Numerical age calibration of the Albian/Cenomanian boundary

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ABSTRACT: New biostratigraphic and sequence stratigraphic correlations of the U.S. Western Interior Albian/Cenomanian sections with North Texas and European sections calibrate the Albian/Cenomanian boundary at 97.2 Ma, which supports previous correlations in the Western Interior. This age, however, is 2.4 myr younger than the recent calibration at 99.6 Ma derived from radiometric ages of volcanic beds with diagnostic marine fossils in northern Japan. This discrepancy suggests that additional analyses are required to test the age calibration of the geologic time scale.

New data of cosmopolitan dinoflagellates enable direct correlation with the European reference sections of the Albian and Cenomanian. Previous correlations in the Western Interior were based on endemic or Boreal ammonites. The first and last occurrences of dinoflagellate species bracket the Albian/Cenomanian boundary in Europe and many of these species also bracket the Clay Spur Bentonite bed previously dated 97.17±0.69 Ma. The high number of radiometrically dated bentonites in the Western Interior provides a numeric age control for the ranges of many dinoflagellates.

Sequence stratigraphic correlation of the North Texas section with the U.S. Western Interior sections also demonstrates that the Clay Spur Bentonite bed correlates with the Ablian/Cenomanian boundary in Texas defined by the ammonite succession. The flooding contact SB WA6 in Texas at the Albian/Cenomanian zonal boundary of *Stoliczkaia dispar* and *Mantelliceras mantelli* correlates into the Western Interior with an erosional sequence boundary SB4 at the base of the Romeroville Sandstone in New Mexico and the "D" Sandstone in Colorado. This contact correlates with the base of the Belle Fourche Shale that overlies the Clay Spur and the Mowry Shale in Montana.

The revised correlation of the Western Interior poses two questions. 1) What is the accurate age of the boundary? Both cannot be correct. 2) What were the durations of the Albian and Cenomanian stages? Cyclostratigraphic analyses estimate that the Albian was 11.9 to 11.6 myr in duration but the Western Interior data project the duration at about 15 myr.

INTRODUCTION

The Global Section and Stratotype Point (GSSP) of the base of the Cenomanian Stage, and thus, the base of the Upper Cretaceous Series are defined at the Mont Risou section near Rosans, Haute-Alps Province in southeastern France (Gale et al. 1996). The diagnostic criterion is the lowest certain occurrence of the planktic foraminifer, *Rotalipora globotruncanoides* Sigal (= *Rotalipora brotzeni* Sigal) 4m below the uppermost Albian ammonites and 6m below the lowermost Cenomanian ammonites. The last occurrence (LO) of *Ticinella ticinensis* is 4m below the first occurrence (FO) of *R. globotruncanoides*. Several dinoflagellate bioevents in European basins bracket the boundary and are integrated with the ammonite and foraminifera ranges (Hardenbol et al. 1998; Williams et al. 2004).

For many years the age of the Albian/Cenomanian boundary was projected from the Clay Spur Bentonite bed in Montana and Wyoming, which is dated at 97.17±0.69 Ma (Obradovich 1993). Correlation and placement of the Albian/Cenomanian boundary in the Cretaceous Western Interior Basin was based on neogastroplitid and engonocerid ammonites in the Mowry Shale (reviewed by Scott 2007). Neogastroplitids were initially correlated with Upper Albian ammonites based on their evolutionary relationships with other genera of the Subfamily Gastroplitinae. Cobban and Kennedy (1989), however, lowered the correlation with base Cenomanian to the middle zone of the five neogastroplitid zones at the base of *Neogastroplites muelleri* Reeside and Cobban 1960 and *Metengonoceras teigenensis* Cobban and Kennedy 1989. This latter species occurs with lower Cenomanian ammonites in France (Amédro et al. 2002). *M. teigenensis* has evolutionary affinities with Cenomanian species of the genus *Metengonoceras* (Cobban and Kennedy 1989). The base of the *N. muelleri* Zone is just above the Arrow Creek Bentonite, which is radiometrically dated at 98.52±0.41 Ma (Obradovich 1993). Subsequently, Hardenbol et al. (1998) projected the boundary even older at 98.9±0.5 Ma, and Ogg et al. (2004) calibrated it at 99.6±0.9 Ma based on radiometrically dated tuff beds in Japan (Obradovich et al. 2002). The ranges of cosmopolitan dinoflagellate species in the Mowry Shale, on the other hand, support the placement of the boundary at the Clay Spur Bentonite (Scott and Stein 1995; Oboh-Ikuenobe et al. 2007).

Upper Albian to Cenomanian intervals in Israel and in southeastern France were dated by different methods that resulted in younger ages. Authigenic feldspar spanning the upper Albian to Cenomanian carbonate shelf in Israel yielded K-Ar ages ranging from 105±3 to 94±3 Ma. However these ages of diagenetic crystallization are younger than primary deposition (Sandler et al. 2004). In France glauconite was dated by K/Ar and integrated with cyclostratigraphy to calibrate the base of the Albian at 106.9±0.4 and the top at 95.3±1.1 (Fiet et al. 2001; Fiet et al. 2006).

The Albian/Cenomanian sedimentary strata were deposited in the narrow Western Interior epeiric seaway (text-fig. 1). This was a foreland basin tectonically related to the proto-Cordillera to the west and the stable craton on the east. The southern part of the seaway was between 30° and 45° north latitude during the middle part of the Cretaceous (Kauffman and Caldwell 1993, text-fig. 2). The southern and northern parts of the seaway were connected during the earliest late Albian flooding that deposited the Kiowa-Skull Creek Cycle (Kauffman 1985; Kauffman and Caldwell 1993). Prior to the end of the Albian the sea retreated and the two sub-basins were separated by a broad alluvial plain (Dolson et al. 1991). Two successive latest Albian sea-level rises partially flooded this plain and ephemeral brackish connections existed (Holbrook and Wright Dunbar 1992; Scott et al. 2004a; Oboh-Ikuenobe et al. 2008). Finally by middle Cenomanian the north and south sub-basins were re-connected (text-fig. 1).

The objective of this paper is to test the hypothesis that the Clay Spur Bentonite correlates with the Albian/Cenomanian boundary in Europe. Because ammonites are largely endemic to the Western Interior, we use cosmopolitan dinoflagellates. Dinoflagellate ranges in the Tethys are well known and integrated with age-diagnostic fossils (Hardenbol et al. 1998; Williams et al. 2004). This stratigraphic experiment utilizes biostratigraphic data of diverse fossil groups from measured sections and cores in the U.S. Western Interior to determine the order of bioevents. The bioevents are scaled relative to the thickness of a reference section. This relative metric scale is converted to mega-annums based on radiometric ages of interbedded bentonites.

METHODOLOGY

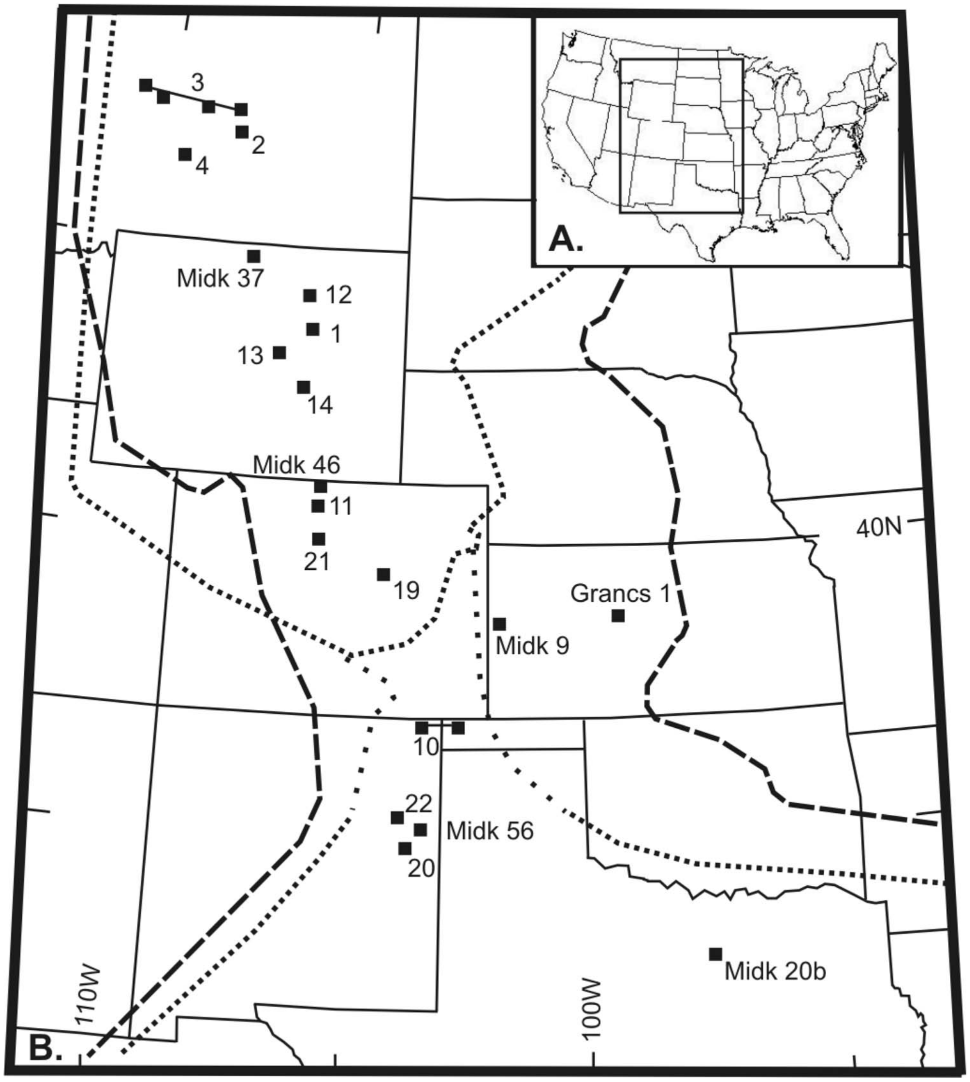
Sequence stratigraphic data was documented in twenty-two outcrop sections and cored wells that span the Albian-Cenomanian interval in the U.S. Western Interior (text-fig. 1, Appendix 1). Biostratigraphic data were recorded in 224 samples from these sections. Five samples from Hokkaido, Japan were donated in order to compare the dinoflagellate assemblage there with that in the U.S. Key sections in the Western Interior previously published were re-measured and collected for megafossils and microfossils. New sections spaced between known sections were also measured and collected. Approximately 100 grams of each sample were processed by standard techniques for microfossils, radiolaria and palynomorphs (Traverse 1988; Oboh-Ikuenobe et al. 2007). The species in each sample from each section are in Excel spread sheets at the Geosciences Department, University of Tulsa. Seven outcrop sections in Montana were composited to form one section (MT Composite Section Mowry 3 in Oboh-Ikuenobe et al. 2007) that includes four of the five ammonite zones. The neogastroplitid species are superposed in sections at Belt Butte and Timber Creek, Montana (Reeside and Cobban 1970). The sections were composited using bentonite beds as the datums (Oboh-Ikuenobe et al. 2007a). Fifteen additional sections in Montana, Wyoming, Colorado, New Mexico, and Kansas were correlated by graphic correlation.

Because fossils are relatively uncommon in these sections, the ranges in each section were integrated in order to define the ranges in the U.S. Western Interior basin. Sections were correlated by bioevents and lithostratigrapic marker beds and the section data were integrated by graphic correlation. Graphic correlation is a quantitative, but non-statistical, technique that proposes coeval relationships between two sections by comparing the ranges of event records in both sections. A graph of any pair of sections is an X/Y plot of the FOs (☐) and LOs (+) of taxa found in both sections (Carney and Pierce 1995). The hypothesis of coeval relations is indicated by the line of correlation (LOC), which the interpreter places by selecting coeval events in both sections. Graphic correlation enables the stratigrapher to integrate sedimentological events with biotic events so that conclusions based on one can test the other. Also, the event beds and radiometrically dated beds add to the precision and accuracy of the correlation.

The graphic correlation experiment used the Montana Composite Section Mowry 3 as the standard reference sections (SRS), because it spans the latest Albian to earliest Cenomanian interval without evident unconformities or changes in rates of sediment accumulation (RSA) (Scott et al. 2004a). The resulting scale of the graphing experiment was in meters thickness relative to the thicknesses in the Montana sections. The second section graphed was the Pike Creek, Montana, section (Porter et al. 1993). This section also appears to record continuous deposition, however, the Mowry Shale is unusually thin in this section (Oboh-Ikuenobe et al. 2007) suggesting a significant change in the RSA. The order of graphing proceeded from nearby sections using the Arrow Creek and Clay Spur bentonite beds as tie points, to those sections farther south where unconformities within the laterally equivalent Dakota Formation become significant. The post-Dakota part of the interval is represented by a composite of six measured outcrops of the Graneros Shale in Kansas (Hattin 1965). The pre-Dakota part of the interval is composed of sections of the Tucumcari Shale and the Skull Creek Shale down to the basal sequence stratigraphic unconformity or transgressive contact in Colorado and New Mexico. All sections were graphed through at least three rounds to test the correlation of unconformable contacts. The order of key bioevents and their first (FO) and last (LO) appearances in the relative composite standard unit (CSU) scale comprises the Mowrycs.1 data base (Appendix 2). The position of sequence stratigraphic contacts is scaled relative to the thickness in the Montana Composite section (Appendix 3).

The next step was to correlate the Western Interior sections to the North Texas section in the Trinity River Valley near Fort Worth (Scott et al. 2003). In this section the Albian-Cenomanian boundary is defined by ammonites and bracketed by dinoflagellates, and sparse planktic foraminifera and nannofossils. This stage/series contact is identified within 0.5m above the contact between the Main Street and Grayson lithostratigraphic units (Hancock et al. 1993; Scott et al. 2003). By means of this correlation the ranges of neogastroplitid and engonocerid ammonites in Montana and Wyoming are integrated with Tethyan, age-diagnostic ammonites.

The relative scale of the Mowry Composite data base was calibrated to numerical mega-annum ages by interpolation of radiometrically dated beds (Obradovich et al. 1993; Obradovich 1996). The reliable ages of the Arrow Creek Bentonite and the Clay Spur Bentonite beds as well as bentonite beds below the Thatcher Limestone Member of the Graneros Shale are precisely integrated into the Mowry data base. Only approximate positions of other dated bentonites in the Skull Creek Shale, the



TEXT-FIGURE 1
Study area. A. Inset map of the conterminous United States showing outline of study area. B. Shoreline paleogeography of the U.S. Western Interior Seaway and location of measured sections and cores. Coarse dashed lines approximate marine boundaries of early late Albian and middle Cenomanian seaways; dense dotted line approximates late late Albian marine boundary and light dotted line approximates brackish boundary. Shorelines modified from Cobban et al. (1994), Brenner et al. (2000) and Oboh-Ikuenobe et al. (2008).

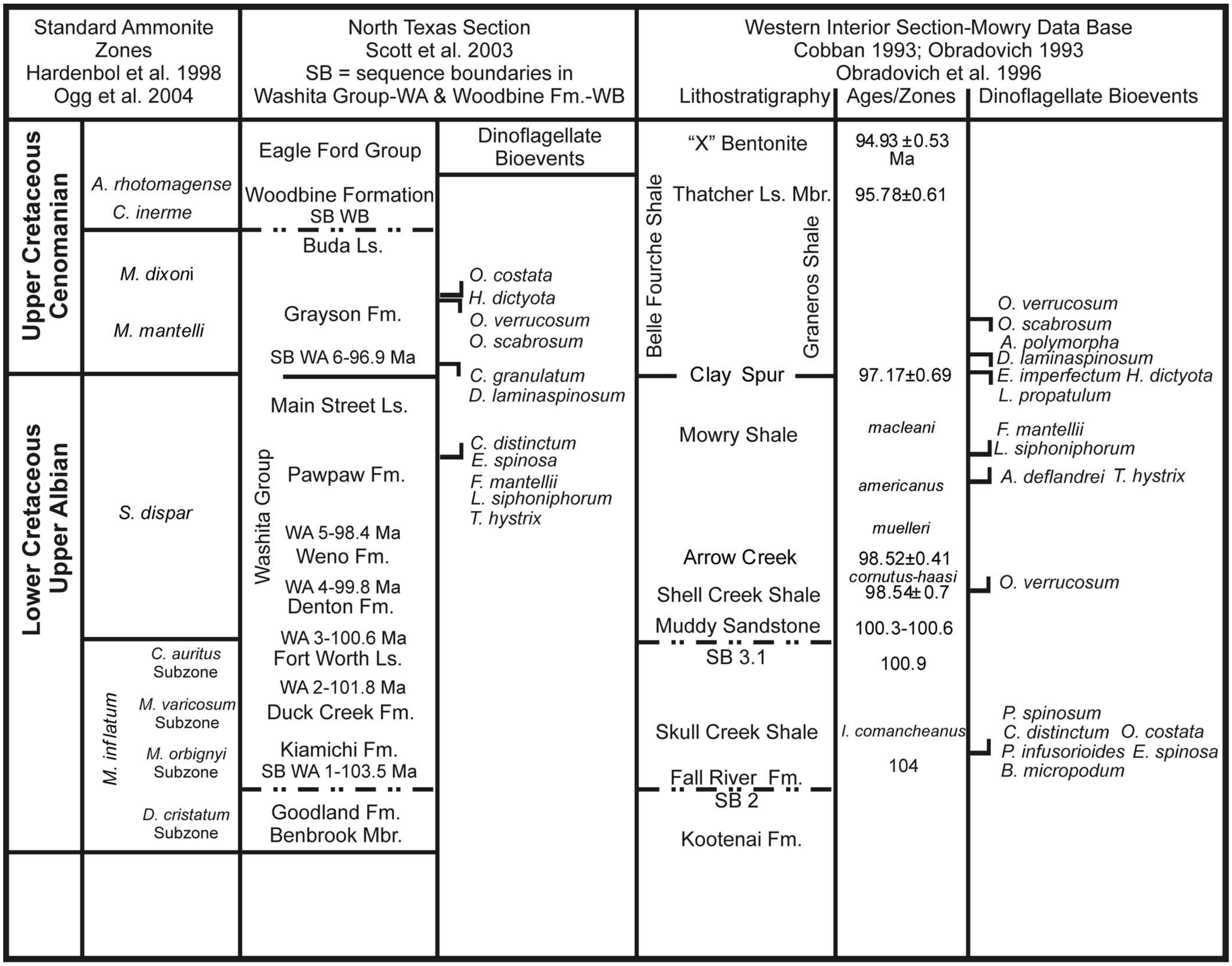
Muddy Sandstone, and the Shell Creek Shale have been reported (Obradovich et al. 1996).

In order to compare the dinoflagellate ranges in the Hokkaido, Japan sections, Professor Matsumoto sent us five samples representing uppermost Albian, Lower and Upper Cenomanian, and lower Turonian. These samples were obtained in the region of, but not at the same sections, as those samples radiometrically dated by Obradovich et al. (2002). We recovered dinoflagellates, spore, pollen, and foraminifers from these samples.

INTEGRATED BIOSTRATIGRAPHY

Gulf Coast correlation

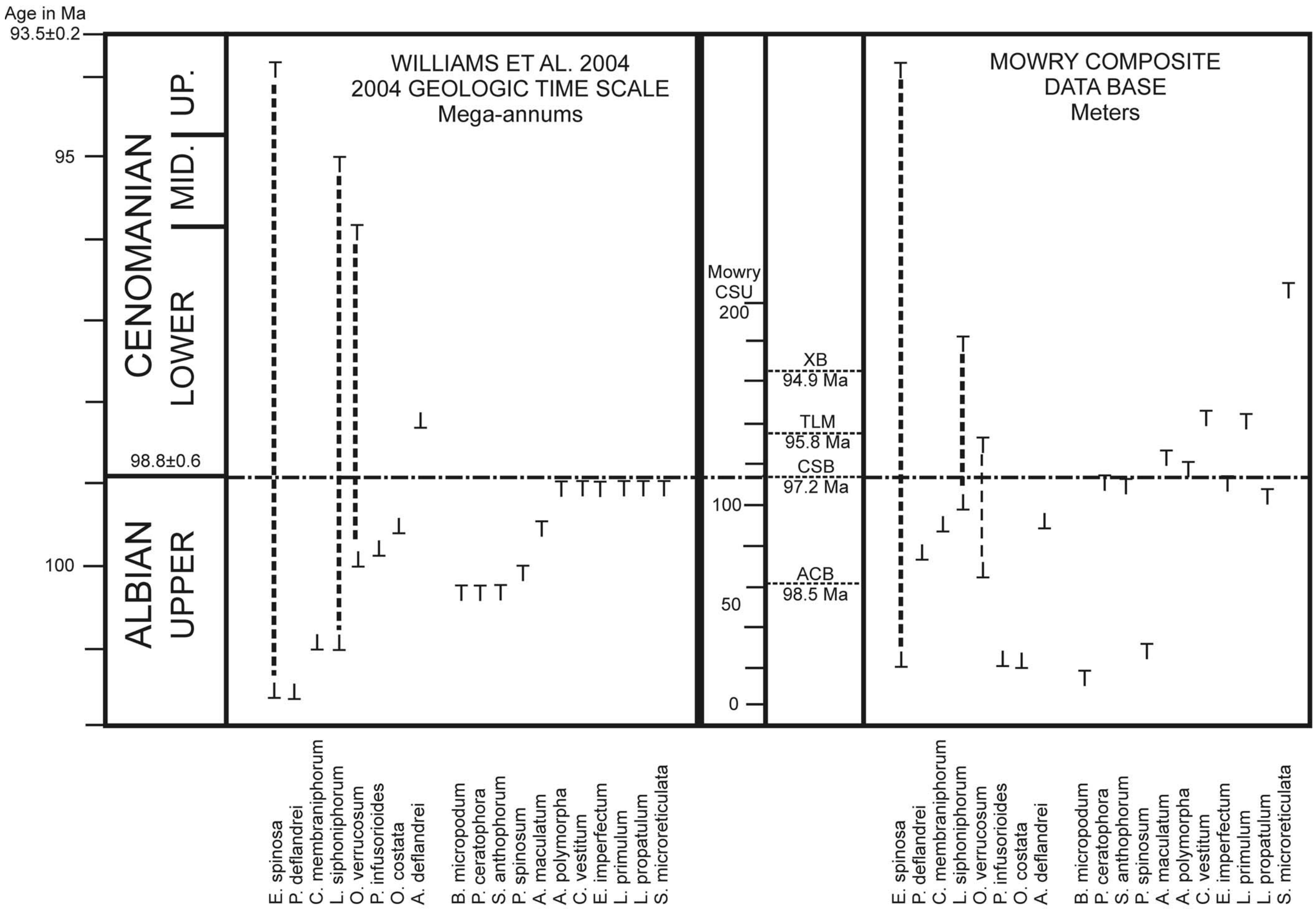
The Albian/Cenomanian boundary in the Texas Gulf Coast is identified by ammonites (text-fig. 2) (Young 1979, 1986a, 1986b; Hancock et al. 1993; Kennedy et al. 1999), dinoflagellates and nannofossils (Scott et al. 2003), and planktic foraminifers (Reichelt 2005). The stage boundary is placed in the transitional 0.5m-thick interval between the Main Street Limestone below and the Grayson Formation above (Kennedy et al. 1999; Scott et al. 2003). The base of the upper Albian substage is defined traditionally by the FO of the ammonite, *Dipoloceras cristatum* (Brongniart 1822) in Europe, which is the basal subzone of the *Mortoniceras inflatum* Zone (text-fig. 2) (Hart et al. 1996). In north Texas this species is known from the upper part of the Benbrook Limestone Member of the Goodland Formation (Scott et al. 2003). The next younger European ammonite subzone, the *Mortoniceras orbignyi* Subzone, extends from the base of the Kiamichi Formation into the lower part of the Duck Creek Formation (Young 1966; Kennedy et al. 1999; Scott et al. 2003). The uppermost upper Albian *Stoliczkaia dispar* Zone in north Texas spans from the uppermost meter of the Fort Worth Limestone to the top of the Main Street Limestone (Kennedy et al. 1999; Scott et al. 2003).



TEXT-FIGURE 2
Albian/Cenomanian stratigraphic classification chart of North Texas and northern U.S. Western Interior. European ammonite zones integrated in North Texas (Hancock et al. 1993); Washita Group sequence stratigraphy - WA (Scott et al. 2003). Radiometric dates of bentonites (Obradovich 1993; Obradovich et al. 1996); Western Interior ammonite and inoceramid zones (Cobban 1993); dinoflagellate ranges from the Mowrycs.1 data base. SB = sequence boundary; WA is sequence defined in Washita Group, north Texas; WB = Woodbine Formation sequence (Scott et al. 2000).

Eleven dinoflagellate bioevents in the Pawpaw, Main Street and Grayson formations in the Trinity River section bracket the ammonite boundary (text-fig. 2). Taxa marked by an asterisk (*) are diagnostic of the Albian/Cenomanian boundary (Williams et al. 2004): the FOs of *Circulodinium distinctum, Epelidosphaeridia spinosa*, Florentinia mantellii*, *Litosphaeridium siphoniphorum**, *Odontochinta costata**, and *Tenua hystrix*, and the LOs of *Carpodinium granulatum*, Dapsilidinium laminaspinosum, Hapsocysta dictyota, Ovoidinium verrucosum*, O. scabrosum.*

The European lower Cenomanian zones of *Mantelliceras mantelli* and *M. dixoni* are recognized in the Grayson Formation and Buda Limestone (text-fig. 2) (Young 1979; Hancock et al. 1993; Scott et al. 2003). The unconformity between the Grayson/Buda and the overlying Woodbine Formation is close to the lower/middle Cenomanian boundary and is interpreted to be a widespread Tethyan discontinuity (Scott et al. 1988). The Lewisville and Templeton members of the uppermost Woodbine yield a diverse molluscan fauna including ammonites of the upper middle Cenomanian *Acanthoceras amphibolum* Zone (Stephenson 1952; Hancock et al. 1993). This species has a short range in the uppermost part of the Graneros Shale below and above the "X" Bentonite marker bed, which extends from Kansas, Colorado, Wyoming, to Montana (Hattin 1965). Thus the transgressive facies in the upper part of the Woodbine correlate with the upper part of the Graneros (Kauffman et al. 1977). The *A. amphibolum* Zone correlates with the upper part of the middle Cenomanian *A. rhotomagense* Zone in Europe (Hancock et al. 1993; Hardenbol et al. 1998). Overlying the Woodbine, the Eagle Ford Group is characterized by middle Cenomanian to Turonian planktic foraminifera (Pessagno 1967) and nannofossils (Valentine 1984).



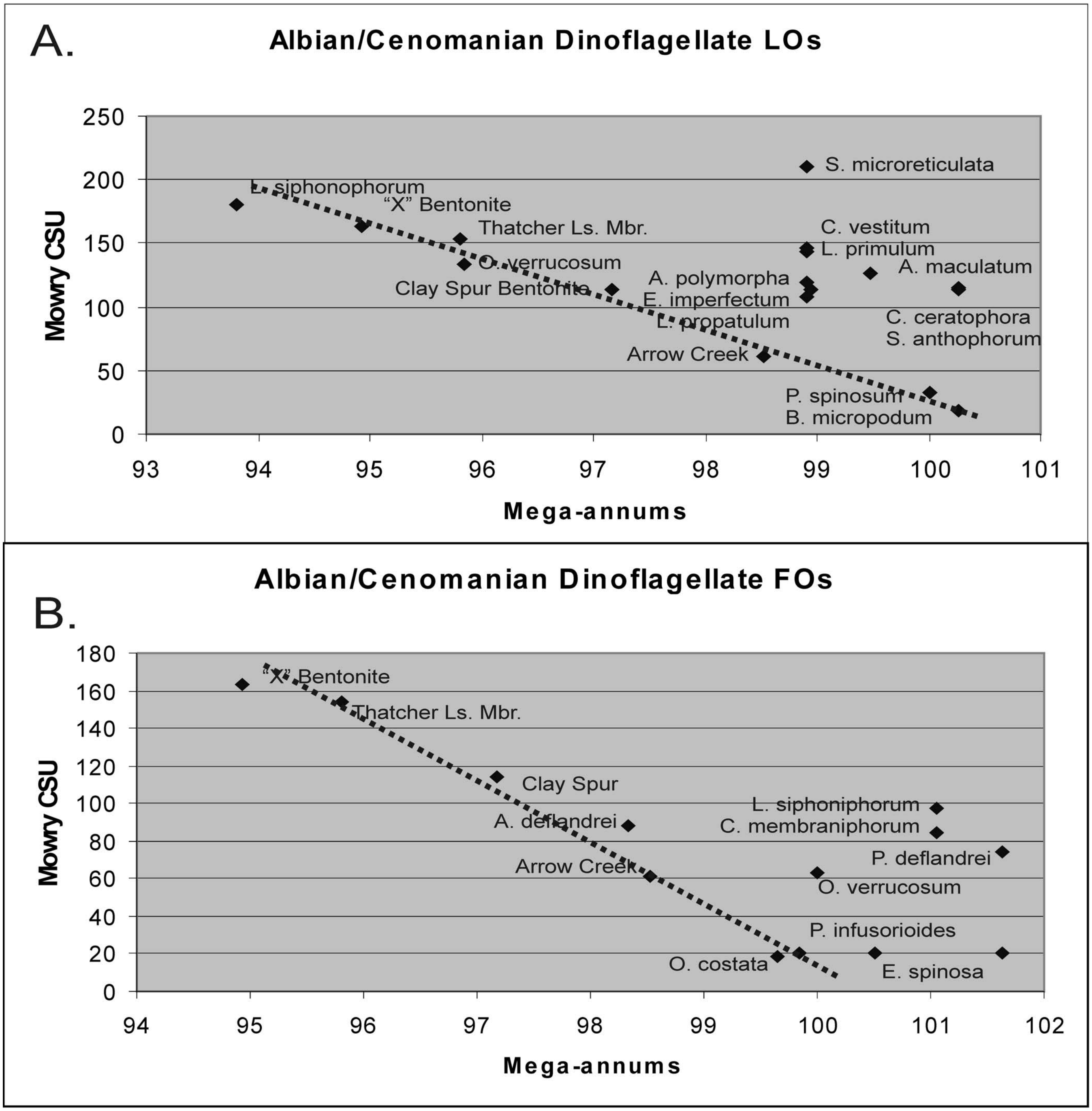
TEXT-FIGURE 3
Comparison of dinoflagellate bioevents bracketing the Albian/Cenomanian boundary in Europe and in the Western Interior. ACB – Arrow Creek Bentonite; CSB – Clay Spur Bentonite; TLM – Thatcher Limestone Member; XB – “X” Bentonite Bed. Geologic time scale of Ogg et al. (2004).

Western Interior correlation

The succession of neogastroplitid species and range zones was first proposed by Reeside and Cobban (1960). The proposed order from older to younger is *Neogastroplites haasi, N. cornutus, N. muelleri, N. americanus*, and *N. maclearni* (text-fig. 2) (Cobban, 1993; reviewed by Scott 2007). Radiometric dates are associated with some species: *N. haasi* in the Shell Creek section, Wyoming, is near a bentonite dated at 98.54±0.7 Ma; *N. cornutus* ranges across the Arrow Creek Bentonite, which is dated at 98.52±0.41 Ma; and *N. maclearni* ranges up to the Clay Spur Bentonite dated at 97.17±0.69 Ma (Obradovich, 1993). The order of the younger four species is further substantiated by their superposed succession in the Belt Butte and Timber Creek localities in Montana (Reeside and Cobban 1960; Oboh-Ikuenobe et al. 2007). However, *N. haasi* is reported only from the Shell Creek section in Wyoming where it is close to the contact of the Shell Creek and Mowry shales (Reeside and Cobban, 1960; Eicher, 1960). The radiometric date associated with it indicates that its range is similar to that of *N. cornutus*. Graphic correlation of the Shell Creek section (Midk.37), however, projects the range of *N. haasi* to overlap the range of *N. americanus*. If, however, the radiometric date is correct, which it seems to be, then the Shell Creek section may be faulted. The Muddy Sandstone is exceptionally thick at 430ft (131m) and the Shell Creek Shale is 260ft (73.3m) thick. If the section is repeated by faulting by as much as 500ft (152.4m), then the range of *N. haasi* at 1170 to 1187ft would project approximately to the position of the Arrow Creek Bentonite in the Mowry database. The age of *N. haasi* at 98.54 Ma is plotted so that it range is partly coincident with *N. cornutus* (text-fig. 2).

The metengonocerid ammonites also have been found at only a few localities (reviewed by Oboh-Ikuenobe et al. 2007; Scott 2007). Their composited ranges overlap the ranges of *N. muelleri* and *N. maclearni*. *Metengonoceras aspenanum* has the longer range from 83.1 CSU to 106.7 CSU and *M. teigenensis* ranges from 96.5 CSU to 97.8 CSU, which overlaps with *N. americanus* and *N. muelleri*.

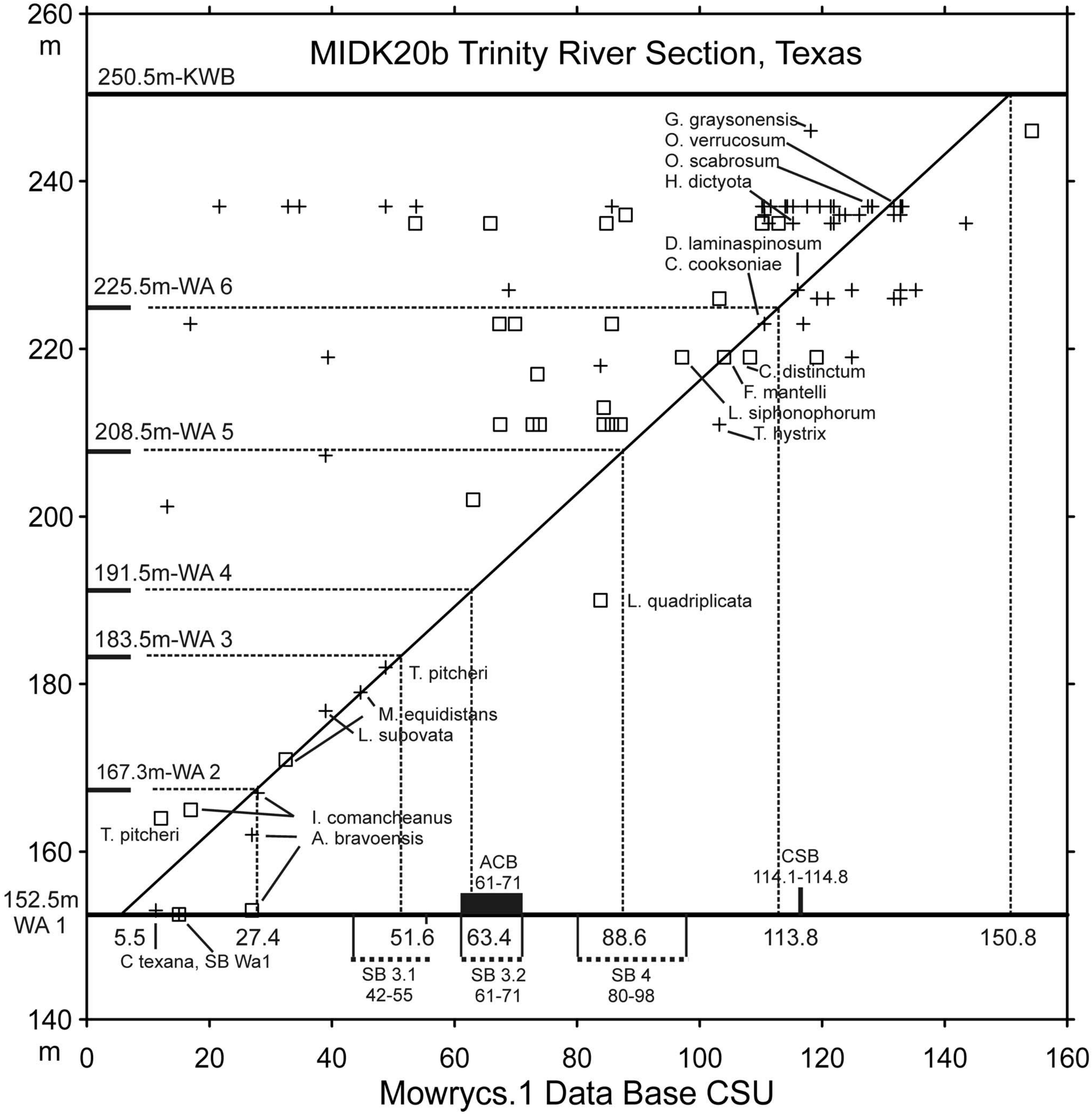
The Dakota Group in the Colorado Front Range has yielded a new radiometric date of 98.72±0.31 Ma (Obradovich, written comm., 2003 in Oboh-Ikuenobe et al. 2008). The dated bentonite bed at Fountain Creek is in the lower part of the Dry Creek Canyon Formation and overlies a dark gray shale 24m (79ft) above the base of Waage’s (1953) Lower Sandstone unit of his Dakota Sandstone. This bed correlates with the Middle Shale Member of the Mesa Rica Sandstone (Scott et al. 2004a).



TEXT-FIGURE 4
Plots of first (B) and last (A) occurrences of dinoflagellate species common to the Western Interior and Europe that bracket the Albian/Cenomanian boundary (Williams et al. 2004). Correlation lines are visually placed to show approximate relationship between CSU scale and 2004 age scale.

Seventeen dinoflagellate species used by Williams et al. (2004) to bracket the Albian/Cenomanian boundary are also in the Western Interior sections (text-fig. 2; appendix 2). Only four lived longer in the Western Interior than in Europe, which indicates that the dinoflagellates appeared in the basin about the same time as in Europe and went extinct at the same time or soon after. It appears that these cosmopolitan species are reliable correlation points of the Albian/Cenomanian boundary in the U.S.

The Thatcher Limestone Member of the Graneros Shale in southeastern Colorado yields a diverse middle Cenomanian ammonite fauna (Cobban 1993). This fauna is found as far north as the Frewens Castle, Wyoming section, which has the ammonite *Borissiakoceras reesidei* and the bivalves *Inoceramus eulesanus* and *I. arvanus*. These species are associated elsewhere with the *Conlinoceras gilberti* Zone (Cobban 1993), which is dated at 95.78±0.61 Ma (Obradovich 1993). The inoceramid species are also found in the Lewisville and

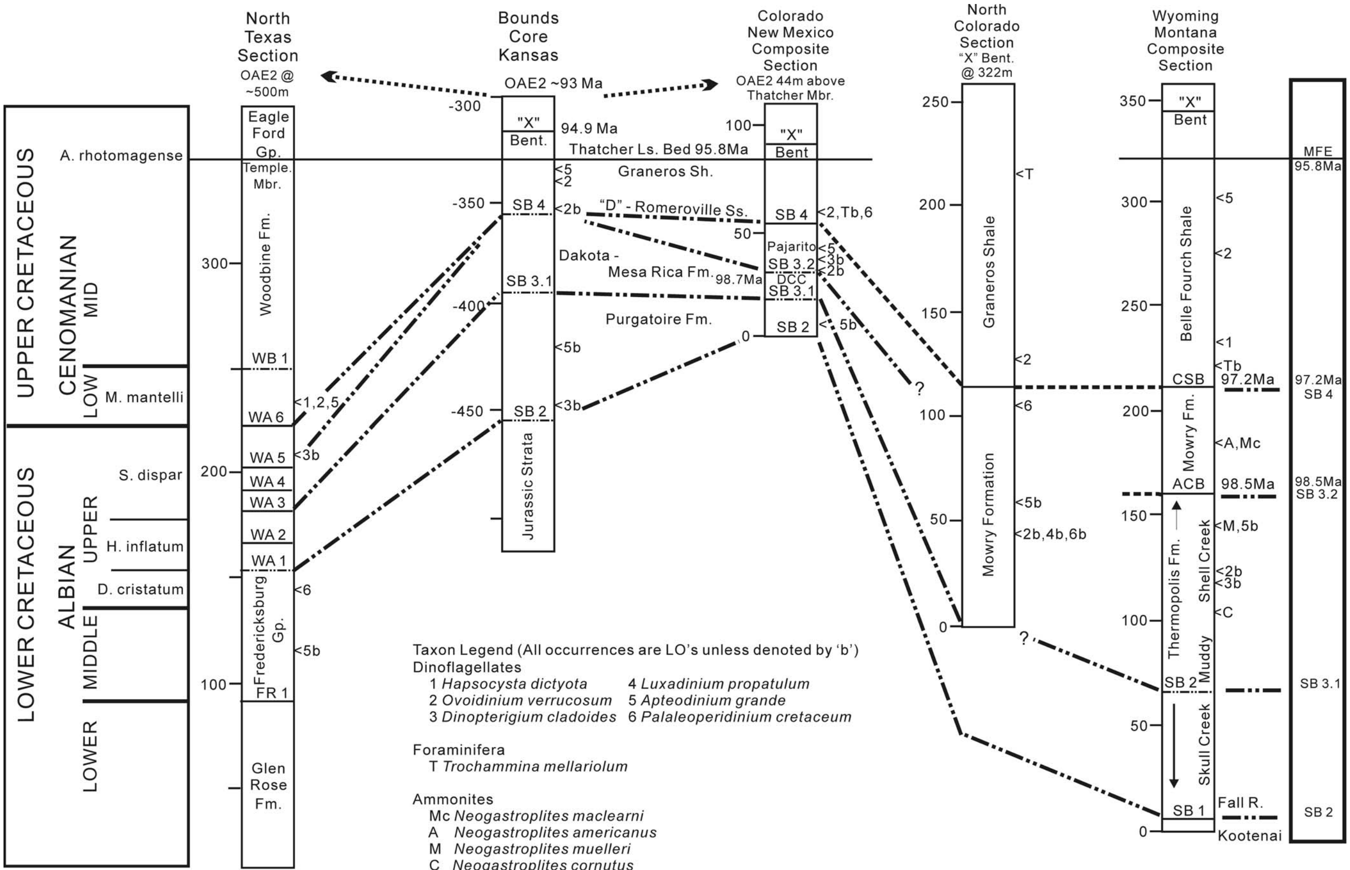


TEXT-FIGURE 5
Graphic correlation of the Trinity River section at Ft. Worth to the Mowyrcs.1 database in composite standard units (CSU). Horizons WA 1-6 and KWB are sequence boundaries in North Texas (Scott et al. 2000). The hiatus thicknesses of the Western Interior sequences are indicated by the dotted boxes on the horizontal axis. FOs are indicated by square symbols and LOs by crosses.

Templeton members of the uppermost Woodbine Formation in north Texas (Stephenson 1952).

The upper middle Cenomanian *A. amphibolum* Zone is in the uppermost Graneros and Belle Fourche shales (Cobban 1993). This zone is dated at 94.93±0.53 Ma (Obradovich 1993) by the widespread marker “X” Bentonite. Species of this zone also occur in the Templeton Member of the Woodbine Formation in north Texas.

The benthic foraminifera and radiolaria in the Mowry Shale are members of Albian/Cenomanian assemblages that span the boundary (Oboh-Ikuenobe et al. 2007). The Gulf Coast calcareous benthic foraminifera, *Gubkinella graysonensis*, in the basal Belle Fourche Shale at the Frewens, Wyoming section is consistent with the lower Cenomanian age of the Belle Fourche. This species in the Texas section ranges from the upper Albian Duck Creek Formation to the lower Cenomanian Grayson Formation (Scott et al. 2003).



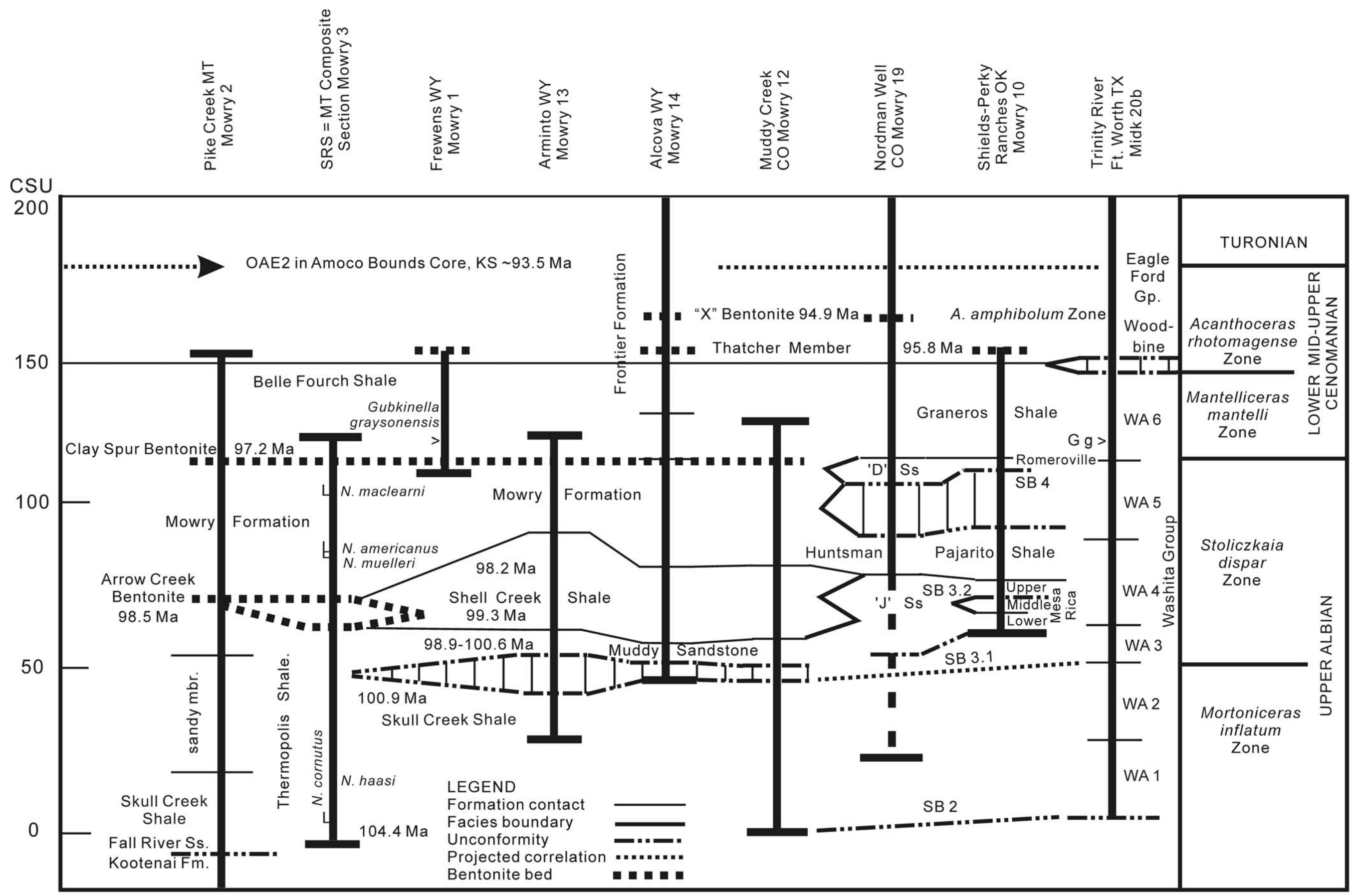
TEXT-FIGURE 6
Regional north-south sequence stratigraphic cross section of middle Cretaceous strata from Montana to Texas.

Correlation by dinoflagellate ranges

Organic-walled dinoflagellate cysts are the most abundant cosmopolitan biota in the Western Interior Basin (Williams et al. 1993; key species are illustrated by Scott et al. 2004 and Oboh-Ikuenobe et al. 2007). The ranges of these microfossils in Europe are well known and they were integrated with other fossils (Hardenbol et al. 1998; Williams et al. 2004). The Albian/Cenomanian boundary is characterized by a number of last occurrences close to the top of the Albian and the first occurrences of others bracket the contact (text-figs. 2, 3). Four species that bracket the boundary also occur in the Trinity River Section near Fort Worth, Texas (Scott et al. 2003). However, none of the six species with LOs at the boundary were found in Texas. More detailed sampling in Texas may record these species.

The sections composing the Mowry data base, on the other hand, contain nineteen diagnostic species and the order of their bioevents is similar to those in Europe (text-fig. 3). Six species that go extinct at or near the top of the Albian have LOs at or slightly above the Clay Spur Bentonite bed and well above the proposed 99.6 Ma age of the Albian/Cenomanian boundary. Likewise five species that first appear in the latest Albian lie between the Arrow Creek and Clay Spur bentonite beds. The order of FOs and LOs of some species differs slightly from the order proposed by Williams et al. (2004); the higher FOs and lower LOs may be extended by more detailed sampling. The ranges of six species are somewhat longer in the Western Interior suggesting slight modifications in the range model of Williams et al. However, the dinoflagellate ranges in the Western Interior support the correlation of the 97.17 Ma Clay Spur Bentonite rather than the older 98.5 Ma Arrow Creek Bentonite.

Albian/Cenomanian dinoflagellate age model in the Western Interior is similar to that in Europe. This conclusion is based on plots of FOs and LOs in the Mowry CSU scale with the numerical ages interpolated by Williams et al. (2004) (text-fig. 4). The first and last occurrences are plotted separately for ease of visual inspection. The Mowry composite scale (text-fig. 4) is approximately linearly correlated with the radiometrically dated beds, although the correlation lines do not pass through the radiometrically dated points because the two scales were derived differently. Eight dinoflagellate bioevents dated in Europe (Williams et al. 2004) are close to the correlation lines, which indicates that the order of events is similar in both databases (four FOs: *Epilsphaeridium spinosa, Paleohystrichosphaeridium infusorioides, Odontochitina costata,* and *Apteodinium deflandrei;* and four LOs: *Batiolatidinium micropodum, Protoellipsodinium spinosum, Ovoidinium verrucosum,* and *Litosphaeridium siphoniphorum*). However, four first occurrences are younger in the Mowry sections than in Europe either because the sampling is inadequate or because their entry into the WI was delayed. Nine last occurrences (LO) are younger in the Mowry sections than in Europe. Three of the seven LOs that define the top of the Albian (*Aptea polymorpha, Ellipsodinium imperfectum,* and *Litosphaeridium propatulum*, Williams et al. 2004) occur close to the Clay Spur Bentonite. Either their ages are too old in the 2004 time scale or they are younger in the Western Interior than in Europe. The coincidence of these three



TEXT-FIGURE 7
Regional north-south time section of middle Cretaceous strata from Montana to Texas.

species with five other LOs supports the correlation of the top Albian with the Clay Spur Bentonite.

The palynostratigraphic and sequence stratigraphic data presented here support correlation of the Clay Spur Benonite dated at 97.17±0.69 Ma with the Albian/Cenomanian boundary in the Trinity River section defined by ammonite ranges (Hancock et al. 1993). The graphic correlation plot of the Mowry data base to the Trinity River section, Texas (text-fig. 5) correlates the Albian/Cenomanian boundary defined by ammonites with the Clay Spur Bentonite bed at the top of the Mowry Shale. The correlation is based on a set of key bioevents from base to top: the LOs of *I. comancheanus*, *L. subovata*, *M. equidistans*, *T. pitcheri*, *C. cooksoniae*, *D. laminaspinosum*, and *O. verrucosum*, among other taxa in the Grayson Shale, and the FOs of *M. equidistans*, *F. mantelli*, and *C. distinctum* (Appendix 4). This plot projects Gulf Coast depositional cycles WA3, WA4, and WA5 with sequence boundaries SB3.1, 3.2, and 4, respectively, in the Western Interior. The cycle boundary WA6 at the contact between the Main Street Limestone and the Grayson Shale, which is approximately the Albian/Cenomanian boundary, correlates with Mowry CSU 113.8 at the top of the Mowry Shale.

REGIONAL SEQUENCE STRATIGRAPHY

Regional stratigraphic cross sections demonstrate for the first time the sequence stratigraphic and chronostratigraphic relationships of upper Albian to middle Cenomanian strata between north Texas and Montana (text-figs. 6, 7). The facies and biostratigraphy of the North Texas composite section are well documented from detailed measured sections along the Trinity River valley between Fort Worth and Dallas (Scott et al. 2003 and references therein). The outcrops in the Oklahoma Panhandle at Shields Ranch and correlative outcrops in northeastern New Mexico and southeastern Colorado yield new sequence stratigraphic and biostratigraphic data (a graphic correlation plot is in Scott et al. 2004a, fig. 14; 2004b). Two cores document long sections of middle Cretaceous strata in the High Plains of westernmost Kansas and eastern Colorado, the Amoco No. 1 Bounds and the Rocky Mountain Production Co. Nordman Trust 32-20, (Scott et al. 1994; Scott et al. 1998). Along the Front Range in northern Colorado and in Wyoming sections previously described by Eicher (1965, 1967) were re-sampled for organic-walled microfossils and foraminifera. Carefully documented classic sections in Montana were re-sampled for foraminifera and palynomorphs. Many of these sections are correlated by bentonite marker beds, and the datum for the sequence stratigraphic section is the Thatcher Limestone Member of the Graneros Shale, which is synchronous with the Templeton Member of the Woodbine Formation in north Texas (text-fig. 6, Templ. Mbr.). The sequence stratigraphic section is scaled by composite units (CSU), which are meters of the Montana and Wyoming sections.

North Texas section

The upper Albian-lower Cenomanian interval in North Texas is the Washita Group in the upper part of the Gulf Coast Comanchean Series (text-fig. 2) (Scott et al. 1994; Scott et al. 2003). The Washita consists of six genetic depositional cycles composed of marine shale grading up into shelf carbonate. These cycles were designated WA1-6 as part of the Washita Group (Scott et al. 2000, 2003). The base of the Washita and cycle WA1 is a regional unconformity that extends from the shelf margin in the south Texas subsurface to southeastern Oklahoma (text-figs. 6, 7). This contact correlates north through the Western Interior Basin as the transgressive contact SB2 (Holbrook and Wright Dunbar 1992; Scott et al. 1994; Scott et al. 2004a). In Texas the Washita overlies the Fredericksburg Group and the contact has been subaerially exposed northward from Austin, Texas (Scott et al. 2003). The tops of the younger cycles are sharp transgressive contacts, and the top of cycle WA5 between the Main Street and Grayson formations locally is a bored, iron-stained, submarine hardground. The carbonate parts of each cycle are composed of alternating marl/limestone couplets less than a meter thick that may represent climatic forcing.

New Mexico-Colorado sections

The upper Albian section in northeastern New Mexico and southeastern Colorado records the complex shoreline shifting of sea-level changes (Holbrook and Wright Dunbar 1992; Scott et al. 2004a; Oboh-Ikuenobe et al. 2008). Detailed mapping and correlation of sequence contacts has unraveled the stratigraphic relations resulting in a correlation with the north Texas section (Scott et al. 1994; Scott et al. 2004a). This correlation hypothesis is revised herein. These northeastern New Mexico and southeastern Colorado sections have been composited to form the Colorado-New Mexico Composite Section (text-fig. 6); the Shields section in NW Oklahoma (text-fig. 7) is central to this composite. At the Colorado-Kansas border the Bounds core (text-fig. 6) spans the complete middle Cretaceous section (text-fig. 6) (Scott et al. 1994; Scott et al. 1998). The Nordman core farther west in Colorado (text-fig. 7) spans the “D” Sandstone and the Huntsman Shale.

The basin-wide sequence boundary SB2 is overlain locally by basal sandstone and regionally by dark gray marine shale deposited when the proto-Gulf of Mexico flooded North America and connected with the Arctic seaway. The strata between SB2 and SB3.1 comprise the Kiowa-Skull Creek Cycle (Kauffman 1985) and correlate with the North Texas cycles WA1 and WA2, which are composed of the Kiamichi, Duck Creek and Fort Worth formations. This correlation is substantiated by ammonites common to both regions (Scott et al. 2003 and references therein). The Kiowa-Skull Creek Cycle is dated by bentonites in the Thermopolis Formation in Wyoming at about 104.4 to 100.9 (Obradovich et al. 1996). Washita sequences WA1 and 2 are dated by graphic correlation at about 104 to 100.6 Ma (Scott et al. 2000; Scott et al. 2003).

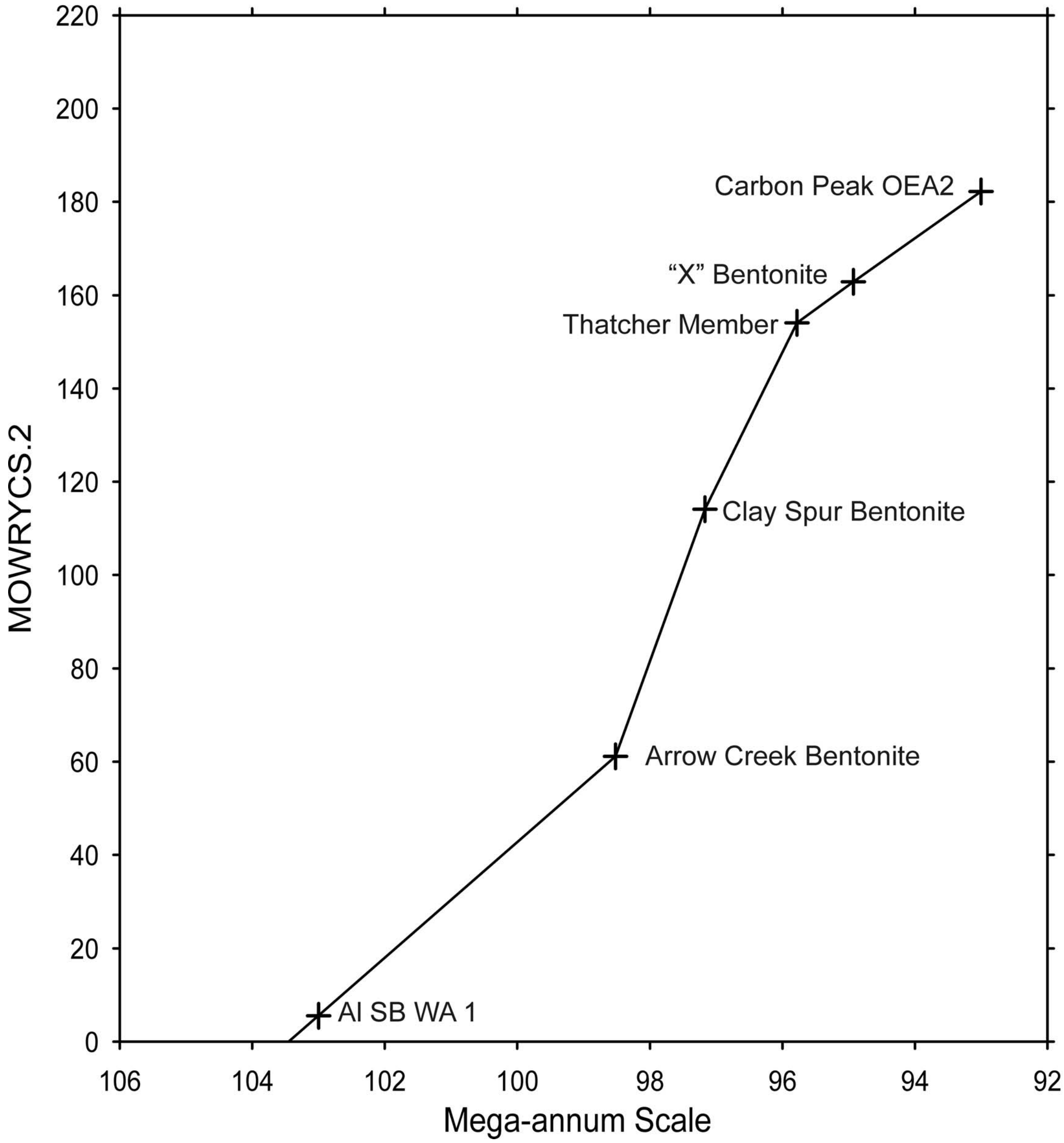
The top of the Kiowa-Skull Creek Cycle in New Mexico and Colorado is a regional erosional contact at the base of the Dakota Group (Scott 1970; Scott et al. 1994) designated SB3.1 (Holbrook and Wright Dunbar 1992; text-figs. 6, 7). Sequence 3.1 comprises the lowstand to transgressive Lower Member of the Mesa Rica Sandstone and the maximum flooding to highstand facies of the Middle Member of the Mesa Rica. The Middle Member is shale, mudstone and siltstone that yielded sparse, long-ranging spores, pollen, dinoflagellates, and trace fossils. Although the Middle Member pinches out west and north of this area, sequence 3.1 correlates northward with the Muddy Sandstone (defined as a formation by MacKenzie 1965) and part of the Shell Creek Shale, which are dated at about 100 to 99 Ma (Obradovich et al. 1996). This interval is dated more precisely at 98.72±0.31 Ma by a bentonite bed in the lower part of the Dry Creek Canyon Formation of the Dakota Group on the Colorado Front Range (Obradovich, written comm., 2003 in Oboh-Ikuenobe et al. 2008). Here we correlate unconformity SB3.1 with the transgressive contact WA3 at the base of the Denton Formation in north Texas (text-figs. 6, 7), which is projected to be 100.6 to 100.3 Ma (Scott et al. 2000).

The contact between the Middle and Upper members of the Mesa Rica Sandstone is SB3.2 in the Oklahoma panhandle and nearby parts of New Mexico and Colorado (Scott et al. 2004a). Sequence 3.2 is composed of the Upper Sandstone Member of the Mesa Rica and the flooding marine shale of the Pajarito Formation, which is correlated by upper Albian dinoflagellates (Scott et al. 2004; Oboh-Ikuenobe et al. 2007). Sequence 3.2 correlates approximately with the base of the Mowry Shale in northern Colorado (text-fig. 6) and the Arrow Creek Bentonite in Montana (text-fig. 7). Sequence 3.2 correlates with Washita sequence WA5 by graphic correlation, the base of which is dated at 98.4 and the top at 96.9 Ma (Scott et al. 2000) (text-figs. 2, 7).

Sequence boundary SB4 underlies the lowstand to transgressive Romeroville Sandstone in New Mexico and Oklahoma panhandle and the “D” Sandstone in the Bounds core at the Colorado-Kansas subsurface. Sandstones at the top of the Dakota Group along the Front Range in the sections at Interstate Highway 70 and at the Little Thompson River, and in the Nordman core are approximately equivalent; however this sandstone unit is absent farther north in Colorado (Figs. 6, 7). In Montana the Big Elk Sandstone at the top of the Mowry Shale (Timber Creek section) also occurs in a similar stratigraphic position as the Romeroville and “D” sandstones, but they are not laterally continuous. The transgressive contact at the top of the Romeroville and “D” sandstones is approximately equivalent with the transgressive contact at the top of the Main Street Limestone in north Texas (text-fig. 7). The overlying Graneros Shale in southern Colorado is the flooding to highstand part of this sequence. It is equivalent with the Belle Fourche Shale in Wyoming and Montana. This flooding began at the beginning of the Early Cenomanian based on the first appearances of several dinoflagellate species. Full marine connection was attained by middle Cenomanian time when the Thatcher Limestone Member was deposited at 95.8 Ma. At the end of the Cenomanian Oceanic Anoxic Event 2 is recorded in the Bounds core and in southeastern Colorado (text-figs. 6, 7).

Wyoming-Montana sections

The Albian/Cenomanian section in Montana is composed of four sequences that are defined by widespread surfaces of erosion (Porter et al. 1993; Porter et al. 1997; Porter 1998). The base of the Fall River Sandstone is a lowstand surface of erosion, SB1 (= SB2 of Holbrook and Wright Dunbar 1992) (text-fig. 6) overlying the Kootenai Formation. The top of the Fall River in the Pike Creek section (Mowry.2, fig. 7) is a regional transgressive surface of erosion that is marked by a conglomeratic pebble lag (TS2). The maximum flooding interval is the Skull Creek Member of the Thermopolis Shale, which contains the widespread biomarker, *Inoceramus comancheanus* (Porter et al. 1993, fig. 4). Above the Skull



TEXT-FIGURE 8
Plot projecting Western Interior fossil ranges in metric composite units to a numerical time scale by means of dated beds.

Creek in the basal 4.5m of the informal "unnamed sandy member" of the Thermopolis is a black-weathering pebble lag bed with fish debris that defines their SB2 (= SB3.1 in this report) (Porter et al. 1997, plate 5). Sequence 2 spans most of the sandy member, the Shell Creek Member of the Thermopolis and part of the Mowry Shale. Porter (1998) traces SB1 and SB2 northwestward into southern Alberta, Canada, at the base of the Colorado Sandstone and Bow Island Formation, respectively. These lowstand erosional surfaces are also traced into southwestern Montana (Porter et al. 1993). There they divide the Mowry Shale into two parts by another lowstand surface of erosion, SB3, and its complementary transgressive surface (SB3 of Porter et al. may correlate with SB4 of this study). These surfaces apparently become conformable northeastward into the basin and are not recognized in the Pike Creek section. Porter et al. (1993) designated another erosional surface SB4 in the overlying Belle Fourche Shale. Biostratigraphic data is needed to test the correlation of this unconformity with that at the base of the Woodbine Formation in Texas. The basal part of the Belle Fourche correlates with the Grayson Shale based on the presence of the calcareous foraminifer, *Gubkinella graysonensis* (text-fig. 7).

Correlation of the Pike Creek section south into Wyoming, Colorado and adjacent areas (text-fig. 6) demonstrates that SB1 at the base of the Fall River Sandstone continues as SB2 at the base of the Kiowa-Skull Creek Cycle. SB2 in Montana correlates with SB3.1 at the base of the Muddy Sandstone in Wyoming and northern Colorado and the Mesa Rica Sandstone in southeastern Colorado and New Mexico. However, SB3 in Montana cannot be correlated directly with any of the younger sequence boundaries, SB3.2 and SB4, to the south.

CALIBRATION TO NUMERICAL AGES

Radiometric data

Numerous radiometric dates of bentonite beds in the Albian/Cenomanian section of the Western Interior enable the calibration of fossil ranges. The ranges have been integrated using a thickness scale independent of assumptions about their ages. A simple graph of the metric composite scale to the ages of the dated beds makes it possible to interpolate the ages by means of the correlation lines between the dated beds (text-fig. 8). The ranges in the Mowry CSU data base were determined from the sections in the Western Interior and the Trinity River section at Fort Worth, Texas. These ranges were calibrated to numerical ages by projection to the correlation lines through the dated beds in the data base (Appendices 5, 6, 7). The reported median age of each bentonite bed was plotted at the base of the marker beds. The age of the basal upper Albian transgression in the Western Interior and at the base of the Washita Group in Texas was assumed to be 103 Ma, which is estimated from several different dating methods. Bentonite dates of about 104.4 to 100.9 are from the Thermopolis Formation in Wyoming (Obradovich et al. 1996). By graphic correlation the base of the Purgatoire Formation in western Kansas is dated at 102.8 Ma (Scott et al. 1998), and the base of the Washita in north Texas is dated at about 104 Ma (Scott et al. 2000; Scott et al. 2003). The numerical ages of the ranges of key dinoflagellates, benthic foraminifera, and megafossils are compared with ages reported by Hardenbol et al. (1998) and Williams et al. (2004) (Appendices 4-6). Two factors must be kept in mind when comparing the ages. First, the age of the Albian/Cenomanian boundary is dated differently by these authors and by us thus, the ages of fossils near the boundary will differ. Also the ranges of many dinoflagellates and some other cosmopolitan fossils may be truncated in the Western Interior either by limited sampling or by the timing of transgressions resulting in an abbreviated depositional record or unsuitable facies. These ranges need to be evaluated in long marine sections.

Cyclostratigraphic data

The duration of the Albian Stage was calibrated at two locales in Italy about 13 km apart. In the Piobbico core the Albian was estimated to have been 11.9±0.5 myr based on counts of 31 to 29 406-kyr eccentricity cycles (Grippo et al. 2004, figs. 15 and 16). The total number of cycles is uncertain because of incomplete core recovery in the upper 5.5m and because of a fault at about -26 to -27m (Grippo et al. 2004, p. 76 and fig. 16). Southeast of Piobbico at Monte Petrano the duration of 11.6±0.2 myr was derived from an outcrop of alternating black shale, marl and limestone (Fiet et al. 2001; Fiet et al. 2006). The base of the Albian in both sections is approximated by the FO of the nannofossil *Prediscosphaera columnata* and the top is defined by the FO of *Rotalipora brotzeni*. At Monte Petrano 28 413-kyr eccentricity cycles were identified between these two biomarkers. Thus, these authors estimated the age of the base of the Albian at 108.8 to 109.1 Ma.

To test whether the cycles at Monte Petrano could be correlated in the Piobbico core the two sections were plotted on an X/Y graph. The Monte Petrano section is the more complete and no faults are reported; therefore the 28 Albian cycles were projected into the Piobbico core by means of a line of correlation based on planktic foraminifera common to both sections (text-fig. 9A). Note that some cycles in the Piobbico core do not match with cycles in the Petrano section (Appendix 8). The base and top of Piobbico cycle 26 at 36m and 38m does not correlate with cycle boundaries at Petrano. The base of Piobbico cycle 20 is in the fault zone and does not match the position of a cycle at Petrano. Likewise the base of Piobbico cycle 8 does not correlate with a cycle at Petrano. Cycles in the Piobbico core that have positions closely matching cycles at Monte Petrano were added to the X/Y plot (text-fig. 9B), which shows that they fall close to the line of correlation defined by the foraminifera bioevents. Cycles 15 through 20 plot slightly to the right suggesting that cycle thicknesses vary slightly between the two sections. In fact, the slope is 1.2 indicating that deposition at Petrano was somewhat faster than at the Piobbico site.

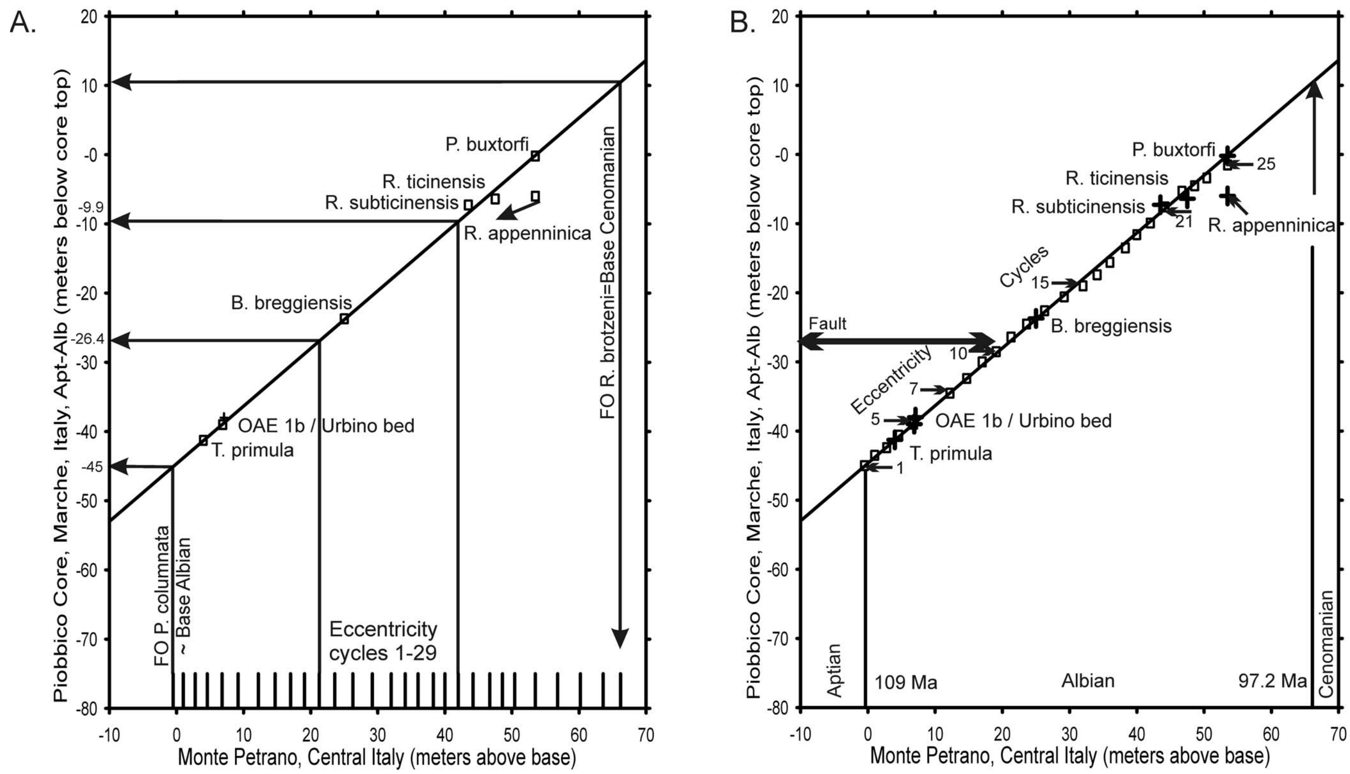
THE DILEMMA

The new biostratigraphic and sequence stratigraphic correlations of the Western Interior Albian/Cenomanian sections with the north Texas section and European sections calibrate the Albian/Cenomanian boundary at 97.2 Ma. However radiometric ages of volcanic tuff beds in a Japanese section with diagnostic marine fossils calibrate the boundary at 99.6 Ma. This 2.4 myr discrepancy poses two questions. 1) What is the accurate age of the boundary? Both cannot be correct. 2) What were the durations of the Albian and Cenomanian stages?

John Obradovich dated sanidine in both the Western Interior bentonites and the Japanese tuff beds by the $^{40}Ar/^{39}Ar$ method, and the precision and accuracy of the laboratory analyses seem to be of the highest quality and the calculations use the most up-to-date factors. So the cause of the difference must be a geologic process. Two potential sources of error are 1) the difference between the time of crystallization and time of deposition and 2) reworking of the sanidine crystals. Tuff beds normally are formed by hot gaseous volcanic eruptions and bentonites are the product of explosive eruptions of air-borne ash. Possibly sanidine crystallized in the magma chamber prior to the eruption of the lava or it was eroded from marginal wall rock of the vents.

The durations of the Aptian, Albian and Cenomanian stages are estimated by cyclostratigraphy. If no cycles are missing at the Monte Petrano section and if the frequency of 413 myr is correct then the Albian may have been 11.6 to 11.9 myr long. Thus the base of the Albian is dated at about 109 Ma suggesting that the duration of the Aptian was 16 myr rather than 13 myr if base Aptian is reliably interpolated at 125 Ma (Ogg et al. 2004). But the Aptian duration is 6.8±0.4 myr as calculated from four cyclostratigraphic studies in France and Italy (Fiet et al. 2006) so the calculated age of the base Aptian would be 115.8 Ma. However two new U/Pb zircon radiometric ages from tuff beds below upper Aptian ammonites in Sonora, Mexico, date uppermost Aptian strata from 118.1± 2.4 to 115.5±0.7 Ma (Gonzáles León et al. 2007). This datum indicates that either the Aptian was much longer than 7 myr or that the Albian was longer than 12 myr or both.

The duration of the Cenomanian Stage also needs to be re-considered. If the accurate age of the beginning of the Cenomanian is 97.2 Ma as projected by dinoflagellate bioevents and sequence correlations and the beginning is 93.5±0.8 projected by Ogg et al. (2004), then the duration of the Cenomanian was 3.7 myr. However, cyclostratigraphy of 212 precession cycles composited from sections in northwestern Europe were assumed to be 21 kyr long, which suggests durations between 4.45 and 5 myr (Gale et al. 1999; Ogg et al. 2004). This pushes back the age of the end Cenomanian to 92.75 to 92.2 Ma, which is significantly younger than the revised radiometric bentonite



TEXT-FIGURE 9
Correlation of sedimentary cycles in the Monte Petrano section with those in the Piobbico core, Italy. A. Projection of long-term eccentricity cycles in the Monte Petrano section into the Piobbico core based on first occurrences of planktic foraminifera and the black shale bed. Piobbico cycles are thus identified with Petrano cycles. The base and top of the Albian are approximated by the bases of two key taxa. B. The bases of cycles common to both sections are plotted on the same correlation line defined by the planktic foraminifera. If the Albian is composed of 28 413-kyr cycles, it was 11.56 myr in duration. OAE = oceanic anoxic event.

date of 93.3±0.2 Ma in New Mexico (Obradovich 1993). But if the duration of the Cenomanian was 3.7 myr, then either the number of cycles was fewer, about 176, or the cycle frequency was shorter, about 17.5 kyr.

The revised correlations of the U.S. Western Interior pose challenging issues for further research and invite study of both new volcanic beds and cyclostratigraphic analyses in other sections of the Aptian, Albian and Cenomanian stages. Calculations of stage durations by cyclostratigraphy must be consistent with radiometric data.

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APPENDICES

Available online at www.precisionstratigraphy.com

1. Mowry measured sections (mowrycat.doc)

2. Mowry Data Base in composite standard units (CSU) relative to Standard Reference Section (SRS) Montana Composite section Mowry 3 without Trinity River Texas section 12/04/07.

3. Stratigraphic positions and composite values of marker beds in Mowry database. [xls]

4. Order of Mowry bioevents that constrain the LOC of graphs [doc file]

5. Numerical ages of key dinoflagellates. [dn.doc]

6. Numerical ages of key benthic foraminifera. [fb.doc]

7. Numerical ages of key megafossils. [am.doc]

8. Albian eccentricity cycles at Mont Petrano and Piobbico core, Italy (Fiet et al. 2001, fig. 4; Grippo et al. 2004, fig. 15). [Appendix 8 eccentricity cycles]