Interactions between environmental change and shallow water carbonate buildup along the northern Tethyan margin and their impact on the Early Cretaceous carbon isotope record

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[1] The evolution of the Early Cretaceous, northern Tethyan carbonate platform was not only influenced by changes in sea level, detrital influx, and surface water temperature but also by changes in trophic levels. We distinguish between phases of carbonate production dominated by oligotrophic photozoan communities and by mesotrophic and eventually colder-water heterozoan communities. Superimposed on this bimodal trend in platform evolution were phases of platform demise for which we provide improved age control based on ammonite biostratigraphy. The initial phase of these episodes of platform demise corresponds in time to episodes of oceanic anoxic events and environmental change in general. On the basis of a comparison between the temporal changes in an Early Cretaceous, ammonite-calibrated δ13C record from southeastern France and coeval changes in the platform record, we suggest that the history of carbon fractionation along the northern Tethyan margin was not only influenced by changes in the oceanic carbon cycle such as in the rate of production and preservation of organic and carbonate carbon and in the size of the oceanic dissolved inorganic carbon reservoir, but it was also influenced by the above-mentioned changes in the ecology and geometry of the adjacent carbonate platform. Phases of heterozoan carbonate production induced positive trends in the hemipelagic carbonate δ13C record. Phases of heterozoan carbonate production pushed the δ13C system toward more negative values. Platform drowning episodes implied an initial increase in δ13C values, followed by a longer-term decrease in δ13C values.

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1. Introduction

[2] Shallow water carbonate successions of Early Cretaceous age are widespread in the western Carpathians, the Alps, southeastern France, the Pyrenees, and the Betic Cordillera [e.g., García-Hernández, 1979; Pascal, 1982; Arnaud-Vanneau and Arnaud, 1990; Masse, 1993; Funk et al., 1993; Michalik, 1994; Föllmi et al., 1994; Bernaux et al., 2003]. They embody the remains of an extensive shallow water carbonate platform, which developed along the northern Tethyan margin along a distance of over 2500 km [e.g., Golonka, 2004]. The central European portion of the platform is presently locked up in the northern, Helvetic Alps, which extend from southeastern Germany and western Austria through Switzerland to eastern France (Figure 1). The structural architecture of the Helvetic nappe and thrust belt allows for the palinspastic reconstruction of proximal-distal transects across the former platform for distances surpassing 80 km (Figure 2), and the Early Cretaceous platform sediments preserved therein provide therefore excellent insight into the spatial and temporal evolution of this platform. Furthermore, the presence of ammonites in marker horizons within the Helvetic succession is the key to excellent time control.

[3] Of special interest is the observation that the Helvetic platform succession does not only document the influence of regional environmental change such as relative sea level fluctuations, variations in ambient sea surface water temperature, and the type and intensity of detrital influx, but also the impact of global paleoceanographic and paleoenvironmental change, such as modifications in the carbon and phosphorus cycles in association with global oceanic anoxic events [Föllmi et al., 1994; Weisssert et al., 1998; Wissler et al., 2003; van de Schootbrugge et al., 2003; Bodin et al., 2006a]. One important indicator of the paleoceanographic influence on the evolution of this carbonate platform system is the near coincidence in timing of the phases of platform demise with episodes of major paleoceanographic change during the Valanginian, Hauterivian, Aptian, and Albian [Schlanger and Jenkyns, 1976; Arthur and Schlanger, 1979; Jenkyns, 1980; Weisssert et al., 1979; Weisssert, 1981; Schlager, 1981; Hallock and Schlager, 1986; Erbacher et al., 2001; Leckie et al., 2002; Höfling and Scott, 2002; Erba et al., 2004].

[4] The changes in carbonate platform growth and the phases of platform demise in association with the global anoxic events had a probable, but poorly quantifiable influence on the marine carbon cycle and associated δ13C
record, in that carbonate carbon burial may have generally been diminished in neritic domains, whereas organic carbon burial may have increased in general [e.g., Weisert et al., 1998; Weisert and Erba, 2004]. Triggering mechanisms for these events proposed so far include modifications in the global output rate of primordial CO₂ by episodes of intense volcanic activity, and eventually by the increased release of methane (see, e.g., Jenkyns [2003] but also compare Heimhofer et al. [2004]).

With this contribution, we give an update on the temporal record of the northern Tethyan carbonate platform exposed in the Helvetic Alps and provide improved time control on the episodes of platform demise by ammonite biostratigraphy, thereby using new data obtained from recently published and ongoing Ph.D. theses [Kuhn, 1996; van de Schootbrugge, 2001; Linder et al., 2006; Bodin et al., 2006b, 2006c]. We also present a new, high-resolution compilation of δ¹³C records for the Early Cretaceous, which has been derived from hemipelagic sections invariably belonging to the Vocontian basin (southeastern France) and its immediate surroundings (Figures 1 and 3). The here presented record is obtained from a single region, thereby precluding the potentially blurring effect related to the accumulation of records from different basins with different environmental and depositional histories. Furthermore, it is derived from a marginal epicontinental basin indented into the northern Tethyan margin, bordered to the north, west, and south by the northern Tethyan carbonate platform [e.g., Bréhéret, 1997]. Its proximity to this platform is, for this reason, ideal for a study of the potential interactions between the northern Tethyan platform and the adjacent basin in terms of the carbon cycle. A further important advantage of this record is its calibration by ammonite biostratigraphy, which facilitates its correlation with the record from the Early Cretaceous northern Tethyan shelf environment.

We also propose a novel interpretation of the changes in the here presented δ¹³C record, which we view not only as the consequence of ocean-wide changes in the ratio of C_carbonate to C_organic burial flux rates, and changes in continental output of dissolved inorganic carbon (DIC) and oceanic DIC reservoir size, but also as the result of changes in the ecology and geometry of the adjacent shallow water carbonate platform. We thereby follow up on earlier publications, in which a close link between the Tethyan whole-rock δ¹³C record and the evolution of the northern Tethyan carbonate platform was already suggested [Föllmi et al., 1994; Weisert et al., 1998; Godet et al., 2006a].

2. Methodology

The sediments of the Helvetic platform have been investigated by a combination of traditional fieldwork consisting of detailed logging and sampling of key sections, the analysis of sedimentological features and determination of biostratigraphically significant fossils (mostly ammonites), and different types of geochemical and mineralogical laboratory analyses (stable carbon and oxygen isotopes, organic matter contents, XRD, XRF, etc.). The data discussed here are extracted from a selection of publications which resulted from a long tradition of research in the Helvetic zone [e.g., Heim, 1910–1916; Fichter, 1934], and are also based on the results of more recent and still ongoing research projects at the ETH Zürich, and the Universities of Berne, Geneva, and Neuchâtel [e.g., Mohr, 1992; Kuhn, 1996; van de Schootbrugge, 2001].

The here proposed compilation of stable carbon isotopes is based on earlier published work. All data were extracted from whole-rock samples of limestone beds within hemipelagic carbonate and carbonate-marl alternating sections [Emmanuel and Renard, 1993; Moullade et al., 1998; Hemig et al., 1999; van de Schootbrugge et al., 2000; Herrle et al., 2004; Godet et al., 2006a]. A small series of stable carbon isotope measurements of Early Cretaceous
Figure 2. Time-space diagram showing the temporal evolution of the distal portion of the northern Tethyan carbonate platform during the Early Cretaceous, based on occurrences in the Helvetic Alps of central and eastern Switzerland (modified from Föllmi et al. [1994]). Timescale is after Gradstein et al. [2004].
Figure 3. Whole-rock carbonate $\delta^{13}$C record from southeastern France. The general trends in the evolution of the northern Tethyan carbonate platform are from Figure 2. On the left side of Figure 3 the numbers on the top of columns refer to 1, stages and substages; 2, ammonite zones; 3, calpionellid zones; 4, planktonic foraminifera zones; 5, calcareous nannoplankton zones; and 6, oceanic anoxic events (all according to Gradstein et al. [2004]). Also shown is the timing of the occurrence of organic-rich layers resulting from oceanic anoxic events in the Vocontian basin [after Bréhèret, 1997; Herrle et al., 2004; Bodin et al., 2006a].
calcite after aragonite were performed for this study at the
geochemistry laboratory, University of Orsay-Paris Sud, by
using a VG SIRA 10 triple collector instrument and the
methods described by Godet et al. [2006a]. The presence of
calcite was confirmed at our laboratory (GEA laboratory,
University of Neuchâtel) by using a Scintag 2000 XRD
device and the methods described by Adatte et al. [1996a].

3. Evolution of the Early Cretaceous northern
Tethyan Carbonate Platform Succession in
the Helvetic Alps

[9] During the Early Cretaceous, the northern Tethyan
carbonate platform witnessed a series of profound changes
in its carbonate-producing platform ecology, which were
superimposed by different episodes of platform demise. The
external portion of this platform is well documented and
dated by ammonite biostratigraphy in the Helvetic zone
of the central European Alps [Wysling, 1986; Föllmi, 1989b;
Mohr, 1992; Kuhn, 1996; van de Schootbrugge, 2001;
Bodin et al., 2006b, 2006c], and its distal position deter-
mines it as an excellent recorder of the interactions between
regional environmental and paleoceanographic change with-
in the Tethyan basin.

[10] Temporal changes in platform paleoecology were
essentially between photozoan and heterozoan carbonate-
producing communities [Lees and Buller, 1972; Caramante
et al., 1988; James, 1997; Mutti and Hallock, 2003]. The
preserved photozoan ecosystem includes hermatypic corals,
rudists, chaetetids, stromatoporoids, and green algae, whereas
the preserved heterozoan community is dominated by
sessile crinoids, and includes byozoans, bivalves, and
brachiopods, in addition to variable amounts of siliceous
spore spicules.

are discerned for the time periods between the latest
Jurassic and the Berriasian-Valanginian boundary (Tros
member, Oehrli Formation (Figure 2)), and the late Barre-
rian and early Aptian (sartosiana to weissi zone: the
Urgonian Chartreuxkalk Formation [Bodin et al., 2006b;
Linder et al., 2006]). These phases are associated with
significant buildup and build out of the platform by
aggradation and progradation (indicated in blue in Figure 2).

[12] Episodes of carbonate production and distribution by
heterozoan communities are documented from the Valangi-
nian (pertransiens to verrucosum zone: Bettis Formation
(Figure 2)), the Hauterivian (radius to nodosocoplicatum
zone: lower Kieselkalk member; ligatus to balearis zone: upper
Kieselkalk member (Figure 2)), and the Aptian
(deshayesi zone: Grünten member; nolani zone: Brisi Beds
(Figure 2)). These phases of heterozoan platform progres-
ion have led to the aggradation and progradation of large
volumes of carbonate (indicated in green in Figure 2).
Undecommpacted accumulation rates are approximately
50% higher than for those in the photozoan mode [Föllmi
et al., 1994].

[13] The construction of the northern Tethyan carbonate
platform was interrupted by a series of episodes of platform
demise, which each lasted up to several million years
(indicated in red in Figure 2). These episodes are registered by
hiatuses and erosion surfaces in proximal parts of the
Helvetic succession, and by the presence of centimeter to
several meters thick glauconite- and phosphate-rich beds in
distal parts, which are either highly condensed or allochth-
onous. These occurrences suggest that carbonate growth
was highly reduced during these episodes and that the
platform was subjected to important erosion instead [Heim,
1910–1916, 1924, 1934; Heim and Seitz, 1934; Gan, 1912;
Fichter, 1934; Schaub, 1936, 1948; Haldimann, 1977;
Föllmi, 1989a; Föllmi and Delamette, 1991; Föllmi et al.,
1994; Kuhn, 1996; van de Schootbrugge, 2001].

[14] Episodes of platform demise are observed and dated for
the periods of the early Valanginian to early Hauterivian
(pertransiens to campylotoxus zone: Büls Bed; verrucosum
to radius zone: Gemsmättli-Pygers and Raaberg Beds
(Figures 2 and 4a–4b)), late early to early late Hauterivian
(nodosocoplicatum to ligatus zone: Lideren Bed (Figures 2
and 4c)), latest Hauterivian to latest early Barremian
(balearis to darsi zone: Altmann member (Figures 2
and 4d)), middle late Barremian (sartosiana zone: Chopf
Bed (Figure 2), early Aptian to middle late Aptian
(deshayesi zone to melchioris zone: Rohrbachstein, Plaine
Morte, and Luitere Beds (Figures 2 and 4e and 4f)), and
latest Aptian to earliest Albian (jacobi to tardefurcata
zones: Twäribeg Bed (Figure 2)).

[15] The episode of demise associated with the Twäribeg
Bed corresponds to the final phase of platform demise in the
history of the central European region of the northern
Tethyan carbonate platform. Shallow water carbonates
younger than the Brisi Beds are not documented. Additional
condensed phosphate- and glauconite-rich beds occur in
sediments of Albian and early Cenomanian age, which are
greatly reduced in thickness and of siliciclastic and hemi-
pelagic facies (Garschella Formation (Figure 2) [see also
Föllmi and Ouwehand, 1987]). These episodes are dated as
tardefurcata to mammillatum zone (Durschlägi Bed), infla-
tum zone (Wannenalp Bed), and dispar zone to middle early
Cenomanian (Kamn Bed) (Figure 2). In the distal part of the
Helvetic succession, one single condensed phosphate
bed occurs, which bundles these former beds and covers
most of the Albian and partly also the early Cenomanian
(Plattenwald Bed (Figure 2)).

4. An Ammonite-Calibrated δ13C Reference
Record From Southeastern France

[16] In order to compare the temporal changes in style and
intensity of platform carbonate production on the northern
Tethyan margin with general changes in the carbon cycle of
the Tethyan ocean, we compiled a high-resolution δ13C
whole-rock record from hemipelagic successions which
were deposited in or near the Vocontian basin (Figure 3).
This basin represents a regional depression within the
northern Tethyan margin during the Jurassic and Cretaceous,
which was bordered by the northern Tethyan carbonate
platform (Figure 1) [e.g., Bréhéret, 1997]. The data for this
compilation were obtained by our research group for the
Hauterivian and Barremian intervals [van de Schootbrugge
et al., 2000; Godet et al., 2006a], and completed by published
Figure 4. Outcrop photos of phosphate- and glauconite-rich beds that formed during the episodes of platform demise along the northern Tethyan margin. (a) Büls Bed (pertransiens zone, early Valanginian) [Kuhn, 1996]: a thin and probably reworked phosphate nodular layer in hemipelagic limestone of the Palfris and Diphoides Formations, Büls near Walenstadt, eastern Switzerland. (b) Gemsmüttli Bed (verrucosum to radius zone, late early Valanginian to early Hauterivian): a nodular phosphatic bed intercalated in heterozoan platform carbonates of the upper Betlis Member and lower Kieselkalk Member, north of Lake Walen, eastern Switzerland. (c) Lideren Bed (nodosoplicatum to ligatus zone, late early to early late Hauterivian): developed here as a glauconite-rich bed (base and top indicated by arrows) following a marly interval on top of the lower Kieselkalk Member, Pilatus, central Switzerland. (d) Altmann Bed (balearis to darsi zone, late Hauterivian to late early Barremian): a thin layer rich in nodular phosphate that reaches down into the underlying top of the upper Kieselkalk Member by bioturbation (arrow), Rawil, central Switzerland. (e) Plaine Morte Bed (deshayesi zone, middle early Aptian): shown here in plain view is the surface of this bed, which consists of nodules of heterozoan carbonate of the Grünnten Member, which are peripherically phosphatized, Rawil, central Switzerland. (f) Luiere Bed (furcata to melchioris zone, late early to middle late Aptian): a sandy and nodular phosphate-rich bed on top of the Grünnten Member, which extends locally down into the top layer of the heterozoan Grünnten Member through burrow-like structures, Rawil, central Switzerland.

records for the Berriasian, Valanginian, and Aptian [Emmanuel and Renard, 1993; Moullade et al., 1998; Hennig et al., 1999; Herrle et al., 2004; cf. also Wissler et al., 2002]. A detailed description and interpretation of the short- and long-term trends in the here compiled northern Tethyan δ13C records is provided in chapter 5.6. The δ18O records show significant offsets in the absolute values and trends between different sections and we refrain therefore from a specific discussion of these data sets (see
5. Discussion and Interpretations

5.1. Correlation Between Episodes of Platform Demise and Paleoenvironmental Change

We observe a fairly good correspondence in time between the phases of platform demise and general paleoenvironmental change, such as is documented by the occurrence of the oceanic anoxic events (Figure 5). The oldest episode of platform demise started in the earliest Valanginian (pertransiens zone) and lasted until the earliest Hauterivian (campylotoxus to radius zone). The onset of this episode appears to predate the onset of the Valanginian “anoxic” event, which was defined to start at the onset of the Valanginian δ13C positive excursion dated as campylotoxus zone [Erba et al., 2004; Weisert and Erba, 2004].

The phase of most intense phosphogenesis during this episode of demise took, however, place during the verrucosum zone [Kuhn, 1996], which corresponds exactly to the period of maximum δ13C values during the Valanginian “anoxic” event.

A second episode of platform demise is dated as late early to early late Hauterivian (nodosoplicatum to ligatus zone), and this phase corresponds to a phase of important sea level change and cold-water inflow into the northern Tethyan realm [e.g., van de Schootbrugg et al., 2003]. A truly anoxic event is, however, not documented from this time period.

The third phase of platform demise started in the latest Hauterivian and lasted until the late early Barremian (balearis to darsi zone). Also here, the onset of the drowning phase appears to predate the Faroani oceanic anoxic event, but a major phase of condensation, phospho-
genesis and glauconite formation appears to coincide with this anoxic event [Bodin et al., 2006c].

[20] Also the onset of the fourth phase of drowning in the history of the northern Tethyan carbonate platform (deshayesi zone to melchioris zone) appears to slightly predate oceanic anoxic event 1a (OAE1a), but this event itself is nicely documented by the presence of a phosphate horizon in distal occurrences of the Helvetic platform (Plaine Morte bed (Figure 2)).

[21] The final drowning episode near the Aptian-Albian boundary coincides with OAE 1b, and younger condensed phosphatic beds (tardefurcata to mammillatum zone, inflatum zone, and dispar zone to middle early Cenomanian) all have their equivalent in oceanic anoxic events (OAE 1b upper part, OAE 1c and d) [e.g., Leckie et al., 2002].

[22] With the exception of the late early to early late Hauterivian phase of platform demise, all phases of erosion, condensation, phosphogenesis and platform demise appear to have their counterpart in a paleoceanographic anoxic event, and especially the early intervals in each episode appear to coincide with periods of widespread dysoxic conditions. The time lag between the onset of platform demise and the start of Early Cretaceous OAE’s was already observed earlier [Föllmi et al., 1994] and it is interpreted here as a lag in the response times of both environments to environmental change: the highly sensitive ecological systems of the northern Tethyan platform appears to have responded rapidly to environmental change, whereas it may have taken up to 1 million year for the establishment of conditions in the deeper basins which allowed for the increased accumulation of organic matter.

5.2. Changes in Trophic Levels and Changes in Platform Ecology and Morphology

[23] As was already outlined by Föllmi et al. [1994] and Weissert et al. [1998], we conceive changes in trophic levels as one of the important mechanisms driving the changes in style, architecture, and the efficiency of the northern Tethyan platform and linking the platform evolution with overall paleoceanographic change.

[24] During the Valanginian and Aptian, phases of platform demise start in distal portions of the platform and proceed by onlap of drowning-related sedimentary bodies onto the platform (Figure 2). During the Valanginian, for example, a first pulse of platform demise is registered by the Bilis Bed in the most distal sections, and younger sediment bodies related to consequent drowning episodes expand onto the platform in the form of the Gemsmättli and the Raaberg Beds [Kuhn, 1996]. These highly condensed phosphate-rich beds formed during periods of progressive sea level rise as part of one or several transgressive system tracts covering major sequence boundaries. In most cases they bundle the effect of a series of successive transgressions into one single and highly condensed bed. The formation of these highly condensed and phosphate-rich beds is related to the influence of deeper-water currents, which arrived onto the platform during times of sea level rise by upwelling, and which were powerful enough to induce a sedimentary regime dominated by erosion and condensation on top of the platform [Delamette, 1988; Ouwehand, 1987; Föllmi, 1989a; Föllmi and Delamette, 1991]. These currents are thought to have consisted of cooler water, enriched in nutrients and especially phosphate, and eventually also dissolved CO₂. Their arrival on the platform pushed the platform into phases of carbonate production in a heterozoan mode and into the episodes of platform demise. Finally, they arrived from an essentially eastern direction, obliquely onto the platform, whereas the transfer of platform material and water from the platform into the outer shelf and basin occurred in truly proximal-distal directions, approximately perpendicular to the platform, as is indicated in the orientation of channel structures and the direction of turbidites [Föllmi, 1989a; Föllmi and Delamette, 1991].

[25] An independent confirmation of the importance of trophic levels is the overall good correlation between the record of oceanic phosphorus accumulation and the state of carbonate production on the shelf (Figure 5) [Föllmi, 1995; van de Schootbrugge et al., 2003; Bodin et al., 2006a]. A further indication of a link between platform evolution and trophic levels is the coincidence of major positive excursions in the northern Tethyan δ¹³C record during the early Valanginian and early Aptian with periods in which the northern Tethyan carbonate platform shifted into a mixed heterozoan, demise mode (indicated by the green and red zones in Figures 2, 3, and 5). These phases of major change in the evolution of the northern Tethyan carbonate platform appear to be marked by major transformations in the ocean carbon cycle, which were highly likely induced by a nutrient-driven change in the ratio of carbonate carbon (C_carb) to organic carbon (C_or) burial (see below) [cf. also Immenhauser et al., 2005].

5.3. Quality and Correlation of the Northern Tethyan δ¹³C Record

[26] The here proposed compilation of the northern Tethyan δ¹³C record shows values typical of Early Cretaceous open-marine carbonates [e.g., Jenkyns and Wilson, 1999; Erba et al., 1999]. The stratigraphic continuity of data derived from different sections is an indication of the general quality of the δ¹³C signal; the only exception is a jump in absolute values at the base of the late Aptian melchioris zone, which is likely induced by a change in diagenetic conditions between two sections [Herrle et al., 2004; J. O. Herrle, personal communication, 2005]. Furthermore, the good correlation of the general trend between the here proposed δ¹³C curve and other published curves is also an indication of its quality as a recorder of original paleoceanographic change rather than diagenetic overprint (Figure 6). The lack of correlation in a δ¹⁸O-δ¹³C cross plot for all data (R² = 0.0264) appears to confirm this interpretation (Figure 7) [e.g., Godet et al., 2006a].

[27] A comparison between the northern Tethyan δ¹³C curve and the δ¹⁵N of the central Tethyan and the Pacific realms [e.g., Weissert and Channell, 1989; Lini et al., 1992; Adatte et al., 1996b; Erbacher et al., 1996; Erba et al., 1999; Jenkyns and Wilson, 1999; Bartolini, 2003] reveals that the long-term trend in the northern Tethyan record fits well with those in the other records, and that especially the two positive excursions during the early
Figure 6
Valanginian and early Aptian are well reproduced (Figure 6). The evolution of the intervals between the major positive excursions is characterized by rather irregular and locally noisy trends, which are, in general, not very well correlated, neither between sections between different oceans nor within the same basin.

[28] We suggest here that whereas the large positive excursions of the early Valanginian and early Aptian are well correlated between the Tethys and the Pacific realms and appear to be a truly global phenomenon, the smaller-scale excursions of the remaining intervals in the Early Cretaceous represent most likely a response to local to regional changes in the carbon cycle.

5.4. Potential Mechanisms Driving the Marine δ13C Record

[29] The (hemi)pelagic δ13C record provides an important tracer of reorganization within the marine carbon cycle [e.g., Kump and Arthur, 1999; Veizer et al., 1999], and temporal changes therein are traditionally interpreted as an approximation of changes in the ratio of burial fluxes of C_carb and C_org [e.g., Scholle and Arthur, 1980; Arthur et al., 1988; Weissert, 1989; Hoefs, 1997; Weissert et al., 1998]. Additional factors of important influence on the marine δ13C record consist in the quality and flux of externally derived carbon species into the (hemi)pelagic marine realm, such as terrestrial and platform-derived C_org and dissolved inorganic carbon (DIC), atmospheric CO2, or methane derived from the dissociation of clathrates [Cerling et al., 1993; Dickens et al., 1995; Kump and Arthur, 1999; Immenhauser et al., 2003; Weisert and Erba, 2004; Swart and Eberli, 2005; Panchuk et al., 2005, 2006]. Furthermore, Bartley and Kah [2004] recently suggested a close relationship between the size of the marine DIC reservoir and the sensitivity of the marine δ13C system to changes in the carbon cycle.

[30] As we will detail out in the following, a combination of these factors influenced the northern Tethyan Early Cretaceous δ13C record, whereby the precise identification of the relative importance of each factor remains a difficult task. In our interpretation, we especially pay attention to the potential effect of the export of particulate and dissolved inorganic carbon (PIC and DIC) from the northern Tethyan carbonate platform and adjacent European continent, and changes therein, on the here described δ13C record. We postulate that the smaller temporal shifts in the northern Tethyan δ13C record, which are not correlated on a wider scale and for which a local or regional cause is to be sought, were influenced by this phenomenon.

Figure 6. Correlation of the northern Tethyan δ13C record with δ13C records from the central Tethys, the western Atlantic, and the Pacific realms [from Cotillon and Rio, 1984; Lini et al., 1992; Adatte et al., 1996b; Erbacher et al., 1996; Erba et al., 1999; Jenkyns and Wilson, 1999; Bartolini, 2003; Price, 2003]. Note that whereas the northern Tethyan δ13C record is calibrated against Early Cretaceous time [Gradstein et al., 2004], the other records shown here are plotted against their lithostratigraphy. Note also that for the northern Tethyan δ13C record, the central Tethyan record by Erba et al. [1999], and the Pacific record by Price [2003], a five-point moving average is shown, whereas for the remaining records, all measured data are shown.

Figure 7. The δ13C-δ18O cross plot of all data used in the δ13C compilation of Figure 3.
There are several reasons for this assumption:

1. On the basis of a quantification of calcareous nannofossils in the hemipelagic carbonates of the Vocontian basin, Reboulet et al. [2003] were able to show that for the Valanginian sections, hemipelagic carbonate accumulation in this marginal basin was for a large part controlled by the export rate of platform-derived carbonate oozes, rather than by depositional rates of pelagic calcareous plankton (see also Colombié and Strasser [2003] for a similar interpretation of late Jurassic carbonate beds in Vocontian sections). The influence of shedding of shallow water carbonate mud into the adjacent basin is also indicated by the important decrease in carbonate accumulation in the Vocontian basin during periods of platform demise, such as during the pertransiens and verrucosum zone (Valanginian [e.g., Reboulet et al., 2003]), and the late early to early late Aptian [e.g., Bréhéret, 1997].

2. As will be shown below, the timing and the negative or positive character of the shifts in the northern Tethyan δ¹³C record appear to be correlated to changes in the style and intensity in carbonate production on the northern Tethyan platform.

3. A numerical model published by Godet et al. [2006a] suggests that the export of platform-derived carbonate and especially aragonite may have an impact on the δ¹³C record in adjacent basins.

5.5. Changes in the Ecology and Geometry of the Northern Tethyan Carbonate Platform and Its Influence on the Northern Tethyan δ¹³C Record

There are several mechanisms related to the predominant ecosystem and geometry of the Early Cretaceous northern Tethyan carbonate platform, which may have influenced the hemipelagic δ¹³C record described here (Figure 8). The northern Tethyan carbonate platform was constituted by photozoan and/or heterozoan ecosystems. The photozoan community included hermatypic corals, rudists, stromatoporoids, chaetitids, and green algae as its main constituents [e.g., Bollinger, 1988; Mohr, 1992; Föllmi et al., 1994]. Of interest here is that these organisms precipitated their hard parts predominantly in aragonite [e.g., Morycowa, 1980; Wefer and Berger, 1991]. This is also true for the Early Cretaceous rudists, which had relatively thick aragonite shells covered by a thin calcitic layer [Steuber, 2002]. The participation of photosynthetic organisms in the form of green and zooxanthellaceae algae was important and the overall high photosynthetic rates in photozoan communities may have increased δ¹³C values in skeletal aragonite. Fractionation toward more positive δ¹³C values was likely also related to the geometry of the photozoan platform, which was confined by marginal reef buildups and oolitic shoals [Linder et al., 2006; Godet et al., 2006b], thereby promoting carbon recycling within the platform [e.g., Swart and Eberli, 2005; Panchuk et al.,...
2005, 2006]. Furthermore, in single carbonate systems, aragonite δ¹³C values tend generally to be higher than calcite δ¹³C values [Romanek et al., 1992]. For instance, Swart and Eberli [2005] reported δ¹³C values of maximal +5‰ for aragonite on the present-day Bahamian platform. A preliminary isotopic survey of platform-derived skeletal material which consists of calcitized aragonite appears to confirm the high initial values for Early Cretaceous aragonite for samples from the Gargano platform (Italy; sample obtained from Jean-Pierre Masse: δ¹³C value = +5‰) and the north Mexican and Texan carbonate platforms (δ¹³C values between 2.3–4.3‰; n = 24, mean value = +3.3‰ [Woo et al., 1993]).

[36] The Early Cretaceous was characterized by broad epicontinental seas and widespread carbonate platforms [e.g., Philip, 2003] and aragonite production rates may have been significant in photozoan shallow water communities in general. The export of this mineral into adjacent basins during, for example, storm events and probably also more generally through the process of platform build out by the formation of progradational carbonate wedges influenced the northern Tethyan δ¹³C signal as a whole either by direct incorporation into pelagic sediments or by dissolution and transfer into the marine DIC reservoir [e.g., Droxlle et al., 1983; Swart and Eberli, 2005; Godet et al., 2006a]. The potential influence of aragonite shedding on the δ¹³C signature in carbonates of the Vocontian basin has been modeled by Godet et al. [2006a]. They were able to show that the presence of 20% aragonite in the total depositional rate of carbonate may increase the δ¹³C signature by 0.2‰, in the case the initial value is at 2‰, and the initial aragonite δ¹³C value is set at 5‰.

[37] In analogy to modern tropical carbonate platforms [Kawahata et al., 1997; Suzuki et al., 2001; Suzuki and Kawahata, 2003, 2004], the confined geometry of photozoan platforms may also have had an effect on the air-sea exchange of CO₂. We assume that most CO₂ derived from respiration of organic matter, precipitation of carbonate, and river influx was directly returned to the atmosphere, rather than transported laterally into deeper waters. This means that photozoan platforms were a likely source of CO₂ to the atmosphere. This also signifies that a nonnegligible part of continental derived DIC was returned to the atmosphere as CO₂ or stored as platform carbonate, rather than transferred into the deep basin. All by all, the dominance of photozoan carbonate platforms may have pushed the oceanic δ¹³C value toward more positive values both by increased aragonite exportation and by decreased output of platform-derived DIC and throughput of continental derived DIC (Figure 8). The possibility that the Early Cretaceous photozoan platform acted as a source of CO₂ to the atmosphere rather than a sink signifies also that this system was less vulnerable toward changes in atmospheric pCO₂ [cf. Wissler et al., 2003; Weissett and Erba, 2004].

[38] Early Cretaceous heterozoan ecosystems consisted predominantly of respiring organisms such as crinoïds, thick shelly bivalves, brachiopods, and bryozoans, which precipitated their hard parts mainly in calcite [e.g., Sprinkle and Kier, 1987; Smith et al., 1998; Flügel, 2004]. Early Cretaceous heterozoan platforms consisted of homoclinal or distally steepened ramps with good connections to the adjacent basin [e.g., James, 1997; Linder et al., 2006]. Very few benthic photosynthetic organisms are preserved from the heterozoan assemblages and benthos-related photosynthetic processes may have been less important, at least in comparison to the photozoan carbonate platform. Because of the specific fractionation pattern of heterozoan organisms and the open-platform architecture, the overall δ¹³C signal of precipitated calcite is less positive in comparison to that of aragonite in photozoan platforms [e.g., Wefer and Berger, 1991; Swart and Eberli, 2005]. In addition, the heterozoan mode of platform carbonate production along the Early Cretaceous northern Tethyan margin was associated with important detrital input, higher nutrient levels and eventually colder waters [Föllmi et al., 1994]. This implies that phytoplankton productivity was important, thereby favoring the suspension-feeding mode exercised by an important part of the heterozoan community (crinoids, brachiopods, bryozoans). Since almost no organic matter is preserved in the heterozoan carbonate deposits, it is assumed that most of it was efficiently decomposed and reintegrated into the DIC pool, whereas ¹³C-enriched C₄ plants was efficiently buried. This induced a decrease in the δ¹³C signal of platform DIC and subsequently also of precipitated calcite [e.g., Immenhauser et al., 2003]. To this comes that the import of terrestrially derived DIC in association with high detrital flux rates may have reinforced the trend toward a more negative δ¹³C signal on top of the heterozoan platform.

[39] Heterozoan platforms may also have acted as a pump of atmospheric CO₂, which was consequently exported into adjacent basins, analogous to the present-day North Sea [Thomas et al., 2004]: the open, ramp-like architecture of heterozoan platforms probably allowed for a better vertical separation of photosynthetic (by planktonic organisms) and respiration processes (by benthic, carbonate-producing organisms) in its external, deeper part. This leads to a corresponding increase of respired CO₂ in subsurface waters, which was ultimately exported into the adjacent basin rather than transferred back to the atmosphere (Figure 8). The absence of aragonite and the increased export of both calcite as well as platform-derived and continentally derived DIC likely influenced the marine δ¹³C system and induced lower values in open marine carbonates. The corresponding increase in the marine DIC reservoir may also have attenuated the sensitivity of the open ocean δ¹³C record [Bartley and Kah, 2004].

[40] The repeated phases of platform demise during the Early Cretaceous occurred in close relation with oceanic anoxic events (Figures 3 and 5). Such phases had an important impact on the δ¹³C system, in that carbonate production and export were greatly diminished on shelves and also in open marine systems through the competition with siliceous organisms, whereas C₄ production and preservation were enhanced. This situation generated a general shift in the δ¹³C record toward more positive values. The greatly reduced output of carbonates and the increased throughput of continentally derived DIC accompanied by an increase in remineralized C would automatically have led to an increase in the oceanic DIC reservoir. The environmental conditions leading to oceanic anoxia and platform drowning
also induced an increase of this reservoir by increased humidity and weathering on the continent [e.g., Föllmi et al., 1994; Föllmi, 1995; Weisssert et al., 1998]. The increase in size of the oceanic DIC reservoir may have also led to a more negative δ¹³C signal by its increased recycling into the photic zone [e.g., van de Schootbrugge et al., 2005] and may have also attenuated short-term shifts in the signal [Bartley and Kah, 2004]. Oceanic anoxic events and corresponding platform drowning episodes may therefore first have led to a rather rapid positive excursion in δ¹³C followed by a longer-term trend toward a more negative δ¹³C record, which was less sensitive toward short-term change.

5.6. Correlation of Changes in Carbonate Platform Ecology Along the Northern Tethyan Margin and Trends in the Northern Tethyan δ¹³C Record

[41] A direct comparison of the evolution in the northern Tethyan δ¹³C record with the changes in platform ecology along the northern Tethyan margin allows us to infer temporal correlations, which are consistent with the above described influences of platform carbonate production and morphology on basinal δ¹³C records. In the Helvetic realm, the minimum in the northern Tethyan δ¹³C record at the Jurassic-Cretaceous boundary corresponds to a halt in the growth of a photozoan platform (Tros Member) and the onset of the deposition of marly, hemipelagic sediments (Zementstein Formation). The negative excursion as such is interpreted as the result of diminished aragonite shedding and an increase in continental DIC input.

[42] The two positive excursions in the early and late boissieri zone correspond to two phases of platform growth in a photozoan mode (lower and upper Oehrikalk members), which were interrupted by a phase of detrital input [Mohr, 1992; Mohr and Funk, 1995]. Here an eventual increase in aragonite shedding and a concomitant decrease in DIC output from the platform may have been influential.

[43] During the early Valanginian, the δ¹³C record is first shifted to slightly more negative values and subsequently rapidly toward heavier values. A first maximum in δ¹³C values corresponds to the early verrucosum zone. Thereafter, δ¹³C values show a slight regression, before they culminate again in the late verrucosum zone. This trend corresponds to the well-known Valanginian positive excursion, which has been established in the Apulian basin and elsewhere [Lini et al., 1992; Föllmi et al., 1994; Hennig et al., 1999; Erba et al., 2004]. A comparison with the Helvetic realm suggests that the slight negative shift at the base of the Valanginian correlates to a change from a photozoan to a heterozoan platform mode (lower Betlis member). The rapid shift toward heavier values during the early Valanginian is coeval with a first platform drowning phase (Büs Beds). The following negative shift corresponds to a return of the platform in a heterozoan mode (upper Betlis member) and the second positive shift is the result of renewed platform drowning (Gemsmättli Bed).

[44] For the remainder of the late Valanginian and the entire Hauterivian, the δ¹³C record is remarkably stable with regards to short-term changes and shows only a long-term change toward more negative values. This started in the verrucosum zone and lasted until the late loryi zone and was followed by a long-term increase toward more positive values ending at the Hauterivian-Barremian boundary [van de Schootbrugge et al., 2000]. The drowning phases during the Hauterivian and near the Hauterivian-Barremian boundary are not obvious in the δ¹³C record with the possible exception that an eventual increase in organic carbon burial during the late Hauterivian (cataclimatic in the Faraoani anoxic event) may have pushed the δ¹³C record slowly to more positive values. The relative stability of the Hauterivian-early Barremian record is probably related to the increased size of the oceanic DIC reservoir, which induced the trend toward more negative values during the late Valanginian and early Hauterivian and attenuated the sensitivity of the δ¹³C signal in general [Godet et al., 2006a].

[45] The late Barremian is characterized by a positive shift in δ¹³C values, which is correlated with the progressive installation of the photozoan Urgonian platform (Drusberg Member and lower Schrattenkalk Member [Godet et al., 2006a; Bodin et al., 2006b]). The Barremian-Aptian boundary is marked by a well-defined negative peak in the δ¹³C record, which may, amongst others, be related to the increased output of continental detritus and DIC, leading to a corresponding increase in the oceanic DIC reservoir. The minimum of this negative excursion appears close to the onset of a widely documented interruption in photozoan platform growth along the northern Tethyan margin accompanied by an increase in detrital input (“lower Orbitolina Beds”).

[46] The Aptian shows a rather unsteady short-term evolution in δ¹³C, which starts off with an important positive shift during the oeglandensis zone. This shift is well correlated with a significant phase of photozoan carbonate production (upper Schrattenkalk member). This first maximum in δ¹³C values during the Aptian is followed by a decrease, which becomes accelerated near the boundary between the weissi and deshayesi zones and forms a negative spike. This decrease in δ¹³C values corresponds to a change to a heterozoan platform mode in the Helvetic zone (Grünten member [Linder et al., 2006]), which is followed by the demise of the Urgonian Schrattenkalk platform (Luitere Bed). The negative spike occurs near the base of the Goguel level, an anoxic bed which corresponds to OAE 1a. It was first described by Menegatti et al. [1998] in the Apulian basin and has been interpreted to represent a short period of increased uptake of recycled ¹²C-enriched carbon and/or increased release of methane [Menegatti et al., 1998; Jenkyns, 2003]. The early Aptian negative spike is followed by a positive excursion toward an early Aptian twofold maximum in δ¹³C values, which lasts until the top of the furcata zone. Subsequently, the δ¹³C record slowly returns to more negative values, and arrives at a minimum near the top of the subnodosocostatum zone. This trend in δ¹³C is paralleled on the Helvetic shelf by a long-lasting drowning episode, and is interpreted to have resulted from increased output of C_org relative to C_carb during OAE 1a, followed by an increase in the oceanic DIC reservoir, which was due to the prolonged diminution in platform carbonate production paralleled by increased input of continental DIC.
The base of the minimum in the late Aptian δ13C record near the boundary of the subnodosocostatum and melchioris zones corresponds to a regional anoxic event (Fallot level [Herrle et al., 2004]). The subsequent excursion toward more positive δ13C values is probably artificial and related to different diagenetic conditions in the set of sections measured by Herrle et al. [2004] (J. O. Herrle personal communication, 2005). A final phase of shallow water carbonate production in a heterozoan mode (Brisi Beds) is documented from the nolani zone, and appears to trace an irregular trend toward more negative values in the δ13C record. In the latest Aptian and earliest Albian, an ultimate drowning phase occurred on the Helvetic platform which is documented by the Twärnberg Bed. The positive shift in δ13C values in sediments of the latest Aptian (jacobi zone) appears to register the final demise of the platform. On the Helvetic shelf, the early Albian witnessed a phase of increased detrital input (Nideri beds), followed by a renewed phase of condensation (Plattenwald Bed), which, for its onset, correlates to OAE 1b represented in the Vocontian basin by the Paquier level [e.g., Herrle et al., 2004]. The onset of OAE 1b is paralleled by an increase in δ13C values of the Vocontian realm, which is followed by a renewed decrease in values.

The good temporal coincidence between changes in the northern Tethyan δ13C record and changes in platform ecology and morphology opens the possibility to explain almost minor and major changes in this curve. This was hitherto not possible in using changes in Tethyan paleoceanography as the exclusive driver of carbon isotope fractionation patterns.

6. Conclusions

The Helvetic zone preserves a distal portion of the Early Cretaceous northern Tethyan carbonate platform and its transition into the deeper outer shelf. The succession recovered in the Alps is not only the result of regional environmental conditions on the shelf, but also of global paleoceanographic conditions as is shown by the temporal correspondence between drowning episodes, OAEs, and the here presented Early Cretaceous δ13C reference record of SE France. The link between paleoceanographic changes and coeval modulations in the style and architecture on the platform is provided by the upwelling of deeper and colder waters, rich in nutrients and likely in dissolved CO2, onto the platform.

Furthermore, virtually every change in the northern Tethyan δ13C record makes sense, if correlated with the evolution of the northern Tethyan platform. This indicates that reciprocally, the northern Tethyan platform system exerted an influence on northern Tethyan ocean chemistry. We propose that this occurred by the production and storage of shallow water carbonates, and by the existing platform geometry and intensity of photosynthetic activity which both were decisive for the degree of CO2 return into the atmosphere and/or ocean, and the degree of output of platform-derived DIC and throughput of continental DIC. Furthermore, the changes within the platform ecosystem between photozoan, aragonite-based carbonate production mode and heterozoan, calcite-based carbonate production mode may have also played an important role in the oceanic carbon budget, especially if corresponding carbonates became exported into the adjacent basin. The high-resolution δ13C record of SE France reflects both the complexity of such changes on the adjacent northern Tethyan platform, as well as coeval changes in paleoceanographic conditions, which episodically culminated in anoxic events, thereby engaging the northern Tethyan carbonate platform in mutual feedback.

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