

Late Cenomanian to Middle Turonian high-resolution carbon isotope stratigraphy: New data from the Münsterland Cretaceous Basin, Germany

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Abstract

New high resolution carbon isotope stratigraphies from two basinal pelagic carbonate successions in northern Germany (Halle and Oerlinghausen, Münsterland Cretaceous Basin) resolve late Cenomanian to early Mid-Turonian carbon cycle variations at timescales of less than 100 kyr. Beside the major carbon isotope excursion of the late Cenomanian oceanic anoxic event (OAE 2), 11 small-scale distinct features are precisely resolved in the $\delta^{13}\text{C}$ carbonate curve and related to boreal macrofossil zonations. The small-scale carbon isotope events correspond to secular $\delta^{13}\text{C}$ carbonate variations identified previously in the English Chalk. The boreal high-resolution $\delta^{13}\text{C}$ carbonate curve shows a detailed coincidence with two Tethyan $\delta^{13}\text{C}$ curves from Italy, what demonstrates the interregional significance of the $\delta^{13}\text{C}$ dates and allows their correlation within error limits of ± 40 kyr. Furthermore, the new $\delta^{13}\text{C}$ curve enables the calibration of boreal and tethyan macro- and microfossil zonations. Accordingly, the Tethyan calcareous nannoplankton boundary NC13/NC14 corresponds to the boreal FO of *C. woollgari*, the index taxon for the Lower-Middle Turonian boundary. The cyclic appearance and the temporal spacing of the small-scale carbon isotope events suggest that orbital forcing exerted control on surface water productivity and organic matter preservation at the sea floor.

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1. Introduction

The Cretaceous was a period of greenhouse climate, when polar ice was mostly absent and the tropics experienced unusual warmth. Numerous studies have demonstrated that marine sedimentation was influenced

by orbital forcing, fast and repeated changes in sea level, the occurrence of oceanic anoxia, as well as sudden and large changes in sea surface temperature, ocean chemistry and marine biota documenting the high degree of Cretaceous climate variability [1–8]. In order to improve our knowledge about the temporal and spatial dimension of processes, it is of great importance to develop stratigraphic tools, which provide a high time resolution and can be applied on a global scale. Biostratigraphic zonation are regional useful stratigraphic tools, but long-range correlations are complicated by climate-zone

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related provincialism of biota, as well as differences in bathymetry and sedimentary facies. To date, large temporal uncertainties exist in the calibration of Late Cretaceous micro- and macrofossil zonations, which have a dimension from hundred thousands to millions of years [9,10].

Carbon isotope stratigraphy has proven as a remarkable tool in stratigraphic correlation, especially in mid-Cretaceous sedimentary successions, where no magnetic reversals can be detected [11–13]. It is shown in numerous studies that the Cenomanian–Turonian carbon isotope curve has significant features, which differ in their magnitude as well as in their long- and short-term variability. The most prominent carbon isotope event is the positive excursion in the Cenomanian–Turonian boundary interval, which is associated to the major oceanic anoxic event OAE 2. The $\delta^{13}\text{C}$ anomaly has a magnitude of 2–3‰, lasted about 400 kyr, and shows detailed features which occur synchronous in various sections worldwide (Western Interior Basin [14,15]; Eastbourne, England [16,17]; Gröbern, Germany [18]; Gubbio, Italy and Tarfaya basin, Morocco [19–21]). Further carbon isotope events, as the Mid-Cenomanian Event (MCE) in the early Middle Cenomanian [22,23] or the Pewsey and Hitchwood Events in the late Turonian [24], are distinctive geochemical marker, which are successfully used for long-range correlation, the detection of sedimentary hiatuses, and the overcoming of biogeographic differences [25–28]. More recently, secular carbon isotope variations are recognised to occur synchronously in geographically widely spaced sections of the English Chalk, and were used to develop a $\delta^{13}\text{C}$ carbonate reference curve for the Cenomanian–Campanian [29].

This study will focus on the recognition of secular carbon cycle variations in the late Cenomanian to early Turonian. The long-term trend of the $\delta^{13}\text{C}$ carbonate curve is characterised by the major positive Cenomanian–Turonian (C–T) excursion, the recovery phase in the earliest Turonian, and the ongoing aftermath in the early and Middle Turonian that is represented by a period of relatively high and stable background values terminated by a sharp decrease [25,28–31]. Here, we will present new high resolution $\delta^{13}\text{C}$ carbonate curves from two expanded basinal successions of the Münsterland Cretaceous Basin in northern Germany (Halle and Oerlinghausen), which recover a stratigraphic complete record of inorganic carbon cycle variations (Fig. 1). The $\delta^{13}\text{C}$ curve shows a distinct cyclicality that will be shown to be orbitally forced by the frequencies of long and short eccentricity. Independent biostratigraphic data based on boreal macrofossil zonation are available for both sections, which will provide the opportunity to

calibrate biostratigraphic dates against distinct features in the $\delta^{13}\text{C}$ carbonate curve.

2. Methods

The basinal successions at Halle and Oerlinghausen provide a continuous sedimentary record of the late Cenomanian to Middle Turonian time interval. Both sections were detailed logged bed-by-bed and sampled in 20 cm intervals for measurements of carbonate and total organic carbon (TOC) content, and carbonate carbon and oxygen isotopic composition. In addition, the carbon isotopic composition of total organic matter was analysed for the black shale succession at Halle. The Halle section was sampled over a 20 m horizon from the Facies Change up to the last two prominent black shale beds associated by the acme occurrence of the inoceramid *Mytiloides mytiloides* (Fig. 2). The succession at Oerlinghausen begins with these two black shales, and was sampled from the base over a horizon of 40 m up to the base of the white limestones of the Weisse Grenzbank“ carbonate maximum, which lies ~6 m beneath the prominent marl layer M Teuto.

A split (750 mg) of powdered sediment samples was acidified by adding HCl in two steps, first a weak solution (~10%), second a stronger solution (~25%) and subsequently neutralized by dilution with de-ionised water. The percentage of CaCO_3 was determined by the dry-weight loss after decalcification, assuming that all carbonate comprised in the samples is calcite. The total organic carbon content is determined by measuring the thermal conductivity of the gaseous products of pyrolysis of a split of the acidified sediment sample (LECO carbon determinator) and the TOC values are calculated as weight percentage. The reproducibility of repeated standard measurements was better than 0.01%. A second split of the decalcified sample was analysed for carbon isotopic composition of organic matter by sample combustion at 950 °C and subsequent measurement of the released CO_2 gas with a Finnigan Delta S mass spectrometer (University of Cologne). The values are given relative to V-PDB and the reproducibility of repeated standard measurements was 0.1‰. Stable isotope analyses of carbonate bulk-rock samples were performed at a reaction temperature of 75 °C using a Finnigan MAT 252 (Erlangen University) with an on-line automated carbonate reaction Kiel III device. All values are reported in ‰ relative to V-PDB and reproducibility is better than 0.08‰ and 0.05‰ for oxygen and carbon.

Spectral analysis was performed for the carbon isotope record of the Oerlinghausen section. The data

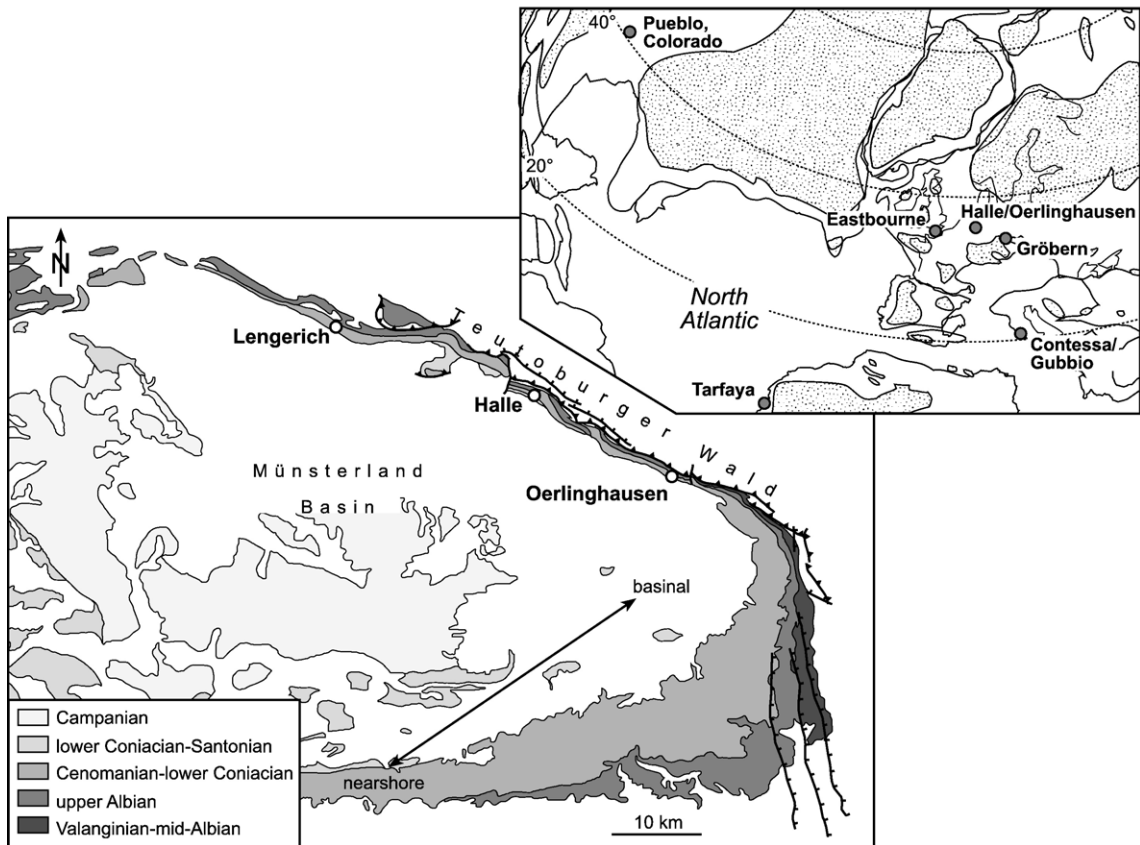


Fig. 1. Palaeogeographic map (a) for the Turonian showing the sections with high resolution carbon isotope stratigraphies mentioned in the text (modified after [31]). (b) Geological map of the Münsterland Cretaceous Basin in northwest Germany with the position of the sections at Lengerich, Halle and Oerlinghausen.

were filtered by LOWESS regression (bandwidths $f=0.2$ and $f=0.15$) and the long-term trend was subtracted from the original data, in order to suppress the dominance of long cycles, which are outside of the Milankovitch frequency band. Power spectra were generated from the residual data sets with the Speclab software package using the Lomb–Scargle algorithm.

3. Geological setting and lithostratigraphy

The studied sections Halle and Oerlinghausen are situated in the central part of the Teutoburger Wald, which lies at the northeast margin of the Münsterland Cretaceous Basin (Fig. 1). The Münsterland Cretaceous Basin forms a depression on Hercynian basement at the northern margin of the Rhenish Massif [32]. The northwest–southeast striking structure of the Teutoburger Wald was uplifted and overthrust during Late Cretaceous and Neogene tectonics forming a chain of outcrops exposing inclined and overthrust Cenoma-

nian–Turonian strata today (Figs. 1 and 2). During Cenomanian and early Turonian times, sedimentation in the Münsterland Cretaceous Basin occurred in a period of relative tectonic quiescence. The Teutoburger Wald area was characterised by higher rates of thermal subsidence forming the distal part of the Münsterland Cretaceous Basin. Basinal successions are exposed in a series of ancient and active cement quarries at Lengerich, Halle and Oerlinghausen and represent a nearly complete and continuous sedimentary record of Cenomanian to Turonian time. Detailed previous litho- and biostratigraphic work enables high resolution correlations between the individual sections [33–37].

Cenomanian–Turonian sediments of epeiric seas in northwestern Germany are dominated by pelagic limestones of the Plänerkalk Group [38]. The lithology in the Upper Cenomanian basinal facies, as it is exposed in the Halle section, is characterised by a sharp facies change from pure white pelagic coccolith limestones to variegated reddish to dark grey coloured marls, black shales

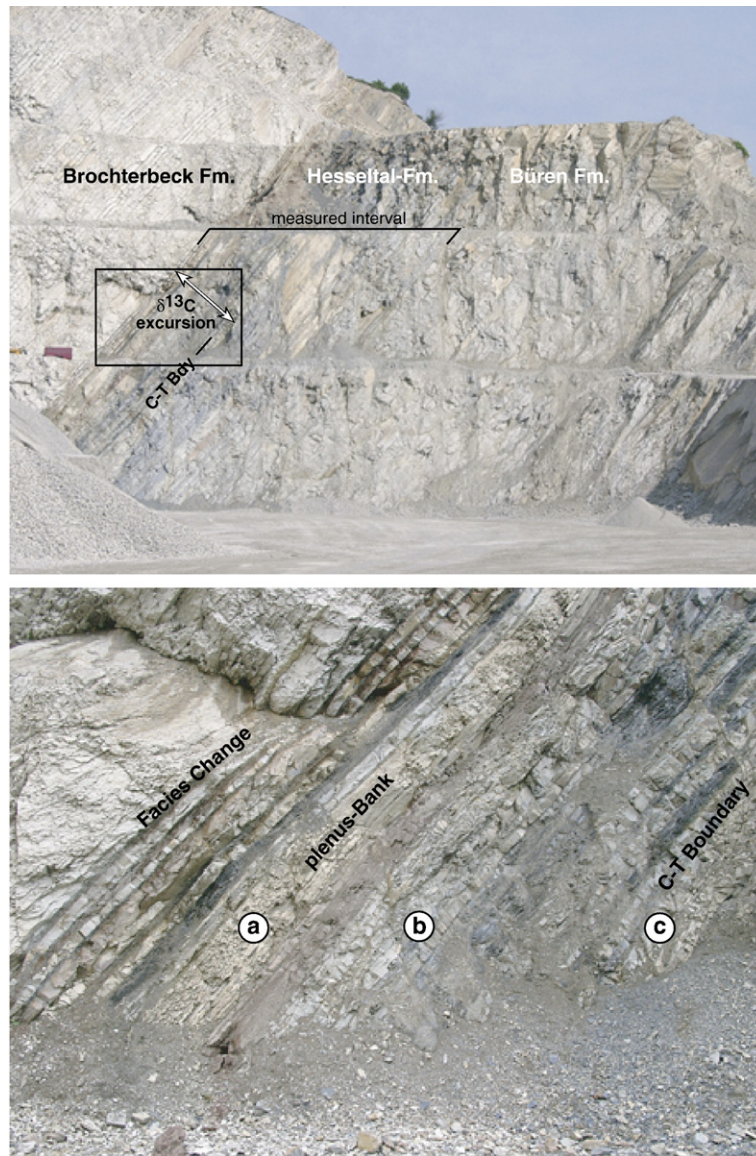


Fig. 2. Outcrop image of the Upper Cenomanian to Lower Turonian horizon at Halle. a) Lithological units of the Brochterbeck Formation (Hoppenstedt Member, former “Arme rhotomagense Schichten”), Hesseltal Formation (“Schwarzbunte Wechselfolge”) and Büren Formation (lower part of the former “Graugrüne Wechselfolge”) after the new definitions of the German Subcommittee on Cretaceous Stratigraphy [40]. The range of the $\delta^{13}\text{C}$ excursion is indicated by the arrow. b) Detail of a) showing the Facies Change, the Plenus Bank and the Cenomanian–Turonian boundary. The letters a, b, and c marks the position of maxima of the carbon isotope excursion.

and limestones. This so-called “Facies Change” marks a European wide lithological marker horizon that represents the commencement of the C–T carbon isotope excursion (Figs. 2 and 3). A prominent limestone bed 1–2 m above the Facies Change (the so-called Plenus Bank) is an additional marker bed for regional correlation in northern Germany. The basal black shale succession is rhythmically bedded and yield black shales (up to 3% TOC) at the base, and more carbonate-rich limestones at the top of each bedding couplet

(Fig. 3). Higher up, the succession grades into grey coloured marls and limestones of early Turonian age, which are exposed in the Oerlinghausen section (Fig. 4). The lower part of these grey limestones yields some horizons with reddish limestones, rich in shell debris of inoceramids. Higher up, the portion of marly horizons decreases (at ~ 10 m), and grey massive and partly nodular limestones with thinner marl seems dominate the succession, which grade into white limestones of the “Weisse Grenzbank” carbonate maximum. The top of

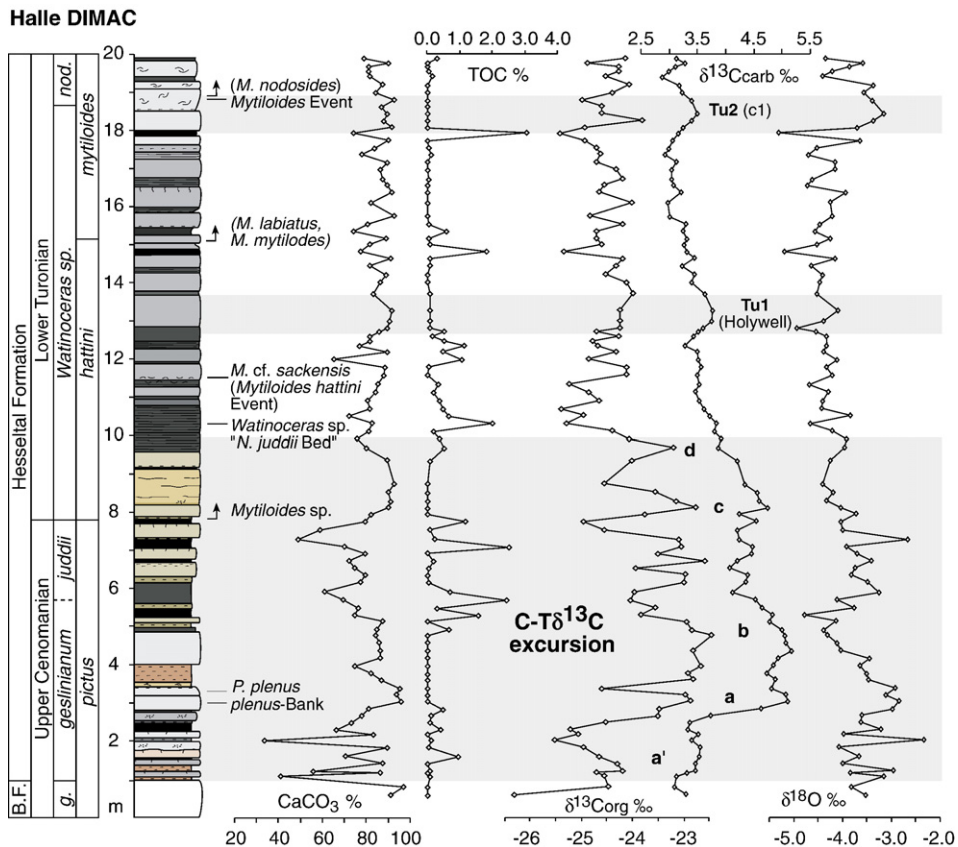


Fig. 3. Upper Cenomanian to lower Turonian carbon and oxygen isotope stratigraphy, biostratigraphy and carbonate and TOC variations of the Halle section in Westfalen. The grey shaded area marks the range of C–T carbon isotope excursion. The carbon isotope event terminology in brackets is from [29]. Occurrences of ammonites and inoceramids are from [67,37]. Macrofossil occurrences in brackets are correlated from equivalent beds at Lengerich. Carbonate and TOC values are expressed as weight percent. Abbreviations: B. F. Brochterbeck Formation, g. — *guerangeri*, nod. — *nodosoides*.

these limestones marks the prominent 20 cm thick marl M Teuto [33].

Traditionally, the Upper Cenomanian–Middle Turonian basal successions in the Teutoburger Wald area are divided threefold into the lithological units “Arme rothomagensche Schichten”, “Schwarzbunte Wechselfolge”, “Graugrüne Wechselfolge”, and “untere Plänerkalkstein–Einheit” [39]. In order to introduce a common lithostratigraphic nomenclature of Upper Cretaceous deposits in northern Germany, the German Subcommission on Cretaceous Stratigraphy divided these lithological units into the Brochterbeck Formation (parts), the Hesseltal Formation, the Büren and the Oerlinghausen (parts) Formations (Figs. 2–4)[40].

4. Biostratigraphy

The sections in the Teutoburger Wald area are subject of detailed biostratigraphic investigations for decades.

Usually, the Cenomanian–Turonian limestones of northern Germany are zoned by inoceramids and acme-occurrences of macrofossils, the so-called bioevents [38,41]. Ammonite occurrences are rare, however, some ammonite records are described from the Münsterland Cretaceous Basin, which allows an integrated biozonation of inoceramids and ammonites, especially in the basal successions.

The most detailed macrofossil collection was performed in the expanded basal section at Lengerich [34,37]. The late Cenomanian index ammonite *Metoicoceras geslinianum* is recorded here from the basal part of the Plenus Bank [37]. The base of the *geslinianum* ammonite zone is placed at the Facies Change by convention, in analogue to the zonation in the English Chalk. The Plenus–Bank is called after the belemnite *Praeactinocamax plenus*, a European wide marker for an intermittent period of cool-water conditions [42]. *P. plenus* is very rare in basal parts of the Münsterland

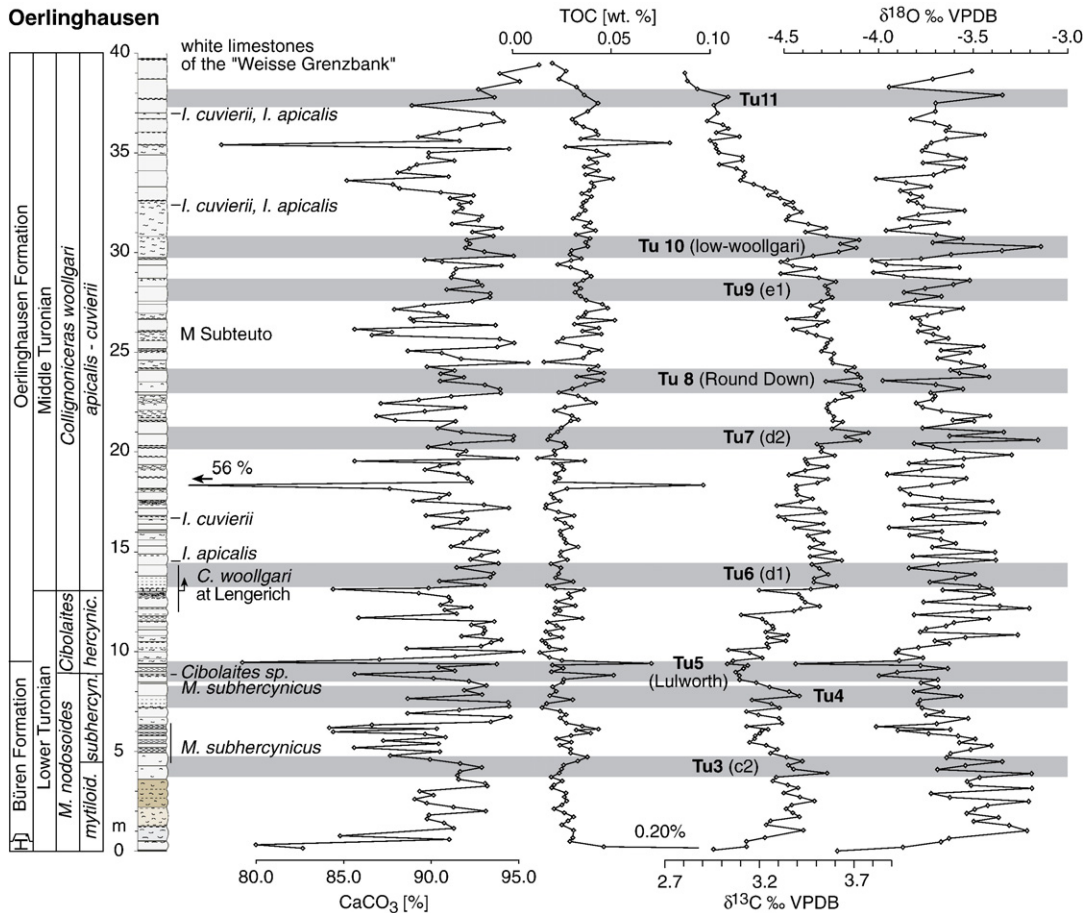


Fig. 4. Lower to lower Middle Turonian carbon and oxygen isotope stratigraphy, ammonite and inoceramid zonation, and carbonate and TOC variations of the Oerlinghausen section, Westfalen. Carbon isotope event terminology in brackets is from [29]. Grey shaded areas indicate the length of small-scale isotope events. H. — Hesseltal Formation.

Cretaceous Basin, but single records are described from the uppermost part of the Plenius Bank at Halle (Diedrich 1996 in [37]) and at Borgholzhausen [43].

The occurrence of the latest Cenomanian zonal ammonite *Neocardioceras juddii* is described from the main black shale bundle of the Hesseltal Formation, and was also termed as “*N. juddii* Bed” in older literature [35,44], (Fig. 3). More recently, Lehmann [37] observed the “*N. juddii* Bed” to occur above the C–T carbon isotope excursion at Lengerich. The Cenomanian–Turonian Boundary is defined by the first occurrence (FO) date of the Turonian ammonite genus *Watinoceras*, which lies in the upper part of the $\delta^{13}\text{C}$ anomaly at the global stratotype in Pueblo, Colorado and the European reference section at Eastbourne [45,46]. Thus, the vertical range of *N. juddii* is limited to the plateau phase of the $\delta^{13}\text{C}$ excursion. Lehmann [37] argued, therefore, that the ammonite specimens occurring in the “*N. juddii* Bed” could belong to the genus *Watinoceras*,

which is hardly to distinguish from *N. juddii* in black shale facies. Additional evidence for a Turonian age of the “*N. juddii* Bed” comes from the occurrence of inoceramid specimens of the genus *Mytiloides* [35]. At the global stratotype, the inoceramid *Inoceramus pictus* disappears and the inoceramid *Mytiloides hattini* appears two beds beneath the FO of *Watinoceras* [45]. The FO date of *M. hattini* in Westfalen is also below the “*N. juddii* Bed”, which argues for a lower position of the Cenomanian–Turonian Boundary [37]. At Halle, the Cenomanian–Turonian Boundary is placed at 7.8 m with the FO date of *Mytiloides* sp. (Fig. 3).

An acme occurrence of *M. cf. sackensis* at 11.5 m at Halle [33] correlates with the *M. hattini* Event at Lengerich [37]. The FO date of *M. labiatus* is recognised in bed 155 at Lengerich, and occurs 3.3 m beneath the FO date of the early Turonian zonal ammonite *Mammites nodosoides* at the level of the first mass occurrence of *Mytiloides labiatus* and *M. mytiloides* [35,37]. The

Mytiloides Event (*Mytiloides* Event 1 of Ernst et al. [38], *Mytiloides* Event s. str. of Kaplan [35]) is interpreted as a tempestite and occurs in Halle at 19 m (Fig. 3).

The uppermost Lower Turonian strata in the basal facies of Westfalen is characterised by shell beds with abundant occurrences of the inoceramids *M. subhercynicus* and *M. hercynicus*. At Lengerich, two distinct shell beds are developed, of which the lower one is characterised by the occurrence of the ammonite genus *Cibolaites*, which is a precursor of *Collignonicerases*, and the upper one by the FO of the index ammonite *Collignonicerases woollgari*, which marks a Middle Turonian age [35]. The lower shell bed with the occurrence of *M. hercynicus* and *Cibolaites* sp. is also recorded from the Oerlinghausen section in a marly horizon at 9 m (Fig. 4). No ammonite records are known from the beds above this horizon. However, it is reasonable to correlate the *M. hercynicus* and *Cibolaites* occurrence from Lengerich. Consequently, the FO of *C. woollgari* in Oerlinghausen should lie about 3–5 m above the *Cibolaites* occurrence at the level between 12–14.5 m (Fig. 4). The occurrence of the inoceramids *Inoceramus apicalis* at 14.5 m and *Inoceramus cuvieri* at 16.6 m provides sure evidence for a Middle Turonian age at this level. The subsequent following grey limestones up to the “Weisse Grenzbank” carbonate maximum yield specimens of the inoceramids *I. cuvieri* and *I. apicalis*. The first occurrence of the species *I. lamarcki* lays ~1.5 m beneath the marl M Teuto at Oerlinghausen, which is about 5 m above the summit of our sampled interval (Fig. 4) [47].

5. Carbon isotope stratigraphy

5.1. Halle

The Hesseltal Formation is one of the classic sedimentary successions from which the C–T carbon isotope excursion originally was described (e. g. at Wunstorf [48], Misburg [49], and Lengerich [50]). The classic outcrop localities are not completely accessible anymore, which makes the Halle quarry to be the best exposed succession of the Hesseltal Formation today. Here, we present the first high-resolution carbon isotope records of carbonates and organic matter from the black shale facies of northern Germany. The carbon isotope stratigraphy shows all diagnostic features of the C–T carbon isotope anomaly, which are well recognised from expanded sections such as the international stratotype at Pueblo, Colorado or the European reference section at Eastbourne [14–17,19]. Especially the three distinct maxima (“a”, “b”, and “c”, Fig. 3) are

well developed at Halle and allow detailed long-range correlation.

Carbonate carbon isotope values increase slightly above the Facies Change from 3.1 to 3.5‰ (a’), and decrease to 3.4‰ in the black shale at 2.5 m. Above the black shale, a prominent $\delta^{13}\text{C}$ increase of 1.7‰ culminates in the Plenus Bank in the first maximum (a). Subsequently, $\delta^{13}\text{C}$ values decrease in the uppermost Plenus Bank to form a minimum in the reddish marl layer above, and rise toward the second maximum (5.2‰) in the limestone bed at 4.4 m (b). The “b”-maximum is followed by a decline of $\delta^{13}\text{C}$ values to 4.1‰ in the black shale at 5.9 m, where the curve describes an inflection towards stable values of ~4.3‰. At 8.1 m, the $\delta^{13}\text{C}$ values form the third maximum (c, 4.7‰) and decline afterwards steadily until a black shale layer at 12.4 m. The horizon between 12.4 m and 14.0 m is characterized by a small-scale positive $\delta^{13}\text{C}$ excursion with a magnitude of 0.5‰ (Tu1, Holywell Event of [29]). Afterwards, the decline of the C–T excursion continuous from 14.0 m to 17.4 m with $\delta^{13}\text{C}$ values dropping from 3.4‰ to 2.9‰. A further small-scale positive 0.5‰ excursion describes a maximum at the level of the first acme occurrence of *M. mytiloides* and *M. labiatus* between 17.4 m and 19.4 m (Tu2).

The $\delta^{13}\text{C}$ record of organic matter resembles the overall trend of carbonate carbon isotopes, but shows a higher degree of variability. The most prominent difference is that the $\delta^{13}\text{C}_{\text{org}}$ signal of the C–T excursion shows a late positive peak when the $\delta^{13}\text{C}_{\text{carb}}$ values already tend to decline (d). At horizons, which are characterised by small-scale minima in the carbonate carbon isotope curve, the $\delta^{13}\text{C}_{\text{org}}$ values display sudden decreases with magnitudes of 1.3–1.6‰ during, and of ~1.0‰ after the C–T excursion. In the course of the C–T carbon isotope anomaly, these negative spikes occur beneath the first a’ peak (0.9 m), beneath and above the first major $\delta^{13}\text{C}$ rise (2 m and 3.5 m), above the “b” maximum (5.3 m), and below the “c” and “d” maxima (7.8 m and 8.7 m). The negative spikes are frequently related to beds with elevated TOC values and tend to precede the carbonate $\delta^{13}\text{C}$ signal by 20–40 cm (Fig. 3). A higher degree of $\delta^{13}\text{C}$ variability in organic matter is also recorded from other European Cenomanian–Turonian Boundary sections (Eastbourne [46], Gröbern [18]), where negative $\delta^{13}\text{C}_{\text{org}}$ excursions occur at similar stratigraphic levels. All these shelf sections have in common that the concentration of organic matter is relative low (mostly 0.1–0.5%) and the magnitude of the $\delta^{13}\text{C}_{\text{org}}$ excursion (~3.0‰) is similar as the magnitude of carbonates (~2.5‰), which suggests that it mainly reflects the inorganic carbon cycle perturbation. The

sections represent a shallow environment, where the organic matter composition is controlled by both, marine productivity and terrestrial input, and changes in the partitioning between both could explain the higher $\delta^{13}\text{C}_{\text{org}}$ variability. However, small-scale negative peaks in the $\delta^{13}\text{C}_{\text{org}}$ signal (1–2‰) are also recorded from deep-marine sections and from sections with higher TOC concentrations and a higher magnitude of the $\delta^{13}\text{C}_{\text{org}}$ anomaly (up to 6‰ at Tarfaya [20], Demerara Rise [51] and Pueblo [14]). Here, the high magnitude of the $\delta^{13}\text{C}_{\text{org}}$ excursion is attributed to a reduced carbon isotopic fractionation of the phytoplankton as a consequence of CO_2 depletion in high-productivity regimes of upwelling zones [52,53]. The repeated occurrence of the small-scale negative $\delta^{13}\text{C}_{\text{org}}$ peaks in a broad variety of marine settings seems to be a common and global feature of the C–T $\delta^{13}\text{C}$ anomaly and possibly indicates an orbital control on production, isotopic composition and/or preservation of organic matter.

5.2. Oerlinghausen

The carbon isotope stratigraphy at Oerlinghausen extends the Halle record into the Lower and Middle Turonian. Carbon isotope stratigraphies of this time interval are characterised by relative high $\delta^{13}\text{C}$ values of 3.0–3.6‰ in several European successions forming a long plateau that ends with a sharp decline in the lower Middle Turonian (English Chalk: [11], Saxony and Lower Saxony Basins: [25], North Cantabrian Basin: [27], Umbria–Marche Basin: [19,28]). More recently, Jarvis et al. [29] recognised a significant $\delta^{13}\text{C}$ inflection from falling to rising $\delta^{13}\text{C}$ values within the long $\delta^{13}\text{C}$ plateau in the English chalk. The authors named this $\delta^{13}\text{C}$ inflection “Lulworth Isotope Event”. Additional isotope events are recognised in England as positive excursions at the end of the $\delta^{13}\text{C}$ plateau, and are named “Round Down Isotope Event” and “Low-woollgari Isotope Event” [29]. The latter marks the inflection to steeply falling $\delta^{13}\text{C}$ values, which is a prominent feature of the $\delta^{13}\text{C}$ curve in the Middle Turonian.

The high-resolution carbon isotope stratigraphy at Oerlinghausen resolves the carbon isotope events of Jarvis et al. [29] with high accuracy and shows additional features, which are unrecognised so far (Fig. 4). Therefore, we introduce a new nomenclature of carbon isotope events by numbering the Turonian isotope events from the bottom to the top, and place the English names in brackets. The negative $\delta^{13}\text{C}$ inflection of Isotope Event Tu5 (Lulworth) occurs in a more marly interval at 9 m together with the occurrence of the ammonite genus *Cibolaites*. Isotope Event Tu8 (Round

Down) is characterised by a small 0.2–0.3‰ positive excursion at 23–24 m and is overlain by a distinct marl layer (M Subteuto). Isotope Event Tu10 (Low-woollgari) terminates the early Turonian interval of relative stable and elevated $\delta^{13}\text{C}$ values, and is represented in Oerlinghausen by a distinct 0.5‰ positive excursion prior steeply falling $\delta^{13}\text{C}$ values that occur in a horizon of more nodular limestones at 30–31 m.

Above Event Tu10, carbon isotope values steeply decline from 3.7‰ to 3.1‰ up to an inflection at 34.4 m, from where the decline succeeds more moderately up to a value of 3.0‰ at 37.8 m. At this level, the $\delta^{13}\text{C}$ values again decrease sharply. The renewed shift to more steeply falling $\delta^{13}\text{C}$ values occurs below the transition from grey to white limestones at the base of the “Weisse Grenzbank” carbonate maximum (39.8 m). This inflection (Tu11) can be recognized at several localities in the Lower Saxony Basin (Söhlde [25], Hoppenstedt [54]) and is also seen in the English localities Culver and Dover [29].

In addition to the isotope events of Jarvis et al. [29], the $\delta^{13}\text{C}$ curve at Oerlinghausen displays a cyclic pattern of variability with maxima at 4 m (Tu3), 14 m (Tu6), 21–23 m, and 30–31 m (Tu10), and minima at 0 m, 9 m (Tu5), 16.5–17.5 m, 26–27 m, and 35–36 m showing a cycle length of ~ 9 m. The carbon isotope minima correspond to horizons with lower carbonate values and bundles of marl layers. Superimposed on the 9 m cycle, several small-scale positive $\delta^{13}\text{C}$ peaks occur at 7.8–8.0 m (Tu4), 10.5–11.0 m, 12.0–12.5 m, 20.5–21 m (Tu7), 23–24 m (Tu8), and 28–28.5 m (Tu9) and represent maxima of less clear developed cycles with a length of 2–3 m (Fig. 5a). Some of them can be related to subsidiary $\delta^{13}\text{C}$ dates of Jarvis et al. [29] (Figs. 4 and 6). Results of spectral analysis of the carbon isotope data show distinct peaks at 9 m and 2–3 m (Fig. 5b). The average sedimentation rate of pelagic carbonates in epicontinental shelf sea settings is in the order of 20–30 m/Myr. Assuming a sedimentation rate of 22 m/Myr, the observed cycles at 9 m and 2–3 m would correspond to the 405 kyr and 100 kyr cycle of the long and short eccentricity, which suggests that eccentricity exerted control on carbon cycle variations. An orbital forcing of global carbon cycle variations was previously documented for the Palaeogene [55,56] and Neogene [57], and is also suggested to modulate small-scale features of the C–T excursion [18].

6. Boreal-tethys carbon isotope correlation

The late Cenomanian to Middle Turonian composite carbon isotope record of Halle/Oerlinghausen has the highest temporal resolution that is available for boreal

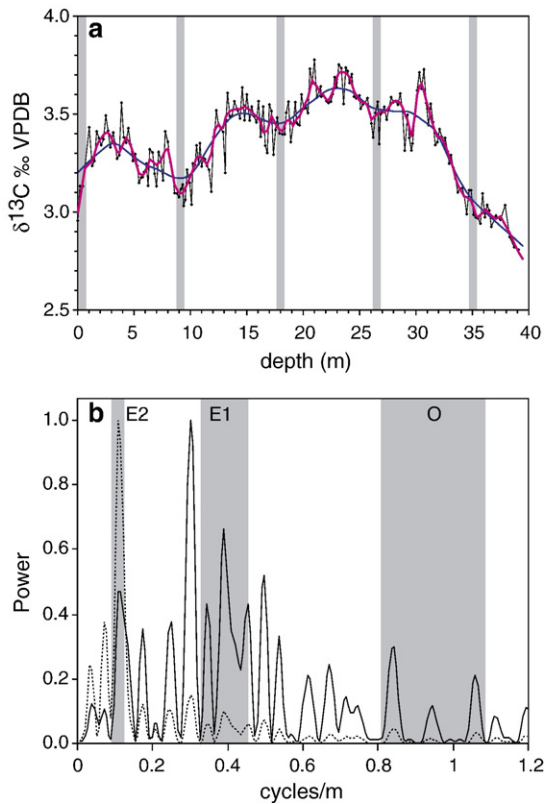


Fig. 5. Analysis of cyclicities in the carbon isotope record of Oerlinghausen. a) LOWESS regression of the $\delta^{13}\text{C}$ data with two different bandwidth ($f=0.15$ and $f=0.03$) resolves a long (blue line) and short-term (red line) cyclicality. Note the 9 m and 2–3 m spacing of individual cycles. b) Power spectra of two filters of the original $\delta^{13}\text{C}$ data (stippled line: $f=0.2$, solid line: $f=0.15$) from which the long-term trends has been subtracted. The estimated sedimentation rate is 22.1 m/Myr and the 9 m and 2–3 m cycles correspond to the 405 kyr and 100 kyr cycle of long and short eccentricity. (For interpretation of the reference to colour in this figure legend, the reader is referred to the web version of this article.)

successions to far, and resolves several distinct small-scale features, which are useful markers for high resolution carbon isotope correlation (Fig. 6). Carbon isotope stratigraphies of comparable time resolution are published from two Tethyan sections at Contessa and Gubbio in the Umbria–Marche Basin, Italy [19,28]. The Tethyan sections expose a stratigraphic continuous pelagic carbonates succession consisting of micritic limestone, rich in calcareous nannofossils and planktonic foraminifera, with common intercalations of cherts and small marl seams. The lower Turonian succession is characterised by the transition from the Scaglia Bianca (white limestones) to the Scaglia Rossa (reddish limestones) Formations (e. g. [58]).

The pattern of early to Middle Turonian small-scale carbon isotope variability in the Tethys is surprisingly

similar to the small-scale features recorded from the boreal composite section at Halle/Oerlinghausen (Fig. 6). Linear scaling of sedimentary thicknesses and corresponding $\delta^{13}\text{C}$ curves from Italy and Germany between the Isotope Events Tu1 and Tu11 results in a close coincidence of both carbon isotope stratigraphies showing a congruent shape of their relative long-term trend and a consistent stratigraphic position of minor positive and negative excursions. This coincidence of carbon isotope variability argues for the stratigraphic completeness of both successions providing a detailed archive of changes in the global carbon cycle.

Some of the Early-to-Middle Turonian carbon isotope events are defined in the English Chalk, mainly based on the $\delta^{13}\text{C}$ stratigraphy of the Culver Cliff section [29]. This isotope record is of lower temporal resolution and possibly not continuous, but most of the isotope events can be correlated with certainty to the carbon isotope stratigraphies in Germany and Italy (Fig. 6). The precise position of FO dates of boreal macrofossil index taxa with respect to carbon isotope events will allow their correlation with FO dates of the Tethyan nannofossil zonation.

6.1. C–T carbon isotope excursion

The positive carbon isotope excursion of the Cenomanian–Turonian Boundary interval is the expression of one of the major oceanic anoxic events (OAE 2), which occurred during Mesozoic times. The excursion is described worldwide in carbonates and marine and terrestrial organic matter. Detailed C–T carbon isotope curves of marine carbonates show distinct minor variations, which occur stratigraphic consistent on a global scale. The identification of these minor peaks in organic matter, however, is rather difficult and resulted in variable descriptions and definitions of the excursion by different authors. Frequently, the commencement of the C–T carbon isotope excursion is defined with the first main $\delta^{13}\text{C}$ increase (“a”, [15,59]). In Western Europe, the commencement $\delta^{13}\text{C}$ anomaly is defined with the Facies Change, where a small-scale $\delta^{13}\text{C}$ increase (a′) precedes the main $\delta^{13}\text{C}$ rise. This feature is also observed at the stratotype in Colorado and is therefore of global significance [14,46]. The following features, a small trough interval, the second rise (“b” maximum) and the broad plateau that ends with the “c” peak, are recognised in nearly all expanded Cenomanian–Turonian boundary successions [19]. A difficulty exists in the definition of the termination of the $\delta^{13}\text{C}$ excursion. The last $\delta^{13}\text{C}$ maximum, which describes the end of the plateau phase (close to the C/T-boundary), is

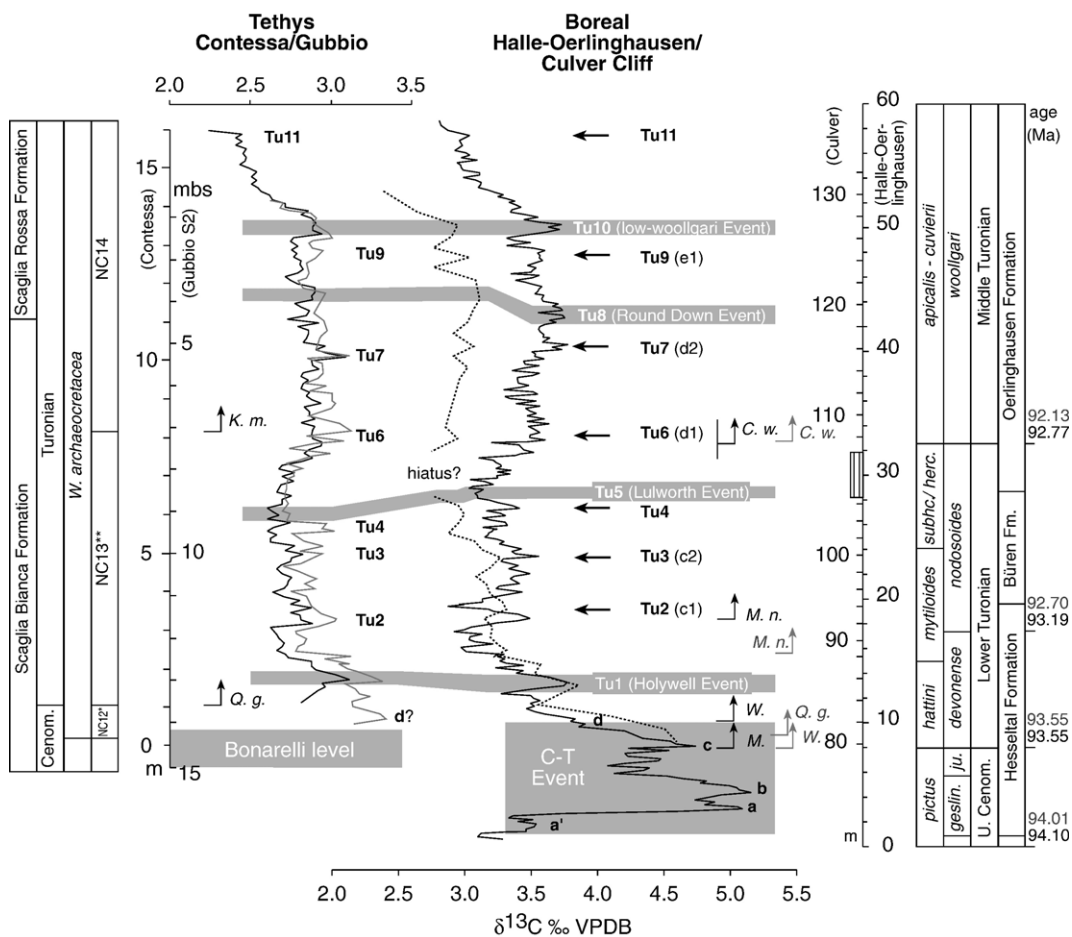


Fig. 6. High resolution Boreal–Tethys correlation based on the late Cenomanian to Mid-Turonian carbon isotope stratigraphies of the composite sections Halle/Oerlinghausen (right curve, solid line), the Culver Cliff section (stippled line; [29]), the section at Contessa (left curve, black line; [28]) and the Gubbio S2 core (grey line; [19]). All carbon isotope stratigraphies are plotted versus depth. The depth scales mark the original metres in the studies of [19,28,29]. The position of the Bonarelli Horizon refers to the Gubbio S2 core. Grey shaded areas show the correlation of carbon isotope events of [29]. Carbon isotope event names in brackets are from [29]. Horizontal arrows indicate the position of subsidiary carbon isotope events. The Tethyan FO dates are from the Gubbio S2 core [19]. The boreal FO dates are from the Münsterland Cretaceous Basin (black [35,37]) and from the English Chalk (grey) with respect to carbon isotope stratigraphy [29]. Ages refer to the GTS 2004 (grey) [67], and to the orbital timescale (black) [14]. Abbreviations: *Q. g.* — *Quadrum gartneri*, *K. m.* — *Kamptnerius magnificus*, *M.* — *Mytiloides* sp., *W.* — *Watinoceras* sp., *M. n.* — *Mammites nodosoides*, *C. w.* — *Collignoniceras wooligari*, *hercyn.* — *hercynicus*, *geslin.* — *geslinianum*, *ju.* — *juddii*.

not synchronous in different depositional settings due to the widespread occurrence of sedimentary hiatuses at this level or due to differences in carbon isotope stratigraphies of carbonates and organic matter as it is illustrated in Halle (Fig. 6). Biostratigraphically, the end of the $\delta^{13}\text{C}$ excursion is of early Turonian age, because the FOs of *Watinoceras* sp. lies in the uppermost plateau phase at the GSSP in Pueblo and at Eastbourne [46].

6.2. Tu1 (Holywell) event

The first early Turonian carbon isotope event is the Tu1 (Holywell) Event. Tu1 corresponds to the Holywell

Marls 4 and 5 in southern England [29] and consists of a positive 0.2–0.5‰ excursion, which lies superimposed on the carbon isotope decline after the C–T excursion. Biostratigraphically, the Tu1 Event is placed after the FO of *Q. gartneri* in both tethyan and boreal sections, and before the FO dates of *M. labiatus* and *M. mytiloides* in Westfalen and the English Chalk. Furthermore, an acme occurrence of *M. hattini* is described from the beds below Tu1 in Westfalen [37], which is similar to an occurrence of *M. cf. sackensis* at Eastbourne [46].

The basal positive excursion at Gubbio and Contessa lies ~1 m above the FO of *Q. gartneri* and is interpreted

as the expression of Event Tu1 (Fig. 6). Originally, the high $\delta^{13}\text{C}$ values of $\sim 3.0\text{‰}$ and the position of this peak only ~ 1.5 m above the top of the Bonarelli Horizon gave reason for the assumption, that this peak is still part of the C–T carbon isotope excursion (“c” Peak) and marks the end of the plateau phase [19]. Our new interpretation of this peak as Event Tu1 is justified by the following reasons: 1) The linear scaling of sedimentary thickness in the sections Contessa, Gubbio and Oerlinghausen results in an almost perfect match in the shape of all three carbon isotope curves and a similar relative position of each small-scale isotope event (Fig. 6). This coincidence argues for a continuous and uninterrupted early Turonian sedimentation at all localities. 2) The magnitude of the C–T $\delta^{13}\text{C}$ excursion is worldwide in the order of 2.5–3‰ in the inorganic carbon reservoir, and usually results in $\delta^{13}\text{C}$ values of 4–4.5‰ for the “c” Peak in European shelf seas. If the lowermost peak at Gubbio would be still part of the $\delta^{13}\text{C}$ anomaly, the magnitude of the inorganic $\delta^{13}\text{C}$ excursion would be distinctly smaller at Gubbio than elsewhere in Europe. However, the equivalent of the Bonarelli Horizon in Sicily (Calabianca section), shows a normal pelagic carbonate signal (values of 4–5‰) for the $\delta^{13}\text{C}$ anomaly [60]. Tsikos et al. [19] presented a $\delta^{13}\text{C}$ record of organic matter from Gubbio with a magnitude of 3.5‰ for the C–T $\delta^{13}\text{C}$ excursion, which is in the same order as it is documented for the Halle section (this study), or for the sections at Eastbourne [46] and Gröbern [18]. It is therefore reasonable to assume a magnitude of 2–3‰ for the inorganic C–T excursion at Gubbio. If the “c” Peak of the C–T excursion would be preserved at Gubbio, it should have a minimum value of $\sim 3.7\text{‰}$, which is not recorded. The lower peak at Gubbio and Contessa is therefore interpreted as the Tu1 Event. A consequence of this reinterpretation is the presence of a hiatus on top of the Bonarelli Horizon. The hiatus comprises the plateau phase of the C–T carbon isotope excursion and approximates the range of the boreal *N. juddii* zone.

Similar $\delta^{13}\text{C}$ peaks, which occur after the C–T excursion and are probably representatives of the Tu1 Event, are described from Demerara Rise in the tropical North Atlantic (peak F at Sites 1258 and 1260 [51], from the GSSP at Pueblo (below Bed 90 [14], and the Tarfaya basin (Core S75, depth 71 m [20]).

6.3. Events Tu2 to Tu5 (Lulworth)

The Tu5 (Lulworth) Event is defined as an inflection from falling to rising $\delta^{13}\text{C}$ values and occurs close to the Lulworth Marl in England [29]. The precise stratigraphic position of Tu5 differs slightly among different English

localities, and lies in bedding couplet F1 (Lulworth Marl and *Roveacrinus* Bed 2) at Culver, but in bedding couplet E 52 at Dover. The FO of the Middle Turonian index ammonite *C. woollgari* is recorded in England from beds above the Lulworth Marl (1–2 m at Glyndebourne, C. J. Wood, pers. comm.) and was transferred to the carbon isotope record at Culver [29]. The Lulworth Marl marks a facies shift from inoceramid rich, nodular chalk to soft white chalk, and possibly represents a sedimentary hiatus in England (pers. comm. C. J. Wood). The definition of the Tu5 Event in a probably incomplete succession makes it difficult to correlate this event with certainty to the more continuous sections of Oerlinghausen or Contessa and Gubbio. Here, we follow the isotopic definition, and place the Tu5 Event in the inflection from falling to rising $\delta^{13}\text{C}$ values, which occurs at the same stratigraphic level in Gubbio, Contessa and Oerlinghausen (Fig. 6). This level lies below the Tu5 Event as it is defined at Culver. The interval between these two horizons could correspond to the length of the sedimentary hiatus in England.

Jarvis et al. [29] observed two subsidiary isotope events (Tu2 (c1), bedding couplet E 37; and Tu3 (c2), bedding couplet E 44) in the interval between Tu1 and Tu5. The isotope records of Oerlinghausen and Gubbio/Contessa are of higher resolution and display more variability than that of Culver. Nevertheless, the Tu2 and Tu3 events can be identified in all sections. In addition, a third event (Tu4) is resolved in Oerlinghausen and Gubbio/Contessa, as well as in Culver, and forms a small positive carbon isotope excursion below Tu5. The Tu2 Event can be related to biostratigraphic data. It occurs slightly above the FO of *Mammites nodosoides* and below the abundant occurrence of *M. mytiloides* in England, and occurs at the first acme occurrence of *M. mytiloides* approximately at the level of the FO of *M. nodosoides* in Westfalen. Thus, the isotope event Tu2 can be used as an independent geochemical feature for correlation with Tethyan sections.

6.4. Events Tu6 to Tu8 (Round Down)

The Tu8 (Round Down) Event marks a carbon isotope maximum (0.1–0.2‰ positive excursion) in the low *C. woollgari* zone close to the end of the early Middle Turonian $\delta^{13}\text{C}$ plateau of relative high and stable $\delta^{13}\text{C}$ values [29]. In England, the Tu8 Event is overlain by the Round Down Marl, a widely distributed distinctive marker bed. Outside of England, Tu8 can be identified by its relative position in the upper third of the early Middle Turonian $\delta^{13}\text{C}$ plateau between the $\delta^{13}\text{C}$ rise after Tu5 and the termination associated with the $\delta^{13}\text{C}$

peak and inflection of the Tu10 Event (Figs. 4 and 6). A prominent marl layer also occurs above Tu8 at Oerlinghausen (marl M Subteuto) and correlates possibly with the Round Down Marl in England. In the Umbria Marche basin, the pelagic limestones are characterised by the prominent colour change from the white Scaglia Bianca to the red Scaglia Rossa Formation. At Gubbio, this transition occurs at 4.3 m, shortly beneath Tu8. Here, the $\delta^{13}\text{C}$ event is not characterised by a positive peak but by a distinctive inflection to lower $\delta^{13}\text{C}$ values (Fig. 6).

Two subsidiary $\delta^{13}\text{C}$ events (Tu6 (d1) and Tu7(d2)) are recorded from the early Mid-Turonian $\delta^{13}\text{C}$ plateau between the Events Tu5 and Tu8 in England, but are not resolved with respect to cyclostratigraphy [29]. Linear scaling of the low-resolution $\delta^{13}\text{C}$ curve of Culver between the $\delta^{13}\text{C}$ peak and inflection of Tu10 and the $\delta^{13}\text{C}$ rise after Tu5 shows these subsidiary events to be stratigraphic consistent with small-scale positive excursions in Oerlinghausen, Gubbio and Contessa (Fig. 6).

6.5. The Tu6 event — a marker for the Lower–Middle Turonian substage boundary?

The definition of substage boundaries, such as the Lower–Middle Turonian boundary, is hindered in tropical–subtropical (Tethyan) and deep sea sections because of the absence of boreal macrofossils. Independent zonations based on planktonic foraminifera and calcareous nannoplankton were developed for this regions [9,61–64], but a reliable calibration of Tethyan and Boreal micro- and macrofossil zonations is a matter of ongoing debate. The high-resolution carbon isotope stratigraphy of this study will provide evidence for the correlation of the Lower–Middle Turonian substage boundary between established tropical–subtropical and temperate-boreal biozonations.

The base of the Middle Turonian is defined by the FO of *C. woollgari*, and the Lower–Middle Turonian boundary is placed at the base of Bed 120 in the stratotype at Pueblo [45,65]. In England, the earliest known record of *C. woollgari* comes from a horizon 1–2 m above the Lulworth Marl (see above), and in Westfalen, the common occurrence of *C. woollgari* and *M. hercynicus* is reported 5 m above a bed with *M. subhercynicus* and *Cibolaites* sp. from Lengerich [35]. The *M. subhercynicus* and *Cibolaites* sp. bed occurs in Oerlinghausen at the level of Event Tu5 and the FO of *C. woollgari* can be expected to occur in the beds 3–5 m above. The FO of *C. woollgari* correlates with Event Tu6 in England and Westfalen, thus, we can state nearly identical FO ages in both areas.

Tsikos et al. [19] provided a calcareous nannoplankton zonation for the Gubbio S2 core and shows the FO of the calcareous nannoplankton species *Kamptnerius magnificus* to occur at 7 m. This horizon also corresponds to Event Tu6 in the carbon isotope stratigraphy. Consequently, the tethyan FO of *K. magnificus* coincides with the FO of the boreal ammonite *C. woollgari*. The FO of *K. magnificus* marks the boundary between the NC13–NC14 zones [63] and the IC53–IC54 zones [55]. Whereas the two zonations mainly focus on occurrences of calcareous nannofossil at low latitudes, Burnett [9] provided an overview of Late Cretaceous calcareous nannofossil zonations on a global scale. According to her accounts, the FO of *K. magnificus* lies close to the FO of *Eiffellithus eximius*, but is below the FO of *E. eximius* at low-latitudes and in southern Oceans and above it at northern temperate and boreal localities. This observation suggests that either *E. eximius* or *K. magnificus* have diachronous FO ages in different climate zones or different oceanic basins. At the current state of knowledge, we only can state that the FO of *K. magnificus* in the low-latitude Tethys coincides with the FO of *C. woollgari* in temperate to boreal shelf seas. Further high resolution carbon isotope studies in different climate zones are needed in order to distinguish isochronous from diachronous FO ages. However, the high-resolution carbon isotope curve of this study shows that the significant $\delta^{13}\text{C}$ inflection of Event Tu5 in combination with the subsequent rise to the level of Event Tu6 can be used as a geochemical marker in addition to biostratigraphy for the definition of the Lower to Middle Turonian substage boundary.

6.6. Events Tu9, Tu10 (low-woollgari) and Tu11

The Tu10 (low-woollgari) Event marks the termination of the long early Middle Turonian $\delta^{13}\text{C}$ plateau and forms a small maximum or inflection towards steeply falling carbon isotope values (Fig. 6) [29]. It lies in the lower *woollgari* zone and can fall together with Tu8 in more condensed sections. In England, the Event Tu10 occurs in the horizon between the Round Down and New Pit Marls above the FO of the inoceramid *I. cuvieri*. At Oerlinghausen, the event is accompanied by more nodular limestones, which yield abundant occurrences of the inoceramids *I. cuvieri* and *I. apicalis*. Event Tu10 is not marked by biostratigraphic dates in Italy, but the $\delta^{13}\text{C}$ inflection is a very distinct feature (Fig. 6). Smaller subsidiary events occur below (Tu9 (e1)) and above (Tu11) Event Tu10. Both are characterised by small-scale maxima or inflections and are visible in the records of Westfalen and Italy.

7. Conclusions

The late Cenomanian to early Middle Turonian composite $\delta^{13}\text{C}$ record of Halle Oerlinghausen resolves 11 distinct small-scale isotope excursions in addition to the C–T $\delta^{13}\text{C}$ anomaly. The high temporal resolution refines the shape and magnitude of isotope events recorded previously from the English Chalk [29]. The studied sedimentary succession in Westfalen comprise a period of 2.6 Myr using the astronomical timescale [14] or of 3.9 Myr using the geological timescale GTS 2004 [66] (Fig. 6). The detection of the long and short eccentricity signal (9 m and 2–3 m cycles) in the $\delta^{13}\text{C}$ record of Oerlinghausen confirms the astronomical age model, and accounts for a duration of 2.7 Myr. The positive carbon isotope events represent maxima of some of the short eccentricity cycles, although not each 100 kyr cycle is characterised by a distinct carbon isotope event. The mean duration of the individual isotope events is in the order 40–60 kyr. The time resolution of the carbon isotope curve is beyond the scale of biostratigraphy and allows the precise tuning of biostratigraphic ages. The common occurrence of the small-scale isotope events in different faunal provinces (boreal vs. tethyan) or different shelf settings (shallow near-shore environment vs. deep outer shelf) demonstrates their interregional significance and argues for a common response of the inorganic carbon reservoir to changes in the carbon cycle. Although climate zones, water depths and open oceanic affinities were different, the sedimentation in the Münsterland Cretaceous basin and the Umbria Marche basin was controlled by pelagic carbonate production. The cyclic appearance and the temporal spacing of the small-scale carbon isotope events suggest that orbital forcing exerted control on surface water productivity and organic matter preservation as a consequence of the redox conditions at the sea floor.

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