurassic, carbon stable-isotope stratigraphy, radiolarites, carbonate platforms, paleoclimate, Umbria-Marche-Sabina Apennines

ABSTRACT

A continuous carbon isotope curve from Middle-Upper Jurassic pelagic carbonate rocks was acquired from two sections in the southern part of the Umbria-Marche Apennines in central Italy. At the Colle Bertone section (Terni) and the Terminilletto section (Rieti), the Upper Toarcian to Bajocian Calcari e Marne a Posidonia Formation and the Aalenian to Kimmeridgian Calcari e Marne a Posidonia and Calcari Diasprigni formations were sampled, respectively. Biostratigraphy in both sections is based on rich assemblages of calcareous nannofossils and radiolarians, as well as some ammonites found in the upper Toarcian-Bajocian interval. Both sections revealed a relative minimum of $\delta^{13}C_{PDB}$ close to + 2‰ in the Aalenian and a maximum around 3.5 ‰ in early Bajocian, associated with an increase in visible chert. In basinal sections in Umbria-Marche, this interval includes the very cherty base of the Calcari Diasprigni Formation (e.g. at Valdorbia) or the chert-rich uppermost portion of the Calcari a Posidonia (e.g at Bosso). In the Terminilletto section, the Bajocian-early Bathonian interval shows a gradual decrease in $\delta^{13}C_{PDB}$ values and a low around 2.3‰. This part of the section is characterised by more than 40 m of almost chert-free limestones and correlates with a recurrence of limestone-rich facies in basinal sections at Valdorbia. A double peak with values of $\delta^{13}C_{PDB}$ around + 3‰ was observed in the Callovian and Oxfordian, constrained by well preserved radiolarian faunas. The maxima lie in the Callovian and the middle Oxfordian, and the minimum between the two peaks should be near the Callovian/Oxfordian boundary. In the Terminilletto section, visible chert increases together with $\delta^{13}C_{PDB}$ values from the middle Bathonian and reaches peak values in the Callovian-Oxfordian. In basinal sections in Umbria-Marche, a sharp increase in visible chert is observed at this level within the Calcari Diasprigni. A drop of $\delta^{13}C$ values towards + 2‰ occurs in the Kimmeridgian and coincides with a decrease of visible chert in outcrop.

The observed $\delta^{13}C$ positive anomalies during the early Bajocian and the Callovian-Oxfordian may record changes in global climate towards warmer, more humid periods characterised by increased nutrient mobilisation and increased carbon burial. High biosiliceous (radiolarians, siliceous sponges) productivity and preservation appear to coincide with the $\delta^{13}C$ positive anomalies, when the production of platform carbonates was subdued and ceased in many areas, with a drastic reduction of periplatform ooze input in many Tethyan basins.

The carbon and silica cycles appear to be linked through global warming and increased continental weathering. Hydrothermal events related to extensive rifting and/or accelerated oceanic spreading may be the endogenic driving force that created a perturbation of the exogenic system (excess CO_2 into the atmosphere and greenhouse conditions) reflected by the positive $\delta^{13}C$ shifts and biosiliceous episodes.

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RESUME

Nous présentons pour la première fois une stratigraphie continue des isotopes stables du carbone du Jurassique moyen et supérieur, basée sur des mesures de carbonates de la Téthys méditerranéenne.

Le Jurassique de l'Apennin sud-oriental de l'Ombrie-Marche-Sabina est caractérisé par l'abondance de resédiments carbonatés pendant tout l'interval biosiliceux téthysien. Cette région était proche de la plateforme de Lazio-Abruzzi, située paléogéographiquement au sud du bassin de l'Ombrie-Marche-Sabina. Les séries du Jurassique moyen-supérieur sont caractérisées par des calcaires à silex interstratifiés avec des resédiments de plateforme sous forme de «mass flows», turbidites fines et surtout de la boue carbonatée «periplateforme». Ces séries se sont révelées particulièrement utiles à la stratigraphie intégrée à l'aide de nannofossiles, radiolaires, ammonites et isotopes stables.

Des analyses d'isotopes du carbone et de l'oxygène ont été effectuées dans la coupe de Colle Bertone (M. Lacerona, Terni), dans la formation des Calcari e Marne a Posidonia (Toarcien – Bajocien) et dans la coupe du Terminilletto (M. Terminillo, Rieti) dans les formations des Calcari e Marne a Posidonia et des Calcari Diasprigni (Aalenien – Kimmérdgien). Les datations biostratigraphiques sont basées sur des riches faunes à nannofossiles et radiolaires, ainsi que quelques ammonites du Toarcien supérieur, de l'Aalenien et du Bajocien.

Les deux coupes étudiées ont montré un minimum relatif du $\delta^{13}C_{PDB}$ d'environ + 2‰ dans l'Aalénien et un maximum d'environ + 3.5‰ dans le Bajocien inférieur. Ce maximum est accompagné d'une augmentation de la silice biogène, visible sous forme de silex dans la coupe. Dans le bassin, ce maximum est biostratigraphiquement correlé avec le début des Calcari Diasprigni à Valdorbia et avec la partie supérieure des Calcari a Posidonia, très siliceuse, à Bosso. Le Bajocien supérieur – Bathonien inférieur du Terminilletto montre une diminution graduelle des valeurs $\delta^{13}C_{PDB}$ et un minimum de + 2.3‰. Cet interval est représenté par plus de 40 m pratiquement dépourvu de silex.

Un double maximum de $\delta^{13}C_{PDB}$ autour de + 3‰ a été mesuré dans le Callovien – Oxfordien, daté par des faunes à radiolaires bien préservées. Un premier maximum se situerait dans le Callovien moyen, un minimum proche de la limite Callovo-Oxfordienne et un deuxième maximum serait daté de l'Oxfordien moyen. A Terminilletto, les silex augmentent ensemble avec les valeurs de $\delta^{13}C_{PDB}$ depuis le Bathonien moyen et sont dominants dans le Callovo-Oxfordien. Dans le bassin les faciès les plus siliceux sont également datés du Bathonien moyen-supérieur. Les valeurs de $\delta^{13}C_{PDB}$ commencent à diminuer dès le Kimméridgien ensemble avec les silex pour arriver à +2‰.

Les maxima observés de $\delta^{13}C_{PDB}$ du Bajocien inférieur et du Callovien – Oxfordien se corrèlent avec des montées eustatiques du niveau marin et enregistreraient donc des changements climatiques globaux vers des époques plus chaudes et humides. Ces époques était charactérisées par une mobilisation accrue de nutriments ayant pour conséquence finale un enfuissement de carbone organique accrue, ce qui se traduit par des valeurs plus positives de $\delta^{13}C_{PDB}$ enregistrées dans les sédiments. La mobilisation de nutriments aurait conduit à une eutrophisation modérée des bassins téthysiens qui a causé une haute productivité et une bonne préservation des organismes siliceux (radiolaires, éponges siliceuses). En même temps la productivité des plateformes carbonatées a sensiblement diminué, voire cessé dans beaucoup de domaines. Le Bajocien est une époque privilégiée du début des radiolarites suite à une réduction drastique de l'apport de boue «periplateforme» dans beaucoup de bassins téthysiens.

Les cycles du carbone et de la silice semblent liées par les processus climatiques du rechauffement et d'une altération continentale accrue, ce qui aurait provoqué un cyclage plus élevé à la fois du carbone et de la silice. Nous pensons que des processus endogéniques soyent à l'origine des fluctuations observées: l'augmentation des taux de dérive océanique et du rifting aurait introduit un excès de CO_2 et de silice dans le système exogène provoquant ainsi un processus de régulation par des méchanismes de «feedback». Cette régulation aurait ramené le système exogène à des conditions proche des initiales.

1. Introduction

Our incentive to study the stable isotope stratigraphy of the Middle-Late Jurassic is twofold. (1) A detailed, continuous and biostratigraphically calibrated carbon isotope record could potentially serve as a tool for global correlation (Scholle & Arthur 1980; Jenkyns et al. 1994). (2) Independent geochemical data pertaining to Jurassic paleoenvironments is needed to understand the onset and the wide distribution of radiolarites in the Tethyan realm and elsewhere.

Carbon-isotopic variation has been linked to changes in ocean structure, productivity and ultimately to the concentrations of greenhouse gases in the atmosphere (Kroopnick et al. 1977; Arthur 1982; Arthur et al. 1985; Berner et al. 1983; Berner & Lasaga 1989; Berner 1990; Lasaga et al. 1985; Shackleton & Pisias 1985; Berger & Vincent 1986; Delaney 1989; Weissert & Bréhéret 1991; Arthur et al. 1991; Kerrick & Caldeira 1993 and many others). Positive carbon-isotope events reflect perturbations in the global carbon cycle and generally coincide with stratigraphic evidence for increased organic carbon burial (Schlanger et al. 1987; Arthur et al. 1985; Arthur et al. 1990). Since organic carbon is preferentially enriched in the lighter isotope ^{12}C, its removal from the oceanic reservoir and escape from oxidative recycling renders ocean waters relatively enriched in ^{13}C (Scholle & Arthur 1980). In recent years, the carbon isotope stratigraphy of the Lower Cretaceous for low latitudes has been refined (Weissert 1989; Weisssert & Lini 1991; Lini et al. 1992; Channell et al. 1993). The Late Valanginian positive $\delta^{13}C$ event has been postulated to be due to accelerated carbon cycling triggered by elevated atmospheric CO_2 levels coupled with a warm and humid climate (Weissert & Lini 1991; Lini et al. 1992). These episodes of greenhouse climate conditions may be related to increased CO_2 emissions caused by extensive volcanic activity (see Larson 1991a, b). Enhanced continental

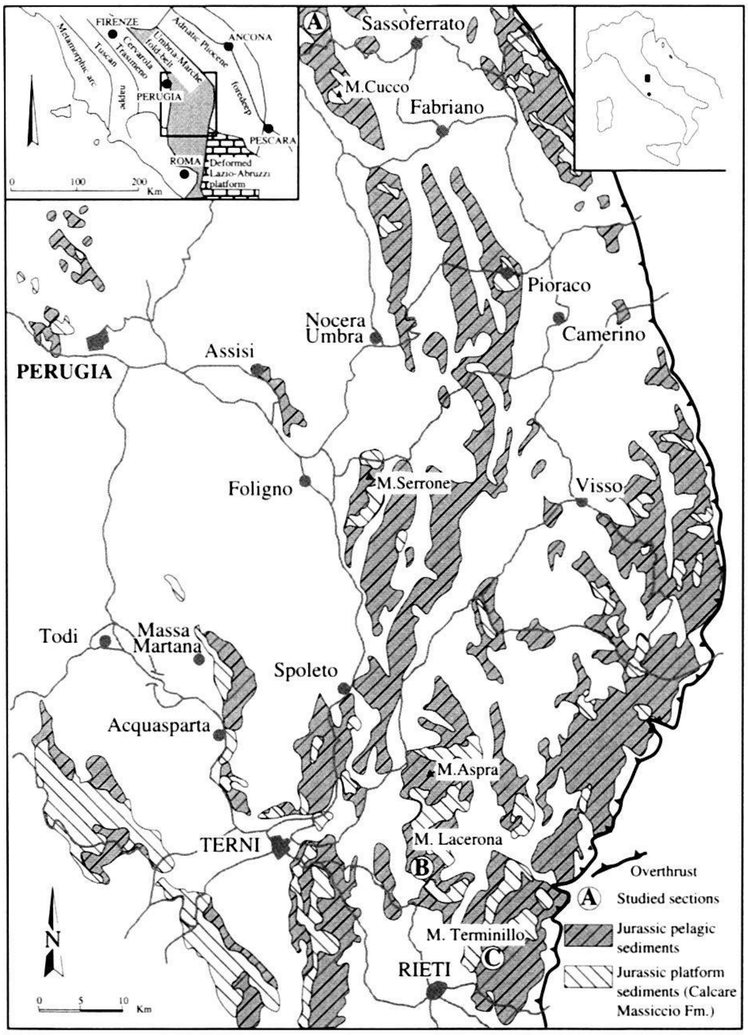


Fig. 1. Simplified geological map of the Umbria-Marche-Sabina Apennines with locations of sections A = Valdorbia; B = Colle Bertone; C = Terminilletto.

weathering and increased runoff may have led to elevated transfer rates of nutrients to the oceans, favouring primary productivity and increasing rates of biological carbon burial in marine sediments. Jenkyns (1985, 1988), Jenkyns & Clayton (1986) and Jenkyns et al. (1991) investigated black shales and carbon isotopes in pelagic sediments from the Tethyan Lower Jurassic. The positive carbon anomaly of the Early Toarcian was attributed to an "oceanic anoxic event", correlating to an Early Toarcian transgression (Hallam 1981), high productivity and the production of an extensive oxygen-minimum zone in both epicontinental and oceanic environments. No continuous carbon-isotope curve for the Middle-Late Jurassic is available. The Bajocian-Kimmeridgian interval of the Alpine-Mediterranean area is generally very siliceous in basinal settings and condensed or absent on submerged structural highs. Weissert & Channell (1989) produced a $\delta^{13}C$ curve of the Upper Jurassic (Kimmeridgian-Tithonian) from Southern Alpine sections. Corbin (1994) studied the Middle Jurassic of the Digne area (Southern France). Bill et al. (1995) and Weissert & Mohr (in press) have studied the Oxfordian from the Helvetic nappes and the Swiss Jura. Jenkyns (in press) has analysed pelagic limestones, ranging from Callovian to Oxfordian in age, from the sections of Chabrières (southern France), Camposilvano and Roverè Veronese (north Italy).

In the Mesozoic basins of Western Tethys the onset of radiolarite sedimentation is diachronous, varying from Late Triassic to Late Jurassic in age (Baumgartner 1984; De Weaver 1989; Gorican 1994). Previously, increased subsidence was seen as the cause of the "drowning" of carbonate platforms and the onset of siliceous sedimentation. Radiolarites were considered as a solution-resistant sediment that accumulated wherever the seafloor dropped below the calcite compensation depth (Garrison & Fischer 1969; Bosellini & Winterer 1975; Hsü 1976; Kälin et al. 1979; Winterer & Bosellini 1981; Jenkyns & Winterer 1982). Radiolarian biostratigraphy and basin-platform correlation in the Western Tethys clearly shows that the onset of radiolarites is controlled by productivity and paleogeography (Baumgartner 1987; Baumgartner 1990; Gorican 1994). Predominantly siliceous sedimentation in the Western Tethys can occur at any time since the middle Triassic in areas connected to an open ocean (Neotethys), provided the basin was sheltered or away from carbonate input from the neighbouring platforms.

For the combined objectives of carbon isotope stratigraphy and the understanding of radiolarites we have chosen an area that is „sensitive“ to monitor the changes in carbonate versus biosiliceous sedimentation. The South-Eastern sector of the Umbria-Marche-Sabina Apennines (Fig. 1) was close to the Lazio-Abruzzi Carbonate Platform. The Middle-Upper Jurassic is characterised by thick, continuous pelagic sections with cherty limestones and abundant platform-derived resediments that occur both as coarse mass flow deposits, fine turbidites, and as periplatform ooze. Well preserved radiolarians occur throughout, allowing for an integrated biostratigraphy by mean of radiolarians, nannofossils and ammonites (Tonielli 1991; Bartolini 1995; Mattioli 1995; Bartolini et al. 1995).

2. Geological Setting

During the Mesozoic, the Umbria-Marche-Sabina (UMS) Basin of Central Italy (Fig.1) was part of the southern continental margin of the Western Tethyan Seaway. During the early Liassic, a large carbonate shelf in this region broke up and drowned due to the com-

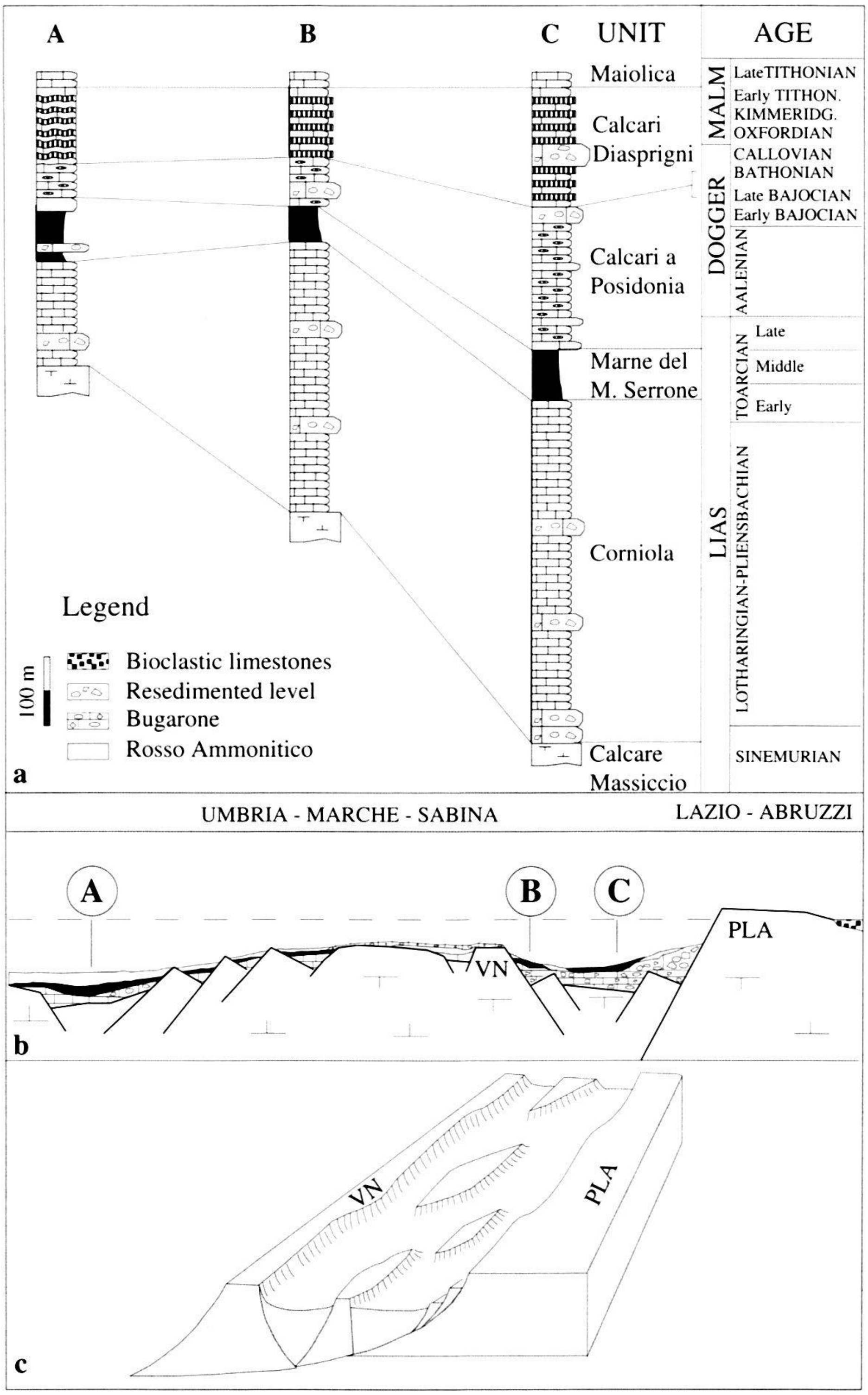


Fig. 2. (a) Simplified columnar sections and (b) paleogeographic transect of the Umbria-Marche-Sabina (UMS) Basin and the adjacent Lazio-Abruzzi (PLA) Platform. (A = Valdorbia, B = Colle Bertone, C = Terminilletto). The studied sections Colle Bertone and Terminilletto are located close to the area that represented the margin between the UMS Basin and the PLA Platform. This area was characterised by abundant carbonate resediment input from the platform, resulting in thicker and more calcareous sections than those out in the basin.
(c) Schematic block model of the Lazio-Abruzzi Platform (PLA), and the proximal UMS Basin, The Valnerina Line (VN) formed a structural high during the Jurassic rifting (after Lavecchia 1985).

bination of ecological factors and intensified extensional tectonics related to continental rifting (Colacicchi et al. 1970; Colacicchi et al. 1988; Alvarez 1989; Bice & Stewart 1990; Santantonio 1993). By the late Sinemurian, shallow-water sediments were replaced by pelagic and resedimented facies. Throughout the Jurassic, shallow water carbonate sedimentation persisted to the south of the UMS basin, in the adjacent Lazio-Abruzzi (LA) carbonate shelf.

The studied sections (Colle Bertone and Monte Terminilletto) crop out in the southern part of the UMS Apennines (Fig. 1). These sections were located proximal to the adjacent Lazio-Abruzzi platform, and therefore received abundant carbonate resediments from the platform (Fig. 2). For this reason, the studied successions are more calcareous than those from the central part of the Umbria-Marche Basin, such as Valdorbia and Bosso (McBride & Folk 1979; Baumgartner 1984, 1987, 1990; Cresta et al. 1988; Monaco et al. 1994). As calcareous plankton was scarce throughout most of the Middle Jurassic, periplatform ooze (Schlager et al. 1976; Schlager & James 1978; Schlager & Chermak 1979) probably constituted the main limestone component present in the basinal sections in the Calcari e Marne a Posidonia and part of the Calcari Diasprigni formations. Sedimentation rates are high through the Early Middle Jurassic and become greatly reduced during the late Middle and Late Jurassic, probably due to a reduced input of periplatform ooze. At Colle Bertone and Terminilletto, the succession is well developed and continuous from the Corniola Formation (lower-middle Lias) to the Maiolica Formation (late Tithonian). The Calcari e Marne a Posidonia are a well-bedded limestone with local chert in nodules or ribbons and common levels of posidoniid bivalves. The Calcari Diasprigni are characterised by cherty limestones and interbedded cherts (Cresta et al. 1988).

Both sections are rich in calcareous nannofossils and radiolarians, and sporadic ammonite-bearing horizons have also been found (Bartolini et al. 1995). The nannofossil biostratigraphy is from Mattioli (1995) (Pl. 1, 2).

3. Colle Bertone Section

The Colle Bertone section (Fig. 3, Pl. 1) crops out on the south-western flank of Monte La Pelosa, along an unpaved track branching off the Polino-Colle Bertone road, shortly after the Fountain of Acquaviva. As resedimented lithologies are mainly intraformational, the Colle Bertone section was probably located in an area protected from direct platform input. Periplatform ooze, however, must have greatly diluted the autochthonous planktonic sedimentation. In the present study we only deal with the Calcari e Marne a Posidonia comprising pale brown-whitish micritic limestones, rich in posidonid remains and radiolarians. Centimetric greenish marly intercalations are also present. Bedding thickness ranges between 20 and 30 cm in the lower portion (0.00 m–43.00 m) and become thinner, from 15 cm to 30 cm, in the upper portion (43.00 m–69.00 m). In the interval from 0.00 m to 43.00 m grey chert is found discontinuously as ribbons and nodules. Most chert replaces carbonate and chert ribbons are often found within resedimented beds. In the interval from 43.00 m to 69.00 m grey-white chert is found regularly in ribbons ranging from few to ~20 cm in thickness. Chert contains abundant and locally well-preserved radiolarians and represents original radiolarian sand layers (radiolarites). Chert becomes red from 64.35 m. Both intraformational pebbly mudstones and graded and laminated calciturbidites occur. Calciturbidites are characterised by posidoniid-echi-

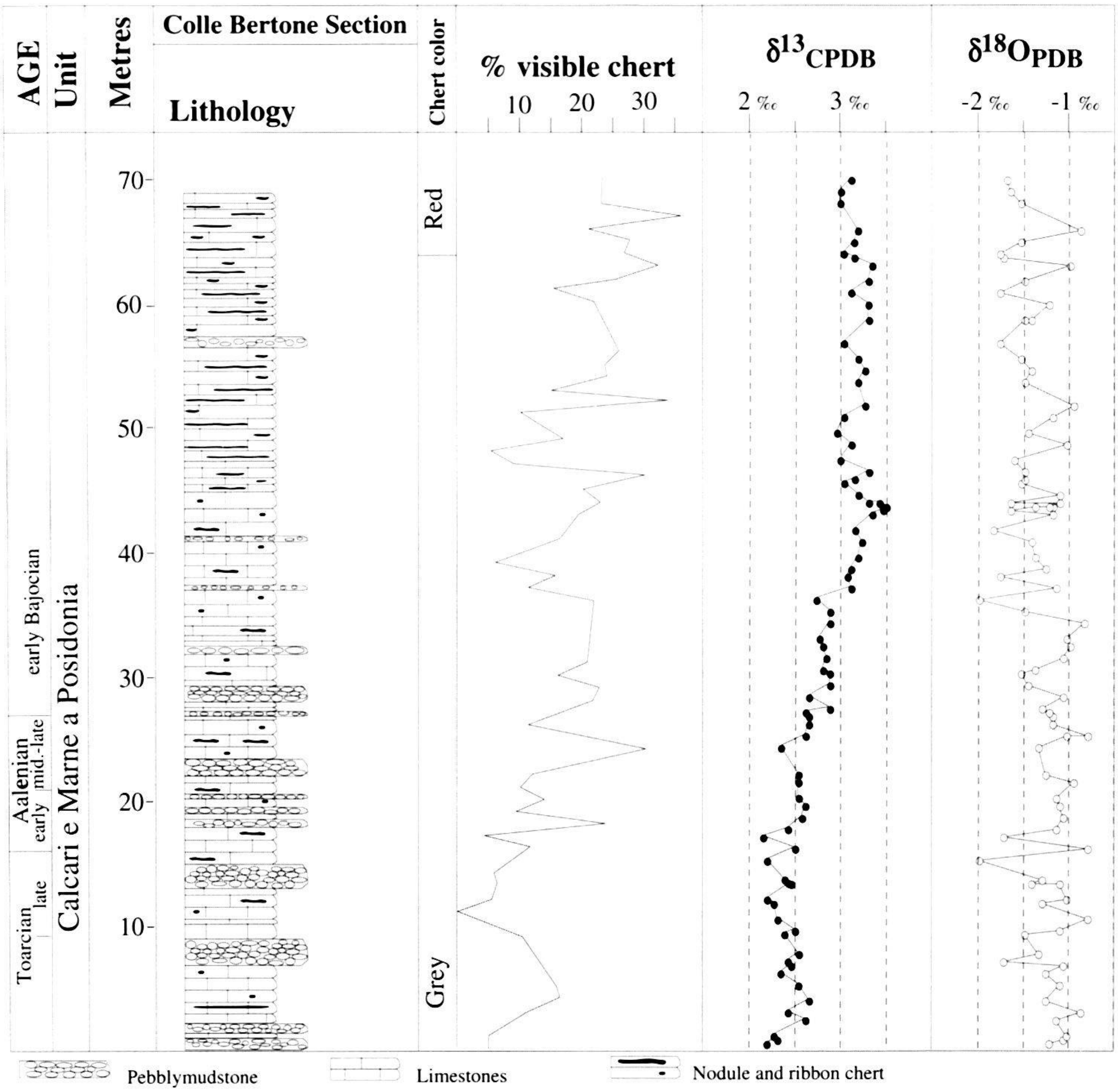


Fig. 3. Summary log of the Colle Bertone section. Lithology, visible chert percentage curve, $\delta^{13}C$ and $\delta^{18}O$ curves of bulk carbonates are simplified. For more details on lithology, sample locations, sample numbers and biostratigraphy see Plate 1.

noderm packstones that show normal grading, parallel and low-angle cross-laminations. Pebbly mudstones are largely composed of intraplasts and intraclasts of micritic limestones rich in echinoderm and posidoniid fragments. Upsection, calciturbidites and pebbly mudstones occur only sporadically.

4. Terminilletto section

The section (Fig. 4, Pl. 2) is exposed along the E-SE side of Monte Terminilletto (Terminillo Group) and its base crops out along the road that leads from Terminillo to Campoforogna and to Sella di Leonessa. During the Jurassic Terminillo area was close to a nor-

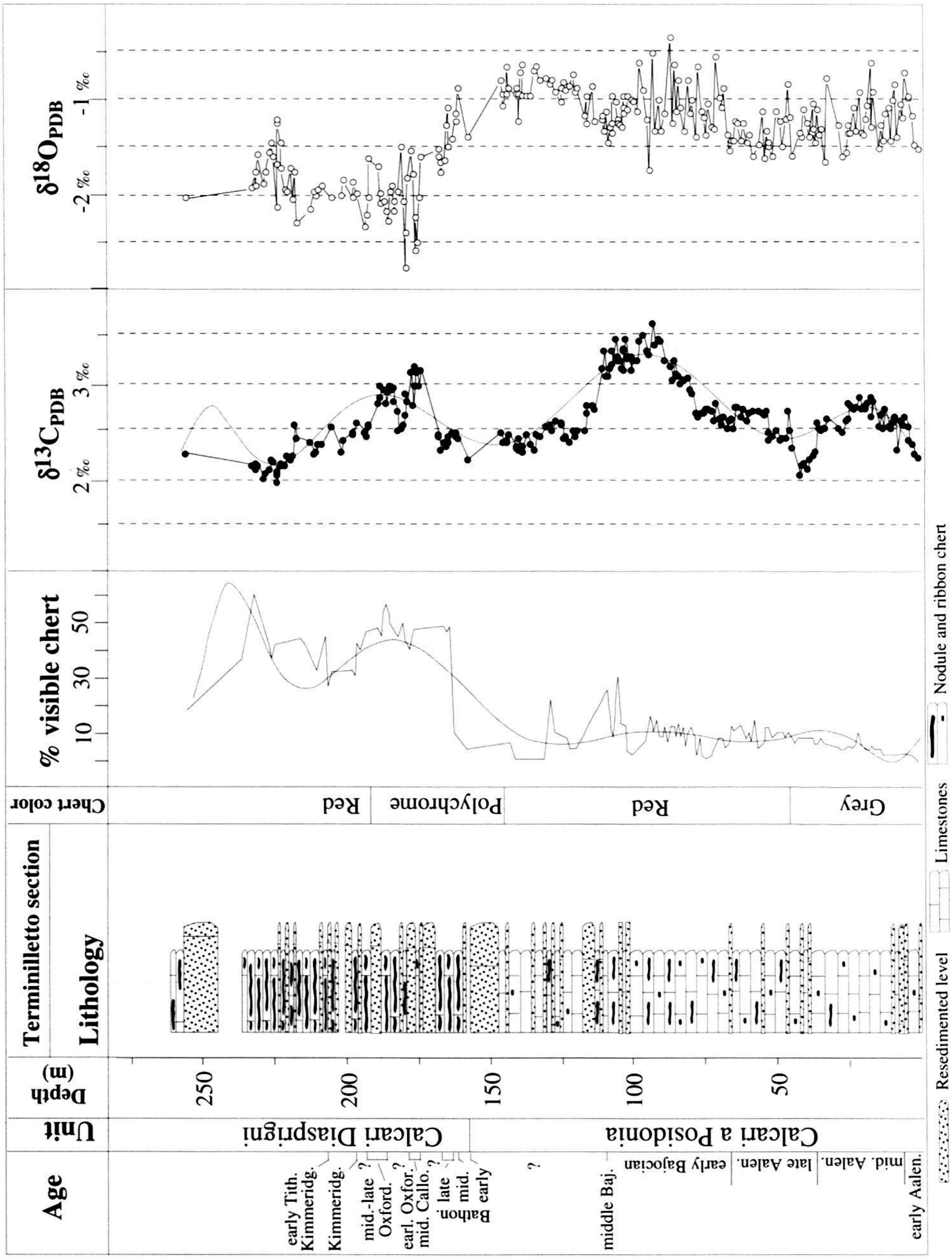


Fig. 4. Summary log of the Terminilletto section. Lithology, visible chert percentage curve, $\delta^{13}C$ and $\delta^{18}O$ curves of bulk carbonates are simplified. For more details on lithology, sample locations, sample numbers and biostratigraphy see Plate 2. The visible chert percentage and $\delta^{13}C$ polynomial regression curves are in phase. In addition to the fluctuations, an upwards increase of visible chert % throughout the Middle Jurassic was observed. Note a sharp increase at about 163 m (middle Bathonian) and a decrease around 225 m (upper Kimmeridgian/lower Tithonian).

mal fault trending N-S, that divided the UMS basin from the Lazio-Abruzzi (LA) carbonate platform (Castellarin et al. 1978; Cantelli et al. 1982; Castellarin et al. 1984). Abundant carbonate resediments derived from the platform occur therefore in the Jurassic sections of this area. The data presented in this paper were obtained from the Calcari e Marne a Posidonia (0.00 m–160 m, upper Toarcian-Bajocian) and the Calcari Diasprigni (160 m–256 m, Bajocian/early Tithonian).

The interval from 0.00 m to 40.00 m (upper Toarcian/middle Aalenian) mainly comprises medium bedded (10 to 20 cm) pale brown micritic limestones, showing mudstones and wackestones with posidoniids. Laminated wackestones and mudstones occur in cycles of about 30 cm thickness. Platform resediments consist of 20–30 cm thick intercalations of oolitic grainstones with parallel and cross laminations and 40–90 cm thick pebbly mudstones. White chert is sporadically present (visible chert 0–5%) in small nodules (2–3 cm in diameter). The interval from 40.00 m to 110 m (middle Aalenian to lower Bajocian) is mainly comprised of mudstones and resedimented beds that decrease in abundance up section. Bed thickness varies around 5 cm. The visible chert content tends to increase to 10–15%, and occurs as nodules and thin, laterally continuous ribbons. Up section from 45 m, chert becomes red. From 100 m upwards, resedimented oolitic grainstones, partially replaced by chert, occur. From 110 m to 160 m (lower Bajocian middle Bathonian) resedimented beds are frequent. Bioclastic packstones-grainstones with dominant echinoderm fragments alternate with fine calcarenites to mudstones-wackestones bearing posidonid shells. Fining-upward cycles can be observed. Chert tends to become sporadic and disappears completely between 130 m and 160 m. From 160 m to 168 m (middle Bathonian) the lower portion of the Calcari Diasprigni is mainly constituted by thin beds (~4–10 cm) of whitish radiolarian mudstones with abundant red chert (30–40%) in irregular nodules and ribbons. Sporadic levels of detritic oolitic white chert of 16–18 cm thickness are found. The interval from 168 m to 196 m (middle Bathonian/ Upper Oxfordian) mainly comprises micritic limestones and greenish, thinly stratified (2–8 cm) and laminated cherty limestones, rich in radiolarians, rhythmically alternating with varicoloured, but dominantly green, ribbon chert (40–50% visible chert). Horizons bearing radiolarian and spicule sands are also present. Resedimented beds of 3–5 m thickness constituted by ooids, crinoids and shelf-derived bioclasts are frequent. Levels of white chert replacing oolites are present. From 196 m to 256 m (Upper Oxfordian/Kimmeridgian), the sediments are mainly composed of whitish radiolarian-rich micritic limestones and fine pale brown calcarenites arranged in thin beds (8–10 cm in thickness) bearing ribbons and nodules of red chert. Up to 236 m, chert is abundant (40–50%), while up section (254.50 m) a decrease in chert content to 18–26% is evident. Resedimented beds are mainly oolitic up to 220 m, and tend to become bioclastic further on. A large shelf resedimented lens-shaped body of about 18 metres of thickness occurs at 224.8 m.

5. Stratigraphic distribution of visible chert

Rock names such as "cherty limestone" or "radiolarite" only qualitatively represent sediment compositions and are inadequate for a paleoceanographic interpretation of pelagic sequences. In soft sediments, semiquantitative sediment compositions are usually obtained from smear slide studies (e.g. ODP practice). In orogenic belts, lithification and burial diagenesis have enhanced lithologic contrasts to the extent that it is difficult to estimate long term shifts in sediment composition based on individual samples.

However, in pelagic sequences, the carbonate/silica ratio of the sediments certainly bears an important paleoceanographic signal (Jenkyns & Winterer 1982). In order to overcome bed-to-bed diagenetic variation, E.L. Winterer (oral communication) developed a semiquantitative field technique to estimate the percentage of visible chert. A metre stick is placed on the section and the number of centimetres of visible chert crossed by the stick is noted for every metre of the section. This method has been used to produce the plots of Plate 1 and Plate 2, Figure 3 and Figure 4.

This method does not account for finely dispersed silica in limestones or shales. The actual bulk silica content of metre-intervals of section is certainly higher by 10% or more than the % of visible chert. Significant amounts of clay in the section may have partially or totally hindered the formation of macroscopically visible chert. Therefore, this method is only useful to show fluctuations of chert content over several metres of section, if the overall clay content is low.

The % of visible chert is thought to be indicative of the evolution of silica/carbonate ratios of an individual section, which is controlled by productivity and sedimentation processes, as well as by dissolution and diagenesis.

6. Stable-isotope stratigraphy

All stable-isotopic analysis were carried on bulk carbonate samples. Previous work has proven the usefulness of bulk carbonate analysis in fine-grained and homogenous rocks (Scholle & Arthur 1980; Anderson & Arthur 1983; Weissert 1989). Only micritic lime-mudstones and wackestones have been sampled, the sampling points being carefully selected in the field and in the laboratory to avoid material containing stylolites and calcite veins. We sampled the sections at intervals of about one metre or less, when the lithology permitted. Bulk carbonate samples of the Aalenian-Bathonian samples are composed mainly of periplatform ooze, while the Callovian-Kimmeridgian interval yields increasing calcareous nannofossil percentage. In some levels calcareous nannofossils become the predominant constituent of limestone (Mattioli 1995). The penecontemporaneous downslope displacement of periplatform ooze should not have affected the long term fluctuations of the carbon isotope values. Platform-derived ooze reaches mineralogical stability in the first few metres of burial (Marshall 1992). The early diagenetic products, therefore, should record average "marine" isotopic signals close to those of the original platform ooze.

The samples were prepared following the conventional procedure of McCrea (1950). We analyzed CO_2 released from a 15 hour reaction between powdered bulk samples and 100% phosphoric acid at 25 °C. A H_3PO_4–$CaCO_3$ fractionation factor of 1.01025 at 25 °C (Sharma & Clayton, 1965) was used. The $\delta^{13}C$ and the $\delta^{18}O$ composition of the released CO_2 gas was analysed on a Finnigan MAT 251 spectrometer. The results are reported in the usual per mil δ-notation relative to the PDB (Pee Dee Belemnite) international isotopic standard. In the isotope laboratory at the University of Lausanne, calibration to PDB is performed by Carrara marble versus NSB19 standard. Replicate analysis of selected samples showed a reproducibility of 0.05 per mil for $\delta^{13}C$ and better than 0.1 per mil for $\delta^{18}O$.

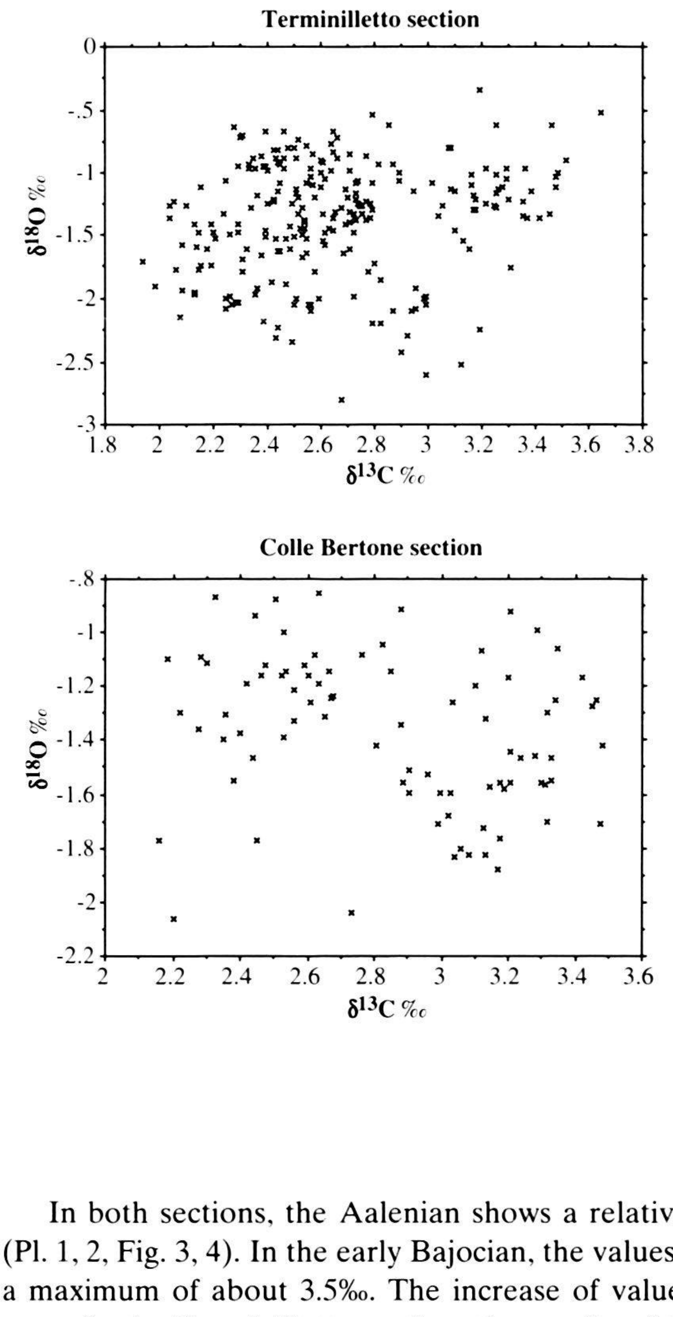


Fig. 5. $\delta^{13}C$ versus $\delta^{18}O$ scatter diagrams of the Terminilletto section and the Colle Bertone section. Data show no covariance, suggesting that the C-isotopic composition of the analysed sediments has not been altered significantly by burial diagenesis.

In both sections, the Aalenian shows a relative minimum of $\delta^{13}C_{PDB}$ close to + 2‰ (Pl. 1, 2, Fig. 3, 4). In the early Bajocian, the values of $\delta^{13}C_{PDB}$ gradually increase towards a maximum of about 3.5‰. The increase of values starts in the *Laeviuscula* ammonite zone. In the Terminilletto section, the results of the Upper-Middle and Upper Jurassic intervall shows a gradual decrease of the $\delta^{13}C_{PDB}$ values in the upper part of the lower Bajocian and a minimum of 2.3‰ in the upper Bajocian/lower Bathonian. A small variation can be discerned in the middle Bathonian, then two distinct peaks around + 3‰ follow in the Callovian and in the middle Oxfordian. The minimum between the two peaks should be near the Callovian/Oxfordian boundary. Small perturbations are present in the upper Oxfordian and lower Kimmeridgian and a drop towards + 2‰ follows during the Kimmeridgian.

$\delta^{18}O_{PDB}$ values are scattered (± 0.5‰), and show no covariance with $\delta^{13}C_{PDB}$ (Fig. 5). The lack of covariance of $\delta^{13}C_{PDB}$ and $\delta^{18}O_{PDB}$ suggests that the C-isotopic composition of the analysed sediments has not been altered significantly by burial diagenesis (Jenkyns & Clayton 1986).

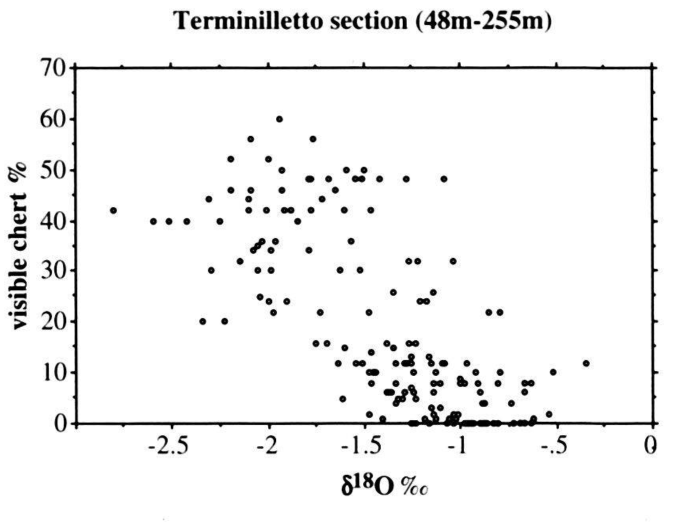


Fig. 6. $\delta^{18}O$ versus visible chert percentage scatter diagram of the Terminilletto section. Note the rough negative covariance between the values. For discussion see text.

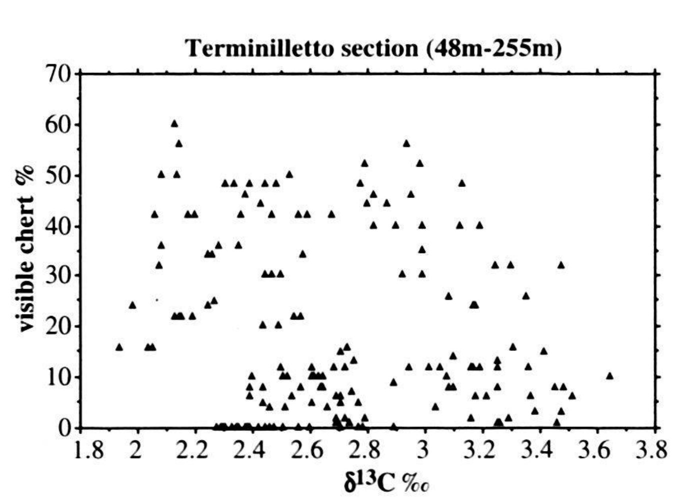
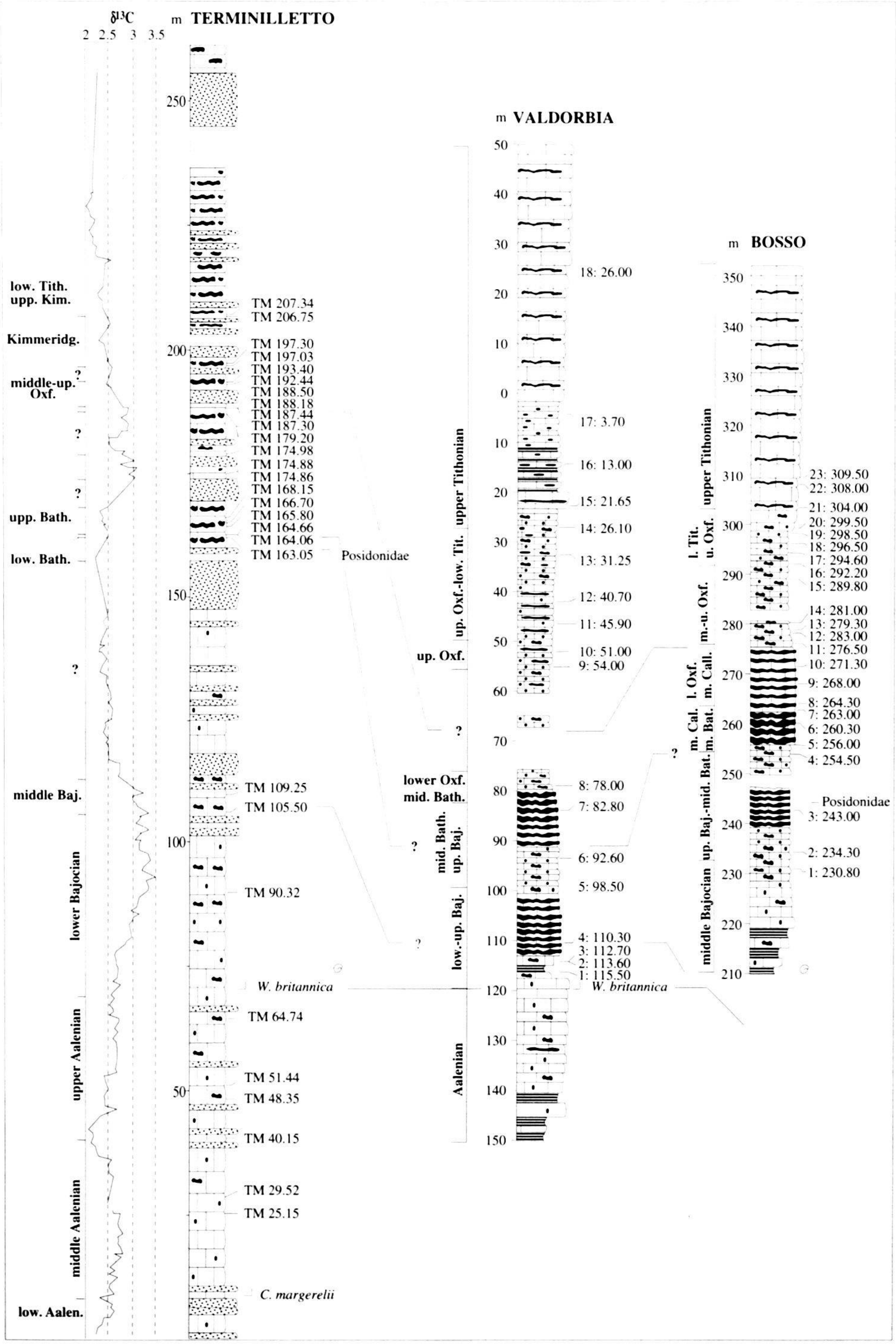


Fig. 7. $\delta^{13}C$ versus visible chert percentage scatter diagram of the Terminilletto section. The values show no covariance indicating that $\delta^{13}C$-values are not affected by the silica diagenesis.

The $\delta^{18}O_{PDB}$ curve of the Terminilletto section presents a negative shift at 163 m (middle Bathonian) with a decrease from ~ –1.6‰ to ~ –2.0‰. This change in $\delta^{18}O$ coincides with a marked lithological change towards more cherty limestones (Calcari Diasprigni Formation) with a sharp increase of visible chert (Fig. 4). Plotted on a $\delta^{18}O$-visible chert % graph, $\delta^{18}O$ values and percentage of visible chert show a negative covariance (Fig. 6). This means that $\delta^{18}O$ values of limestones are more negative in the presence of abundant chert.

Fig. 8. Correlation of the $\delta^{13}C$ curve of Terminilletto section with the lithological changes in the basinal sections. The correlation is based on radiolarians, calcareous nannofossils and ammonites (Bartolini et al. 1995; INTERRAD Jurassic-Cretaceous Working Group 1995). The numbers to the right of the logs indicate the radiolarian samples. The lower Bajocian carbon positive shift is correlated with the very cherty base of Calcari Diasprigni in the Valdorbia section and with an increase in visible chert within the Calcari a Posidonia seen in the Terminilletto and Bosso sections. The Callovian and Oxfordian carbon positive shifts are associated with an increase in visible chert within the Calcari Diasprigni at Terminilletto and Bosso sections.


δ13C
2 2.5 3 3.5
m TERMINILLETTO
low. Tith. upp. Kim.
Kimmeridg.
middle-up. Oxf.
upp. Bath.
low. Bath.
middle Baj.
lower Bajocian
upper Aalenian
middle Aalenian
low. Aalen.
TM 207.34
TM 206.75
TM 197.30
TM 197.03
TM 193.40
TM 192.44
TM 188.50
TM 188.18
TM 187.44
TM 187.30
TM 179.20
TM 174.98
TM 174.88
TM 174.86
TM 168.15
TM 166.70
TM 165.80
TM 164.66
TM 164.06
TM 163.05
Posidonidae
TM 109.25
TM 105.50
TM 90.32
W. britannica
TM 64.74
TM 51.44
TM 48.35
TM 40.15
TM 29.52
TM 25.15
C. margerelii
m VALDORBIA
upper Tithonian
up. Oxf.-low. Tit.
up. Oxf.
lower Oxf. mid. Bath.
mid. Bath. up. Baj.
low.-up. Baj.
Aalenian
18: 26.00
17: 3.70
16: 13.00
15: 21.65
14: 26.10
13: 31.25
12: 40.70
11: 45.90
10: 51.00
9: 54.00
8: 78.00
7: 82.80
6: 92.60
5: 98.50
4: 110.30
3: 112.70
2: 113.60
1: 115.50
W. britannica
m BOSSO
upper Tithonian
l. Tit. u. Oxf.
m.-u. Oxf.
l. Oxf. m. Call.
m. Cal. m. Bat.
up. Baj.-mid. Bat.
middle Bajocian
23: 309.50
22: 308.00
21: 304.00
20: 299.50
19: 298.50
18: 296.50
17: 294.60
16: 292.20
15: 289.80
14: 281.00
13: 279.30
12: 283.00
11: 276.50
10: 271.30
9: 268.00
8: 264.30
7: 263.00
6: 260.30
5: 256.00
4: 254.50
Posidonidae
3: 243.00
2: 234.30
1: 230.80

7. $\delta^{13}C$ values and visible chert percentages

If we plot $\delta^{13}C$ values against visible chert percentages for metre-intervals of the Terminilletto section no covariance is seen (Fig. 7). This suggests that $\delta^{13}C$ values are not influenced by the silica diagenesis, although positive fluctuations of $\delta^{13}C$ are accompanied by a general increase of visible chert (Fig. 8). $\delta^{13}C$ and the visible chert % curves (confidence interval from 90 to 95%, selected regression order of 9) are in phase. The early Bajocian, the Bathonian, the Callovian and the Oxfordian positive $\delta^{13}C$ shifts are all accompanied by positive fluctuations of visible chert %. The actual values of % visible chert are not comparable between shifts, because they are controlled by sedimentation processes (e. g. the rate of input of periplatform ooze and platform resediments) rather than silica productivity alone. Radiolarian biostratigraphy has allowed us to correlate fluctuations of the carbonate/silica ratio observed at Terminilletto to other sections of the UMS Basin (Fig. 8). The early Bajocian $\delta^{13}C$ peak is related to an increase of visible chert in the Calcari e Marne a Posidonia of Terminilletto section, which biostratigraphically correlates with the chert-rich uppermost portion of the Calcari e Marne a Posidonia of the Bosso section (Baumgartner 1984, 1987a, 1990), and to the very cherty base of the Calcari Diasprigni Formation of the Valdorbia section (McBride & Folk 1979; Baumgartner 1984, 1987, 1990). The Bajocian/early Bathonian interval produced low $\delta^{13}C$ values around 2.3‰. At Terminilletto this part of the sequence is characterised by more than 40 m of almost chert-free limestones. In basinal sections a recurrence of limestone-rich facies is observed at Valdorbia in the Calcari Diasprigni Formation. In the Terminilletto section visible chert increases together with $\delta^{13}C$ values from the middle Bathonian and reaches peak values in the Callovian-Oxfordian. In basinal sections a sharp increase in visible chert can be observed within the Calcari Diasprigni. At Bosso section it is roughly dated as mid-Bathonian/early Callovian and at Valdorbia it is constrained to the middle-late Bathonian by radiolarian biostratigraphy (Baumgartner 1990; INTERRAD Jurassic Working Group 1995).

8. Interpretation of oxygen-isotope record

The oxygen-isotope record of Mesozoic sediments is always suspect and is probably influenced by diagenesis as the ratio of oxygen in pore waters to oxygen in carbonate sediment is high, unlike the situation with carbon isotopes. In addition, burial diagenesis at elevated temperatures and the influence of meteoric-water can add isotopically light cement during late diagenesis. The presence of biogenic silica also seems to alter the oxygen-isotope record. Our data from the Terminilletto section (Fig. 6) clearly show a lowering of $\delta^{18}O$-values in the presence of abundant chert. Brennecke (1977) pointed out the same phenomenon after studying the isotopic composition of Jurassic and Cretaceous limestones of DSDP site 367, where nodular chert is associated with carbonates depleted in ^{18}O. Lighter $\delta^{18}O$ values in chert-rich carbonates are reported from the Valdorbia and Fonte Avellana sections (Umbria-Marche) (Hadji 1991), where a positive shift in $\delta^{18}O$ coincides with the passage from chert-rich (Calcari Diasprigni) to chert-poor (Scisti ad Aptici and Maiolica) lithologies.

Lawrence (1973) suggested that the alteration of biogenic silica to chert may be important in lowering the $^{18}O/^{16}O$ ratio of the pore waters. According to Brenneke (1977) current theories regarding chert formation can not explain the lighter $^{18}O/^{16}O$ ratio in carbonates associated with biogenic chert. Biogenic silica ranges in oxygen isotope composition from + 2.4‰ to + 6.3‰ (Mopper & Garlick 1971; Knauth & Epstein 1975). Mesozoic and Cenozoic deep-sea cherts range in composition from + 0.5‰ to + 6.0‰ and microcrystalline quartz is depleted in ^{18}O relative to co-existing opal-CT (Knauth & Epstein 1975; Pisciotto 1981). Thus the transition from opal-CT to quartz or the direct precipitation of quartz tends to enrich pore waters in ^{18}O. Knauth & Epstein (1975) have presented data suggesting that opal-CT forms during shallow burial (less than 100 m in depth). Opal-CT replaces the calcite matrix, releasing calcium carbonate which reprecipitates in the surrounding carbonate ooze. Authigenic carbonate formed at this temperature (very shallow burial) should be relatively heavy in $\delta^{18}O$, even if the pore water was somewhat depleted in ^{18}O due to chert formation.

We speculate that the release of isotopically highly negative water during the transition from opal-CT to quartz could account for the lower $\delta^{18}O$ values of the pore water around the chert. Knauth & Epstein (1975) provided some data to support such a speculation. When they dried an opal-CT sample at 1000 °C, they found a total water loss of 1.2 wt % with a corresponding gain of 0.7‰ in $\delta^{18}O_{SMOW}$. This means that the lost water had an $\delta^{18}O$ composition of around – 60‰. In order to shift porewater composition around chert by – 2‰ (as observed by Lawrence 1973), we would need to add about 3% lighter water from opal-CT. This is only possible in the immediate vicinity of chert, since the opal-CT chert transformation possibly releases only around 3 vol. % of light water which rapidly becomes diluted by diffusion away from chert bodies.

The observed negative shift of $\delta^{18}O$ may be a primary paleoceanographic signal, recording a change in paleotemperature and/or isotopic composition of sea-water. If the temperature coefficient of $\Delta^{18}O$ ($CaCO_3 - H_2O$) is ~ 0.2‰ per 1 °C (McCrea 1950), this change in $\delta^{18}O$ may account for an increase in temperature of ~ 2 °C. Although the oxygen isotopic values of the studied sediments have a clear diagenetic overprint (see the scatter trend), general primary trends may still be preserved. Jenkyns et al. (1994) observed a consistent trend in the oxygen-isotope values of various Cretaceous British Chalk sections and of the more lithified Scaglia Rossa and Scaglia Bianca formations in the Umbria-Marche Apennines. The authors concluded that this trend may reflect real variation in palaeotemperature. In any case, further analyses of more sections of the same age and from different depositional environments are needed to find out if the observed negative shift is diagenetic or paleoenvironmental in origin.

9. Correlation of Middle-Late Jurassic carbon isotope stratigraphy

In Figure 9, we present a tentative correlation among Jurassic carbon-isotopic stratigraphies. The correlation of Middle-Upper Jurassic carbon-isotope events is an important step towards understanding their origin. The early Bajocian carbon isotope excursion observed in the UMS Basin correlates with an analogous excursion reported from the Digne area, in the Northern Tethyan margin (Corbin 1994). The Chaudon-Norante section studied by Corbin (1994) yielded an exceptional Bajocian ammonite record (Pavia 1973, 1983). Although the absolute $\delta^{13}C$ values of the Chaudon-Norante section are offset by about 1‰ with respect to the UMS Basin pelagic limestones (a fact that presumably relates to different diagenesis), an analogous positive excursion of about 1.3‰ can be observed. The $\delta^{13}C$ values increase in the lower part of the *Laeviuscula* Zone and reach maximum values in the upper part of the *Sauzei* Zone. Corbin's $\delta^{13}C$ curve represents a composite peak, where the values decrease in the lower part of the *Humphriesianum* Zone and increase again in the middle to upper part of the same zone. This pattern was not observed in the UMS Basin sections.

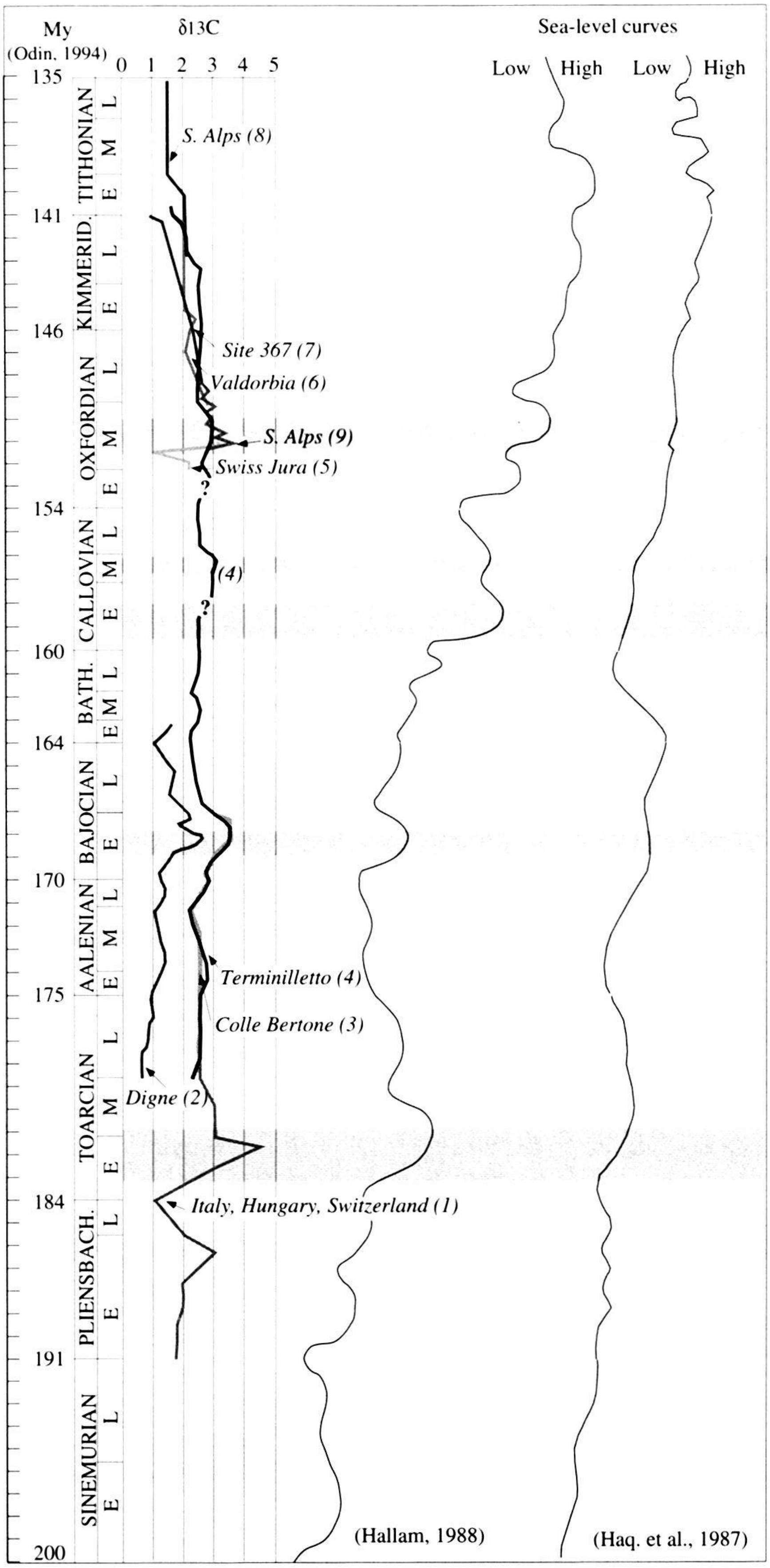
The Callovian positive excursion observed at Terminilletto section can be correlated to peaks of $\delta^{13}C_{TOC}$ ‰ picked out in the Peterborough and Stewartby Members of the British Oxford Clay formation (Kenig et al. 1994). The more evident $\delta^{13}C_{TOC}$ peaks are in the *Calloviense* Zone (lower Callovian) and in the *Jason* Zone (middle Callovian). Carbon-isotope stratigraphy from condensed pelagic section of Camposilvano (north Italy) revealed a positive $\delta^{13}C$ in the Lower-Middle Callovian interval (Jenkyns, in press).

Coralliferous mid-Oxfordian facies from northern Poland show $\delta^{13}C$ values in the range 2.5 to 3.5‰ (Gruszczynski et al. 1990). Hoffman et al. (1991) found positive excursions in the *Cordatum* Zone and *Transversarium* Zone from brachiopod calcite taken from Oxfordian sponge facies in central Poland. Carbon-isotope data from brachiopods from Late Jurassic carbonates in eastern Spain show $\delta^{13}C$ values that increase through the mid Oxfordian (Pisera et al. 1992). Bill et al. (1995) found a positive 2–2.3‰ excursion of $\delta^{13}C$ in the *Transversarium* Zone (middle Oxfordian) from the platform carbonate echinoderm fragments of the Liesberg Beds Member of the Swiss Jura. A $\delta^{13}C$ positive excursion in the transversarium Zone was documented by Jenkyns (in press) in the pelagic limestones from the sections of Chabrières (southern France), and Camposilvano and Roverè Veronese (northern Italy). A similar Upper Jurassic $\delta^{13}C$ trend has recently been reported by Weissert and Mohr (in press). The authors studied carbon and oxygen isotopic compositions from Northern Tethyan shallow-shelf pelagic sediments of the Schilt Formation (lower to middle Oxfordian) and of the Quinten Formation (upper Oxfordian to upper Tithonian) of the Helvetic nappes of eastern Switzerland. Their data show a change in the $\delta^{13}C$ of + 1‰ in the middle-late Oxfordian, with a minor positive shift in the late Kimmeridgian (~ 0.5‰). A $\delta^{13}C$ shift of – 1.5‰ is recognised between early and late Tithonian corresponding to a comparable decrease in carbonate carbon-isotope records established in the North Atlantic (Brennecke 1977; Létolle et al. 1978), in the Southern Alps (Weissert & Channell 1989) and in the Umbria-Marche Basin (Hadji 1991). The positive $\delta^{13}C$ events of the early Bajocian and middle Oxfordian are recorded in both Southern and Northern Tethyan margin sediments, and the middle Oxfordian event has been found in pelagic and carbonate-platform sediments. Further analysis is required to evaluate the other events.

10. Positive $\delta^{13}C$ events and the sedimentary record

Positive shifts in carbon-isotope values in biogenic carbonate are conventionally interpreted in terms of local or regional burial patterns of organic carbon. The Early Jurassic

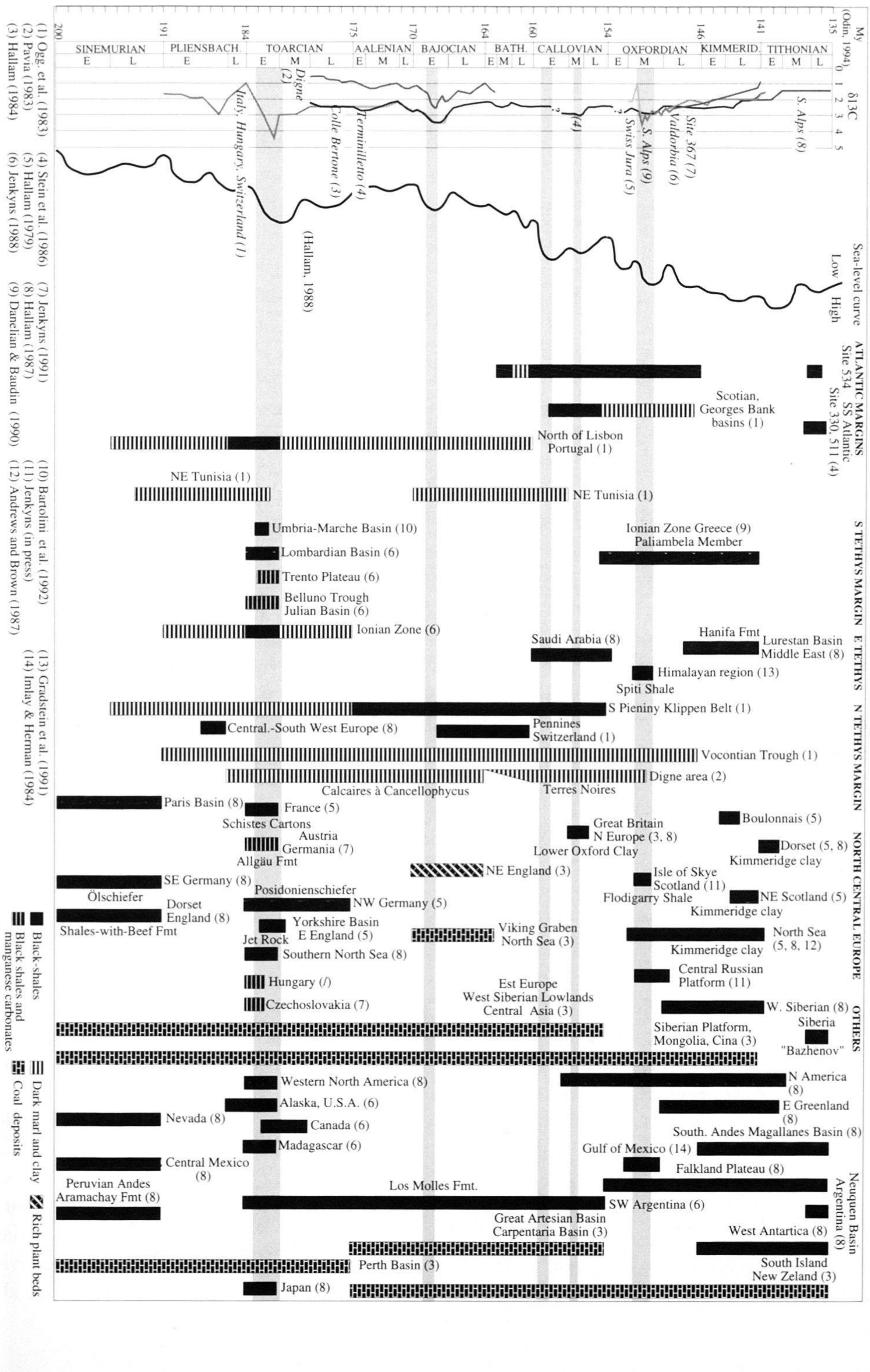
Fig. 9. Tentative correlation between the carbon isotope events described in this paper (grey shading), results published previously, and the sea-level curves of Hallam (1988) and Haq et al. (1987). Sources: (1) Jenkyns (1988, 1991); (2) Corbin (1944); (3) and (4) this paper; (5) Bill et al. (1995); (6) Haidji (1991); (7) Brenneke (1977); (8) Weissert & Channell (1989); (9) Jenkyns (in press). Timescale after Odin (1994) informal stage subdivisions after Gradstein et al. (1994).


My
(Odin, 1994)
δ13C
0 1 2 3 4 5
Sea-level curves
Low High Low High
135
141
146
154
160
164
170
175
184
191
200
TITHONIAN
KIMMERID.
OXFORDIAN
CALLOVIAN
BATH.
BAJOCIAN
AALENIAN
TOARCIAN
PLIENSBACH.
SINEMURIAN
S. Alps (8)
Site 367 (7)
Valdorbia (6)
S. Alps (9)
Swiss Jura (5)
(4)
Terminilletto (4)
Colle Bertone (3)
Digne (2)
Italy, Hungary, Switzerland (1)
(Hallam, 1988)
(Haq. et al., 1987)

Toarcian positive anomaly is clearly related to the deposition of widespread and short ranging black-shales (Fig. 10). For this reason, Jenkyns (1988, 1991) named the early Toarcian event as an "Oceanic Anoxic Event". On the other hand, individual Middle-Late Jurassic carbon isotope shifts cannot be easily related to individual black-shale events. Other positive carbon-isotope excursions that are not accompanied by an obvious "global" marine black-shale record are the Paleocene (Shackleton 1986), the Late Valanginian (Lini et al. 1992) and the mid-Cenomanian (Jenkyns et al. 1994). Storage of terrestrial organic carbon may have to be considered in these cases (Shackleton 1987). Examples of Bajocian black-shales are known in Southern Pieniny Klippen Belt (Ogg et al. 1983) and in Southern Argentina (Los Molles Formation ranging from Pliensbachian to lower Bajocian, Jenkyns 1988). Lower-middle Callovian black shales occur in the Lower-Oxford Clay outcropping in Central-Southern England (Hallam 1987a; Kenig et al. 1994). In the Svalbard, Callovian-Tithonian black-shales are present (Steel & Worsley 1984). In the Central Graben of the North Sea, Callovian hydrocarbons are characteristic of the Pentland Formation (Brown 1989). Ulmishek & Klemme (1990) dated up to 29% of available fossil fuel reserves as Late Jurassic in age. Near Staffin Bay, on the Isle of Skye (Scotland), the mid Oxfordian locally shows a change in facies from sandy siltstones (Digg Siltstone) to bituminous shales and mudstone (Flodigarry Shale) within the *Transversarium* Zone (Jenkyns, in press). Jenkyns (in press) suggested the correlation of the black locally bituminous clay unit in the central Russian platform, (attributed to the *Alternoides* Zone of the upper Oxfordian) with, at least part of, the *Transversarium* Zone of the middle Oxfordian. The black shales of the Nupra Formation (Central Nepal) has yielded a rich ammonite fauna of *Transversarium*-Zone age (Gradstein et al. 1991; Ogg et al. 1992). Stratigraphically wide-ranging black shales, including Oxfordian ones, are documented in Northern Alaska (Upper Kingak Formation, Oxfordian-Kimmeridgian, Embry 1989), in the North American Gulf Coast (Smackover Formation, Oxfordian; Claypool & Mancini 1989, Fails 1990); in the Svedrup basin (Ringnes Formation, Oxfordian-?, Embry 1989), in the Western Barents Sea (Hekkingen Formation, Oxfordian-Berriasian, Dalland et al. 1988), in the Haltenbanken (Norway, Spekk Formation, Oxfordian-Berriasian, Dalland et al. 1988), in the Eastern Rift of the Greenland (Hareelv and Bjernberg Formations, Oxfordian-?, Surlyk 1978), in the North Sea (Brown 1989; Vollset & Dore 1984), in Siberian Basin (Oxfordian and Volgian/Tithonian, Nesterov et al. 1990) and in the Arabian Shield (Oxfordian-Kimmeridgian, Alsharhan 1993) .

A more detailed survey on the stratigraphic position of major organic carbon-rich deposits shows major peaks in the Late Oxfordian, the Kimmeridgian and in the Early Tithonian (Hallam, 1987; Ulmishek & Klemme 1990; Doré 1991; Weissert & Mohr, in press), but the $\delta^{13}C$ curve presents only modest positive excursions. Some other mechanisms must have affected the mass balance of carbon reservoirs and counterbalanced the high organic-matter burial during the Late Jurassic.

Fig. 10. Carbon-isotope events (grey shading) compared to occurrences of organic-rich sediments. Facies and stratigraphic ranges are taken from the indicated literature. The lower Toarcian positive anomaly is clearly related to the deposition of widespread and short ranging black-shales (early Toarcian "Oceanic Anoxic Event", Jenkyns 1988, 1991). In contrast, Middle and Upper Jurassic carbon-isotope events are not easily related to peak occurrences of organic-rich sediments.


My (Odin, 1994)
200
191
184
175
170
164
160
154
146
141
135
SINEMURIAN
PLIENSBACH.
TOARCIAN
AALENIAN
BAJOCIAN
BATH.
CALLOVIAN
OXFORDIAN
KIMMERID.
TITHONIAN
δ13C
Italy, Hungary, Switzerland (1)
Digne (2)
Colle Bertone (3)
Terminilletto (4)
(4)
Swiss Jura (5)
S. Alps (9)
Valdorbia (6)
Site 367 (7)
S. Alps (8)
Sea-level curve
Low
High
(Hallam, 1988)
ATLANTIC MARGINS
Site 534
SS Atlantic
Site 330, 511 (4)
Scotian, Georges Bank basins (1)
North of Lisbon Portugal (1)
NE Tunisia (1)
NE Tunisia (1)
S TETHYS MARGIN
Umbria-Marche Basin (10)
Lombardian Basin (6)
Trento Plateau (6)
Belluno Trough Julian Basin (6)
Ionian Zone (6)
Ionian Zone Greece (9) Paliambela Member
E TETHYS
Saudi Arabia (8)
Hanifa Fmt
Lurestan Basin Middle East (8)
Himalayan region (13)
Spiti Shale
N TETHYS MARGIN
S Pieniny Klippen Belt (1)
Central.-South West Europe (8)
Pennines Switzerland (1)
Vocontian Trough (1)
Digne area (2)
Calcaires à Cancellophycus
Terres Noires
NORTH CENTRAL EUROPE
Paris Basin (8)
France (5)
Schistes Cartons
Austria Germania (7)
Allgäu Fmt
Great Britain N Europe (3, 8)
Lower Oxford Clay
Boulonnais (5)
Dorset (5, 8)
Kimmeridge clay
SE Germany (8)
Ölschiefer
Posidonienschiefer
NE England (3)
Isle of Skye Scotland (11)
Flodigarry Shale
NE Scotland (5)
Kimmeridge clay
Dorset England (8)
Shales-with-Beef Fmt
NW Germany (5)
Yorkshire Basin E England (5)
Jet Rock
Viking Graben North Sea (3)
North Sea (5, 8, 12)
Kimmeridge clay
Southern North Sea (8)
Central Russian Platform (11)
Hungary (/)
Czechoslovakia (7)
OTHERS
Est Europe West Siberian Lowlands Central Asia (3)
W. Siberian (8)
Siberian Platform, Mongolia, Cina (3)
Siberia "Bazhenov"
Western North America (8)
N America (8)
Alaska, U.S.A. (6)
E Greenland (8)
Nevada (8)
Canada (6)
South. Andes Magallanes Basin (8)
Madagascar (6)
Gulf of Mexico (14)
Central Mexico (8)
Falkland Plateau (8)
Peruvian Andes Aramachay Fmt (8)
Los Molles Fmt.
SW Argentina (6)
Neuquen Basin Argentina (8)
Great Artesian Basin Carpentaria Basin (3)
West Antartica (8)
Perth Basin (3)
South Island New Zeland (3)
Japan (8)
(1) Ogg, et al. (1983)
(2) Pavia (1983)
(3) Hallam (1984)
(4) Stein et al. (1986)
(5) Hallam (1979)
(6) Jenkyns (1988)
(7) Jenkyns (1991)
(8) Hallam (1987)
(9) Danelian & Baudin (1990)
(10) Bartolini et al. (1992)
(11) Jenkyns (in press)
(12) Andrews and Brown (1987)
(13) Gradstein et al. (1991)
(14) Imlay & Herman (1984)
Black-shales
Black shales and manganese carbonates
Dark marl and clay
Coal deposits
Rich plant beds

The Middle-Late Jurassic was a time of widespread accumulation of radiolarites in Tethys and elsewhere. Until recently, radiolarites were considered to be typically of top Middle and early Late Jurassic age (Jenkyns & Winterer 1982), but their age ranges in fact from Late Triassic to middle Cretaceous (Baumgartner 1987; De Wever 1989; Gorican 1994). The onset of radiolarites over shallow-water carbonates or deeper-water carbonate resediments is highly diachronous and may extend from Late Triassic to Late Jurassic in age (Jenkyns and Winterer 1982; Baumgartner 1984, 1987, 1990; De Wever 1989). Detailed biostratigraphic work in many areas (INTERRAD Jurassic-Cretaceous Working Group 1995) (Fig. 11) unravels three privileged times of onset of radiolarite sedimentation: the late early Toarcian, the early-middle Bajocian and the Callovian-Oxfordian. These periods correspond to times of positive $\delta^{13}C$ shifts.

11. Siliceous versus carbonate sedimentation

A drastic reduction of sedimentation rates on the Lazio-Abruzzi (LA) Platform that began in the middle-late Toarcian, but essentially characterised the Middle and early Late Jurassic, was documented by Colacicchi & Bigozzi (in press). Sedimentation rates dropped from 5–7 cm / 1000 y to 1.3–1.5 cm / 1000 y (Fig. 12). The authors suggested that this drop of carbonate productivity is a general phenomenon, observed also in other areas. Despite the drop in carbonate production, the LA Platform did not drown, but continued to accumulate slowly in the photic zone. This is ascribed to very low subsidence rates (Colacicchi & Bigozzi, in press).

During the Middle and early Late Jurassic, crinoid-bioclast resediments were deposited in the most proximal marginal areas (e.g. Sella Dei Due Corni Section, Gran Sasso). According to Föllmi et al. (1994) the dominance of crinoid-bryozoan carbonate production indicates deteriorated platform conditions due to eutrophication. In more distal marginal settings (e.g. Terminilletto section) abundant resedimentation of siliceous sponge spicules reflects a crisis of carbonate production and meso-eutrophic sea water conditions on the platform edge (Kitchell 1983; Hallock et al. 1988). In the internal part of the platform cyclothemic sediments, characterised by an oligotypic community with dominant green algae, accumulated (Bigozzi 1993; Colacicchi & Bigozzi, in press).

During the late Oxfordian/early Tithonian, carbonate productivity recovered on the LA platform. Coral-chetetid patch reefs grew in the marginal areas and established a progradation tendency (Colacicchi & Bigozzi, in press). Reef growth was a widespread phenomenon during this time, both on Southern and Northern Tethyan margins (Wilson 1975; Beauvais 1980; Gygi 1986; Flügel & Flügel-Kahler 1992; Leinfelder et al. 1993), as well as in the Arabian Shield and in Central Asia (Nalivkin 1973; Wilson 1975). During the Kimmeridgian/early Tithonian, colonies of thamnastreid corals became common also on highs of Umbria-Marche Basin (Cecca et al. 1981; Pallini & Schiavinotto 1981).

The drop in platform sedimentation rate during the Middle and early Late Jurassic must correspond to a crisis of carbonate productivity and it is reflected in the basin as a reduction of periplatform ooze input. Our observations in the proximal Terminilletto section allow us to date the onset and the peak of this crisis in carbonate productivity. During the Aalenian/early Bajocian the periplatform ooze input to the basin was substantial (Fig. 12). By middle Bathonian time a sharp decrease of periplatform ooze input is evidenced by much more siliceous sediments. Of course, basinal sedimentation rates are al-

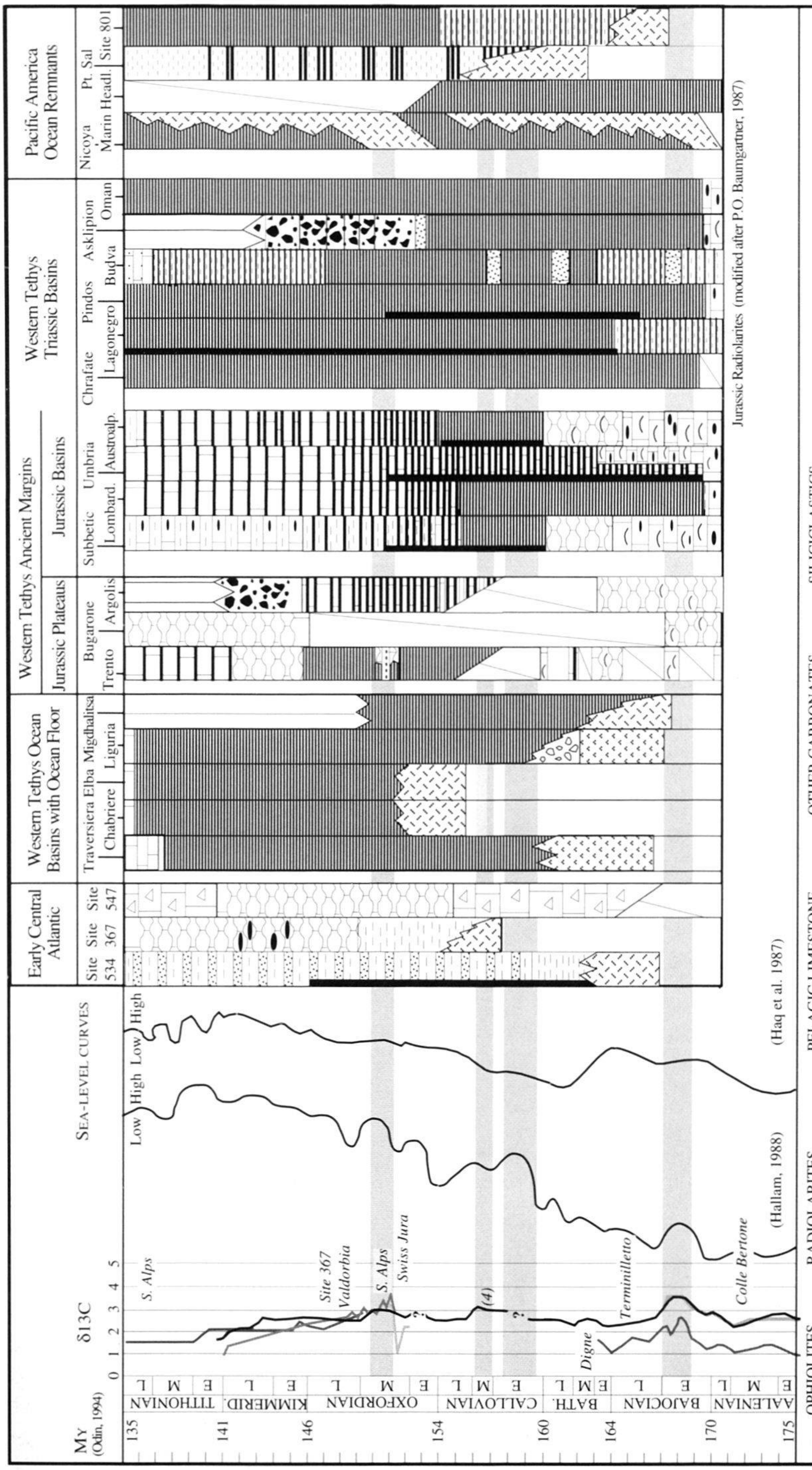


Fig. 11. Carbon-isotope events (grey shading) compared to radiolarite distribution during the Middle-Upper Jurassic. Occurrences of radiolarites and other pelagic lithologies are modified after Baumgartner (1987), and recalibrated in age by INTERRAD Jurassic-Cretaceous Working Group (1995).

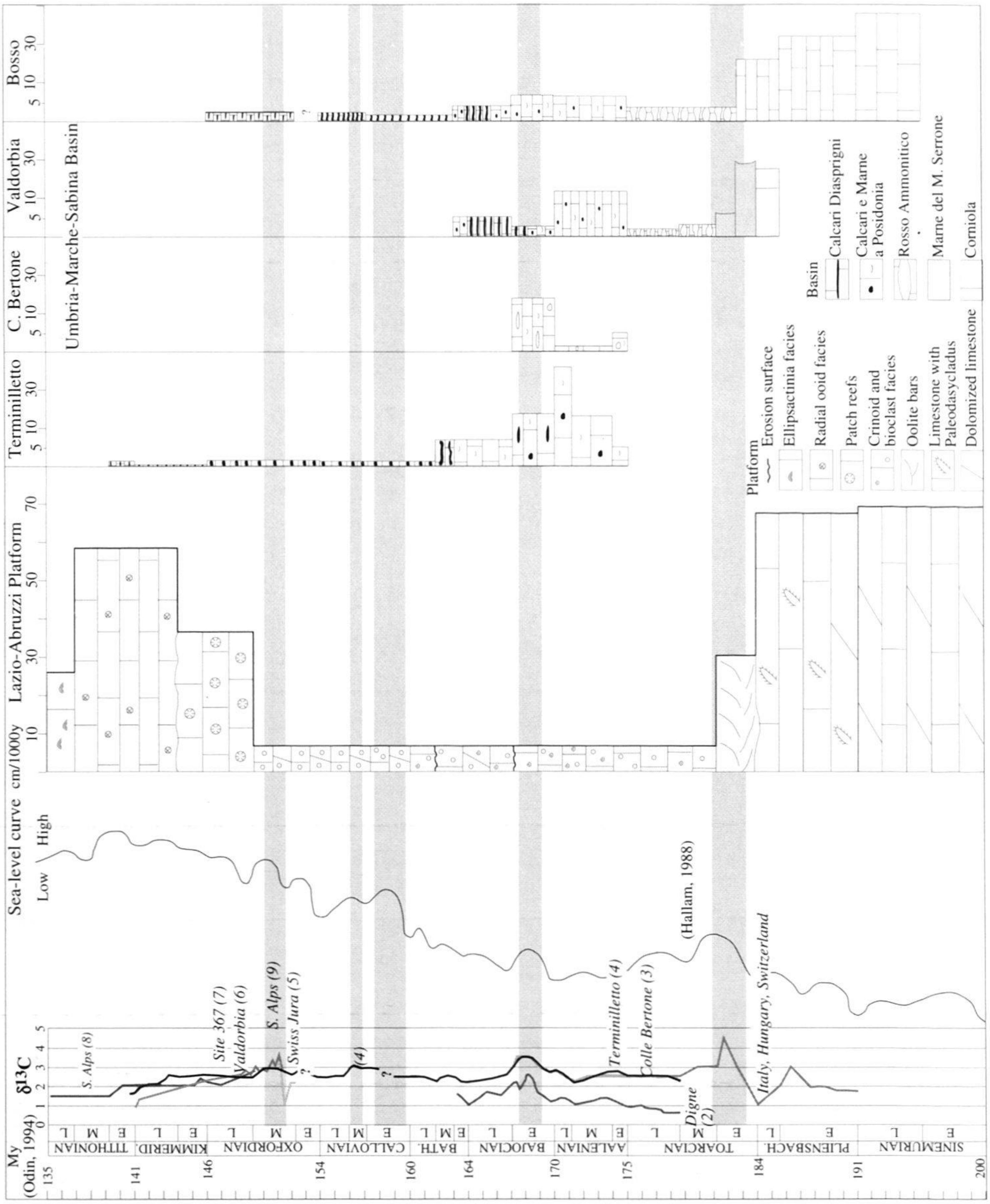


Fig. 12. Carbon-isotope events (grey shading) compared to Jurassic sedimentation rates on the Lazio-Abruzzi Platform (PLA) and some thick Umbria-Marche-Sabina basinal sections. PLA data are after Colacicchi & Bigozzi (in press), Terminilletto and Colle Bertone data are from the present work; early Jurassic data of the Valdorbia and Bosso sections are respectively after (Monaco et al. 1993) and Cecca et al. (1990); Middle-Late Jurassic data of Valdorbia and Bosso sections are after Baumgartner (1990) and INTERRAD Jurassic-Cretaceous Working Group (1995).

so a function of the distance from the platform, paleotopography and local synsedimentary tectonics.

The onset of radiolarites took place in the deepest part of the UMS basin during the early Bajocian (e.g. Valdorbia section) or the middle-late Bathonian (e.g. Bosso, Terminilletto sections), depending on the paleotopography and the paleogeographic position with respect to the platform. Since the middle-late Oxfordian basinal biosiliceous sediments became gradually diluted by carbonate, that was supplied mainly by planktonic nannofossils.

Besides nutrient availability, the presence/absence of radiolarite sedimentation was controlled by dilution by other sediments, such as clays, periplatform ooze or calcareous planktonic ooze (Baumgartner 1987). During the Paleozoic-Jurassic period, however, radiolarians were the only major producers of zooplanktonic skeletal material. Any medium-to high-fertility zone in the Jurassic ocean may have resulted in sufficient radiolarian productivity and preservation to produce radiolarites (Caulet 1974; Renz 1976; Kennett 1982; Baumgartner 1987, 1990; Takahashi 1988; De Wever et al. 1993). Even low-fertility areas may have accumulated siliceous shales at very low rates containing radiolarians as the only fossils (Murchey 1984; Baumgartner 1993; Holdsworth & Nell 1992). In marginal basins such as the Jurassic UMS-basin and most other Western Tethyan basins, carbonate and terrigenous input from the margins largely determined basinal facies evolution. Meso-eutrophic sea-water conditions caused the carbonate productivity crisis and the reduction of periplatform ooze input into the basins. At the same time, meso-eutrophic sea-water conditions favoured high radiolarian productivity. The combined effect of these two tendencies is a change to radiolarite accumulation in the basin.

Radiolarite facies attained a maximum areal extent during the early-middle Oxfordian and encroached onto many submerged platforms and pelagic paleohighs (Baumgartner 1984, 1987, 1990). Soon after, coral buildups became common on Southern Tethyan platforms. The apparent coexistence of radiolarites in basins and coral buildups on platforms is incompatible with a fertility-controlled carbonate/silica sedimentation pattern as developed above. In the Budva Basin (Gorican 1994) pure radiolarites, were deposited during the Oxfordian-Kimmeridgian, while reef buildups developed on the adjacent High Karst margin. These buildups must have prevented periplatform ooze and calciturbidites from entering the basin (bypass situation, Gorican 1994). It is interesting to note that radiolarite accumulation rates were minimal at the same time (Gorican 1994). A similar minimum can be observed in the UMS basin (Baumgartner 1990). At least the late Oxfordian-Kimmeridgian radiolarites of the Budva and other basins could represent slow accumulations in an overall low to medium fertility area, where reefs developed and silica preservation at the bottom was enhanced by silica-rich compaction waters from underlying radiolarites. On the other hand, the apparent coexistence of reefs and radiolarites may result from poor dating of the reefs. In the Swiss Jura, reef buildups (St. Ursanne Formation) rapidly prograde over organic-rich shales (Terrain à Chailles) within the *Transversarium* Zone (mid Oxfordian) (Gygi 1995; Bill et al. 1995). It is likely that the widest expansion of radiolarites coincides with the observed mid Oxfordian $\delta^{13}C$ peak and precedes the late-middle Oxfordian $\delta^{13}C$ decline.

12. Carbon burial in carbonates and the carbon isotope record

The Early-Middle Jurassic carbonate production was essentially relegated to the carbonate platforms, with only a small part to calcareous plankton. Nannofacies studies in Lower-Middle Jurassic pelagic limestones in the UMS Basin (Farinacci 1968; Kälin & Bernoulli 1984; Bombardiere 1993; Mattioli 1995) suggest that most of the calcareous portion can be ascribed to periplatform ooze and only a minor part to nannofossils. During Jurassic the isotopic composition of dissolved inorganic carbon in sea-water was probably controlled by the organic- matter burial rate, as well as by the productivity and health state of carbonate platforms (Schidlowski 1987; Weissert and Mohr, in press; Baumgartner et al. 1995). In times of global high platform carbonate productivity, the carbon cycle was dominated by carbon burial in carbonates at $\delta^{13}C$ values close to zero. This situation tended to stabilise the isotope record and the burial of moderate amounts of negative organic carbon, did not result in evident shift of the isotope curve. On the other hand, during times of crisis in carbonate-platform productivity a small increase of C_{org} burial must have resulted in a positive $\delta^{13}C$ shift. During part of Middle Jurassic, carbonate platforms suffered from eutrophication and a global carbonate productivity crisis can be postulated. Budyko et al. (1987) calculated that the ratio C_{carb}:C_{org} was of 5:1 during the Early Jurassic and changed to 3:1 during the Middle Jurassic. During these times even a moderate increase of organic carbon burial rate became quantitatively important and resulted in positive shifts of the isotope curve. Hence, the scarcity of black-shale records coeval with the Middle Jurassic carbon isotope shifts may turn into a positive argument for the important control of carbonate burial on the Jurassic global isotopic composition of sea water. During the Late Jurassic, organic rich sediments accumulated in many epicontinental basins of North-Eastern Europe, while the productivity of carbonate platforms recovered both on Southern and Northern Tethyan margins. As a result, the Late Jurassic represents a time of high C_{org} burial rate in basins at middle to high latitudes and a re-established growth of carbonate platforms at low latitudes. Budyko et al. (1987) outlined the Late Jurassic as a period of efficient carbonate accumulation with a ratio of C_{carb}: C_{org} of 6: 1. This explains why late Jurassic $\delta^{13}C$ shifts are modest, despite a well documented black-shale deposition. According to Weissert and Mohr (in press) these $\delta^{13}C$ values could reflect a new stabilised mode of carbon cycling with both elevated C_{org} and C_{carb} burial rates during the Late Oxfordian/Early Tithonian.

13. $\delta^{13}C$ values versus sea-level variations and hydrothermal events

The observed $\delta^{13}C$ fluctuations can be correlated with global sea-level curves (Haq et al. 1987; Hallam 1988; Fig. 9). The link between high relative sea-level and positive carbon isotope anomalies has been noted in a large number of studies (Tappan 1968; Berger 1977; Fisher & Arthur 1977; Arthur 1982; Broecker 1982; Woodruff & Savin 1985; Jenkyns 1985, 1988; Myers & Wignall 1987; Magaritz & Holser 1990; Weissert & Lini 1991; Hallam 1992; Föllmi et al. 1994; Weissert & Mohr in press; Jenkyns in press). The Jurassic long-term sea level changes were probably induced, in large part, by the variations of spreading rates and mid-ocean ridge volumes.

Jones et al. (1994) produced a detailed curve of strontium isotopic variations in Jurassic and Cretaceous sea water. In their view, the Jurassic $^{87}Sr/^{86}Sr$ curve should be more "sensitive" to the hydrothermal events than weathering, and the downward excursions of $^{87}Sr/^{86}Sr$ can be best interpreted in terms of increased hydrothermal activity. The $^{87}Sr/^{86}Sr$ ratio decreases from the early Bajocian, correlative with the early Bajocian positive carbon isotope shift. Evident minima of the $^{87}Sr/^{86}Sr$ ratio have been identified in the early Callovian and early Oxfordian and seem to precede the positive carbon-isotope shifts observed in this study.

Hydrothermal activity due to extensive seafloor spreading and/or rifting phases certainly had their impact on Jurassic climate. The history of atmospheric CO_2 levels and of the global carbon cycle must be mirrored in the marine carbonate carbon isotope curve (-Scholle & Arthur 1980): positive $\delta^{13}C$ excursions may be regarded as response signals to fluctuations of global climate linked to atmospheric carbon dioxide concentrations (Arthur et al. 1985; Weissert 1989; Hollander & McKenzie 1991; Weissert & Lini 1991; Weissert & Mohr, in press).

During the Bajocian, Callovian and Oxfordian, hydrothermal events may have provoked high atmospheric CO_2 levels and an accelerated carbon cycling (Fig. 13): warmer-humid climate (greenhouse effect) led to an intensified global water cycling with increased continental weathering and runoff and higher input of nutrients (Weissert 1989). Consequently, the biosphere responded to these high energy climates with a hyper-productivity ("biological pumping", Volk & Hoffert 1985) that tended to remove the excessive CO_2 from atmosphere and bury it in the sedimentary reservoir (Weissert & Lini 1991; Weissert & Mohr in press).

14. Conclusions

The presently available data suggest that rifting and/or oceanic spreading, relative sea-level changes, positive carbon-isotope shifts, carbonate-platform crises and radiolarite onset, may be directly or indirectly linked. Biosiliceous sediments, chiefly radiolarites, are common in oceanic areas throughout the Late Paleozoic and the Mesozoic (Maliva et al. 1989). They become more episodic during the Cretaceous-Tertiary as a result of more efficient calcareous plankton production and probably fundamental differences in silica cycling (Siever 1957; Wollast 1974; Wollast & MacKenzie 1983; Maliva et al. 1989; De Master et al. 1991; Takahashi 1991). Radiolarites and siliceous shales certainly constitute the bulk of pre-Cretaceous oceanic sediments in the Circumpacific and Tethyan realms. Silica accumulation rates, however, may vary by an order of magnitude, as revealed by refined radiolarian biostratigraphy (Baumgartner 1984; Baumgartner 1987; INTERRAD Jurassic-Cretaceous Working Group 1995). Local, regional and global episodes of high silica burial can be determined and related to local, regional or global paleoceanographic and/or paleoclimatic situations. During the Jurassic, episodes of expanding biosiliceous sedimentation are clearly related to times of elevated δ13C-values measured in coeval carbonates.

Hydrothermal events related to extensive rifting and/or accelerated oceanic spreading must be the endogenic driving force that created a perturbation of the exogenic system reflected by the positive $\delta^{13}C$ shifts and biosiliceous episodes (Fig. 13). Global episodes of high silica burial necessitate high silica input into the ocean system by continental weathering and/or hydrothermal input. The silica and the carbon cycles were linked during the Middle-Late Jurassic. Times of increased hydrothermal input of CO_2 lead to high-

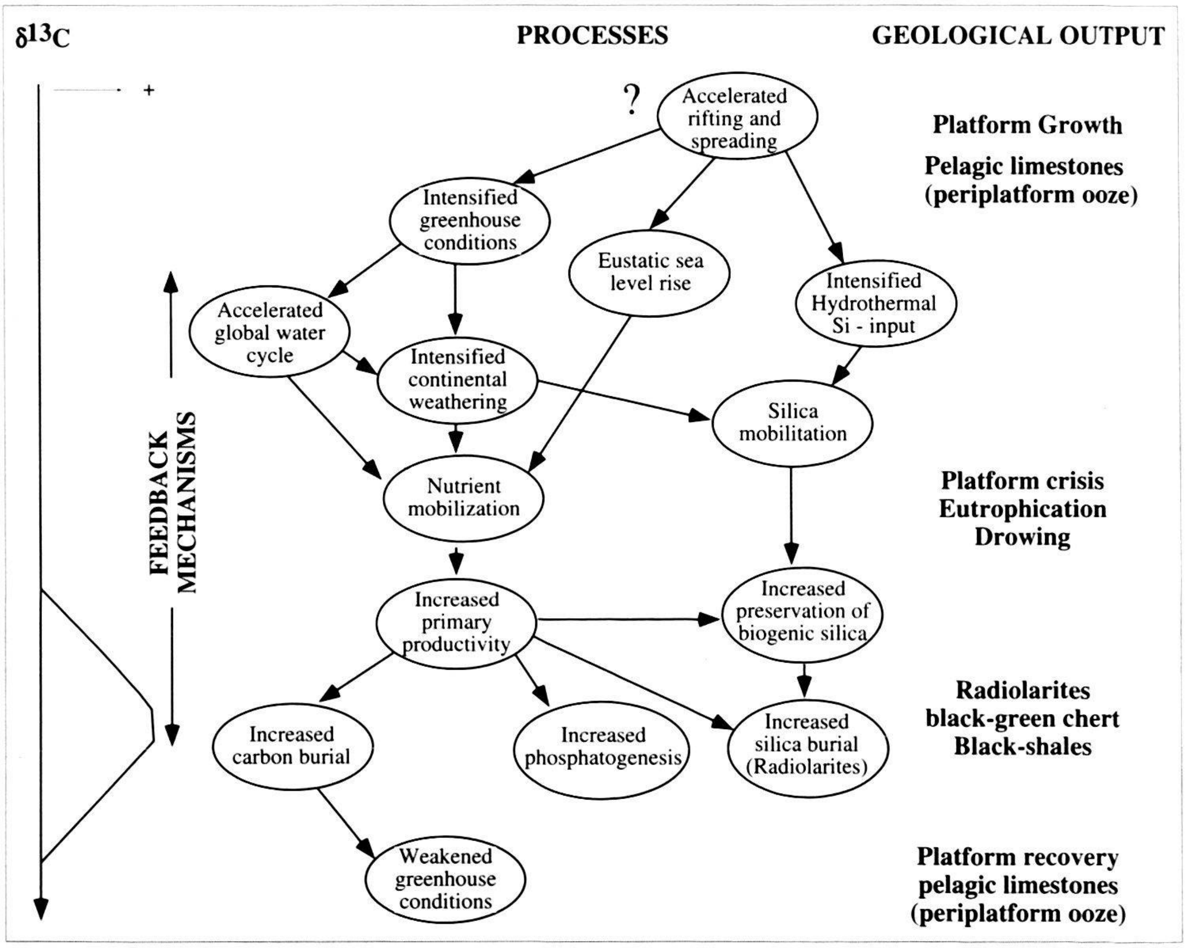


Fig. 13. Flow chart illustrating the links between carbon and silica cycles during the Middle-Late Jurassic, accelerated rifting and/or spreading supposedly was the endogenic force that triggered an exogenic regulation process through feedback mechanisms. It resulted in increased carbon and silica burial that re-established conditions like those prior to the endogenic perturbation. The time axis is from top to bottom without scale. Further explanations in the text (carbon cycle modified after Föllmi et al. 1994).

er atmospheric CO_2 concentrations (greenhouse climate). Intensified continental weathering, which occurred during times of warm-humid climate, caused highest nutrient mobilisation, resulting in increased primary bioproductivity. The increased primary bioproductivity may have resulted both in high organic carbon burial (recorded in coeval carbonates by elevated $\delta^{13}C$-values) and in high biosiliceous productivity and preservation. The preservation after deposition of biosiliceous sediments was also enhanced by the high input of silica into the ocean system by continental weathering and hydrothermal activity (Ellis & Baumgartner 1995). The increased nutrient and silica input resulted, therefore, in high organic carbon and high silica burial. In a steady-state ocean an increase in overall silica input must result in an increase of overall silica burial. The areas and the rates of silica burial will, however, be controlled by local, regional and global factors, such as basin configuration and paleocirculation patterns. We stress that high silica burial is the combined result of biological silica fixation, silica input to the water column and preservation on the seafloor and during diagenesis. Increased productivity tends to increase silica preservation on the seafloor, if the recycling within the ocean is kept constant. Alternatively, increased overall silica input may have enhanced silica preservation on the seafloor by reducing the oceanic recycling without necessary changes in productivity.

Efficient burial of organic carbon and silica may occur in similar overall paleoceanographic conditions. Sluggish deep-water circulation and density stratification may have favoured both bottom-water anoxia and saturation in dissolved silica, leading to low C and Si recycling (Siever 1957, 1962; Lewin 1961; Kennet 1982; Koutsoukos & Hart 1990).

In marginal seas surrounded by carbonate platforms, like the Mesozoic Mediterranean Tethys, radiolarite sedimentation competed with the input of periplatform ooze and turbidites (Baumgartner 1987, 1990). Highly siliceous sedimentation took place whenever the production of platform carbonate was subdued or ceased, either by platform drowning or emergence, or by eutrophication. Evidences for platform eutrophication are the dominance of crinoid-bryozoan over coral-ooid facies on platform and in resediments, and the abundant sponge spicules in all marginal siliceous sediments. Eutrophication acts both for plankton and benthos in favour of silica secreting organisms and against photosynthetic carbonate secreting communities (Morris 1980; Kennett 1982; Kitchell 1983; Hallock et al. 1988).

Both the Bajocian and the Callovian-Oxfordian are times of peak expansion of siliceous sedimentation in Tethys and elsewhere that can be reasonably explained by a scenario of general eutrophication in a greenhouse climate with concomitant $\delta^{13}C$-shifts. Jurassic radiolarites are therefore a "paleoclimatic phenomena" deposited in suitable areas sheltered from terrestrial or periplatform input, possibly related to intensified greenhouse episodes.

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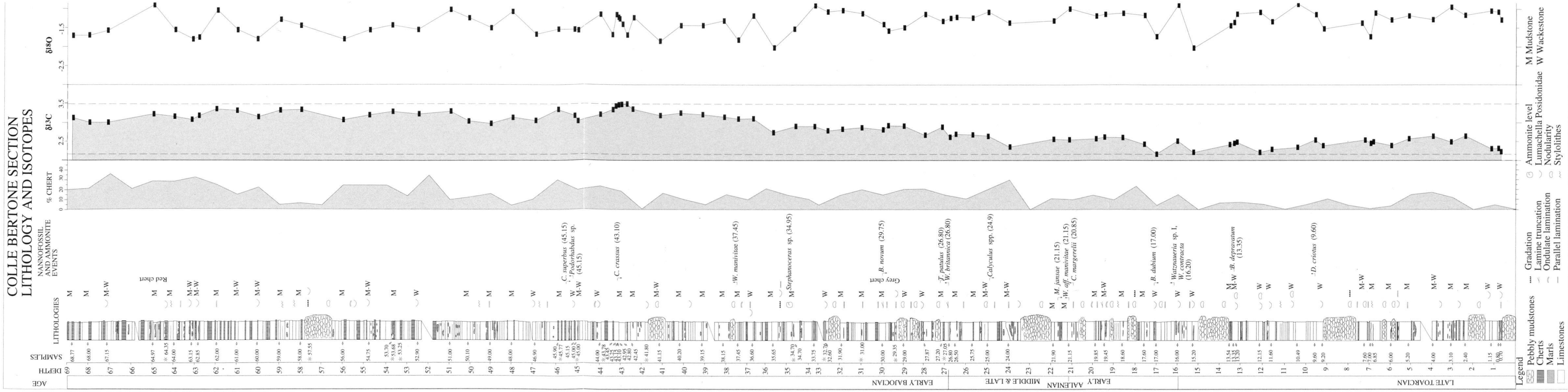

Plate 1. Detailed log of the Colle Bertone section including age, lithology, sample levels, biostratigraphic data, visible chert percentages and stable-isotope stratigraphy.

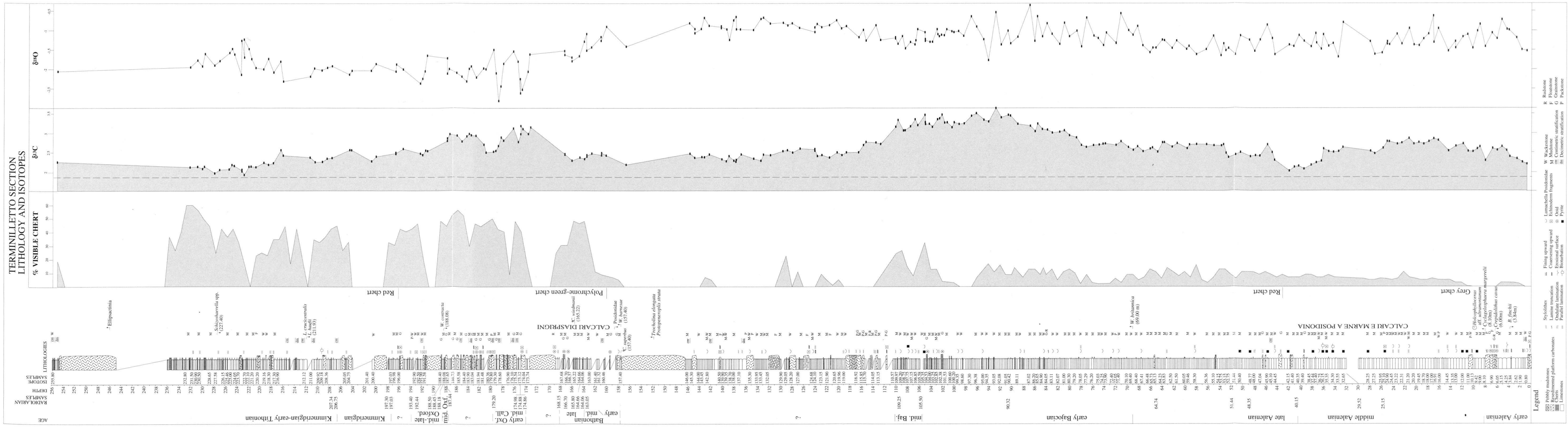

Plate 2. Detailed log of the Terminilletto section including age, lithology, sample levels, biostratigraphic data, visible chert percentages and stable-isotope stratigraphy.