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The Global Boundary Stratotype Section and Point (GSSP) of the Campanian Stage at Bottaccione (Gubbio, Italy) and its Auxiliary Sections: Seaford Head (UK), Bocieniec (Poland), Postalm (Austria), Smoky Hill, Kansas (U.S.A), Tepayac (Mexico)

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Following the unanimous vote of the Executive Committee of International Union of Geological Sciences in October 2022, the Global boundary Stratotype Section and Point for the base of the Campanian Stage is confirmed as the magnetic polarity reversal from Chron 34n (top of the Long Cretaceous Normal Polarity–Chron) to Chron C33r at the 221.53 m level in the Bottaccione Gorge section at Gubbio, Umbria–Marche Basin, Italy. This event has been widely identified in oceanic settings and in widespread onshore outcrops. Sedimentation across the Santonian–Campanian boundary interval in the proposed GSSP appears to be continuous, supported by evidence from the carbon isotope record and complete micro– and nannofossil biostratigraphy. The succession comprises deep–water cherty limestones (mudstones and foraminiferal wackestones) which provide a detailed record of calcareous nannofossils and planktonic foraminifera and yields an excellent palaeomagnetic record. The high–resolution carbon isotope record, derived from bulk sediment, provides an important additional means of correlation to other regions.

Introduction

A reconstruction of the Campanian world is provided (Fig. 1) which shows the position of localities mentioned in the text.

Historical Background

The étage Campanien was introduced by Henri Coquand in 1857 in his Position des *Ostrea columba* et *biauriculata* dans le groupe de la craie inférieure (1857, p. 749) as the third division of the former étage Sénonien, introduced by d'Orbigny in 1843 (p. 403).

"*Troisième étage. – Campanien* Craie tendre (*Ostrea vesicularis*, Lam., *O. larva*, Lam., *Sphaerulites hoeninghausi*, des Moul., *Anachytes ovata*, Lam.). Cet étage correspond au septième étage des rudistes."

Coquand (1857) revised his former 1856 subdivision of his Craie Supérieure, and defined the Coniacien, Santonien, Campanien and Dordonien as the 1st, 2nd, 3rd and 4th étages of the Craie supérieure, respectively. The named localities for the Campanien, formerly named *Deuxième étage* by Coquand in 1856 (pp. 88–92) included Grande–Champagne, the escarpments that dominate the banks of the Dronne, at the southern end of the department, the surroundings of Aubeterre, the village of Archiac, and the cliffs that extend from Mortagne to Royan. Subsequent research on the Campanian in northern Aquitaine is reviewed in detail by Seronie–Vivien (1972), Kennedy (1986) and Platel (1989), who document the progressive refinements of knowledge of the sequence.

For Coquand (1856, 1857), the Campanian Stage was characterised by a diverse assemblage of bivalves (including rudists), and echinoids. Coquand (1858, 1859, 1860) cited various ammonites as characteristic of the Campanian, discussed by Kennedy (1986) who concluded that many were inappropriately used names referring mostly to what are now regarded as Maastrichtian species. Arnaud (1878) subsequently subdivided the Campanian of the Aquitaine Basin into three units (P1, lower; P2, middle; P3, upper), and suggested a correlation with the chalks of northern France. De Grossouvre (1894) revised the ammonite faunas of the 'Craie Supérieure' of France, and in 1901 (pp. 810, 830) established a three–fold ammonite zonation for the Campanian as now conceived, based on records from Aquitaine (Table 1; his fourth zone of *Pachydiscus neubergicus* is now regarded as Lower Maastrichtian).

Kennedy (1986), in a revision of the ammonite faunas of the Campanian of Aquitaine, noted that *Placenticeras bidorsatum,* index of the lowest Campanian ammonite zone recognised by De Grossouvre was rare in Aquitaine (12 specimens known), and had not been collected since the nineteenth century. The species is otherwise known only from Touraine and the Corbières in France, northern Spain, Germany,

Table 1. De Grossouvre's 1901 ammonite zonation for the Campanian of Aquitaine

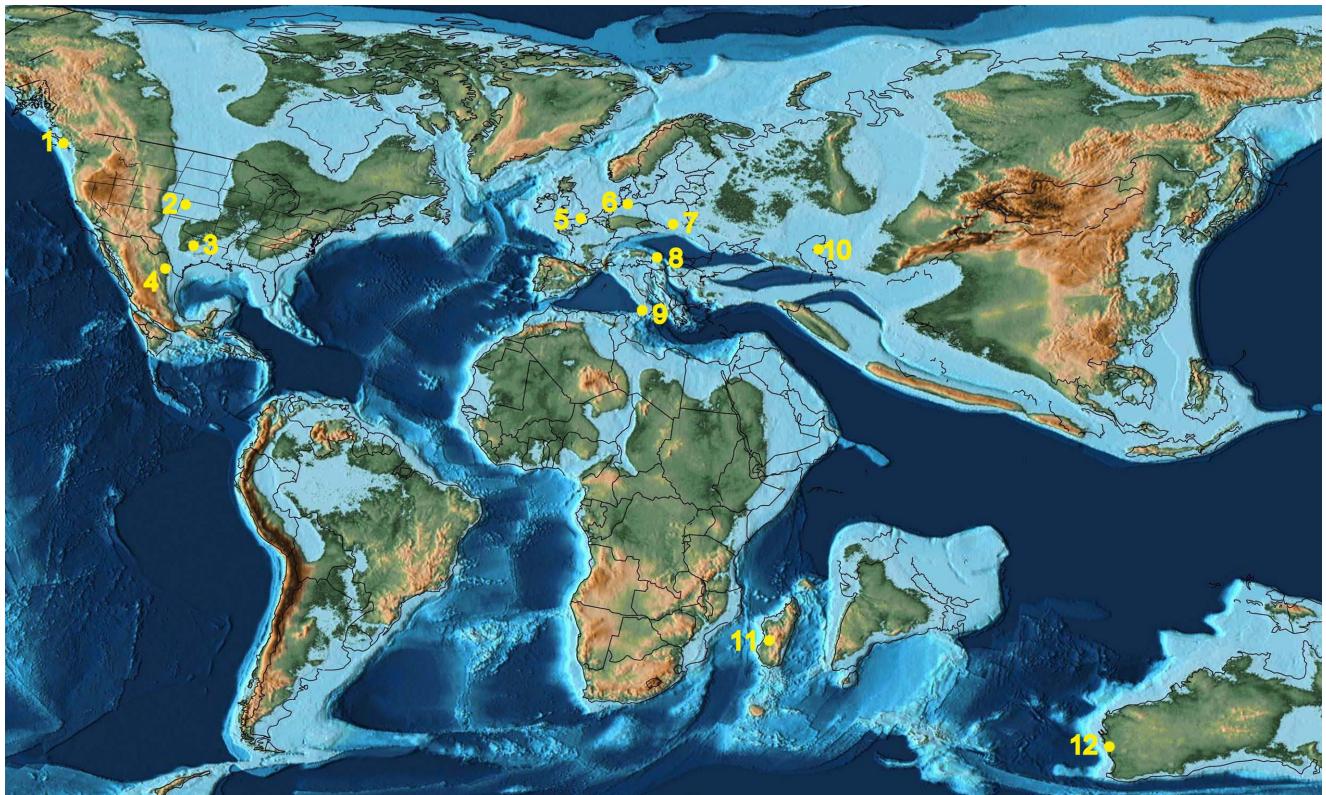| Upper	Hoplites vari
Lower	Mortoniceras delawarense Placenticeras bidorsatum

Figure 1. Map of the Campanian world (Paleomaps, with permission from Dr Chris Scotese) to show important sections mentioned in the text. 1, Vancouver Island, British Columbia, Canada. 2, NW Kansas, USA. 3, Waxahachie, Ellis County, Texas, USA. 4, Tepeyac, Mexico. 5, Seaford Head, Sussex, UK. 6, Lägerdorf, Germany. 7, Biocieniec, Poland. 8, Postalm, Austria. 9, Gubbio, Italy. 10, Mangyschlak, Kazakhstan. 11, Madagascar. 12, Carnarvon Basin, Western Australia.

and Austria (Kennedy, 1986; Kennedy and Kaplan, 1995) and its approximate co–occurrence with the belemnite *Gonioteuthis granulata quadrata* led to this latter level being adopted as a Campanian boundary marker (Schmid, 1956, 1960; Ernst, 1964). Subsequently, this level was shown to coincide with the highest occurrence of the globally distributed crinoid *Marsupites testudinarius* (Ernst, 1968), which was proposed as a potential boundary marker (Schulz et al., 1984; Birkelund et al., 1984). Although *M. testudinarius* has a global distribution, it is virtually restricted to relatively shallow water chalks and is absent in deeper water and most clastic facies (Gale et al., 2008).

Marks (1984) noted that stratigraphically diagnostic planktonic foraminifera of the *Dicarinella* lineage are absent from the Aquitaine sections but suggested that the extinction of *Dicarinella asymetrica* provided a widely identifiable marker for the top of the Santonian in deeper water Tethyan successions. Following the work of Premoli Silva (1977) and Premoli Silva and Sliter (1995), it has been demonstrated that the base of magnetochron C33r is approximately coincident with the highest occurrence of *D. asymetrica* in the Scaglia Rossa at Gubbio, Italy. The Santonian–Campanian boundary at Gubbio, and elsewhere in deep–water Tethyan settings (e.g., Caron, 1985; Robaszynski and Caron, 1995; Premoli Silva and Sliter, 1995; Petrizzo et al., 2011;

Coccioni and Premoli Silva, 2015), in Crimea (Kopaevich et al., 2020), and in the US Gulf Coastal Plain (Puckett, 2005) has been taken at the top of the range of *D. asymetrica*, which is also widely recognised across ocean basins at various Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP) and Integrated Ocean Discovery Project (IODP) sites (e.g., Petrizzo, 2000; Petrizzo et al., 2011; Ando et al., 2013; Miniati et al., 2020).

In the United States Western Interior and Gulf Coast regions, ammonites have been used to define the base of the Campanian. In Texas, the base of the Campanian was placed at the base of the *Submortoniceras tequesquitense* Zone by Young (1963), in the Dessau Member of the Austin Chalk. Gale et al. (2008, 2020a) provided a detailed record of occurrences of *Marsupites* and *Uintacrinus* in Texas and demonstrated that the extinction of *M. testudinarius* lay close to the top of the Austin Chalk and was thus significantly younger than the first occurrence of *S. tequesquitense*. In the Western Interior, Cobban (1969) took the base of the Campanian at the base of the zone of *Scaphites leei* III; *Marsupites testudinarius* occurs in association with *S. leei* II in the underlying *Desmoscaphites bassleri* Zone (Cobban, 1995).

The Pacific Basin comprised two–thirds of the Late Cretaceous world, and Santonian–Campanian boundary intervals are known from
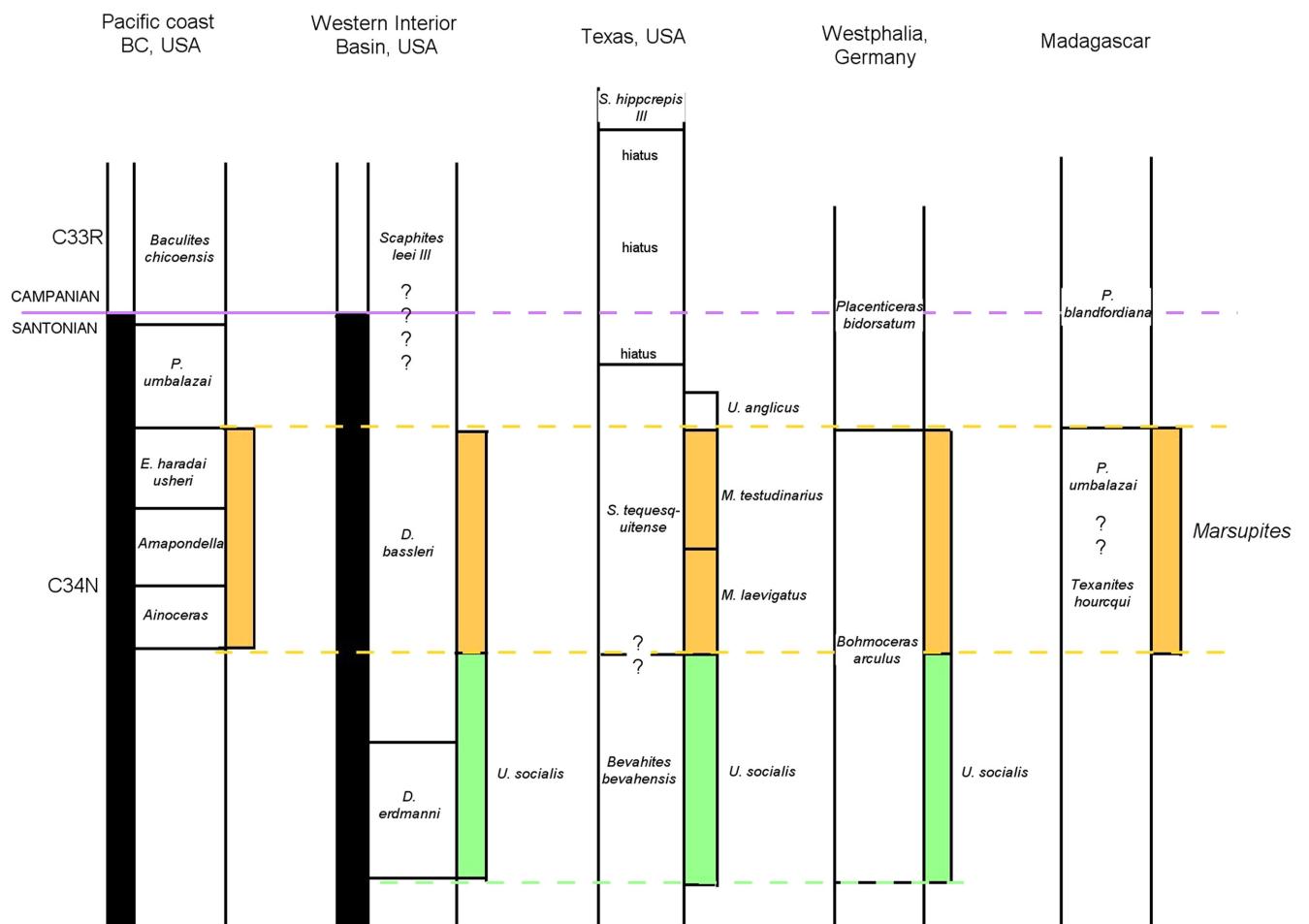

Figure 2. Correlation of regional ammonite zonations using magnetostratigraphy and distributions of crinoids Uintacrinus and Marsupites, to illustrate the problems of provincialism of the ammonite record, and the use of Marsupites in correlation. Pacific Realm data from Verosub et al. (1989), Ward et al. (2012), Haggart and Graham (2017). Western Interior Basin from Cobban (1995) and Kita et al. (2017). Texas from Young (1963), Gale et al. (2008, 2020b). Germany from Kaplan et al. (2005). Madagascar from Walaszczyk et al. (2014).

a number of regions therein, including the Pacific coast of United States and Canada, as well as Japan. Unfortunately, extensive regional endemicity of ammonite and inoceramid faunas in this region complicates interregional correlation of numerous Cretaceous boundaries, including the Santonian–Campanian. In California, Matsumoto (1960) placed the boundary just below the first occurrence of *Submortoniceras chicoense* and *Baculites chicoensis*, a placement subsequently followed by Haggart (1984), Verosub et al. (1989), and Ward et al. (2012). In Pacific coastal Canada, Jeletzky (1970) placed the boundary at the first occurrence of the Pacific–endemic ammonite *Eupachydiscus haradai*, but Ward (1978) subsequently identified *Submortoniceras chicoense* at this level, providing a more significant interregional tie. In the Japanese Islands, Matsumoto (1959) placed the boundary at the occurrence of the ammonites '*Neopachydiscus*' *naumanni* and *Desmophyllites diphylloides* and the inoceramid *Inoceramus orientalis*, all, unfortunately, restricted to the North Pacific Province (Matsumoto, 1959; Haggart and Ward, 1989). Toshimitsu et al. (1998) subsequently placed the boundary at the first occurrence of the somewhat rare *Submortoniceras* cf. *condamyi*, as well as the first occurrence of *Globotruncana arca*, identifying taxa useful for interregional correlation. Identification of the base of magnetochron 33r in the California succession allowed Ward et al. (1983) to confidently place the Santonian–Campanian boundary there and more recently, Haggart and Graham (2017) have recognized the benthic crinoid *Marsupites testudinarius* in the western British Columbia succession, providing a valuable means of correlation (Gale et al., 1995).

The 1995 Brussels Second International Symposium on Cretaceous Stage Boundaries agreed that a number of criteria should be taken into account in defining the Campanian stage boundary and establishing a GSSP (Hancock and Gale, 1996, p. 107). The following motion, put to those present was accepted without dissent:

"1. The definition of the base of the Campanian stage should be compatible with the classic definition by de Grossouvre (1901), that is the lowest level with *Placenticeras bidorsatum.*

2. This corresponds to the extinction level of *Marsupites testudinarius* (Schlotheim) which we recommend provisionally as the boundary marker for the base of the Campanian stage.

3. This datum–level should be linked to:

(a) extinctions in the planktonic foraminiferal group of *Dicarinella concavata*;

(b) nannofossil data, including the lineage of *Broinsonia parca* (*note: Aspidolithus parcus parcus* of other authors and herein);

(c) directly or indirectly to the C33r–C34n paleomagnetic boundary.

4. We invite reports on correlation of these events from members of the working group."

It was further agreed that "should the crinoid standard eventually be adopted, there were candidate boundary stratotypes in Texas and southern England. Accordingly, reports should be prepared on the sections in England at Seaford Head, Sussex (and possibly Foreness Point, Kent)… and in north–central Texas at the Waxahachie dam–spillway."

Detailed accounts of the micropalaeontology of the Seaford Head section were published by Hampton et al. (2007), and Gale (2018) described the distribution of the crinoids; the results are discussed further below (see below). The locality has not provided a reliable palaeomagnetic record and lacks diagnostic planktonic foraminifera.

The section at the Waxahachie dam spillway, Ellis County, was proposed as a candidate GSSP by Gale et al. (2008), who provided a detailed account of the biostratigraphy (calcareous nannofossils, planktonic foraminifera, crinoids, inoceramid bivalves, ammonites) of the section. However, the absence of a palaeomagnetic record, the incomplete ranges of key planktonic foraminifera and the presence of a major erosional disconformity between the Austin Chalk and overlying Ozan (Taylor) Formation (Gale et al., 2020a) 2.7 m above the proposed GSSP marker (extinction of *Marsupites testudinarius*) render the locality inappropriate as a GSSP. Important biostratigraphical records from the Waxahachie section are provided (Fig. 3). The Bocieniec locality near Warsaw in southern Poland was proposed by Dubicka et al. (2017) as a potential GSSP candidate, and we here propose it as an auxiliary section (see below). However, the succession is very thin and there is a hiatus close to the level of the proposed boundary.

Boundary Markers

Previous studies have proposed several viable options for definition of the base of the Campanian; namely, the extinction of the benthic crinoid *M. testudinarius* (only recorded from shallower water chalks and clastics, worldwide); the top of the Cretaceous Long Normal magnetozone C34n (global), the approximately coincident extinction of the planktonic foraminiferan *Dicarinella asymetrica* (deeper water, lower latitude, ocean basins), and the appearance of the calcareous nannofossil *Aspidolithus parcus parcus* (ocean basins to shallow water chalks, global event). Because magnetic reversals are global, and potentially identifiable in all palaeoenvironments, we selected the base of Chron C33r as the now confirmed primary marker. This helps especially in correlation to non–marine continental successions such as those in North America (e.g., Albright and Titus, 2016) and China (e.g., He et al., 2012).

Although the base of polarity Chron C33r has not been identified widely outside the oceanic seafloor, laterally extensive and high–resolution correlation of Santonian–Campanian boundary strata is possible using carbon isotope stratigraphy and development of evolutionary subspecies in the *Aspidolithus parcus* (Stradner, 1963) coccolith lineage (syn. *Broinsonia parca* of Bukry, 1969; see Miniati et al., 2020 and Nannotax3, https://www.mikrotax.org/Nannotax3/). A succession of species and subspecies of the family Arkhangelskiellaceae and particularly of the coccolith genus *Aspidolithus* have been described from the Gubbio section (Gardin et al., 2001; Miniati et al., 2020), including the FO of *Arkhangelskiella cymbiformis* (Vekshina, 1959) and the first occurrence (FO) and first common occurrence (FCO) of successive subspecies of *Aspidolithus parcus* (*A. p. expansus, A. p. parcus, A. p. constrictus*). Some of these events can be identified widely; for example, Kita et al. (2017) recognised the *A. p. parcus* and *A. p. constrictus* levels in the northern part of the Western Interior Basin, USA.

A double positive excursion in bulk carbonate δ^{13}C, the Santonian–Campanian Boundary Event (SCBE), was originally described from southern UK chalks (Jarvis et al., 2006), coincident with the upper part of the range of *M. testudinarius* and immediately succeeding its extinction level. This event is now demonstrated to fall beneath the base of the Campanian and is therefore re–named as the Late Santonian Event (LSE–Fig. 4). The isotope excursion can also be identified in chalks in Yorkshire, north–east England (Deville de Periere et al., 2019), in the Paris Basin (Chenot et al., 2016; Pearce et al., 2022), at Lägerdorf
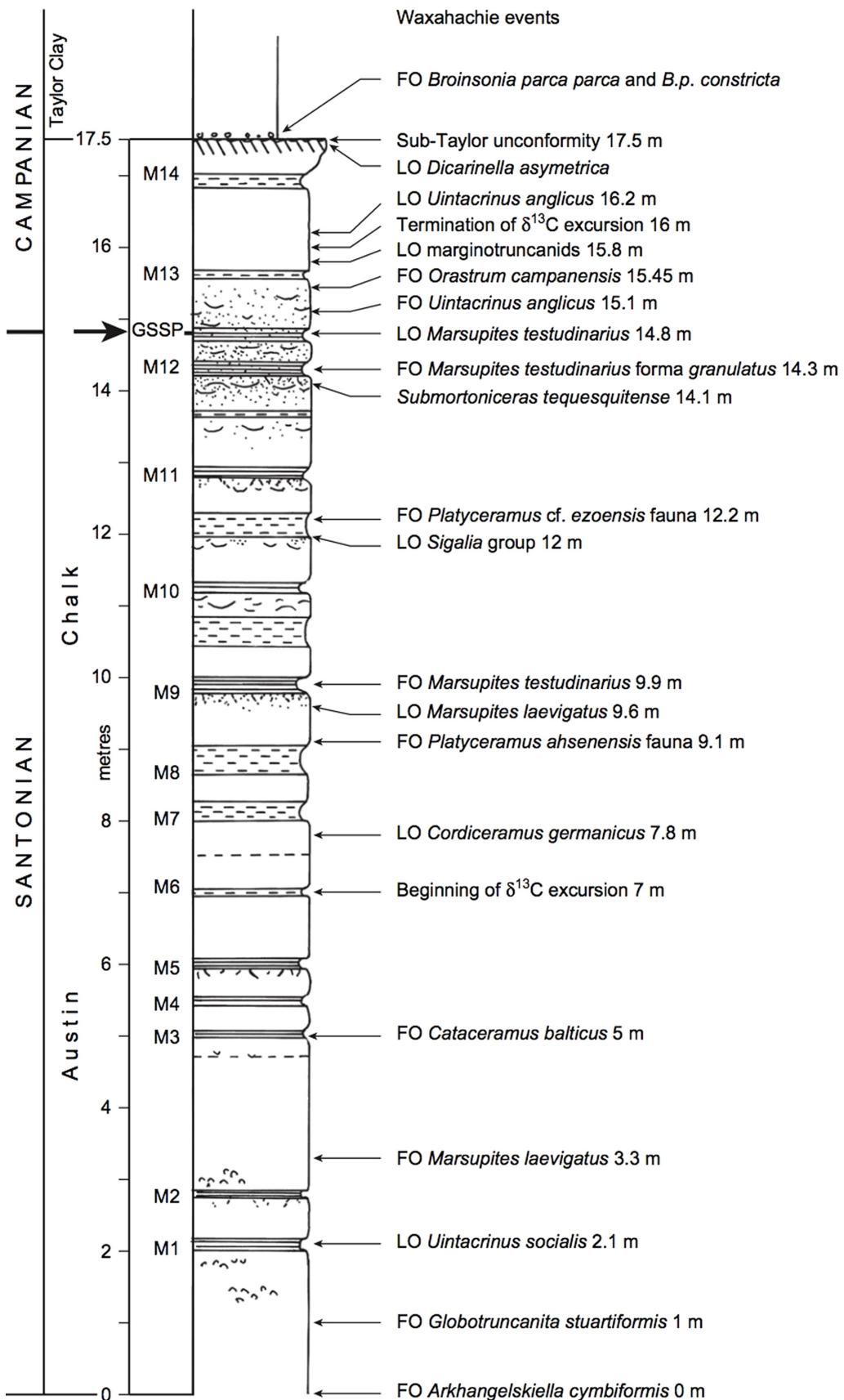
Figure 3. Biostratigraphic markers in the Waxahachie dam spillway, proposed as a potential Campanian GSSP, after Gale et al. (2008, fig. 24.) Note the co–occurrences of inoceramids and crinoids and the abrupt termination of the range of Dicarinella asymetrica at the sub–Taylor (=Ozan) unconformity. See also Gale et al. 2020b for further details.
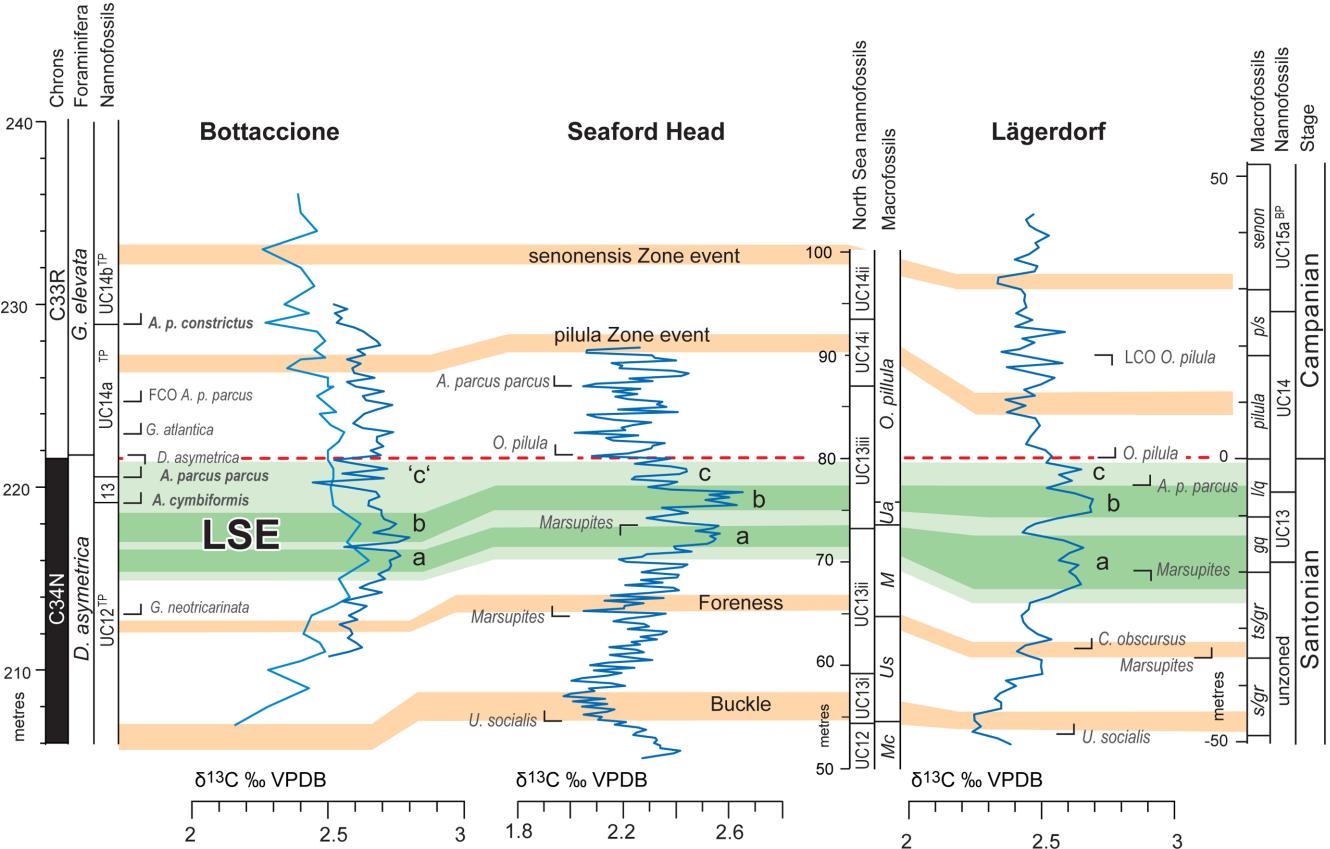
Figure 4. *Correlation between the Tethyan pelagic carbonate succession at the Bottaccione section (Gubbio, Umbria, Italy) and Boreal chalk successions at Seaford Head (UK) and Lägerdorf (northern Germany), showing correlations based on carbon isotopes, calcareous nannofossils and planktonic foraminifera. Note that the Late Santonian carbon isotope event (LSE) (including peaks a–c), supported by calcareous nannofossils, provides a means of high–resolution correlation between the successions. Modified from Thibault et al. (2016 fig. 4). FCO = first common occurrence; LCO = last common occurrence.*

in northern Germany (Voigt et al., 2010), in marls at Bocieniec, Poland (Dubicka et al., 2017), and, critically, in the Global Stratotype section in the Scaglia Rossa in the Bottaccione Gorge at Gubbio, Umbria–Marche Basin, Italy (Fig. 4; see Thibault et al., 2016). It has also been identified in the United States Western Interior Basin (Joo and Sageman, 2014; Kita et al., 2017) and in Japan (Takashima et al., 2019).

Bottaccione Gorge, Gubbio, Umbria Marche, Italy: the Global Boundary Stratotype Section for the Base of the Campanian Stage

The Upper Santonian–Lower Campanian Bottaccione Section (Gubbio, central Italy)

The investigated portion of the Bottaccione section that includes the Global Stratotype Section and Point (GSSP) for the base of the Campanian Stage, is located 1.4 km NNE of the town of Gubbio (central Italy). It is continuously well–exposed with a strike of 140° and a dip of 50°NE along the Regional Road 298 "Eugubina" that crosses the Bottaccione Gorge (Fig. 5), where a continuous magneto–biochronologic record characterizes the Early Cretaceous–Paleogene pelagic carbonates of the Umbria–Marche Apennines (Coccioni and Premoli

Silva, 2015, and references therein; Coccioni et al., 2016, and references therein) and played a prominent role in the establishment of the standard Late Cretaceous time scale (Gale et al., 2020b).

The upper Santonian–lower Campanian Bottaccione section (Fig. 6; 560 m above sea level; coordinates: 43°21′45.6″N, 12°34′58.2″E), which following the study of Coccioni and Premoli Silva (2015), extends from 210.79 to 233.63 m was logged to define a detailed lithostratigraphy, described at the centimetre scale in the field and marked on the outcrop with light blue paint at 1 m intervals. It is 22.84 m thick and consists of well–bedded, pink to red and white bioturbated limestones with bedding thickness ranging from 6 to 80 cm. Pink to reddish and grey to greenish–grey chert nodules and limestone beds with thickness ranging from 3 to 6 cm occur throughout. As a result, the limestone beds are frequently silicified. In particular, the occurrence of white limestone beds together with grey to greenish–grey chert nodules characterises the 228.94–232.75 m interval.

The upper Santonian–lower Campanian Bottaccione section, which following Alvarez and Montanari (1988) is positioned within the upper part of the stratigraphic member R1 (lower Turonian–lower Campanian) of the Scaglia Rossa Formation, is absolutely devoid of turbidites and substantial internal structural deformation. Only a negligible fault with a displacement of a few decimetres occurs at 221.20 m (Maron and Muttoni, 2021). The displaced strata can be easily reconnected
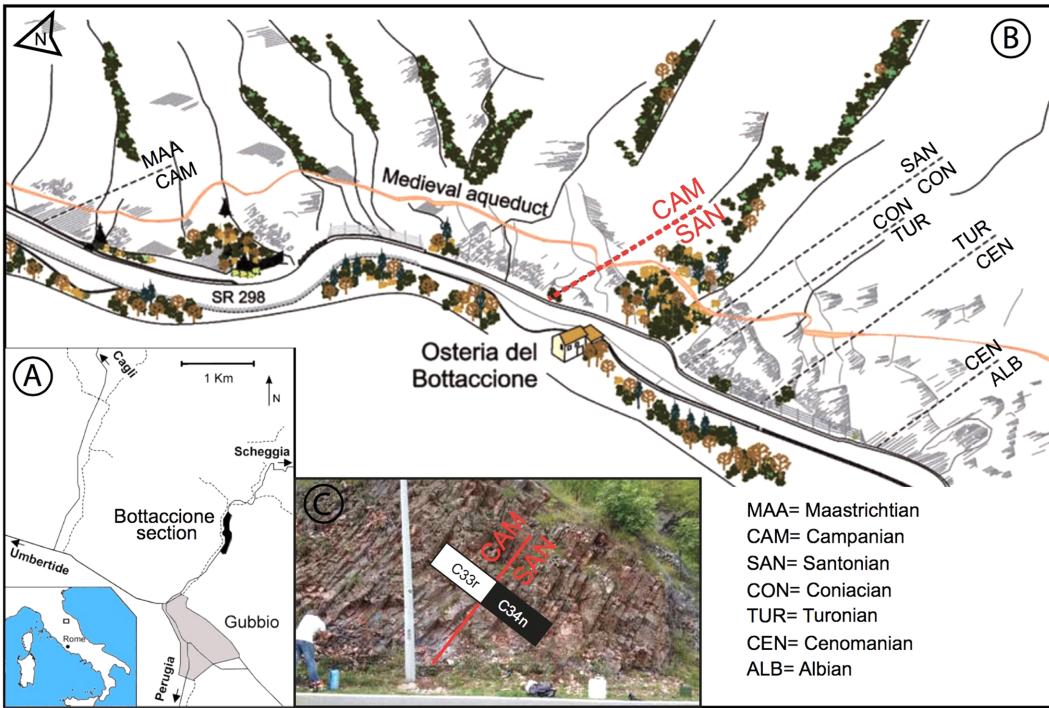
Figure 5. A, Map showing the location of the Bottaccione section at Gubbio, Umbria–Marche Basin, Italy. B, cartoon of the Bottaccione section. C, photograph of the GSSP. After Miniati et al. (2020).

and therefore the stratigraphy is regarded as continuous. Stylolites are common in the thicker beds.

The biogenic pelagic rocks of the upper Santonian–lower Campanian Bottaccione section, which were formed following lithification of nannofossil and planktonic foraminiferal ooze, were deposited at an inferred lower bathyal palaeodepth of 1,000–2,000 m (Frontalini et al., 2016) with a mean accumulation rate of ~11 m/myr (Maron and Muttoni, 2021) in a low energy, open marine setting of the central–western Tethys at an estimated palaeolatitude between 19.5°N and 22.7°N (Maron and Muttoni, 2021). Some benthic foraminifera, ostracods, and radiolarians also occur, but have not been documented to date. Macrofossils are conspicuously absent, as expected in deep water sediments. Samples processed from the boundary section have proven barren of palynomorphs.

Magnetostratigraphy

The base of magnetic polarity Chron C33r, that marks the top of Chron 34n (Cretaceous Long Normal), was indicated by Coccioni and Premoli Silva (2015) as a possible primary criterion for the base of the Campanian Stage, in agreement with Alvarez et al. (1977) and Premoli Silva and Sliter (1995). In the Geologic Time Scale (GTS) 2020, the base of magnetic polarity Chron C33r is used as provisional base for the Campanian Stage at 83.65 Ma (Gale et al., 2020b). A reliable and robust magnetostratigraphic reassessment of the upper Santonian–lower Campanian Bottaccione section has been provided by Maron and Muttoni (2021), who analysed a total of 112 samples for palaeomagnetism (Fig. 7) and 12 for rock magnetism experiments using isothermal remanent magnetization (IRM). The samples were thermally demagnetized up to 675°C (in steps of 50–25°C) and then analyzed with a 2G Enterprises DC–SQUID cryogenic magnetometer. Also, the S–Ratio ($-IRM_{-0.3T}/SIRM_{1.0T}$) and the HIRM [$(IRM_{-0.3T} + SIRM_{1.0T})/2$] were calculated for 94 of 112 samples, equally distributed through the section.

The IRM experiments show that the ferromagnetic fraction within the samples is dominated by magnetite, with secondary hematite interpreted as mainly pigmentary (Maron and Muttoni, 2021). This type of hematite, causing the pervasive red colour of the Scaglia Rossa, probably derived from dehydration of goethite (Channell, 1978; Channell et al., 1978, 1982). Hematite becomes sporadic in occurrence in the whitish interval between ~228.9 and ~232.7 m, where hematite formation/preservation was prevented by more reducing conditions (Channell et al., 1982). These variations in hematite content are well displayed by both the S–Ratio and HIRM curves (Fig. 7C; Maron and Muttoni, 2021).

Thermal demagnetization of NRM revealed an initial 'A' component, oriented north with positive inclination, isolated from room temperature up to 150°C, and observed in all the 112 samples analysed. The mean direction of the 'A' component in *in situ* coordinates is in agreement with the direction of the present–day magnetic field, suggesting a viscous origin for this component. A secondary 'B' component, isolated up to ~300°C in 105 samples and antipodal to the 'A' component (in in situ coordinates), resembles the secondary component recognized by Channell et al. (1982) in the Scaglia Rossa of Gubbio. Channell et al. (1982) interpreted this component as a chemical overprint (CRM) acquired during exhumation and weathering, or as a "hard" viscous component (e.g., Dunlop and Stirling, 1977) acquired during a recent magnetochron of reversed polarity (Channell et al., 1982). The characteristic component (ChRM) has been isolated in 111 of 112 samples between ~300 and ~575°C (sometimes up
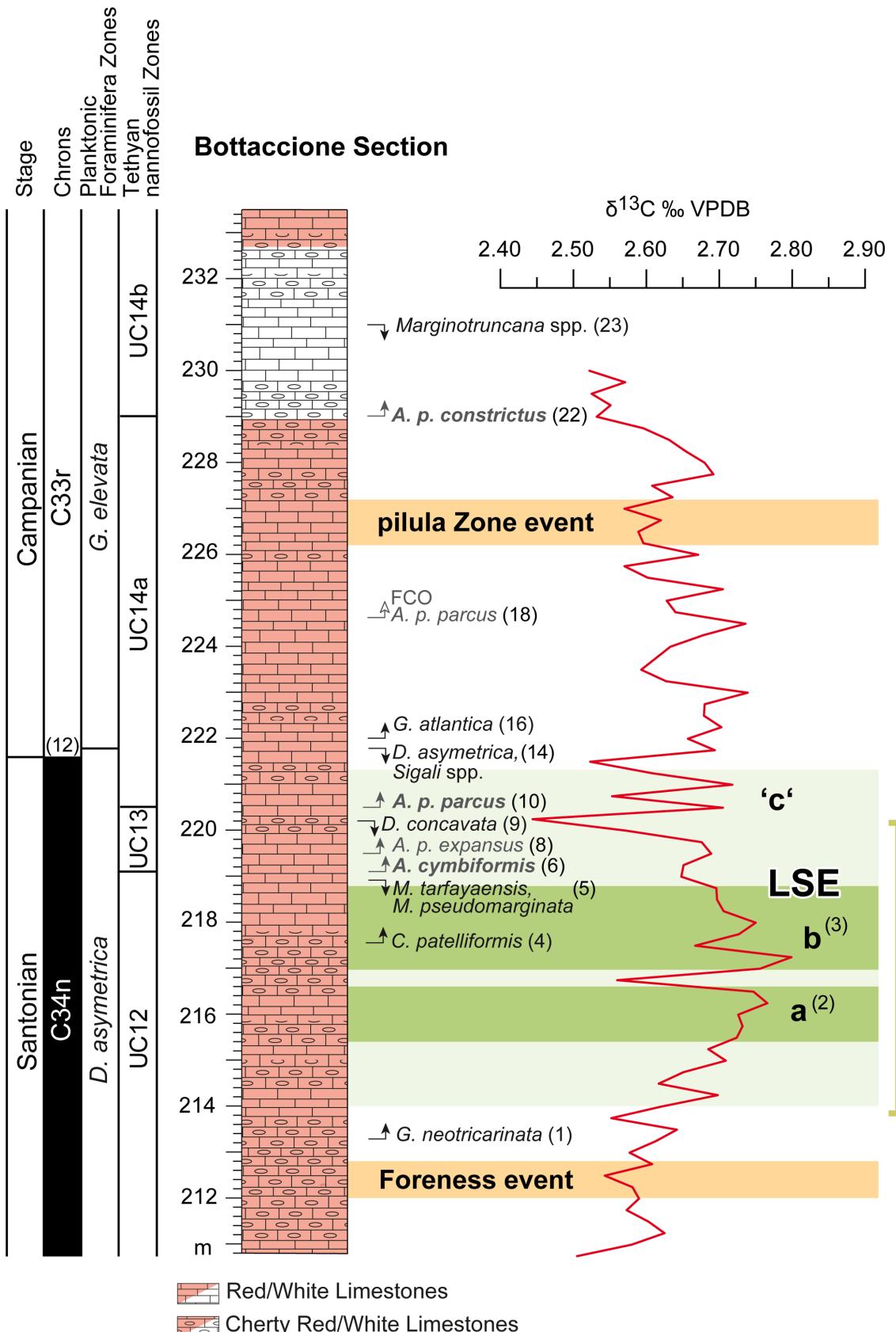
Figure 6. Litho– and magnetostratigraphy of the Bottaccione proposed GSSP section (see Fig. 5 for location), after Maron and Muttoni (2021); calcareous microplankton after Miniati et al. (2020), and carbon isotopes after Sabatino et al. (2018) with the auxiliary markers of the Late Santonian Event (LSE) LSE–a and LSE–b after Thibault et al. (2016). The total extent of the LSE carbon isotope excursion is revised to achieve consistency in correlation and includes LSE–c (see text for further explanation). The numbers refer to boundary and auxiliary markers explained in the text.
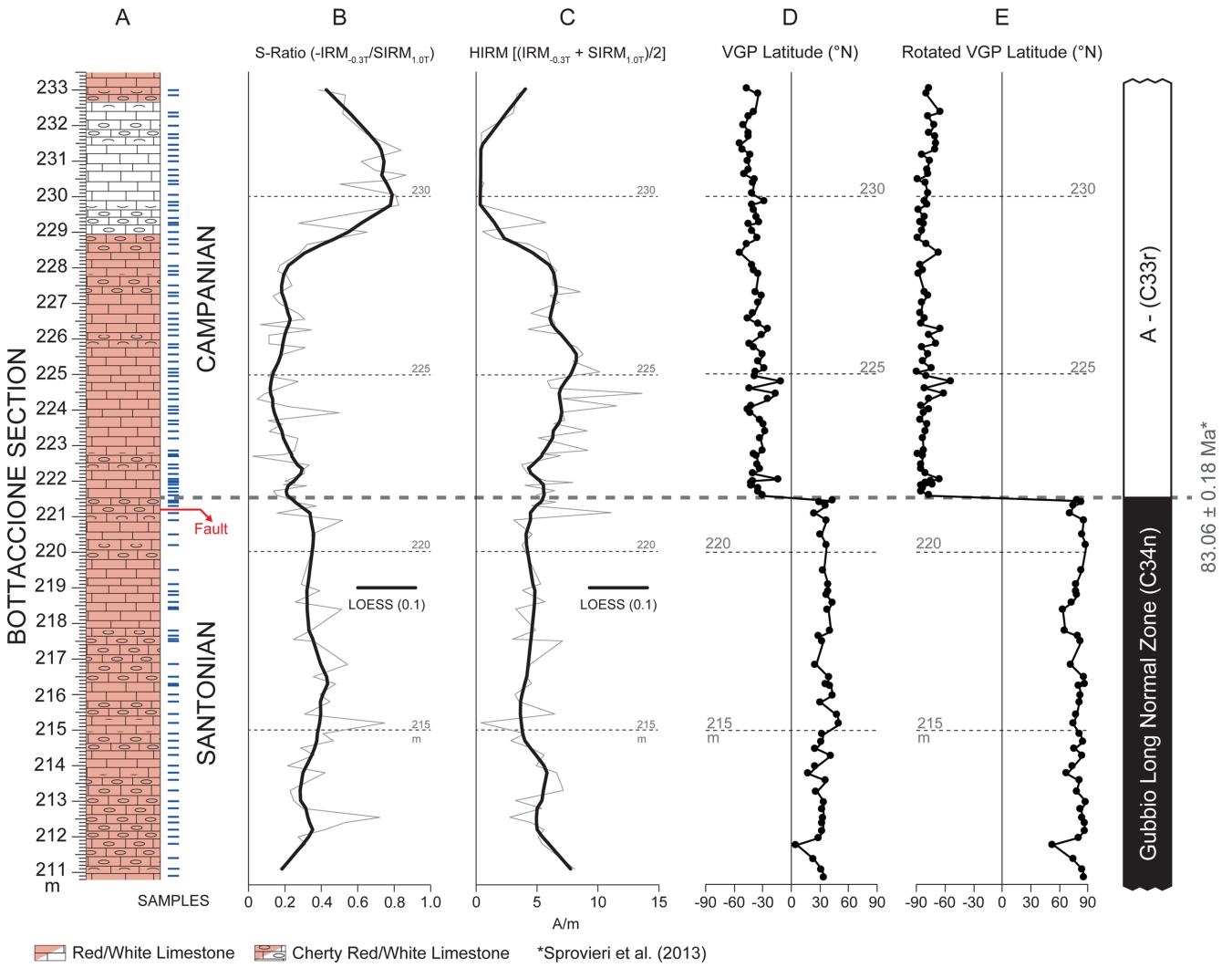
Figure 7. Rock magnetic properties and magnetostratigraphy of Scaglia Rossa at the Bottaccione section. From left to right: A) lithostratigraphy, B) S–Ratio, C) HIRM, D) VGP latitudes, and E) rotated VGP latitudes. S–Ratio and HIRM curves show a decrease in hematite and a relative increase in magnetite between ~228.9 m and ~232.7 m, where layers become whitish in color. Magnetostratigraphy derived from rotated VGP latitudes show a normal polarity zone identified as the top of C34n, followed by a reverse polarity zone identified as the lower C33r.

to ~625°C), showing antipodal distribution in both *in situ* and tilt–corrected coordinates. The mean direction of the ChRM component non corrected for sedimentary inclination flattening (Dec. = 306.0°E, INC = 28.9°, k = 32.8, 95 = 2.4°, n = 111; Maron and Muttoni, 2021) is similar to the mean direction calculated for the Cretaceous Scaglia Rossa of Gubbio by Lowrie and Alvarez (1977a, b) and Channell et al. (1978). The Virtual Geomagnetic Pole (VGP) latitudes obtained from each ChRM component (Fig. 7D) were restored to palaeo–coordinates (see Maron and Muttoni, 2021 for details) and used to interpret the magnetostratigraphy, identifying a lower normal polarity zone overlain by a reverse polarity zone (Fig. 7E). Maron and Muttoni (2021) interpret the normal and reverse polarity intervals respectively as the uppermost "Gubbio Long Normal Zone" (GLNZ) and the A–magnetozone of Lowrie and Alvarez (1977a), corresponding to the top of C34n and base of C33r Chrons. The C34n–C33r polarity reversal boundary is placed at 221.525 ± 0.075 m in the Bottaccione section (Maron and Muttoni, 2021) and assigned a nominal age of 83.06 ± 0.18 Ma based on the astrochronological tuning of the Bottaccione $\delta^{13}C_{carb}$ data of

Sprovieri et al. (2013).

The palaeomagnetic pole derived from the ChRM component mean direction (non corrected for sedimentary flattening) falls at Lat.: 36.5°N, Long: 268.5°E, A_{95} = 1.5°, and is rotated counter–clockwise by 39.5 ± 3.3° (Maron and Muttoni, 2021) relative to the Africa–Adria reference pole of Muttoni et al. (2013). The pole rotation is interpreted as reflecting the rotation of the central Apennines relative to parautochthonous Adria (e.g., Lowrie and Alvarez, 1977a, b; Roggenthen and Napoleone, 1977; Channell et al., 1978; Maron and Muttoni, 2021). The palaeolatitude, corrected for sedimentary inclination flattening using the E/I method of Tauxe and Kent (2004), places the Bottaccione area at 21.1°N (±1.6°) in substantial agreement with the palaeolatitude predicted at Gubbio by the Late Cretaceous Adria–Africa mean palaeopole of Muttoni et al. (2013).

Biostratigraphy

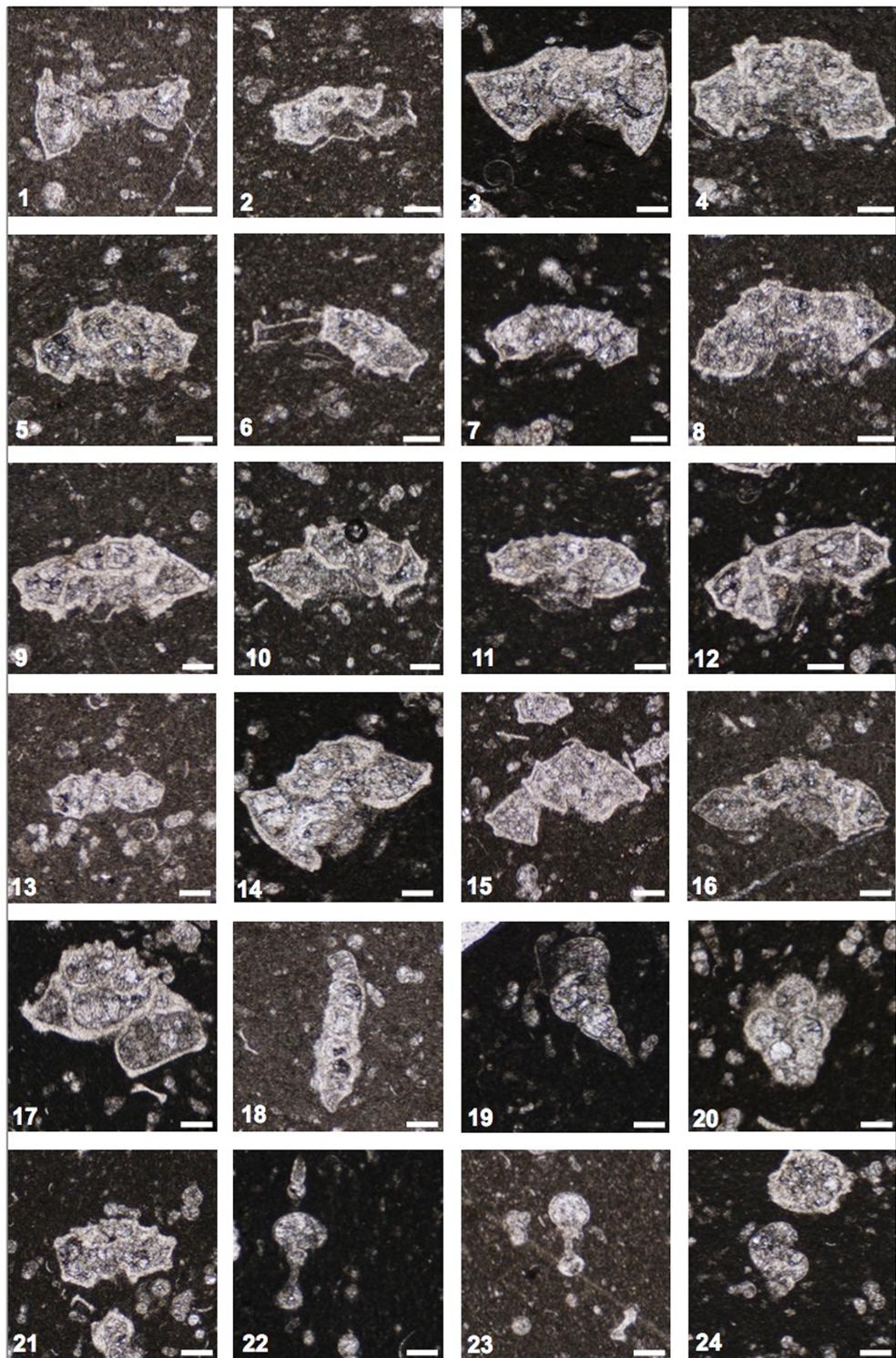The biostratigraphy of calcareous plankton across the Santonian–

Figure 8. Selected planktonic foraminifera species from the Bottaccione section (after Miniati et al., 2020, Plate 3). Scale bars = 100 mm. 1) Dicarinella asymetrica, sample 221.72 m. 2) Globotruncana linneiana, sample 212.20 m. 3) Globotruncanita elevata, sample 224.60 m. 4) Contusotruncana fornicata, sample 221.71 m. 5) Globotruncana arca, sample 223.92 m. 6) Marginotruncana coronata, sample 212.20 m. 7) Marginotruncana pseudolinneiana, sample 224.60 m. 8) Marginotruncana undulata, sample 225.75 m. 9) Marginotruncana sinuosa, sample 218.92 m. 10) Marginotruncana schneegansi, sample 217.55 m. 11) Marginotruncana pseudomarginata, sample 218.40 m. 12) Globotruncana neotricarinata, sample 221.71 m. 13) Globotruncana bulloides, sample 222.05 m. 14) Globotruncanita stuartiformis, sample 220.25 m. 15) Contusotruncana patelliformis, sample 221.71 m. 16) Globotruncana orientalis, sample 221.21 m. 17) Globotruncanita atlantica, sample 222.05 m. 18) Sigalia sp., sample 221.71 m. 19) Pseudotextularia nuttalli, sample 229.75 m. 20) Ventilabrella eggeri, sample 214.30 m. 21) Globotruncana hilli, sample 224.60 m. 22) Planohedbergella (= Globigerinelloides) prairiehillensis, sample 231.76. 23) Laeviella (= Globigerinelloides) bollii, sample 213.30 m. 24) Laeviheterohelix pulchra, sample 232.33 m. The generic assignments of the planispiral planktonic foraminifera previously assigned to Globigerinelloides follow revision by Huber et al. (2022).

Campanian boundary interval of the Bottaccione section was directly calibrated with polarity magnetozones by Premoli Silva (1977), Premoli Silva and Sliter (1995), Gardin et al. (2001), Tremolada (2002), Petrizzo et al. (2011), Coccioni and Premoli Silva (2015) and Miniati et al. (2020), with an increasing resolution over time that provides a reliable and robust identification of several primary and secondary biohorizons. The base of polarity Chron C33r at 221.525 m, the marker candidate for the Santonian–Campanian boundary, falls in the lowermost
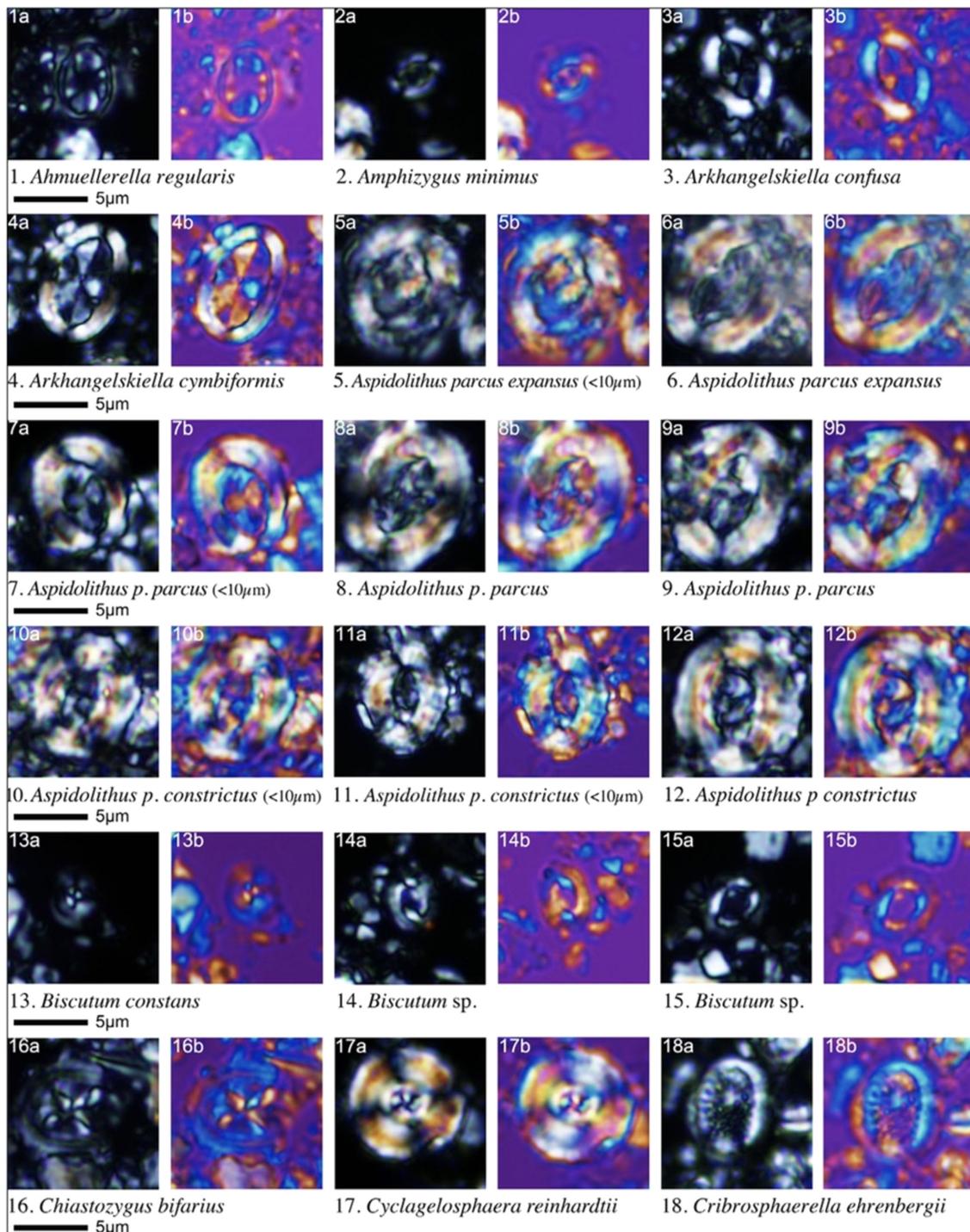

Figure 9. Selected calcareous nannofossil species from the Bottaccione section (after Miniati et al., 2020, Plate 1). For each taxon (a) cross–polarized light; (b) quartz lamina. 1) Ahmuellerella regularis, sample 213.8 m. 2) Amphizygus minimus, sample 219.75 m. 3) Arkhangelskiella confusa, sample 219.5 m. 4) Arkhangelskiella cymbiformis, sample 221.4 m. 5) Aspidolithus parcus expansus var. "small", sample 220.5 m. 6) Aspidolithus parcus expansus, sample 227.5 m. 7) Aspidolithus parcus parcus var. "small", sample 229 m. 8) Aspidolithus parcus parcus, sample 232.33 m. 9) Aspidolithus parcus parcus, sample 233 m. 10) Aspidolithus parcus constrictus var. "small", sample 230.6 m. 11) Aspidolithus parcus constrictus var. "small", sample 232.85 m. 12) Aspidolithus parcus constrictus, sample 230.6 m. 13) Biscutum constans, sample 220.9 m. 14) Biscutum sp., sample 212.40 m. 15) Biscutum sp., sample 220.2 m. 16) Chiastozygus bifarius, sample 218.4 m. 17) Cyclagelosphaera reinhardtii, sample 221.4 m. 18) Cribrosphaerella ehrenbergii, sample 221.9 m.

part of the calcareous nannofossil CC18 zone of Sissingh (1977), NC18 zone of Roth (1978), NC18* zone of Bralower et al. (1995) and UC14a^{TP} zone of Burnett (1988) and in the topmost part of the planktonic foraminiferal *Dicarinella asymetrica* zone of Premoli Silva and Sliter (1995), Coccioni and Premoli Silva (2015), and Miniati et al. (2020). More specifically, the base of Chron C33r lies between the first occurrence (FO) of the calcareous nannofossil *Aspidolithus parcus parcus* at the 220.50 m level, previously recorded as the FO of "small" *A. parcus parcus* at meter level 220.50 by Gardin et al. (2001) and as the FO of *A. parcus parcus* at 220.00 m by Tremolada (2002), and the last occurrence (LO) of *D. asymetrica* at 221.72 m, previously documented at 221.40 m by Coccioni and Premoli Silva (2015). These biohorizons are reliable secondary markers for the base of Chron C33r. Selected planktonic foraminifera and calcareous nannofossils occurring in the Bottaccione section are illustrated in Figs. 8 and 9.

Carbon Isotope Stratigraphy

The double–peaked positive δ^{13}C excursion, originally described from English chalks, is a prominent feature in the chalk successions of north–west Europe and was named the Santonian–Campanian Boundary Event (SCBE) by Jarvis et al. (2006). Its proper identification at Gubbio was achieved by Thibault et al. (2016, fig. 8) using the combined evidence of low– and high–resolution δ^{13}C curves from both sides of the Bottaccione Gorge. However, the characteristic double peak of the SCBE, is less distinct at Bottaccione than elsewhere and thus more difficult to define with high accuracy (Fig. 4). The event has been identified in the Bottaccione section as a single carbon isotope event by Sabatino et al. (2018) and Maron and Muttoni (2021) and is further interpreted as representing a minimum in a 405 kyr–long eccentricity cycle (Sprovieri et al., 2013; Thibault et al., 2016).

The stratigraphical extent of the SCBE differs at Bottaccione between the single event definition (213.8–220.2 m, Sabatino et al., 2018; Maron and Muttoni, 2021) and the double–peak definition (215.4–218.8 m, Thibault et al., 2016). Furthermore, the base of the Campanian, the base of Chron C33r, places the stratigraphic range of the SCBE completely in the uppermost Santonian (upper UC12 and UC13, upper *D. asymetrica* Zone). To provide a uniform definition, the SCBE is renamed here as Late Santonian Event (LSE) and its stratigraphic range is revised to achieve consistency in correlation and improve its potential as subsidiary marker for the Santonian–Campanian boundary.

The LSE at Bottaccione extends from 214.0 m to 221.3 m and includes the subsidiary features LSE–a, LSE–b and LSE–c (Fig. 6). LSE–a and LSE–b are the lower and upper SCBE–peak of Thibault et al. (2016). LSE–a and LSE–b serve as auxiliary boundary markers (2) and (3) of the GSSP. The base of the LSE is equivalent to the definition of Sabatino et al. (2018), and the top is extended close to the base of the Campanian to include the subsidiary peak LSE–c (Fig. 6). The LSC–c peak is, although of subsidiary nature, well–developed in chalk sections. At the Bottaccione section, LSE–c is less distinctive, as a result of which it cannot be precisely limited and labelled here with 'c'. However, the combined evidence of both sides of the Bottaccione Gorge show LSE–c as a distinct positive peak immediately beneath the boundary (Thibault et al., 2016, fig. 8). Altogether, the positive carbon isotope excursion of the LSE may represent a 405–kyr cycle with the subsidiary events LSE–a to LSE–c corresponding to 100–kyr

cyclicity (Thibault et al., 2016). This interpretation is also supported by the 405 kyr orbital calibration of the Bottaccione carbon isotope record whereby the wrongly correlated 'Horseshoe Bay' event identified at Gubbio just prior the magnetochron reversal, and which can now be recognized as the LSE, corresponds to a single 405 kyr cycle (Sprovieri et al., 2013, figs. 2 and 4). Thereby, LSE–b is the peak with the highest magnitude reflecting the highest amplitude of eccentricity modulated precession. This interpretation is however challenged by the demonstration by Laurin et al. (2015) of a strong 1.07 Myr cycle pacing the Late Cretaceous carbon isotope record, probably associated with the ~1.2 Myr s4–s3 term that is the largest modulation term of the obliquity (see Laskar, 2020). In the latter interpretation, the 'SCBE' here renamed as the LSE, corresponds to one of those ~1.1 Myr cycles, in which case LSE–a, LSE–b and LSE–c would rather represent three g2– g5 405 kyr eccentricity cycles.

Accessibility and Protection

Access

The section is accessible thanks to the Regional Road 298 "Eugubina", which allows easy access to the outcrop in front of a free parking lot. Free access to the section is guaranteed.

Permanent protection

The area around the section is designated for tourism and as a wilderness, with no planning for any kind of urban development. Local institutions (the town of Gubbio, the Province of Perugia in the Umbrian Region, the University of Urbino and the Osservatorio Pianeta Terra of Corinaldo) are willing to cooperate. We have a letter from the mayor of Gubbio supporting the protection of the GSSP.

The Boundary Level: Primary and Auxiliary Markers

(oldest)

(1) First occurrence of the planktonic foraminiferan *Globotruncana neotricarinata* (213.30 m). This species is cosmopolitan in marine settings at thermocline depth with occurrences in all biogeographic realms.

(2) Carbon isotope peak LSE–a (215.4 to 216.6 m). This event, and the succeeding one, have been identified globally.

(3) Carbon isotope peak LSE–b (217.0 to 218.8 m). The LSE–b peak forms the maximum of the LSE carbon isotope excursion.

(4) First occurrence of the planktonic foraminiferan *Contusotruncana patelliformis* (217.55 m). This species occurs in marine settings at mixed layer to thermocline depth at low to mid–latitudes in the Tethyan realm, Western Interior Seaway, and in the Atlantic, Pacific and Indian Oceans.

(5) Last occurrence of the planktonic foraminiferan *Marginotruncana tarfayaensis, Marginotruncana pseudomarginata, Muricohedbergella flandrini* (218.92 m). *Marginotruncana tarfayaensis* occurs in marine settings at thermocline depth at low to mid–latitudes in the Tethyan realm, and in the Atlantic, Pacific, and Indian Oceans. *Marginotruncana pseudomarginata* and *M. flandrini* are cosmopolitan species with occurrences at mixed layer to thermocline depth in all biogeographic realms.

(6) First occurrence of the coccolith *Arkhangelskiella cymbiformis* (base of zone UC13) (219.10 m).

(7) First occurrence of the planktonic foraminiferan *Hendersonites carinatus* (219.33 m). This species occurs in marine settings at lower mixed layer depth at low to mid–latitudes in the Tethyan realm, Western Interior Seaway, and in the Atlantic, Pacific, and Indian Oceans.

(8) First occurrence of the coccolith *Aspidolithus parcus expansus* (middle zone UC13) (219.5 m).

(9) Last occurrence of the planktonic foraminiferan *Dicarinella concavata* (220.2 m). This species occurs in marine settings at mixed layer to thermocline depth at low to mid–latitudes in the Tethyan realm, Western Interior Seaway, and in the Atlantic, Pacific, and Indian Oceans.

(10) First occurrence of the coccolith *Aspidolithus parcus parcus* (base of zone UC14) (220.5 m).

(11) First occurrence of the planktonic foraminiferan *Pseudoguembelina costellifera* (221.45 m). This species occurs in marine settings at mixed layer depth at low latitudes in the Tethyan realm, Western Interior Seaway, and in the Atlantic, Pacific, and western Indian Ocean. It is rare in mid–latitude deep sea sites in the south Indian Ocean.

(12) Primary marker, magnetic reversal Chron 33r (221.53 m). Globally recognised reversal, base of C–sequence in oceanic settings.

(13) Last occurrence of the planktonic foraminiferan *Marginotruncana schneegansi* (221.6 m). This species occurs in marine settings at thermocline depth at low to mid–latitudes in the Tethyan realm, Western Interior Seaway, and in the Atlantic, Pacific and Indian Ocean.

(14) Last occurrences of the planktonic foraminiferan *Dicarinella asymetrica* and *Sigalia* spp. (221.72 m) (base of *Globotruncanita elevata* Zone). *Dicarinella asymetrica* occurs in marine settings at mixed layer to thermocline depth at low to mid– latitudes in the Tethyan realm, Western Interior Seaway, and in the Atlantic, Pacific and Indian Oceans. *Sigalia* spp. occur at lower mixed layer depth at low latitudes in the Tethyan realm, in the North Atlantic and in the western Indian Ocean.

(15) First occurrence of the planktonic foraminiferan *Globotruncana hilli* (221.72 m). This species is cosmopolitan in marine settings at thermocline depth with occurrences in all biogeographic realms.

(16) First occurrence of the planktonic foraminiferan *Globotruncanita atlantica* (222.05 m). This species occurs in marine settings at thermocline depth at low latitude in the Tethyan realm, Western Interior Seaway, and in the North Atlantic, western Indian and central Pacific Ocean.

(17) First occurrence of the planktonic foraminiferan *Globotruncana orientalis* (222.21 m). This species is cosmopolitan in marine settings at thermocline depth with occurrences in all biogeographic realms.

(18) First common occurrence of the coccolith *Aspidolithus parcus parcus* (224.60 m) (base of zone UC14a[TP]).

(19) Last occurrence of the planktonic foraminiferan *Marginotruncana undulata* (225.75 m). This species occurs in marine settings at thermocline depth at low latitudes in the Tethyan realm and western Indian Ocean and is rare in mid–latitude deep sea sites in the south Indian Ocean.

(20) First occurrence of the planktonic foraminiferan *Pseudoguembelina costulata* (227.0 m). This species occurs in marine settings at mixed layer depth at low to mid–latitudes in the Tethyan realm, Western Interior Seaway, and in the Atlantic, Pacific and Indian Ocean.

(21) Last occurrence of the planktonic foraminiferan *Marginotruncana sinuosa* (227.50 m). This species is cosmopolitan in marine settings at mixed layer to thermocline depths with occurrences in all biogeographic realms.

(22) First occurrence of the coccolith *Aspidolithus parcus constrictus* (229 m) (base of zone UC14b[TP])

(23) Last occurrence of the planktonic foraminiferan *Marginotruncana* spp. (230.98 m). This genus is cosmopolitan in marine settings at mixed layer to thermocline depth with occurrences in all palaeobiogeographic realms.

(youngest)

Auxiliary Sections

Seaford Head, Sussex, England, UK

The sea cliff section in the English Channel at Seaford Head, east of Seaford in Sussex, UK (Figs. 10-13; 50°45′47.25″N, 0°0.6′41.11″E) provides a continuously exposed succession in white chalk facies across the Santonian–Campanian boundary. An early biostratigraphical (zonal macrofossil) description was given by Rowe (1902); Mortimore (1986) and Mortimore et al. (2001) provided a detailed lithological profile and some macrofossil distribution data (echinoids, crinoids). Hampton et al. (2007, fig. 8) included distribution data for selected nannofossils and benthic foraminiferan. Planktonic foraminifera are rare, but Hampton et al. (2007) record a major incursion of double keeled taxa at the level of the Brighton Marl (66–68 m in Figs. 11 and 12). Jenkyns et al. (1994) provided an oxygen– and carbon isotope curve for this section, and Thibault et al. (2016) published high–resolution carbon and oxygen isotope curves, and an orbitally tuned timescale based on these data. Gale (2018) described microcrinoid occurrences in the uppermost Santonian and lowest Campanian parts of the succession. Jarvis et al. (2022) provided detailed palynological data and a high-resolution carbon isotope curve (Fig. 13). Although proposed as a potential GSSP (Hampton et al., 2007), the absence of important planktonic foraminifera and reliable magnetostratigraphy preclude its use. However, it provides an excellent carbon–isotope curve which permits correlation of the crinoid zones to the Bottaccione GSSP section, and palynological data from the stage boundary interval at Seaford Head (Fig. 13) from Jarvis et al. (2022).

The section can be accessed only on low spring tides, from the promenade east of Seaford (50°45′50.70″N, 0°0.6′33.07″E). Care should be taken, as the shore is slippery and cliff–falls are common. The Santonian–Campanian boundary interval is exposed 160–200 m southeast of the promenade. The succession here is in the Newhaven Chalk Formation and comprises soft, white pelagic chalks containing thin marls and numerous layers of nodular flint. A detailed lithostratigraphical nomenclature for the marl and flint layers was provided by Mortimore (1986) and is shown in Figs. 11 and 12. Key markers are the Buckle Marl, the Exceat Flint, the Brighton and Friar's Bay Marls, which extend across the northern part of the Anglo–Paris Basin (Gale, 2018).

Macrofossil subdivision of this section is based primarily upon the distribution of four successive species of stemless benthonic crinoid (*Uintacrinus socialis*, *Marsupites laevigatus*, *M. testudinarius*, *U. anglicus*) which are of worldwide distribution in chalk facies (Gale et al., 2008; see below). These are overlain by an assemblage zone characterised by an echinoid, *Offaster pilula*, within which successive horizons
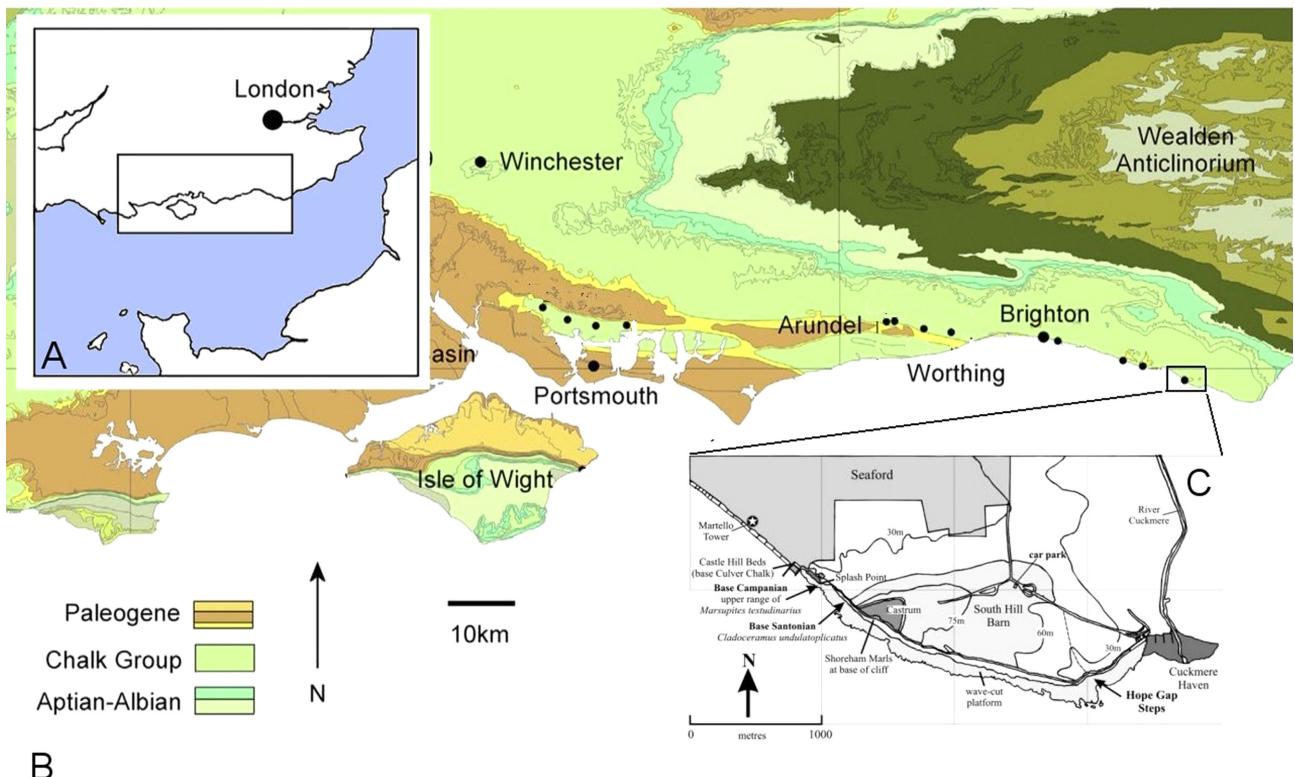
Figure 10. Map showing the location of the Seaford Head section, Sussex, U.K. A, southern England, to show area in B. B, geological map of southern English coast to show location of C. C, detailed map of Seaford and Seaford Head. After Hampton et al. (2007) and Gale (2018).

are recognised using shape variants of the echinoid *Echinocorys scutata* (Brydone, 1914; Mortimore, 1986; Gale, 2018). Microcrinoid zones (Gale, 2018, 2019) extend from SaR4–6 to CaR1, 2; the Santonian–Campanian boundary falls within the upper part of CaR1 (Fig. 12). Nannofossil data (Hampton et al., 2007) include the first occurrence of the coccolith *Aspidolithus parcus parcus*, between the Rottingdean Pair and Rottingdean Triple Marls (9 m above the Late Santonian carbon isotope event–LSE), which possibly correlates with the FCO of the subspecies in the Bottaccione section (Fig. 6) (Miniati et al., 2020).

A new palynological study of 40 samples (average ~1 m spacing) from Seaford Head was completed for this work, spanning the interval from the Buckle Flint (basal upper Santonian, *U. socialis* Zone) to the Old Nore Marl in the lower Campanian *O. pilula* Zone (Fig. 13; Jarvis et al., 2022). The floras are overwhelmingly dominated by organic walled dinoflagellate cysts (~90% of the total) with a moderate species richness of 30 to 64 taxa (average 43), although algae (particularly the prasinophyte *Leiosphaeridia*) are well represented in the Santonian. A conspicuous influx of fungal hyphae and insect remains associated with the Late Santonian CIE may be significant as a similar event is observed at Bocieniec (see below).

The dinoflagellate component is represented by a mixture of the marginal marine *Circulodinium–Heterosphaeridium* (C–H; see Pearce et al., 2003) assemblage, and the more distal *Spiniferites–Palaeohystrichophora* (S–P) assemblage (Pearce et al., 2003; Prince et al., 2008; Pearce et al., 2009; Jarvis et al., 2021), with a ratio of ~2:1. Absolute abundances (palynomorphs per gram, ppg) are relatively low and range from 90–1,400 ppg (Fig. 12). The average value of ~300 ppg is con-

sistent with the type C–H assemblage recovered from the Chalk of Berkshire, southern England by Pearce et al. (2003).

Some stratigraphic markers are missing at Seaford Head, presumably due to the relatively marginal setting. Regionally significant events are briefly discussed below, in stratigraphic order from the lowest upwards, which effectively constrain the Santonian–Campanian boundary. Results are compared to other macrofossil–calibrated, high–resolution studies with $\delta^{13}C$ data: eastern England (Trunch borehole, Norfolk), southern England (Foreness Point and White Ness sections, Isle of Thanet, Kent; Whitecliff, Isle of Wight), France (Poigny 701 borehole, Seine–et–Marne), and Poland (Bocieniec, this paper, see below).

(oldest)

(1) The first occurrence of *Cordosphaeridium catherineae* at Seaford Head is observed at 57 m in the low *U. socialis* Zone, at the top of the Buckle CIE (Fig. 12). Pearce et al. (2020) recorded the first occurrence of the species slightly higher in the upper Santonian (high *U. socialis* Zone) at the base of the Hawks Brow CIE in the type material from the Trunch borehole. More recent work on the Poigny 701 borehole (Pearce et al., 2022) confirms the first occurrence in the (low) *U. socialis* Zone immediately above the Buckle CIE (although due to the wide sampling interval, the event may occur closer to, or within, the Buckle CIE).

(2) First occurrence of *Odontochitina porifera*. Pearce et al. (2020) reported a first occurrence (a likely First Appearance Datum) of *O. porifera* in the lower Santonian as a near globally synchronous event, while noting that a delayed first occurrence in the upper Santonian is
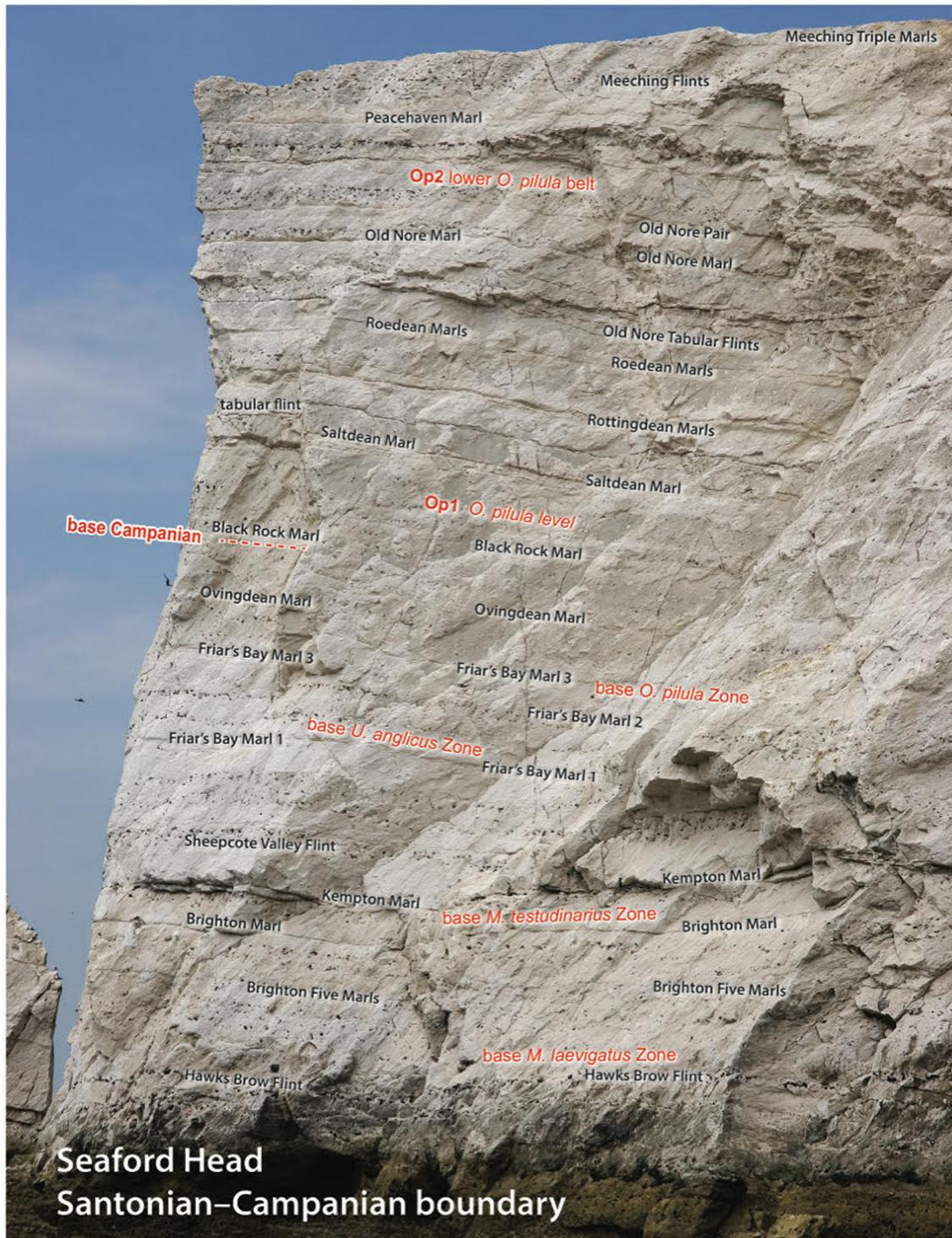
Figure 11. Photograph of Santonian-Campanian chalk succession at Seaford Head, Sussex, UK, looking north-westwards. Modified after Jarvis et al. (2022, fig. 2).

typical in NW Europe. This delayed first occurrence occurs consistently between the Buckle and Hawks Brow CIEs (i.e., in the *U. socialis* Zone) at Bocieniec (see Section 3.2), Trunch (Pearce et al., 2020), Whitecliff (Prince et al., 1999), and White Ness (Prince et al., 2008). At Seaford Head, the lowest occurrence of *O. porifera* occurs at 61 m (*U. socialis* Zone), also below the Hawks Brow CIE, consistent with

other records.

(3) The lowest occurrenc of *Dimidium striatum*. As discussed by Pearce et al. (2020), the lowest occurrence of *D. striatum* recorded by Prince et al. (1999) from Culver Cliff (Whitecliff) is tentatively taken to represent the First Appearance Datum of the species and occurs between the Horseshoe Bay and Buckle CIEs. At Seaford Head, the
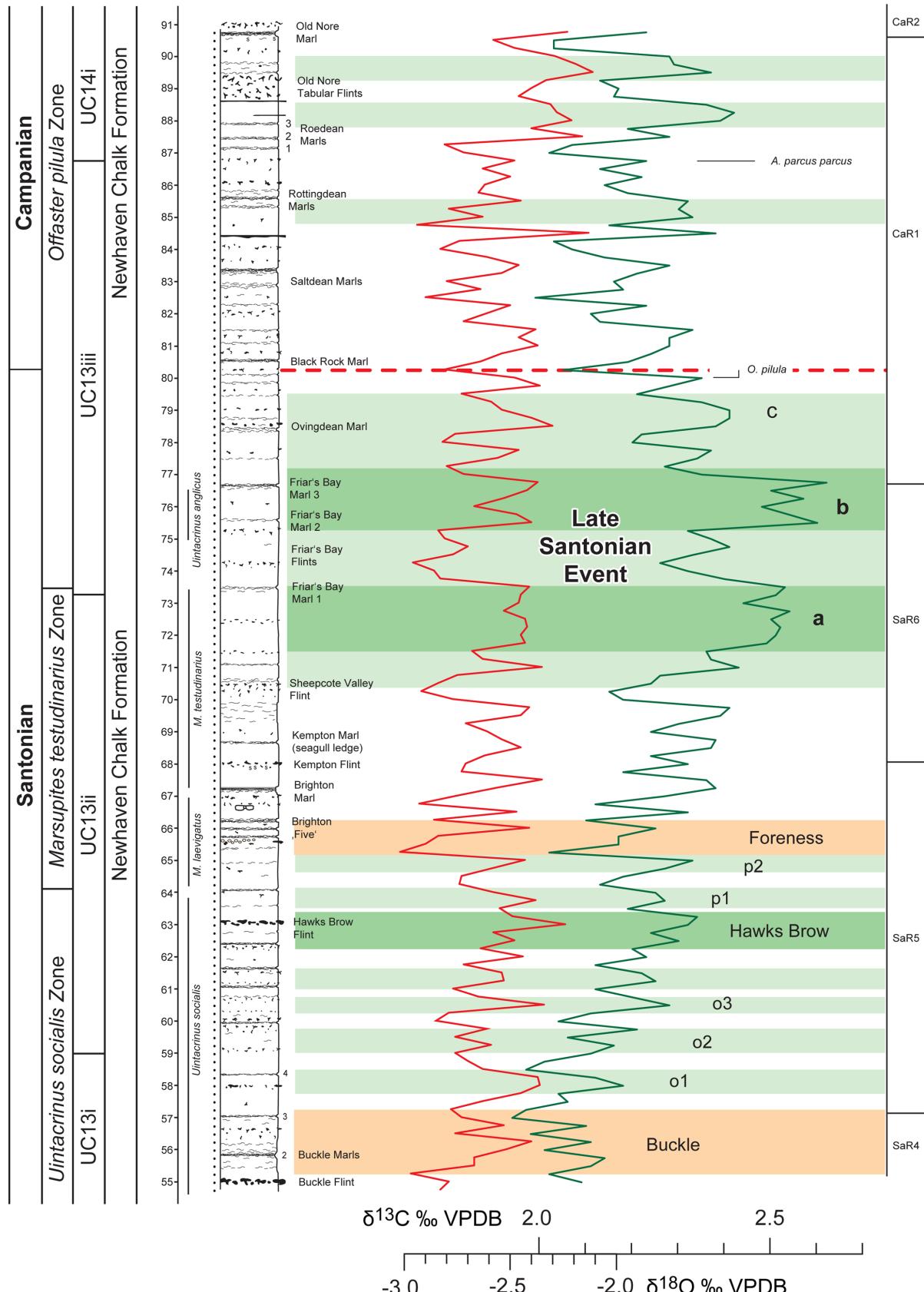
Figure 12. The succession at Seaford Head, Sussex, UK, modified after Thibault et al. (2016). The dotted red line immediately beneath the Blackrock Marl marks the inferred base of the Campanian, based on correlation of the carbon isotope record with the proposed GSSP. Minor carbon isotope excursions are labelled as o1– o3 and p1, 2, Buckle, Hawks Brow and Foreness. The columns on the right shows the microcrinoid zones (SaR4–6 to CaR1, 2, after Gale 2018, 2019) and the North Sea nannofossil zonation (Thibault et al. 2016). Lithostratigraphical terminology after Mortimore (1986).

event occurs stratigraphically higher between the Hawks Brow and Foreness CIEs, but it is still a useful marker for a position no lower than middle Santonian.

(4) Lowest occurrence of *Rhynchodiniopsis saliorum*. According to Pearce et al. (2020), the First Appearance Datum of *R. saliorum* occurs within Hawks Brow CIE in the *U. socialis* Zone in southern England. At Seaford Head, the lowest occurrence of *R. saliorum* occurs above

the Foreness CIE in the *M. testudinarius* Zone. Although this level is slightly higher than the FAD, it is apparently synchronous at Trunch (Pearce et al., 2020) and Poigny (Pearce et al., 2022) and is consistent as a marker for the upper Santonian.

(5) The recognition of a conspicuous absence or minimum relative abundance for *Surculosphaeridium longifurcatum* within the late Santonian is emerging from multiple sections across Europe. At Seaford
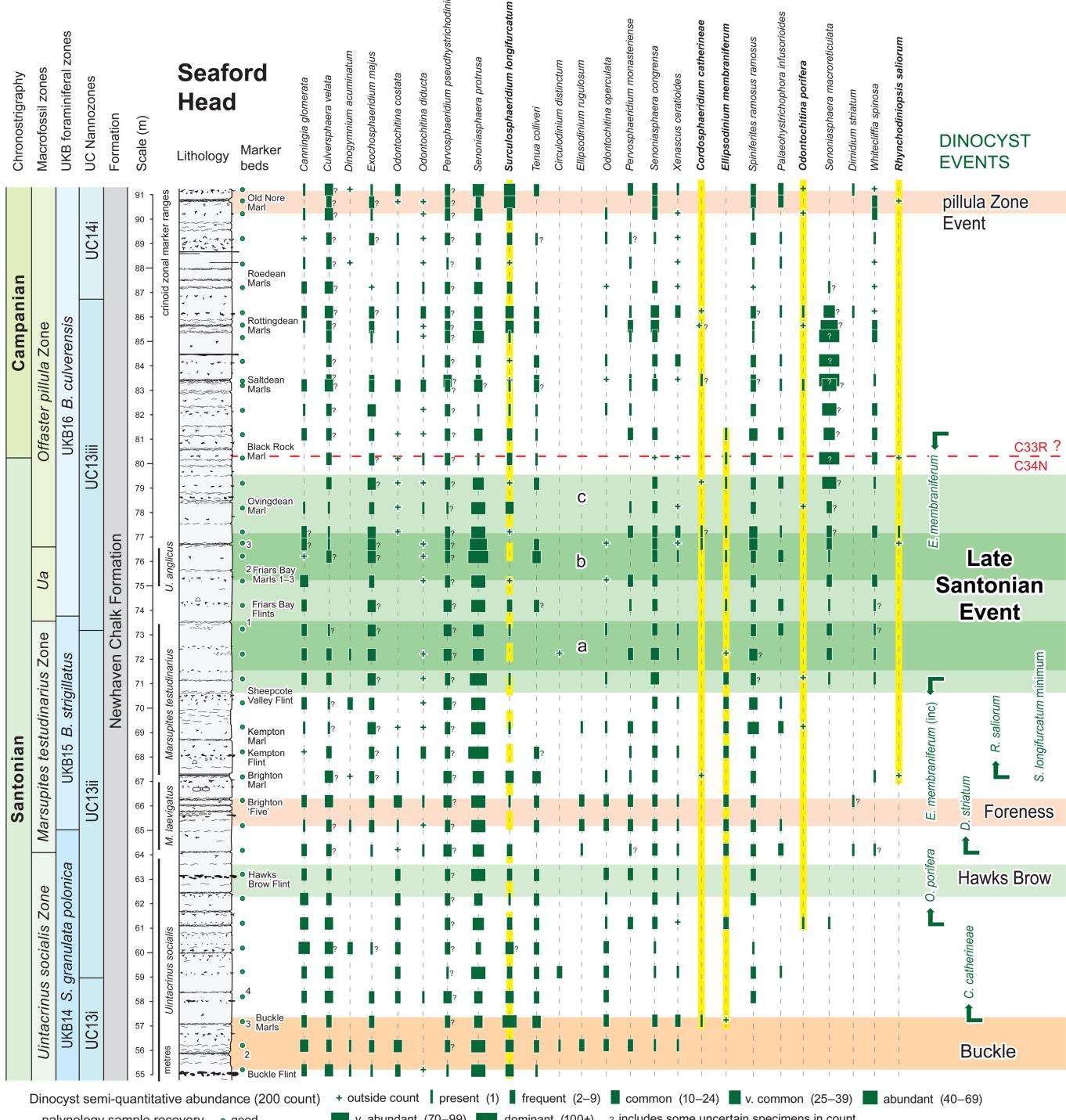

Figure 13. Ranges of selected organic walled dinoflagellate cysts and significant dinocyst events at Seaford Head, Sussex, U.K. See Fig. 12 for additional stratigraphical details. After Jarvis et al. 2022, fig. 5.

Head (Fig. 12), Poigny (Pearce et al., 2022), Trunch (Pearce et al., 2020, suppl. table 2) and Whitecliff (Prince et al., 1999), *S. longifurcatum* is poorly represented from below the Hawks Brow CIE upwards to above the Late Santonian CIE b. In all cases the stratigraphic mid–point of this poor recovery interval lies below the Late Santonian CIE within the *M. testudinarius* Zone. Interestingly, at Bocieniec, where the species is particularly common, a clear minimum in relative abundance occurs at the same stratigraphic level.

(6) The last occurrence of *Ellipsodinium* spp. appears to be a particularly significant, albeit currently local marker for the Santonian–Campanian boundary in NW Europe (Pearce et al., 2022). The last occurrence of *E. membraniferum* at Seaford Head occurs at 81 m, in the basal *O. pilula* Zone, above the Late Santonian Event, and ~1 m above the inferred position of the C34n–C33r boundary (Fig. 12). At Poigny (Pearce et al., 2022), and Trunch (Pearce et al., 2020, suppl. table 2) the last occurrence of *Ellipsodinium* spp. occurs slightly lower, but consistently within the Late Santonian Event. In the type material at Whitecliff, the last occurrence of *Ellipsodinium membraniferum* occurs in the lower *O. pilula* Zone (Prince pers. comm), which according to Jarvis et al. (2006, fig.11), presumably lies a few metres above the Late Santonian Event. Interestingly, in sites from southern England where *Ellipsodinium* is particularly well represented (Seaford Head; Whitecliff, Prince et al. pers. comm.; Foreness, Prince et al., 2008), a last common occurrence event is also recognised in the high *M. testudinarius* Zone, below the Late Santonian Event.

(youngest)

The Seaford Head section has provided a high–resolution carbon isotope stratigraphy based upon analysis of closely spaced bulk chalk samples (Thibault et al., 2016; Jarvis et al., 2022). Important features of potential global significance are, successively:

(oldest)

The Buckle Event (Jarvis et al., 2006), a 0.5 per mil symmetrical trough in the lower and middle *U. socialis* Zone.

The Hawks Brow Event, a 0.4 per mil positive peak which is present in the uppermost *U. socialis* Zone.

The Foreness Event, (sensu Thibault et al., 2016) is a short 0.3 per mil trough in the *M. laevigatus* Zone.

The Late Santonian Event, a double peak with amplitudes of approximately 0.4 per mil, of which the lower maximum (peak a) is close to the top of the *M. testudinarius* Zone and the higher maximum (peak b) is coincident with the range of *U. anglicus*. A minor peak (c) is present above.

The *O. pilula* Zone Event, a 0.5 per mil trough is situated at the level of the Old Nore Marl (Fig. 11).

(youngest)

The magnetostratigraphy of the Seaford section given by Barchi (1995) and Montgomery et al. (1998) has been shown to be unreliable (Hampton et al., 2007; Thibault et al., 2016). Thus, the main importance of the Seaford Head section is the relationship between features of the high–resolution carbon isotope curve and successive crinoid zones, which permits these to be correlated into successions in which the crinoids are absent (Fig. 4). The base of the Campanian falls between the higher peak of the Late Santonian Event and the first occurrence of common *Aspidolithus parcus parcus*, a level immediately underlying the Blackrock Marl at 80. 2 m (Figs. 11 and 12).

Bocieniec, Kraków, Poland

An old quarry in the village of Laski Dworski, 25 km north of Krakow (Fig. 14; 50°16′21.21″N, 19°56′1.09″W) exposes 5.5 m of Upper Cretaceous sediments, unconformably overlying Jurassic limestones (Dubicka et al., 2017). The succession (Fig. 15) comprises a thin basal glauconitic marl, overlain by 4.9 m of monotonous grey marls, and capped by 0.6 m of siliceous "opoka" chalk. The succession is thin, but has provided important data on magnetostratigraphy, biostratigraphy (nannofossils, planktonic and benthic foraminifera, crinoids), and a detailed carbon isotope curve, all summarised in Fig. 15, and the results of a recent palynological study (Jarvis et al., 2022) are presented here (Fig. 16). The magnetostratigraphy demonstrates that Chron 34n extends up into the range of *Marsupites*, and that the highest metre is reversed, with an intervening zone of uncertain polarity. The last occurrence of *D. asymetrica* lies 20 cm above the last occurrence level of *Marsupites testudinarius*. The carbon isotope curve shows the negative Foreness Event in the *M. laevigatus* Zone, and a single well developed 0.5 per mil peak of the Late Santonian Event. This was interpreted by Dubicka et al. (2017) as the higher of the double peaks of the LSE, but the coincidence of the main peak with the last occurrence of *M. testudinarius* indicates that it is the lower of the pair (peak a, Fig. 15). Moreover, *Uintacrinus anglicus* is absent, suggesting a minor hiatus around the 4.4 m level, and, in our interpretation, there is a minor hiatus around the 4.3 m level as a result of which the upper part of the LSE (peak b) and the *U. anglicus* Zone are missing. The last occurrence of *D. asymetrica* is recorded at 4.38 m. However, the level of this latter bioevent includes a wide uncertainty, relying on only 3 discontinuous occurrences of the taxon within the lower 4.4 m of the section (Fig. 15). The base of the Campanian at Bocieniec is thus taken at ca. 4.45 m where Dubicka et al. (2017) positioned the base of Chron 33r,

Figure 14. Map to show location of Bocieniec, Poland. After Dubicka et al. (2017).
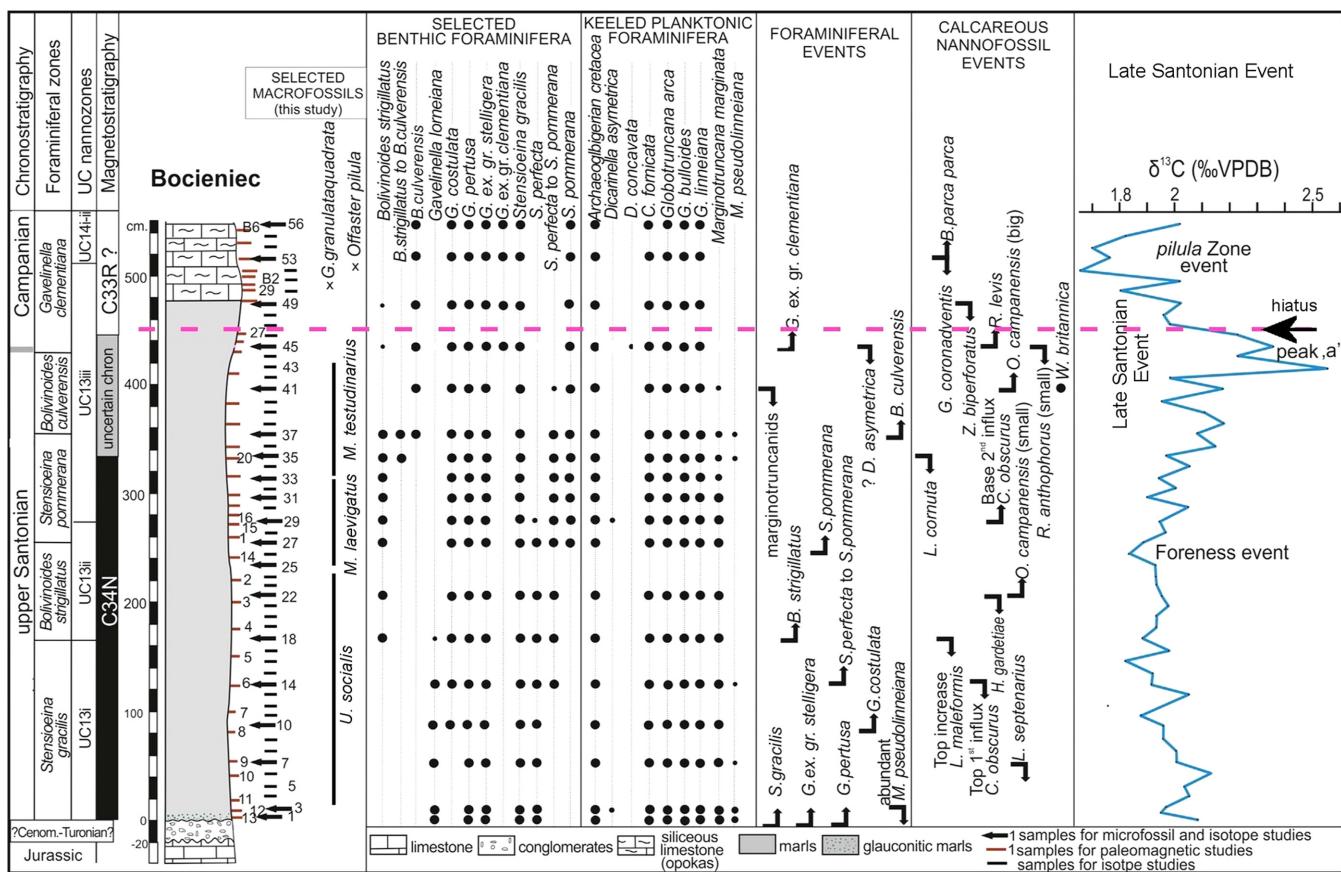
Figure 15. The succession at Bocieniec, near Krakow, Poland, modified after Dubicka et al. (2017). The base of the Campanian is taken at the base of Chron C33r, at 4.5 m. Crinoid distributions as observed by ASG.

within the upper part of *Stensioeina pommerana* Zone, slightly below the FO of true *Bolivinoides culverensis* (for benthic foraminifera zonation see Walaszczyk et al., 2016).

The palynology of 21 samples from Bocieniec (0.03 to 5.5 m, average spacing of 0.27 m) were studied by Jarvis et al. (2022; Fig. 16). Two samples at 0.03 and 5.28 m had extremely poor recovery with assemblages composed mostly of spores and pollen; these are excluded from further discussion due to statistical unreliability. The floras are overwhelmingly dominated by organic walled dinoflagellate cysts (67–97% of the total) and species richness systematically declines up section from over 70 to 11 taxa in the uppermost sample. As at Seaford Head, a mixture of the C–H and S–P assemblages are observed, but in contrast, the latter dominates at Bocieniec (comprising mostly *Palaeohystrichophora infusorioides*) for most of the section (0.1–4.48 m). From 4.63–5.48 m, the dominant C–H assemblage is characterised by *Sentusidinium* spp., *Circulodinium distinctum* and *Surculosphaeridium longifurcatum*. This switch in assemblages coincides with an up section increase in the relative proportion of spores and pollen from 3.83 m, and fungal and insect remains from 4.08 m. All these observations are consistent with a significant shoaling through time.

Several stratigraphic markers occur through the section and are described below;

(oldest)

(1) The first occurrence of *Senoniasphaera protrusa*. As discussed by Pearce et al. (2020) *S. protrusa* is essentially restricted to the

Northern Hemisphere and has a probable First Appearance Datum in the middle Santonian. The lowest occurrence has been recorded at the Barrois Sponge Bed at White Ness (southern England, Prince et al., 2008), below the Horseshoe Bay CIE in the middle Santonian. At Bocieniec, the event occurs at 0.1 m, well below the Foreness CIE, and therefore, suggests an age no older than middle Santonian.

(2) The first occurrence of *Dimidium striatum*. According to Pearce et al. (2020) the FAD of *D. striatum* occurs at Whitecliff (southern England, Prince et al., 1999, below the Exceat Flint), between the Horseshoe Bay and Buckle CIE's. At Bocieniec, the event is questionable at 0.1 m and confident at 0.54 m, well below the Foreness CIE, suggesting an age no older than middle Santonian.

(3) The first occurrence of *Cordosphaeridium catherineae*. As discussed above (Section 3.1.), the lowest occurrence of *Cordosphaeridium catherineae* is recorded in the low *U. socialis* Zone, at the top of the Buckle CIE (Fig. 13) at Seaford Head, and immediately above the Buckle CIE at Poigny (Pearce et al., 2022). These observations extend the first occurrence of the species in the type material (Pearce, 2010) where it occurs in the Hawks Brow CIE. At Bocieniec, the first occurrence of *C. catherineae* is at 0.88 m, within the *U. socialis* Zone, providing additional evidence for a late Santonian age.

(4) The LO of *Odontochitina porifera*. A first occurrence of *O. porifera* occurs consistently between the Buckle and Hawks Brow CIEs (as at Seaford Head) in NW Europe (see below). At Bocieniec, the first occurrence is at 1.56 m and is supporting evidence for a late
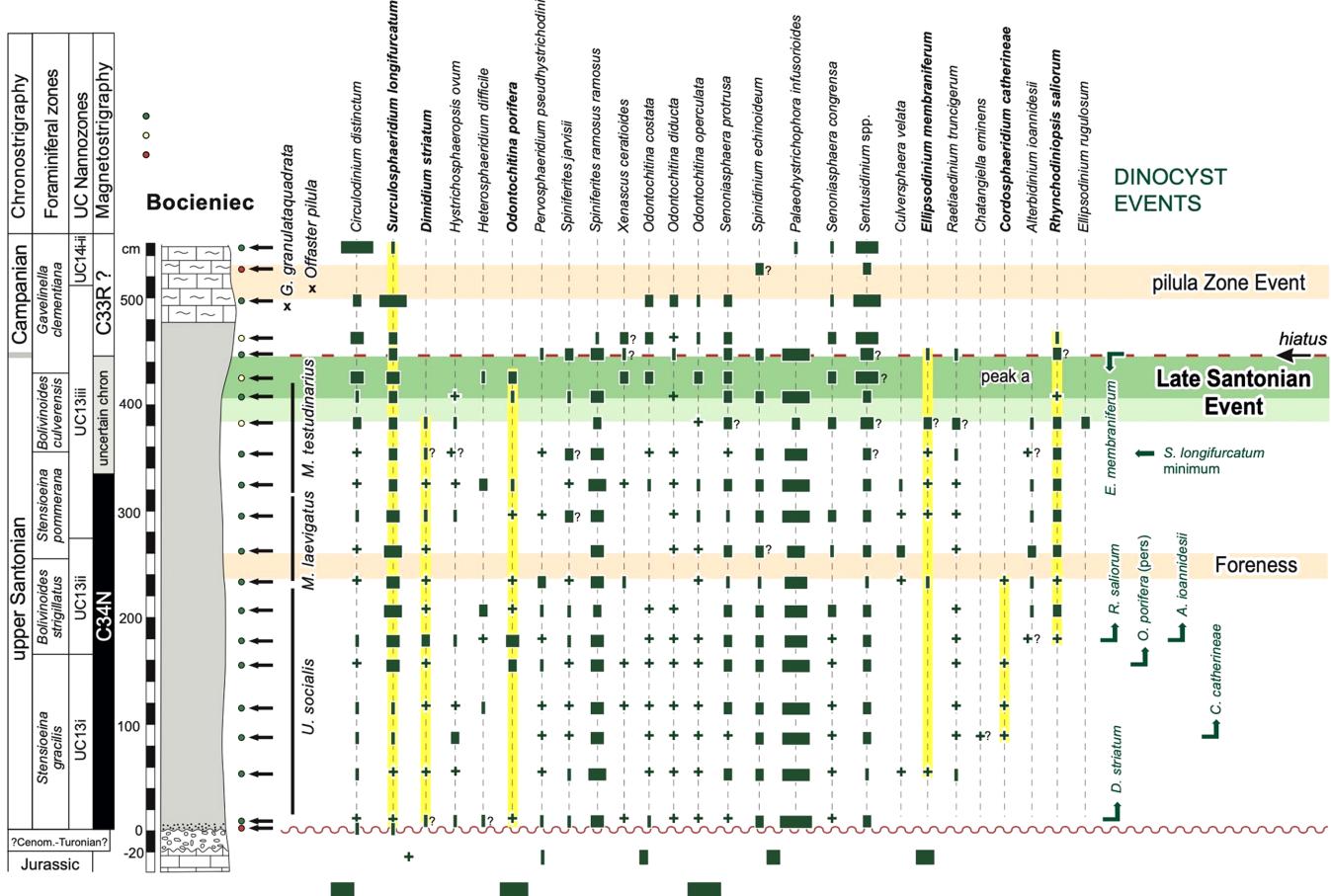
Figure 16. Ranges of selected organic walled dinoflagellate cysts and significant dinocyst events at Bocieniec, Poland, after Jarvis et al. 2022 fig.10. See Fig. 15 for additional stratigraphical details.

Santonian age.

(5) The first occurrence of *Rhynchodiniopsis saliorum*. The FAD of *R. saliorum* occurs within Hawks Brow CIE in the *U. socialis* Zone in southern England. At Bocieniec, the event occurs at 1.79 m within the range of *U. socialis*, and is therefore, a consistent feature of the upper Santonian.

(6) The poor recovery of *Surculosphaeridium longifurcatum* in the upper Santonian appears to be a consistent feature in many high–resolution studies from France and southern England (see Seaford Head, above). Similarly, at Bocieniec, where the species is unusually abundant, a clear minimum in relative numbers occurs at 3.54 m, below the Late Santonian CIE within the *M. testudinarius* Zone. This 'event' requires testing but may be stratigraphically significant.

(7) The first occurrence of rare *Heterosphaeridium difficile*. According to Pearce et al. (2020), the last occurrence of *H. difficile* lies in the upper Santonian (mid–*U. socialis* Zone), below the Hawks Brow CIE. The event has subsequently been raised to within the Late Santonian CIE at Poigny (Pearce et al., 2022), and is synchronous at Bocieniec where it was recorded at 4.26 m.

(8) The last occurrence of *Ellipsodinium* spp. This appears to closely approximate the Santonian–Campanian boundary in France, and eastern and southern England (see Seaford Head, above). At Bocieniec, the last occurrence of *E. membraniferum* is recorded at 4.48 m, 3 cm above

the proposed position of the Santonian–Campanian boundary. These results are encouraging, but the geographical extent of the event requires further testing.

(youngest)

Biocieniec is an important section which demonstrates the correspondence of crinoid zones, planktonic foraminifera, calcareous nannofossils, dinoflagellate cysts and magnetostratigraphy across the boundary. However, it is a very thin succession which contains at least one minor hiatus.

Postalm, Austria

The Santonian–Campanian boundary interval of the Postalm section within the Gosau Group of the Northern Calcareous Alps of Austria (Figs. 17 and 18) was proposed as a Campanian reference section for the northwestern Tethys (Wolfgring et al., 2018, 2020). Including nearby complementary sections like Schattau and Sandkalkbank (Wagreich et al., 2010), the stratigraphy for this time interval in the Gosau Basin is based on palaeomagnetic and stable isotope data, planktonic foraminifera and calcareous nannoplankton biostratigraphy, and strontium isotope stratigraphy, together with published upper Santonian ammonite (e.g., *Placenticeras paraplanum*, *Boehmoceras arculus*, *Placenticeras maherndli*, *Texasia dentatocarinata*; Summesberger, 1985; Wagreich,

Figure 17. Map to show position of Postalm, Austria, after Wolfgring et al. (2018).

Figure 18. The succession at Postalm, Austria, after Wolfgring et al. 2018. Note the minor extension of the range of D. asymetrica into the basal part of Chron C33r. The oxygen and carbon isotope records appear to be compromised partly by diagenesis.

2010), crinoid (single horizon occurrence of *Marsupites laevigatus*; Wagreich et al., 2010) and inoceramid data (*Cordiceramus muelleri muelleri, Sphenoceramus* ex gr. *pachti/cardissoides*; Wagreich et al., 2010; Summesberger et al., 2017).

The 20 m thick interval of the Postalm section studied (Fig. 18) shows a deepening trend from upper Santonian conglomerates and sandstones, uppermost Santonian grey neritic marls to pelagic upper bathyal red marly limestones of mainly early Campanian age. Sediment accumulation rates of 19–23 mm/kyr were calculated for the fine–grained parts of the Postalm section (Wolfgring et al., 2018, 2020).

Palaeomagnetic data allow recognition of the top of the Long Cretaceous Normal Polarity–Chron 34n and the following reversal Chron C33r in the lower part of the red marly limestones (Fig. 18). This sharp reversal occurs within a 15 cm–thick interval with the first reversed sample at 2.81 m above the top of the conglomerate bed. A 1 m–thick interval of high magnetic susceptibility is present at the top of Chron C34n.

Biostratigraphic events have been correlated to the magnetostratigraphic primary marker. Eight nannofossil and four foraminifera events occur in the Gosau Group successions around the Postalm section (Wolfgring et al., 2018). The closest consistent event above the magnetostratigraphic boundary is the last occurrence of *D. asymetrica* which occurs at 4.08 m, c. 50–60 kyr after the reversal, and overlaps with the range of *Globotruncanita elevata,* defining the *D. asymetrica* Zone below and the *G. elevata* Zone above this bioevent. The first occurrence of large *Aspidolithus parcus parcus* (defined by a length above 9 μm), occurs at 4.47 m, c. 80 ka younger than the base of Chron C33r, marking the base of standard nannofossil zones CC18a (Sissingh, 1977) and UC14 (Burnett, 1998). Below this, the first occurrence of

the benthic foraminiferan *Stensioina pommerana*, (1.32 m) the last occurrence of the planktonic foraminiferan *Muricohedbergella flandrini* (3.45 m) and the first consistent occurrence of the nannofossil *Calculites obscurus* with widely separated sutures (1.30 m) may provide additional bioevents close to the boundary.

The base of the Campanian corresponds to a Sr isotope value of 0.707534 (±0.000005, mean of four analyses around the boundary interval). Although the carbon isotope signal seems to be somehow distorted due to diagenesis in this Alpine section, a constant rise can be seen in the upper Santonian, but no clearly defined Late Santonian Event can be recognized due to a plateau of high δ^{13}C above the base of C33r. A negative oxygen isotope excursion just below the base of the Campanian and a positive magnetic susceptibility excursion may provide further means of correlation, corresponding to a short sea–level high in the late Santonian followed by a distinct lowstand around the Santonian–Campanian boundary. Cyclostratigraphy using spectral analyses (REDFIT) of the carbon isotope values and magnetic susceptibility from the lower 7.5 m part of the section shows significant frequencies in the precession band and a faint signal that may correspond to 120 kyr eccentricity (Wolfgring et al., 2018).

Smoky Hill, Kansas, USA

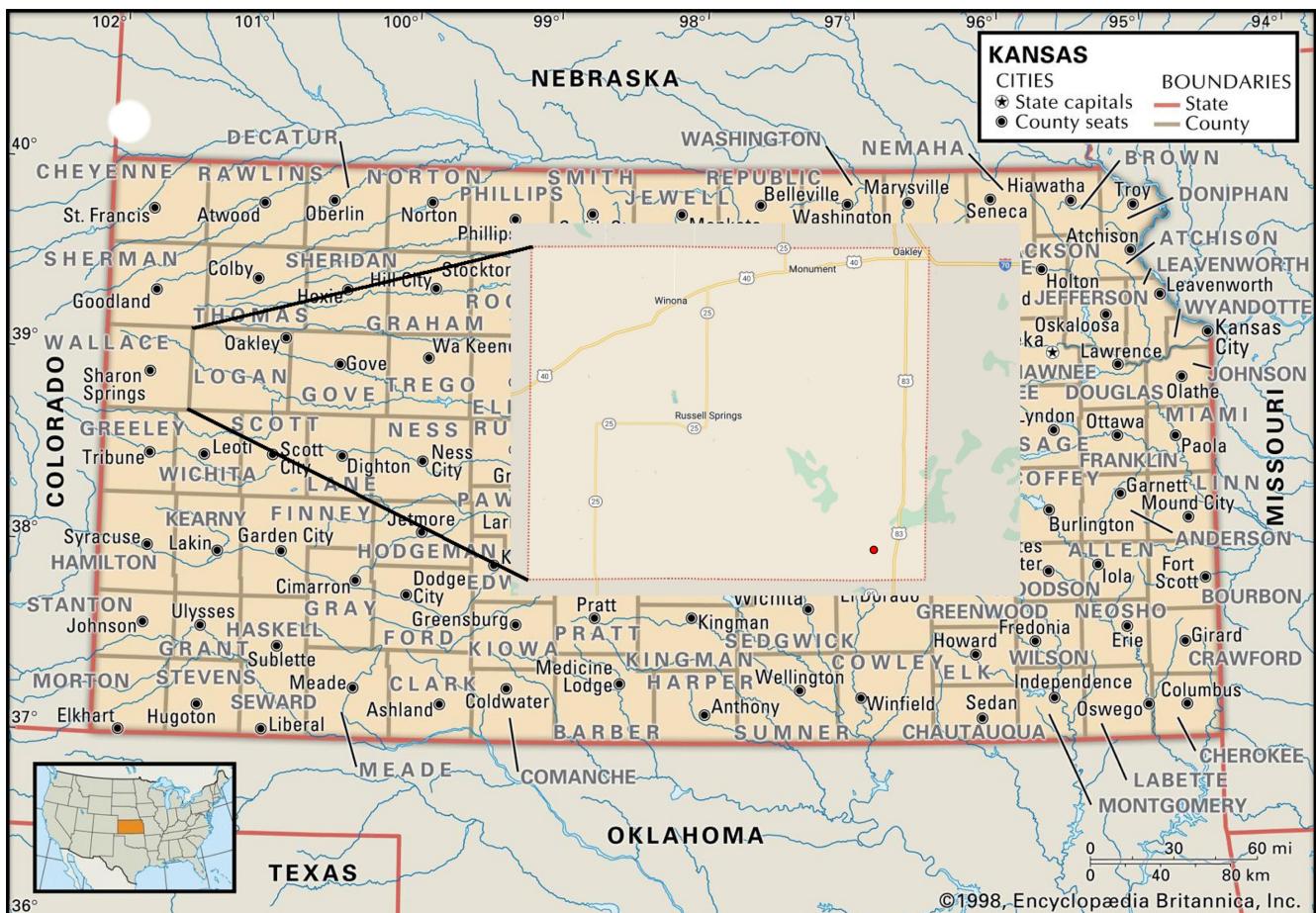The Santonian–Campanian succession in the Western Interior Basin of

Figure 19. Map to show position of key counties in northern Kansas, and the location of the auxiliary boundary section 24 in Logan County (red dot).

the USA has been documented by Cobban (1952, 1969), Scott and Cobban (1964) and Cobban et al. (2006). The stratigraphy, sedimentology and palaeoecology of the Smoky Hill Chalk Member of the Niobrara Formation of Kansas was described by Hattin (1982), who provided detailed logs. We select locality 24 of Hattin (1982, p. 25) as an auxiliary reference section (Figs. 19 and 20), described by Hattin as "Bluff on east side of Ladder Creek in SW1/4, Sec. 30, T15S, R32W, Logan County, Kansas". Kita et al. (2017) studied a composite section of the Smoky Hill Member of the Niobrara Formation across Logan, Gove and Trego counties in north Kansas, including locality 24, where the base of Chron 33r was recorded at the 174 m level (Fig. 20). The succession is developed in rhythmically bedded marly chalks. Magnetostratigraphic information (Paul Montgomery, unpublished data) showed that the boundary between Chrons 34n and 33r falls at 174 m in the profile (Fig. 20).

Kita et al. (2017) provided a detailed nannofossil record for the section, showing, importantly, that *Aspidolithus parcus parcus* first occurs at 166.3 m and *A. parcus constrictus* at 193.15 m. They inferred that the base of the *Scaphites leei* III ammonite zone corresponds with the reversal, from data derived from the Aristocrat Angus 12–8 core in northern Colorado (Joo and Sageman, 2014), but this assignation was made by inference; no ammonites have been recovered from the core. Hattin (1982) did not find ammonites diagnostic of the *Desmoscaphites bassleri* Zone nor the succeeding *S. leei* III Zone anywhere in Kansas.

There is some doubt about the precise relationships between ammonite zones and *Marsupites* occurrences in the Western Interior Basin. Cobban (1995) recorded *Marsupites* from only two localities in the United States Western Interior. The key record of *Marsupites* is that of Keefer and Troyer (1956, 1964, p. 88) in the upper part (the Sandy Member) of the Cody Shale west of Thermopolis in Fremont County, Wyoming,

associated with *Desmoscaphites bassleri*, *Scaphites leei* II of Cobban, 1969, and *Mancosiceras mancosense*. The *Marsupites* is described (Cobban, 1995, p. C50) as being a species characterised by "dominantly smooth calyx plates, like those of *M. milleri* Mantell". *Marsupites milleri* is a synonym of *M. testudinarius* (Gale, in Gale et al., 2008, p. 143), and if Cobban's comparison is correct, then the last occurrence of *Scaphites leei* II could be either within or above the range of *M. testudinarius*.

Tepeyac Section, Coahuila, Mexico

The section is located ca. 5 km south of the small village Tepeyac, about 40 km north of Piedras Negras and 15 km SSW of Jiménez, Coahuila (28°54′45″N, 100°44′29″W). It is situated in the bed of the intermittent Arroyo Blanco, a tributary to the Rio Grande, and close to the mouth of the Arroyo Tecolote (Fig. 21). The locality probably corresponds to the original site of Böse (1928), Renz (1936) and Young (1963). It was recently redescribed by Ifrim and Stinnesbeck (2021) and Ifrim et al. (2021) and exposes 28.9 m of rhythmically bedded grey to light yellow–coloured layers of limestone, and intercalated units of marl. The beds dip at about 3° to the east and are well exposed over tens to hundreds of metres along the dry river bed, allowing for a detailed search for fossils over hundreds of square metres up to the level of bed 69 (Fig. 22).

The terrain around the outcrop of the Tepeyac section is in private property. The outcrop itself is in a river bed, which in Mexico is state property. The owner has always been open to giving access for the scientific study of the section; access can be arranged through the Museo del Desierto in Saltillo. This museum is the state museum of Natural History in Coahuila. The region has been safe for fieldwork since 2015.

The ammonite assemblage documented from Tepeyac consists of about 220 specimens and permits identification of a succession of zones originally identified in the Gulf Coast states of the USA and from the Atlantic seaboard. These include;

(oldest)

(1) The *Plesiotexanites shiloensis* Interval Zone

The base of this zone is defined by the first occurrence of the index species. At Tepeyac, this species first occurs in bed 12, but layers below this level are little exposed and the fossil record is scarce. We therefore suggest that the first occurrence of *Plesiotexanites shiloensis* may even extend below the base of the Tepeyac section. Species co–occurring with *Plesiotexanites shiloensis* are *Parapuzosia* (*P.*) *leptophylla*, *Pseudoschloenbachia* (*P.*) *mexicana*, *Texanites lonsdalei*; *Menuites stephensoni* has its FO in this zone.

(2) The *Menabites* (*Delawarella*) *tequesquitense* Interval Zone

The base of this zone is defined by the first occurrence of the index species in bed 25 at 10.7 m of the Tepeyac section. The zone is 5.3 m thick. Co–occurring species are *Amapondella amapondense, Plesiotexanites shiloenis, Pseudoschloenbachia* (*Pseudoschloenbachia*) *mexicana, Menuites stephensoni,* and *Texanites lonsdalei. Bevahites bevahensis, Menabites* (*Delawarella*) *mariscalense, Menabites* (*Delawarella*) *vanuxemi* and *Parapuzosia* (*Parapuzosia*) *seppenradensis* have their first occurrences within this zone. The index is an endemic species. In spite of this, *Menabites* (*Delawarella*) *tequesquitense* is chosen as the index here because it occurs in several beds, whereas *B. bevahensis*, the other potential zonal marker, is scarce and only found in bed 33, at 14.5 m of

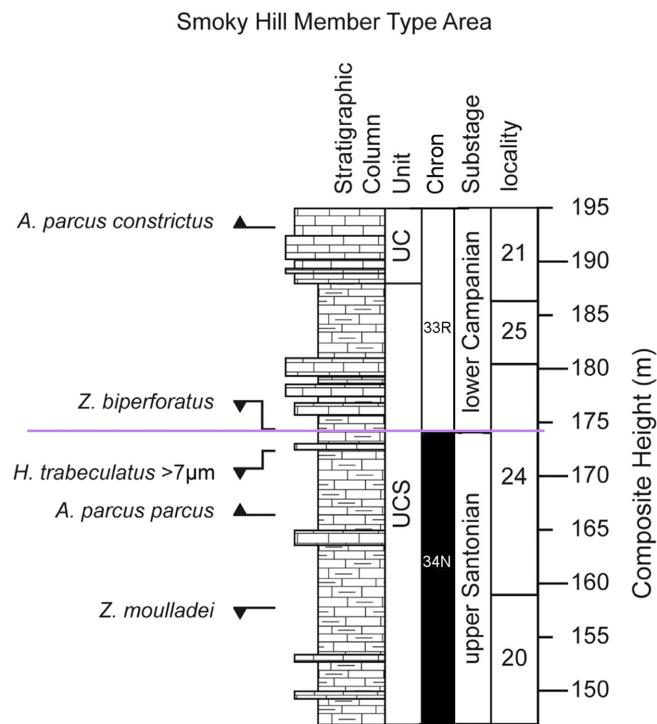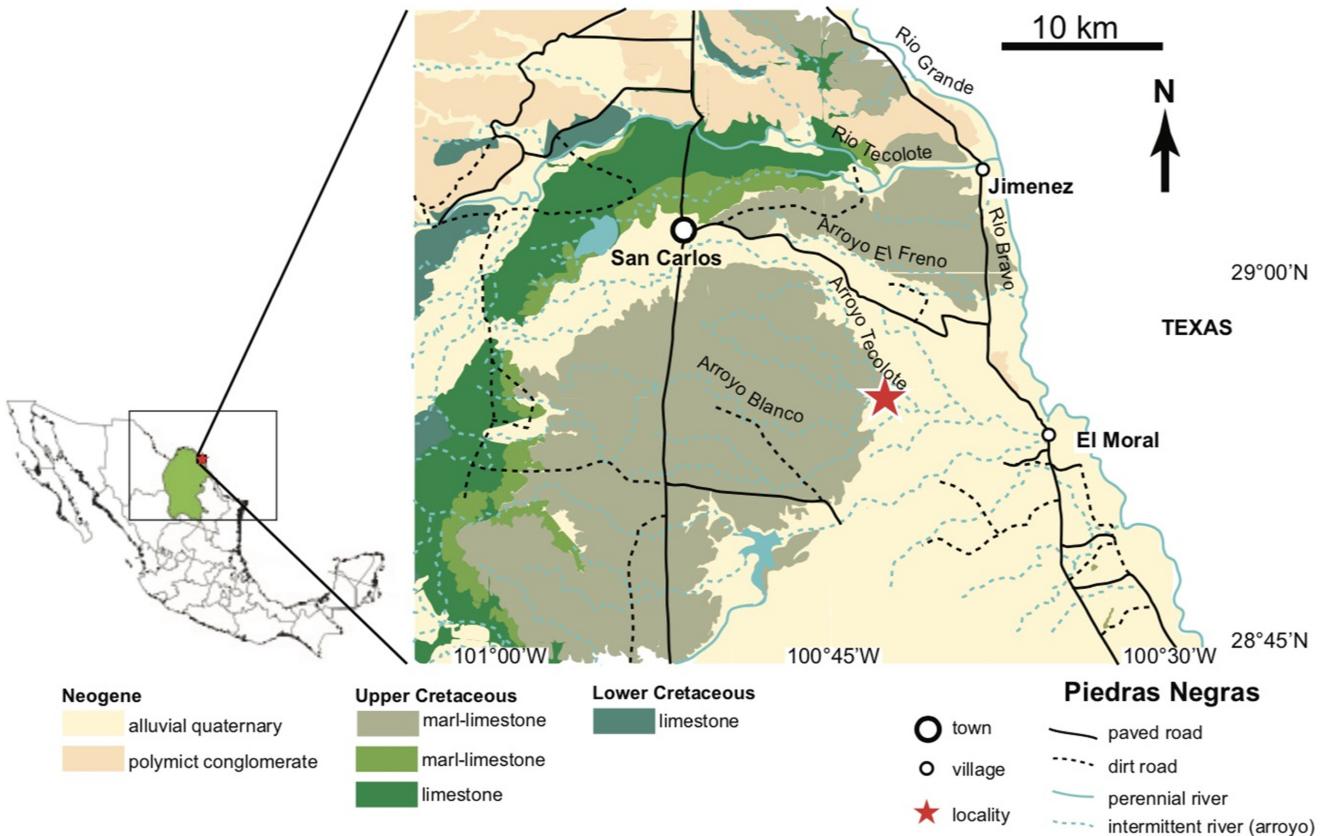**Smoky Hill Member Type Area**

Figure 20. Composite succession in the Smoky Hill Chalk Member of the Niobrara Formation in northern Kansas, after Kita et al. (2017). Stratigraphical log and locality numbers after Hattin (1982).

Figure 21. Map to show position of the Tepeyac section, Mexico, after Ifrim and Stinnesbeck (2021).

the section.

(3) The *Menabites* (*Delawarella*) *delawarensis* Interval Zone

The base of this zone is defined by the first occurrence of the index species in bed 35 at 16.0 m of the section. The zone is 6.6 m thick. *Amapondella amapondense, Bevahites costatus coahuilaensis, Menabites* (*Delawarella*) *tequesquitense, Menuites stephensoni, Plesiotexantes shiloenis, Texanites lonsdalei* and the index species have their last occurrences in this zone, while *Parapuzosia* (*Parapuzosia*) *seppenradensis, Pseudoschloenbachia* (*Pseudoschloenbachia*) *mexicana, Menabites* (*Delawarella*) *mariscalense* and *Menabites* (*Delawarella*) *vanuxemi* range throughout the zone, and *Glyptoxoceras texanum, Baculites haresi, Menabites* (*Bererella*) *walnutensis, Menabites* (*Delawarella*) *danei, Pachydiscus* (*P.*) *duelmensis* and *Menuites sp.* have their first occurrences. This zone may correspond to the full range of the index fossil, but it is defined as an interval zone.

(4) The *Baculites taylorensis* Interval Zone

The base of this zone is defined by the first occurrence of the index species in bed 64, at the 22.6 m level of the section. The zone is 5.7 m thick at Tepeyac and is truncated by a disconformity. Co–occurring taxa are *Glyptoxoceras texanum, Baculites haresi, Menabites* (*Bererella*) *walnutensis, Menabites* (*Delawarella*) *danei, Menabites* (*Delawarella*) *mariscalense, Menabites* (*Delawarella*) *uddeni, Menabites* (*Delawarella*) *vandaliense, Menabites* (*Delawarella*) *vanuxemi, Menuites* sp., *Pachydiscus* (*P.*) *duelmensis, Parapuzosia* (*Parapuzosia*) *seppenradensis, Pseudoschloenbachia* (*Pseudoschloenbachia*) *mexicana* and *Scaphites hippocrepis III*.

(youngest)

In addition, 213 in situ specimens of inoceramids were recorded from the Tepeyac section, which include twelve species (Fig. 19). The inoceramids in the Tepeyac section provide the most abundant and detailed record of this group known across the Santonian–Campanian boundary and await detailed further study.

The stable carbon isotope curve from the Tepeyac section is suitable for long–distance correlation. The following carbon isotope events were identified:

- The Horseshoe Bay Event (Jarvis et al., 2006), a 0.5 per mil peak and turning point to decreasing values in the stable carbon isotope curve, in bed 6, lower *P. shiloensis* Zone.
- The Buckle Event, a 0.5 per mil symmetrical trough in bed 14, middle *P. shiloensis* Zone.
- The Hawks Brow Event, a 0.4 per mil positive peak which is present around bed 20, upper *P. shiloensis* Zone.
- The Foreness Event, a short 0.3 per mil trough in bed 26, lower *M. (D.) tequesquitense* Zone.
- The Late Santonian Event, a peak with amplitude of approximately 0.4 per mil in upper bed 30, middle *M. (D.) tequesquitense* Zone.
- The Pilula Event, a negative excursion in beds 42, 43.

The carbon–isotope succession demonstrates that the correlated GSSP marker falls between the Late Santonian Event and the Pilula Event and corresponds approximately with the base of the *Menabites (Delawarella) delawarensis* Zone. The Tepeyac section has not yielded stratigraphically important crinoids, and the original palaeomagnetic signal seems to have been destroyed by diagenesis (Moreno–Bedmar, pers. comm. 2020).
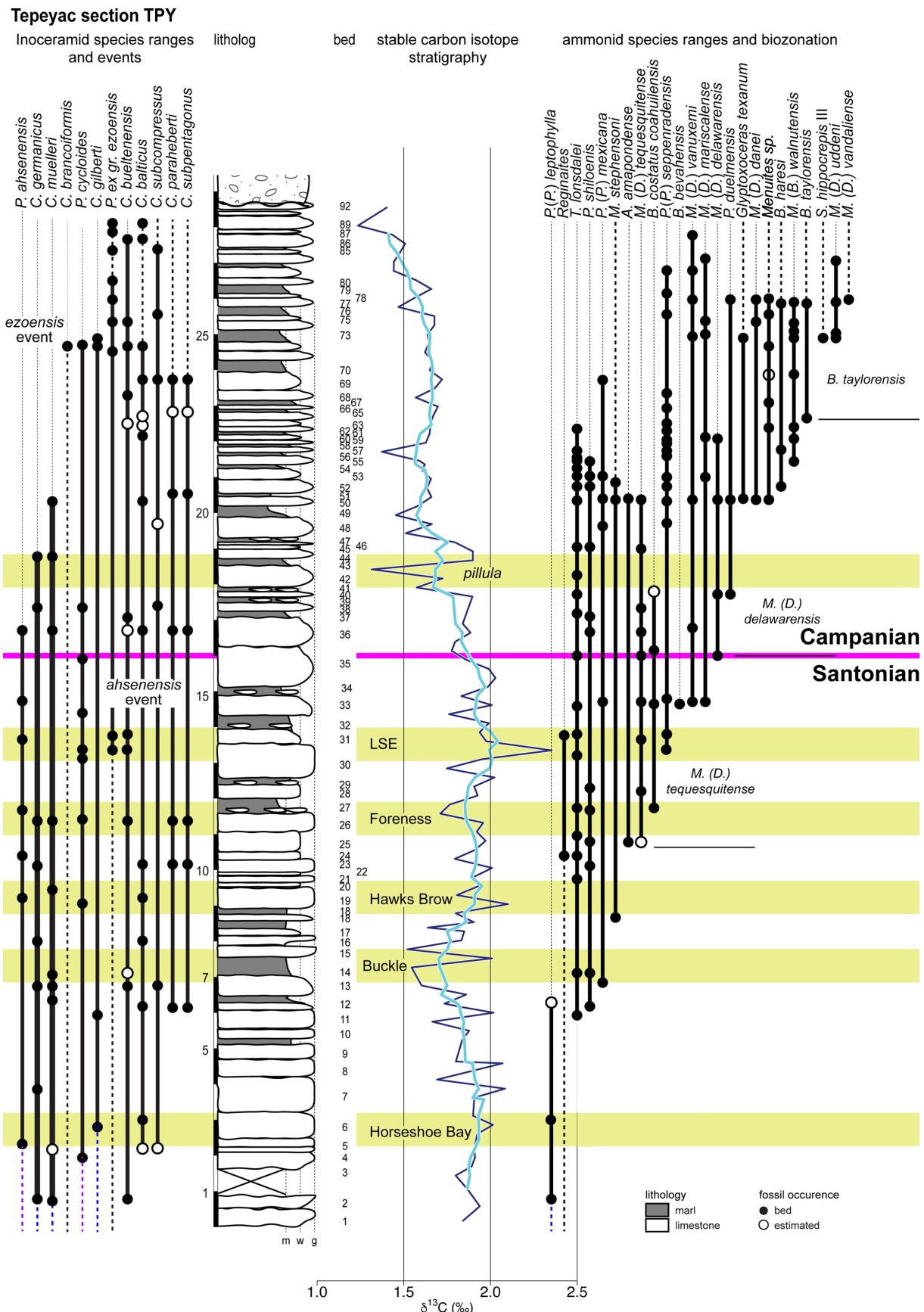
Figure 22. Distribution of inoceramid bivalves, ammonites and carbon–isotope stratigraphy, Tepeyac section in Mexico, after Ifrim and Stinnesbeck (2021). The base of the Campanian is identified from the carbon isotope record and coincides approximately with the base of the M. (D.) delawarensis Zone.

Geochronology

Dates from altered volcanic ash beds (bentonites) in the Western Interior Basin of the USA provide the firmest evidence for the age of the base of the Campanian (Obradovitch, 1993). Sageman et al. (2014) used paired Ar/Ar and U/Pb ages derived from a series of Late Cretaceous bentonites in Montana. However, the key sampled horizon, in the *Desmoscaphites bassleri* Zone of Montana (Sageman et al., 2014) could not be more precisely horizoned than to within the zone itself. The *D. bassleri* Zone includes the upper part of the range of *Uintacrinus socialis* and the total range of *Marsupites testudinaris* (Cobban, 1995 – see discussion above) and may extend to significantly higher levels. From the tuning of Thibault et al. (2016) the total duration of the *D. bassleri* Zone equivalent represents about 600 kyr. Sageman et al. (2014) provided a date of 84.14 ± 0.38 Ma for the Santonian–Campanian boundary. The top of Chron C34n was identified at the junction of the *D. bassleri* Zone and overlying *Scaphites leei* III Zone (Kita et al. 2017), but the supporting evidence is not clear, as noted above. Wang et al. (2016), studying a lacustrine succession in China, dated a bentonite (using U–Pb CA–ID TIMS) some distance beneath the supposed Chrons C34n–C33r boundary to 83.27 ± 0.11 Ma, and, using sedimentation rates in a cyclic succession, dated the base of the Campanian at 82.90 ± 0.18 Ma. Gale et al. (2020b) placed the boundary at 83.65 Ma, based on a combination of data from radiometric dates, the oceanic magnetostratigraphic record, and orbital tuning. All that can be said with certainty at present is that, according to the present array of proposed radiometric dates and their uncertainties, the boundary must lie between 82.7 and 84.5 Ma.

Discussion

Criteria for Correlation of the Santonian–Campanian Boundary Interval

In this section we review recognised and proposed criteria for correlation with the boundary interval, drawing on records from the GSSP and auxiliary sections.

Magnetostratigraphy

Chron C33r marks the base of the C–sequence of magnetozones, a fundamental boundary which has been recognised globally in the magnetic anomaly record of oceanic crust, originally calibrated in the South Atlantic (Cande and Kent, 1992, 1995; Ogg, 2020). Correct identification of the C34n–C33r boundary in onshore sedimentary successions has been more limited, but the high–resolution magnetostratigraphy recorded at Gubbio (Alvarez et al., 1977; Maron and Muttoni, 2021) provides an unambiguous record which can be calibrated to the calcareous micro–and nannoplankton and carbon isotope record (Fig. 6). The C34n–C33r boundary has been identified in the auxiliary sections at Postalm in Austria (Wolfgring et al., 2018), Bocieniec in Poland (Dubicka et al., 2017), in the Smoky Hill Chalk in northern Kansas (Kita et al., 2017) and in the Aksu–Dere section in the Crimea (Guzhikov, 2021a).

Locally there have been problems with the incorrect identification of the C34n–C33r boundary, most notably in the English Chalk (Barchi, 1995; Montgomery et al., 1998), which led to a significant misinterpretation of the biostratigraphical age of the reversal as falling within the *U. socialis* Zone of the Santonian (Gale et al., 1995), corrected by Thibault et al. (2016). A parallel situation occurred in the northern part of the Western Interior Basin, where Lerbekmo (1989), Lerbekmo and Braman (2002), Leahy and Lerbekmo (1995) and Lillegraven (1991) identified the C34n–C33r boundary as falling within the "smooth *Baculites* Zone" of Cobban et al. (2006), 5 zones above the *D. bassleri* Zone, and well above the base of the Campanian as now defined. This was corrected by Kita et al. (2017), who reported the chron boundary close to the base of the *Scaphites leei* III ammonite zone within the Upper Chalky Shale (Fig. 20).

Carbon isotopes

Carbon isotopes provide a valuable tool in the correlation of successions developed in contrasting facies and faunal realms, sometimes widely separated geographically. The carbon isotope stratigraphy of the investigated interval was first described from the English Chalk by Jenkyns et al. (1994); subsequently, Jarvis et al. (2006) named successive events in the Santonian–Campanian boundary interval:

(oldest)
- Buckle Event; a broad negative excursion within the *U. socialis* Zone.
- Hawks Brow Event; a minor positive peak, at the top of the range of *Uintacrinus socialis*.
- Foreness Event; (sensu Thibault et al., 2016) a minor negative event, coincident with the range of *Marsupites laevigatus*.
- Late Santonian Event, LSE (formerly Santonian–Campanian Boundary Event, SCBE); a double positive peak (a, b), with values reaching 2.4 per mil; the top of the lower peak (a) is coincident with the top of the range of *Marsupites*, the top of the higher peak (b) with the last occurrence of *Uintacrinus anglicus*.
(youngest)

Joo and Sageman (2014) found the LSE (formerly SCBE) in the Western Interior Basin, and it was also reported from Japan (Takashima et al., 2019).

The carbon isotope stratigraphy identified in Santonian–Campanian chalks at Lägerdorf in northern Germany (Voigt et al., 2010) is essentially identical to that in southern England (Fig. 4; Thibault et al., 2016, fig. 3), and the Buckle and all events listed above were also identified at Bottaccione (Thibault et al., 2016, fig. 5), although their amplitude is generally dampened in this Tethyan location as compared to NW European localities. In the lower Campanian, Thibault et al. (2016) defined three additional successive events that correlate between the English and German Chalk and the Bottaccione section in Italy and have also been identified in the North Sea (Perdiou et al., 2016; Eldrett et al., 2020) in the central Paris Basin (Pearce et al., 2022) and in eastern Tethys locations such as Iran (Razmjooei et al., 2018, 2020). These three successive events are in ascending order:

(oldest)

The *pilula* Zone Event, a marked trough that correlates with the Old Nore Marl and the middle of the *Offaster pilula* Zone at Seaford Head and is situated just above the first occurrence of the coccolith *Aspidolithus parcus parcus* in the UK and at Bottaccione and within Chron

33r according to the Italian record.

The *senonensis* Zone Event, a minor shift in carbon isotopes characterised by a small negative excursion followed by a rapid, albeit also minor positive shift, correlates with the level of the Telscombe Marls at Seaford Head and the highest common occurrence of *O. pilula*, as well as the base of the *senonensis* Zone at Lägerdorf, North Germany, while being situated approximately in the middle of Chron C33r at Gubbio.

The *papillosa* Zone Event is a marked positive carbon isotope excursion showing a well– defined local maximum at Gubbio that coincides with the C33n – C33r reversal and correlates to a similar maximum at the base of the *papillosa* Zone at Lägerdorf.

(youngest)

Planktonic foraminifera

The highest occurrence of the planktonic foraminiferan *Dicarinella asymetrica* marks the top of the *D. asymetrica* Total Range Zone, and the base of the *Globotruncanita elevata* Interval Zone (Miniati et al., 2020) and falls 19.5 cm above the base of Chron C33r at Bottaccione (Figs. 6 and 23). This result differs slightly from previous observations on extinction of species within the *Dicarinella* lineage at Bottaccione, where *D. asymetrica* and *D. concavata* are recorded as disappearing simultaneously 32 cm below the base of Chron C33r (Premoli Silva and Sliter, 1995; Petrizzo et al., 2011; Coccioni and Premoli Silva, 2015). An additional bioevent is the last occurrence of the *Sigalia* lineage that coincides with the last occurrence of *D. asymetrica* and is especially useful at low latitudes in the Gulf of Mexico and in the Tethyan Realm (e.g., Nederbragt, 1991). At Postalm, Austria, the highest occurrence of *D. asymetrica* is at 1.24 m above the base of Chron C33r (Fig. 21; Wolfgring et al., 2018). In Turkey (Wolfgring et al., 2017) the highest *D. asymetrica* occur 2 m beneath the base of Chron 33r. On the Exmouth Plateau, at ODP Site 762C (Petrizzo, 2000) the highest *D. asymetrica* slightly postdate the reversal (Fig. 23; Miniati et al., 2020). Bocieniec, in Poland, is the only locality where both *Marsupites* and *D. asymetrica* are present, and the latter taxon disappears 20 cm above the highest *M. testudinarius* specimen (Fig. 15). In the Crimea sections, the highest record of *D. asymetrica* is approximately 5 m beneath the base of Chron C33r (Guzhikov et al., 2021a, b).

The higher part of the range of *D. concavata*, the ancestral species to *D. asymetrica* (e.g., Petrizzo et al., 2017) is characterized by a decrease in abundance followed by its extinction at 220.20 m in the Bottaccione section. Its extinction level correlates with observations from the Betic Cordillera in southeast Spain (Linares Rodriguez, 1977), in the eastern Indian Ocean (Exmouth Plateau, Petrizzo, 2000) and in the Mangyshlak Peninsula (Kopaevichet al., 2007) and is consistent with the planktonic foraminiferal distributions and biozonation by Postuma (1971). In contrast, *D. concavata* is reported to disappear at the same level as *D. asymetrica* in the US Western Interior (north Texas, Gale et al., 2008) and in the Tethyan record (Tunisia, Robaszynski et al., 2000; Southern Tibet, Wendler et al., 2009). *Globotruncana neotricarinata* appears to provide a reliable bioevent for wide geographic correlation as its first appearance within the *D. asymetrica* Zone in the Bottaccione section at 213.30 m falls at approximately the same stratigraphic level observed in the eastern Indian Ocean (Exmouth Plateau, Petrizzo et al., 2011). Remarkable also is the first occurrence of *Globotruncanita atlantica*, a common species in tropical and subtropical

settings, that falls slightly above the extinction level of *D. asymetrica* in agreement with the record from Tunisia (Kalaat Senan, Robaszynski et al., 2000).

Benthic foraminifera

The Santonian–Campanian transition is also marked by some stratigraphically important lineages of the benthic foraminiferan genera *Stensioeina*, *Bolivinoides* and *Gavelinella*. While *Stensioeina* and *Gavelinella* are limited to the European epicontinental Upper Cretaceous, from the Atlantic to Kazakhstan (Dubicka and Peryt, 2014 and literature cited therein), *Bolivinoides* is characterized by its worldwide distribution (Dubicka and Peryt, 2016 and literature cited therein) probably owing to the presence of planktonic larvae or propagules (Alve, 1999) or a tychopelagic mode of life (Dubicka and Wierzbowski, 2019).

In the chalk facies of northern Europe, *Bolivinoides strigillatus*, which is the oldest species of the genus, arose in the upper part of the upper Santonian and evolved into *B. culverensis*, a transitional species to *B. decoratus*, within the basal Campanian (i.e., slightly above the last occurrence of the crinoid *Marsupites testudinarius*–Barr, 1966; Hart et al., 1989; Walaszczyk et al., 2016; Dubicka and Peryt, 2016; Dubicka et al., 2017; Fig. 13). It is important to note that in some important stratigraphical papers on the German Cretaceous succession (e.g., Hiltermann, 1952; Koch, 1977; Schönfeld, 1990) *B. culverensis* is not identified within the *B. strigillatus*–*B. decoratus* lineage. This results in significant discrepancies in the stratigraphical position of the bolivinoidid succession within western Europe, and in Germany the position of the last occurrence of *B. strigillatus* is interpreted as occurring higher, in the middle lower Campanian (*senonensis* Zone).

The second benthic foraminiferal event with high potential for recognition of the proximity of the base of the Campanian is a transition within the *Stensioeina perfecta* – *S. pommerana* lineage. The lowest occurrence of true *S. pommerana* occurs slightly below the top of the Santonian in the chalk facies of northern Europe, within the range of *Marsupites testudinarius* and *Bolivinoides strigillatus* (Fig. 15) (Walaszczyk et al., 2016; Dubicka et al., 2017; Schönfeld, 1990). In the Tethyan Postalm section, *S. pommerana* is rather rare, but first occurrs about 1.5 m below the base of C33r (Wolfgring et al., 2018).

In the succession of *Gavelinella* species, the last occurrence of the crinoid *Marsupites testudinarius* corresponds with the first occurrence of *Gavelinella costulata* of the *G. amonoides* lineage in western Ukraine (see Dubicka and Peryt, 2014). However, it must be noted that *Gavelinella costulata* evolved from *G. lorneiana* within the upper Santonian and its first occurrence is recorded earlier in the upper Santonian at Bocieniec, Poland, within the range of the crinoid *U. socialis* (Fig. 15). The consistent occurrence of *Gavelinella* ex. gr. *clementiana*, which is the base of the *G. clementiana* Zone (*sensu* Walaszczyk et al., 2016), was considered to be recorded in the lower part of the lower Campanian (upper part of the *Sphenoceramus patootensiformis* inoceramid Zone) in central and eastern Europe (Schönfeld, 1990; Dubicka et al., 2014; Walaszczyk et al., 2016; Dubicka et al., 2017) but this bioevent is actually situated immediately below (<20 cm) the projection of the boundary level at Bocieniec (Fig. 15). Moreover, the event occurs significantly earlier in the Anglo–Paris Basin (Edwards, 1981; Hampton et al., 2007). This is probably because the *G. clementiana* group was especially sensitive to specific ecological requirements and its

migration into central Europe Poland and Ukraine (Walaszczyk et al., 2016) probably represents a delayed response to substantial palaeoenvironmental changes.

According to the projection of the GSSP level at Bocieniec and recorded bioevents in that section (Fig. 15), the successive benthic foraminiferan events are:

(oldest)

- The first occurrence of *Gavelinella costulata* (upper Santonian, within the range of *Uintacrinus socialis,* though a delayed first occurrence has been noted above the top of the range of *Marsupites testudinarius* in Ukraine)
- The first occurrence of *Bolivinoides strigillatus* (upper Santonian, within the range of *U. socialis*)
- The first occurrence of true *S. pommerana* (upper Santonian, within the range of the *Marsupites laevigatus*)
- The first occurrence of *Bolivinoides culverensis* (upper Santonian, within the range of *M. testudinarius*)
- The first consistent occurrence of *Gavelinella* ex. gr. *clementiana* (base of the *G. clementiana* Zone and base of the Campanian, above the range of the crinoid *M. testudinarius*)

(youngest)

Calcareous nannofossils

Recent work on the *Aspidolithus parcus* lineage at Gubbio (Miniati et al., 2020) has established a detailed succession of subspecies which provide an evolutionary succession through the late Santonian and early Campanian, and with respect to the position of the base of Chron C33r (221.53 m):

(oldest)

- The first occurrence of *A. parcus expansus* (≥10 μm, 219.5 m)
- The first occurrence of *A. parcus expansus* (small, <10 μm, 220.2 m)
- The first occurrence of *A. parcus parcus* (≥10 μm, 220.5 m)
- The first occurrence of *A. parcus parcus* (small, <10 μm, 221.3 m)
- The first occurrence of common *A. parcus parcus* (224.6 m)
- The first occurrence of *A. parcus constrictus* (229 m)

(youngest)

In addition, the first occurrence of *A. cymbiformis* is recorded at 219.1 m

At Gubbio, the base of Chron 33r thus falls between the first occurrence and the first common occurrence of *A. parcus parcus* (Miniati et al., 2020). However, it is not always possible to separate the FO and the FCO of *A. parcus parcus*, which can leave some doubt as to the significance of the lowest occurrence of the species. Thus, in the Western Interior Basin (Kita et al., 2017; Fig. 20), the FO of *A. parcus parcus* falls within Chron 34n, whereas at Postalm in Austria (Wolfgring et al., 2018; Fig. 18) the FO is 1.66 m above the base of Chron 33r while it is also recorded above that level (though with uncertainty due to a hiatus) at Bocieniec, Poland (Fig. 15). In some localities (Austria, Turkey, Western Interior Basin), the first occurrence of *A. parcus constrictus* provides a useful and consistent marker at a slightly higher level (Miniati et al., 2020; Fig. 20).

In addition to events within the *A. parcus* lineage, other nannofossil bioevents, that have not been recorded at Gubbio, appear to correlate across various ocean basins such as the first occurrence of *Zeugrhabdotus biperforatus* recorded in near coincidence with the reversal in the Western Interior basin (Kita et al., 2017), close to the base of Chron

C33r at Bocieniec in Poland (Dubicka et al., 2017), and above the FO of *A. parcus parcus* at Seaford Head, England (Hampton et al., 2007). Although the FO of *Reinhardtites levis* must always be considered with caution due to its gradual evolutionary change from *R. anthophorus* and potential confusion with the latter in poorly preserved material that features overgrown coccoliths (Razmjooei et al., 2018, 2020), this bioevent has been recorded well above the boundary reversal in the Western Interior Basin (6.3 m above base Chron 33r, Kita et al., 2017), in between the FO of *A. parcus parcus* and LO of *Z. biperforatus* at Seaford Head, England, UK (Hampton et al., 2007), and in coincidence with peak a of the LSE at Bocieniec in Poland (Dubicka et al. 2017). The first occurrence of *A. cymbiformis* which defines nannofossil zone UC13 of Burnett (1998) is systematically found well below the boundary level (Hampton et al., 2007; Dubicka et al., 2017; Wolfgring et al., 2018; Miniati et al., 2020).

Palynology

Valuable syntheses of dinoflagellate cysts ranges through the Cretaceous have been produced by Williams and Bujak (1985), Stover et al. (1996), Costa and Davey (1999) and Williams et al. (2004) and are cited widely in the literature. High resolution studies from NW Europe (e.g., Slimani, 2001; Surlyk et al., 2013; Pearce et al., 2020, 2022; Jarvis et al., 2022) have extended the range of some of these species previously considered significant for the Santonian–Campanian boundary interval. Of the events still considered to occur high in the Santonian (last occurrence of *Scriniodinium campanula*, first occurrence of *Odontochitina porifera*, first occurrence of *Spongodinium delitiense*) only the first occurrence of *O. porifera* was recorded at Bocieniec and Seaford Head (between the Buckle and Hawks Brow CIEs, typical in NW Europe).

Of the events still considered to be markers for the former Santonian – Campanian boundary (now latest Santonian following the now confirmed definition of the boundary): the last occurrence of *Canningia senonica* and the last occurrence of rare *Heterosphaeridium difficile*, only the latter event was recorded at Bocieniec, within the Late Santonian CIE (Fig. 16).

The last occurrence of *Ellipsodinium* spp. may be a good palynological marker for the Santonian–Campanian boundary. Williams and Bujak (1985) and Hardenbol et al. (1998) placed the HO of *Ellipsodinium* (*rugulosum*) in the mid–Santonian, while Stover et al. (1996) and Costa and Davey (1999) recorded it low in the Santonian. Williams et al. (2004) placed the last occurrence of *Ellipsodinium* (*rugulosum*) in the lowermost Campanian. Results from France (Pearce et al., 2022), southern and eastern England (Prince et al., 1999, 2008; Pearce et al., 2020) and Bocieniec (Jarvis et al., 2022) show that the last occurrence of *Ellipsodinium* (*rugulosum* or *membraniferum*) lies within the Late Santonian CIE, or in the lowermost Campanian.

Finally, Pearce et al. (2020) provided a detailed review of palynological events calibrated by macrofossil and δ^{13}C data through the Cenomanian to lower Campanian, with a focus on NW Europe, discussing the spatial and temporal distribution of marker taxa. Many of the species discussed currently were described relatively recently and their distribution requires testing. Incorporating all the available data, the following calibrated sequence of events is considered significant for the Santonian–Campanian boundary.
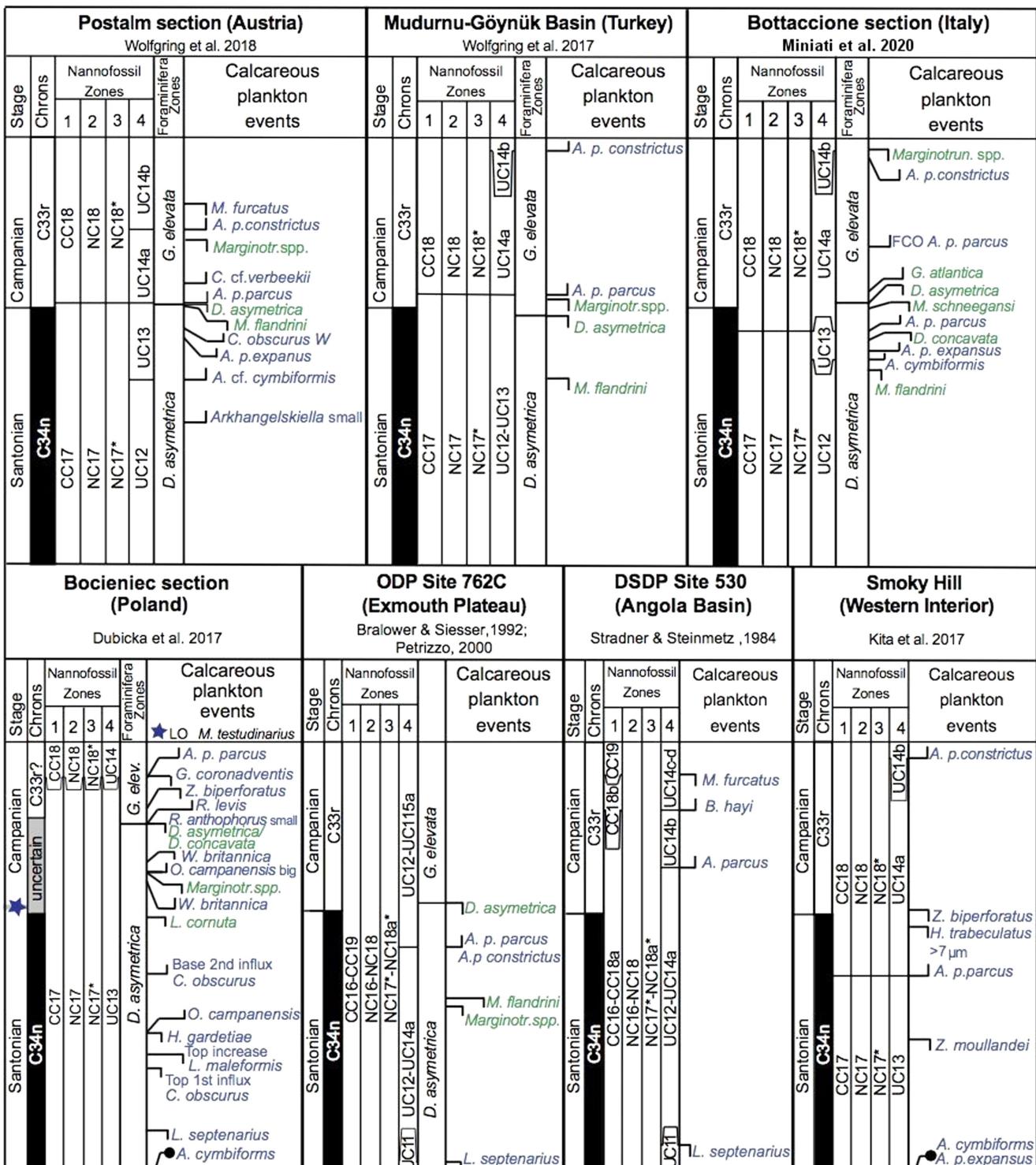
Figure 23. Comparative magnetostratigraphy and calcareous microplankton distribution of localities containing the Santonian–Campanian boundary interval. After Miniati et al. (2020).

(oldest)

- First occurrence of *Dimidium striatum* (between the Horseshoe Bay and Buckle CIEs)
- First occurrence of *Cordosphaeridium catherineae* (top of the Buckle CIE)

[middle–upper Santonian boundary]

- First occurrence of *Odontochitina porifera* (between the Buckle and Hawks Brow CIEs)

- First occurrence of *Rhynchodiniopsis saliorum* (within the Hawks Brow CIE, occurs high at Seaford Head)
- Last occurrence of rare *Heterosphaeridium difficile* (within the mid–Late Santonian CIE)
- Last common occurrence of *Ellipsodinium* spp. and minimum of *Surculosphaeridium longifurcatum* (below the Late Santonian

Event 'peak a')

[*U. socialis–M. testudinarius* zone boundary]

- Last occurrence of *Ellipsodinium* spp. (immediately above the C34n–C33r boundary)

[Santonian–Campanian boundary]

(youngest)

Crinoids

The stemless benthic (Milsom et al., 1994) crinoid genera *Uintacrinus*

and *Marsupites* are restricted to the late Santonian and occur worldwide but are largely restricted to shallower water chalk facies (Rasmussen, 1961; Gale et al., 2008; Guzhikov et al., 2021b). One species, *M. testudinarius*, is found in sandstones at the level of its acme occurrence, in south–east India, Madagascar, British Columbia, Canada and Mississippi, USA. There are four stratigraphically successive species of the genera (Gale et al., 2008), illustrated in Fig. 24:

(oldest)

- *Uintacrinus socialis* (Utah, Kansas, Texas, USA, UK, France,

Figure 24. The crinoids Uintacrinus and Marsupites from the late Santonian. A, B, F–G, Marsupites testudinarius. C–E, Marsupites laevigatus. K, Uintacrinus socialis. J, L, Uintacrinus anglicus Rasmussen, 1961. A–D, Margate Chalk, Foreness Point, Thanet, Kent, UK. E, Newhaven Chalk, Sussex, UK, locality unknown. G, H, L, Waxahachie dam spillway, Ellis County, Texas, USA. K, Smoky Hill Chalk, Kansas, USA. I, J, level of Friars Bay Marls 2–3, Newhaven Chalk, Brighton, Sussex, UK.

Germany, Poland, Kazakhstan, Western Australia)

- *Marsupites laevigatus* (Texas, USA, UK, France, Germany, Poland, Kazakhstan, Western Australia, Crimea)
- *Marsupites testudinarius* (Texas, Mississippi, Colorado, Montana, USA, Vancouver, Island Canada, UK, France, Germany, Poland, Algeria, Tunisia, Madagascar, Kazakhstan, India, Western Australia, Crimea)
- *Uintacrinus anglicus* (UK, Kazakhstan, Texas, USA, Western Australia)

(youngest)

Complete successions with all four species are known from the United Kingdom, Mangyschlak, Kazakhstan, Texas, USA and Toolonga, Western Australia (Gale et al., 1995, 2008). *Uintacrinus socialis* and *M. testudinarius* appear to be the most widespread of the species with the longest ranges; those of the other two taxa are shorter, and they have probably been overlooked in some regions. An estimation of the duration of individual species ranges is made using the orbitally tuned succession at Seaford Head (Thibault et al., 2016). The correlative value of *Uintacrinus* and *Marsupites* is enhanced through their co–occurrence with provincially restricted ammonite faunas (Fig. 2) in the Pacific Realm (Haggart and Graham, 2017), in the Western Interior Basin (Cobban, 1995), Texas (Gale et al., 2008, 2021), Europe (Kaplan and Kennedy, 2005) and Madagascar (Walazczyk et al., 2014). Additionally, the precise relationships of the crinoids to carbon isotope events is known from Seaford Head (Figs. 11–13), and demonstrates that the Buckle Event falls within the lower part of the range of *U. socialis*, the Foreness Event is in the zone of *M. laevigatus*, the lower LSE carbon isotope peak is coincident with the higher part of the range of *M. testudinarius* and the higher LSE peak approximates

to the range of *U. anglicus*. This information permits correlation between the crinoid zones and the Tethyan deep water succession in the Bottaccione section (Fig. 25). However, the crinoids and distinctive associated carbon isotope excursions all fall *beneath* the GSSP primary marker, the C34n–C33r reversal (Guzhikov et al., 2021a, b) and thus do not help correlation of the boundary itself, although they give some indication of its proximity.

In terms of pelagic microcrinoids, the base of the Campanian as defined herein falls within the middle part of zone CaR1 (Gale, 2018) as defined at Seaford Head (Fig. 12). This interval extends from the LO of *Uintacrinus anglicus* to the FO of *Stellacrinus hughsae* forma *cristatus* Gale, 2018.

Ammonites

The provincialism of many Santonian and lower Campanian ammonites, and their scarcity in critical localities has been a barrier to global correlation in this interval using the group (Fig. 2 – see also Kennedy, 1984). In North America, there are three distinct faunas, respectively in the Pacific Realm, the Western Interior Seaway and in the Gulf Coast. On Vancouver Island, Canada, in the Pacific province, Haggart and Graham (2017) found *M. testudinarius* immediately beneath the (local) *Pseudoschloenbachia umbulazi* ammonite zone; the base of C33r, and hence of the Campanian, lies at a higher level (Fig. 2; Ward et al., 2012, fig. 13). In the Western Interior Basin, *M. testudinarius* occurs within the *Desmoscaphites bassleri* Zone in association with *Scaphites leei* II (Cobban, 1995; see above), and the base of C33r must fall around or above the contact with the overlying *Scaphites leei III* Zone, although there is some doubt as to its exact position

Figure 25. Summary correlation of the Global boundary Stratotype Section and Point for the base of the Campanian Stage and auxiliary sections, showing how biostratigraphy, magnetostratigraphy and carbon isotope stratigraphy can be used to correlate from the GSSP to auxiliary sections. Localities shown in Fig. 1. Abbreviations: LSE = Late Santonian Event; FCO = first common occurrence; A. p.c. = Aspidolithus parcus constrictus; A. p.p. * = Aspidolithus parcus parcus; D. a. = Dicarinella asymetrica.

(Fig. 2). In Texas, *U. socialis*, *M. testudinarius* and *Uintacrinus angli-cus* all occur in the the *Submortoniceras tesquesquitense* Zone (Gale et al., 2008, 2020a). In Wesphalia, Germany, the base of the *Placen-ticeras bidorsatum* Zone is approximately equivalent to the top of the range of *M. testudinarius* (Fig. 2; Kaplan et al., 2005), and the base of the Campanian must fall within this zone. In Madagascar, *M. testudi-narius* occurs in the upper part of the *Pseudoschloenbachia umbulazi* Zone (Walaszczyk et al., 2014), and the base of the Campanian must therefore fall within the overlying *P. blandfordiana* Zone. The differ-ence in the comparative ranges of *P. umbulazi* between Vancouver Island and Madagascar requires investigation.

Inoceramid bivalves

In the Santonian–Campanian boundary interval, inoceramid bivalves are amongst the best– represented marine macrofossil groups world–wide. The structure of the record is, however, only moderately known, both in terms of the stratigraphic distribution of inoceramids and of their biogeographic significance. The Santonian–Campanian bound-ary interval is the time of highest taxonomic diversity in the Late Cre-taceous history of the group (e.g., Tröger, 1976; Voigt, 1995, 1996); however, it is not clear whether this peak represents a record of their genuinely high standing diversity or the cumulative effect of their high evolutionary turnover rates. Undoubtedly, biogeographic differentiation played a role; inoceramids of the Santonian–Campanian boundary inter-val show a well–documented biogeographical variability, with four biogeo-graphic biochores (biogeographic units after Kauffman, 1973) recognised: the Tethyan–Euramerican marginal area; the northern Euramerican biogeographic region; the East–African Province subprovince; and the North Pacific Province.

A boundary zone exists between the Euramerican Region and the Tethyan Realm (e.g., North American Gulf Coast, southern Europe, Caucasus, Kopet–Dagh). The details of the inoceramid succession in this biochore were studied in detail in the Waxahachie section, SE Texas, USA (Gale et al., 2008) (Fig. 3). There, the Santonian–Campa-nian boundary as defined by the LO of *Marsupites testudinarius* is not reflected by a single, corresponding inoceramid event with a world–wide expression. However, the inoceramid succession has a well–defined pattern, composed of three successive faunas, which seems to be recorded on a much wider geographic scale, thus potentially having an evolu-tionary significance, and consequently chronostratigraphic value. In stratigraphic order these three successive faunas are those of *Cordice-ramus* ex gr. *muelleri*, *Platyceramus ahsenensis* and *Platyceramus* cf. *ezoensis* (Fig. 3).

The *Cordiceramus muelleri* fauna is dominated by *Cordiceramus germanicus*. It is very probable that the disappearance level or at least the distinct drop in the abundance of this species approximates to the first appearance of *Marsupites testudinarius* and represents its evolu-tionary last occurrence. Besides a single specimen of *C. germanicus* regarded as of lower Campanian age (Sornay, 1982, pl. 1, fig. 2) from the smectitic facies of the Vaals Formation in northeast Belgium, there are no other convincing records of this species from the lower Campanian (e.g., Seitz, 1961; Tröger, 1989; Lopez, 1992; Tröger and Summesberger, 1994).

The *Platyceramus ahsenensis* fauna is dominated by the eponymous species, with some morphotypes transitional to *Pl. cycloides*. *Platyce-ramus ahsenensis* is a long–ranging species; it first appears in the early Santonian, ranging through the entire stage and possibly into the early Campanian.

The *Platyceramus* cf. *ezoensis* fauna, stratigraphically the highest, spans the Santonian–Campanian boundary itself. It is the most char-acteristic fauna present in the boundary interval, being represented by huge, flat–lying individuals, dominated by species of *Platyceramus* and rare *C. bueltenensis*. Provisionally, all representatives of the third fauna are referred to *Platyceramus* cf. *ezoensis*, but stratigraphic and evolutionary relationships between them remain poorly known. In Japan, the members of the group are referred to as *P. ezoensis*, *P. vanuxemi-formis* (Nagao and Matsumoto, 1940) (originally described as a vari-ety of *P. ezoensis*), and *P. miyahisai* (Noda, 1983). Very close too is *P. colossus* Sornay, 1969 (p. 211, pl. H, fig. 1) from the lower Campanian of Madagascar, characterised by a rhomboid outline. Very similar forms have also been recorded from California under the name of *Inoceramus chicoensis*; this species has recently been reported from Japan (Noda et al., 1996).

Northern areas of the Euramerican Biogeographic region (northern Europe; north–western Siberia; Greenland; northern part of the North American Western Interior): the inoceramids of this biochore are characterised invariably by *Sphenoceramus* faunas; the boundary falls within the range of the *S. patootensiformis–S. lundbreckensis* clade (Beyenburg, 1936; Seitz, 1965; McLearn, 1929; Walaszczyk and Cob-ban, 2006, 2007). Walaszczyk (1992) suggested that a change in orna-mentation within this clade around the *Marsupites* extinction level could be a potential boundary marker; both species lost their radial ornament. This, however, still needs confirmation, and even when con-firmed, would be limited to the northerly portions of the Euramerican region which is characterised by a regular occurrence of the *Sphenoc-eramus* fauna. Moving southwards, a clear diachroneity in the distri-bution of this fauna is observed (Walaszczyk and Cobban, 2006); it is completely absent from the most southerly areas of the Euramerican biogeographic region.

East–African Province–subprovince (South Africa, Madagascar, India): The Santonian–Campanian boundary inoceramid record of the biochore resembles the general pattern of the record from the boundary zone between the northern Tethyan and southern Euramerican Region (see Walaszczyk et al., 2014). The interval is dominated by *Cordicer-amus* clade, however, with a distinct presence of members of the *Platyceramus ezoensis* fauna at the boundary itself, which may sug-gest its widespread, evolutionary occurrence.

North Pacific Province (Japan, Pacific Russia, western margin of North America): The Santonian–Campanian inoceramid boundary record of this province is poorly known. Traditionally the base of the Campanian in Japan was correlated with the base of the '*Inoceramus*' *japonicus* Zone (see Toshimitsu et al., 1995, 1998). Recent correlations based on the carbon isotope curve and additional tephrochronological studies (Takashima et al., 2019 and Kuwabara et al., 2019) support this correlation, although Takashima et al. (2010) suggested that this taxon first appears distinctly higher, and that the base of the Campanian lies somewhere in the upper part of the *Platyceramus amakusensis* Zone. In contrast, some magnetostratigraphic dating in Japan (Toshimitsu and Kikawa, 1997), as well as the recent report of *Marsupites testudinarius* from the Canadian Pacific coast Nanaimo Group and its correlation with the inoceramid succession there (Haggart and Graham, 2017), suggest

that the base of the Campanian in Japan should be placed distinctly higher, at the base of, or even within, the succeeding zone of *Sphenoceramus orientalis–Sphenoceramus schmidti*. Consequently, the entire '*Inoceramus*' *japonicus* Zone of Japan would be of Santonian age.

Inoceramid Markers of the Santonian–Campanian Boundary

Although the Santonian–Campanian boundary as now defined is not reflected by a single inoceramid event, the boundary interval reveals some inoceramid events that may potentially be of chronostratigraphic importance as secondary boundary markers. Among these are:

(1) The *Platyceramus* cf. *ezoensis* acme Zone; first defined in the Waxahachie section (Gale et al., 2008), this zone spans the Santonian – Campanian boundary itself and may represent a good marker of the boundary interval. The regional extent of this zone is still not fully known; further tests are required.

(2) The highest occurrence or distinct drop in abundance of *Cordiceramus germanicus*; this event should point to a level coinciding with the base of the *Marsupites testudinarius* Zone.

(3) The first appearance of *Cataceramus balticus*; this event has often been quoted as being close to the Santonian–Campanian boundary and regarded as its potential inoceramid marker (e.g., Ernst et al., 1979; Schulz et al., 1984). It would seem, however, that the species first appears in the *C.* ex gr. *muelleri* Zone of the lower upper Santonian (e.g., Europe: Seitz, 1967; Tröger, 1989; Western Interior: Larson et al., 1991; Kauffman et al., 1993, and Hancock and Gale, 1996; Gulf Coast: Gale et al., 2008).

Summary

The Bottacione Gorge section at Gubbio, Italy, is confirmed as the Global boundary Stratotype Section for the base of the Campanian Stage. Sedimentation in the Santonian– Campanian boundary interval appears to be continuous, supported by evidence from the carbon isotope record and complete calcareous plankton biostratigraphy. The succession comprises deep–water cherty limestones (mudstones and foraminiferal wackestones) which provide a detailed microfaunal record for calcareous nannofossils and planktonic foraminifera and yields an excellent palaeomagnetic record. The high–resolution carbon isotope record, as well as rising strontium isotope values, derived from bulk sediment, provides important additional means of correlation to other regions.

The base of the Campanian Stage is defined by the magnetic polarity reversal from Chron C34n (top of Long Cretaceous Normal Polarity–Chron) to Chron 33r. This has been widely identified in oceanic crust, and in widespread onshore outcrops.

Secondary markers include first and last occurrences of widely distributed planktonic foraminifera and calcareous nannofossils, and positive and negative excursions in the δ^{13}C record. In ascending order, the most important are (Fig. 25):

(oldest)

1) The first occurrence of the widespread planktonic foraminiferan *Globotruncana neotricarinata*

2,3) The Late Santonian Event (LSE), a double (a, b) positive excursion in δ^{13}C, identified globally

4) The first occurrence of the planktonic foraminiferan *Contusotruncana patelliformis*

5) The last occurrences of the planktonic foraminiferan *Marginotruncana tarfayaensis* and *M. pseudomarginata*

6) The first occurrence of the calcareous nannofossil *Arkhangelskiella cymbiformis*

8) Thefirst occurrence of the calcareous nannofossil *Aspidolithus parcus expansus*

9)The last occurrence of the planktonic foraminiferan *Dicarinella concavata*

10) The first occurrence of the calcareous nannofossil *Aspidolithus parcus parcus*

12) The primary marker, base of Chron C33r

14) The last occurrences of the planktonic foraminiferan *Dicarinella asymetrica* and *Sigalia* sp.

16) The first occurrence of the planktonic foraminiferan *Globotruncanita atlantica*

18) The first common occurrence of the calcareous nannofossil *Aspidolithus parcus parcus*

22) The first occurrence of the calcareous nannofossil *Aspidolithus parcus constrictus*

23) The last occurrence of the planktonic foraminiferan *Marginotruncana* spp.

(youngest)

Auxiliary sections are:

Seaford Head, Sussex, UK, which is developed in white chalk facies, and can be correlated to the candidate GSSP section through carbon isotope stratigraphy (Fig. 4–LSE peaks a, b) and the first occurrence of the calcareous nannofossil *Aspidolithus parcus parcus*. This correlation is particularly important because it demonstrates the relative position of the Santonian crinoid zones (*Marsupites, Uintacrinus*) to the proposed GSSP, and because the Seaford Head section has been tuned to orbital cyclicity (Thibault et al., 2016) it is thus potentially valuable for securing a more precise age for the Santonian-Campanian boundary. The palynology indicates the site was relatively close to the basin margin and with significantly less surface water fertility than at Bocieniec, and this is the probable reason why a number of stratigraphic markers are absent. The Santonian–Campanian boundary lies between the older first occurrence of *Rhynchodiniopsis saliorum* and first common occurrence of *Ellipsodinium* events and the last occurrence of *Ellipsodinium*.

Biocieniec, near Warsaw, Poland, is a thin development in a marly facies, and provides evidence of the palaeomagnetic reversal at the base of Chron 33r, the last occurrence of the planktonic foraminiferan *Dicarinella asymetrica*, the first occurrence of the calcareous nannofossil *Aspidolithus parcus parcus* and the carbon isotope peak LSE1a. It also yields the crinoids *Uintacrinus* and *Marsupites* which allow precise correlation to the Seaford Head section. The palynology indicates a clear increase in proximity to the shoreline through time at Bocieniec. The surface waters were initially more eutrophic than at Seaford Head (and presumably more distal) but became significantly oligotrophic in the Campanian opoka facies. The Santonian–Campanian boundary lies between the older first occurrence of *Rhynchodiniopsis saliorum*, minimum in *Surculosphaeridium longifurcatum*, and last

occurrence of rare *Heterosphaeidium difficile* events, and the last occurrence of *Ellipsodinium*.

Postalm, Austria, set in the northwestern Tethys, is developed in a rhythmically–bedded, deep–water hemipelagic facies, and provides palaeomagnetic evidence for the base of Chron C33r, the last occurrence of the planktonic foraminiferan *Dicarinella asymetrica*, and the first occurrence of the coccolith *Aspidolithus parcus parcus*.

The Smoky Hill Chalk Member of northern Kansas, USA, is set in the Western Interior Seaway, developed in a marly chalk facies, and has provided correlation to the palaeomagnetic reversal at the base of Chron C33r. It provides a suite of high–resolution calcareous nannofossil datums, including the first occurrences of *Aspidolithus parcus parcus* and *A. p. constrictus*.

The Tepeyac section in northern Coahuela, Mexico, provides a detailed ammonite biostratigraphy through the Santonian–Campanian boundary interval, and a high–resolution carbon–isotope record that permits correlation with the candidate GSSP and other auxiliary sections. It demonstrates that the position of the GSSP primary criterion falls approximately at the base of the *Menabites (Delawarella) delawarensis* Zone of the ammonite zonation developed in the USA Gulf Coast and eastern Atlantic seaboard.

Detailed evidence for the correlation of the GSSP with the auxiliary sections and Lägerdorf, Germany is summarised in Fig. 25. This utilises data from biostratigraphy, carbon isotopes and magnetostratigraphy described in the text.

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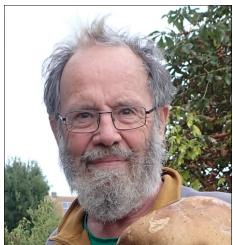
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