

## High-resolution calcareous nannofossil biostratigraphy for the Coniacian/Santonian Stage boundary, Western Interior Basin

Stacie A. Blair<sup>a,\*</sup>, David K. Watkins<sup>b</sup>

<sup>a</sup> Department of Geological Sciences, Florida State University, Tallahassee, FL 32306, USA

<sup>b</sup> Geosciences Department, University of Nebraska, Lincoln, NE 68588, USA

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### ABSTRACT

The Ten Mile Creek area (Dallas, Texas) is a proposed Global Stratotype Section and Point (GSSP) candidate for the Coniacian/Santonian Stage boundary. The Santonian Working Group has designated the first appearance of *Inoceramus (Cladoceramus) undulatoplicatus* as the diagnostic macrofossil bioevent for the base of the Santonian Stage. Calcareous nannofossils were examined from sediments of the Bruceville Marl at the proposed GSSP site and from well-preserved sediments of the coeval Smoky Hill Member-type area (northwestern Kansas) of the Niobrara Formation. Nannofossil bioevents were correlated with the lowest stratigraphic occurrence of *I. undulatoplicatus* to create a high resolution biostratigraphic framework and stratigraphic proxy for the Coniacian/Santonian Stage transition.

Six bioevents are useful for recognition of the Coniacian/Santonian transition within the Bruceville Marl and Smoky Hill Member. The first appearance datums (FADs) of *Prediscosphaera desidero grandis*, n. sp. and *Amphizygus megalops*, n. sp. as well as the FADs of two rare taxa, *Orastrum campanensis* and *Tortololithus dodekachelyon*, n. sp., are in close stratigraphic proximity to the lowest occurrence of *I. undulatoplicatus*. In addition, two nannofloral acmes occur near the boundary: *Watznaueria quadriradiata* and *Zeughrabdotus scutula*.

This study describes eight new species from the Smoky Hill Chalk type area; *Amphizygus megalops*, *Bifidalithus phenax*, *Pharus evanescens*, *Gartnerago margaritatus*, *Helicolithus tectufissus*, *Tortololithus dodekachelyon*, *Prediscosphaera desidero grandis* and *Helicolithus varolii*. Light microscope images are provided for rare and well-preserved specimens of *Reinhardtites clavica viformis* Varol, 1991, *Orastrum campanensis* (Cepek) Wind & Wise, 1977, *Rhombolithus rhombicum* (Bukry) Black, 1973, and *Gartnerago clarusora* Varol, 1991. This study extends the ranges of several species from those documented in previous literature.

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### 1. Introduction

Calcareous nannofossils are prolific in Upper Cretaceous sediments in the North American Western Interior Basin and Gulf of Mexico. The Niobrara Formation and coeval Bruceville Marl (Austin Group) have diverse nannofossil assemblages, although fine-scale nannofossil correlation studies have not been performed previously.

The first appearance datum (FAD) of the bivalve, *Inoceramus undulatoplicatus*, has been designated as the Coniacian/Santonian boundary macrofossil bioevent (Lamolda and Hancock, 1996). This species is abundant in Niobrara and Bruceville strata and can be used to calibrate a high-resolution calcareous nannofossil biostratigraphy for the transition from the upper Coniacian to lower Santonian.

Two Cretaceous sections were utilized for biostratigraphic study. The first is a proposed Global Stratotype Section and Point (GSSP) candidate for the Coniacian/Santonian Stage in Dallas, Texas, along Ten Mile Creek. A complete biostratigraphic analysis is necessary before consideration for formal adoption; however, the Ten Mile Creek section consists of only ~8.0 meters of exposed strata to which traditional nannofossil zonations are at too coarse in resolution to be applied. The Smoky Hill Member of the Niobrara Formation in its type area of northwestern Kansas spans the entire upper Coniacian to lower Santonian transition, and is used to corroborate the order of nannofossil events seen at Ten Mile Creek. It has abundant macrofossils, including a well-documented first appearance of *Inoceramus undulatoplicatus*, and is noted for exquisite preservation of calcareous nannofossils.

Study of calcareous nannofossils from the Smoky Hill type area and the proposed GSSP at Ten Mile Creek was used to create a new, high-resolution biostratigraphic framework for the Coniacian/Santonian Stage boundary, as defined by the FAD of *I. undulatoplicatus*.

\* Corresponding author.

E-mail address: [blair@gly.fsu.edu](mailto:blair@gly.fsu.edu) (S.A. Blair).

## 2. Coniacian/Santonian Stage biostratigraphy

The Santonian Stage was named after the town of Saintes, France, by Coquand in 1857. This Upper Cretaceous stage is defined by the International Commission on Stratigraphy to span from 85.8 to 83.5 Ma (Ogg et al., 2004). The Second International Symposium on Cretaceous Stage Boundaries (1995) discussed the utility of macrofossil events as Santonian Stage biomarkers. The first appearance datums of *Texanites* (*Texanites*) and *Inoceramus* (*Cladoceramus*) *undulaticus* were nominated as Coniacian/Santonian Stage boundary events. Hancock (1991), however, noted that *Texanites* was found to be absent in northwestern European sections and was too rare to be a cosmopolitan marker (Lamolda and Hancock, 1996).

The FAD of *I. undulaticus* has been documented in sections of the North American Western Interior (Kauffman et al., 1994), Germany and Poland (Tröger, 1989), England (Bailey et al., 1984), France and Spain (Lopez et al., 1992), Austria (Tröger and Summesberger, 1994), and the Caucasus region and central Asia (Moskvin, 1986). In Japan, a different inoceramid FAD, that of *Inoceramus amakusensis*, is noted at the Santonian boundary. *Inoceramus undulaticus* appears to be absent only in sections of far-eastern Russia (Lamolda and Hancock, 1996). As a result, the Santonian Working Group designated the FAD of the inoceramid bivalve, *I. undulaticus* (Roemer), as the primary marker for the Coniacian/Santonian Stage boundary (Lamolda and Hancock, 1996).

A Global Stratotype Section and Point (GSSP) has yet to be named for the Coniacian/Santonian Stage boundary. Sections proposed are the Olazagutia Quarry (Navarra, Spain), Seaford Head (Sussex, England), and the Ten Mile Creek section (Dallas, Texas) (Lamolda and Hancock, 1996). Before these sections can be considered for formal adoption, each must have a biostratigraphic analysis performed, with particular emphasis on bioevents that can serve as Coniacian/Santonian boundary markers.

Calcareous nannofossil bioevents have been utilized as proxies for stage boundaries when macrofossil resolution is too coarse or macrofossils are poorly preserved. Currently, published nannofossil schemes for the Coniacian/Santonian lack the resolution necessary to define this stage boundary (Fig. 1).

Sissingh (1977) placed the FAD of *Micula decussata* as an upper Coniacian biohorizon and the FAD of *Reinhardtites anthophorus* as a middle Santonian biohorizon. Sissingh (1977) also proposed the first appearance datums of *Lucianorhabdus cayeuxii* and *Calculites obscurus* as potential candidates for the stage boundary. Perch-Nielsen (1979b) recommended utilizing the LAD (last appearance datum) of *Lithastrinus septenarius* as a Santonian Stage nannofossil bioevent. According to Perch-Nielsen (1985), the Coniacian/Santonian Stage boundary lies within nannofossil Zone CC14 (upper Coniacian to lower Santonian), which is defined as the interval from the FAD of *Micula decussata* to the FAD of *Reinhardtites anthophorus*.

Burnett (1998) placed the Coniacian/Santonian boundary within Subzone UC11c, defined as the interval from the FAD of *L. cayeuxii* in the upper Coniacian to the LAD of *Lithastrinus septenarius* in the lower Santonian. Key bioevents noted in this zone include the first appearance datums (in stratigraphic order) of *Cribrorocorona gallica*, *Prediscosphaera grandis*, *Micula concava*, *Amphizygus minimus*, *Rucinolithus hayi*, *Microrhabdulus undosus*, and *Staurolithites mielnicensis*, with the FAD of *P. grandis*, *M. concava*, and *A. minimus* occurring closest to the Coniacian/Santonian boundary (Burnett, 1998).

Melinte and Lamolda (2002) examined Coniacian/Santonian sediments at ~1-m intervals in the Olazagutia Quarry of Spain (Fig. 1). They recommended the following succession of bioevents to characterize the Coniacian/Santonian transition: FAD of *Lithastrinus grillii*, FAD of *Lucianorhabdus cayeuxii*, and the FAD of *Calculites obscurus-ovalis* within the upper Coniacian, the FAD of

*Dicarinella asymetrica* (planktonic foraminifer [PF]) just above the Santonian boundary, and the FAD of *Sigalia carpatica* (PF) and LAD of *Lithastrinus septenarius* in the lower Santonian. Crux (1982) examined sediments from the proposed GSSP Seaford Head section and placed the Coniacian/Santonian boundary in his *Lucianorhabdus maleformis* Zone, defined as the interval from the FAD of *L. maleformis* to the FAD of *R. anthophorus* (Fig. 1).

Bergen in Bergen and Sikora (1999) noted the following succession of bioevents in NW Europe: FAD-*L. grillii* (upper Coniacian), LAD-*E. floralis*/*H. turonicus* (upper Coniacian), LAD-*W. viginica* (upper Coniacian), LAD-*H. trabeculatus* acme (upper Coniacian), LAD-*A. brooksii*, early form/FAD-*A. minimus* (lower Santonian), LAD-*Q. enebrachium* (lower Santonian), and the LAD-*L. moratus* (lower Santonian).

A preliminary study by Burnett placed the Ten Mile Creek section between the nannofloral bioevents of the *Quadrum gartneri* LAD and the LAD of *Lithastrinus septenarius* (Burnett and Whitham, 1999). Gale et al. (2007) examined calcareous nannofossils from the Wal-mart section in Dallas County near the Ten Mile Creek section. They noted the FAD of *I. undulaticus* within the nannofossil zone UC11c and that the FAD of *M. concava* was seen below the FAD of *I. undulaticus*. Finally, Howe et al. (2007) observed from 13 samples of the Ten Mile Creek section that the FAD of *I. undulaticus* occurred between the LADs of *W. paradubia* (PF) and *C. simplex* (PF). The FAD of *A. minimus* was noted as a good bioevent seen ~2.0 m below the FAD of *I. undulaticus*.

Zonation schemes proposed by Sissingh (1977), Perch-Nielsen (1985), Crux (1982), and Melinte and Lamolda (2002) use nannofossil bioevents that predate or postdate the base of the Santonian Stage. Other nannofossil schemes use biomarkers that are rare or absent within Western Interior Seaway sediments. Three nannofossil bioevents were noted for their preliminary potential as Coniacian/Santonian Stage biomarkers in Western Interior sediments: *P. grandis* (FAD), *M. concava* (FAD), and *A. minimus* (FAD).

## 3. Regional setting and lithostratigraphy

### 3.1. Smoky Hill Member (Niobrara Formation), Gove County, Kansas (SE 1/4, Sec. 29, T15S, R26W)

The Smoky Hill Member of the Niobrara Formation accumulated from the Coniacian to the early Campanian (Late Cretaceous), when the basin-floor sediments of the Western Interior Seaway were a soupy ooze with water depths estimated between 150–300 meters (Hattin, 1982). Depositional rates are extremely high (~0.036 mm/yr). Fossil preservation is excellent and is attributed to anoxic bottom waters and absence of suspension feeders (Hattin, 1982).

The type area for the Smoky Hill Member is in northwestern Kansas (Fig. 2). Hattin (1982) used a combination of 12 key sections in Logan, Gove, and Trego counties to construct a composite section 181.8 m thick for the entire Smoky Hill Member.

The first occurrence of *Inoceramus undulaticus* is documented from the section at Locality 13 (SE 1/4, Sec. 29, T15S, R26W, Gove County, Kansas; Hattin, 1982). Twenty-nine meters of olive gray to grayish orange laminated chalk with abundant bentonite, iron, and gypsum seams is exposed at Locality 13 (Fig. 3). Hattin (1982) placed the FAD of *I. undulaticus* 78.4 m above the base of the underlying Fort Hays Member and 14 m above the base of the Locality 13 section in Bed 13. Bed 13 is approximately 3 m thick; however, the exact placement of the FAD within this bed was not documented.

### 3.2. Bruceville Marl (Austin Group), Ten Mile Creek, Dallas, Texas (32° 20' N, 96° 48' W)

The Austin Group crops out along a trend from the northeastern portion of Texas to the southwestern corner of Maverick County

Substage	Cosmopolitan Zones				
	Sissingh Zonation (1977)	Perch-Nielsen Zonation (1979a & 1985)	Burnett Zonation (1998)	Melinte and Lamolda (2002) Olazagutia Quarry (Spain)	Crux (1982) Seaford Head (England)
Lower Santonian	↓ <i>R. anthophorus</i> C C 1 5	↓ <i>L. septenarius</i> ↓ <i>R. anthophorus</i> ↓ <i>L. grillii</i> ↓ <i>M. concava</i> C C	↓ <i>L. septenarius</i> ↓ <i>M. undosus</i> ↓ <i>S. mielnicensis</i> ↓ <i>R. hayi</i> U C ↓ <i>A. minimus</i>	↓ <i>L. septenarius</i> ↓ <i>S. carpatica</i> (PF) ↓ <i>J. D. asymerica</i> (PF)	↓ <i>R. anthophorus</i> L u c i a n o r h a
Upper Coniacian	↙ FO of <i>Inoceramus undulaticus</i> ↓ <i>M. decussata</i> ↓ <i>C. obscurus</i> ↓ <i>L. cayeuxii</i> C C 1 3	↓ <i>M. decussata</i> C C 1 4	↓ <i>P. grandis</i> ↓ <i>M. concava</i> 1 1 c ↓ <i>C. gallica</i> consistent ↓ <i>C. obscurus</i> ↓ <i>L. cayeuxii</i>	↓ <i>C. obscurus</i> ↓ <i>L. cayeuxii</i> ↓ <i>L. grillii</i>	b d u s m a l e f o r m i s N F Z o n e ↓ <i>L. maleformis</i>

Fig. 1. – Previous zonation schemes for the Coniacian/Santonian boundary based on calcareous nannofossils.

(Fig. 2). These sediments were deposited on a low-energy carbonate shelf and proximal basin (Haymond, 1991; Young and Woodruff, 1985). In the Waco and Dallas regions, the Austin Group is subdivided into three units: the Lower Chalk, the Middle Marl (Bruceville Marl), and the Upper Chalk. The Bruceville Marl is upper Coniacian to lower Santonian based on molluscan biostratigraphy (Young and Woodruff, 1985).

Outcrops of the Bruceville Marl along Ten Mile Creek consist predominantly of white chalk alternating with dark olive-grey chalky marl (Fig. 3). These beds range in thickness from 10 cm to 2 m with chalk intervals dominating the section. The chalk is composed of planktonic microfossils (coccolithophores, foraminifers, and calcispheres) with minor components of echinoderms, molluscs, and benthic foraminifers (Dravis, 1981).

#### 4. Materials and methods

Samples from the Locality 13 key section were collected at 10-cm intervals by Watkins and others in 2000. Samples for this study were prepared at 10-cm intervals for 5.0 m above and below Bed 13 and at 1.0-m intervals for the remaining section, yielding 146 samples (Fig. 3). Sampling was concentrated around the Coniacian/Santonian boundary, as defined by the FAD of *I. undulaticus* to examine the transition at high resolution.

Brooks Ellwood collected the Ten Mile Creek section and sampled 6.3 m of proposed GSSP section at 10-cm intervals (Fig. 3). These 64 samples were used to collect calcareous nannofossil data. The first appearance datum of *I. undulaticus* was observed 3.45 m (Paul Sikora and Richard Howe, personal communication) above the base of the section. A stratigraphic column of the sampled Ten Mile Creek proposed GSSP section is given in Fig. 3.

Smear slides were prepared using a 'double slurry' technique. Using a sterile razor blade, thin shavings were taken across a generous surface area from clean outcrop samples to ensure sampling from multiple fecal pellets. An aliquot of water was added to these shavings situated on a glass cover slip and homogenized

with a flat toothpick. This cover slip was quickly dried. Homogenization and drying was repeated to fully deflocculate the sediment. The cover slip was adhered to a glass slide using Norland Optical Adhesive (NOA-61).

Abundance counts were made on a Zeiss Photoscope III at 1250× magnification. The percent abundance of nannofossil species was estimated by counting 456 specimens for each slide, yielding accurate abundance estimates at the 95% confidence interval (Chang, 1967). Whole coccoliths and fragments greater than half the original size were subject for counting. Specimens smaller than 2 µm in size were not counted as their placement into species was not possible on a routine basis. The slide was then scanned for an additional fifteen minutes to identify rare taxa for biostratigraphic studies. Nannofossil preservation at Locality 13 and the Ten Mile Creek was analyzed using criteria discussed in Watkins et al. (1998). Data are archived at the World Data Center-A for Paleoclimatology <http://www.ncdc.noaa.gov/paleo/data.html> (Blair and Watkins, 2008).

Rock samples and smear slides are housed within the collections of the ODP Micropaleontological Reference Center at the University of Nebraska State Museum (UNSM). Holotype and paratype materials (i.e., smear slides and photographic negatives) and topotype samples are housed in the Invertebrate Paleontology Type Collection at the UNSM.

#### 5. Results

The chinks of the Smoky Hill Member yield abundant, well-preserved calcareous nannofossils. The Ten Mile Creek section also contains abundant nannofossils, though preservation varies from moderate to good. In all, 138 and 131 calcareous nannofossil taxa were identified from Smoky Hill and Ten Mile Creek sediments, respectively.

Previously recommended biomarkers for the Coniacian/Santonian boundary were analyzed for their stratigraphic distribution in relation to the first occurrence of *I. undulaticus*. Eight were

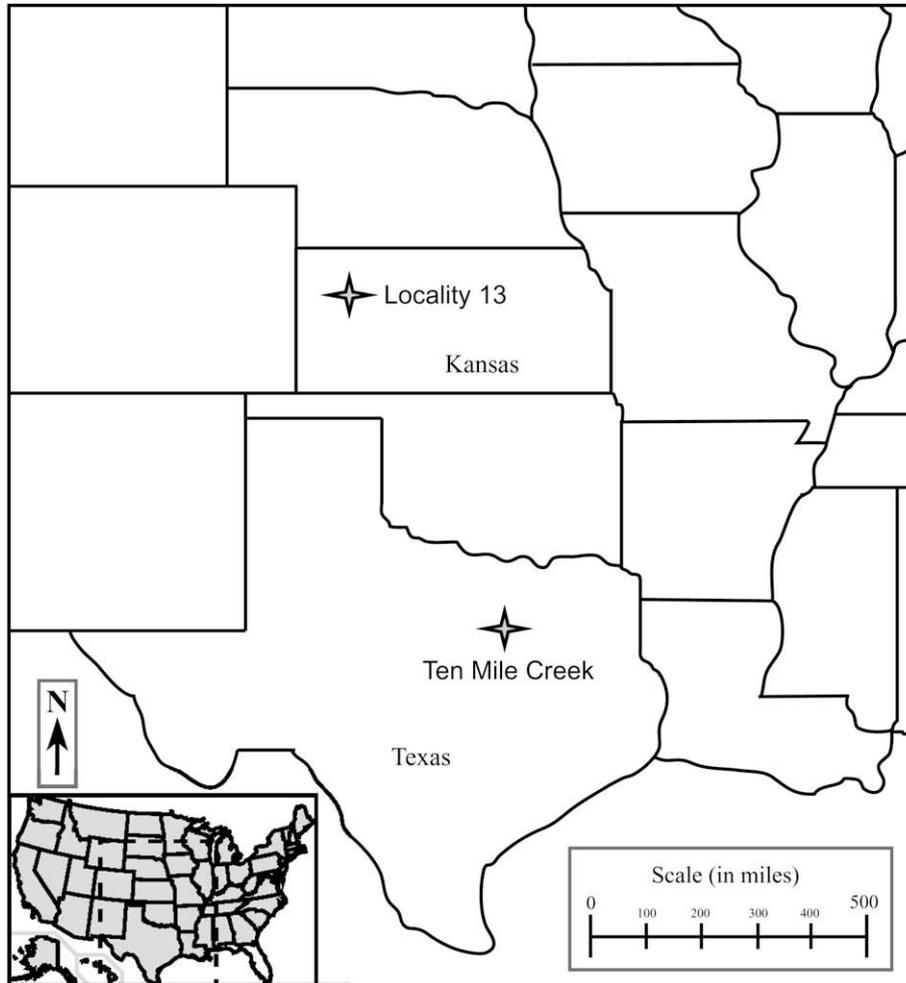


Fig. 2. – Study section area for the Coniacian/Santonian boundary interval.

immediately eliminated because their first appearance or last appearance datums predate or postdate the two study sections. *Calculites obscurus*, *Calculites ovalis*, *Micula decussata*, *Lucianorhabdus cayeuxii*, *Lucianorhabdus maleformis*, and *Lithastrinus grillii* are present at the base of these sections, at least 14.0 and 2.5 m below the FAD of *I. undulatoaplicatus* in the Kansas and Texas study sections, respectively. *Reinhardtites anthophorus* (the zonal marker for CC15) is present in the lowest samples at both the Smoky Hill and Bruceville localities, however, indicating that its first appearance is in the upper Coniacian. The last appearance of *L. septenarius*, cited as a boundary marker by Perch-Nielsen (1985), is of questionable use due to its rare occurrence in these sections. It is present throughout most of the Locality 13 section; however, is represented by only 12 specimens in the lower 20.0 m of section. At Ten Mile Creek, only two specimens were documented (at 4.95 m). *Lithastrinus septenarius* is not observed in the last 2.6 and 7.5 m of Ten Mile Creek and Locality 13 strata, respectively, but it is such a rare taxon at these localities that it is unlikely the actual last occurrence coincides with the last observed appearance.

Several other nannofossil events have been proposed as useful markers for the boundary interval, but were either absent or too rare to be useful in the study sections. *Cribracorona gallica* and *Microrhabdulus undosus*, used by Burnett (1998), were not observed in the study sections. *Amphizygus minimus*, used by Burnett (1998), Gale et al. (2007), and Howe et al. (2007), is absent in the Smoky Hill section and was questionably noted in the Ten Mile Creek section. *Rucinolithus hayi* was observed at both localities, but is too

rare to use reliably as a biohorizon (only two specimens were noted at Ten Mile Creek). The first appearance of *Micula concava* occurs in the upper 5 m of Locality 13 and at 5.35 m within the Ten Mile Creek section. It is also rare; only four specimens were observed in the Ten Mile Creek section. Finally, *Staurolithites mielnicensis* was only noted in one sample within the upper 5.0 m of Locality 13.

One bioevent from previous zonation schemes was similarly noted to occur near the Coniacian/Santonian Stage boundary in Bruceville and Smoky Hill strata: the first appearance of *Prediscosphaera* sp. cf. *P. grandis*. Previous work suggested that *P. grandis* had a late Campanian speciation (Perch-Nielsen, 1985). Burnett (1998) noted the occurrence of *P. sp. cf. P. grandis*, a smaller form, in the Santonian from the Plymouth Bluff, Mississippi (Plate 6.6, Fig. 26). This species differs markedly in size from *Prediscosphaera grandis* and is separated in this paper as a new species, *Prediscosphaera desidero grandis* (Plate 5, Figs. 3–7). *Prediscosphaera* sp. cf. *P. grandis*, as figured in Burnett, 1998, is believed to be synonymous with *P. desidero grandis* and is referred to its new species name in this investigation. The first appearance of *P. desidero grandis* is 7.0 m below the Coniacian/Santonian boundary at Locality 13 and is seen at the base of the Ten Mile Creek section. *Prediscosphaera desidero grandis* was noted in 57 of 64 slides (0.6% average abundance) and 99 of 142 slides (0.2% average abundance) at Ten Mile Creek and Locality 13, respectively. *Prediscosphaera desidero grandis* is a common taxon in both the Ten Mile Creek and Locality 13 sections. Its large size and resistance to dissolution makes it an easily recognizable and reliable biostratigraphic marker.

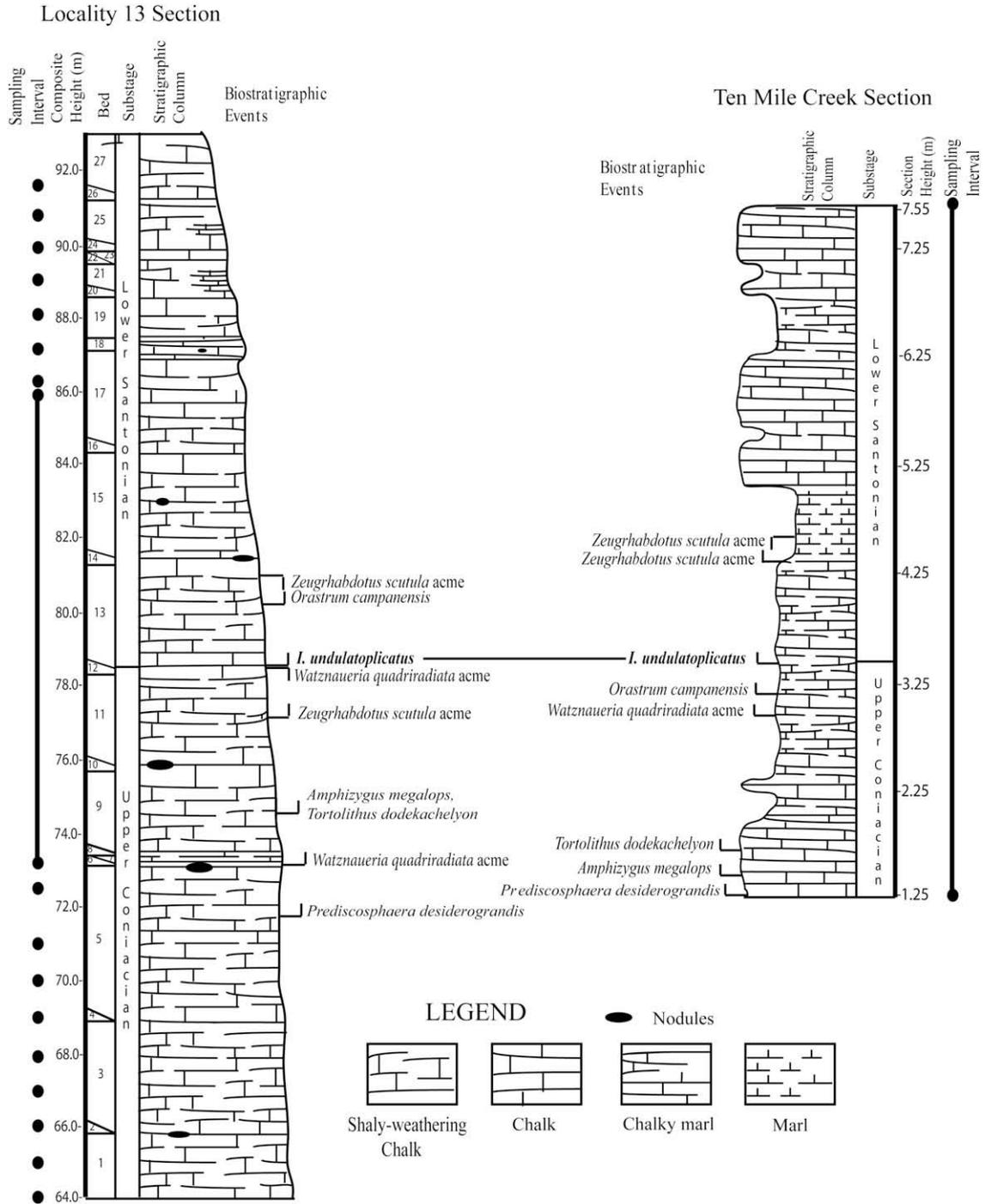


Fig. 3. – Stratigraphic columns and calcareous nannofossil events observed at Locality 13 and Ten Mile Creek sections. Sampling intervals demarcated. Solid lines represent a sampling interval of 10-cm. Note difference in scale between sections. Adapted from Hattin (1982) and Howe et al. (2007).

The first appearance of *P. desidero grandis* and five other bio-events have been recognized for their utility as biostratigraphic markers for the Coniacian/Santonian boundary transition. Fig. 4 illustrates the relative positions of proposed biomarkers from this study for the Santonian Stage boundary in the Kansas Smoky Hill Member and the Texas Bruceville Marl. A second potential nannofossil bioevent is the FAD of *Amphizygus megalops*, n. sp. (Plate 1, Figs. 13–16; Plate 2, Fig. 1). This event occurs 4.0 m below the first appearance of *I. undulatopticatus* at Locality 13 and 2.15 meters below the FAD of *I. undulatopticatus* in the Ten Mile Creek section. *Amphizygus megalops* comprises as much as 0.4% of the nannoplankton assemblage at Ten Mile Creek and up to 1.5% of the

assemblage at Locality 13. Although these abundances are low, *A. megalops* was consistently noted when examining slides for rare taxa after original abundance counts. This species has been previously identified as *Amphizygus brooksii* (Burnett, 1998; Plate 6.2, Fig. 1), but these two species appear to be constructed differently and exhibit different stratigraphic appearances (see Systematic Paleontology).

Because a boundary may not always be precisely defined by the first or last appearance of an individual taxon, it is important to use abundance data to look for acme events of an individual taxon or groups of taxa. *Watznaueria quadriradiata* (Plate 3, Fig. 16) exhibits a significant increase in abundance immediately below the

Coniacian/Santonian boundary. At Locality 13, it has an average abundance of 1.1% from 64.38 to 73.28 m. Its abundances increase to as much as 4.6% (averaging 2.65%) from 73.38 to 78.58 m (Fig. 5). In the upper 13 m, *W. quadriradiata* abundances decrease to below 1%. This acme event can be correlated to the stratigraphic level of 2.95 meters above the base of the Ten Mile Creek section (0.50 m below the FO of *I. undulatopticatus*). An acme event of *W. quadriradiata* is only seen within one sample of the Ten Mile Creek section limiting its biostratigraphic utility.

There is a degree of caution needed when utilizing *Watznaueria* acme events as biostratigraphic markers. Increased abundances of *Watznaueria barnesiae* have been related to warmer surface waters (Bukry, 1973; Wind, 1979; Watkins et al., 1996) or to poor preservation (e.g., Roth and Krumbach, 1986). If the acme event of *W. quadriradiata* was a product of preservation or warming surface waters, it would also be reflected in the abundances of *W. barnesiae*. *Watznaueria barnesiae* abundances do not exhibit any such acme trend concurrent with *W. quadriradiata*.

An acme of *Zeugrhabdotus scutula* (Plate 4, Fig. 8) occurs 0.8 m below the FAD of *I. undulatopticatus* at Locality 13 (77.58 m). *Zeugrhabdotus scutula* averages 0.85% of the total assemblage in the lower 13.1 m of Locality 13. It increases to an average of 9.2% of the nannofossil assemblage, with abundances as high as 20% from 77.58 to 81.38 m (Fig. 5). This species decreases to an average of 1.5% in the upper 10.5 meters. This acme event may be correlated to part of the Ten Mile Creek section, although the magnitude of the abundance increase is not as marked. For most of the Ten Mile Creek section, *Z. scutula* abundances average less than 2%. From 4.45 to 4.65 m, its abundances increase up to 5.7%.

Calcareous Nannofossil Bioevents		
Substage	Smoky Hill Member Locality 13	Bruceville Marl Ten Mile Creek
Lower Santonian	<i>Z. scutula</i> acme <i>O. campanensis</i>	<i>Z. scutula</i> acme <i>Z. scutula</i> acme
	<i>W. quadriradiata</i> acme <i>Z. scutula</i> acme	<i>O. campanensis</i> <i>W. quadriradiata</i> acme
Uppermost Coniacian	<i>A. megalops</i> <i>T. dodekachelyon</i>	<i>T. dodekachelyon</i>
	<i>W. quadriradiata</i> acme	<i>A. megalops</i>
	<i>P. desidero grandis</i>	<i>P. desidero grandis</i>

Fig. 4. – Calcareous nannofossil events seen at the Coniacian/Santonian boundary transition. Santonian boundary is defined by the first appearance of *Inoceramus undulatopticatus* (dashed line).

The abbreviated nature of this acme is similar to that of *W. quadriradiata* at Ten Mile Creek. The brevity of these acme events in the Ten Mile Creek section could result from two different causes. If the acmes are a product of environmental fluctuations, it may be that this environmental shift was not as pronounced in Ten Mile Creek surface waters. The Ten Mile Creek area may have also had reduced depositional rates. The stratigraphic thickness of the interval from FAD *P. desidero grandis* to LAD *Z. scutula* is ~9 meters at Locality 13, but only about 3.4 meters at Ten Mile Creek. This supports the latter alternative suggesting that the depositional rate at Ten Mile Creek was about two and a half times less than at Locality 13.

The FAD of *Orastrum campanensis* (Plate 1, Figs. 6–9) has been placed in the Campanian (Wise and Wind, 1977; Cepek, 1970), although Burnett (1998) questionably placed it in the Santonian. Its occurrence in the Coniacian and Santonian of the Niobrara Chalk and Bruceville Marl indicates a significantly lower first appearance. The lowest stratigraphic occurrence of *O. campanensis* at Locality 13 is at 80.48 m, approximately 2.1 m above the lowest *I. undulatopticatus*. Its FAD in the Bruceville Marl is approximately 30-cm below the FAD of *I. undulatopticatus*. *Orastrum campanensis* is rare with a maximum abundance of 0.44%. *Orastrum campanensis* was observed in 32 of the 62 slides after its first noted occurrence within Locality 13, and only 10 of the 45 slides from the Ten Mile Creek section.

*Tortolitus dodekachelyon*, n. sp. (Plate 4, Figs. 1–7) first occurs about 4.0 meters and 1.95 m below the lowest stratigraphic occurrence of *I. undulatopticatus* at the Kansas and Texas localities, respectively. *Tortolitus dodekachelyon*, n. sp. is rarer than *O. campanensis*; however, when seen it provides a biostratigraphic marker for the Coniacian/Santonian Stage boundary. This species' first appearance is tentatively placed 4.0 m below the *I. undulatopticatus* FAD at Locality 13 and was noted in 25 slides after its first appearance. *Tortolitus dodekachelyon* was only noted in five slides at Ten Mile Creek (FAD at 1.55 m).

## 6. Discussion

High-resolution nannofossil study from Bruceville and Smoky Hill strata suggest that bioevents used in previous schemes as Coniacian/Santonian boundary markers predate or postdate the stratigraphic datum of *I. undulatopticatus*, the macrofossil bioevent for the Coniacian/Santonian stage boundary. The FADs of *M. decussata*, *R. anthophorus*, *L. cayeuxii*, *C. obscurus*, *L. grillii*, *C. ovalis*, and *L. malleiformis* all have been suggested as Coniacian/Santonian boundary bioevents (Sissingh, 1977; Crux, 1982; Perch-Nielsen, 1979b, 1985; Burnett, 1998; Melinte and Lamolda, 2002); however, these species all occur at the base of both the Ten Mile Creek and Locality 13 sections, approximately 2.2 and 14 meters below the FO of *I. undulatopticatus*, respectively. Similarly, *L. septenarius* and *Q. gartneri*, whose LADs also have been proposed as Santonian boundary bioevents, were present throughout both Kansas and Texas localities.

Nannofossil bioevent discrepancies exist between the three proposed Coniacian/Santonian type sections. *Amphizygus minimus*, which was seen as a useful Coniacian/Santonian biohorizon by Bergen and Sikora (1999) in northwest Europe, and by Howe et al. (2007) at the Olazagutia Quarry (Spain), was absent at the Seaford Head (England) and Arbor Park sections (Dallas, TX). *Amphizygus minimus* was identified and used as a bioevent by Gale et al. (2007) at the Wal-mart outcrop near the Ten Mile Creek section; however, Howe et al. (2007) noted that within the Ten Mile Creek section itself, it is an extremely rare taxon. This study agrees with the findings of Howe et al. (2007) that, even at high-resolution intervals, *A. minimus* is just too rare a taxon to be used as a Coniacian/Santonian biomarker at both the Ten Mile Creek and Smoky Hill sections.

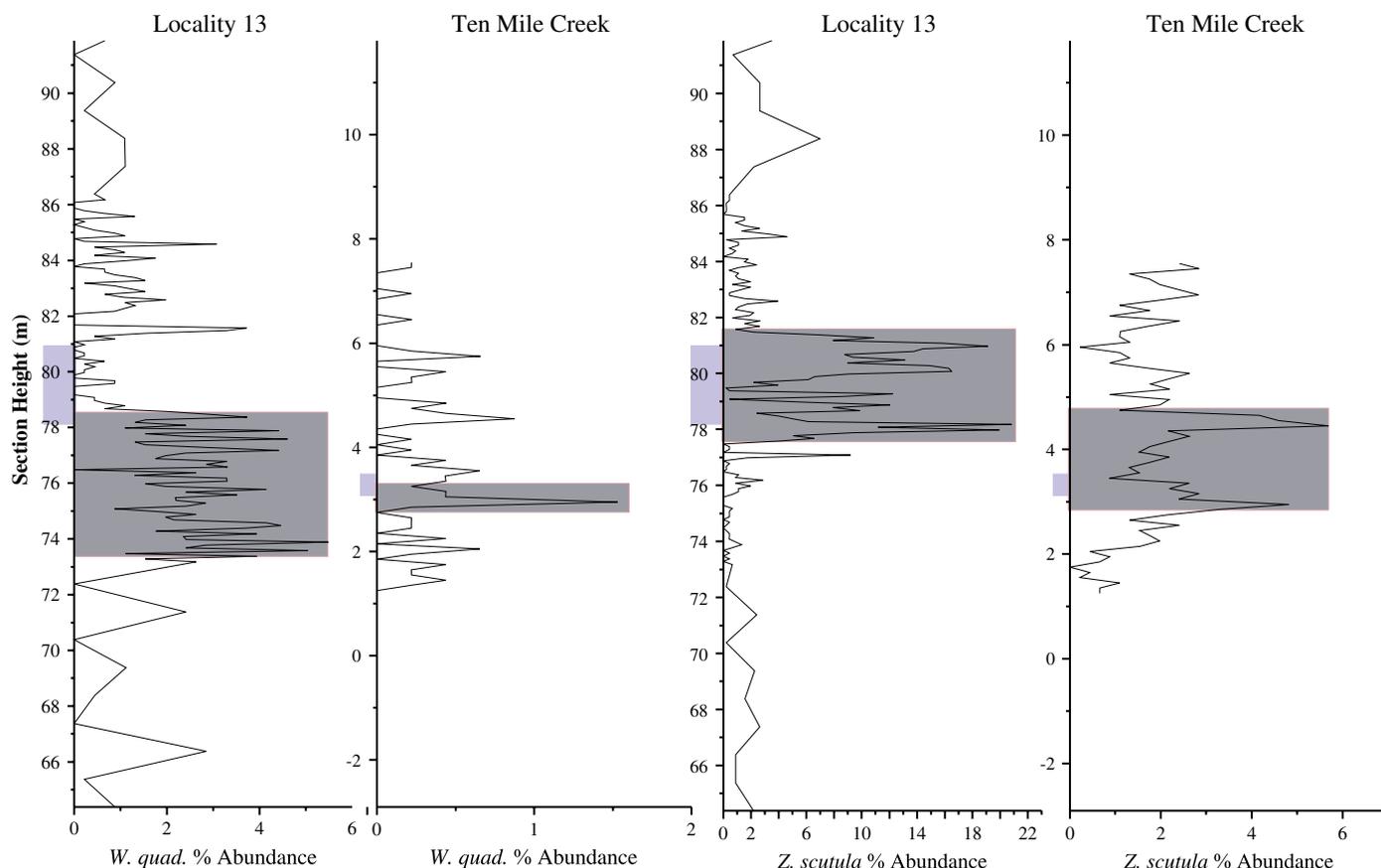


Fig. 5. % abundance of *W. quadricradiata* and *Z. scutula* at Locality 13 and Ten Mile Creek sections. Dark shaded boxes indicate FAD of *I. undulatopticatus*. Light shaded boxes indicate extent of acme events.

Bergen and Sikora (1999) noted an acme of *Helicolithus trabeculatus* near the Coniacian/Santonian boundary in northwest European sections which was similarly identified by Howe et al. (2007) at the Olazagutia Quarry. *Helicolithus trabeculatus* is also very abundant in Smoky Hill and Bruceville sediments making up as much as 8.6% and 6.8% of the total nannofossil abundance, respectively. Unlike Bergen and Sikora (1999), an LAD of this acme cannot be placed at these sections as there was no sharp decrease in *H. trabeculatus* abundance noted.

The zonation scheme from the two study sections was developed at a high resolution across the Coniacian/Santonian Stage boundary. Hattin (1982) estimated a depositional rate of 0.036 mm/yr for Smoky Hill sediments deposited in the type area. If one assumes constant sedimentation and given a sampling interval of 10-cm, it is estimated that each 10-cm increment represents approximately 3,600 years (Smoky Hill composite section). Thus, the section sampled at 10-cm intervals at key section Locality 13 (~5.0 meters above and below the FAD of *I. undulatopticatus* at Bed 13) represents approximately 468,000 years. If this is true, the Ten Mile Creek section represents approximately the same duration of time and has an estimated depositional rate of 0.013 mm/yr.

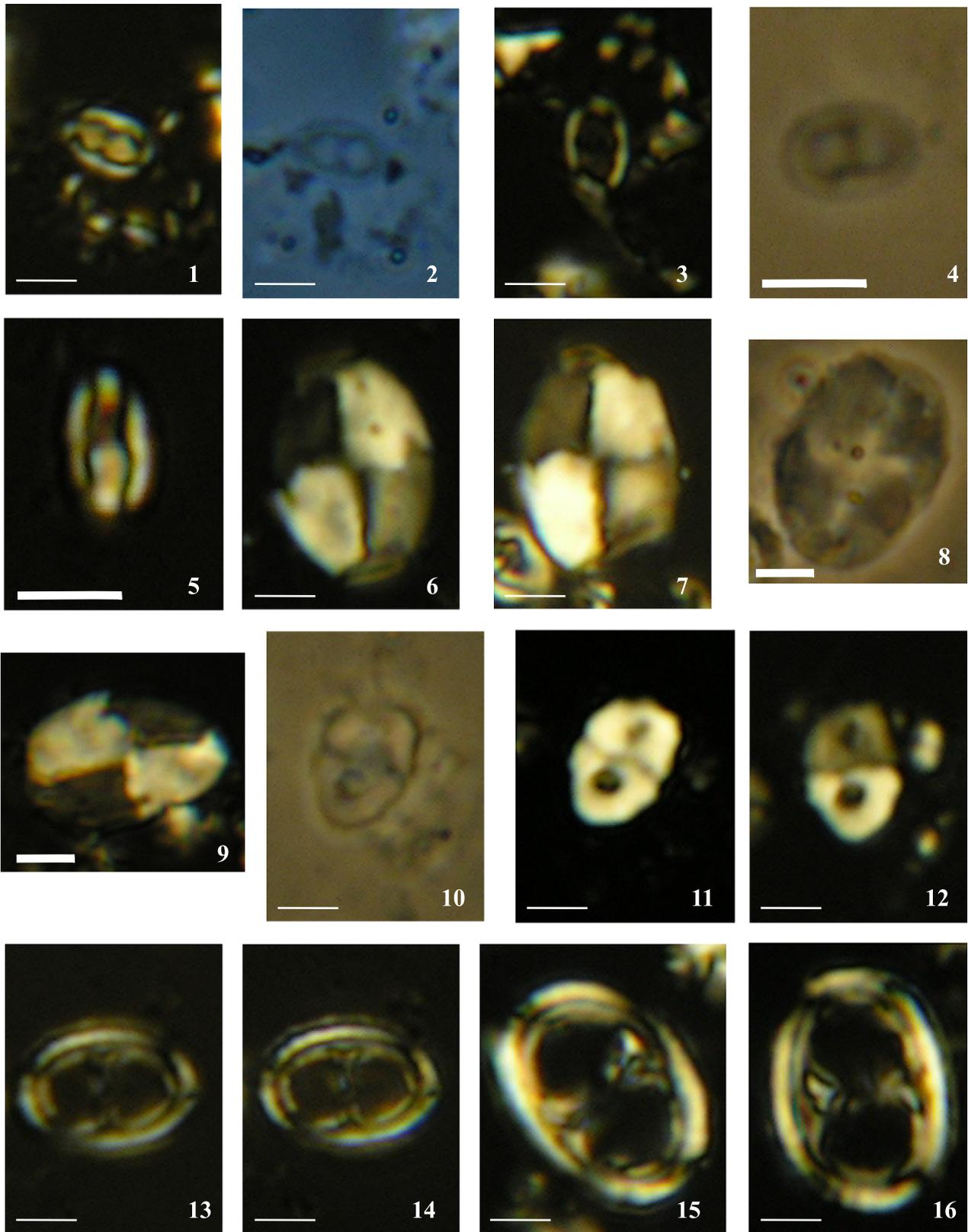
This allows us to make a rough estimation of the occurrence of nannofossil bioevents with the Santonian Stage boundary, as defined by the FAD of *I. undulatopticatus*. If the above criteria hold true then for the Smoky Hill composite section:

- (1) The FAD of *P. desidero grandis* occurs ~252 kyr before the Santonian Stage boundary
- (2) The acme event of *W. quadricradiata* lasts for ~187 kyr. It begins ~180 kyr before and ends just 7.2 kyr before the Santonian Stage boundary

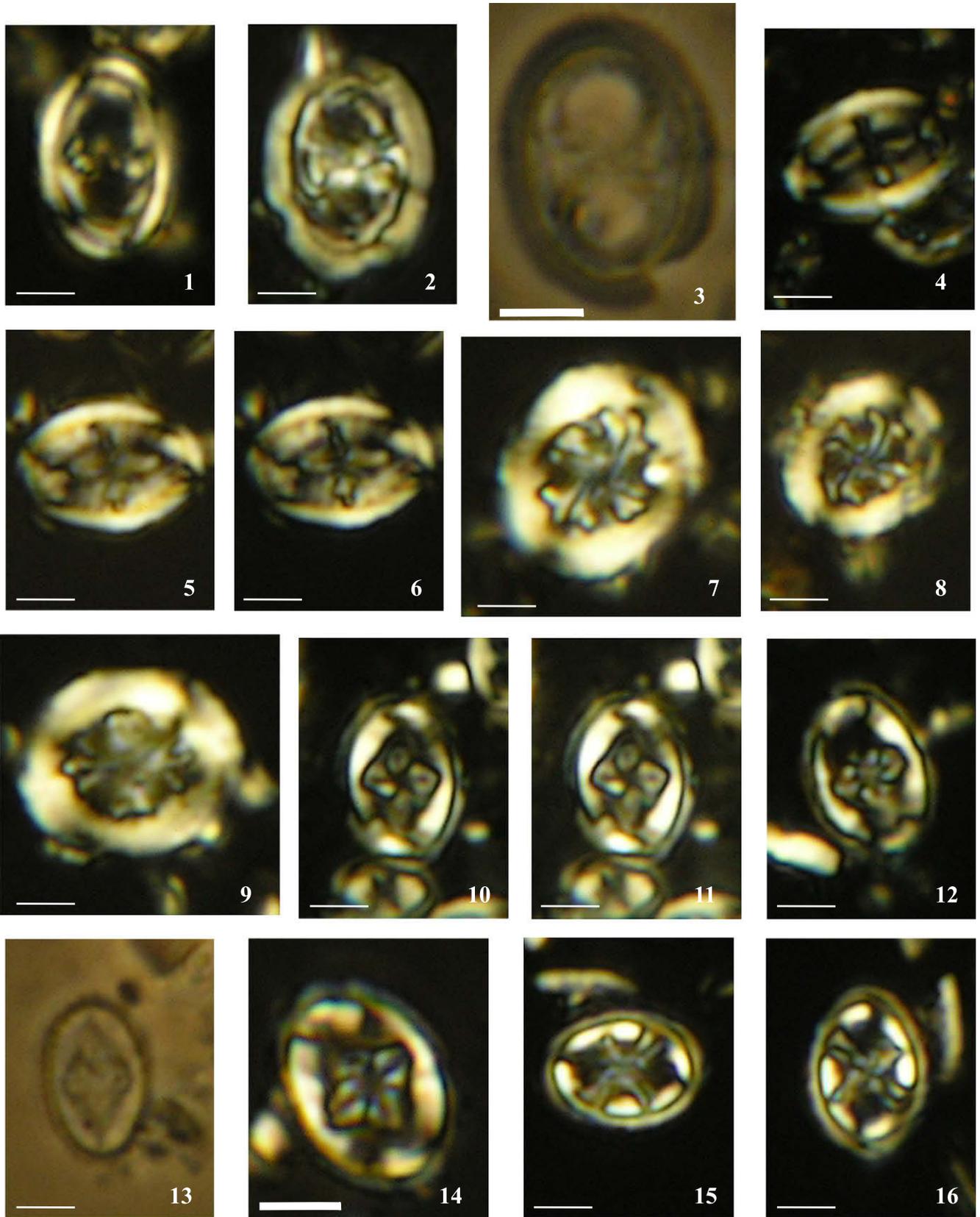
- (3 and 4) The FAD of *A. megalops* and *T. dodekachelyon* occurs ~144 kyr before the Santonian Stage boundary
- (5) The acme of *Z. scutula* lasts for ~140 kyr. It begins ~28.8 kyr before the Santonian Stage boundary and ends ~110 kyr after the Santonian Stage boundary
- (6) The FAD of *O. campanensis* occurs ~75.6 kyr after the Santonian Stage boundary.

There is an implication of diachroneity in the FAD of *O. campanensis*, which appear to be a lowermost Santonian event in one section and an uppermost Coniacian event in the other. This is probably due to uncertainty in the placement of the FAD of *I. undulatopticatus*. Hattin (1982) placed the FAD of this mollusc in a 3-m thick bed (Bed 13) at Locality 13 in the Smoky Hill type area, but did not identify its exact stratigraphic position. Similar difficulties are seen in placing the FAD of *I. undulatopticatus* at Ten Mile Creek as this section is a relatively small exposure that limits the amount of strata that can be examined at this datum level. Alternatively, direct correlation of the stage boundary is based on the assumption that the FAD of *I. undulatopticatus* is isochronous within the Western Interior Basin. Hancock (2002) noted that *I. undulatopticatus*' first appearance can occur suddenly and in great numbers, which led him to propose it could be the product of an immigration event.

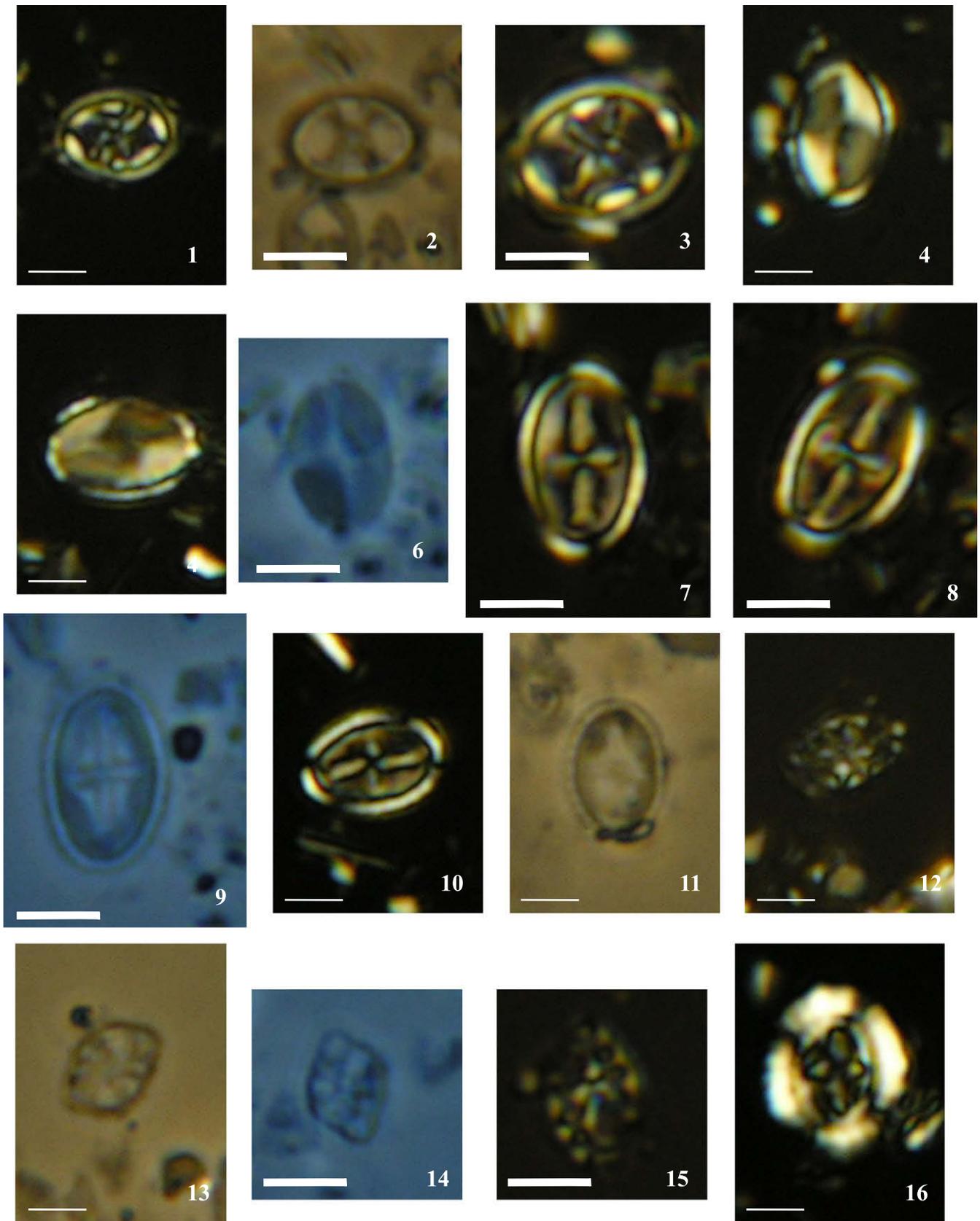
Disregarding the placement of the Santonian boundary using *I. undulatopticatus*, the sequence of nannofossil bioevents occur in consistent stratigraphic succession, which suggests that these bioevents provide a more reliable basis for recognition of the Coniacian/Santonian Stage transition within the Western Interior Seaway.



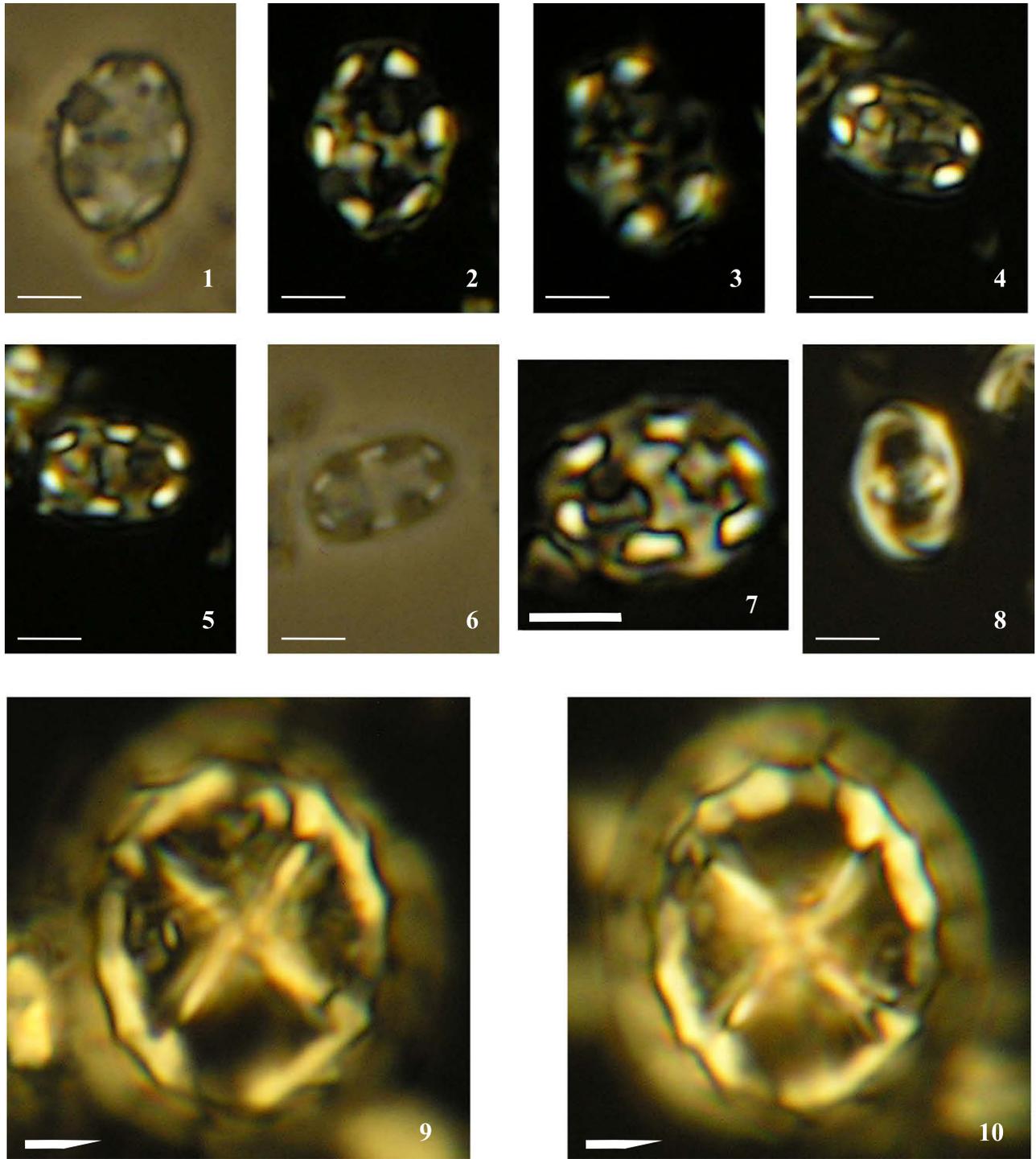
**Plate 1.** Figures 1–5 - *Bifidalithus phenax* n. sp., BLAIR and WATKINS, this study. Figures 1, 3, and 5 taken in cross-polarized light. Figure 2 and 4 taken in phase contrast light. Holotype images for *I. phenax* are Figures 1–3. Figures 6–9 - *Orastrum campanensis* (CEPEK) Wise and Wind, 1977. Figures 6–7, and 9 taken in cross-polarized light. Figure 8 taken in phase contrast light. Figures 10–12 - *Pharus evanescens*, n. sp., BLAIR and WATKINS. Figures 11–12 taken in cross-polarized light. Figure 10 taken in phase contrast light. Holotype images for *Pharus evanescens* is Figures 10–12. Figures 13–16 - *Amphizygus megalops*, n. sp., BLAIR and WATKINS. Figures 13–16 taken in cross-polarized light. Holotype image for *A. megalops* is Figure 13–14.



**Plate 2.** Figures 1 - *Amphizygus megalops*, n. sp., BLAIR and WATKINS. Figure 1 taken in cross-polarized light. Figure 2-3 - *Amphizygus brooksii* Bukry, 1969. Figure 2 taken in cross-polarized light. Figure 3 taken in phase contrast light. Figures 4-6 - *Reinhardtites clavicaviformis* Varol, 1991. Figures 4-6 taken in cross-polarized light. Figures 7-9 - *Retecapsa schizobrachiata* (GARTNER) Grun, 1975, taken in cross-polarized light. Figures 10-14 - *Helicolithus varolii* n. sp., BLAIR and WATKINS. Figures 10-12 and 14 were taken in cross-polarized light. Figure 13 were taken in phase contrast light. Holotype images for *E. crucisacrum* are Figures 10-11. Figures 15-16 - *Helicolithus tectufissus*, n. sp., BLAIR and WATKINS, taken in cross-polarized light. Holotype images for *H. stellafissus* are Figures 15 and 16.



**Plate 3.** Figures 1–3 - *Helicolithus tectufissus*, n. sp., BLAIR and WATKINS. Figures 1 and 3 taken in cross-polarized light. Figure 2 taken in phase contrast light. Figure 1 and 3 illustrate the subtle split by the second crossbar. Figures 4–6 - *Gartnerago clarusora* Varol, 1991. Figures 4–5 were taken in cross-polarized light. Figure 6 was taken in phase contrast light. Figures 7–11 - *Gartnerago margaritatus* n. sp., BLAIR and WATKINS. Figures 7, 8, and 10 were taken in cross-polarized light. Figures 9 and 11 were taken in phase contrast. Holotype images for *G. margaritatus* are Figures 7–9. Figures 12–15 - *Rhombolithion rhombicum* (STRADNER and ADAMIKER) Bukry, 1969. Figures 12 and 15 were taken in cross-polarized light. Figures 13 and 14 were taken in phase contrast light. Figure 16 - *Watznaueria quadriradiata* Bukry, 1969, in cross-polarized light.



**Plate 4.** Figures 1–7 – *Tortololithus dodekachelyon* n. sp., BLAIR, this study. Figures 2–5 and 7 were taken in cross-polarized light. Figures 1 and 6 was taken in phase contrast light. Holotype images for *T. dodekachelyon* are Figures 1–3. Figure 8 – *Zeugrhabdotus scutula* (BERGEN, 1994) RUTLEDGE & BOWN, 1996, in cross-polarized light. Figures 9–10 – *Prediscosphaera grandis* (Perch-Nielsen, 1979a) in cross-polarized light.

**7. Systematic paleontology**

Eight new species are described from the Coniacian and Santonian of the Western Interior Basin. Documentation of several rare taxa, primarily from the Smoky Hill Member, is also discussed in this section. In addition, this section notes several species' first appearance datums in upper Coniacian or lower Santonian sediments extending their biostratigraphic ranges from those recorded in previous literature.

Family Calyptosphaeraceae Bordreaux & Hay, 1969

Genus *Bifidalithus* Varol, 1991

*Bifidalithus phenax* Blair and Watkins, new species  
 Plate 1, Figs. 1–5

*Description.* This holococcolith has a narrow, high wall and a central area composed of two semicircular blocks separated by a transverse suture. It lacks a central stem. The wall averages ~0.25 µm in width.

*Holotype*. Plate 1, Figs. 1–3

*Holotype size*. length: 2.7  $\mu\text{m}$ ; width: 2.0  $\mu\text{m}$

*Holotype material*. Chalk from Locality 13 of the Smoky Hill Member type area (northwestern Kansas)

*Etymology*. phenax-, Greek for imposter, cheat

*Occurrence*. *Bifidalithus phenax* is more abundant in the upper 12 meters of the Smoky Hill Member, comprising up to 1.3% of the nannofossil assemblage. This species composes as much as 0.9% in Ten Mile Creek sediments.

*Discussion*. *Bifidalithus phenax* averages 3.52  $\mu\text{m}$  in length and 2.24  $\mu\text{m}$  in width (Table 1). *Bifidalithus phenax* also differs from *I. compactus* because it lacks a central spine. *Bifidalithus phenax* differs from *Isocrystallithus compactus* and *Bifidalithus geminicatillus* by its small size (distal view measurements generally between 2.5–4  $\mu\text{m}$  in length and 1.8–2.4  $\mu\text{m}$  in width). *Isocrystallithus compactus* varies between 6.0–10.0  $\mu\text{m}$  in length and 3.5–6.5  $\mu\text{m}$  in width and *B. geminicatillus* holotype dimensions measure 6.2  $\mu\text{m}$  in length and 3.7  $\mu\text{m}$  in width. This small form occurs in the uppermost Coniacian and lower Santonian of the Ten Mile Creek and Smoky Hill type area sections. *Bifidalithus phenax* is mostly likely a cavate form. Thus far, this species has been documented only from the distal view. Its name was given because of its resemblance to *I. compactus*.

#### Family Calyptosphaeraceae Boudreaux & Hay, 1969

Genus *Orastrum* Wise & Wind, 1977

*Orastrum campanensis* (Cepek) Wind & Wise in Wise & Wind, 1977

*Tetralithus campanensis* Cepek, 1970, p. 246–247, p. 25, fig. 1,2

*Orastrum campanensis* (Cepek, 1970) Wind & Wise in Wise & Wind, 1977, not illustrated

*Occurrence*. *Orastrum campanensis* is a rare taxon in the study sections. Its FAD is 2.1 m above (Locality 13) and 30-cm below (Ten Mile Creek section) the Santonian boundary as defined by the FAD of *I. undulatopticatus*. *Orastrum campanensis* was observed in 32 of the 63 slides above its FAD at Locality 13. This species is most abundant in slides 30-cm below to 2.0 m above the Santonian boundary at Ten Mile Creek. Previous studies of this species suggested a Campanian origination (Wise and Wind, 1977; Cepek, 1970). Perch-Nielsen (1985) placed it exclusively in the Campanian, while Burnett (1998) questionably extended its range into the Santonian. This study provides evidence to extend its range to at least the lower Santonian.

*Remarks*. Cepek (1970) illustrated *Tetralithus campanensis* from TEM. It was transferred into the genus *Orastrum* by Wise and Wind (1977), but lacked accompanying light microscope images. This study provides light microscope images of *O. campanensis* in cross-polarized and phase contrast light (Plate 1, Figs. 6–9).

Sediments from upper Coniacian/lower Santonian Smoky Hill Member type area have yielded numerous well-preserved specimens of *Orastrum campanensis*. In light microscope, *O. campanensis*

**Table 1**

Biometric measurements of *Bifidalithus phenax* taken from Locality 13 (Smoky Hill Member, Niobrara Formation)

Length ( $\mu\text{m}$ )	Width ( $\mu\text{m}$ )	Axial Ratio
3.60	2.40	1.50
4.00	2.24	1.79
3.60	1.84	1.96
3.44	2.40	1.43
3.44	2.40	1.43
3.20	1.84	1.74
3.60	2.40	1.50
3.44	2.24	1.54
4.00	2.40	1.67
2.70	2.00	1.60

is optically separated into four large, similar blocks divided by sinuous sutures and two small blocks that cap the axial ends of the central area (Plate 1, Figs. 6–7, 9). *Orastrum campanensis* is only weakly birefringent with respect to the cross-polarizers, but shows its greatest birefringence when oriented north to south. The outer rim is inconspicuous in cross-polarized light.

Wise and Wind (1977) distinguish *O. campanensis* from *O. asarotum* by its construction symmetry, but is also easily separated from most *Orastrum* species by its large size (averages 11.3  $\mu\text{m}$  in length and 8.4  $\mu\text{m}$  in width; averages taken from 10 specimens). *Orastrum campanensis* differs from *Orastrum porosuturalis* by its lack of suture pores.

#### Family Calyptosphaeraceae Boudreaux & Hay, 1969

Genus *Pharus* Wind & Wise in Wise & Wind, 1977

*Pharus evanescens* Blair and Watkins, new species

Plate 1, Figs. 10–12

*Description*. This elliptical coccolith is composed of two, nearly symmetrical calcite blocks separated by a distinct, sinuous suture. Each block contains a small, central circular opening ( $\sim 1$   $\mu\text{m}$  in width). There is no central spine. These two blocks exhibit different optical properties in cross-polarized light. When the major axis is oriented north to south, one calcite block appears dull or extinct, while the second exhibits pronounced birefringence.

*Etymology*. *evanescens* – Latin for disappearing

*Holotype*. Plate 1, Figs. 10–12

*Holotype size*. 4.4  $\mu\text{m}$  in length; 3.2  $\mu\text{m}$  in width

*Holotype material*. Chalk from Locality 13 of the Smoky Hill Member type area (northwestern Kansas)

*Occurrence*. Six specimens were observed from Locality 13

*Remarks*. *Pharus evanescens* differs from *Pharus simulacrum* because it lacks a central spine and does not have calcite blocks that act optically similar. Wise and Wind (1977) assign a Campanian age for *P. simulacrum*. This species was not observed in Coniacian and Santonian sediments at Locality 13 and Ten Mile Creek sections. *Pharus evanescens* is seen in the lower Santonian at Locality 13 and is an extremely rare taxon.

#### Family Chiastozygaceae Rood, Hay, & Barnard, 1971

Genus *Amphizygus* Bukry, 1969

*Amphizygus megalops* Blair and Watkins, new species

Plate 1, Figs. 13–16; Plate 2, Fig. 1

*Amphizygus brooksii* Burnett, 1998, Plate 6.2, Fig. 1

*Description*. This elliptical coccolith is characterized by a bicyclic rim, a transverse bar, and two symmetrical circular openings that occupy the central area. The proximal rim cycle is very narrow ( $< 1$   $\mu\text{m}$ ) and shows pronounced birefringence in cross-polarized light. The distal cycle is thin and relatively inconspicuous in the light microscope. Two large circular openings occupy the central area and are separated by a transverse bar. The circular openings are lined with a ring of elements that is largely inconspicuous in light microscope. The transverse bar is slender and is composed of four elements that meet at a central knob or short spine.

*Holotype*. Plate 1, Fig. 13–14

*Holotype size*. 6.64  $\mu\text{m}$  in length, 4.0  $\mu\text{m}$  in width, circular opening width: 1.20  $\mu\text{m}$

*Holotype material*. Chalk from Locality 13 of the Smoky Hill Member type area (northwestern Kansas)

*Etymology*. *megalo*-Greek for larger; *ops*-Greek for eye

*Occurrence*. This species of *Amphizygus* first appears 4.0 m below the FAD of *I. undulatopticatus* and comprises as much as 1.5% of the assemblage at Locality 13. It is first seen 2.15 m below the FAD of *I.*

*undulatoplicatus* at the Ten Mile Creek and can make up as much as 0.4% of the assemblage.

**Remarks.** The central knob is highly susceptible to dissolution as even well-preserved Smoky Hill specimens commonly lack the knob. It averages in size 7.12  $\mu\text{m}$  in length and 4.96  $\mu\text{m}$  in width (Table 2).

*Amphizygus megalops* has been previously placed in synonymy with *Amphizygus brooksii* (see Plate 6.2, Fig. 1 in Burnett, 1998). *Amphizygus brooksii* (Plate 2, Figs. 2–3) is defined by having a bicyclic rim, two circular openings, and a ring of elements that surrounds these openings. The bicyclic rim appears dull in cross-polarized light and is relatively thick. The transverse bar is composed of four bundles of rods that meet at a central spine. *Amphizygus megalops* (Plate 1, Figs. 13–16; Plate 2, Fig. 1) also has a bicyclic rim; however, the two cycles of elements are very thin. In cross-polarized light, the distal cycle of elements remains dull while the proximal rim exhibits pronounced birefringence. The central area has a transverse bar and spine, however, does not appear to be made up of rod bundles. *Amphizygus brooksii* has an Albian through Maastrichtian range (Burnett, 1998). Bisotriographically, separation of *Amphizygus megalops* from *Amphizygus brooksii* is important as its first appearance is seen near the Coniacian/Santonian boundary.

*Amphizygus megalops* can be differentiated from other *Amphizygus* species (such as *A. brooksii nanus* and *A. minimus*) by the size of the circular openings. Circular openings measure between 1.0 to 2.4  $\mu\text{m}$  in size and average 42% of the total coccolith length. Circular openings in *A. brooksii nanus* compose 9 to 19% of the total central area width. In *A. minimus* they compose 8 to 17% of the total central area width (Bukry, 1969). Table 2 near here

#### Family Chiastozygaceae Rood, Hay, & Barnard, 1973

##### Genus *Reinhardtites* Perch-Nielsen, 1968

*Reinhardtites clavicaiformis* Varol, 1991

*Reinhardtites clavicaiformis* Varol, 1991, p. 237, fig. 8, pic. 1–5

**Occurrence.** Varol (1991) noted that this species is widely distributed in the North Sea area but occurs in low abundances. This species occurs rarely in Ten Mile Creek assemblages, being observed in only 12 of the 63 slides. It is also a rare taxon in the Smoky Hill section, but occurs more frequently in the upper 8.5 meters (noted in 21 of the 36 slides). *Reinhardtites clavicaiformis*

**Table 2**

Biometric measurements of *Amphizygus megalops* taken from Locality 13 (Smoky Hill Member type area, Niobrara Formation)

Length ( $\mu\text{m}$ )	Width ( $\mu\text{m}$ )	Axial Ratio	Circular Open. Width ( $\mu\text{m}$ )
6.00	4.80	1.25	1.20
8.00	5.20	1.54	–
6.40	4.80	1.33	1.20
7.60	5.20	1.46	1.20/1.60
7.20	4.80	1.50	1.44
5.60	3.60	1.56	1.04
6.80	4.80	1.42	1.20
7.84	6.00	1.31	2.00
7.20	4.80	1.50	1.84
8.24	6.00	1.37	2.40
7.84	6.00	1.31	2.00
7.60	5.44	1.40	0.8/1.44
7.04	5.04	1.40	1.84
7.20	5.04	1.43	2.00
7.04	4.40	1.60	1.60
6.40	4.40	1.45	0.80
6.80	4.80	1.42	1.84
6.40	4.80	1.33	1.44
7.04	4.80	1.47	1.44
7.84	5.04	1.56	1.60

has been designated a Campanian age (Varol, 1991; Burnett, 1998). Evidence from the study sections indicates that it occurs throughout the upper Coniacian and lower Santonian Smoky Hill Chalk section, extending its range.

**Remarks.** Campanian specimens of *R. clavicaiformis* have a delicate axial cross composed of a transverse bar and a keyhole-shaped axial bar (Varol, 1991). Santonian specimens from the Smoky Hill Member and Bruceville Marl exhibit a more robust and wider keyhole-shaped axial bar as opposed to the slender structure seen in the type material original LM images. Varol's (1991) images also show a transverse bar that does not extend to the edges of the central plate area. Santonian specimens (Plate 2, Figs. 4–6) contain a transverse bar that spans the entire width of the central plate.

Varol (1991) noted that *R. clavicaiformis* is an overall non-birefringent form, but exhibits some birefringence within the central plate and axial cross with increasing calcification. In well-preserved specimens from Locality 13, the entire coccolith remains dull except for outer rim elements which exhibit weak birefringence. Lastly, recognition of *R. clavicaiformis* becomes extremely difficult when slightly overgrown or etched.

#### Family Retecapidae Thierstein, 1973

##### Genus *Retecapsa* Black, 1971a

*Retecapsa schizobrachiata* (Gartner) Grun, 1975

*Vekshinella schizobrachiata* Gartner, 1968, p. 31, Plate 13, Figs. 10–11.

*Retecapsa schizobrachiata* (Gartner, 1968) Grun in Grun & Allemann, 1975

**Occurrence.** *R. schizobrachiata* is a rare taxon in the study material always occurring as less than 1% of the nannofossil assemblage.

**Discussion.** *Retecapsa schizobrachiata* has been placed in the Campanian and Maastrichtian ages (Burnett, 1998). Evidence from the Smoky Hill Member (Plate 2, Figs. 7–9) indicates a lower Santonian origination. These specimens are an early form of *Retecapsa schizobrachiata*. Gartner (1968) noted that the axial crossbars of *R. schizobrachiata* have three arms that attach at the bar end in Campanian examples. *Retecapsa schizobrachiata* in Smoky Hill and Bruceville sediments are less ornate. upper Coniacian/lower Santonian specimens appear transitional; some axial crossbars have only two arms while others have three. These arms are typically shorter than Campanian and Maastrichtian examples. Overall size of *R. schizobrachiata* in Smoky Hill and Bruceville sediments average 7.6  $\mu\text{m}$  in length and 5.92  $\mu\text{m}$  in width (averages taken from 10 specimens). Measured specimens of Maastrichtian age from ODP Leg 144 average 9.68  $\mu\text{m}$  in length and 6.34  $\mu\text{m}$  in width (averages taken from 10 specimens).

#### Family Eifellithaceae Reinhardt, 1965

##### Genus *Helicolithus*, Noel, 1970

*Helicolithus varolii* Blair and Watkins, new species

Plate 2, Figs. 10–14

**Description.** This ellipsoidal coccolith has a bicyclic rim and an axial cross. The proximal rim cycle exhibits pronounced birefringence in LM while the distal cycle remains dull. The central area is demarcated with an axial cross composed of four overlapping elements. The axial cross does not reach to the ends of the central area. These elements are triangular and contain a medial suture. The medial suture does not span the entire length of the crossbar.

**Holotype.** Plate 2, Figs. 10–13

**Holotype size.** length: 6.4  $\mu\text{m}$ ; width: 4.3  $\mu\text{m}$

**Holotype material.** Chalk from Locality 13 of the Smoky Hill Member type area (northwestern Kansas)

**Etymology.** *Helicolithus varolii* is named in recognition of Osman Varol for his work with the genus *Helicolithus*

**Remarks.** *Helicolithus varolii* averages in size 6.24  $\mu\text{m}$  in length and 4.64  $\mu\text{m}$  in width (Table 3). It differs from most *Helicolithus* species by having an axial cross instead of a diagonal cross. *Helicolithus turonicus* contains a near-axial cross that is offset from both the major and minor axes. It superficially resembles *Eiffellithus eximius*, but differs in having triangle-shaped crossbar elements and a suture that does not span the entire crossbar length. This species is first noted at the base of Locality 13, but was observed only in 24 of the 147 samples after its FAD. Only six specimens of this species were observed from the Ten Mile Creek section.

*Helicolithus tectufissus* Blair and Watkins, new species

Plate 2, Figs. 15–16; Plate 3, Figs. 1–3

**Description.** This ellipsoidal coccolith has a bicyclic rim and a thin, diagonal cross. The proximal rim cycle exhibits pronounced birefringence in LM while the distal cycle remains dull. The narrow central area contains a delicate diagonal cross that overlaps the proximal rim and is composed of eight elements. The central area lacks a back plate. Each diagonal arm is composed of two calcite elements. When the major axis aligned north to south in cross-polarized light, visible sutures divide the dextral crossbar. The sinistral crossbar of the diagonal cross will also exhibit a divisional suture when the major axis is 10–30° away from the north-south orientation. This second sutural split is much more subtle. There is no central spine.

**Holotype.** Plate 2, Figs. 15–16

**Holotype size.** length: 5.6  $\mu\text{m}$ ; width: 4.24  $\mu\text{m}$

**Holotype material.** Chalk from Locality 13 of the Smoky Hill Member type area (northwestern Kansas)

**Etymology.** tectus-, Latin for concealed, secret; fissus-, Latin for split

**Occurrence.** *Helicolithus tectufissus* comprise up to 5.6% of the assemblage with an average abundance of 1.3% at Locality 13. From the Ten Mile Creek section, *H. tectufissus* composes up to 2.2% of the assemblage with an average of 1.0%.

**Remarks.** *Helicolithus tectufissus* averages 5.44  $\mu\text{m}$  in length and 4.08  $\mu\text{m}$  in width (Table 4). It can be separated from all *Helicolithid* and *Eiffellithid* species by the unique sutural division of the sinistral crossbar of the diagonal cross. This species differs from *H. trabeculatus* and *H. compactus* by its delicate diagonal cross and the absence of a back plate. *Helicolithus anceps* also contains a central spine making it easily distinguishable from *H. stellafissus*. *Helicolithus tectufissus* is a rare to common taxon within the Smoky Hill type area and Ten Mile Creek section and is seen consistently throughout both of these sections.

Family Kamptneriaceae Bown & Hampton in Bown & Young, 1997

Genus *Gartnerago* Bukry, 1969

*Gartnerago clarusora* Varol, 1991

**Table 3**

Biometric measurements of *Helicolithus varolii* taken from Locality 13 (Smoky Hill Member, Niobrara Formation)

Length ( $\mu\text{m}$ )	Width ( $\mu\text{m}$ )	Axial Ratio
6.40	4.80	1.33
6.00	4.00	1.50
5.84	4.40	1.33
6.40	4.80	1.33
6.64	4.64	1.43
6.80	4.80	1.42
6.64	5.44	1.22
6.64	5.44	1.22
4.80	4.24	1.13
6.24	4.24	1.47
6.80	4.80	1.42

**Table 4**

Biometric measurements of *Helicolithus tectufissus* taken from specimens in Locality 13 (Smoky Hill Member, Niobrara Formation)

Length ( $\mu\text{m}$ )	Width ( $\mu\text{m}$ )	Axial Ratio
5.20	4.00	1.30
4.80	4.00	1.20
6.00	4.40	1.36
6.00	4.40	1.36
6.40	5.20	1.23
5.60	4.40	1.27
5.20	4.00	1.30
6.40	4.80	1.33
4.80	3.20	1.50
5.20	4.00	1.30
4.40	3.20	1.38
5.60	4.24	1.32
5.44	3.60	1.51
4.80	3.04	1.58
5.44	4.40	1.24
5.60	4.24	1.32
5.04	4.00	1.26
4.80	3.60	1.33
6.80	5.04	1.35
5.60	4.00	1.40

*Gartnerago clarusora* Varol, 1991, Fig. 6 (13–16)

**Occurrence.** Varol (1991) documented *Gartnerago clarusora* from the Turonian–Santonian of Ecuador and Peru, but it has not been noted since then. Within the Smoky Hill Chalk Member and Bruceville Marl this species occurs in very low abundances.

**Remarks.** The median cycle of rim elements in *G. clarusora* is composed of 40–50 crown elements, similar to what is seen in *Gartnerago margaritatus*, n. sp., this study. Light microscope images from well-preserved specimens of *G. clarusora* are presented in Plate 3, Figs. 4–6. Varol (1991) describes *G. clarusora* as having four equal size plates within the central area separated by axial sutures. This species has non-birefringent shields and strongly birefringent crown elements. This description and original LM images are similar to specimens seen in the Coniacan and Santonian study sections.

*Gartnerago margaritatus* Blair and Watkins, new species

Plate 3, Figs. 7–11

**Description.** This ellipsoidal coccolith has a thin, three-tiered rim structure and a delicate, axial cross. The proximal rim is extremely thin (<0.3  $\mu\text{m}$ ) and is very dark in LM. The median cycle is very bright and is composed of a series of individual calcite elements that resemble glass beads or pearls in cross-polarized and phase contrast light. This median rim cycle contains between 32 and 40 crown elements. The thin distal rim is inconspicuous in LM.

The central plate contains a thin axial cross that extends to the proximal rim. This axial cross is demarcated by a series of near axial sutures. The crossbars are slightly offset from the major and minor axes and are composed of 2 thin (<1  $\mu\text{m}$  in width) bar elements.

**Holotype.** Plate 3, Figs. 7–9

**Holotype size.** Length: 5.5  $\mu\text{m}$ ; Width: 4.0  $\mu\text{m}$

**Holotype material.** Chalk from Locality 13 of the Smoky Hill Member type area (northwestern Kansas)

**Etymology.** margaritatus-, Latin for adorned with pearl

**Remarks.** *Gartnerago margaritatus* averages 4.0  $\mu\text{m}$  in width and 5.64  $\mu\text{m}$  in length (Table 5). This species can be easily separated from most *Gartnerago* species by its small size, distinct “beaded” median rim cycle, and thin axial cross structure. *Gartnerago clarusora*, also exhibits a similar size and a beaded median rim cycle, however, lacks a central cross structure. The crowned rim composed of bead-like elements is seen most clearly in phase contrast light (Plate 3, Figs. 9, 11).

*Gartnerago margaritatus* is rare in the lower part of Locality 13, but is noted in the 14 of the 29 slides in the upper 10 m. This species

is first observed in the lower two meters of Locality 13 and continues to top of the sampled section. Only a few specimens were recognized from the Bruceville Marl.

Family Prediscosphaeraceae Rood, Hay & Barnard, 1971

Genus *Prediscosphaera* Vekshina, 1959

*Prediscosphaera desidero-grandis* Blair and Watkins, new species

*Prediscosphaera* cf. *P. grandis* Burnett, 1998, p. 178–179, Plate 6.6, fig. 26

**Description.** This placolith is ellipsoidal in form, has a diagonal cross supporting a robust stem, and two outer shields. The distal shield is composed of 16 non-imbricated elements and appears dark in cross-polarized light. The inner shield is very bright in LM and is approximately half the width of the distal shield in diameter. Visible sutures divide the dextral and sinistral cross-bars on the diagonal cross. *Prediscosphaera desidero-grandis* averages 9.8  $\mu\text{m}$  in length and 8.8  $\mu\text{m}$  in width.

**Material examined.** Chalk from Locality 13 (Smoky Hill Chalk Member, Kansas) and the Ten Mile Creek section (Bruceville Marl, Texas)

**Etymology.** *desidero-*, Latin for desire, long for; *grandis-*, Latin for large, great

**Holotype.** Plate 5, Figs. 3–4

**Holotype size.** Length: 10.0  $\mu\text{m}$ ; Width: 8.6  $\mu\text{m}$

**Holotype material.** Chalk from Locality 13 composite section of the Smoky Hill Member (northwestern Kansas)

**Occurrence.** *Prediscosphaera desidero-grandis* ranges in abundance between 0.2 to 1.3% of the nannofossil assemblage at Locality 13 (Plate 5, Figs. 3–7). This species was also observed in 57 of the 64 Ten Mile Creek slides and 99 of the 142 Locality 13 slides. Its FAD is approximately 7.0 and 2.25 m below the Santonian boundary in the Locality 13 and Ten Mile Creek sections, respectively.

**Remarks.** *Prediscosphaera desidero-grandis* averages 8.8  $\mu\text{m}$  in width and 9.8  $\mu\text{m}$  in length (Table 6). Some specimens reach well over 10  $\mu\text{m}$  in length, similar to the measurement range of *P. grandis* (10–15  $\mu\text{m}$  in length) documented by Perch-Nielsen (1979a). Perch-Nielsen (1985) designated an upper Campanian to Maastrichtian range for *Prediscosphaera grandis*. Burnett (1998) noted the occurrence of *P. sp. cf. P. grandis*, a smaller form, in Santonian sediments from Plymouth Bluff, Mississippi.

Size measurements were taken from 30 specimens of *Prediscosphaera grandis* in Maastrichtian sediments from ODP Leg 144 (Plate 4, Figs. 9–10; Plate 5, Figs. 1–2). Average length and width of these specimens was 15.6  $\mu\text{m}$  and 12.8  $\mu\text{m}$ , respectively. Similar measurements were taken for 30 specimens from the Santonian-age Locality 13 section. These averaged 9.8  $\mu\text{m}$  in length and 8.8  $\mu\text{m}$  in width. This marked separation in size supports the division of *P. desidero-grandis* from *P. grandis* on size-based criterion.

**Table 5**

Biometric measurements of *Gartnerago margaritatus* taken from Locality 13 (Smoky Hill Member, Niobrara Formation)

Length ( $\mu\text{m}$ )	Width ( $\mu\text{m}$ )	Axial Ratio
5.60	3.84	1.46
5.04	3.60	1.40
5.84	3.60	1.62
5.20	3.84	1.35
6.24	4.80	1.30
6.00	4.40	1.36
5.84	3.60	1.62
6.64	4.00	1.66
7.04	4.24	1.66
5.84	4.00	1.46
5.60	3.84	1.46
5.60	4.00	1.40

**Table 6**

Biometric measurements of *Prediscosphaera desidero-grandis* taken from Locality 13 (Smoky Hill Member, Niobrara Formation)

Length ( $\mu\text{m}$ )	Width ( $\mu\text{m}$ )	Axial Ratio
9.80	8.60	1.14
10.0	8.40	1.19
9.80	8.20	1.20
9.80	9.20	1.07
9.40	9.20	1.02
10.4	8.80	1.18
9.20	8.40	1.10
10.0	8.60	1.16
9.40	8.40	1.12
9.00	7.80	1.15
9.40	9.20	1.02
9.60	9.20	1.04
9.80	8.20	1.20
10.2	9.40	1.09
10.2	8.40	1.21
9.60	8.80	1.09
9.40	9.20	1.02
10.4	9.00	1.16
10.4	9.60	1.08
8.60	8.20	1.05
9.20	8.80	1.05
10.6	8.80	1.20
10.4	9.40	1.11
9.20	8.40	1.10
10.6	9.80	1.08
9.80	8.60	1.14
9.60	8.40	1.14
9.80	9.00	1.09
9.60	8.40	1.14
10.8	10.4	1.04

A more detailed biometric analysis should be performed between *P. grandis*, *P. desidero-grandis*, as well as *P. cretacea* (this species also appears to increase in size from sediments observed here in the Santonian and Maastrichtian) to delineate more exact size parameters. The Santonian form, *P. desidero-grandis*, is noted to range between 9–11  $\mu\text{m}$  in length (based on measurements from the Smoky Hill Chalk Member). The Maastrichtian form (from specimens studied here) ranges between 13–19  $\mu\text{m}$  in length making separation of these two species simple.

Family Stephanolithiacea Black, 1968

Genus *Rhombolithion* Black, 1973

*Rhombolithion rhombicum* (Bukry, 1969) Black, 1973

*Zygotolithus rhombicus* Stradner & Adamiker, 1966, p. 339, pl. 2, fig. 1

*Zygotolithus rhombicus* Stradner & Adamiker, Stradner et al., 1968, p. 40, pl. 37, figs. 5–7; pl. 38

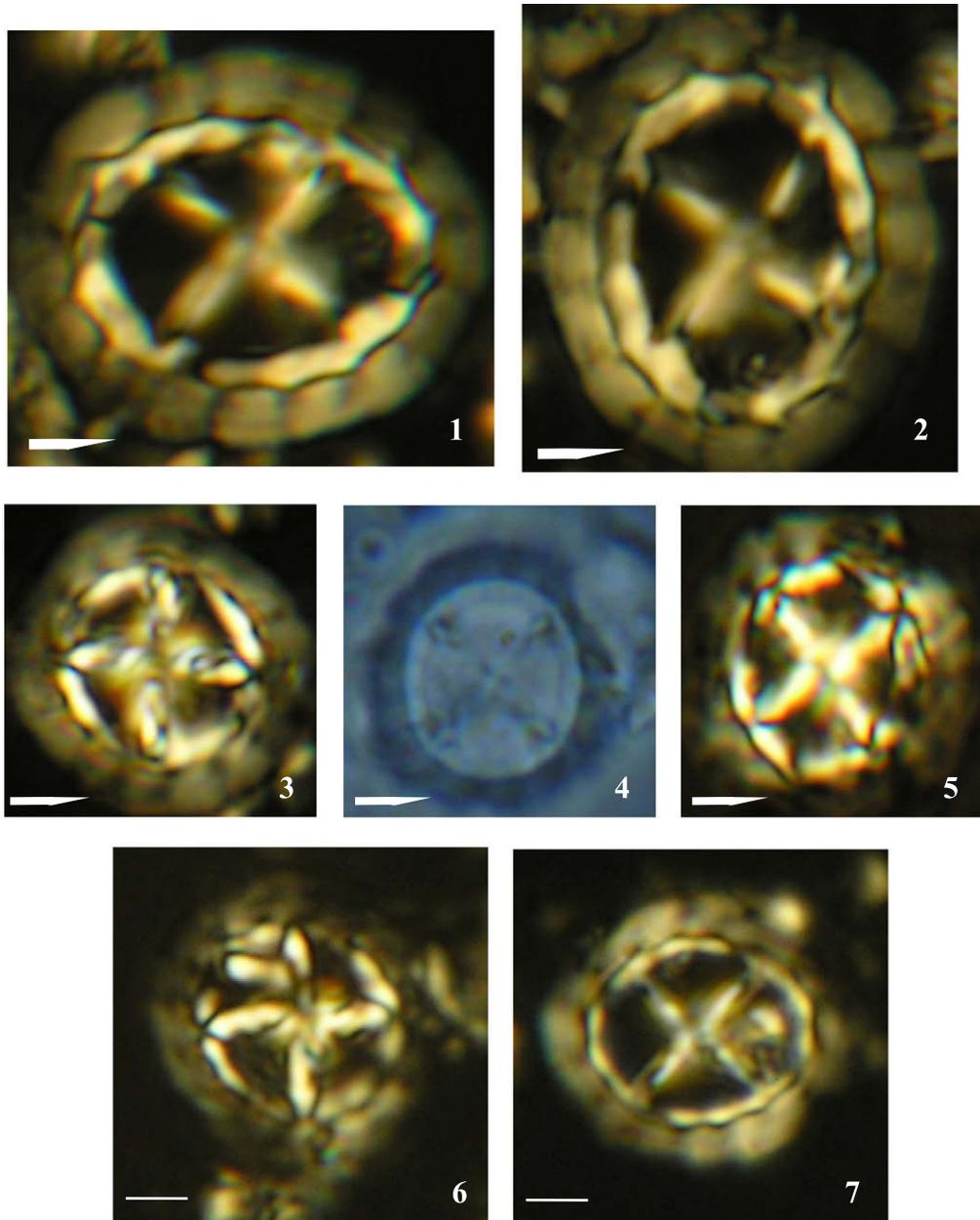
*Corollolithion rhombicum* (Stradner & Adamiker) Bukry, 1969, p. 41, pl. 19, figs. 2–4

*Rhombolithion rhombicum* (Stradner & Adamiker) Black, 1973, pl. 30, figs. 2–4

*Stradnerlithus rhombicus* (Stradner & Adamiker) Bukry (sic) in Burnett, 1998, pl. 5.9, fig. 27

**Occurrence.** This species occurs in low abundances (between 0 and 1.0% in well-preserved assemblages of the Smoky Hill Member). Only two specimens were noted from Ten Mile Creek.

**Remarks.** Due to the thin, delicate nature of bar elements of *R. rhombicum*, it is extinct or extremely dull in cross-polarized light (Plate 3, Figs. 12–15). Under phase contrast; however, rod elements are distinct, making this species easily recognizable. These specimens of *R. rhombicum* have an elliptical rim or frame with bar elements that intersect at an axial bar. Upper Coniacian and lower Santonian examples consistently have eight bar elements that connect to the axial bar.



**Plate 5.** Figures 1–2 – *Prediscosphaera grandis* Perch-Nielsen, 1979a taken in cross-polarized light. Figures 3–7 – *Prediscosphaera desidero grandis* n. sp., BLAIR AND WATKINS, this study. Figures 3 and 5–7 taken in cross-polarized light. Figure 4 taken in phase contrast light. Holotype images for *P. desidero grandis* are figures 3–4.

#### Incertae Sedis

#### Genus *Tortolithus* Crux in Crux et al., 1982

*Tortolithus dodekachelyon* *Tortolithus dodekachelyon* Blair, new species

Plate 4, Figs. 1–7

**Description.** This species of *Tortolithus* has a murolith rim composed of 12 elements and a central area composed of several plates separated by non-axial sutures. These rim elements exhibit differing optical characteristics best seen in cross-polarized light. The rim is composed of exactly 12 elements arranged tangentially to the central area margin. The central area is made up of three to five overlapping plates separated by non-axial sutures. The central area appears very dull in light microscope, while the rim contains elements that show great birefringence in certain orientations.

**Holotype.** Plate 4, Figs. 1–3

**Holotype size.** length: 6.24  $\mu\text{m}$ ; width: 4.0  $\mu\text{m}$

**Etymology.** dodeka-, Greek for twelve; chelyon-, Greek for tortoise shell

**Holotype material.** Chalk from Locality 13 (Smoky Hill Chalk Member, Kansas) and the Ten Mile Creek section (Bruceville Marl, Texas)

**Occurrence.** This species is a rare taxon in both Smoky Hill and Bruceville Marl sediments.

**Remarks.** *Tortolithus dodekachelyon* averages in size 5.84  $\mu\text{m}$  in length and 3.68  $\mu\text{m}$  in width (Table 7). This species is separated from most *Tortolithus* species by having exactly 12 rim elements. The appearance of *T. dodekachelyon*'s outer rim elements in cross-polarized light is very diagnostic. *Tortolithus caistorensis* can have between 12 and 20 rim elements, but has rim elements oriented radially away from the central area. The rim elements of *T. dodekachelyon* lay flat around the central area. Other species of *Tortolithus* such as *T. pagei* and *T. furlongii* have more than 12 rim elements easily differentiating it from *T. dodekachelyon*. The taxon, *T. furlongii*

**Table 7**

Biometric measurements of *Tortololithus dodekachelyon* taken from Locality 13 (Smoky Hill Member, Niobrara Formation)

Length (μm)	Width (μm)	Axial Ratio
6.24	3.60	1.73
5.20	2.40	2.17
6.64	5.04	1.32
5.04	3.44	1.47
5.84	3.44	1.70
6.00	4.24	1.42
5.20	2.80	1.86
5.84	4.00	1.46
6.80	4.80	1.42
7.04	4.40	1.60
6.40	4.40	1.45

has 34 rim elements, and *T. pagei* has 14 rim elements (Bukry, 1969). *Tortololithus hallii* can also be easily distinguished because it has a second cycle of rim elements (Crux in Crux et al., 1982; Perch-Nielsen, 1985).

## 8. Conclusions

Eight new species were described from the Smoky Hill Member and Bruceville Member: *Amphizygus megalops*, *Bifidalithus phenax*, *Garternago margaritatus*, *Helicolithus varolii*, *Helicolithus tectufissus*, *Pharus evanescens*, *Prediscosphaera desidero grandis*, and *Tortololithus dodekachelyon*. Revised descriptions and light microscope images were provided for *Retecapsa schizobrachiata*, *Rhombolithion rhombicum*, *Gartnerago clarusora*, *Orastrum campanensis*, and *Reinhardtites clavicaviformis*.

High resolution study of calcareous nannofossils from the Smoky Hill type area and the proposed GSSP at Ten Mile Creek yields a biostratigraphic framework for the Coniacian/Santonian Stage transition. Within the Smoky Hill Member, the acme onset of *Z. scutula* is seen just shortly before the FAD of *I. undulatopticatus*. This event is pronounced, easily recognizable, and extremely useful as a boundary marker in Smoky Hill sediments; however, its utility in other areas may be limited due to the diachronous nature of Mesozoic oceanic basins. *Prediscosphaera desidero grandis*, n. sp. and *Amphizygus megalops*, n. sp. are recognized in this study to be the most useful Santonian bioevents in terms of accurate placement of their FADs, abundance, and potential use in other basins. The succession of nannoevents noted within Bruceville and Smoky Hill strata during the Coniacian/Santonian transition can now be incorporated into other nannofossil schemes. In addition, these events provide a link between Coniacian/Santonian boundary strata (based on the designated macrofossil bioevent of *I. undulatopticatus*) and equivalent nannofossil schemes developed for deep-water sections.

There are problems associated with utilizing the Ten Mile Creek section as the Santonian Stage GSSP. As has been discussed, it exposes only ~7.0 meters of strata and is located in a growing urban region just south of Dallas; however, Gale et al. (2007) describes a 23-m thick section (the Wal-mart outcrop), near the Ten Mile Creek section which may be more appropriate as a boundary type section. While this study provides a nannofossil bioevent scheme for the Ten Mile Creek section, the acme events proposed can only be recognized in a few samples, and the first appearance of *P. desidero grandis* most likely occurs slightly below the exposed section. In addition, *A. megalops*, *O. campanensis*, and *T. dodekachelyon* are less common taxa at the Ten Mile Creek than at Locality 13.

Consideration should be given for the Smoky Hill Member type area as a type boundary section discussed in this study and mentioned by Gale and Hancock (2002) at the International

Symposium on Stage Boundaries in 2002. Preservation is excellent for macrofossils including vertebrates and molluscs, as well as calcareous nannofossils. It is located in an extreme rural region avoiding the urban sprawl issue of the Ten Mile Creek; however, it is on private property. Inoceramids are abundant, but ammonites are extremely rare and foraminifers are all but absent in the composite section. Nannofossil bioevents are easily recognizable including the acme of *Z. scutula*, which neatly spans the uppermost Coniacian and lowermost Santonian and begins just ~28.8 ky before the Coniacian/Santonian Stage boundary. Evidence from this study also provides promise for other Coniacian/Santonian Stage GSSP nominees that, with a similar high-resolution approach, the Coniacian/Santonian Stage transition can be more precisely defined.

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