The Boquillas Formation of the Big Bend National Park, Texas, USA, a reference Cenomanian through Santonian (Upper Cretaceous) carbonate succession at the southern end of the Western Interior Seaway

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ABSTRACT:

Cooper, R.W., Cooper, D.A., Stevens, J.B, Stevens, M.S. Cobban, W.A. and Walaszczyk, I. 2017. The Boquillas Formation of the Big Bend National Park, Texas, USA, a reference Cenomanian through Santonian (Upper Cretaceous) carbonate succession at the southern end of the Western Interior Seaway. *Acta Geologica Polonica*, **67** (4), 547–565. Warszawa

The upper lower Cenomanian through middle Santonian (Upper Cretaceous) of the Boquillas Formation in the Big Bend Region of Trans-Pecos Texas consists of a marine carbonate succession deposited at the southern end of the Western Interior Seaway. The Boquillas Formation, subdivided into the lower, c. 78 m thick limestone-shale Ernst Member, and the upper, c. 132 m thick limestone/chalk/marl San Vicente Member, was deposited in a shallow shelf open marine environment at the junction between the Western Interior Seaway and the western margins of the Tethys Basin. Biogeographically, the area was closely tied with the southern Western Interior Seaway. The richly fossiliferous upper Turonian, Coniacian and lower Santonian parts of the Boquillas Formation are particularly promising for multistratigraphic studies.

Key words: Boquillas Formation; Upper Cretaceous; US Western Interior Seaway; Lithostratigraphy; Biostratigraphy; Paleoenvironment.

INTRODUCTION

A Cenomanian through Santonian (Upper Cretaceous) marine succession is well exposed in the Big Bend Region and Big Bend National Park (BBNP) in Trans-Pecos Texas (Text-figs 1, 2). This marine succession of the area is referred to the Boquillas Formation, subdivided into the Ernst and San Vicente members. The Boquillas Formation is primarily a carbonate sequence, c. 200 m thick.

During the Late Cretaceous the Big Bend region was located at the junction of the Western Interior Seaway, a north-south elongated Cretaceous marine basin that extended from the present day Gulf of Mexico to the Arctic Ocean, and the westernmost part of the North Atlantic / Tethys Ocean sys-

Text-fig. 1. Paleogeographic reconstruction of North America ~ 85 Ma during OAE 3 showing location of the Big Bend Region near the height of the Western Interior Seaway (WIS). Reconstruction/illustration used with the permission of Ron Blakey, Colorado Plateau Geosystems, Inc.

tem including the Gulf of Mexico and the Proto-Caribbean (Text-fig. 1). The Pacific Ocean was to the west and south-west. To the west the Cordillera island arc system (presently represented by parts of the Sierra Nevada and Rocky Mountains) was active with a related foreland tectonic / thrust fault system (Laramide) developing at its eastern side.

The Laramide thrust fault system and related
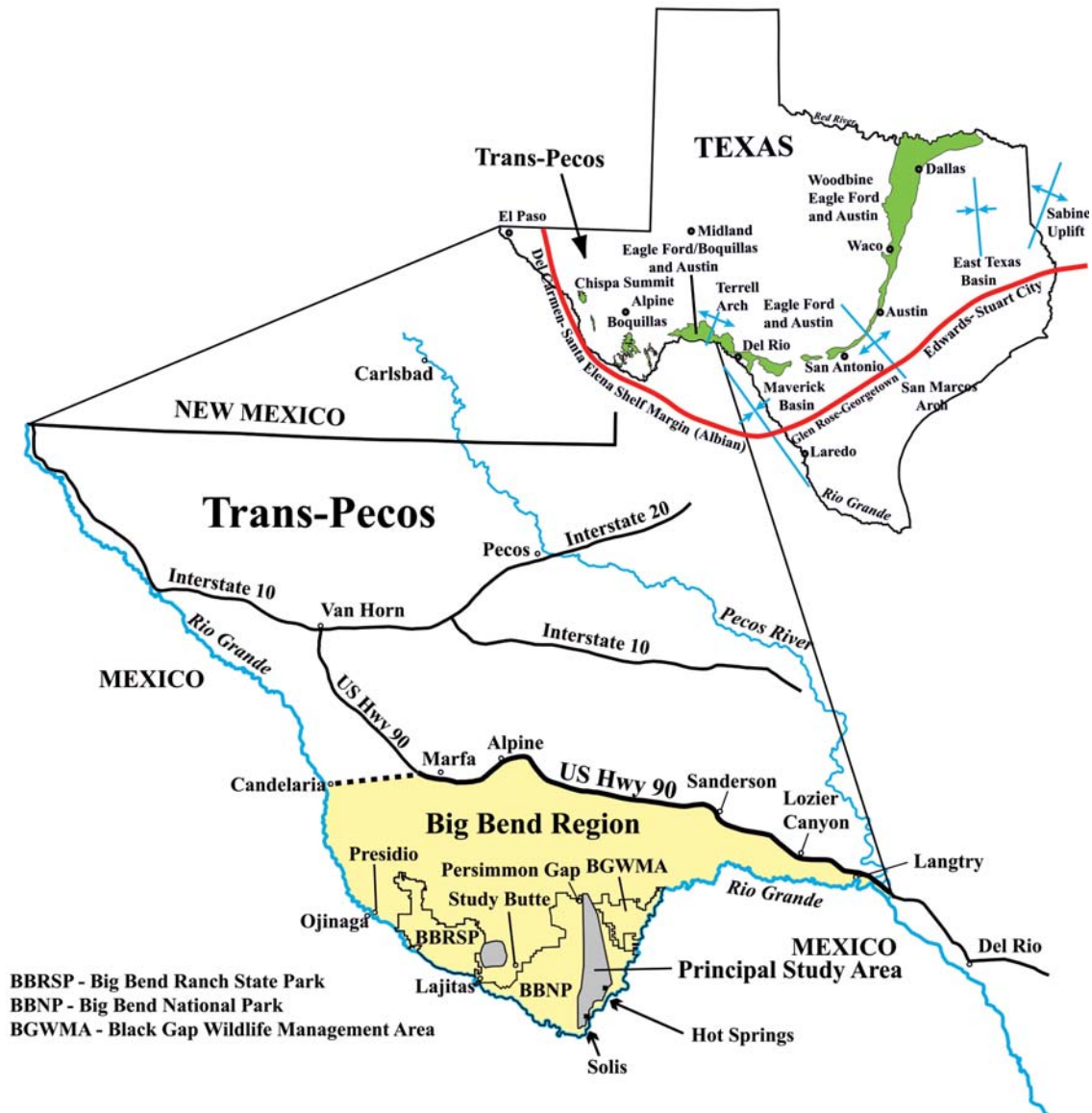
Text-fig. 2. Location of study area and geologic quadrangle maps (Cooper, 2011) that include the study area. Major surface exposures of the Boquillas Formation and laterally equivalent units in Texas also showing the location of major structural and physiographic features modifed from Barnes (1979 a and b), Cooper (2011), Cooper and Cooper (2014d), and Donovan (2015)

folding in the Big Bend region started in the latest Cretaceous and continued to the middle Paleogene (~70–50 Ma) (Turner *et al.* 2011). Paleogene plutonic and volcanic igneous activity (46–28 Ma) resulted in low-grade and contact metamorphism in the region and especially within and near BBNP. Subsequently, the Big Bend Region was affected by Basin and Range-related high angle normal faults (25–2 Ma) that created a series of graben, half-graben, and horst features (Morgan and Shanks 2008; Turner *et al.* 2011; Cooper 2011; Cooper and Cooper 2014d).

The Boquillas Formation is laterally equivalent to all or parts of the Graneros Shale, Greenhorn Formation, Carlile Shale, and Niobrara Formation, exposed in the central Western Interior Seaway in Colorado, Kansas, Wyoming, Nebraska, Montana, South Dakota, and North Dakota; Woodbine Formation, Eagle Ford Formation and Austin Chalk in north central, central and south Texas; Chispa Summit Formation of the Permian Basin in western Jefferson Davis County, Texas (Text-fig. 1); and Ojinaga Formation in adjacent parts of Mexico. It is

also laterally equivalent to the Cuesta del Cura, Agua Nueva, and San Felipe Formations in northeastern Mexico (Goldhammer 1999).

The present paper describes and discusses the lithostratigraphy, biostratigraphy, and biogeographic affinity of the uppermost lower Cenomanian through to middle Santonian of the Boquillas Formation. Although in many aspects the present study is a preliminary presentation, the paleogeographic location of the Big Bend Region makes the Boquillas succession of extreme significance for the proper interpretation of the Western Interior biogeographic evolution. The studied area, through its rich and taxonomically variable ammonite and inoceramid record, may potentially be a critical area in identifying the most suitable standard sections for the Coniacian stage and substages boundaries.

The paper presents the results of more than 20 years of field mapping and research in the Big Bend area by the senior authors. All identified specimens are permanently stored in the Cooper and Cooper Collection and the Stevens and Stevens Collection at the Non-vertebrate Paleontology Laboratory, Texas Natural Science Center, University of Texas, Austin.

PREVIOUS WORK

The Cenomanian–Santonian succession of what is today the Boquillas Formation, was first defined as the Boquillas 'Flags', in the southern part of the Big Bend Region by Udden (1907) to include sedimentary rocks from the top of the Buda Formation to the base of a unit composed of chalk and chalky marl zone. Maxwell *et al.* (1967) redefined the Boquillas Formation and formally divided it into the Ernst and San Vicente members in Big Bend National Park (BBNP). They defined the contact between the two members by the presence of an conformable conglomerate located c. 30 m above what they referred to as brown siliceous flagstone containing the heteromorphic ammonite *Allocrioceras hazzardi*. Despite numerous efforts by subsequent researchers and detailed field mapping (Cooper 2011), none has been able to identify the contact between the Ernst and San Vicente members as described by Maxwell *et. al.* (1967).

The contact between the Ernst and San Vicente members was revised by Cooper *et al.* (2005) to be a lithostratigraphically and biostratigraphically distinct ferruginous interval that includes the *Allocrioceras hazzardi* Beds (AHB). The United States Geological Survey (Turner *et al.* 2011) formally recognized the

top of the AHB as being the contact between the Ernst and San Vicente members.

Various aspects of the Boquillas Formation in the southern part of the Big Bend Region and BBNP were studied by various authors (Yates and Thompson 1959; Frush and Eicher 1975; Moustafa 1988; Sanders 1988; Stevens and Stevens 1989; Miller 1990; Stevens and Stevens 1990; Stevens *et al.* 1996; Reed 1996; Stevens *et al.* 1997; Stevens *et al.* 1999; Cooper 2000; Cooper *et al.* 2005, 2007, 2008; Cobban *et al.* 2008; Cooper and Cooper 2008; Gray and Page 2008; Tiedemann 2010; Turner *et al.* 2011; Cooper 2011; and Cooper and Cooper 2014a–e).

LITHOSTRATIGRAPHY

The early Cenomanian Del Rio and Buda formations underlie the Boquillas Formation (Text-fig. 3, 4). The Del Rio Formation primarily consists of bluish and greenish-gray claystone that weathers to shades of yellow, brown, and tan. Thin inter-beds of sandstone, limestone, and siliceous limestone occur locally. In addition, there are coquina deposits consisting of lenticular oyster beds, with *Haplostiche texana* (Conrad 1857)*,* various *Exogyra* species, and the foraminifer *Cribratina texana*. The Del Rio Formation is extremely variable in thickness in the southern part of the Big Bend Region and ranges from less than 1 m to 56 m (Maxwell *et al.* 1967). Both the lower and upper contacts of the Del Rio Formation are disconformities.

The 30–36 m thick Buda Formation consists of massive limestone at the base and top with a middle part comprised of marly limestone (Maxwell *et al.* 1967). The basal massive limestone, often forming a distinctive ledge, is approximately 7.5–9.0 m thick and consists of beds that are 0.6–1.8 m thick. It is gray-white in color, fine-grained, compact, and tends to have conchoidal fracture. The middle marly limestone unit is 6–9 m thick in average, although locally it may be significantly thinner. It consists of nodular limestone and marl and forms a distinctive slope between the lower and upper massive limestone intervals. The upper massive limestone is 3–18 m thick and consists of beds that are very similar to the lower massive limestone interval (Maxwell *et al.* 1967). The upper surface of the upper massive limestone unit often forms a distinctive ledge or dip slope in many areas. In the eastern part of Big Bend National Park, detailed mapping of the contact of the Buda with the overlying Ernst Member of the Boquillas Formation indicates that the upper contact of the
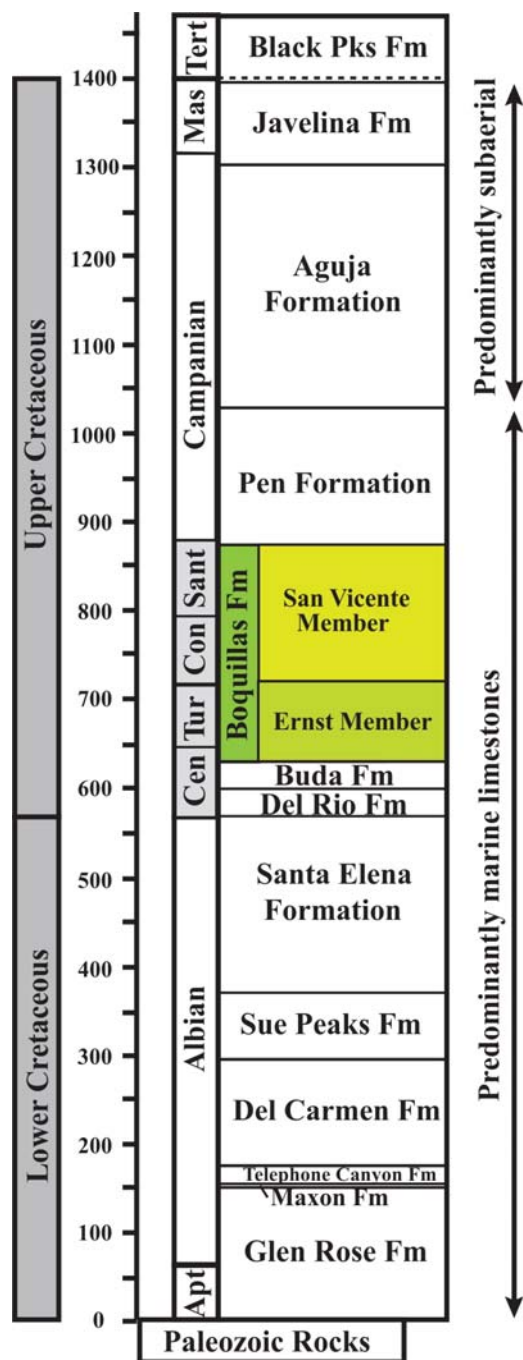
Text-fig. 3. Cretaceous stratigraphy in the southern Big Bend Region and eastern part of Big Bend National Park, Texas (modified from Maxwell *et. al*. 1967)

Buda is a disconformity with a relief of < 1–4 m on the Buda (Cooper 2011).

In the southern Big Bend Region and BBNP, the Pen Formation overlies the Boquillas Formation (Text-figs 3, 4). It primarily consists of yellow weathering blue-gray to dark gray calcareous shale with a few thin (< 10 cm) limestone layers near the base. Scattered occurrences of concretions and septarian concretion layers (10–25 cm thick) are present throughout the formation. Thin sandy and sandstone layers are present in the upper part of the unit. Occasional beds (5–20 cm thick), consisting almost entirely of *Turritella* sp. and scattered *Cymbophora* sp., occur in the upper part of the unit. The Pen Formation typically forms an extremely low relief surface and is commonly covered by alluvial deposits. The thickness appears to range from 67 to 213 m (Maxwell *et al*. 1967). The rare identified macrofossils in the Pen Formation suggest that it is late Santonian to early Campanian age.
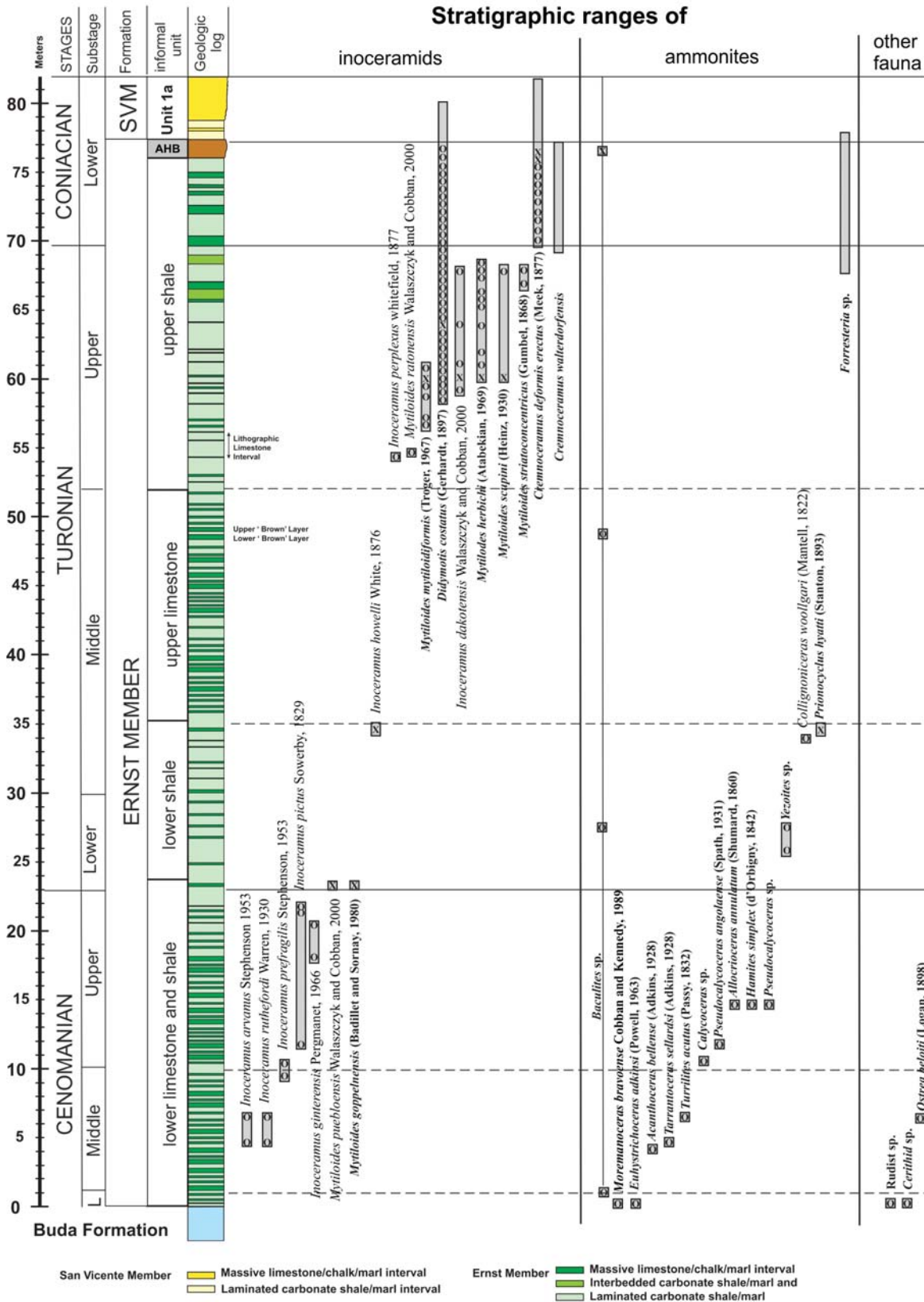
Ernst Member

The contact of the Buda Formation with the Ernst Member of the Boquillas Formation is sharp (Text-fig. 10a). The lowermost 1–2 m of the Ernst Member are locally partially recrystallized above the contact with the Buda Formation and some of the mm-thick layers are often partially silicified. This is especially true in the vicinity of sill-like igneous intrusions of Paleogene age (~46–28 Ma). The discontinuous silicification partially to totally replaces individual mm-scale lamination in the Ernst.

The Ernst Member (Text-figs 4, 6) generally consists of alternating limestone and carbonate shale. Four informal units, based on [the ratio of] limestone-to-shale layers, are distinguished (modified after Cooper and Cooper 2014d): (1) lower limestone and shale; (2) lower shale; (3) upper limestone and shale; and (4) upper shale unit, with *Allocrioceras hazzardi* Beds (AHB) at its top (Text-figs 5, 8, 9). The AHB was mapped throughout the eastern part of BBNP and constitutes a reliable and easily identifiable lithostratigraphic marker. The Ernst Member spans the uppermost lower Cenomanian through to the lower Coniacian. The entire Ernst Member can be examined in the Hot Springs area adjacent to the Rio Grande where it is well exposed (Text-fig. 6).

1. Lower limestone and shale unit: This unit consists of alternating layers of limestone and carbonate shale intervals with a total thickness of c. 24 m. The limestone layers usually have a "boudinage" or undulatory appearance and are often internally cross-bedded (Text-figs 6, 10b). The undulatory lower and upper surfaces of the limestone layers are the result of scouring by relatively strong currents as evidenced by the internal cross-bedding. The intervening shales
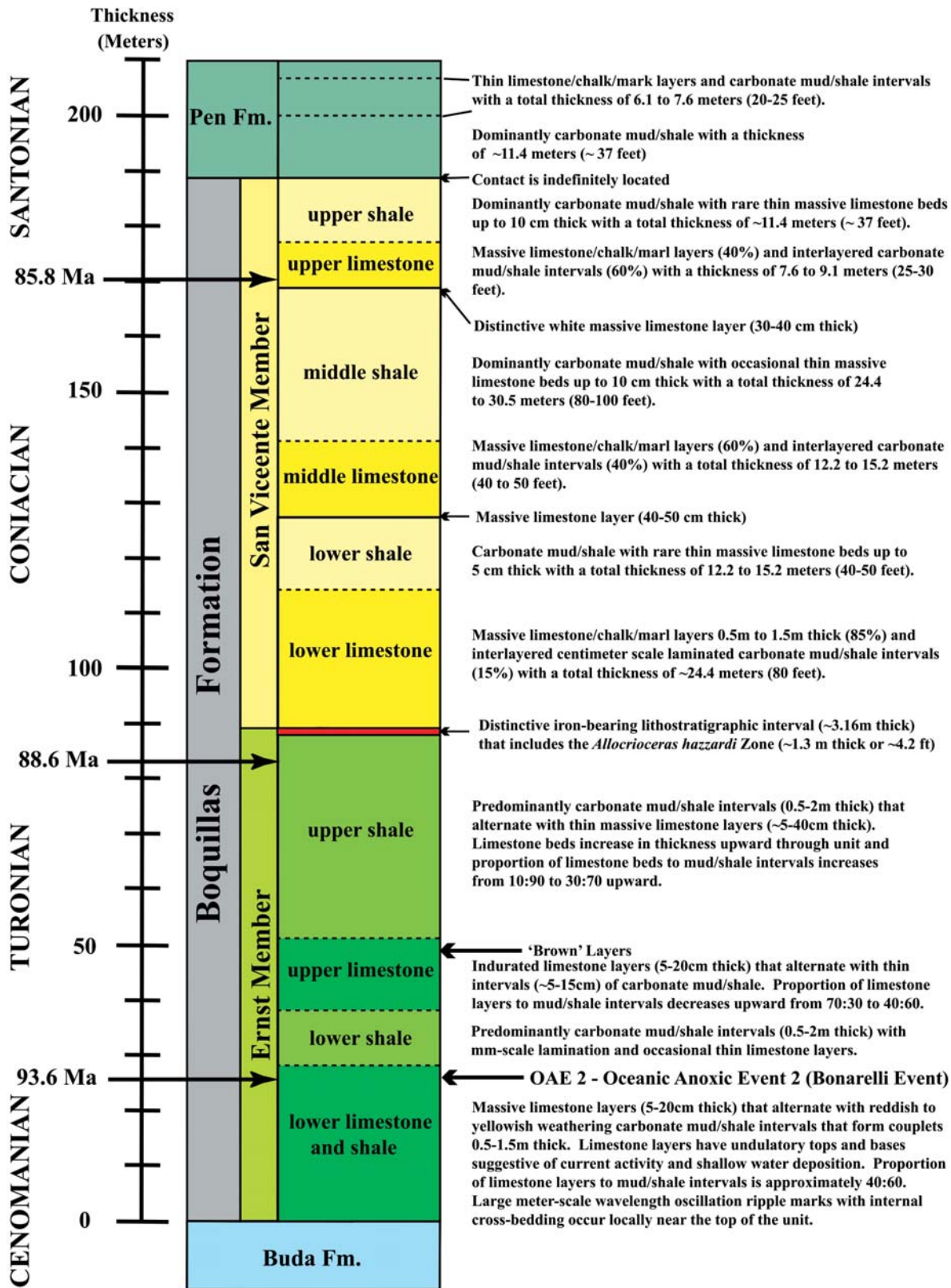
Text-fig. 4. Lithostratigraphy of the Boquillas Formation, Eastern Big Bend National Park, Texas showing location of stage boundaries (modified from Cooper and Cooper, 2014d)

Text-fig. 5. Generalized composite lithostratigraphy and biostratigraphy of the Ernst Member of the Boquillas Formation
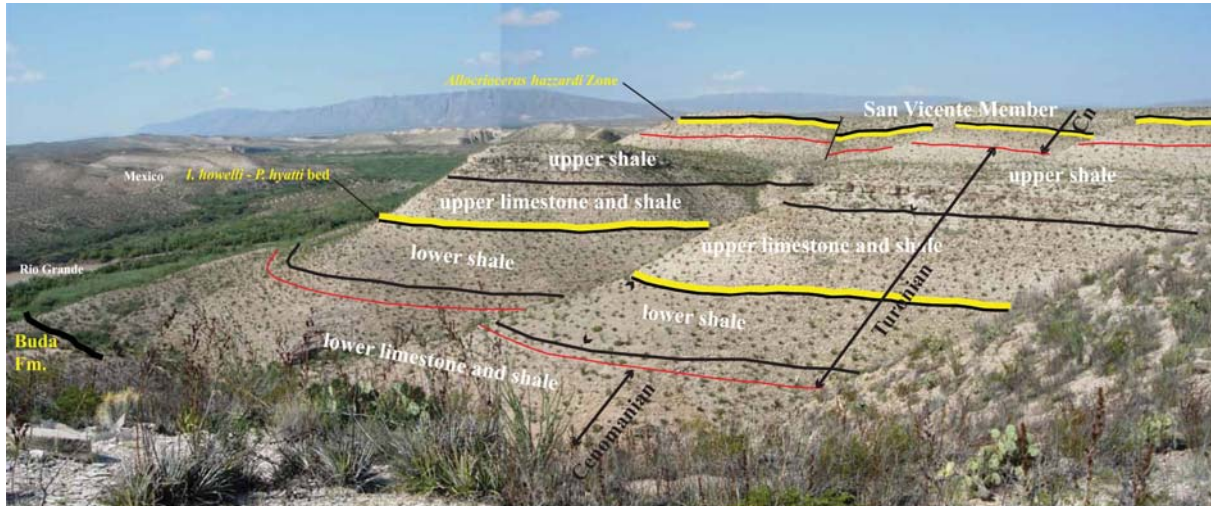
Text-fig. 6. Panoramic view of the Ernst Member of the Boquillas Formation showing the Buda-Ernst contact, approximate location of the Cenomanina–Turonian Stage Boundary, Middle Turonian limestone layer with *Inoceramus howelli* and *Prionocyclus hyatti*, Turonian–Coniacian Stage Boundary, and the *Allocrioceras hazzardi* Zone marking the top of the Ernst Member, Hot Springs area, Big Bend National Park as well as informal subunits of the Ernst Member

have mm-scale lamination forming cm-scale layers. Cross-bedding within the cm-scale carbonate mud layers has been observed locally. Each limestone-shale couplet may represent cyclostratigraphic climate/depositional cycles (Cooper 2000). The unit typically weathers to a reddish-brown to tan color. In the lowermost 1–3 m of the Ernst Member, a few isolated occurrences (2–7 cm thick) of pure quartz-sandstone (c. 95% of quartz) have been found. These intervals are local in occurrence and none is traceable for more than 30 m laterally. The Cenomanian–Turonian boundary occurs near the top of this unit.

2. Lower shale unit: This unit predominantly consists of carbonate shales with mm-scale lamination intervals that are 0.5–2.0 m thick. Thin limestone layers are intercalated. The unit has a total thickness of c. 11 m. This interval is usually poorly exposed. It is dark grey to black on relatively fresh surfaces and weathers to various shades of grey. A distinctive 12–17.5 cm thick white limestone bed (N29° 11.094' W102° 59.580') with middle Middle Turonian *Inoceramus howelli* White, 1876 and *Prionocyclus hyatti* (Stanton, 1893) occurs near the top of the unit. The white limestone layer includes very thin (<1 mm) discontinuous black organic rich layers along which invertebrate fossils are most often found. Black organic rich layers up to several cm thick also occur immediately above and below the distinctive white limestone layer. Elsewhere in the Hot Springs area a 6 cm thick intraformational conglomerate layer

dominated by 0.5–2.0 cm limonitic clay pebbles and a 7 cm thick terrigenous sandstone layer has been found a short distance below the Middle Turonian limestone layer. Several *Ptychodus* sp. (shark- or ray-like) teeth have been collected from this laterally discontinuous sandstone and conglomerate layer. In the Hot Springs Trail Reference Section (HST) (Cooper *et al.* 2007) a 1–3 mm thick claystone and sandstone layer has been found below the Middle Turonian limestone layer that may the lateral equivalent of the thicker conglomerate and sandstone layers found elsewhere. The limestone layer also exhibits a number of soft sediment features including bioturbations at the base of the black organic-rich layers.

3. Upper limestone and shale unit: Overlying the lower carbonate shale is an interval of limestone with thinner intervals of carbonate shale (Text-figs 5, 6) with a total thickness of c. 16 m. The most distinctive lithostratigraphic interval occurs at about 49 m stratigraphically above the base of the Ernst near the top of this unit. It consists of two carbonate- and iron-bearing sandstone layers informally referred to as the lower and upper 'brown' layers. The lower of the two layers (N29° 11.145' W102° 59.641') is 38 cm thick, bioturbated the top of the layer. It also contains hummocky and regular cross bedding, flaser bedding, as well as some evidence for soft sediment deformation and water expulsion through or within the layer. The upper layer is 28 cm thick and contains similar features to the lower layer. Both layers have mm-scale lamina-
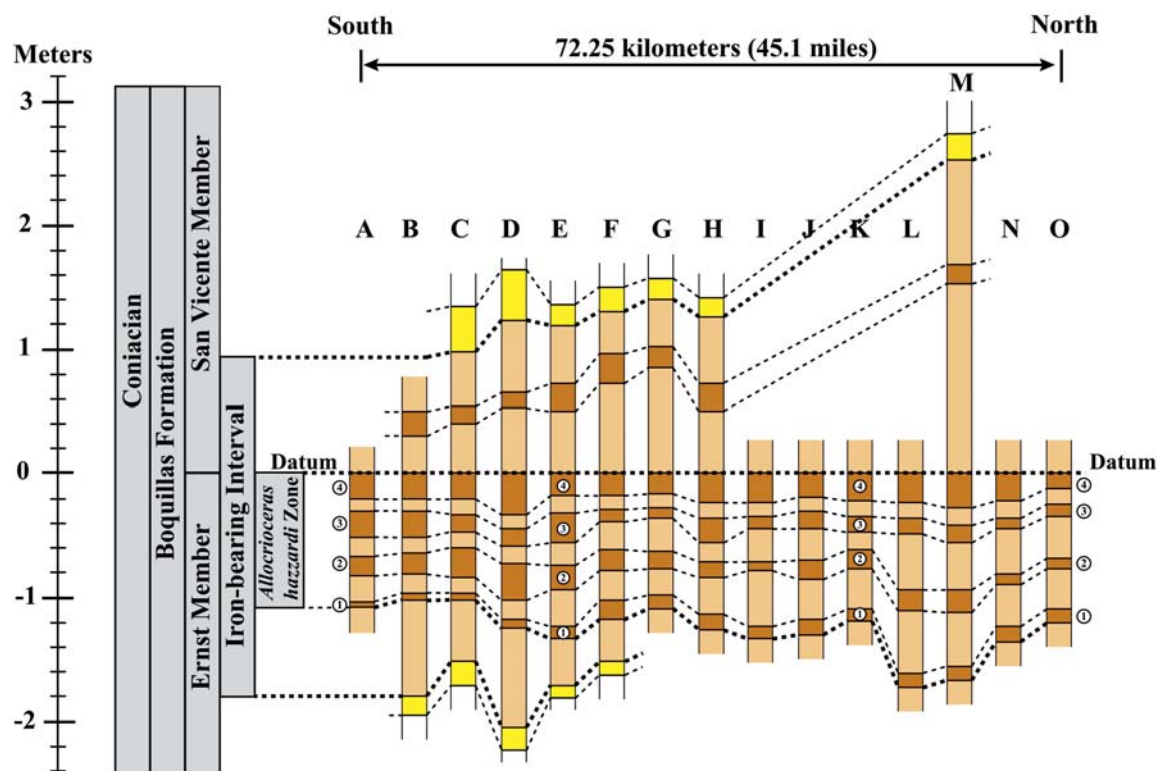
Text-fig. 7. Cross section showing selected measured stratigraphic sections of the *Allocrioceras hazzardi* Beds and iron-bearing interval

tions that form 10–15 mm thick layers. In addition, the layers have small-scale cross-bedded channels with erosional bases and very small (2–4 cm wide) troughs. The sand-bearing parts of both layers appear to have been deposited rather quickly with the intervening 3–7 mm thick micrite intervals deposited during quiescent periods. These layers, or similar layers have been noted in the same approximate stratigraphic position at several locations in the eastern part of BBNP. Approximately 2–3 m stratigraphically above the upper 'brown' layer is the base of the upper shale unit.

4. Upper shale unit, with *Allocrioceras hazzardi* Beds (AHB) at its top: This unit is dominated by carbonate shale with intercalated limestone beds that increase in thickness and abundance upward with an overall unit thickness of c. 27 m (Text-figs 5, 6). The shale intervals range from 0.5 to 2 m thick while the limestone layers in the upper part of the unit are 5–40 cm thick. Approximately 3 m above the base of the unit, there is a c. 2 m thick sub-lithographic to lithographic limestone interval (Text-fig. 5) with mm-scale lamination. It weathers to a cream color and often forms a distinctive bench/ledge in the eastern part of BBNP.

***Allocrioceras hazzardi* Beds (AHB):** This is c. 1.27 m thick ferruginous interval with the ammonite *Allocrioceras hazzardi* (Text-figs 5, 7, 8). The actual ferruginous interval extends from c. 0.5 to 1 m below the AHB to c. 1 to 2.5 m above the zone, and has an average thickness of c. 3.16 m (Text-fig. 7). The AHB itself consists of 4 indurated ferruginous siliceous intervals separated by 3 intervals of ferruginous shale (Text-figs 7, 8, 10b, e). It was referred to earlier as the *Crioceras* Zone or *Crioceras* ledge (i.e. Lonsdale *et. al.* 1955; Yates and Thompson 1959; Maxwell *et al.* 1967).

The ferruginous interval as well as the AHB was mapped in detail (Cooper 2011) throughout the eastern part of BBNP from the Solis area along the Rio Grande north to the Persimmon Gap area (Text-fig. 2). The AHB forms a distinctive ledge that weathers to a tan to brownish red color (Text-fig. 10f) that can be easily identified and traced. The consistency of the subunits and overall uniform thickness of the AHB as well as the entire ferruginous interval over a distance of c. 80 km is illustrated in Text-fig. 7. The remarkable consistency in the overall thickness and internal structure of the AHB suggests it was deposited on a relatively featureless surface. In addition, the AHB contains a unique and distinctive

Text-fig. 8. Upper shale of Ernst member and lower limestone of San Vicente member with *Allocrioceras hazzardi* Beds identifying the contact

faunal assemblage that also aids in its identification even where it has been contact metamorphosed by intrusive igneous rocks.

The AHB consists of four indurated limestone intervals with small amounts of terrigenous quartz that are interbedded with three intervals of ferruginous shales (Text-figs 7, 8, 10b, 10e). The four indurated layers are generally comprised of ferruginous limestones with 1–2.5 cm thick graded layers. The basal part of a graded layer is composed of very fine- to medium-grained sand size fragments as well as some silt-size material. Typical individual bedding plane surfaces in the lower parts of the graded layers were visually estimated as to the proportion of variously sized material. A typical surface is comprised of 50–80% (average of 64%) fine to very fine sand-size material; 10–35% (average of 21%) medium sand-size material; < 1% coarse sand-size material; 5–10% (average of 8%) unidentifiable fragmental shell material that ranges from 1–3 mm in size; and 5–10% (average of 7%) identifiable macrofauna and/or macro-

fauna fragments. The upper parts of graded layers are largely comprised of very fine-grained sand size material as well as silt- and mud-size material.

It is estimated that the sedimentation rate during deposition of the AHB was ~1.2 cm/1,000 years based on analogy with the lower part of the Fort Hays Limestone of the Niobrara Formation (Locklair and Sageman 2008). This rate would result in the entire AHB being deposited in ~105,500 years and thus may represent a single cyclostratigraphic depositional cycle. Based on the same sedimentation rate the entire ferruginous interval (~3.16 m thick) would have been deposited in ~263,600 years.

San Vicente Member

The San Vicente Member consists of 6 informal units (Text-fig. 9) that are widely traceable and locally very well exposed in the eastern part of BBNP. The subunits are identified from 1 (oldest) to 6 (youngest). The San Vicente ranges in age from the early Early
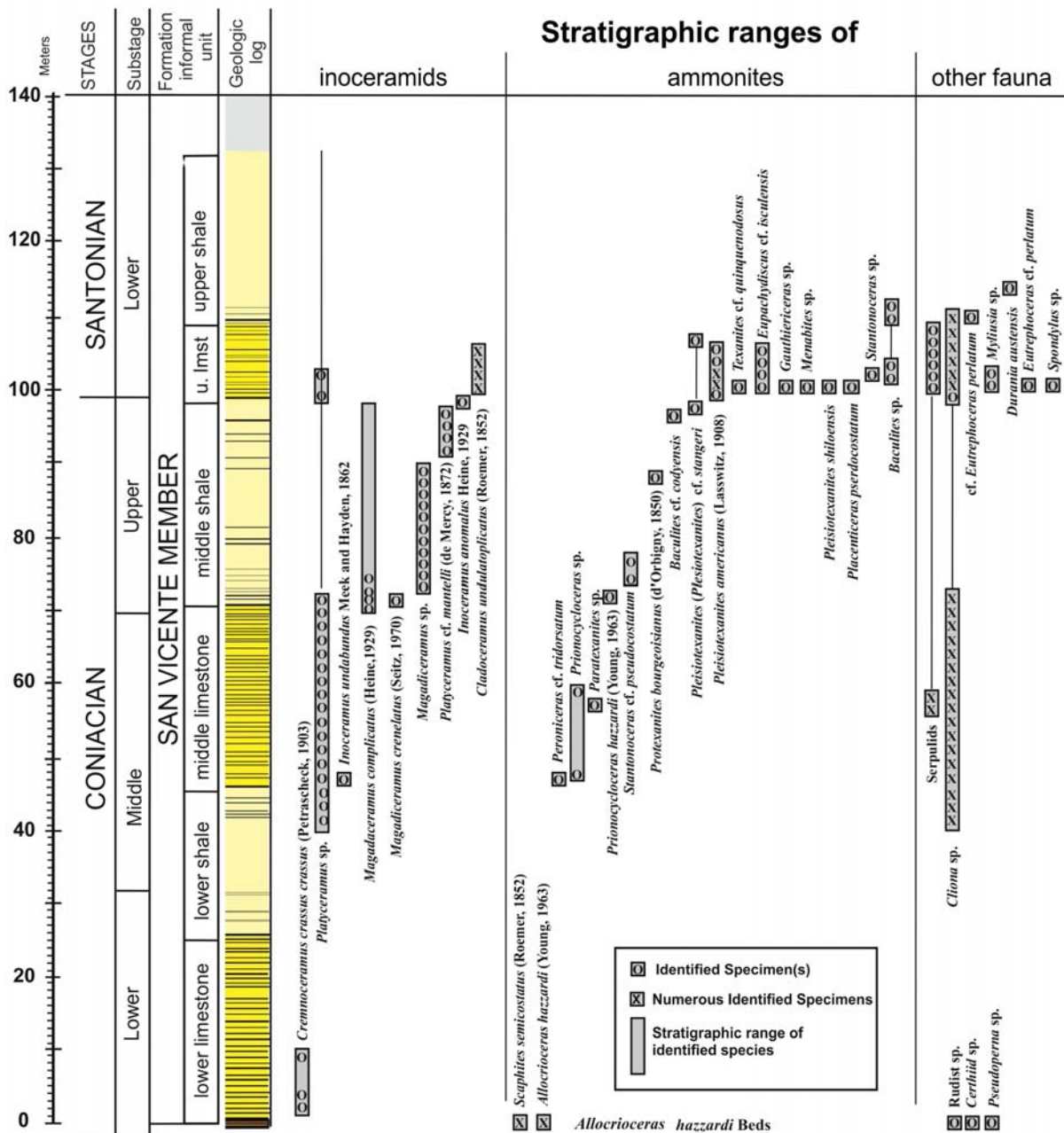
Text-fig. 9. Composite lithostratigraphy and biostratigraphy of the San Vicente Member of the Boquillas Formation, eastern part of Big Bend National Park, Texas

Coniacian to possibly middle Santonian based on invertebrate fauna (see below). The San Vicente Member was deposited during an extended transgression that occurred during the Coniacian and Santonian. The Coniacian–Santonian stage boundary has been identified and mapped throughout much of the eastern part of BBNP. The San Vicente Member is well exposed in the Hot Springs area (Text-fig. 10d, f, g).

1. Lower limestone: This unit consists of c. 24.4 m of massive predominantly limestone beds, 0.5 m to 1.5 m thick (85%), and interlayered centimeter scale laminated carbonate shale intervals (15%).

2. Lower shale: This unit consists of carbonate shale with rare thin massive limestone beds up to only 5 cm thick with a total thickness of 12.2 to 15.2 m. The

Text-fig. 10. Field photographs of the Boquillas Formation; Big Bend National Park, Texas. **A** – Contact of the Buda Formation and of the Ernst Member of the Boquillas Formation (N29° 20.452' W103° 02.989'). **B** – Ferruginous interval including the *Allocrioceras hazardi* Beds at the top of the Ernst Member, Hot Springs area, (N29°10.613' W103°0.068'). **C** – Lower limestone and shale unit of the Ernst Member (N29° 22.531' W103° 02.451'). **D** – Lower shale and middle limestone units of the San Vicente Member, as exposed along the road to the Hot Springs (near N29° 10.916' W103° 00.182'). **E** – *Allocrioceras hazzardi* Beds at the type section locality (N29° 11.777' W102° 59.805') showing the four indurated layers and three intervening shale units. The distinctive pyrite/limonite markers present in three of the indurated layers are also identified. **F** – Distinctive reddish-brown weathering ferruginous interval (yellow arrow) that includes the *Allocrioceras hazzardi* Beds; near Nine Point Draw (near N 29° 36.929' W 103° 08.382'). **G** – Middle shale unit of the San Vicente Member also showing the top of the middle limestone unit in the foreground and lowermost part of the upper limestone unit at the top of the cuesta, Hot Springs area

contact with the underlying lower limestone, where exposed, is extremely sharp with no interbedding whatsoever suggesting it may be a disconformity. The contact of the unit with the overlying middle limestone is conformable. It is well exposed along the road to the Hot Springs (Text-figs 10d, g). In the uppermost 3 m of the lower shale are occasional 1–10 mm thick layers of kaolinite similar to those found in the lower part of the middle limestone unit (see below).

3. Middle limestone: This unit is lithologically similar to the lower limestone unit. It consists of massive predominantly limestone layers (60%) and interlayered carbonate shales (40%) with a total thickness of 12.2 to 15.2 m. The lower 10 m of the unit is characterized by the presence of 1–50 mm thick layers of kaolinite. Several of the layers have been analyzed using scanning electron microscopy (Cooper 2000). This indicates they are ~99% pure kaolinite.

4. Middle shale: This unit consists of carbonate mud/shale with occasional thin massive limestone beds up to 10 cm thick with a total thickness of 24.4 to 30.5 m. Its contact with the underlying middle limestone is rarely well exposed. It is overlain conformably by the upper limestone unit.

5. Upper limestone: The base of this unit is marked by a prominent and easily identifiable white massive 30–45 cm thick limestone layer. It is well exposed immediately on the north and south sides of the park highway (N29° 11.767' W103° 00.206') in the Hot Springs area and has been mapped (Cooper 2011) throughout the eastern part of BBNP from the Solis and Mariscal Mountain areas along the Rio Grande to the Dagger Flat Auto Trail in the McKinney Springs Quadrangle. The unit is composed of massive limestone/chalk/marl layers (40%) and interlayered carbonate mud/shale intervals (60%) with a total thickness of 7.6 to 9.1 m. It is well exposed in the Hot Springs area along the park highway immediately east of the bridge over Tornillo Creek.

6. Upper shale: This unit is dominantly carbonate mud/shale with rare thin massive limestone beds up to 10 cm thick with a total thickness of ~11.4 m (Text-fig. 9).

BIOSTRATIGRAPHY AND PALEONTOLOGY

The oldest identified ammonites in the Boquillas Formation are *Moremanoceras bravoense* Cobban and Kennedy and *Euhystrichoceras adkinsi* Powell, indicative of the late early Cenomanian *Acompsoceras inconstans* Zone (Cobban and Kennedy 1989; Cobban *et. al.* 2008). They occur c. 40 cm above the contact of the Boquillas Formation with the underlying Buda Formation (Text-fig. 5). The ammonites are accompanied by rudistid bivalves, cerithiid gastropods, and *Baculites* sp.

The middle Cenomanian is documented by *Acanthoceras bellense* (Adkins), *Inoceramus arvanus* Stephenson, and *Inoceramus rutherfordi* Warren, identified between 4 and 7 m above the base of the Boquillas Formation (Text-fig. 5). Other fauna found in the same stratigraphic interval include *Tarrantoceras sellardsi* (Adkins), *Ostrea beloiti* (Logan), and *Turrilites acutus* (Passy). In addition, the upper middle Cenomanian and lower upper Cenomanian index fauna *Inoceramus prefragilis* Stephenson and *Calycoceras* sp., were identified between 9 and 11 meters above the base of the Ernst Member (Text-fig. 5).

The base of the upper Cenomanian is placed in the mid-point of the range of *I. prefragilis*, (between 9 and 11 m). The substage is also documented by *Inoceramus pictus* Sowerby and *Inoceramus ginterensis* Pergament. Other identified upper Cenomanian fauna include: *Allocrioceras annulatum* (Shumard), *Hamites simplex* (d'Orbigny), *Calycoceras* sp., and *Pseudocalycoceras angolaense* (Spath). The latter species documents the late Cenomanian zone of *Euomphaloceras septemseriatum* (Text-fig. 5).

The identified lower Turonian index fauna include *Mytiloides puebloensis* Walaszczyk and Cobban and *Mytiloides goppelnensis* (Badillet and Sornay), both occurring in an 8–11 cm thick limestone bed located at c. 23 m above the base of the Boquillas Formation. *Pteria* sp., *Yezoites* sp., *Baculites* sp., and a belemnite-like cephalopod, were found in an interval 23.5–28 m above the base of the Boquillas Formation (Text-fig. 5).

The middle Turonian is documented by the early middle Turonian *Collignoniceras woollgari* (Mantell), and the late middle Turonian *Inoceramus howelli* White and *Prionocyclus hyatti* (Stanton). The *C. woollgari* specimen was collected from surface float so its exact stratigraphic position is not known. Abundant specimens of *I. howelli* and *P. hyatti* occur in a 14 cm thick limestone layer located at the 34.5 m level in the Ernst Member (Text-fig. 5). An unidentified *Baculites* sp. occurs ~49 m above the base of the Ernst Member and is associated with the upper and lower 'Brown' layers that are interpreted to represent deposition during a low stand in the Ernst Member (Text-fig. 5).

The upper Turonian is documented by *Inoceramus perplexus* Whitfield, *Inoceramus dakotensis* Walaszczyk and Cobban, *Mytiloides scupini* (Heinz), *Mytiloides ratonensis* Walaszczyk and Cobban, *Mytiloides mytiloidiformis* (Tröger), *Mytiloides herbichi* (Atabekian), and *Mytiloides striatoconcentricus* (Gümbel), from an interval between 54.5 and 69 m above the base of the Ernst Member (Text-fig. 5). The bivalve *Didymotis costatus* (Gerhardt) is continuously present from 58 m (upper Turonian) and ranges up to 77 m (lower Coniacian) (Text-fig. 5).

The first *Cremnoceramus deformis erectus* (Meek), defining the base of the Coniacian, is noted at 69.8 m above the base of the Ernst Member. Above the *Allocrioceras hazzardi* Beds appears *Cremnoceramus crassus crassus* (Petrascheck) (Text-figs 5, 8).

The *Allocrioceras hazzardi* Beds, that define the top of the Ernst Member of the Boquillas Formation, contain a diverse faunal assemblage. It includes: *Allocrioceras hazzardi* (Young), *D. costatus*, *Scaphites semicostatus* (Roemer), *Nicaisolopha lugubris* (Conrad), *Forresteria* sp., *Baculites* sp., certhiid gastropods, *Pseudoperna* sp., rudist bivalves, and an unidentified belemnite-like specimen. *Baculites* sp. is most abundant in the zone followed by *C. deformis erectus, A. hazzardi,* and *S. semicostatus*. The top of the iron-bearing interval that includes the *A. hazzardi* Beds is likely a disconformity. This may explain the apparent stratigraphic gap associated with the zone, suggested by the appearance of *C. crassus crassus* directly above the zone of *C. deformis erectus* (Text-fig. 9). The stratigraphic position of the base of the middle Coniacian has yet to be recognized.

The middle Coniacian is poorly constrained biostratigraphically. Its upper boundary is placed at the first appearance of the inoceramid genus *Magadiceramus*, at c. 69 m of the San Vicente succession. The position of the lower boundary of the substage is, however, unknown. It is definitely at or below the lowest occurrence of *Platyceramus*, but may be distinctly lower, somewhere between the highest *C. crassus crassus* and lowest occurrence of *Platyceramus* sp. (Text-fig. 9). The middle Coniacian is also documented by *Inoceramus undabundus* Meek and Hayden, and *Peroniceras* cf. *tridorsatum*.

The upper Coniacian, understood as an interval between the first occurrence of the inoceramid genus *Magadiceramus* and the first occurrence of *Cladoceramus undulatoplicatus*, is well documented; *Magadiceramus* has an almost continuous range. The genus is represented by *Magadiceramus complicatus* (Heine), *Magadiceramus crenelatus* (Seitz), and some specifically unidentified forms. Other associ-

ated upper Coniacian forms include: *Platyceramus* sp. (with *Cliona* sp.), *Prionocycloceras hazzardi* (Young), *Protexanites bourgeoisianus* (d'Orbigny), *Platyceramus* cf. *mantelli* (de Mercy), *Baculites* cf. *codyensis*, *Texanites* cf. *stangeri* (Bailey), *Inoceramus anomalus* Heine, and *Plesiotexanites americanus* (Lasswitz).

The basal Santonian is characterized by abundant occurrence of the index species *Cladoceramus undulatoplicatus* (Römer) (Text-fig. 9), including its variety *michaeli*. This taxon is accompanied by various *Platyceramus* species, and numerous ammonites including *P. americanus*, *Texanites* cf. *quinquenodosus* (Redtenbacher), *Eupachydiscus* cf. *isculensis* (Redtenbacher), *Gauthiericeras* sp., *Menabites* sp. *Pleisiotexanites shiloensis* (Young), *Placenticeras* sp., *Stantonoceras* sp., *Baculites* sp., and *T.* cf. *stangeri*. Other fauna includes *Eutrephoceras* cf. *perlatum*, *Durania austensis*, *Spondylus* sp., and *Myliusia* sp.

GEOLOGIC SETTING, PALEOGEOGRAPHY, AND PALEOENVIRONMENT

The regional paleogeographic and paleotectonic components that subsequently affected the deposition of the Boquillas Formation in the Big Bend region and the laterally equivalent Ojinga Formation in Mexico initially developed during the Late Triassic and Early Jurassic along what is now the Texas-Mexico border (Muehlburger 1980; Poole *et al.* 2005). These components included the Maverick and Sabinas Basins, the Chihuahua Trough as well as the Diablo Platform and Burro-Salado Arch (Text-fig. 11). Many of these features continued to be present during the mid-Cretaceous. The Chihuahua Trough became a more prominent feature with the deeper part of the trough migrating eastward near the end of the Jurassic (Goldhammer 1999; Haenggi 2002). This may have been the result of the shallowing subduction zone of the Farallon Plate relative to the North American Plate or eastward migration of the Alisitos/Cordilleran Island Arc System located to the west (Text-fig. 1).

The Boquillas Formation in the eastern part of Big Bend National Park was largely deposited on the Diablo Platform and Burro-Salado Arch (Text-fig. 11). The Ernst Member of the Boquillas Formation reflects the transgression and subsequent regression of the shelf margin due to global changes in sea level during the Cenomanian and Turonian (Text-fig. 12).

The lower limestone and shale unit of the Ernst Member reflects the overall Cenomanian transgres-
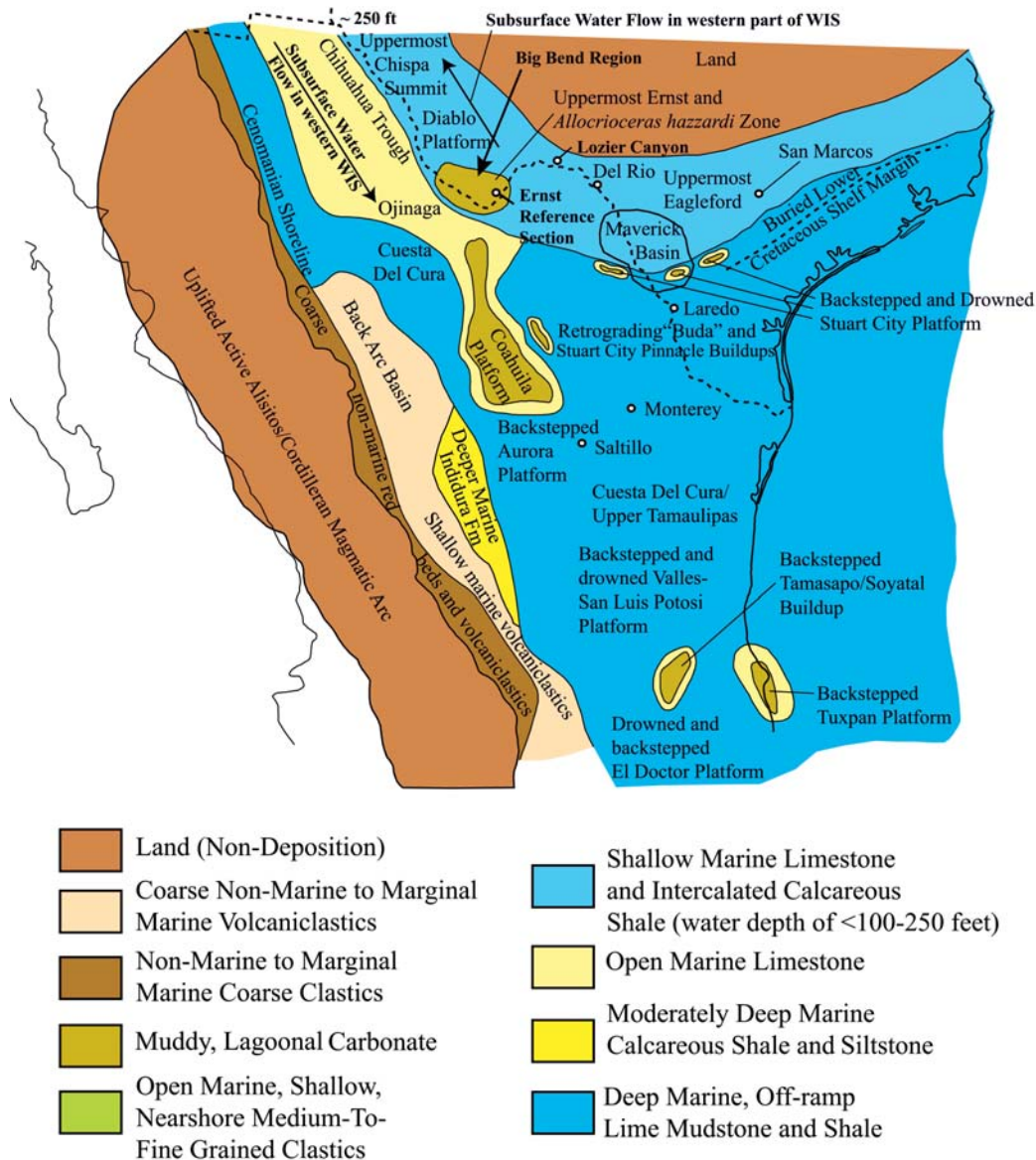
Text-fig. 11. Latest Turonian–Coniacian (~88.6 Ma) regional paleogeography of West Texas. West Texas portion of map modified from Goldhammer (1999) to reflect latest Turonian and earliest Lower Coniacian deposition in the Big Bend Region of Texas as defined by the *Allocrioceras hazzardi* Zone (Cooper et al., 2008 and unpublished data). Subsurface water flow in the eastern and western parts of the Western Interior Seaway based on Kump and Slingerland (1999). Land area in Texas modified from Late Cretaceous (~85 Ma) reconstruction/illustration by Ron Blakely, Colorado Plateau Geosystems, Inc. and used with permission

sion in the southernmost part of the Western Interior Seaway. Primary sedimentary features such as cross-bedding and ripple marks as well local evidence of soft sediment slumping in the lowermost Ernst Member correlates with local evidence of debris flows in the lowermost Boquillas Formation in the Lozier Canyon area located c. 100 km to the northeast (Lock 2008).

The petroliferous lower shale unit of the Ernst Member was deposited during the high stand that also includes Oceanic Anoxic Event 2 (Text-fig. 12). A laterally equivalent stratigraphic interval in the Maverick Basin to the southeast (Text-fig. 11) is a significant source of hydrocarbons.

The transition from the upper limestone unit to the upper shale unit of the Ernst Member reflects an overall major regression during the late Turonian. This regression is marked by two significant re-
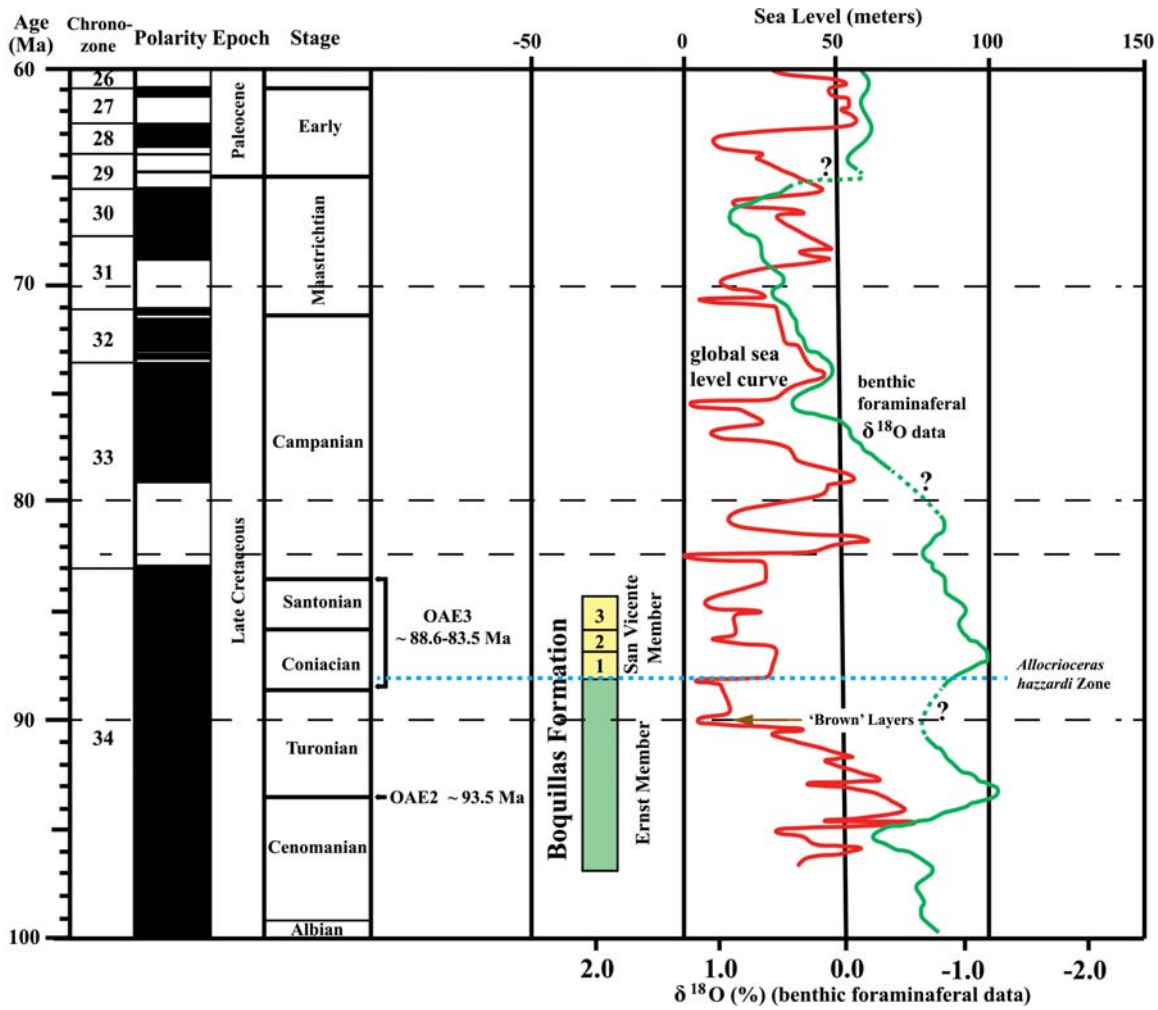
Text-fig. 12. Sea level curve and δ 18O (in %) benthic foraminiferal curve for the Late Cretaceous to Early Paleocene (modified from Miller et al., 2005) compared to Boquillas Formation and Oceanic Anoxic Events (OAE). Relative sea level change is indicated by 0 representing modern-day sea level. Dashed blue line is stratigraphic location of iron-rich interval that includes the *Allocrioceras hazzardi* Beds

gressive troughs represented by the lower and upper 'brown' layers in the upper part of the upper limestone unit. Within the upper shale unit the thin massive limestone beds that increase in number and thickness upward may represent the late. Turonian transgression.

Approximately 23 m of upper Turonian strata have been documented based on the presence of various inoceramid species (Cooper and Cooper 2008; Cooper *et al.* 2007; and this paper).

The early Coniacian regression is marked by the fossiliferous *Allocrioceras hazzardi* Beds (AHB). This interval corresponds well to equivalent phenomena in the North American Western Interior as far north as southern Alberta, Canada (see Walaszczyk *et al.* 2014, 2016).

The massive limestone intervals of the San Vicente Member represent a transgression during the Coniacian and Santonian in West Texas and the Western Interior Seaway (Text-fig. 12). OAE3 represents a regional or hemispheric event that has been identified in the equatorial Atlantic Ocean, the Caribbean, and the Western Interior Seaway (Leckie *et al.* 2008).

SUMMARY

The Upper Cretaceous Boquillas Formation in the Big Bend Region of Trans-Pecos Texas was deposited near the junction of the Western Atlantic/Tethys Ocean System and the Western Interior Seaway. The sequence consists of marine limestone and carbonate

shale deposited in an open marine shelf environment. The Late Cretaceous basins developed over the Early Cretaceous limestone shelf and reefs that formed the edge of the continental shelf during the Late Cretaceous sea level rise. Lithostratigraphic evidence of significant transgressions and regressions within the Boquillas Formation corresponds to changes in global sea level from the late Cenomanian to the middle Santonian documented in North America, Europe and elsewhere.

The late early Cenomanian to the early Santonian ammonite and inoceramid faunas of the studied sequence, represent forms known from the Western Interior Seaway. The presence of the key index fauna allows direct correlation with sequences in the Gulf Coast area and southern Western Interior Seaway.

The ferruginous *Allocrioceras hazzardi* Beds (AHB) yielded *C. deformis erectus*, *Scaphites semicostatus*, *Baculites* sp., and *Didymotis costatus*, and is dated as belonging to the late *C. deformis erectus* Zone. The occurrence of *C. crassus crassus* in beds immediately above suggest a stratigraphic gap, dating to the middle lower Coniacian.

Acknowledgements

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