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Cretaceous $\delta^{13}C$ stratigraphy and the age of dolichosaurs and early mosasaurs

L.L. Jacobs*, K. Ferguson, M.J. Polcyn & C. Rennison

Department of Geological Sciences, Southern Methodist University, Dallas, Texas 75275, USA.

* Corresponding author. Email: jacobs@smu.edu

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Abstract

Sediments in north-central Texas, ranging in age from >117 to 85 Ma, represent a variety of terrestrial and marine depositional settings. Isotopic analyses of wood fragments found throughout the section allow correlation to the standard secular marine $\delta^{13}C$ curve because of characteristic peaks at the Aptian-Albian and Cenomanian-Turonian boundaries. Consistency of the north-central Texas $\delta^{13}C$ curve with the marine standard facilitates correlation among non-marine and marine environments on a global scale. Radiometrically dated ammonite zones recognised in Texas provide calibration for the Cenomanian and Turonian portions of the section. Cenomanian and Turonian sediments in north-central Texas preserve the oldest (96 Ma) and the youngest (<85 Ma) well-documented *Coniasaurus*, a dolichosaur also known from the southern North Sea Basin during that interval. *Haasiasaurus*, the oldest known well-documented early mosasaur, is found at 'Ein Yabrud, Israel (98 Ma), followed by other poorly dated Cenomanian taxa from the eastern Mediterranean region, and then by *Dallasaurus turneri* and *Russellosaurus coheni* in Texas (92 Ma) and *Tethysaurus* (90.5 Ma) in Morocco. Neither shifts in $\delta^{13}C$ nor large-scale sea level change seem to have influenced dolichosaur or mosasaur evolution in substantial ways during the Cenomanian and Turonian stages.

Keywords: Carbon, isotopes, Cretaceous, mosasaurs, stratigraphy, Texas

Introduction

In this paper we present an Aptian to Coniacian ^{13}C curve derived from carbonized terrestrial plant remains in north-central Texas. This organic carbon isotope curve is then correlated with the global marine secular carbonate ^{13}C curve for the Cretaceous (Arthur et al., 1985). The correlation is calibrated using radiometrically dated ammonite zones recognised in the Texas section. Local early occurrences of mosasaurs and dolichosaurs are integrated into the resulting comprehensive stratigraphic and chronological framework and compared globally.

North-central Texas (Fig. 1) lay near the southern extent of the North American Western Interior Seaway during the Late Cretaceous. Because of its geographic position, sea level fluctuations governed sedimentary regimes. Coastal and nearshore environments ranging in age from >119 Ma to 85 Ma (Aptian to Coniacian stages) are particularly well represented. In the terrestrial realm, this time interval encompasses significant biotic changes, including the rise of angiosperms, the decline of gymnosperms and the transition from basal tribosphenidan mammals to easily recognisable marsupials and placentals. There was a major mid-Cretaceous turnover in dinosaur faunas. In the marine realm, this interval is particularly significant for mosasaur evolution, the diversification of sea turtles, and as documented in the eastern Mediterranean, possibly the first known invasion of the sea by macrostomatan snakes.

Thus, the >30 million year $\delta^{13}C$ curve reported here samples a complex set of facies during a palaeobiologically significant interval of time in both the terrestrial and marine realms and therefore provides a refined chronology for the events recorded in the region. Moreover, because of the characteristic signature

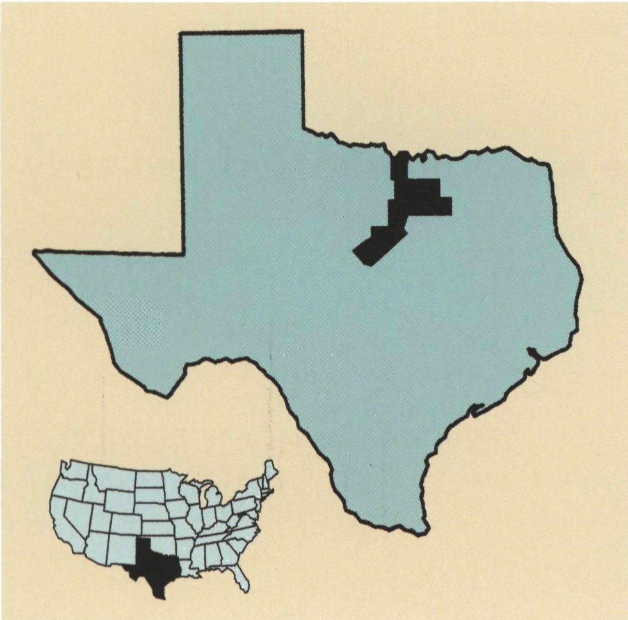

Fig. 1. Location map of study area in north-central Texas (USA).

of the carbon curve during the Cenomanian and Turonian stages, and because of radiometric control provided by dated ammonite zones in the Western Interior Seaway, this long carbon curve is anchored at the portion of the section where mosasaurs were undergoing their initial evolution and diversification. In addition, because the carbon curve is global in application and because the ammonites and their absolute dating are globally relevant for correlation, the record of the earliest occurrences of mosasaurs and dolichosaurs (presumed close relatives of mosasaurs) can be compared across the Cretaceous world.

The reason that carbonized terrestrial plant remains were chosen as samples from which to derive $\delta^{13}C$ values for this study is because plant remains were recovered in marine as well as non-marine facies. All of the marine formations under consideration were deposited in settings into which wood could be washed, waterlogged and preserved. Thus, by using wood samples, isotope values obtained in both marine and non-marine contexts are directly comparable. The carbon isotope curve derived from wood, calibrated by radiometrically dated ammonite zones in the marine Cenomanian and Turonian part of the section and correlated to the global secular carbonate curve, provides a robust chronological tool for the entire marine and non-marine interval in this region.

The theoretical basis for why the variation in organic carbon from plants might mirror secular variation in marine carbonate ratios over time stems from the geologically rapid exchange of carbon among the ocean, the atmosphere, and the biosphere acting as temporary carbon reservoirs prior to the carbon becoming more permanently fixed in the rock record. Plants, as primary producers, should present a similar secular pattern but negatively offset from the marine carbonate record because of the fractionation bias against $\delta^{13}C$ in photosynthesis.

The utility of plant samples and terrestrial organic carbon for isotopic stratigraphy has been demonstrated (e.g., Gröcke et al., 1999; Hasegawa et al., 2003; Robinson & Hesselbo, 2004). The present paper bridges the Early and Late Cretaceous terrestrial organic carbon records presented in those publications. The complex relationship among sea level and terrestrial and marine facies in north-central Texas reflects global sea level curves, which along with ammonite biostratigraphy, complements the $\delta^{13}C$ curve and facilitates long-range correlations.

Stratigraphy of the Eagle Ford Shale

The stratigraphic interval under study encompasses sea level fluctuations both prior to and after the completion of the North American Western Interior Seaway, which transected the continent from north to south. The completion of the Western Interior Seaway occurred at approximately 102 Ma. Prior to that time at the end of the Early Cretaceous, transgressive events were less extensive. The formation of primary concern in this paper is the Upper Cretaceous Eagle Ford Shale because it contains mosasaurs. It overlies the Woodbine Formation, and is itself overlain by the Austin Chalk. The Cretaceous section below the Eagle Ford Shale is discussed by Jacobs & Winkler (1998).

It is necessary to discuss Eagle Ford stratigraphy in some detail because the $\delta^{13}C$ curve is primarily anchored by the characteristic values found in the Eagle Ford, dated ammonite zones are recognised in the Eagle Ford, and the oldest known North American mosasaurs are found in the Eagle Ford. In ascending order, the members of the Eagle Ford Shale are the Tarrant, Britton, Kamp Ranch and Arcadia Park (see also fig. 1 in Polcyn & G.L. Bell, 2005).

The Cenomanian-Turonian boundary falls within the Eagle Ford. A distinct condensed zone occurs at the contact of the Eagle Ford with the overlying Austin Chalk. The Turonian-Coniacian boundary is within the condensed zone in the study area. The Austin Chalk is of Coniacian to Santonian age. A bentonite in the Austin Chalk of Dallas County dated (but not published) by Arco Oil and Gas Company at 85.08±1.66 approximates the Coniacian-Santonian boundary (Gradstein & Ogg, 2004; the reported date is the average of four K/Ar dates on biotites considered reliable because the biotites appeared unaltered; unpublished University of Texas at Arlington MS thesis by Collins, 1997).

Outcrops of the Eagle Ford Shale are transient in the study area due to construction and fossil localities disappear relatively rapidly. It has a total thickness of over 130 m. At its base is the sandy Tarrant Member underlying the Britton Shale Member. The total thickness of the Britton is approximately 100 m. Undated bentonites occur in the Britton above the Tarrant Member. The Britton Shale is overlain by the metre-thick Kamp Ranch Limestone Member at the base of the Arcadia Park Shale Member, which has a total thickness of 30 m. The Kamp Ranch

Limestone is a set of thin, sandy, predominately bioclastic beds composed mostly of calcitic inoceramid bivalve prisms. It contains a diverse fauna, most importantly the ammonite *Collignoniceras woollgari* (Reid, 1952; Kennedy, 1988). Even though the total thickness of the Kamp Ranch Limestone is usually one metre or less, it is found consistently 30 m below the base of the Eagle Ford-Austin contact in outcrops across the study area. It is the most easily recognised marker unit in the Eagle Ford Shale.

An unconformity has been variously placed between the Britton and Arcadia Park shales primarily because of the absence of certain ammonite zones or other biostratigraphic units below the Kamp Ranch Limestone in one outcrop or another or in a well core (Kennedy, 1988; Kennedy & Cobban, 1990; and references therein). Kennedy (1988, p. 12), based on one transient roadside outcrop, stated, 'There is an unconformity 2.5 m below the Kamp Ranch Limestone, the latter being the mappable base of the Arcadia Park Formation.' We have been unable to locate the unconformity recognised by Kennedy in the outcrops we have examined and therefore reject the notion that the base of the Arcadia Park is mappable at that position.

Table 1 lists Western Interior ammonite zones (Kennedy, 1988; Kennedy & Cobban, 1990) as recognised in the Eagle Ford study area. Radiometric dates for ammonite zones given are those reported in Gradstein et al. (1995; from Obradovich, 1994). The base of the Eagle Ford (i.e., the Tarrant Member) contains *Conlinoceras tarrantense*, an equivalent of the *Conlinoceras gilberti* Zone of the Western Interior. The overlying *Acanthoceras bellense* Zone is not recorded in the study area, although the next higher zone, the *Acanthoceras amphibolum* Zone, is present in both the Britton Shale and Lewisville Member of the Woodbine Formation. The overlying *Plesiacanthoceras wyomingense cobbani* Zone is absent from the Eagle Ford but recorded in the Templeton Member of the Woodbine Formation. The overlying two zones (*Calycoceras canitaurinum*, *Metoicoceras mosbyense*) are not reported, but they are followed by the *Sciponoceras gracile* Zone in the Britton. The three succeeding zones (*Burroceras clydense*, *Neocardioceras juddii* and *Nigericeras scotti*) are not reported. That is where Kennedy (1988) placed an unconformity and the contact of his Britton and Arcadia Park formations. A formational contact placed in that position is 2.5 metres below the Kamp Ranch Limestone, as discussed above. In that interval, the *Pseudaspidoceras flexuosum* and *Vascoceras birchbyi* zones are reported, as is the *Collignoniceras woollgari* Zone in the Kamp Ranch; however, the intervening *Mammites nodosoides* Zone is not. *Collignoniceras woollgari* is a significant taxon for long-distance correlation.

Above the Kamp Ranch, most of the Arcadia Park is in the *Prionocyclus hyatti* and *Prionocyclus macombi* zones. The *Prionocyclus percarinatus* Zone is not reported, nor are the

Table 1. Cenomanian and Turonian ammonite zones of the Western Interior Seaway (after Kennedy, 1988; Kennedy & Cobban, 1990). Radiometric dates after Obradovich (1994), as discussed by Gradstein et al. (1995). Note that the Cenomanian-Turonian boundary falls between the S. gracile *and* P. flexuosum *zones in the study area. Zones recognised in Dallas are in bold face. An asterisk (*) denotes zones recognised in Eagle Ford sections elsewhere or in the Woodbine Formation.*

Prionocyclus quadratus (not reported)
**Scaphites whitfieldi* (not reported in study area, but present in the Waco area)
**Prionocyclus wyomingensis* (not reported in study area, but present in northern Collin and southern Grayson counties)
Prionocyclus macombi **(Arcadia Park; 90.21±0.72; most of this zone missing in study area)**
******Prionocyclus hyatti*** **(Arcadia Park, 90.51±0.45; Bouldin Member of Lake Waco Formation and South Bosque Formation)**
Prionocyclus percarinatus (not reported)
Collignoniceras woollgari **(Kamp Ranch)**
Mammites nodosoides (not reported)
Vascoceras birchbyi **(below Kamp Ranch, 93.40±0.63)**
Pseudaspidoceras flexuosum **(below Kamp Ranch, 93.23±0.55; early Turonian)**
Nigericeras scotti (not reported)
Neocardioceras juddii (not reported; 93.30±0.40, 93.78±0.49, 93.59±0.58; late Cenomanian)
Burroceras clydense (not reported)
Sciponoceras gracile **(Britton; correlative with *Metoicoceras geslinianum* Zone in Europe)**
Metoicoceras mosbyense (not reported)
Calycoceras canitaurinum (not reported)
**Plesiacanthoceras wyomingense cobbani* (Woodbine, Templeton Member, not known in Eagle Ford)
******Acanthoceras amphibolum*** **(Britton, 94.93±0.53; Blue Bonnet Member of Eagle Ford south of Dallas-Fort Worth area; Lewisville Member of Woodbine)**
**Acanthoceras bellense* (Bluebonnet Member of Eagle Ford in Bell County)
******Conlinoceras tarrantense*** **(= *C. gilberti* Zone, Tarrant Member of Eagle Ford, 95.78±0.61)**

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Prionocyclus wyomingensis and *Scaphites whitfieldi* zones (although the *Prionocyclus wyomingensis* Zone is recognised in Eagle Ford outcrops to the north and the *Saphites whitfieldi* Zone to the south; Kennedy, 1988).

Thus, of the twenty ammonite zones for the Western Interior Seaway listed by Kennedy (1988), twelve (60%) are not known from the study area. Of those twelve, four have been reported from the Eagle Ford elsewhere or from the Woodbine Formation. As for the stratigraphic distribution of zones missing from either the Woodbine or the Eagle Ford in the study area, two sets occur in groups of three and three are single zones interspersed among those represented.

Kennedy (1988) suggested that the unconformity below the Kamp Ranch may vary in magnitude or that there may be more than one unconformity present. Judging from the number and distribution of missing zones, that could well be correct. Nevertheless, dates on the *Neocardioceras juddii* Zone (Table 1) suggest that the maximum hiatus in a Britton-Arcadia Park unconformity (if one exists) could be on the order of 100,000 years and quite likely could be considerably less. The local absence of ammonite zones in specific sections is not unlikely, but the recognition of a clear regional unconformity within the study area is difficult.

Nevertheless, the distribution and recognition of missing zones in the region, and the presence of the same zone in adjacent formations is relevant to understanding temporal relationships and palaeogeography. Part of the Lewisville Member of the Woodbine Formation in the study area has an *Acanthoceras amphibolum* Zone fauna, as does the lower Britton. Further north, the Templeton Member of the Woodbine has a *Plesiacanthoceras wyomingense cobbani* Zone fauna, which is younger than *Acanthoceras amphibolum*, and which is not reported from the Eagle Ford. These examples indicate the time-transgressive nature of the rock units involved and demonstrate a close proximity to the shoreline as expressed in time-equivalent facies.

Essentially all samples used for isotopic stratigraphy are point samples, as are most macrofossil, including mosasaur and dolichosar, localities. For the purposes of this study, it is only necessary to demonstrate superposition of the point samples to develop a carbon isotope curve for the Tarrant, Britton, Kamp Ranch and Arcadia Park units within the Eagle Ford Shale. The stratigraphic position of dated ammonite zones within that sequence provides age constraints on samples and on first occurrences of mosasaurs and dolichosaurs in the section.

Methods

Our primary objective is to present the Cretaceous $\delta^{13}C$ stratigraphy of north-central Texas based on carbonized terrestrial plants. Carbon isotopic ratios are expressed as delta values measured in parts per thousand (‰) relative to the PDB standard (Craig, 1957). Delta values are calculated as follows:

$$\delta^{13}C = [(^{13}C/^{12}C)_{sample} \;/\; (^{13}C/12C)_{standard} - 1] \times 1000$$

The original framework for this study was a suite of 291 samples collected by Rennison (1996; Table 2). Additional samples were collected specifically for this study (Table 3). Laboratory methods are described in the Appendix 1.

Results

Figure 2 shows the marine carbonate $\delta^{13}C$ curve redrawn from Arthur et al. (1985). The relevant portion of the curve begins with relatively depleted values in the Aptian, becoming enriched in the upper Aptian and lower Albian. The remainder of the Albian and most of the Cenomanian trends negatively. In the upper Cenomanian and Turonian there is a sharp positive increase followed by a rapid upper Turonian and Coniacian depletion of $\delta^{13}C$, then a return to more positive values. This is a characteristic pattern not repeated elsewhere in the Cretaceous.

The organic carbon curve derived from carbonized terrestrial plant fragments closely tracks the marine carbonate curve for its entire interval. However, the organic carbon curve is consistently offset (depleted) relative to the marine carbonate curve by approximately 25‰. Nevertheless, the extreme negative excursion following a rapid positive excursion expressed in the upper Eagle Ford Formation and lower Austin Chalk is particularly compelling and argues strongly for consistency between the two curves. Therefore, the characteristic pattern allows regional and global correlation based on carbon isotopes.

The two most important portions of the curve for correlation are the positive spike in the Aptian and early Albian and the positive spike encompassing the Cenomanian-Turonian boundary. The negative spike at the end of the Turonian extends into the Coniacian in the Texas section. In a regional context, relatively positive values indicate that the Antlers Formation in Oklahoma, at least the portion from which samples were derived, is late Aptian to early Albian in age, correlating with the middle Twin Mountains to middle Glen Rose formations. This correlation links terrestrial vertebrate-bearing sections and the marine Glen Rose (see Jacobs & Winkler, 1998, for discussion of formations below the Woodbine).

Globally, the lower portion of the isotope curve in Texas correlates with an Aptian-Albian organic carbon curve from Australia reported by Ferguson et al. (1999) although the Australian values are offset by ~ −2‰ from Texas values. The Texas curve correlates through the Aptian-Albian spike with a curve based on terrestrial wood from the Wealden Group of southern England (Robinson & Hesselbo, 2004), and through the Cenomanian-Turonian peak with a carbonate curve from the overlying English Chalk and Italian Scaglia (Jenkyns et al.,

Table 2. Mean $\delta^{13}C$ value for plant sample locations for the lower portion of the Texas Cretaceous section (Aptian-Cenomanian; data from Rennison, 1996).

Locality	Unit	Number of samples	Mean $\delta^{13}C$ value	Standard deviation	Stratigraphic level (m)
Bear Creek	Woodbine	4	−23.5	1.5	397
Lake Grapevine	Woodbine	7	−21.7	0.7	390
Ruth Wall. Street	Woodbine	4	−22.0	1.1	389
FM 2499	Woodbine	9	−23.6	0.7	387
Valley Lane	Woodbine	1	(−23.5)		352
Twin Coves	Woodbine	2	−23.8	1.2	342
Exit 21c on IH 30	Woodbine	7	−23.5	1.9	309
Old Decator Road	Washita	1	(−21.1)		217
US 377, Erath	Paluxy	1	(−22.3)		157
Lake Worth Point	Paluxy	2	−22.6	0.0	156
Eagle Mountain Lake	Paluxy	3	−22.6	0.3	151
Lake Weatherford	Paluxy	1	(−23.2)		150
Perkins Road	Paluxy	1	(−21.1)		146
Lake Granbury	Glen Rose	5	−21.3	0.5	101
Barker Branch	Glen Rose	7	−21.8	1.6	57
Cedar Brake	Glen Rose	3	−21.9	0.8	54
Paluxy River	Glen Rose	3	−21.2	0.6	53
Jones Ranch	Twin Mountains	5	−21.5	0.7	36
Doss Ranch	Twin Mountains	4	−21.6	0.8	33
Hobson Ranch	Twin Mountains	4	−20.8	0.8	23
Garner-Adell Road	Twin Mountains	1	(−20.1)		10
Promontory Park	Twin Mountains	2	−22.6	1.1	5
Leon River	Twin Mountains	1	(−23.6)		0.3

Table 3. Mean $\delta^{13}C$ value for plant sample locations for Woodbine Formation, Eagle Ford Shale and Austin Chalk (Cenomanian-Coniacian).

Locality	Unit	Number of samples	Mean $\delta^{13}C$ value	Standard deviation	Ammonite zone	Approximate age
Pinnacle	Austin	1	−22.5			
Frisco	Basal Austin	1	−23.9			89
Celina Needlefish	Arcadia Park	1	−25.1		*P. hyatti*	91
4 Localities	Kamp Ranch	4	−24.1	1.2	*C. woollgari*	92
Grapevine Creek	Britton	1	−24.2		*S. gracile*	94
Protohadros Locality (SMU 303 = FM 2499)	Woodbine	1	−23.9			96
Grapevine Paleosol	Woodbine	2	−23.1	0.1		96

1994). Further, the long terrestrial organic carbon curve from the Naiba section (Sakhalin Island, Far East Russia; see Hasegawa et al., 2003), extends from the Cenomanian through the Maastrichtian. The Cenomanian and Turonian portions of the curve presented by Hasegawa et al. (2003) have been correlated with equivalent parts of isotopic curves from Kansas, Colorado, England, Italy and Japan, and now the isotopic curve can be correlated with the Texas section. The sampling of the Texas section is less dense than that presented for the Cenomanian-Turonian of Pueblo (Colorado) by Keller et al. (2004) and therefore cannot be compared at such fine detail, although the correlation between those two sections is not in question.

Discussion and conclusions

The interval considered here extends from beyond 117 Ma (Aptian) to 85 Ma (Coniacian), thus spanning a length of time approaching 35 million years in duration. One of the important attributes of stable carbon isotope stratigraphy is that it can be applied in both marine and non-marine settings, using either carbonate or organic carbon. Clearly, secular changes in $\delta^{13}C$ reflect global reservoir dynamics. However, offsets in values in curves with similar topologies, such as the −2‰ offset of organic carbon from Australia relative to Texas, are difficult to explain and beyond the scope of the present paper.

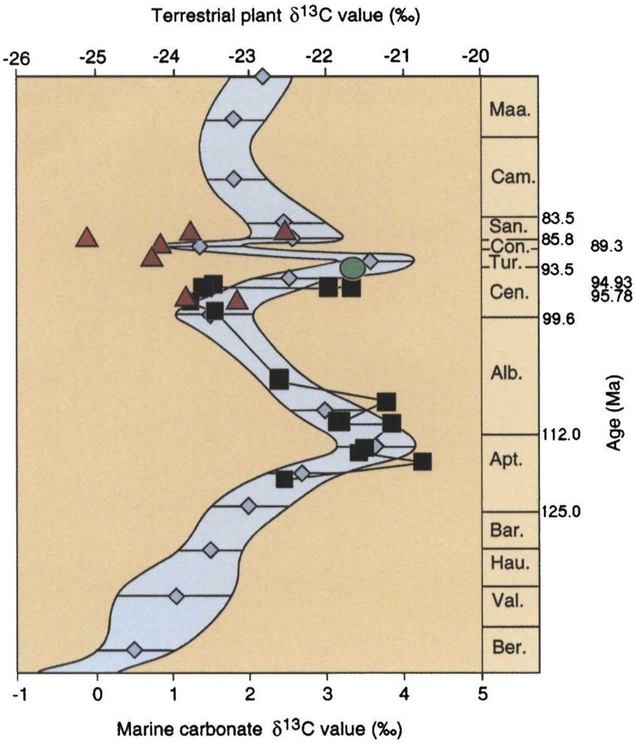

Fig. 2. $\delta^{13}C$ values of pelagic marine carbonates and Texas terrestrial plant fossils versus age. Note the horizontal scales are offset by 25‰. Marine curve redrawn from Arthur et al. (1985); time scale based on Gradstein & Ogg (2004). Texas plant values (solid squares) from Rennison (1996) and (open triangles) determined for the present study. Siderite value from Eagle Ford Shale (open circle) from Jacobs et al. (2005). Age estimates of stage boundaries from Gradstein and Ogg (2004). Other dates are for ammonite zones from Obradovich (1994; 95.78 = C. tarrantense *Zone, 94.93 =* A. amphibolum *Zone).*

Particularly significant with respect to the broad utility of carbon isotopes is its relevance to changing sea level. This is obvious in the Texas section, which trends from more terrestrial to more marine throughout the interval under consideration. The same pattern holds true for southern England and for the Mediterranean region (Ettachfini & Andreu, 2004), and for the same reason: global sea-level rose during the Cretaceous. Jenkyns et al. (1994) presented a discussion of carbon isotope changes and sea levels as they relate causally to transgressions and regressions in the Anglo-Paris Basin. Such a discussion based on our data from Texas is beyond the scope of the present paper and must be taken up elsewhere. Nevertheless, the discussion of Jenkyns et al. (1994) is consistent with secular variation in the $\delta^{13}C$ curve being a consequence of carbon sequestration through burial and to erosion of carbon reservoirs, and thus affected by global sea level and shelf exposure.

Given the geological and environmental setting of advancing and retreating seas, the Cenomanian and Turonian stages are especially relevant for mosasaurs adapting to life in the sea (Polcyn et al., 1999). Thus, supported by the general correlations of the carbon isotope curves, the ages of early mosasaurs and dolichosaurs can be placed in a framework utilizing sea-level events, biostratigraphy and correlated absolute age determinations. Specifically, the ammonite zones recognised in the Eagle Ford Formation of Texas allow correlation to areas of the Western Interior Seaway where some of the zones have been radiometrically dated, and to other regions around the globe where particular ammonite zones and dolichosaurs and primitive mosasaurs also occur.

Age of dolichosaurs and early mosasaurs in north-central Texas

Dates on ammonite zones in the Eagle Ford constrain the absolute ages of mosasaurs and dolichosaurs in the north-central Texas section. The dolichosaur *Coniasaurus* (B.A. Bell et al., 1982) first appears in the Tarrant Member of the Eagle Ford and ranges throughout the formation. Thus, its first occurrence in this section is 96 Ma (*Conlinoceras tarrantense* Zone). However, a portion of the lower Cenomanian is missing in Texas at the base of the Woodbine Formation. The youngest record of *Coniasaurus* in Texas is in the condensed between the Eagle Ford and AUstin Chalk, in which the Turonian-Coniacian boundary (89.3 Ma) falls.

The type specimens of *Dallasaurus turneri* and *Russellosaurus coheni*, both primitive mosasaurs (G.L. Bell & Polcyn, 2005; Polcyn & G.L. Bell, 2005), occur less than 20 cm above the Turonian Kamp Ranch Limestone, which lies in the *Collignoniceras woollgari* Zone. The ten metres overlying the Kamp Ranch have no reported ammonites and the *Prionocyclus percarinatus* Zone is not recorded. Because of the proximity of *Dallasaurus* and *Russellosaurus* to the Kamp Ranch, we consider that the position of the types approximates the *Collignoniceras woollgari* Zone. In addition, fragmentary specimens of *Russellosaurus* are found in the Kamp Ranch at several localities. At any rate, the absolute age is constrained by the underlying *Vascoceras birchbyi* Zone (93.40±0.63) and the overlying *Prionocyclus hyatti* Zone (90.51±0.45), each separated from the *Collignoniceras woollgari* Zone by one missing zone (Table 1). An estimate of ~ 92 Ma for the first appearance of these primitive mosasauroid taxa is not unreasonable.

Dolichosaurs, primitive mosasaurs, or both, have been reported from further north in the Western Interior Seaway (G.L. Bell & VonLoh, 1998; VonLoh & G.L. Bell, 1998), from west Texas (G.L. Bell & VonLoh, 1998) and from Mexico (Buchy et al., 2005). A plesiopedal mosasauroid from Nuevo León is reported to be early Turonian in age (*Watinoceras coloradoense* Zone; Buchy et al., 2005). Other occurrences of dolichosaurs or mosasaurs appear to be no older than middle Turonian (*Collignoniceras woollgari* Zone, ~ 92 Ma; G.L. Bell & VonLoh, 1998). Therefore, none of these occurrences requires modification of our discussion of north-central Texas in any critical way.

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The age of dolichosaurs and primitive mosasaurs in Europe, Africa and the Middle East

There are relatively few occurrences of dolichosaurs and primitive mosasaurs globally. In addition, earlier collections made in Europe do not bear the level of stratigraphic control that is required for precise correlation. For this review, biostratigraphic correlation follows Hardenbol et al. (1998) and Hardenbol & Robaszynski (1998). The relevant stages for dolichosaur and primitive mosasauroid occurrences are the Cenomanian and Turonian, which include ammonite zones that can be recognised over long distances and therefore facilitate trans-Atlantic correlation. The only reported candidate for primitive mosasaur older than Cenomanian is *Proaigialosaurus* from Solnhofen (southern Germany), known solely from the type specimen which is now lost and whose description is inadequate to verify its status (Carroll & DeBraga, 1992).

Anglo-Paris Basin

Dolichosaurus and *Coniasaurus* were first discovered during the nineteenth century in Kent (southern England), which lies near the centre of the Anglo-Paris Basin, a southern extension of the North Sea Basin. The biostratigraphy for the Cenomanian and Turonian stages of the Anglo-Paris Basin has been well studied, as has the Cenomanian sequence stratigraphy of sections both near the basin margin and towards the centre (Robaszynski et al., 1998). Robaszynski et al. (1998) studied the Kent succession between Folkestone and Dover in the North Downs; however, *Coniasaurus* has also been recovered from the South Downs.

Caldwell (1999) and Caldwell & Cooper (1999) reviewed the stratigraphic distribution of each specimen of two species of British *Coniasaurus*. While there is considerable uncertainty regarding exact stratigraphic placement according to original records, none appears older than the upper portion of the *Mantelliceras mantelli* Zone (lower, but not lowest, Cenomanian). On the other hand, some or all of the specimens could be younger, although none appears younger than the Plenus Marls, which fall within the *Metoicoceras geslinianum* Zone (equivalent to the *Sciponoceras gracile* Zone of the Britton Member in Texas) of the upper (but not uppermost) Cenomanian (but see Caldwell, 1999, p. 440). Overlying the Plenus Marls is the Melbourn Rock, which contains the latest Cenomanian *Neocardioceras juddii* Zone (overlying the *M. geslinianum* Zone) and the *Watinoceras coloradoense* and *Mammites nodosoides* zones of the lower Turonian. The Cenomanian-Turonian boundary lies within the Melbourn Rock.

According to Caldwell & Cooper (1999) the stratigraphic distribution of *Dolichosaurus longicollis*, the type and only named species of the genus, is similar to that of *Coniasaurus*. The holotype is from the *Holaster subglobosus* Zone, which extends from the upper part of the ammonite *Acanthoceras rhotomagense* Zone to the base of the *Neocardioceras juddii* Zone, or middle to upper Cenomanian (Hardenbol et al., 1998; Robaszynski et al., 1998).

In terms of sequence stratigraphy, the base of the Plenus Marls (the highest unit that may have produced the known English dolichosaur specimens) rests on a marked erosion surface interpreted as the summit of Robaszynski et al.'s (1998) Sequence 5. The initiation of Sequence 6 begins within the Plenus Marls, following a hardground and erosional surface, which therefore documents discontinuous sedimentation within the Plenus Marls. The Plenus Marls fall within the positive $\delta^{13}C$ spike at the Cenomanian-Turonian boundary measured in the English Chalk (Jenkyns et al., 1994). The *Neocardioceras juddii* Zone, which lies above the Plenus Marls, has been dated at ~ 93.5 Ma in the Western Interior Seaway, providing a radiometric date for the Cenomanian-Turonian boundary and for the $\delta^{13}C$ excursion.

Caldwell & Cooper (1999) suggested that the upper limit to *Coniasaurus* in England may be a reflection of extinctions at the Cenomanian-Turonian boundary. However, Rage (1989) reported a dolichosaur vertebra from France, found within the middle Turonian *Collignoniceras woollgari* Zone. *Dolichosaurus* is not known outside of Europe, but *Coniasaurus*, a dolichosaur, occurs in the Turonian of North America and France, younger than it is known in England. It is unclear how the stratigraphic distribution of *Coniasaurus* (or other dolichosaurs) would fit into a specific Cenomanian-Turonian boundary extinction scenario for England in the Anglo-Paris Basin, although the interval surrounding the Cenomanian-Turonian boundary was clearly a time with significant sea level change and coeval isotopic excursions. At any rate, the oldest dolichosaurs in the Anglo-Paris Basin cannot be demonstrated to be older than those known from North America, but the youngest North American *Coniasaurus* is younger than any documented from the Anglo-Paris Basin.

Northwest Germany

The stratigraphically most precisely placed specimens of *Dolichosaurus* and *Coniasaurus* in Europe are from the Halle/Westfalen area in NW Germany. The region was in the southern North Sea Basin and separated from the Anglo-Paris Basin by the submarine London-Brabant High. Diedrich (1997, 1999) reported both *Dolichosaurus longicollis* and *Coniasaurus crassidens* from the upper Cenomanian *M. geslinianum* Zone in scour troughs referred to as the *Puzosia* Event I. The erosional surface on which the *M. geslinianum* Zone is deposited in Germany appears correlative with that at the base of the Plenus Marls in England. If so, the German occurrences are consistent with the youngest likely placement of *Dolichosaurus* and *Coniasaurus* in England.

Eastern Mediterranean, Kazakhstan and Africa

Dolichosaurs and primitive mosasaurs have a wide distribution along the Mediterranean and its tectonic precursors. Averianov (2001) identified a dolichosaur vertebra from what he termed an upper Cenomanian?-Turonian horizon in Kazakhstan. The plesiopedal mosasaurs *Aigialosaurus*, *Opetiosaurus* and *Carsosaurus* are known from the Adriatic region. Most of the specimens were collected in the nineteenth century and all are referred to as being Cenomanian-Turonian in age without further precision (Carroll & DeBraga, 1992).

Polcyn et al. (1999) explored the distribution of Adriatic early mosasaurs in the context of plate tectonics and dynamic sea levels. The large-scale sea level curve of Haq et al. (1988) was integrated into a biogeographic scenario of the eastern Mediterranean region (including Croatia and Israel) as it pertained to the tectonic assembly of southern Europe. Increasing water depth throughout the Cretaceous is a major large-scale attribute of the sea level curve and is consistent with the Texas section, the Anglo-Paris Basin, the eastern Mediterranean and Africa. As sea level was rising during the Cretaceous, the carbonate platforms of northeastern Gondwana were developing, even as Apulia and other microcontinents were rifting from Africa and drifting northwards to dock as southern Europe. Balkan mosasauroid localities can be viewed in this context.

In Israel, the locality of 'Ein Yabrud produced the plesiopedal mosasaur *Haasiasaurus gittelmani* (Polcyn et al., 1999, 2003). The age of 'Ein Yabrud is constrained by Albian ammonites in the underlying Kesalon Formation and the Early Cenomanian ammonites *Graysonites wooldridgei* and *Stoliczkaia amana*, which occur within the Bet Meir Formation (Lewy & Raab, 1978). Those ammonites appear to correlate with the *Mantelliceras mantelli* Zone of more boreal regions such as the Anglo-Paris Basin (see Lewy, 1990, p. 624). Thus, *Haasiasaurus gittelmani*, from the Early Cenomanian and approximately 98 Ma in age, is currently the oldest documented mosasaur.

In Lebanon, three relevant Cenomanian localities are known: Hajula, Hakel and Al Nammoura. The first two were discussed by Hückel (1970; see also Saint-Marc, 1975) and their depositional setting examined along with 'Ein Yabrud by Lewy & Raab (1978). The dolichosaur *Aphanizocnemus libanensis* and an undescribed taxon (Dal Sasso & Renesto, 1999) were discovered at al Nammoura (Dalla Vecchia & Venturini, 1999). The description of Al Nammoura and the quality of the fossils are more reminiscent of 'Ein Yabrud than the other Lebanese localities because of the presence of plants and tetrapods. Anoxic conditions leading to exquisite fossil preservation at al Nammoura (e.g., Caldwell & Dal Sasso, 2004) were terminated by an influx of oxygenated waters that supported benthic foraminifera and indicate a middle Cenomanian age for the site (Dalla Vecchia & Venturini, 1999), younger than either Hajula and Hakel in Lebanon or 'Ein Yabrud in Israel.

The mosasaur *Tethysaurus nopcsai* was described by Bardet et al. (2003) from the Goulmima region of Morocco; its phylogenetic position is discussed by Polcyn & G.L. Bell (2005). Although the exact provenance of the type specimen is unknown, the beds from which *Tethysaurus* was likely derived have generally been considered to be of early Turonian age (Cavin & Dutheil, 1999). However, Ettachfini & Andreu (2004) have shown that the beds in question extend into the upper middle and upper Turonian because of the discovery of the ammonites *Pseudaspidoceras* sp. and *Coilopoceras* sp., or in terms of European ammonite zones the upper *Romaniceras deverianum* and lower *Subprionocyclus neptuni* zones. These, in turn, correlate with the *Prionocyclus hyatti* and *P. macombi* zones of the Western Interior Seaway, dated at 90.51±0.45 and 90.21±0.72, respectively.

Summary

Globally, the oldest well-dated dolichosaur is *Coniasaurus* at 96 Ma (middle Cenomanian). Both its oldest and youngest (85 Ma) records are in the north-central Texas region. The oldest known primitive mosasauroid is *Haasiasaurus* (98 Ma, early Cenomanian) from 'Ein Yabrud, Israel. 'Ein Yabrud was deposited in an intertidal setting, but a eustatic drop was eschewed by Lewy (1990) in favour of a biosedimentary model that induced local shallowing and restriction on a carbonate shelf. Assuming the accuracy of the age estimate for 'Ein Yabrud, this interval falls within a time of relatively low sea level and missing section in north-central Texas, and during a time of negative $\delta^{13}C$ excursion.

The Cenomanian-Turonian transition is marked by a major positive $\delta^{13}C$ excursion. The Plenus Marls, which underlie the Cenomanian-Turonian boundary and mark the maximum transgression of the North Atlantic Transgressive-Regressive Cycle (Jacquin & de Graciansky, 1998), are included in the $\delta^{13}C$ excursion. The transgression of the North Atlantic Cycle is the greatest of the Cretaceous Period. The dolichosaurs from Halle/Westfalen (Germany) are from strata correlative with the Plenus Marls. The youngest dolichosaur known from Europe is middle Turonian in age, and they are also known from North America in the Turonian. Because dolichosaurs have been recorded from above the Cenomanian-Turonian boundary, and they are known both above and below maximum flooding marked by the Plenus Marls, there is no clear link between these events and global or regional dolichosaur extinction at the current level of resolution (*contra* Caldwell & Cooper, 1999).

In the middle Turonian of north-central Texas, the mosasaurs *Dallasaurus turneri* and *Russellosaurus coheni* are ~ 92 Ma. Both were found within 20 cm above the Kamp Ranch Limestone, which lies in the *Collignoniceras woollgari* Zone. The Kamp Ranch Limestone is a bioclastic unit that may reflect a small-scale sea level drop during the Turonian (Haq et al., 1988). The *Collignoniceras woollgari* Zone is also recognised in the clastic unit of the upper Ora Formation in Israel (Lewy & Avni, 1988; Lewy, 1989, 1990), suggesting homotaxis that is consistent with (but does not prove) a synchronous global event. *Tethysaurus* of Morocco, at 90.5 Ma, is ~ 1.5 million years younger than *Dallasaurus*.

It remains intuitive that the evolution of marine squamates should be influenced by sea level, but just how sea level might have influenced the origin and early evolution of dolichosaurs and mosasaurs is more problematic. There being no substantive evidence to the contrary, it appears that dolichosaurs and mosasaurs began their evolution as distinct aquatic groups near the beginning of the Late Cretaceous, around the start of the Cenomanian Stage. This was also a time of widespread carbonate shelves and epeiric seas leading to the highest transgression of the Cretaceous. It appears that dolichosaurs (almost certainly) and mosasaurs (probably) had global distributions during the Cenomanian in nearshore marine environments where water temperatures and other ecological factors were tolerable. Dolichosaurs apparently went extinct around the Turonian-Coniacian boundary, based on young occurrences in the Texas section, for reasons unknown to us. Mosasaurs, on the other hand, evolved, diversified and flourished throughout the Late Cretaceous until the Cretaceous-Paleogene extinctions. For both dolichosaurs and mosasaurs, neither sea level changes nor sweeping (and possibly correlated) $\delta^{13}C$ excursions of the middle portion of the Cretaceous seem to have had deleterious effects.

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Appendix 1

Methods

All organic carbon-bearing samples were treated with 1 N HCl to dissolve carbonate. Samples were rinsed with distilled water and dried. Examination of each sample under a binocular microscope allowed identification of wood, stem and leaf fragments. Organic carbon samples were processed in the Stable Isotope Laboratory of the Department of Geological Sciences at Southern Methodist University (SMU) using the method described by Boutton (1991). Samples were weighed and placed in vycor sample boats. Sample weights varied depending on the plant material, for example, 1 - 5 mg of clean wood, stem or leaf material, and up to 297 mg of sand with sparse plant fragments were used. Sample boats were placed in vycor combustion tubes previously loaded with ~ 1 g of CuO wire, and ~ 0.5 g of Cu turnings was added. The tube was shaken gently to ensure contact between substances, then evacuated and sealed. To convert organic carbon to carbon dioxide gas, the tube was heated to 900° C for two hours, cooled at 1° per minute (25° per 25 minutes) to 650° for two hours, and cooled to room temperature. The tube was broken on a carbon vacuum extraction line and the CO_2 purified cryogenically. The $\delta^{13}C$ value of the gas was measured on a Finnigan MAT delta E, 251 or 252 mass spectrometer.

Vycor tubing and CuO were heated prior to use to remove organic contaminants, and Cu was washed with 99.8% pure benzene to remove contaminants. Unwashed Cu used to run the initial samples was found to produce a significant amount of CO_2 gas; 0.5 g of Cu placed in each combustion tube releases 7 µmoles of CO2 with an average $\delta^{13}C$ value of −26.6 ‰. Using mass balance equations, samples run with contaminated Cu were corrected. 0.5 g of washed Cu produced 0.9 µmoles of CO_2 with a $\delta^{13}C$ value of −27‰, so a correction was applied to all later samples to remove the effect of this contaminant. On large samples this correction was insignificant with values for the standard typically changing 0.01‰, which is less than the analytical precision. On smaller samples the correction had greater effect, but values remained within the envelope defined by other samples.

Suites of two samples and a graphite standard were treated with base solutions of differing concentration to determine whether adhered modern organic matter was a significant contaminant. 5 - 10 mg of a dense amorphous wood, a porous wood with well-preserved cell structure, and a graphite standard were treated with 0.27 N, 0.67 N, or 0.11 N NaOH solution following 1 N HCl treatment. Only the porous wood showed any colour change during the 24-hour base treatment. These samples did not show further reaction during a second base treatment. All samples were neutralised, reacidified to remove any precipitated carbonate, and neutralised again.

The $\delta^{13}C$ value of each sample treated with base solution was measured, as was the D value of four samples, to determine whether the base treatment removed adhered modern organic matter and thus altered the isotopic value. Isotopic values showed no consistent offset following base treatment; therefore, all other analyses were performed on samples that had been treated with acid only.

To measure a sample's D value, water was collected from each sample in a dry ice-methanol slush on the carbonate extraction line after standard sample preparation and heating. The water was frozen into a sample tube and transferred to the hydrogen silicate line where each sample was purified and its volume measured. The D value was measured on a Finnigan MAT 252 mass spectrometer.

Carbonate whole rock samples were analysed using standard techniques. Between 9 and 160 mg of samples were placed in a reaction vessel with 3 mils of 100% phosphoric acid, evacuated, then left to react for 8 hours at 25° C. The CO_2 gas was purified cryogenically and its isotopic composition was measured on a Finnigan MAT delta E or 252 mass spectrometer. Care was taken in the carbonate sample selection to avoid areas of high organic carbon content, although organic contamination was unlikely due to the low temperature of the carbonate extraction process.

Descriptions, locations and statistical evaluations of samples collected from the Woodbine and lower formations are included in Rennison's MSc thesis (1996, on file at the Department of Geological Sciences, SMU, Dallas, Texas). Additional samples, especially from the Eagle Ford Formation and Austin Chalk, were collected specifically for this study.