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High-resolution calcareous nannofossil biostratigraphy of the Santonian/Campanian Stage boundary, Western Interior Basin, USA

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ABSTRACT

The base of the Campanian Stage does not have a ratified Global Stratotype Section and Point (GSSP); however, several potential boundary markers have been proposed including the base of the *Scaphites leei* III ammonite Zone and the base of the paleomagnetic Chron C33r. Calcareous nannofossil assemblages from the Smoky Hill Member of the Niobrara Formation in the central Western Interior Seaway, USA were analyzed from two localities to determine relevant biohorizons and their relationships to these potential boundary markers. In a previous study, the Aristocrat Angus 12-8 core (Colorado) was astrochronologically dated and constrained using macrofossil zonations and radiometric ages. The Smoky Hill Member type area (Kansas) provides an expanded interval with good to excellent nannofossil preservation.

Five biohorizons are useful for recognition of the Santonian/Campanian transition within the Smoky Hill Member type area, and three are useful in the Aristocrat Angus 12-8 core. The first occurrences (FOs) of *Aspidolithus parcus parcus* and *Aspidolithus parcus constrictus*, as well as the last occurrences (LOs) of *Zeugrhabdotus moulladei*, *Helicolithus trabeculatus* specimens larger than 7 μm, and *Zeugrhabdotus biperforatus* are in close stratigraphic proximity to the base of the *Scaphites leei* III Zone and the base of Chron C33r.

1. Introduction

Since the naming of the Campanian Stage by Coquan in 1857, the definition of its base has been debated. There is currently no ratified marker or Global Boundary Stratotype Section and Point (GSSP) for the base of the Campanian Stage (Ogg and Hinnov, 2012). Several markers have been proposed including paleomagnetic chrons, ammonite zones, isotope excursions, calcareous nannofossils bioevents, and other macrofossil events. The authors of this study follow the definition of the Santonian/Campanian Stage boundary used by Ogg and Hinnov (2012), which is the base of the paleomagnetic Chron C33r.

The Upper Cretaceous Niobrara Formation of the North American Western Interior Basin contains diverse and well-preserved calcareous nannofossil assemblages. Two Niobrara Formation sections were utilized for biostratigraphic analyses (Fig. 1). The Aristocrat Angus 12-8 core from Weld County, Colorado was previously examined for stable isotopes (Joo and Sageman, 2014) and placed within a chronostratigraphic framework using cyclostratigraphy, macrofossils, and radiometric ages (Locklair and Sageman, 2008; Sageman et al., 2014). Paleomagnetic data are not available from this core, so the base of the *Scaphites leei* III ammonite zone has been used as the base of the Campanian (Joo and Sageman, 2014; Sageman et al., 2014). Preservation of nannofossils in this core is poor and chalk intervals directly above the base of the Campanian were not recovered. The Smoky Hill Member of the Niobrara Formation in its type area in northwestern Kansas was also sampled. The study interval spans the upper Santonian to lower Campanian and contains well-preserved calcareous nannofossils. Biostratigraphic data collected from the Smoky Hill Member type area and the Aristocrat Angus 12-8 core samples were used to create a new, high-resolution biostratigraphic framework for the Santonian/Campanian Stage boundary (Fig. 2).

2. Materials and methods

Localities 20, 24, 25, and 21 of the Smoky Hill Member type area (Hattin, 1982; Fig. 3) in Kansas were collected at 10 cm intervals in

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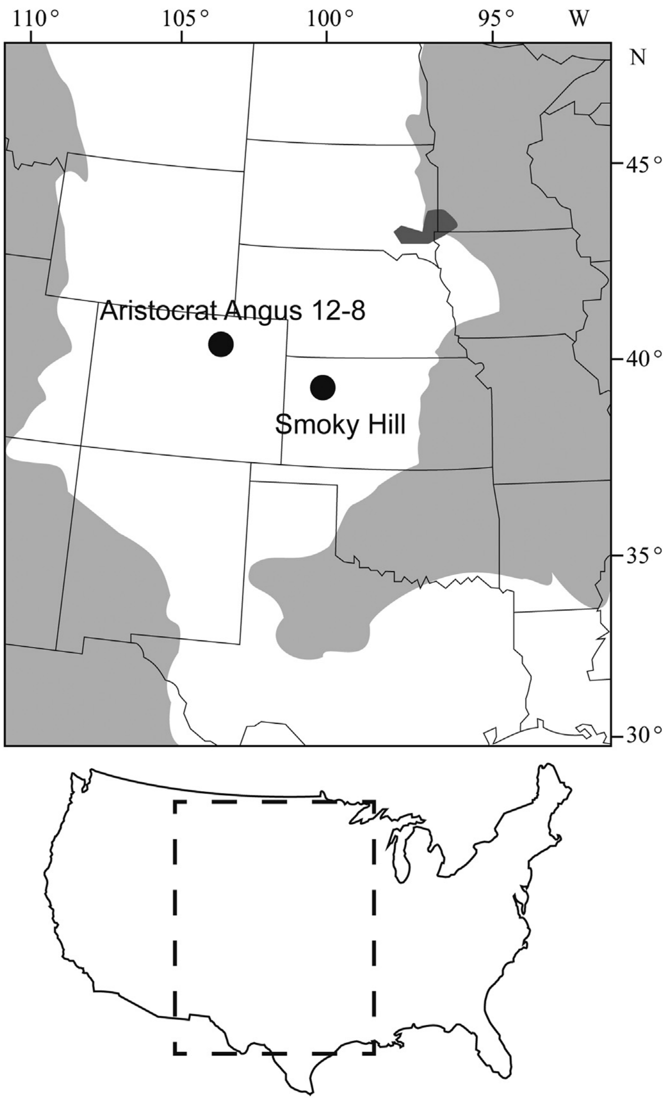

Fig. 1. Study section area for the Santonian/Campanian boundary. Extent of Western Interior Seaway (white) and land (gray) modified from Blakey (2015).

2000. Samples for this study were prepared at approximately 1.0 m intervals, while the Aristocrat Angus 12-8 core was sampled at 60 cm intervals, yielding a total of 53 and 17 samples, respectively.

Smear slides were prepared from outcrop and core sediments using the double slurry method detailed by Watkins and Bergen (2003). Calcareous nannofossils were observed using an Olympus BX 51 microscope at total magnification of 1250× using cross-polarized light, plane polarized light, phase contrast, and a one-quarter λ gypsum plate. Photomicrographs were taken using an Olympus DP71 camera. Whole coccoliths and fragments greater than half the original size were counted. The cascading counting technique of Styzen (1997) was used to collect assemblage data for the Smoky Hill Member type area. Total counts of relevant taxa were then converted to percent relative abundances to limit the bias of sample thickness and for comparison with previously published data. Only presence/absence data were collected from the Aristocrat Angus 12-8 core due to poor preservation and low nannofossil abundance.

3. Santonian/Campanian Stage boundary

3.1. Definition of the Santonian/Campanian Stage boundary

The Campanian Stage was named by Coquand (1857) after the hillside exposures of Grande Champagne near Aubeterresur-Dronne (northern Aquitaine province, France), but due to changes in stratigraphic definitions, the bulk of the type "Campanian" at Aubeterre is currently classified as Maastrichtian (van Hinte, 1965; Séronie-Vivien, 1972). No clear base was documented in the lower portion of the Aubeterre section, therefore preventing designation of a lower Campanian boundary.

The base of the Campanian was placed at the first occurrence (FO) of the ammonoid *Placenticeras bidorsatum* by de Grossouvre (1901); however, due to its rarity and geographic limitation to northwest Europe, the FO of *P. bidorsatum* was later deemed impractical for use as a boundary marker event (Hancock and Gale, 1996). The extinction of the crinoid *Marsupites testudinarius* is synchronous with the FO of *Placenticeras bidorsatum*, which has led to the use of the extinction of *M. testudinarius* as a provisional boundary marker for the base of the Campanian (Hancock and Gale, 1996; Gale et al., 2008). *Marsupites testudinarius* appears to be restricted to shelf environments and thus should not be used as a global marker. In the Western Interior Seaway, the base of the Campanian has been correlated to the base of the *Scaphites leei* III ammonite Zone (e.g., Cobban et al., 2006). Unfortunately, several of the ammonites used in the Western Interior Seaway zonal scheme are not distributed worldwide. Therefore, the Campanian Working Group of the International Commission on Stratigraphy is considering using the base of the paleomagnetic Chron C33r as the primary criterion for the base of the Campanian, thereby enabling global recognition in pelagic, continental, and other non-shallow-marine settings (Ogg and Hinnov, 2012) when magnetostratigraphy is available.

While no boundary stratotype has been ratified for the Santonian/Campanian boundary, two have been proposed. The Waxahachie dam spillway section (north central Texas) could be a candidate if the extinction of *M. testudinarius* is selected for the boundary based on the multidisciplinary study by Gale et al. (2008). If the base of Chron C33r is chosen as the boundary marker, the Gubbio section in Italy could be selected as the stratotype because of its compilation of biostratigraphy and magnetostratigraphy (e.g., Lowrie and Alvarez, 1977; Tremolada, 2002; Gardin et al., 2001).

3.2. Calcareous nannofossil proxies for the Santonian/Campanian Boundary

Calcareous nannofossil biohorizons have been utilized as proxies for stage boundaries due to the cosmopolitan distribution and high abundance of nannofossils in marine sediments. Currently, published nannofossil zonation schemes exhibit uncertainty in markers for the Santonian/Campanian Stage boundary (Fig. 2).

In 1977, Sissingh first published a cosmopolitan calcareous nannofossil zonation scheme for the Cretaceous with 26 zones based largely on low-to middle-latitude outcrop sections. Perch-Nielsen (1985) revised Sissingh's zonation scheme and increased resolution through the addition of subzones. She determined that the FO of *Aspidolithus parcus parcus* (base of Zone CC18) marked the base of the Campanian (Fig. 2).

Shortly after Sissingh published his cosmopolitan zonation based on outcrop, Roth (1978) published a cosmopolitan zonation scheme created from deep-sea sections. In this scheme, the

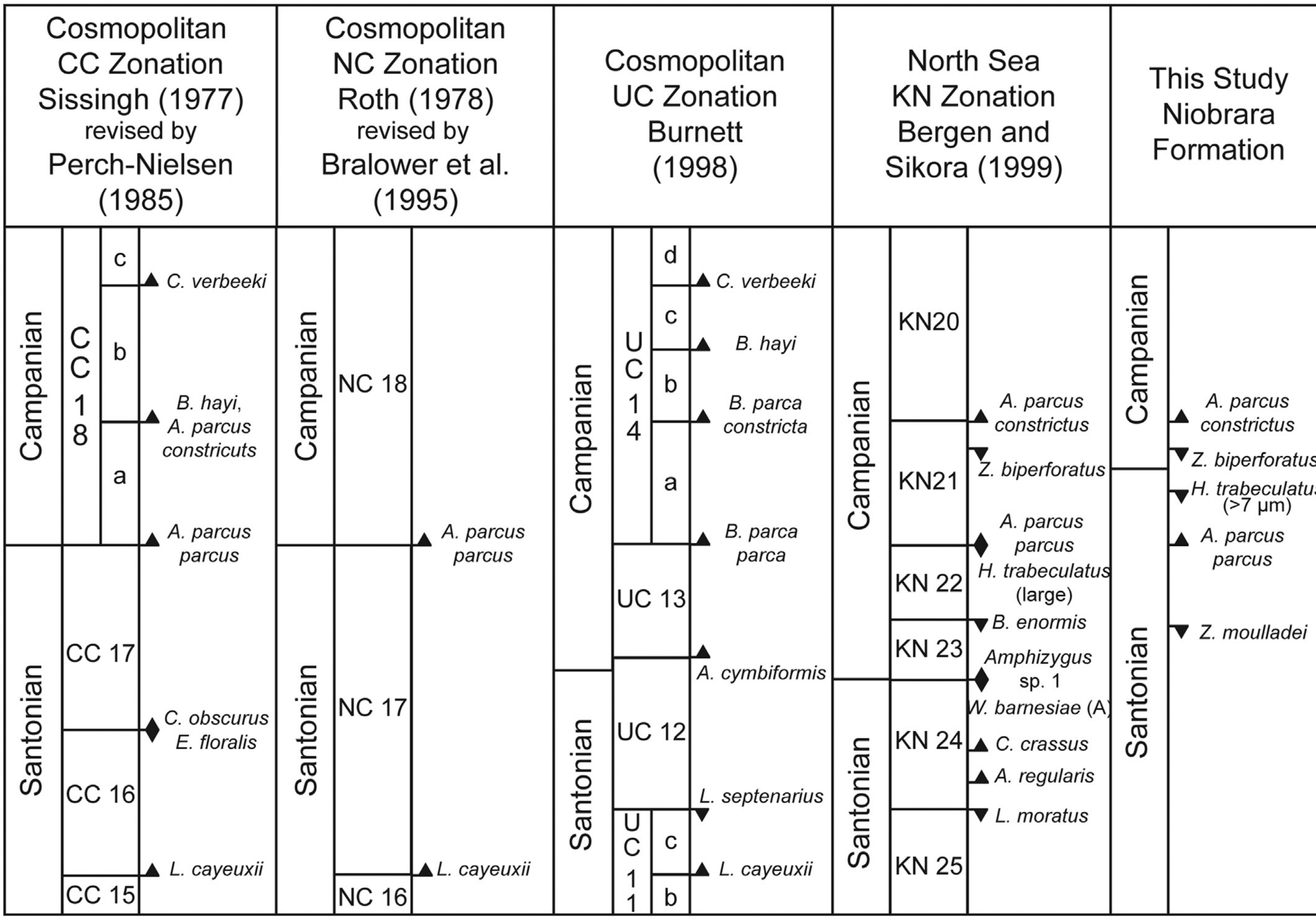

Fig. 2. Calcareous nannofossil zonation schemes with interpreted Santonian/Campanian Boundary.

Santonian/Campanian boundary, at the base of Zone NC18, is defined by the FO of *A. parcus parcus* in agreement with Perch-Nielsen (1985). Bralower et al. (1995) later revised Roth's (1978) zonation through integration with paleomagnetic data, using the base of Chron C33r to define the Santonian/Campanian boundary and the FO of *A. parcus parcus* was again confirmed to be located at this boundary (Fig. 2).

Burnett (1998) later developed a cosmopolitan zonation scheme for the Late Cretaceous and placed the Santonian/Campanian boundary within the uppermost portion of Zone UC12, defined as the interval between the LO (last occurrence) of *Lithastrinus septenarius* and the FO of *Arkhangelskiella cymbiformis* (Fig. 2). The FO of *Arkhangelskiella cymbiformis* was listed as occurring right above the Santonian/Campanian boundary, marking the base of Zone UC13. The FO of *Broinsonia parca parca* (herein referred to as *Aspidolithus parcus parcus*) is located in the early Campanian, marking the base of Zone UC14 (Fig. 2).

Bergen and Sikora (1999) constructed a Late Cretaceous boreal calcareous nannofossil zonation scheme from the North Sea. The authors used the LO of the crinoid *Marsupites testudinarius* as the marker for the Santonian/Campanian boundary by correlating the North Sea section with potential stratotypes in Texas and England. The Santonian/Campanian boundary was placed at the base of Zone KN23, which is marked by the LO of abundant *Watznaueria barnesiae* and the FO of an undescribed calcareous nannofossil species of the genus *Amphyizygus* (Fig. 2). Other early Campanian markers in the KN zonation scheme were the FO of *A. parcus parcus* and the LO of *Helicolithus trabeculatus* (large). These two markers were used for the base of KN21. Based on these zonation schemes, there are several nannofossil biohorizons to potentially mark or constrain the Santonian/Campanian boundary.

4. Lithostratigraphy and Regional Setting

During the Late Jurassic and Cretaceous, subduction of the Farallon Plate, along with crustal loading in the Sevier Orogenic Belt of western North America, led to the development of a retroarc foreland basin. Subsidence of this basin, coupled with global sea-level rise, resulted in repeated flooding of the foreland basin (Kauffman and Caldwell, 1993). Following peak regression of the Greenhorn marine cycle, a late Turonian transgression flooded the seaway and hemipelagic carbonate-rich sediments were deposited from the Texas Gulf Coast to the Western Canadian Sedimentary Basin and from western Utah to eastern Kansas until the early Campanian (Kauffman and Caldwell, 1993). Both boreal and tethyan waters were drawn into the Western Interior Basin creating a strong counterclockwise gyre occupying the entire north-south extent of the seaway (Slingerland et al., 1996; Longman et al., 1998). The stratigraphic section in the Western Interior Basin was deepest in the west and generally shallowed eastward (Roberts and Kirschbaum, 1995). In the central part of the Western Interior Basin, hemipelagic units comprise the Niobrara Formation. Formal

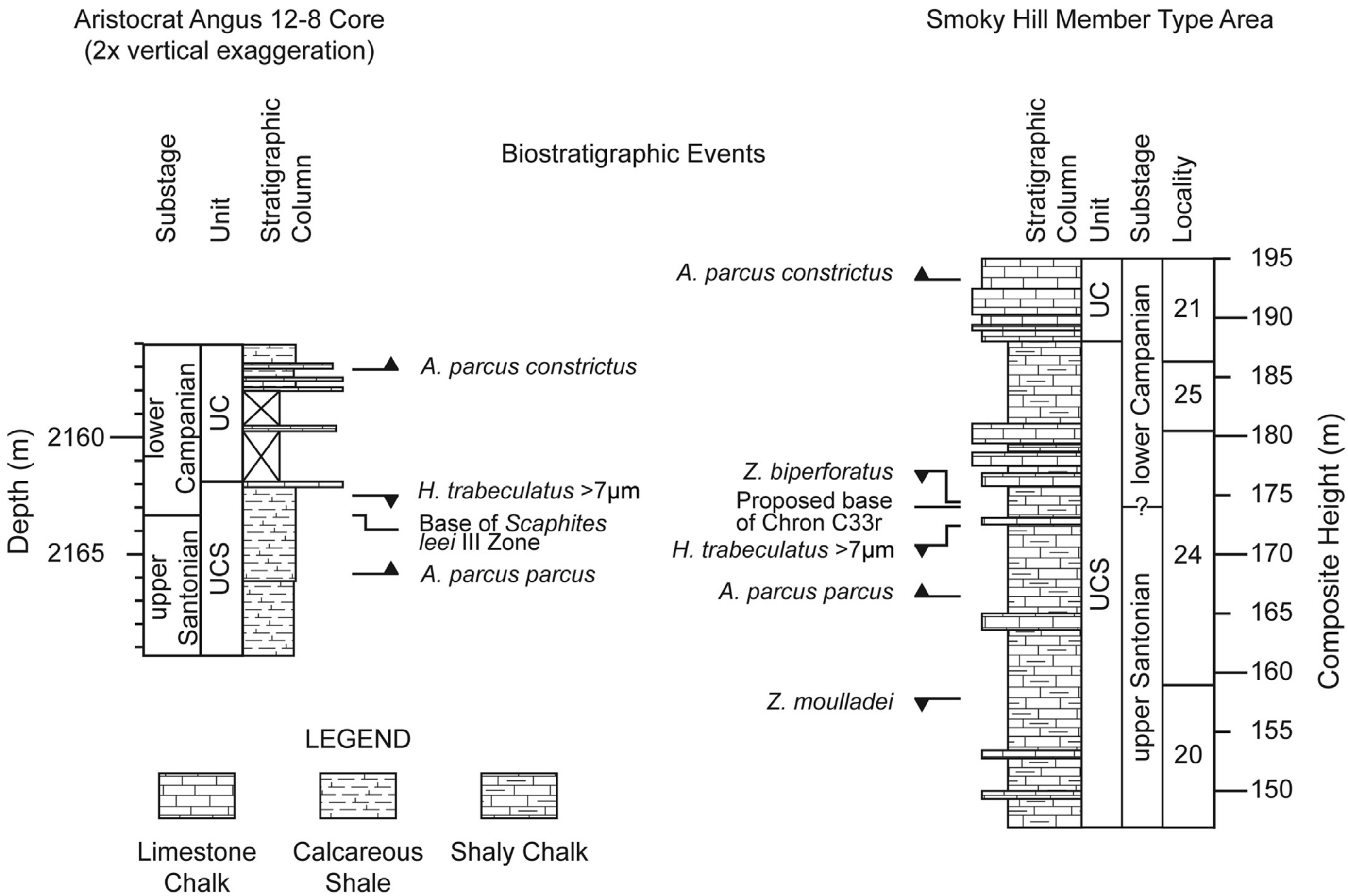

Fig. 3. Stratigraphic columns, potential Santonian/Campanian boundary markers, and calcareous nannofossil events observed at the Smoky Hill Member type area and the Aristocrat Angus 12-8 core. The base of paleomagnetic chron C33r was used as the boundary marker for the Smoky Hill Member type area. The base of the *Scaphites leei* III ammonite Zone was used in the Aristocrat Angus 12-8 core as a boundary marker. Note the difference in scale between the sections. Adapted from Hattin (1982) and Joo and Sageman (2014). Abbreviations for Niobrara lithostratigraphic units from Scott and Cobban (1964) are: upper chalk (UC) and upper chalky shale (UCS).

members of the Niobrara Formation include the Fort Hays Limestone and the overlying Smoky Hill Chalk (Scott and Cobban, 1964).

The Smoky Hill Member of the Niobrara Formation accumulated from the Coniacian to the early Campanian, when the basin-floor sediments of the Western Interior Seaway consisted of ooze under water depths estimated between 150 and 300 m (Hattin, 1982). The Smoky Hill Member was subdivided by Scott and Cobban (1964) into seven informal units including, from top to bottom: upper chalk, upper chalky shale, middle chalk, middle shale, lower limestone, lower shale, and the lower shale and limestone.

The type area for the Smoky Hill Member was deposited as cycles of shaly chalk and pure chalk (Fig. 3). The type area consists of a composite of outcrops in northwestern Kansas (Fig. 1), constructed by Hattin (1982), using a combination of twelve key sections in Logan, Gove, and Trego counties. The Smoky Hill Member measures 181.8 m-thick in its type area. Fossil preservation is excellent and is attributed to anoxic bottom conditions (Hattin, 1982). Hattin (1982) estimated a depositional rate of 36.0 mm/kyr for the Smoky Hill Member in its type area.

The Aristocrat Angus 12-8 well is located in the Wattenberg Gas Field in the western Denver Basin (Fig. 1). Sediments in this core were deeply buried (greater than 2100 m; Joo and Sageman, 2014) resulting in poor preservation of calcareous nannofossils. The drill core extends from the lower Campanian Pierre Shale through the Cenomanian Graneros Shale with over 90% recovery (Joo and Sageman, 2014). The Smoky Hill Member of this core is predominantly calcareous shale and chalk (Fig. 3) and is approximately 76 m-thick.

5. Results

Chalky units of the Smoky Hill Member yielded abundant, well-preserved calcareous nannofossils. The Aristocrat Angus 12-8 core yielded sparse nannofossils with preservation ranging from poor to moderate. In all, 159 and 63 calcareous nannofossil taxa were identified from the Smoky Hill Member type area and Aristocrat Angus 12-8 core, respectively.

Previously suggested calcareous nannofossil markers for the Santonian/Campanian boundary (Section 3.2) were analyzed for their stratigraphic distribution in relation to the base of paleomagnetic Chron C33r. The base of paleomagnetic Chron C33r was identified in Locality 24 of the Smoky Hill Member type area at approximately 174 m in the composite section (Paul Montgomery, personal communication; Fig. 3). The FO of *Aspidolithus parcus parcus* (Fig. 4-A,B) occurs at 166.3 m, approximately 7.5 m below the base of Chron C33r, in the Smoky Hill Member type area and at a depth of 2165.9 m, approximately 2.0 m below the base of *Scaphites leei* III ammonite Zone, in the Aristocrat Angus 12-8 core (Fig. 3). The FO of *Cylindralithus crassus* was documented by Bergen and Sikora (1999) as occurring below the Santonian/Campanian boundary, but was absent in both the Smoky Hill Member type area and Aristocrat Angus 12-8 core (Fig. 2).

Other biohorizons were identified near the supposed base of Chron C33r in the Smoky Hill Member type area and the base of the *Scaphites leei* III ammonite Zone in the Aristocrat Angus 12-8 core. The LO of *Helicolithus trabeculatus* >7 μm (Fig 4-D; *Helicolithus*

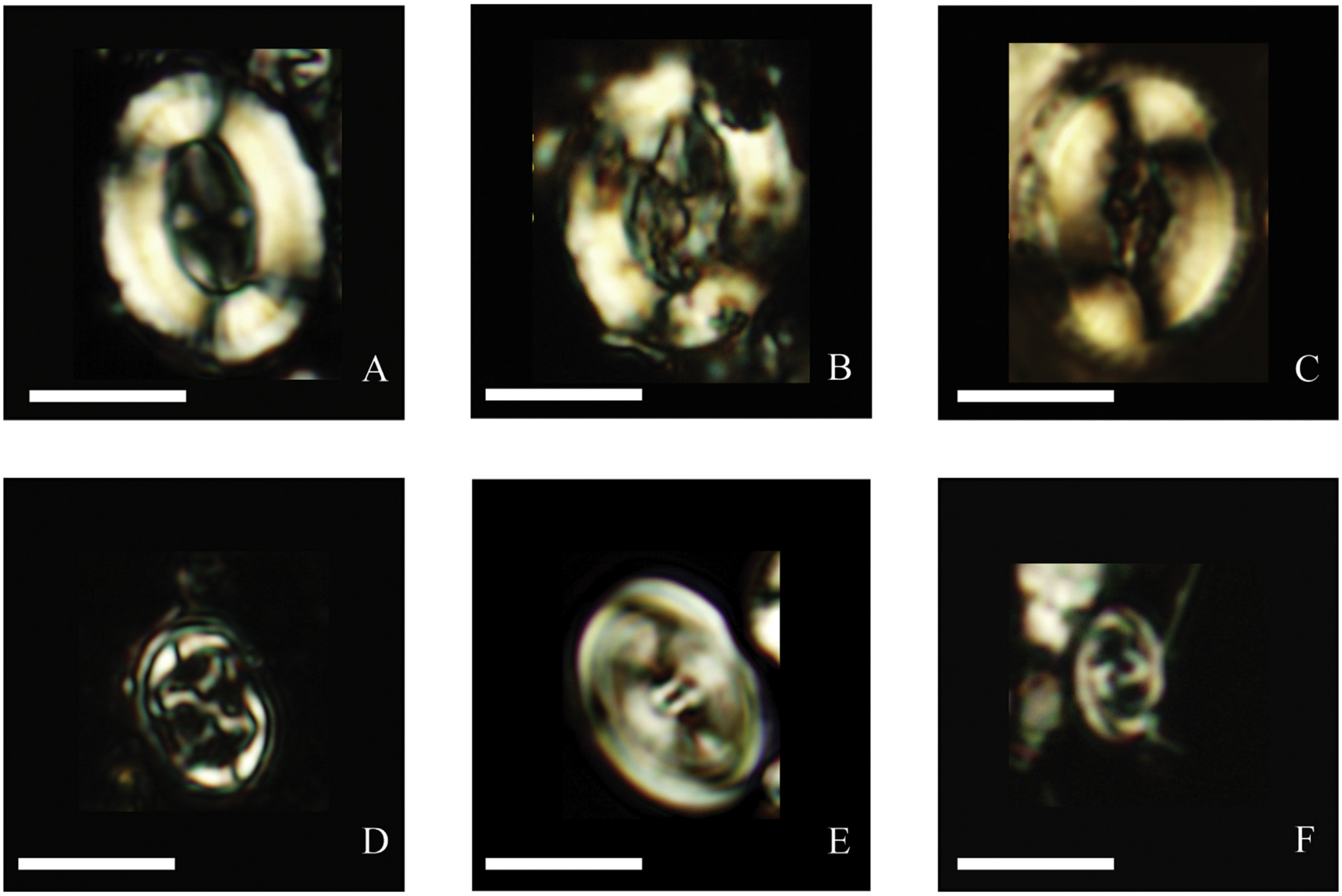

Fig. 4. Light photomicrographs of selected specimens at 1250× magnification. Scale bars are 5 μm. All photographs are in cross polarized light. **A.** *Aspidolithus parcus parcus,* Smoky Hill Member type area, Locality 21, 0.9 m. **B.** *Aspidolithus parcus parcus*, Aristocrat Angus 12-8 core, 2165.5 m. **C.** *Aspidolithus parcus constrictus*, Smoky Hill Member type area, Locality 21, 8.0 m. **D.** *Helicolithus trabeculatus* > 7 μm, Smoky Hill Member type area, Locality 24, 2.0 m. **E.** *Zeugrhabdotus biperforatus*, Smoky Hill Member type area, Locality 24, 11.0 m. **F.** *Zeugrhabdotus moulladei*, Smoky Hill Member type area, Locality 20, 2.0 m.

trabeculatus large in Bergen and Sikora, 1999) was identified at 172.3 m in the Smoky Hill Member type area, approximately 1.5 m below the supposed base of Chron C33r. It was identified at a depth of 2162.56 m in the Aristocrat Angus 12-8 core, approximately 1.0 m below the *Scaphites leei* III ammonite Zone (Fig. 3). Additionally, the LO of *Zeugrhabdotus biperforatus* (Fig. 4-E) was identified at 174.3 m in the Smoky Hill Member type area, less than a meter above the supposed base of Chron C33r (Fig. 3). *Zeugrhabdotus biperforatus* was not consistently identified in the Aristocrat Angus 12-8 core.

Other nannofossil biohorizons were identified within the studied intervals. The FO of *Aspidolithus parcus constrictus* (Fig. 4-C) is located at 193.15 m, approximately 20 m above the base of Chron C33r, in the Smoky Hill Member type area and a depth of 2157.07 m, approximately 6 m above the base of the *Scaphites leei* III Zone, in the Aristocrat Angus 12-8 core (Fig. 3). The LO of *Zeugrhabdotus moulladei* (Fig. 4-F) occurs at 157.0 m, approximately 15 m below the supposed base of Chron C33r, in the Smoky Hill Member type area (Fig. 3). *Zeugrhabdotus moulladei* was not identified in the Aristocrat Angus 12-8 core.

6. Discussion

High resolution analyses of calcareous nannofossils from the Smoky Hill Member type area and Aristocrat Angus 12-8 core suggest that biohorizons and zonation schemes from previous studies (Section 3.2: Fig. 2) are not easily used in the Niobrara Formation. The most successful boundary marker from a previous zonation is the FO of *Aspidolithus parcus parcus* proposed in the cosmopolitan CC and NC zonation schemes of Perch-Nielsen (1985) and Bralower et al. (1995), respectively. This biohorizon corresponds closely with the supposed base of Chron C33r in the Smoky Hill Member type area and the base of the *Scaphites leei* III ammonite Zone in the Aristocrat Angus 12-8 core.

Previous studies have shown the FO of *A. parcus parcus* to be diachronous, most likely because it was referred to different morphotypes and/or to the different subspecies (Hancock and Gale, 1996; Gardin et al., 2001). Wise (1983) described the stratigraphic and phylogenetic relationships among *Aspidolithus parcus* subspecies and related forms based on the ratio between the central area (b) and rim (a) width. Specimens with a b/a ratio of 1.0–2.0 are classified as *Aspidolithus parcus parcus*. Specimens with a b/a ratio greater than 2.0 are *A. parcus expansus* and specimens with a b/a ratio lesser than 1.0 are *A. parcus constrictus*. As noted by Wise (1983), the relative size of the central area decreases through time with *A. parcus expansus* being the oldest and *A. parcus constrictus* the youngest. These criteria were followed in the present study and the three subspecies belonging to this lineage were detected (see range chart in Supplementary material 1).

Bralower et al. (1995) observed the FO of *Aspidolithus parcus parcus* at the base of Chron C33r. Erba et al. (1995) also documented the FO of *A. parcus parcus* near the base of Chron C33r in the central and western Pacific during Ocean Drilling Program (ODP) Leg 144. Tremolada (2002) observed the FO of *A. parcus parcus* near the base of Chron C33r at the Bottaccione section in Gubbio, Italy, which is a potential GSSP for the Santonian/Campanian boundary (Ogg and Hinnov, 2012). Verosub et al. (1989) used nannofossil data from Filewicz (1986) and found the FO of *A. parcus parcus* near the base of Chron C33r in the Forbes Member in the Sacramento Valley, California. In contrast, Stradner and Steinmetz (1984) found the FO of *A. parcus parcus* approximately 15 m above the base of Chron C33r in the Angola Basin during Deep Sea Drilling Program (DSDP) Leg 75. They claim to have seen b/a ratios between 1.0 and 1.25 in their samples which are in the smaller range of b/a ratios. This indicates that they did not include potential *A. parcus parcus* specimens in the 1.25 to 2.0 range which could have been older and closer to the base of Chron C33r. The current study documented the FO of *A. parcus parcus* approximately 7.5 m below the base of Chron C33r in the Smoky Hill Member type area and approximately 2.0 m below the base of *Scaphites leei* III Zone in the Aristocrat Angus 12-8 core, indicating that it is very near the proposed Santonian/Campanian boundary in the Niobrara Formation. The FO of *A. parcus parcus* appears to be a good marker for the base of the Campanian as long as consistent taxonomic concepts are used.

Other proposed nannofossil boundary markers are not useful in the sections of the Niobrara Formation in this study. Bergen and Sikora (1999) use an abundance change in *Watznaueria barnesiae* and an undescribed species of *Amphizygus*. The use of *Watznaueria barnesiae* abundance changes as biostratigraphic markers is tenuous. Increased abundances have been attributed to warm surface waters (Bukry, 1973; Wind, 1979; Watkins et al., 1996) and/or poor preservation of taxa (e.g., Roth and Krumbach, 1986). Without taxonomic details, the *Amphizygus* species is not useful as a biostratigraphic marker. The best nannofossil marker for the base of the Campanian in the UC Zonation is the base of *Arkhangelskiella cymbiformis* (Burnett, 1998). The FO of this species was far below the supposed boundary in the Smoky Hill Member type area (24 m; see range chart in Supplementary material 1) and the Aristocrat Angus 12-8 core (>6 m; see range chart in Supplementary material 2) indicating that it is not a useful nannofossil marker for the base of the Campanian in the Niobrara Formation.

Other biohorizons (i.e., LOs of *Helicolithus trabeculatus* >7 μm and *Zeugrhabdotus biperforatus*) were found closer to the boundary in the Niobrara Formation than the FO of *A. parcus parcus*. The FO of *A. parcus parcus* and the LO of *H. trabeculatus* >7 μm mark the base of the KN21 Zone of Bergen and Sikora (1999), and the LO of *Z. biperforatus* is noted within Zone KN21. Bergen and Sikora (1999) placed this zone in the early Campanian, indicating that these biohorizons occurred later in the North Sea than in the Western Interior Basin. Conversely, it may indicate that their definition of the Santonian/Campanian boundary, LO of *Marsupites testudinarius*, is older than the base of Chron C33r and the base of the *Scaphites leei* III Zone.

Correlation of the calcareous nannofossil biohorizons between the Smoky Hill Member type area and the Aristocrat Angus 12-8 core indicates that the base of Chron C33r and the base of the *Scaphites leei* III Zone occur nearly synchronously, but with the base of Chron C33r potentially being slightly younger. The LO of *Helicolithus trabeculatus* >7 μm appears slightly below (1.5 m) the base of Chron C33r indicating that this biohorizon is older. In contrast, this biohorizon occurs slightly above (1.0 m) the base of the *Scaphites leei* III ammonite Zone indicating the boundary marker is older than the biohorizon. Sageman et al. (2014) determined the age of the Santonian/Campanian boundary using the base of the *Scaphites leei* III Zone to be at 84.19 ± 0.38 Ma. Correlating the LO of *Helicolithus trabeculatus* >7 μm biohorizon between the two studied sections indicates that the base of Chron C33r is slightly younger.

7. Conclusions

High resolution study of calcareous nannofossils from the Smoky Hill Member type area and the Aristocrat Angus 12-8 core yields a biostratigraphic framework for the Santonian/Campanian Stage transition. Within these two sections, the FO of *Aspidolithus parcus parcus* occurs approximately 7.5 m below the base of Chron C33r in the Smoky Hill Member type area and 2.0 m below the base of the *Scaphites leei* III Zone in the Aristocrat Angus 12-8 core. The LO of *Helicolithus trabeculatus* >7 μm occurs 1.5 m below Chron C33r in the Smoky Hill Member type area and 1.0 m above the base of the *Scaphites leei* III Zone in the Aristocrat Angus 12-8 core. The LO of *Zeugrhabdotus biperforatus* is documented 2.0 m above the base of Chron C33r in the Smoky Hill Member type area, but was not identified in the Aristocrat Angus 12-8 core.

Based on biostratigraphic correlations, the base of Chron C33r and the base of the *Scaphites leei* III Zone appear to be nearly synchronous, indicating that the base of Chron C33r occurred at approximately 84.19 ± 0.38 Ma (Sageman et al., 2014). This study demonstrates the importance of comparisons between potential markers for the Santonian/Campanian boundary and the necessity of multidisciplinary approaches to boundary studies.

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References

Bergen, J., Sikora, P., 1999. Microfossil diachronism in southern Norwegian North Sea chalks: Valhall and Hod fields. In: Geological Society, London, Special Publications, 152, pp. 85–111.

Blakey, R.C., 2015. North American Paleogeographic Maps. Colorado Plateau Geosystems.

Bralower, T.J., Leckie, R.M., Sliter, W.V., Thierstein, H.R., 1995. An integrated Cretaceous microfossil biostratigraphy. Geochronology Time Scales and Global Stratigraphic Correlation. In: SEPM Special Publication, 54, pp. 65–79.

Bukry, D., 1973. Coccolith and silicoflagellate stratigraphy, Tasman Sea and southwestern Pacific Ocean, Deep Sea Drilling Project Leg 21. In: Burns, R.E., Andrews, J.E. (Eds.), Proceedings of the Oceans Drilling Programs, Scientific Results, 21, pp. 885–891.

Burnett, J., 1998. Upper Cretaceous. In: Bown, P.R. (Ed.), Calcareous Nannofossil Biostratigraphy. Chapman and Hall, Cambridge, pp. 132–199.

Cobban, W.A., Walaszczyk, I., Obradovich, J., McKinney, K., 2006. USGS Zonal Table for the Upper Cretaceous Middle Cenomanian-Maastrichtian of the Western Interior of the United States Based on Ammonites, Inoceramids, and Radiometric Ages. U.S. Geological Survey Open-File Report 2006-1250, 45.

Coquand, H., 1857. Position des Ostrea columba et biauriculata dans le groupe de la craie inférieur. Bulletin de la Société Géologique de France 14, 745–766.

de Grossouvre, A., 1901. Recherches Sur La Craie Supérieure. Partie 1: Stratigraphie Generale. Memoires Pour Servir a l'Explication De La Carte Geologique Detaillee De La France. Imprimerie Nationale, Paris.

Erba, E., Silva, I.P., Watkins, D.K., 1995. Cretaceous calcareous plankton biostratigraphy of Sites 872 through 879. In: Haggerty, J.A., Permoli Silva, I., Rack, F., McNutt, M.K. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 144, pp. 157–169.

Filewicz, M.V., 1986. Late Cretaceous (Santonian/Campanian) calcareous nannofossils from the Forbes Formation along Salt Creek, western Sacramento Valley, California. In: Abbot, P.L. (Ed.), Cretaceous Stratigraphy, Western North America.

Society of Economic Paleontologists and Mineralogists, Pacific Section, pp. 153–160.
Gale, A.S., Hancock, J.M., Kennedy, W.J., Petrizzo, M.R., Lees, J.A., Walaszczyk, I., Wray, D.S., 2008. An integrated study (geochemistry, stable oxygen and carbon isotopes, nannofossils, planktonic foraminifera, inoceramid bivalves, ammonites and crinoids) of the Waxahachie Dam Spillway section, north Texas: a possible boundary stratotype for the base of the Campanian Stage. Cretaceous Research 29, 131–167.
Gardin, S., Del Panta, F., Monechi, S., Pozzi, M., 2001. A Tethyan reference record for the Campanian and Maastrichtian stages: the Bottaccione section (Central Italy); review of data and new calcareous nannofossil results. In: Odin, G.S. (Ed.), The Campanian – Maastrichtian stage boundary. Characterization at Tercis les Bains (France) and correlation with Europe and other continents, Developments in Palaeontology and Stratigraphy, 19, pp. 745–757.
Hancock, J.M., Gale, A., 1996. The Campanian Stage. Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Science de la Terre 66, 103–109.
Hattin, D.E., 1982. Stratigraphy and depositional environment of Smoky Hill Chalk Member, Niobrara Chalk (Upper Cretaceous) of the type area, western Kansas. Kansas Geological Survey Bulletin 225, 1–108.
Joo, Y.J., Sageman, B.B., 2014. Cenomanian to Campanian Carbon Isotope Chemostratigraphy from the Western Interior Basin, USA. Journal of Sedimentary Research 84, 529–542.
Kauffman, E.G., Caldwell, W.G.E., 1993. The Western Interior Basin in space and time. In: Caldwell, W.E., Kauffman, E.G. (Eds.), Evolution of the Western Interior Basin, Special Papers Geological Association of Canada, 39, pp. 1–30.
Locklair, R.E., Sageman, B.B., 2008. Cyclostratigraphy of the Upper Cretaceous Niobrara Formation, Western Interior, USA: a Coniacian–Santonian orbital timescale. Earth and Planetary Science Letters 269, 540–553.
Longman, M.W., Luneau, B.A., Landon, S.M., 1998. Nature and distribution of Niobrara lithologies in the Cretaceous Western Interior Seaway of the Rocky Mountain region. Rocky Mountain Association of Geologists 35, 137–170.
Lowrie, W., Alvarez, W., 1977. Late Cretaceous geomagnetic polarity sequence: detailed rock and palaeomagnetic studies of the Scaglia Rossa limestone at Gubbio, Italy. Geophysical Journal of the Royal Astronomical Society 51, 561–581.
Ogg, J.G., Hinnov, L.A., 2012. Chapter 27, Cretaceous. In: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), The Geologic Time Scale 2012. Elsevier, pp. 793–853.
Perch-Nielsen, K., 1985. Mesozoic calcareous nannofossils. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (Eds.), Plankton Stratigraphy. Cambridge University Press, Cambridge, pp. 329–426.
Roberts, L.N.R., Kirschbaum, M.A., 1995. Paleogeography of the Late Cretaceous of the Western Interior of middle North America: Coal distribution and sediment accumulation. United States Geological Survey Professional Paper, 115.
Roth, P.H., 1978. Cretaceous nannoplankton biostratigraphy and oceanography of the northwestern Atlantic Ocean. In: Initial Reports of the Deep Sea Drilling Project, 44, pp. 731–759.
Roth, P.H., Krumbach, K.R., 1986. Middle Cretaceous calcareous nannofossil biogeography and preservation in the Atlantic and Indian Oceans: implications for paleoceanography. Marine Micropaleontology 10, 235–266.
Sageman, B.B., Singer, B.S., Meyers, S.R., Siewert, S.E., Walaszczyk, I., Condon, D.J., Jicha, B.R., Obradovich, J.D., Sawyer, D.A., 2014. Integrating $^{40}Ar/^{39}Ar$, U-Pb, and astronomical clocks in the Cretaceous Niobrara Formation, Western Interior Basin, USA. Geological Society of America Bulletin 126, 956–973.
Scott, G.R., Cobban, W.A., 1964. Stratigraphy of the Niobrara Formation at Pueblo, Colorado. U.S. Geological Survey Professional Paper, Report: P 0454-L, L1–L30.
Séronie-Vivien, M., 1972. Contribution à l'étude du Sénonien en Aquitaine septentrionale: ses stratotypes: Coniacien, Santonien, Campanien. Les Stratotypes Francais 2, 195.
Sissingh, W., 1997. Biostratigraphy of Cretaceous calcareous nannoplankton. Geologie en Mijnbouw 56, 37–65.
Slingerland, R., Kump, L., Arthur, M., Fawcett, P., Sageman, B., Barron, E., 1996. Estuarine circulation in the Turonian Western Interior Seaway of North America. Geological Society of America Bulletin 108, 941–952.
Stradner, H., Steinmetz, J., 1984. Cretaceous calcareous nannofossils from the Angola Basin, Deep Sea Drilling Project Site 530. In: Initial Reports of the Deep Sea Drilling Project, 75, pp. 565–647.
Styzen, M., 1997. Cascading counts of nannofossil abundance. Journal of Nannoplankton Research 19, 49.
Tremolada, F., 2002. Aptian to Campanian calcareous nannofossil biostratigraphy from the Bottaccione section, Gubbio, central Italy. Rivista Italiana di Paleontologia e Stratigrafia 108, 441–456.
van Hinte, J., 1965. The type Campanian and its planktonic Foraminifera. Proceedings of the Koninklijke Nederlandse Akademie Van Weteschappen, Series B 68, 8–28.
Verosub, K.L., Haggart, J.W., Ward, P.D., 1989. Magnetostratigraphy of Upper Cretaceous strata of the Sacramento Valley, California. Geological Society of America Bulletin 101, 521–533.
Watkins, D.K., Bergen, J.A., 2003. Late Albian adaptive radiation in the calcareous nannofossil genus Eiffellithus. Micropaleontology 49, 231–251.
Watkins, D.K., Wise Jr., S.W., Popsichal, J.J., Crux, J., 1996. Upper Cretaceous calcareous nannofossil biostratigraphy and paleoceanography of the Southern Ocean. In: Microfossils and Oceanic Environments. University of Wales, Aberystwyth Press, Aberystwyth, United Kingdom, pp. 355–381.
Wind, F., 1979. Maestrichtian-Campanian nannofloral provinces of the Southern Atlantic and Indian Oceans. In: Talwani, M., Hay, W.W., Ryan, W.B.F. (Eds.), Deep Drilling Results in the Atlantic Ocean: Continental Margin and Paleoenvironment, Maurice Ewing Series, 3. American Geophysical Union, Washington D.C., pp. 123–137
Wise Jr., S.W., 1983. Mesozoic and Cenozoic Calcareous Nannofossils Recovered by Deep Sea Drilling Project Leg 71 in the Falkland Plateau Region. Southwest Atlantic Ocean. In: Initial Reports of Deep Sea Drilling Project, 71, pp. 481–550.

Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.cretres.2016.08.015.

Species list

Arkhangelskiella cymbiformis Vekshina, 1959
Aspidolithus parcus constrictus (Hattner et al., 1980) Perch-Nielsen, 1984
Aspidolithus parcus expansus (Wise & Watkins in Wise, 1983) Perch-Nielsen, 1984
Aspidolithus parcus parcus (Stradner, 1963) Noël, 1969
Cylindralithus crassus Stover, 1966
Helicolithus trabeculatus (Górka, 1957) Verbeek, 1977
Lithastrinus septenarius Forchheimer, 1972
Watznaueria barnesiae (Black, 1959) Perch-Nielsen, 1968
Zeugrhabdotus biperforatus (Gartner, 1968) Burnett, 1997
Zeugrhabdotus moulladei Bergen, 1994