

**STRATIGRAPHY OF THE GLEN ROSE FORMATION
IN BIG BEND NATIONAL PARK, TEXAS**

by

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THESIS

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DEDICATION

This thesis is dedicated to my wife Kristin Lane Casiano. Thank you for your constant love and support, and for being a wonderful mother to our sons Augustine Ignatius and Samuel Martin, especially during the time I was pursuing this degree.

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During the Early Cretaceous, a broad carbonate platform developed on the northern margin of the ancestral Gulf of Mexico. Although its sedimentary succession has been studied in other areas of Texas, the Lower Cretaceous succession has been overlooked in Big Bend National Park (BBNP). This is particularly the case of the Glen Rose Formation which lacks a precise facies description and age control. The aim of this study is to fill this gap in knowledge by describing the Glen Rose Formation in BBNP, analyze its microfacies and constrain its age by utilizing stable isotope chemostratigraphy and sequence stratigraphy.

Facies of the Glen Rose Formation at BBNP belong to a low-profile ramp formed in a shallow carbonate shelf environment. This is consistent with the reconstruction of depositional environments performed in central and southern Texas. Carbon isotope chemostratigraphy indicates that the $\delta^{13}\text{C}$ values in BBNP match the $\delta^{13}\text{C}$ trend of the Comanche platform of south Texas and other locations worldwide. The $\delta^{13}\text{C}$ trend also suggests that part of the Glen Rose Formation is not sampled in this study, and permits the identification of OAE1b near the base of the Glen Rose Formation in BBNP. This chemostratigraphic correlation is supported by the sequence stratigraphic interpretation of the studied sections. The unconformity at the base of the Glen Rose Formation, identified as the composite sequence boundary is followed by a transgressive systems tract, maximum flooding surface and a highstand systems tract. This

reinforces the comparison and correlation of the Glen Rose Formation from BBNP with the other areas of Texas.

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CHAPTER ONE: INTRODUCTION

Big Bend National Park (BBNP) was established in 1944 in Texas and covers 801,163 acres (3,242 km²). The park is located along a 118 mile (190 km) long “bend” of the Rio Grande at the United States–Mexico border (Figure 1). Its geomorphology varies from high mountains to broad desert lowland basins. A geologist, the First Superintendent of BBNP, Ross Maxwell (1968) once stated , “the rocks are strangely mixed up, most of the strata are lopsided or standing on end, and some of the mountains are turned upside down and piled where they do not appear to fit.”

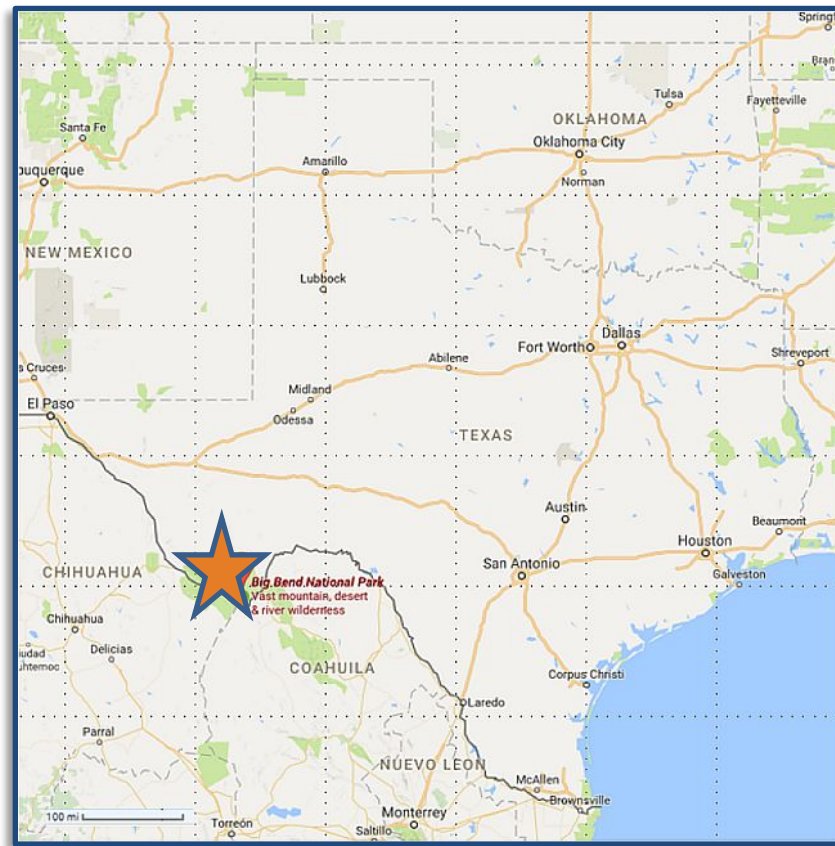


Figure 1. Location map of Big Bend National Park in west Texas (extract from Google Maps).

A majority of the formations outcropping in BBNP have been described (Hill, 1891; Maxwell et al., 1967; Dietrich and Maxwell, 1972; Muehlberger and Tauvers, 1988; Bohannon

et al., 2008; Miggins et al., 2008; Tiedman, 2010; Cooper and Cooper, 2014; Peavey et al., 2017) However, the Lower Cretaceous succession has been mostly overlooked due to logistical difficulties or possibly lack of economic interests. This is especially the case of the Glen Rose Formation that has been otherwise studied other places in Texas since Hill (1831) defined it in the Paluxy riverbed.

The Glen Rose Formation in central Texas is a thick shallow-marine carbonate succession deposited on a shelf on the northern margin of the ancestral Gulf of Mexico (Figure 2), exposed and researched from South Texas to North Central Texas. The Glen Rose Formation is a part of the Upper Trinity sequence and is usually divided into 2 members, an upper and a lower. The division is a lithostratigraphic boundary defined by the “Corbula” zone containing abundant *Eoursivious harveyi* bivalves (Ward and Ward, 2007). Shallow seas transgressed and the overlap of marine carbonates onto terrigenous facies is apparent and common in shallow marine shelf depositional environments (Stricklin et al., 1971; Scott and Kidson, 1977). The Glen Rose Formation is known to contain dinosaur tracks in its beds, indicative of very shallow seas (Sellards et al., 1932; Ward and Ward, 2007).

Research on the Glen Rose Formation in BBNP is needed to compare to previous research in other portions of the state (e.g., Stricklin et al., 1971; Pittman, 1989; Scott, 1993; Kerans and Loucks, 2002; Mancini and Scott, 2006; Ward and Ward, 2007; Phelps et al., 2015) (Figure 3), and to complete our understanding of its deposition in west Texas. The research will suggest, the oldest Early Cretaceous series, the Glen Rose Formation, observed in BBNP, corresponds to the Glen Rose Formation research of the central Texas Comanche Ramp system and will indeed correlate to the overall system.

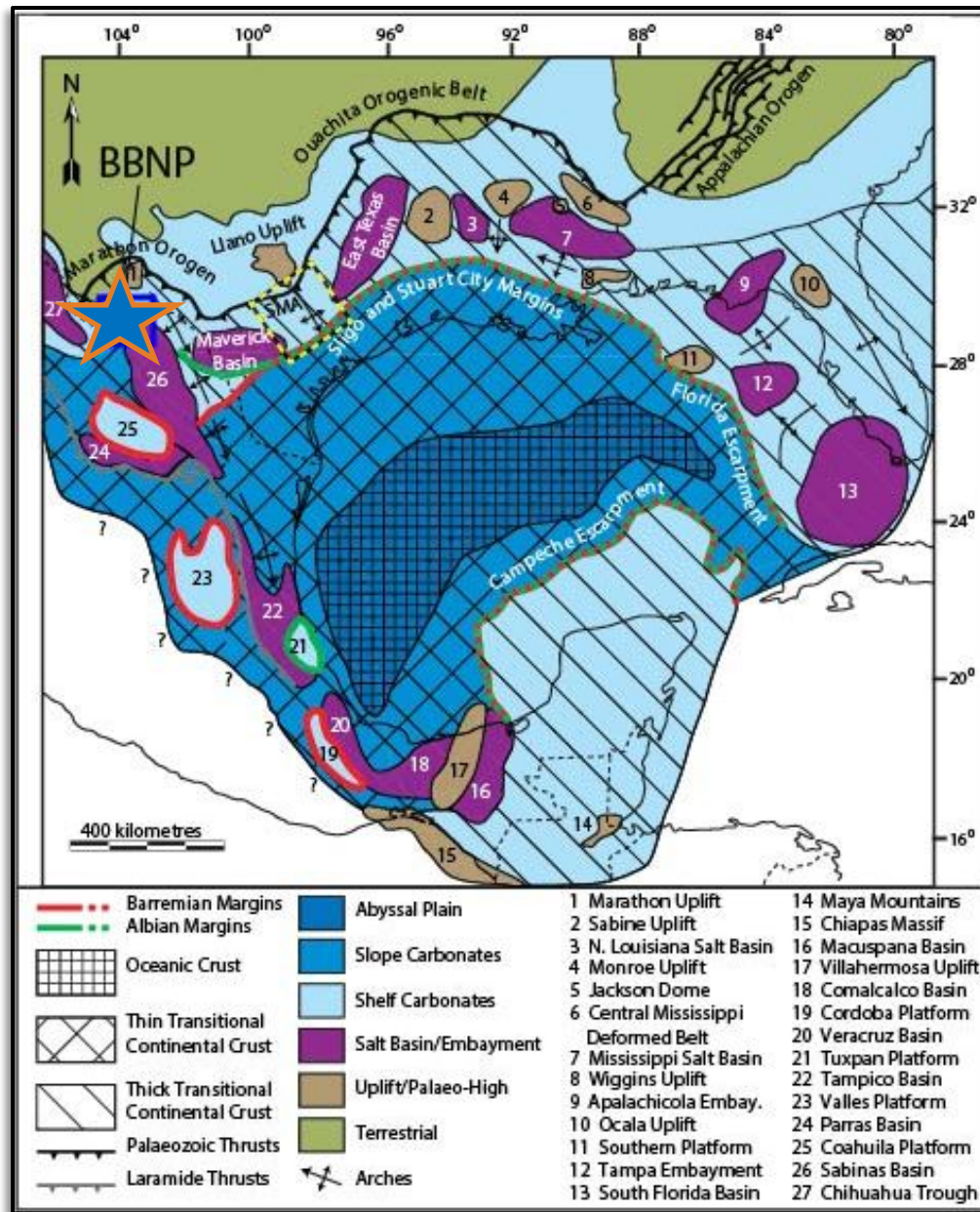


Figure 2. This map of the Gulf of Mexico includes modern geography, paleogeography, prominent structural features, salt basins, embayments and platforms during the Cretaceous. The study area centered over BBNP is located between the Marathon uplift and the Sabinas Basin (blue box). Map modified after Winkler and Buffer 1988; Ewing 1991; MacFarlan and Menes 1991; Goldhammer and Johnson 2001; Phelps et al, 2013.

Consequently, the first goal of this research is to refine the stratigraphy of Early Cretaceous series cropping out at Persimmon Gap and Santa Elena Canyon, where the USGS map reports the oldest Cretaceous deposits in BBNP; this will be achieved by integrating outcrop

descriptions, their sequence stratigraphic interpretation, and carbon isotope chemostratigraphy. Building on to this integrated stratigraphic framework, the second goal of this thesis will be to determine paleogeographic similarities with other occurrences of the Glen Rose Formation in south Texas.

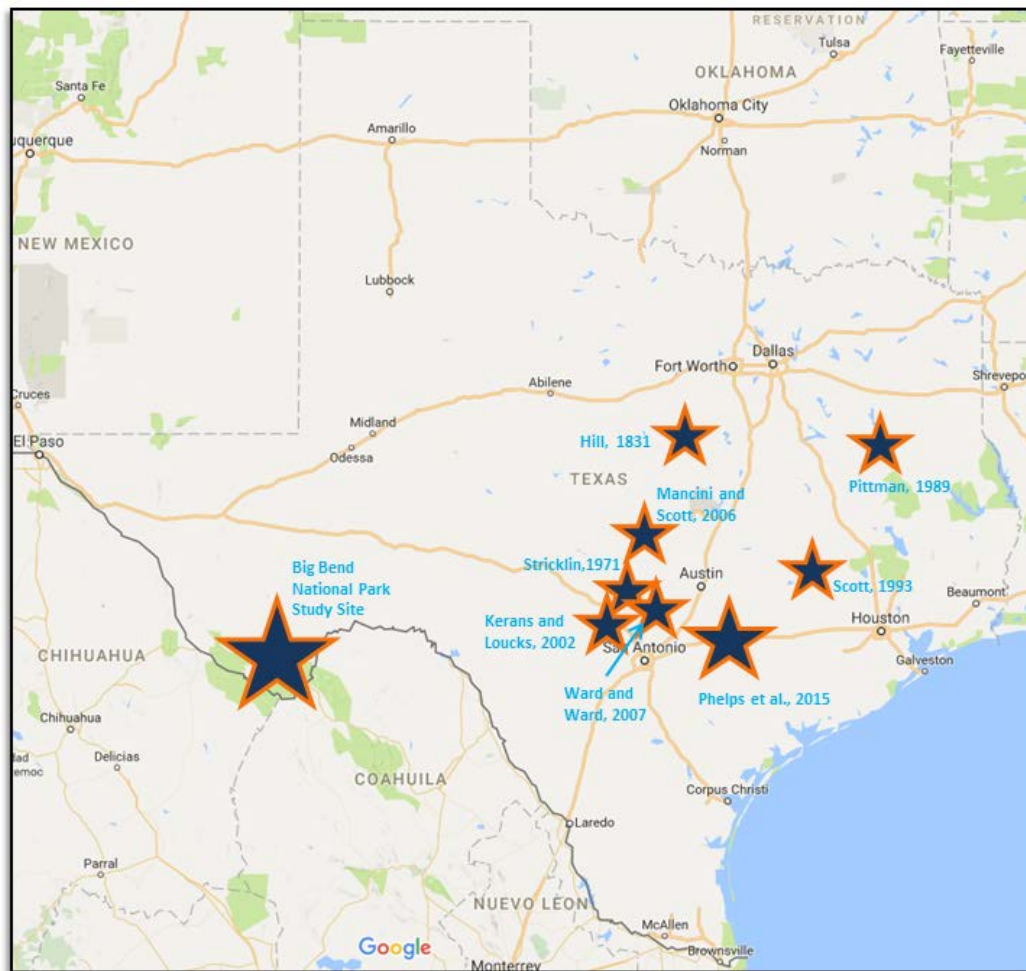


Figure 3. Locations of other research in Texas (Hill, 1831; Stricklin et al., 1971; Pittman, 1989; Scott, 1993; Kerans and Loucks, 2002; Mancini and Scott, 2006; Ward and Ward, 2007; Phelps et al, 2015).

CHAPTER TWO: METHODS

Outcrops were selected using the United States Geological Survey's geologic map of BBNP (Turner et al., 2011). A total of five potential outcrops were initially selected, but because of technical concerns (duration of hike, water limitation), only two sites were chosen based on their proximity to the road and relatively less difficult access. The outcrops at Persimmon Gap and Santa Elena were not only satisfactory logistically, they were ideal because the base of the Glen Rose Formation is exposed at Persimmon Gap and the top of the Glen Rose Formation is exposed at Santa Elena Canyon (Turner et al., 2011) (Figure 4). Prior to collecting samples a permit from the National Park Service was requested and granted. The majority of the samples were taken approximately one meter apart from each other if no obstacle was present. The

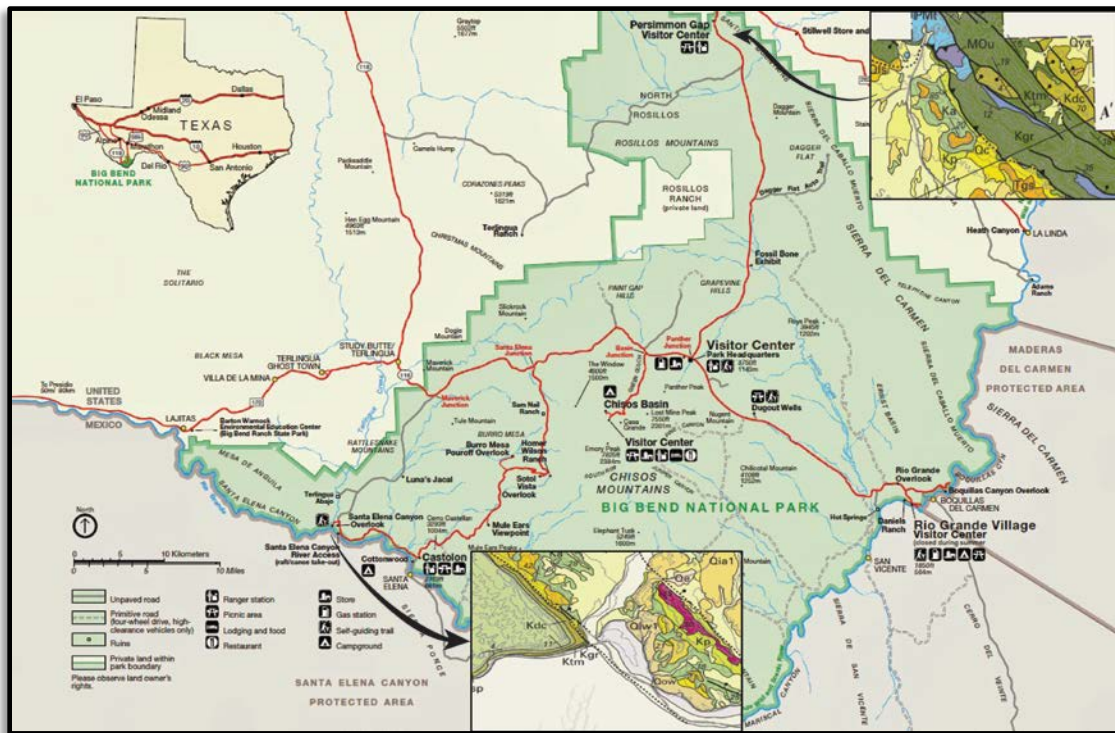


Figure 4. National Park Service BBNP Park Map of outcrop locations with USGS geologic map inserts (Turner et al., 2011). The Glen Rose Formation is symbolized by Kgr on geologic map. The Santa Elena Canyon outcrop is located in the southwest and the Persimmon Gap outcrop is located in the northeast of BBNP.

samples collected were brought back to the University of Texas at San Antonio (Figure 5). All samples were slabbed using water-cooled rock saws (Geology Rock Preparation Lab, UTSA), and subsequently polished to describe their texture using a stereo-microscope (Leica, M80). Selected, non-friable samples were cut into billets (25 x 30 x 10mm) and sent out to Quality Thin Section (Tucson, AZ) to produce thin sections. Thin sections were described using a Nikon Eclipse E4000 POL petrographic microscope. All samples were named using the Dunham classification system (1962; modified by Embry & Klovan, 1971). The Dunham classification of samples and the identification of allochems defined 10 distinct facies in the Glen Rose Formation in BBNP. Facies were subsequently interpreted in terms of depositional environments. Their stratigraphic stacking pattern will contribute to the sequence stratigraphic interpretation of the succession. Polished slabs were also used for carbon and oxygen stable isotope analysis in the Stable Isotope Lab at UTSA (Figure 6). 228 microsamples of matrix, fossils or ichnofossils were collected using a dental drilling device mounted to a stereoscope (Leica, M80) from the 91 total carbonate samples. Approximately 0.120 mg of powdered sample was transferred into a sealed Exetainer®. Exetainers® were flushed with Helium to remove the oxygen and subsequently injected with phosphoric acid to react with the sample at 70°C for one hour. The introduction of phosphoric acid initiated the following reaction:



The CO₂ generated from the reaction is analyzed using a Gasbench II system coupled with a ThermoFinnigan Delta+ XP isotope ratio mass spectrometer in the Geochemistry lab at UTSA. The stable carbon and oxygen isotope ratios are reported in the delta(δ) notation as the per mil (‰) deviation relative to the Vienna Pee Dee Belemnite standard (VPDB) using internally calibrated and international standards. External reproducibility is reported as ±0.1‰



Figure 5. *a. At the UTSA Geology Rock lab, 81 billets prepared for thin sections; b. cutting Santa Elena Canyon samples with rock saw prior to polishing; c. polished sample ready for describing.*

via repeated analyses of an internal standard (Sundance Formation Belemnites). Isotope analysis will provide an isotope profile revealing isochronous changes in global Cretaceous ocean water chemistry and aid in correlations to relatively adjacent studies (Scholle and Arthur, 1980).

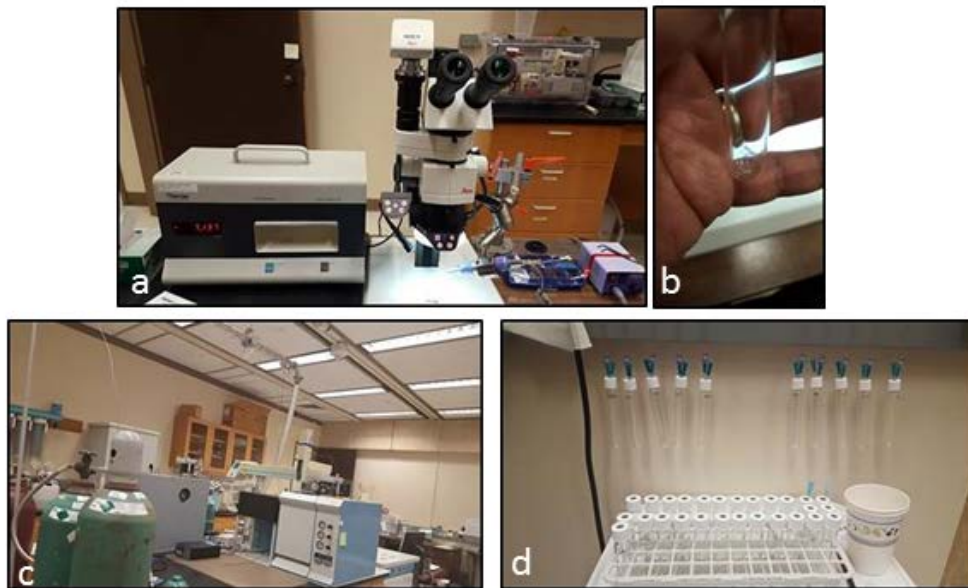


Figure 6. *a. Stereoscope with drill and scale for microsampling, UTSA Geochemistry lab; b. Collected carbonate microsample in vial, 0.120 mg; c. Gas bench and mass spectrometer; d. Helium flushing station.*

CHAPTER THREE: GEOLOGIC BACKGROUND

Tectonic Setting

Even though the earliest tectonism in BBNP is associated with the Paleozoic Marathon orogeny, regional Proterozoic rifting and proto-continental plate collision events had a profound impact in forming the terrain of BBNP (Muehlberger, 1980). These older events established the northwest trend of major structural and geographic features (Muehlberger, 1980).

Neoproterozoic rifting (about 800–550 Ma) along the southern fringe of the North American continent induced northwest-striking continental transform faulting that laterally offset the southern continental margin (Thomas, 1991; Poole et al., 2005). Major tectonic events occurred in the Late Paleozoic, Early Cretaceous, Late Cretaceous, Tertiary and into recent time (Dietrich and Maxwell, 1972). During the Late Paleozoic, tectonic movements induced the buckling of newly lithified rocks. Belts of deformed strata flanked the North American continent where depositional troughs once extended. The folded rocks of the Ouachita orogeny, resulting from the collision during the Middle Mississippian to Early Permian of Laurasia and Gondwana, flanked the continent on the south and the Appalachian Mountains on the west (Powers, 1928; Flawn et al., 1961; Maxwell, 1968; Thomas, 1991; Noble, 1993). During the Late Cretaceous to Early Tertiary the Laramide orogeny impacted the BBNP area. The major subduction of the Farallon Plate below the western edge of North America resulted from a plate convergence and formed the Cordilleran overthrust belt inducing the Laramide Orogeny and the formation of the Rocky Mountains (Maxson and Tikhoff, 1996; McGookey, 2004). The Laramide Orogeny led to the formation of Mariscal Mountain anticline, the Sierra del Carmen-Santiago Mountains monocline, and the Mesa de Anguila monocline in the Big Bend region (Maxwell, 1968; McGookey, 2004; Lehman and Busbey, 2007) (Figure 7).

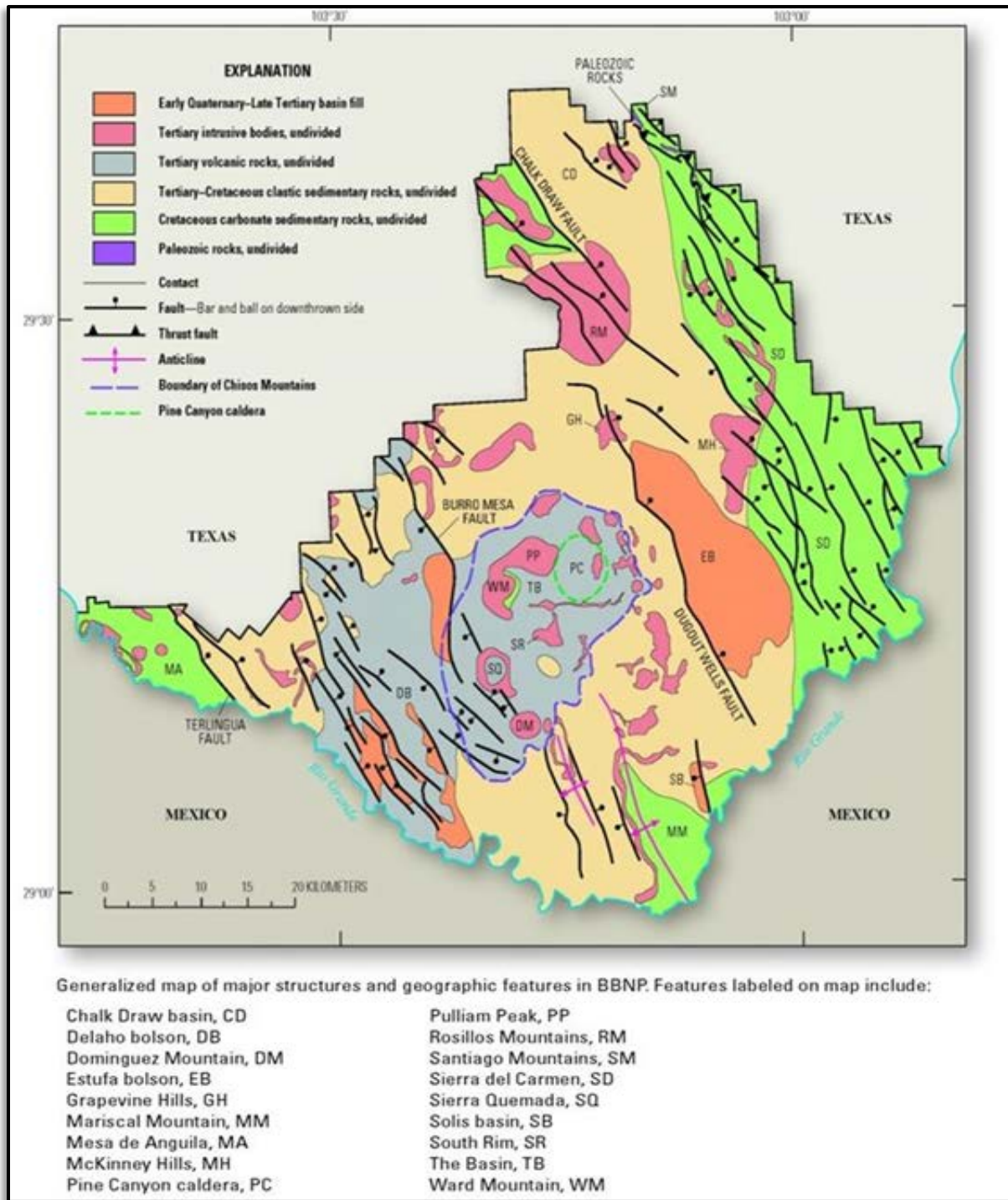


Figure 7. Structure and geological features map of BBNP. The park is bound on the east and west by Cretaceous outcrops. The center of the park is occupied by massive Tertiary volcanic mountains often referred to as the Basin (Turner et al., 2011).

Beginning in the Late Tertiary, extension induced the basin and range setting related to the uplift of mountain ranges and the down-drop of basins; it resulted in the development of the Rio Grande Rift system that extends from Texas into southern Colorado (Price and Henry, 1984). BBNP is located within the Rio Grande Rift system: some of its basins display only small displacement whereas others are characterized by displacement of as much as 900 m along the Terlingua Fault (Maxwell et al., 1967). Two Paleozoic thrusts are evidenced at Persimmon Gap: the first thrusts the Paleozoic upwards and the second thrusts the Upper Ordovician Maravillas Formation onto the Mississippian Tesnus Formation. Subsequent tectonic events are related to the Laramide Orogeny. The doming of the Marathon Basin uplift resulted in the creation of the Santiago Mountain Range, before the left-lateral movement of the Texas Lineament zone occurred (Muehlberger, 1980; Muehlberger and Tauvers, 1988).

Lithologic Stratigraphy

A wide variety of sedimentary, extrusive volcanic and intrusive igneous rocks are exposed in BBNP (Figure 8). The total thickness of sedimentary and extrusive volcanic rocks is over 4,300 m. The Paleozoic rocks found in BBNP are part of the Ouachita Trend; the types of rocks include limestones, novaculites, sandstones, and shales that were deposited in a deep marine trough (Stewart, 1988; McBride, 1989; McGookey, 2004; Cooper and Cooper, 2014). The Paleozoic consists of more than 430 m of black to greenish grey shales of the Tesnus Formation, the red beds of the Maravillas Formation and cherty Caballos deposits (Muehlberger and Tauvers, 1988; McBride, 1989; McGookey, 2004). From the Cambrian through the earliest Mississippian, this structural trend existed as a rifted accumulation (Thomas, 1991; Noble, 1993). They are now locally exposed along the base of the Santiago Mountain Range at Persimmon Gap in BBNP.

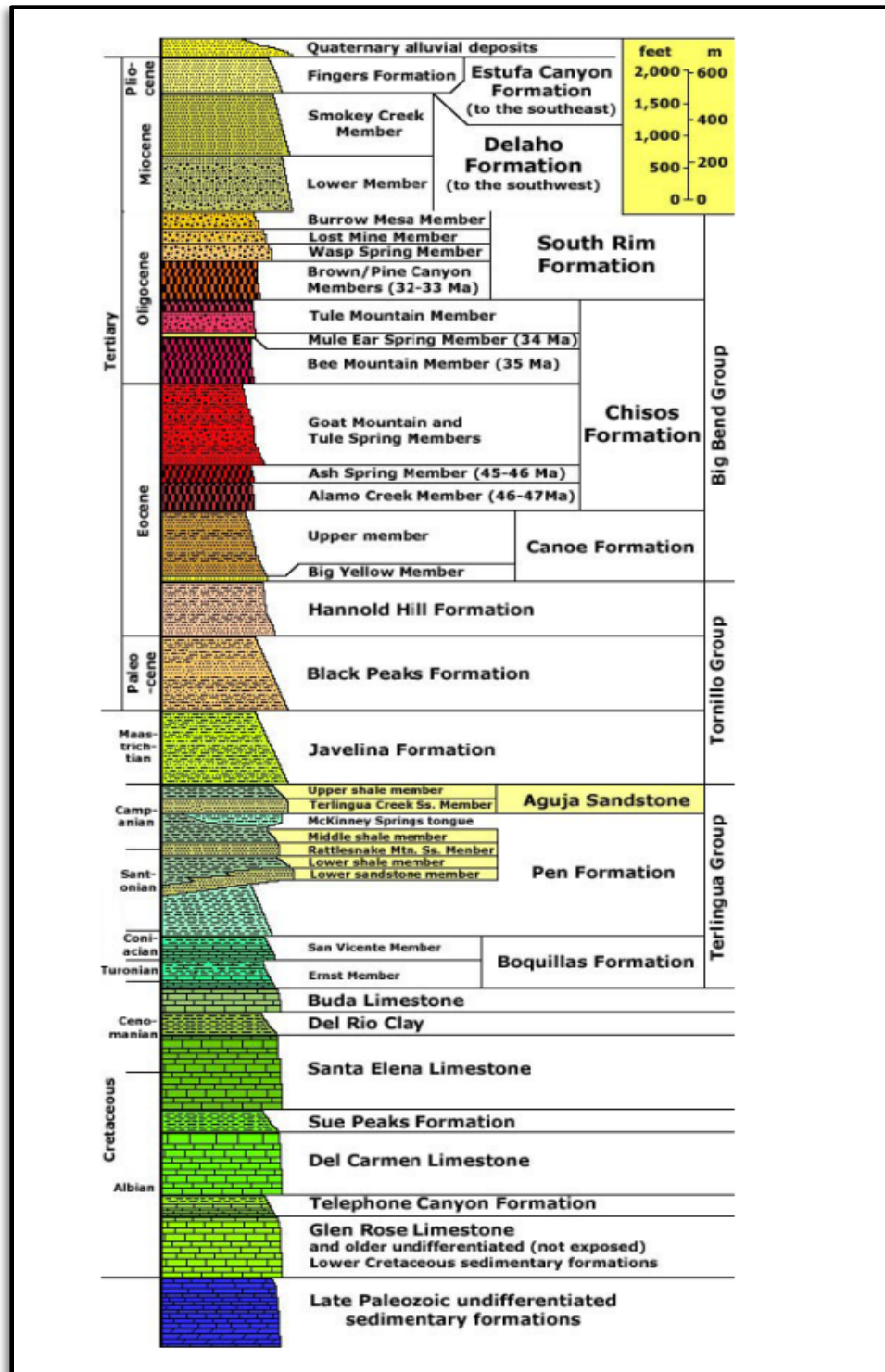


Figure 8. Stratigraphic column of BBNP (Laroche and Viveiros, 1994). As represented in the column above, BBNP has a wide variety of lithologies, from Paleozoic shales to igneous intrusions to volcanic ash beds.

Increased volcanism and plate tectonics during the Cretaceous Period led to a warmer planet and higher sea levels (Sellards et al., 1932; Embry and Osadetz, 1988; Hay, 2008; de Lamotte et al., 2015). During that time the Western Interior Seaway extended from the Proto-Caribbean, through the future Gulf of Mexico to the Arctic (Schroder-Adams, 2014; Blakey, 2017) (Figure 9). During the mid-Mesozoic, the formation of the Gulf of Mexico and associated ongoing rifting facilitated the formation of the Chihuahua trough (Haenggi, 2002; Cooper and Cooper, 2014) (Figure 10). The Chihuahua Trough ran northwest to southeast and is located to the northwest of the Maverick Basin (Cooper and Cooper, 2014) (Figure 9). Most of the Cretaceous limestones now preserved in BBNP were deposited on the Diablo platform located on the Tamaulipas Block on the eastern side adjacent to the Chihuahua Trough (Muehlberger, 1980; Cooper and Cooper, 2014).

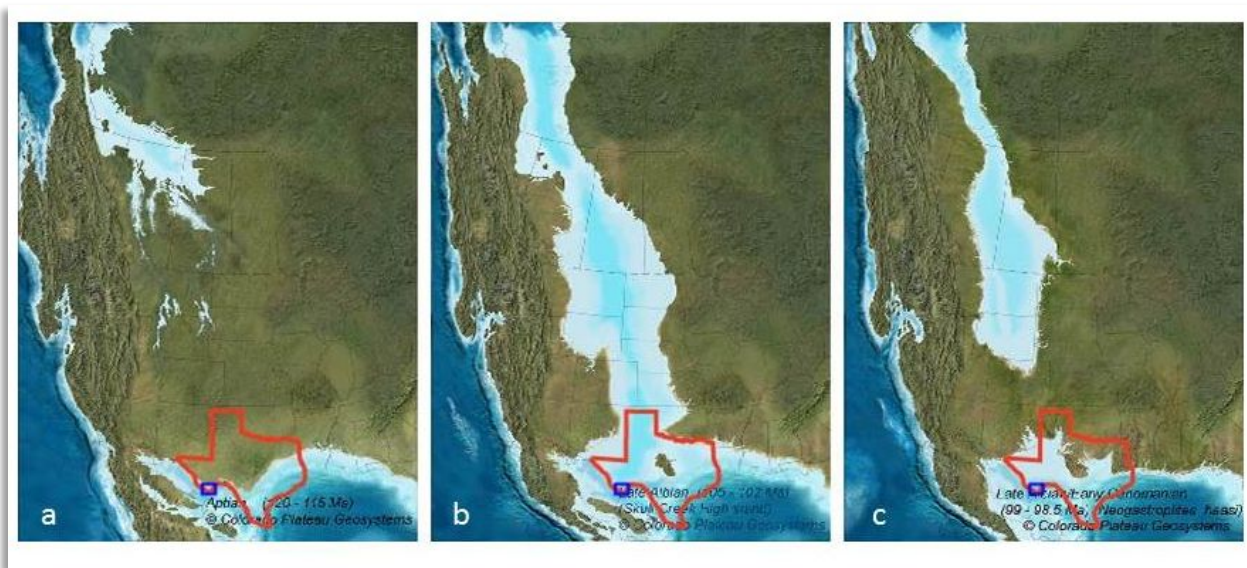


Figure 9. During the Aptian (a), the Western Interior Seaway has yet to connect from the north to the south, whereas it is fully connected from the Arctic to the ancient Gulf of Mexico during the late Albian (b). This connection ceased during the Cenomanian (c). The State of Texas is outlined in red, and BBNP is located in the blue rectangle. All maps are after (Blakey, 2017).

Lower Cretaceous deposits (600 m thick) mostly correspond to a thick succession of massive marine limestone, with small amounts of nodular limestone, marl and mudrock (McGookey, 2004; Cooper and Cooper, 2014). Five lithostratigraphic units are distinguished at BBNP: the Glen Rose, Telephone Canyon, Del Carmen, Sue Peaks and Santa Elena Formations (Maxwell and Dietrich, 1965; Turner et al., 2011; Cooper and Cooper, 2014). All Early Cretaceous formations outcrop at Santa Elena Canyon (Maxwell, 1968).

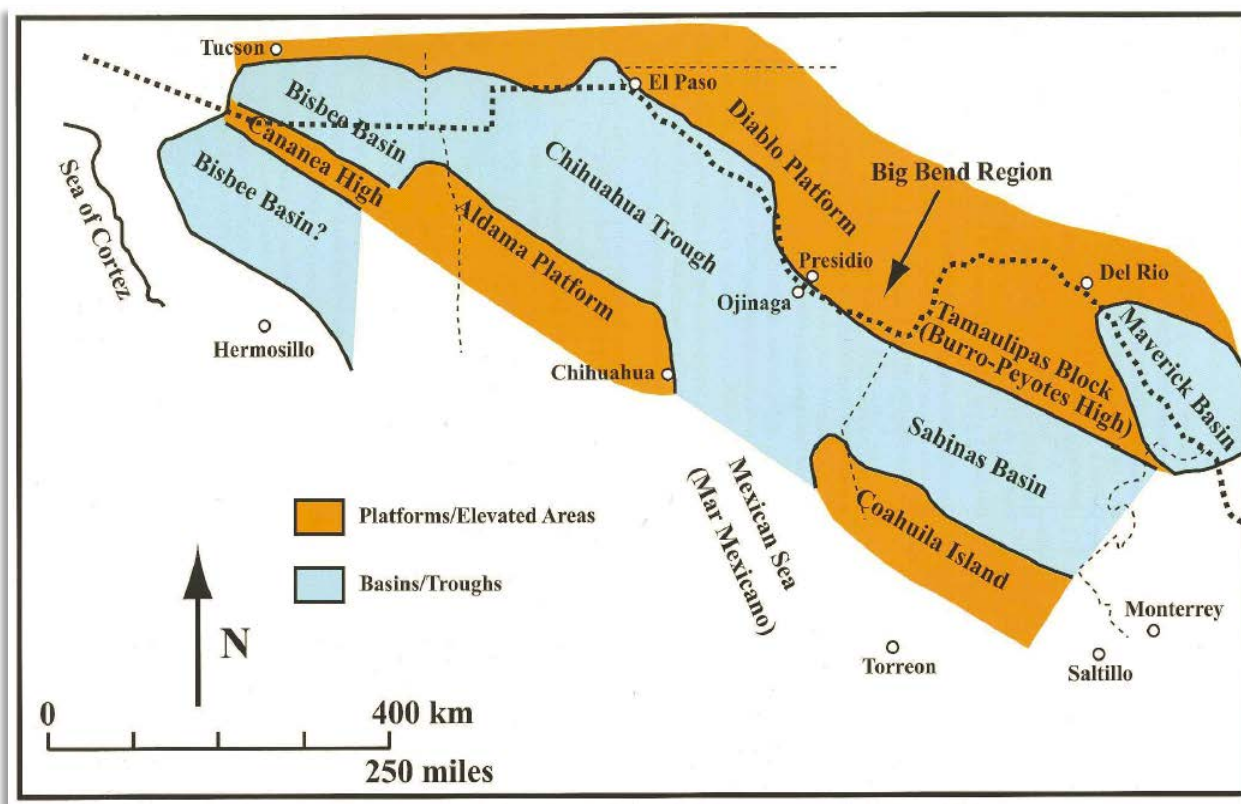


Figure 10. The Glen Rose Formation was deposited on the Diablo Platform which is a part of the Tamaulipas Block in west Texas. This is a paleogeographic map during the Aptian and Albian ages of northeastern Mexico, southwest Texas and west Texas (Cooper and Cooper, 2014; modified from Haenggi, 2002).

The Late Cretaceous sedimentary succession (950 m thick; McGookey, 2004; Cooper and Cooper, 2014) includes flaggy argillaceous limestone, chalk, clay, bentonic clay, and sandstone. The Del Rio, Buda, Boquillas, Pen, Aguja, and Javelina Formations make up this portion of the

Cretaceous in the park. The lower two-thirds of this section consist of marine sediments and the upper third is non-marine (McGookey, 2004; Turner et al., 2011; Cooper and Cooper, 2014).

Fossils associated with this Late Cretaceous succession include benthic foraminifera and ammonite shell fragments (Del Rio Clay Formation), gastropods and pelecypods (Buda Limestone Formation), echinoids, cephalopods, foraminifera, abundant inoceramids, fish bones and ammonites (Boquillas Formation), bivalves and gastropods (Pen Formation), vertebrate fossils, oysters, and petrified tree stumps (Aguja Formation), and vertebrate fossils and petrified wood (Javelina Formation) (Turner et al., 2011).

The Lower Tertiary sedimentary succession consists of the Black Peaks, Hannold Hill, and Canoe Formations. These formations fill the bolsons within the graben and half-graben structure within the park related to the larger basin and range faulting (Bohannon et al., 2008; Cooper and Cooper, 2014). The Black Peaks Formation of the Lower Tertiary contains crocodile remains, turtle bones, fish scales and bones, petrified wood debris, and Paleocene mammals (Turner et al., 2011). The Hannold Hill Formation contains abundant vertebrate fossils, whereas the Canoe Formation includes vertebrate fossils belonging to a wide variety of mammals. Following on top, the South Rim and Chisos Formations are dated to the middle Cenozoic (Bohannon, 2011). The latter consists of six separate members consisting of tuffy clays, mudstones, lavas, conglomerates, lacustrine limestones, silicified ash-flows, and siltstones. These lithologies support a strong volcanic activity in the BBNP area during this time in the Tertiary. Volcanism occurred during the late Cretaceous (Befus et al., 2007) but the last evolution of the Big Bend area was in the Late Tertiary. Volcanoes, sills, dikes, basalts, skarn, tuff, ash beds, calderas, and laccoliths constitute the youngest geological features in BBNP (Maxwell et al.,

1967; Price and Henry, 1984). Due to the volcanic activity, little fossil record was preserved. Late Tertiary deposits are all alluvial (Maxwell, 1968; Turner et al., 2011).

Persimmon Gap Outcrop

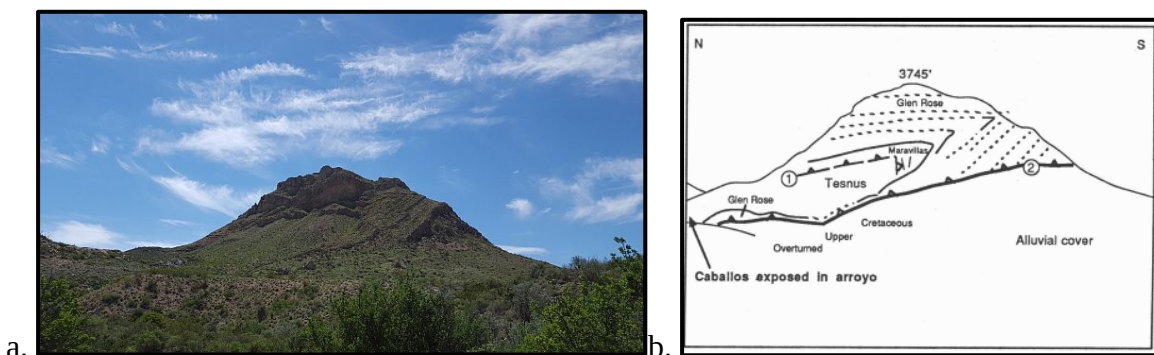


Figure 11. a. Glen Rose Formation thrust outcrop at Persimmon Gap; b. Structure of Persimmon Gap thrust mountain (Muehlberger and Tauvers, 1988).

Persimmon Gap separates the Santiago Mountains at the north entrance of BBNP; there, the thrust peak east of the park entrance culminates at 1135 m (Muehlberger and Tauvers, 1988) (Figure 11).

Structures related to three major orogenies outcrop north of Persimmon Gap. Severe thrusting of the Ouachita system (Upper Ordovician thrust over Lower Pennsylvanian) are over thrust by Cretaceous deposits as a result of the Laramide Orogeny (Muehlberger and Tauvers, 1988). At the very base of the mountain the Lower Devonian Caballos formation is exposed in a creek. The Novaculite Member of the Caballos Formation is exposed and is only 10 meters thick. The Novaculite is a very competent ridge builder in the Marathon Basin. The Lower Mississippian Tesnus Formation overlies the Caballos Formation at Persimmon Gap. The base of the Tesnus Formation is a conglomerate which grains are mainly made of clasts of the underlying Novaculite Member. The rest of the formation is siliceous shale with interbedded sandstones. Moving stratigraphically up section, the Maravillas Formation is dated to the Upper

Ordovician and was thrust over the Caballos and Tesnus Formations at Persimmon Gap during the Ouachita Orogeny (Muehlberger and Tauvers, 1988). The Maravillas Formation at Persimmon Gap is an illite-bearing, red to greenish shale. Directly above the Maravillas Formation, the Glen Rose Formation is dated to the Lower Cretaceous: the contact therefore is an unconformity (Muehlberger and Tauvers, 1988). The base of the Glen Rose consists of a conglomerate made of cobbles of lithologies from underlying deposits. The Glen Rose Formation is the lowest unit of the Comanchean section. The Glen Rose Formation is a fossiliferous, 200 m thick, competent series that forms the high ridges of the Santiago Mountains along the northeast boundary of BBNP (Muehlberger and Tauvers, 1988). Lithologies of the Glen Rose Formation range upward from conglomerate to sandstone and then to fossiliferous mudstone, wackestone, packstone and floatstone.

Santa Elena Canyon Outcrop

The Rio Grande River slices through the Early Cretaceous limestone in the southwest border of BBNP, separates the United States from Mexico and contributes to the formation of the Santa Elena Canyon. The walls of the canyon are generally ca. 460 meters tall, and can become as narrow as 10 m in some places. The Terlingua Fault at the entrance of the canyon also contributed to the formation of the canyon: uplift during the mid-Cenozoic time elevated the Mesa de Anguila block along the Terlingua fault, thus exposing the stratigraphy of the Lower Cretaceous (Maxwell, 1968) (Figure 12).

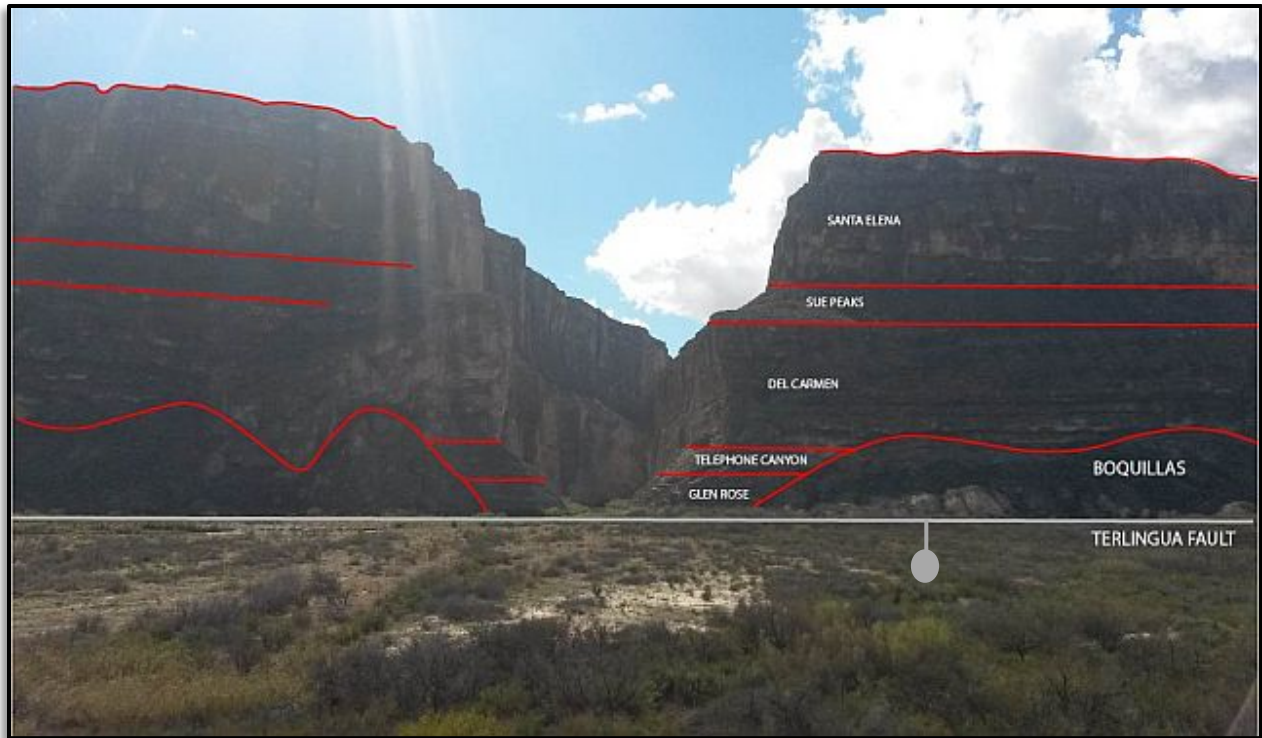


Figure 12. The Santa Elena Canyon is located in the southwest portion of BBNP. Near side of photo is downthrown along the Terlingua fault. Canyon walls are ca. 460 m tall and as narrow as 10 m wide. The Canyon outcrop on the right is in the United States and the outcrop on the left side of the Rio Grande is in Mexico.

The top portion of the Glen Rose Formation outcrops at the base of the entrance to Santa Elena Canyon (Turner et al., 2011). Overlying the Glen Rose Formation, approximately 33 m above the Rio Grande River, the Telephone Canyon Formation is the equivalent of the Walnut Clay Formation that is described farther east in the central part of Texas (e.g., Phelps et al., 2014) (Figure 13). In Figure 12, the first vertical wall of the canyon corresponds to the Del Carmen Limestone that is the equivalent of the Edwards Limestone Formation of Central Texas (Maxwell, 1968). The Del Carmen Limestone Formation forms the base of most of the ridges in the Sierra del Carmen mountain range (Maxwell, 1968). Above the Del Carmen Limestone Formation, the Sue Peaks Formation forms the slight slope in the middle of the cliff of the

canyon. The highest cliff of the canyon is the Santa Elena Limestone that marks the top layer of numerous mountain ranges in the study area (Maxwell, 1968).



Figure 13. At Santa Elena Canyon the top of Glen Rose Formation is observed from the Rio Grande near the Mexican river bank. The formation seems to have several beds of variable thicknesses; however the beds were mostly very similar in composition, competency and description (especially with naked eye and hand lens).

Stable Isotopes and Oceanic Anoxic Events

Without carbon dioxide the Earth would be uninhabitable, it keeps the planet warm enough to have available water and provides food for plants. Carbon is also the critical component of the Earth's major energy source, fossil fuels. Ignoring the mantle and the atmosphere, there are three major reservoirs for carbon in the crust: the sedimentary inorganic carbon in carbonates, carbon in crystalline rocks and organic carbon (Sharp, 2007). The atmosphere acts as the flux for transferring the CO₂ from reservoir to reservoir is. The transfer

of CO₂ between the hydrosphere, lithosphere and atmosphere is referred to as Earth's Carbon Cycle (Sharp, 2007).

During the precipitation of carbonates, fractionation of carbon isotopes (¹²C and ¹³C) is minimally sensitive to temperature; in ancient marine carbonates, the values of δ¹³C are preserved and reflect the δ¹³C values of dissolved inorganic carbon (Scholle and Arthur, 1980). The dissolved inorganic carbon values, noted δ¹³C, is preserved on a long term scale. Carbon and oxygen isotope composition of carbonate rocks are representative of paleotemperatures and paleosalinities of ancient waters; the diagenesis that carbonate rocks experienced can also be determined (Scholle and Arthur, 1980). Productivity, ocean circulation and weathering are related to the δ¹³C values of dissolved inorganic carbon. The difference in values has been linked to organic productivity: the oxidation of ¹²C-enriched organic matter leads to negative δ¹³C values. In the case of higher organism production and more bioturbation, the values are often dampened to a certain extent (Scholle and Arthur, 1980). Productivity including photosynthesis impacts the values of δ¹³C in the ocean by utilizing ¹²C, and the pool of carbon in the oceans becoming enriched in δ¹³C (Sharp, 2007). Well established ocean circulation and upwelling lead to more nutrient-enriched and ¹²C-enriched waters to reach the surface; therefore stable stratified sections of oceans have positive δ¹³C values (Sharp, 2007).

Positive δ¹³C excursions correspond to periods of worldwide fluctuations in the carbon cycle with a clear separation between reduced and oxidized marine carbon sinks and increased productivity (Sharp, 2007). Negative excursions or “light” δ¹³C values are caused by a reduction in productivity. Less terrestrial and marine life leads to increased oxidation of organic carbon (Herrle et al., 2004). These major isotopic variations in marine sequences are able to be correlated over vast distances due to the long residence time of the dissolved inorganic carbon in

the ocean (Scholle and Arthur, 1980) (Figure 14). On the other hand, temperature has an effect on $\delta^{18}\text{O}$, colder climates lead to higher values, warmer climates cause ^{16}O to be preferentially extracted during evaporation, allowing more negative $\delta^{18}\text{O}$ values to be recorded (White, 2013).

Disturbances of the global C-cycle punctuate the Earth's history. The acknowledged Oceanic Anoxic Events (OAEs; Schlanger and Jenkyns, 1976) correspond to periods of increased burial of marine organic carbon which activated increased $\delta^{13}\text{C}$ values of marine and atmospheric Dissolved Inorganic Carbon (DIC), and of carbonate mineral, which precipitated from it. Since Schlanger and Jenkyns (1976) and Scholle and Arthur (1980), numerous studies established stratigraphic locations of OAEs (Leckie et al., 2002; Herrle et al., 2004; Godet et al., 2006; Phelps et al., 2014). OAEs correspond to brief episodes of deposition of organic-rich, black shale beds recognized by their pronounced carbon and/or oxygen isotopic properties (Leckie et al., 2002). The global character of these organic shale beds indicates a different triggering mechanism other than basin geometries. Increased volcanism, along with rapid

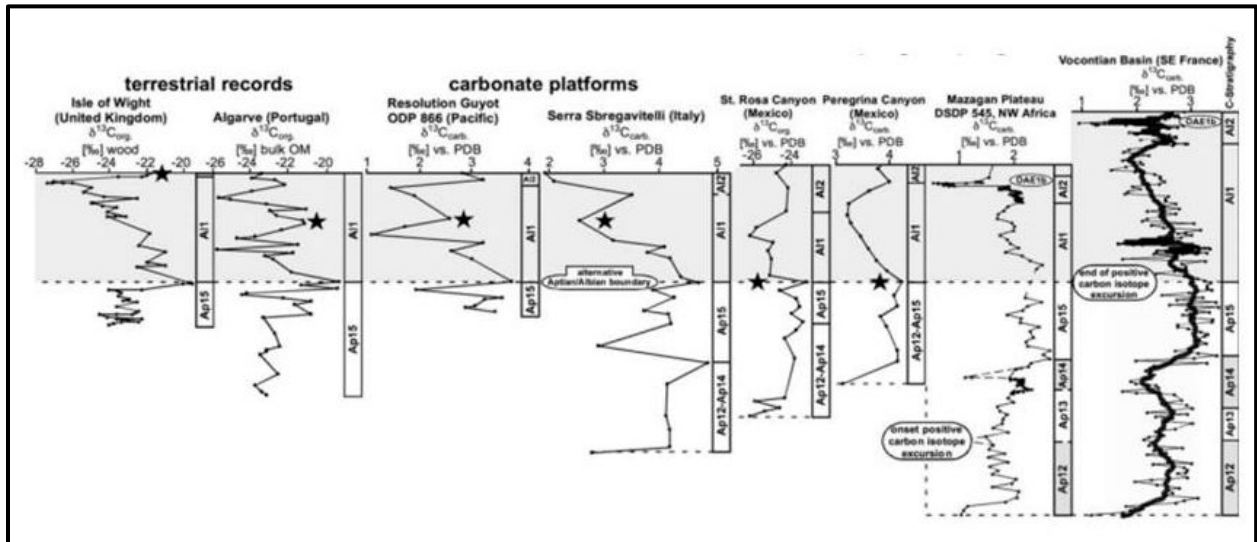


Figure 14. Example of $\delta^{13}\text{C}$ chemostratigraphic correlation of sections from terrestrial (Portugal, United Kingdom) and marine (Pacific, Italy, Mexico, Atlantic, France) that support the reliability of this stratigraphic tool to perform long-distance correlation (Herrle et al., 2004).

formation of plateaus during the Cretaceous led to the development of marginal seas. There was also an increase of organic carbon due to intervals of dysoxia (Schlanger and Jenkyns, 1976; Leckie et al., 2002). The overall temperatures in the tropics and the poles were significantly warmer due to, the equable, greenhouse climate, free of ice caps, which contributed to a weak temperature gradient and reduced the supply of cold oxygenated bottom water to the world ocean (Hay, 2008). This warmer climate favored different current patterns that contributed to the development of regional and global anoxic oceans (Leckie et al., 2002; Hay, 2008). There is one OAE in the Jurassic and seven OAEs in the Cretaceous, T-OAE (Toarcian), OAE1a (early Aptian) and the OAE2 (Cenomanian – Turonian boundary) being the most extensive (Jenkyns, 2010) (Figure 15). These OAEs deeply affect the carbonate sediment production and deposition of shale on carbonate platforms during the Cretaceous (Phelps et al., 2014).

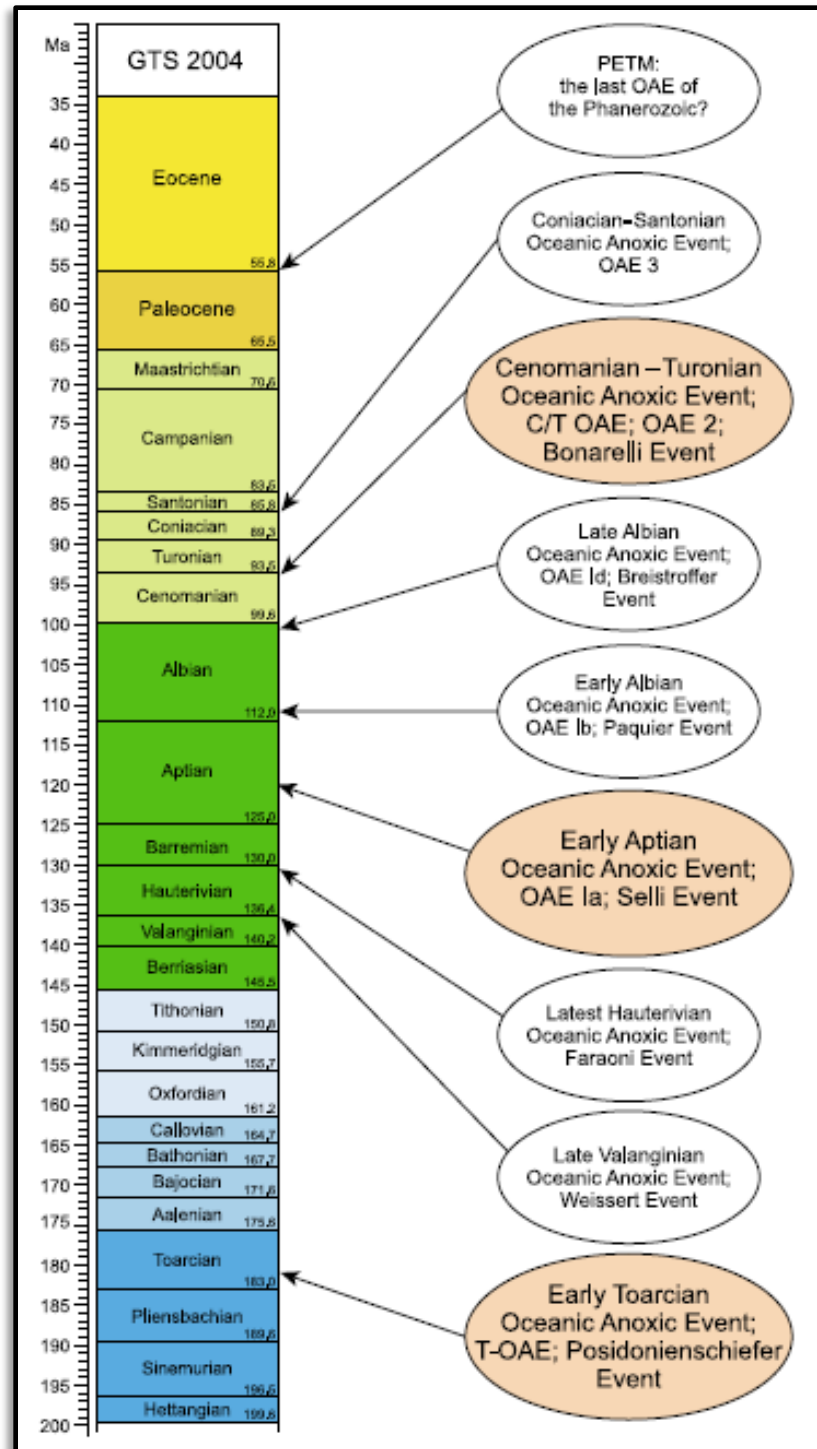


Figure 15. The distribution of significant OAEs (according to Jenkyns, 2010) during the Mesozoic and the Cenozoic range from the Toarcian in the Jurassic, to the Cretaceous, and possibly even to the Eocene. Major OAEs are colored in pink, and are thought to be caused by enhanced greenhouse conditions, productivity, equable seas and stratified ocean columns, among other factors.

CHAPTER FOUR: RESULTS

Outcrops

A total of 109 meters of section comprises 73 samples at the Persimmon Gap outcrop. Sampling commenced halfway up the north face of the mountain at Persimmon Gap (Figure 15), first in the Paleozoic shales, through an unconformity separating the Paleozoic from the lower Cretaceous, and continued into Glen Rose Formation.

From sample PG 01 to PG 33 (Figure 16), the beds of the northwest facing side of the mountain were dipping slightly southeast. The lithology transitioned from oligomictic conglomerates at the base of the Glen Rose Formation, to medium to fine sand grading into carbonates. The first carbonate rocks encountered were wackestone and floatstone containing a fair amount of oysters; some beds contained annelid worm tubes. Samples were collected up the mountain until there was no safe outcrop. At that point, a marker bed with abundant annelid tubes (Figure 17) was correlated to the north western limb of the thrust mountain where the second part of the section was measured.



Figure 16. Sampling path at Persimmon Gap. The samples were collected along red dashed line. Dangerous cliffs prevented continuous collecting along this outcrop.

This western limb was composed of slightly overturned beds dipping at 78° towards the NE. The annelid-rich bed (sample PG 34) permitted to resume the sampling to the west and over multiple small ridges until sample PG 67. In this interval, carbonate textures range from wackestone, floatstone, rudstone and mudstone. A large cliff prohibited further sampling west beyond the location of sample PG 67; after following the bed down towards the base of the mountain at PG 68, sampling commenced west to PG 73. The final interval in Persimmon Gap was comprised of all mudstones.



Figure 17. Annelid worm tubes. This bed was used to correlate across the hinge of the thrust once the outcrop became too steep to sample safely.

At Santa Elena, the Glen Rose Formation was sampled along steep walls where beds were dipping slightly southwest (Figure 18). Sampling at the base of the canyon required navigation along the north bank of the U.S. side of Rio Grande River. All samples collected at the Santa Elena Canyon outcrop were mudstones. Most of the beds were fairly massive with little



Figure 18. *Santa Elena hurdles. The abundant vegetation and Rio Grande hampered the access to the beds.*

to no variance in competency. There were individual bed divisions present however most of the beds seemed to be identical in composition and texture.

Sample Lab Descriptions

The collected samples were made into thin sections and described using a petrographic microscope. Samples not made into thin-sections; were slabbed and described with a stereoscope. It was determined 10 different rock types were collected at the Glen Rose Formation outcrops in BBNP.

The basal beds of the Glen Rose Formation include red coarse conglomerates (mean clast approximately 2cm), poorly sorted coarse sub angular oligomictic conglomerates, medium sandstones, plurimetric bedded sandstones, poorly sorted sandstones, quartz clasts, laminated fine sandstone, very fine sandstone, siltstone, siltstone with mudclasts (Figure 19).

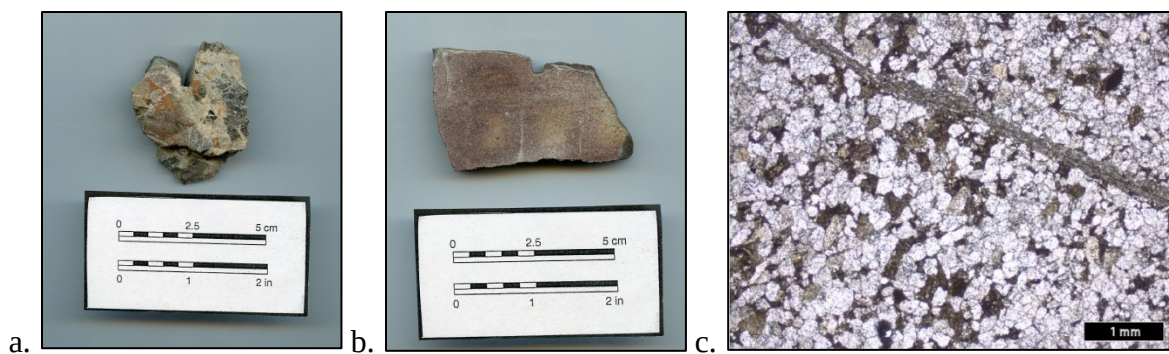


Figure 19. Example of siliciclastic rocks from Persimmon Gap. a. Oligomictic conglomerate, sample PG 06; b. Sandstone, sample PG 09a; c. Sandstone, thin section of sample PG 9a.

Continuing sampling up section, beds are outcropping slightly and strata are not very competent with portions covered by scree. From the base to this portion of the section, siliciclastic material starts occupying the space between and within large allochems (oysters). These molluscan siliceous rudstones (Figure 20) and the basal siliciclastic material are unique and do not repeat in the Glen Rose Formation outcrops sampled in BBNP.

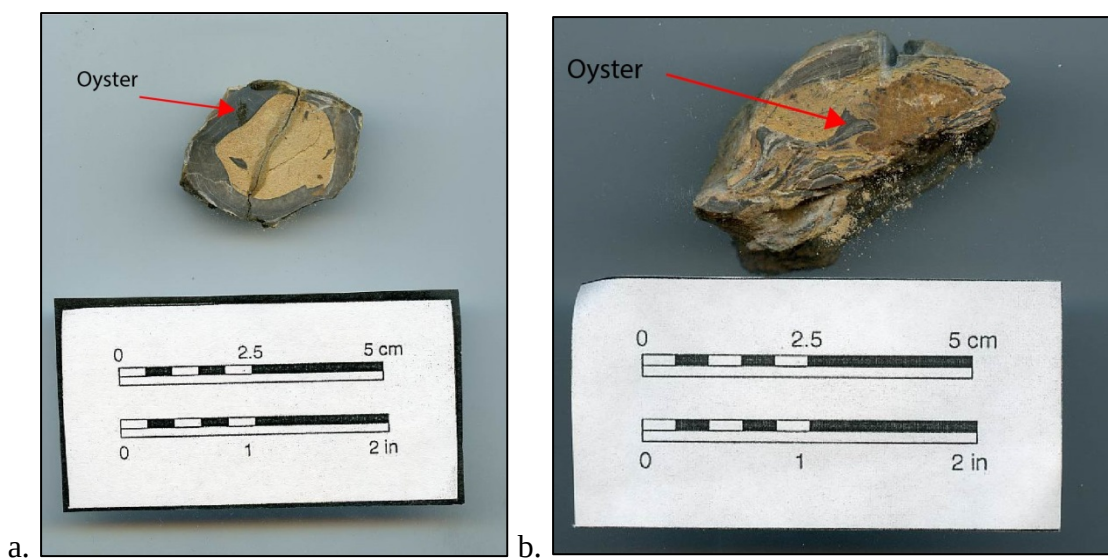


Figure 20. Example of molluscan siliceous rudstones with oyster allochems. a. Rudstone, sample PG 11; b. Rudstone, sample PG 12.

Following on top, an oyster facies becomes dominant. The facies consists of mudstone, wackestone and floatstone comprised of mostly molluscan bivalve oyster allochems (Figure 21).

The oyster abundant bed transitions into a mudstone with little macroscopic evidence of allochems present. This facies is described as a bioclastic mudstone (Figure 22).

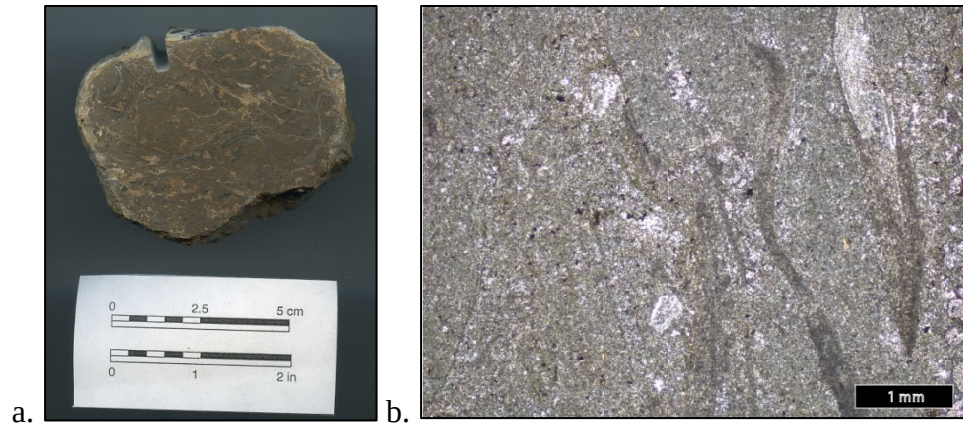


Figure 21. Example of oyster wackestone-floatstone. *a.* Wackestone, sample 16; *b.* Wackestone, thin section of Sample 16.

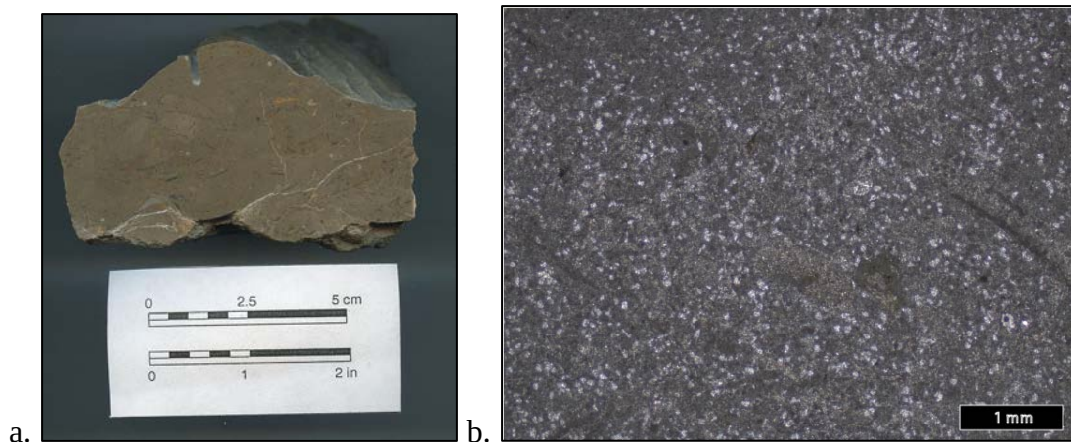


Figure 22. Example of bioclastic mudstone. *a.* Mudstone, sample PG 53; *b.* Mudstone, thin section of sample PG 53.

Rudists constitute the main allochems in the next lithofacies (Figure 23), which texture varies from floatstone to mostly rudstone. Dolomite, iron-oxide and small amount of glauconite are present. These beds form the steep cliff and the ridges on the Persimmon Gap outcrop.

The next facies is a molluscan mudstone-floatstone (Figure 24) that contains glauconitic grains. Rudists and other large bivalves are present along with smaller bioclasts.

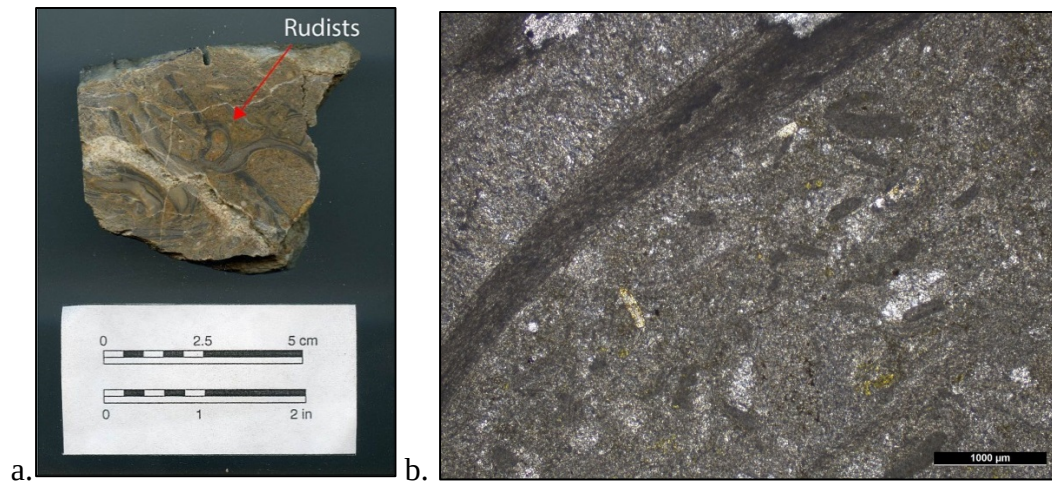


Figure 23. Example of rudist rudstone. *a.* Rudstone, sample PG 34; *b.* Rudstone, thin section of sample PG 34.

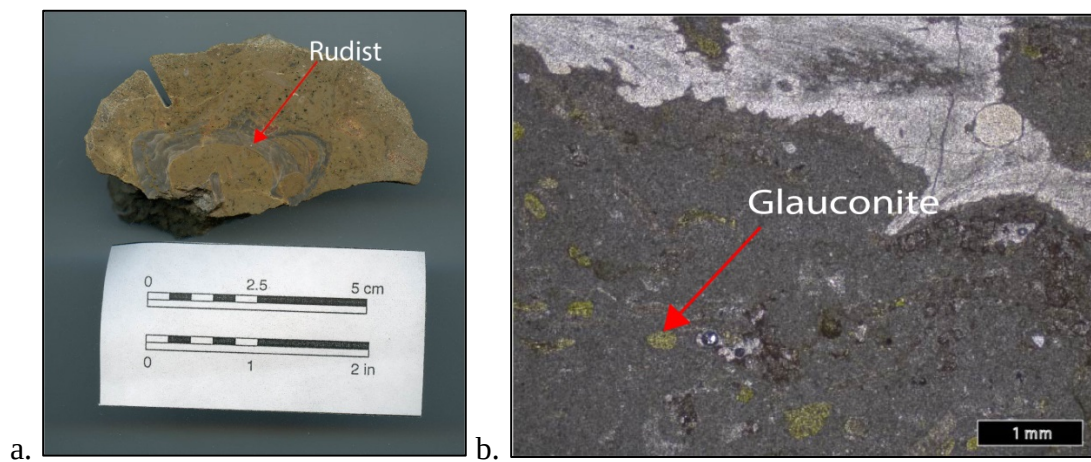


Figure 24. Example of molluscan mudstone-floatstone. *a.* Floatstone, sample PG 43; *b.* Floatstone, thin section of sample 43.

The next facies, a wackestone to floatstone exhibits corals in hand specimen, whereas molluscan, echinodermal and gastropod bioclasts are also present when examined in slab or thin-section (Figure 25).

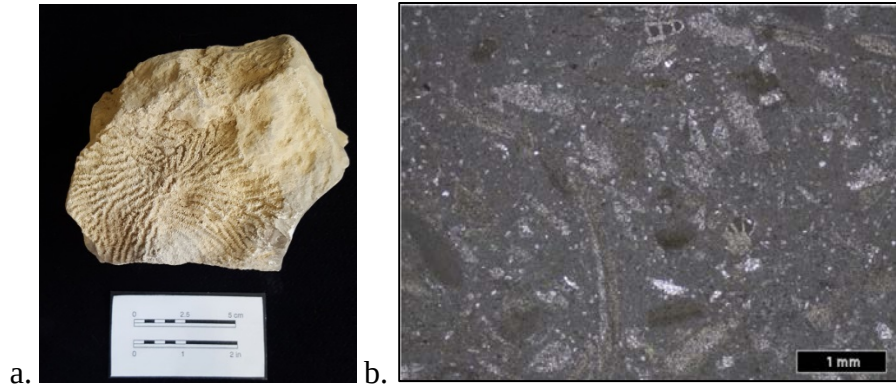


Figure 25. Example of wackestone. a. Coral; b. Wackestone, thin section of sample 52.

Additionally, a bioclastic wackestone to packstone presents variable amount of allochems, which correspond to gastropods, rudists, bivalves and some crinoid remains (Figure 26).

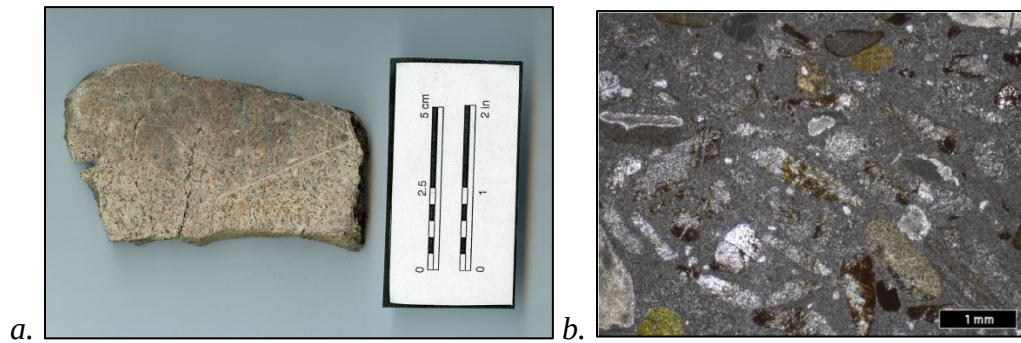


Figure 26. Example of bioclastic wackestone to packstone. a. Packstone, sample PG 45; b. thin section of Sample PG 45.

The following facies is a semi-competent bioclastic mudstone (Figure 27) exhibits a small amount of bioclasts. There are some larger allochems; echinoderms, bivalves, crinoid remains and foraminifera, are present in more friable beds before reaching the competent bioclastic beds. An ammonite and a large gastropod were identified at the base of the larger cliff building portion of this lithofacies section.

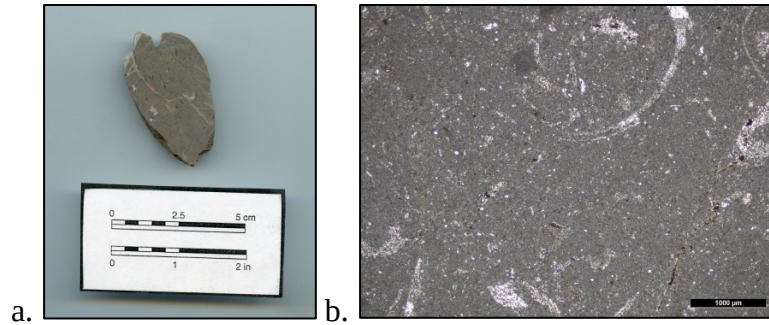


Figure 27. Example of bioclastic mudstone; a. Mudstone, sample PG 59; b. Thin section of Sample PG 59.

At Santa Elena Canyon, a dark molluscan bioclastic mudstone (Figure 28) is present. This mudstone lacks allochems and lamination, exhibits conchoidal fracture, very little variance in composition or texture and some variation in bed thickness.

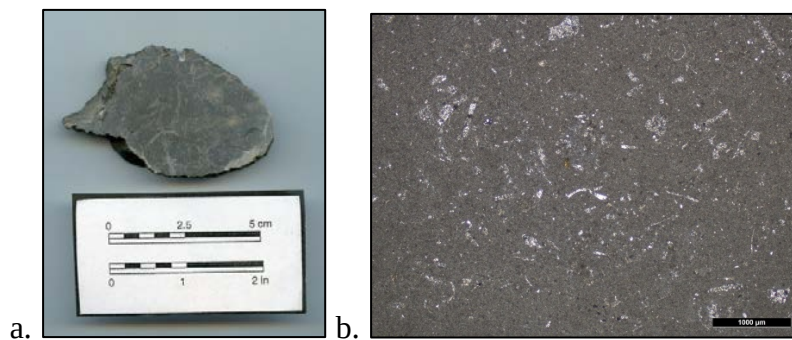


Figure 28. Example of Molluscan bioclastic mudstone. a Mudstone sample SE 11; b. Thin section of sample SE 11.

After the siliciclastics, the lithologic column (Figure 29) reflects slight repetition between, the molluscan floatstones, rudist rudstones and the plain mudstones (between 45 meters and 124 meters), up to the bioclastic mudstones. The bioclastic mudstone and molluscan bioclastic mudstone facies become more consistent and there is no more repeating at the top of the sampled sections. The molluscan floatstone and mudstones dominate up to the bioclastic mudstone, until the samples at Santa Elena Canyon where the molluscan bioclastic facies is dominant.

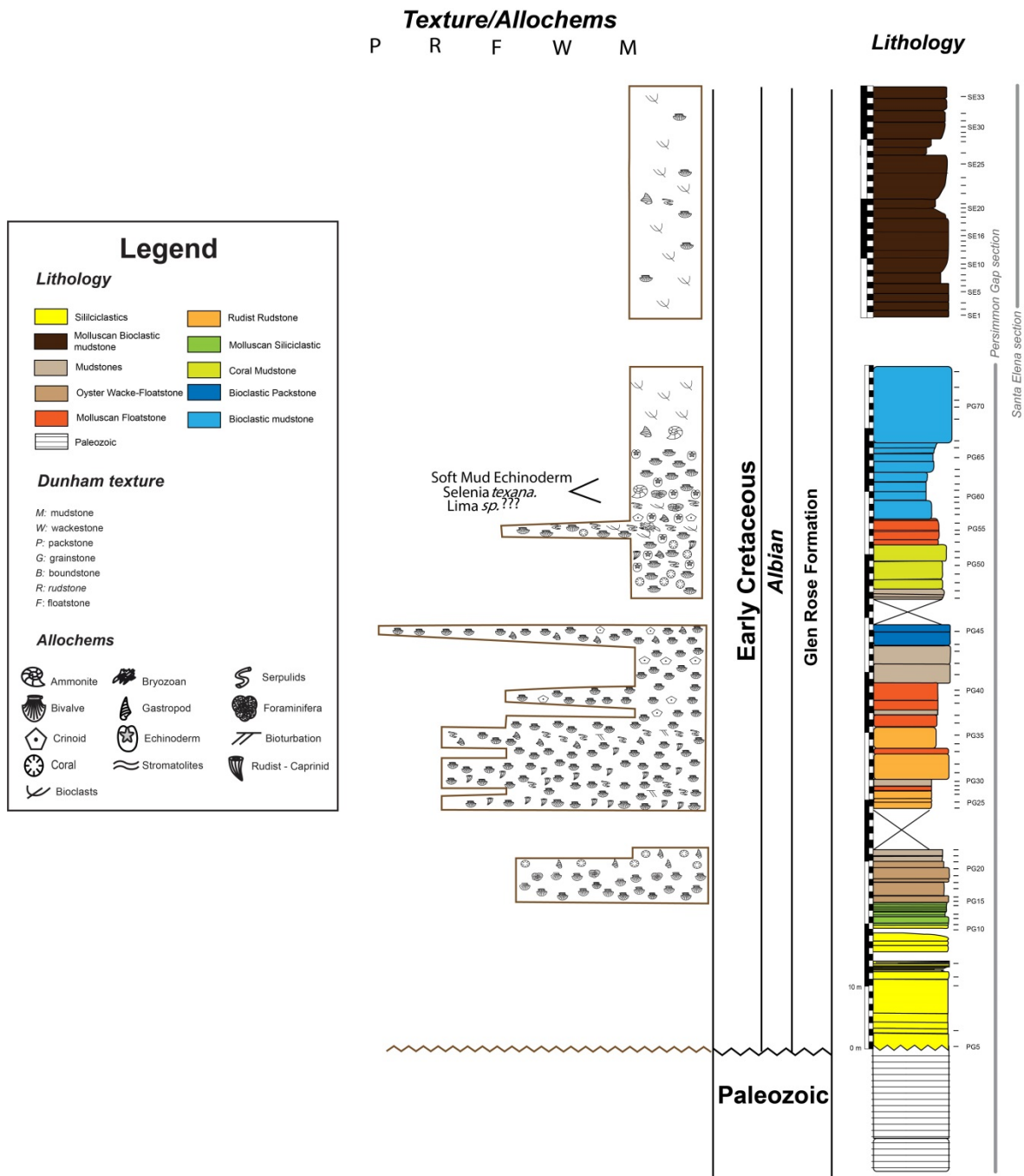


Figure 29. Lithologic column with texture and allochems. Texture based on Dunham (1962) classification as modified by Embry and Klován (1971). Lithologic column begins at the base with siliciclastic and transitions into mudstones, wackestones-floatstones, fossiliferous mudstones and finally dark molluscan bioclastic mudstones sampled at Santa Elena Canyon at the top. There is a gap between the Persimmon Gap location and Santa Elena Canyon location, this gap could represent approximately 50 m (Muehlberger and Tauvers, 1988).

Carbon and Oxygen Stable Isotopes

Whole-rock $\delta^{13}\text{C}$ values range from -1‰ – 6‰ and the $\delta^{18}\text{O}$ values vary from -12‰ to 4‰. Near the base of the outcrop, $\delta^{13}\text{C}$ values of the carbonates are slightly negative and quickly increase up to slightly above 2‰ within the next 10 meters. This positive excursion is followed by an increase in values up to 3‰, until a sampling gap at 70m. $\delta^{13}\text{C}$ values resume at 3‰ and get slightly heavier, up to 5.5‰ at 58 meters, until the last few samples collected at Persimmon Gap (~110 m) decrease in value to less than 3‰ (Figure 29). The $\delta^{18}\text{O}$ values remained mostly negative throughout the section. The oxygen isotope curve exhibited the same trend as the carbon values through the measured section (See Figure 30).

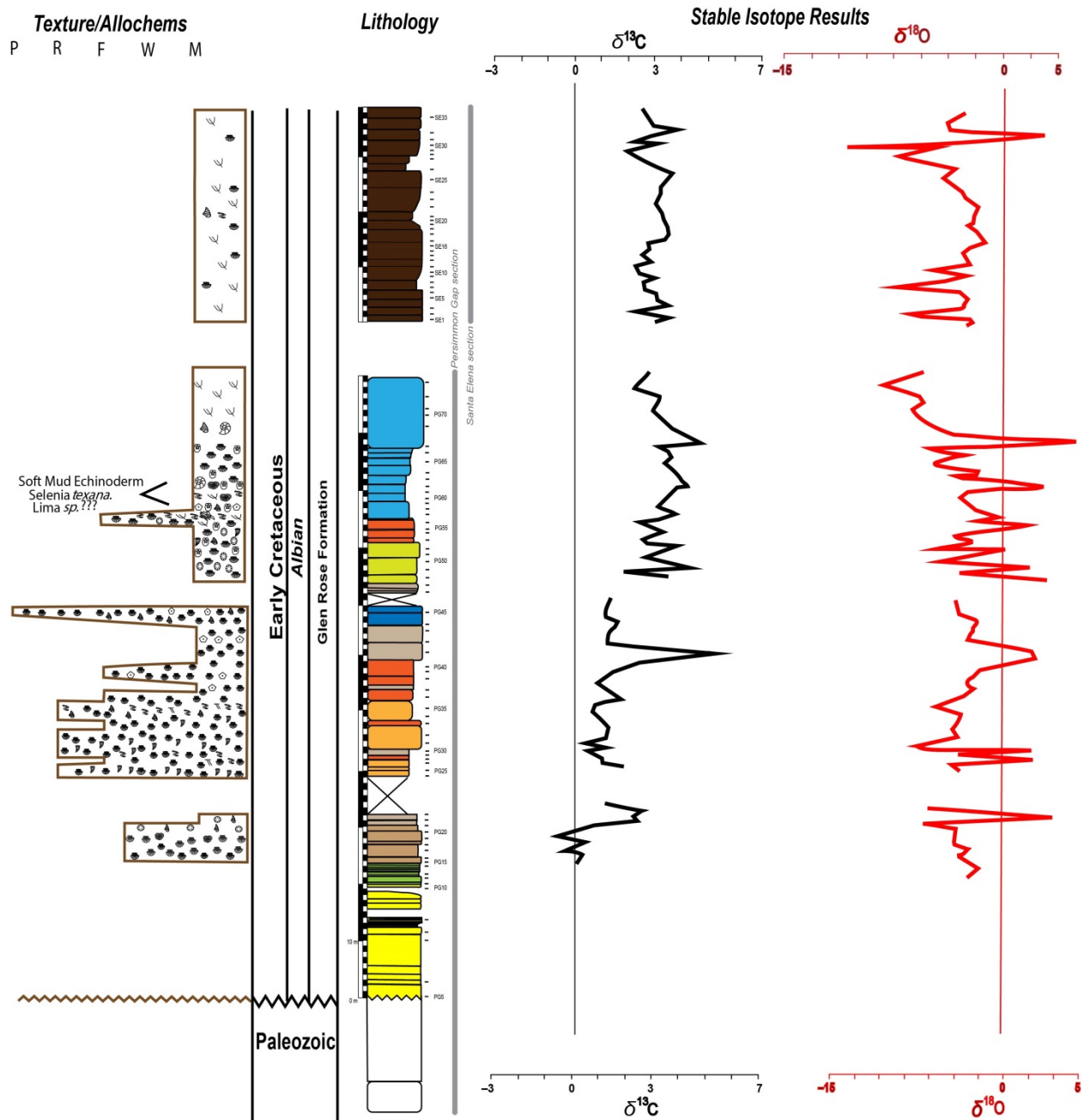


Figure 30. Evolution of carbon and oxygen stable isotope values at BBNP. Note the negative excursion at the base and how the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ covary up section.

CHAPTER FIVE: DISCUSSION

Depositional Environment

The Glen Rose Formation from Persimmon Gap and Santa Elena Canyon is interpreted to describe facies assemblages that characterize depositional environments during this portion of the Early Cretaceous. Assigning the samples to a particular depositional environment enables additional interpretation of the climate, source, location, platform structure and other processes. Carbonate platform models help understanding distribution of carbonate facies and to a lesser extent, primary porosity distribution (Read, 1985). The Glen Rose Formation in BBNP exhibits six different environments of deposition which can be organized along a proximal to distal transect across a shallow shelf carbonate ramp, following the model put forward by Phelps et al. (2014).

The terrestrial shoreline facies assemblage is the most proximal facies found at the base of the Glen Rose outcrop at Persimmon Gap: the poorly sorted and large clasts suggest that conglomerate facies corresponds to alluvial/fluvial environments, preferentially developed during regressive periods, whereas the well-sorted, finely grained sandstones with carbonate limes would rather indicate a more transgressive trend (Hettinger et al., 1993). The transition in grain size indicates a change in sea-level and the beginning of a composite sequence (Van Wagoner et al., 1988). Based on the grain size and texture of the sandstone beds, these siliciclastic deposits were deposited in a very proximal, near shoreline (Boggs, 2006). Provenance for these terrestrial shoreline facies are the exposed Ouachita Mountains, the Marathon Uplift or possibly the Llano uplift just as the Hensel sands from central and south Texas (Scott et al., 2007).

Moving away from shore along the transect from proximal to distal, the next facies is a molluscan shoreface facies assemblage. This deeper setting favors the establishment of oysters which are typically found in estuaries, bays and lagoons (Puffer and Emerson, 1953; Parker, 1956). For the Early Cretaceous of the Comanche platform, Perkins (1974) interpreted oyster rich biostromes to form in the most proximal part of the lagoon where detrital supply remains significant. Certainly, this environment is close enough to shore to be effected by terrestrial sediments that can be transported in channels by storms, floods, or possibly abrupt transgression to a deeper depositional setting (Wilson, 1974). The porosity of the molluscs in this facies has been filled with siliciclastic material that is prominent in the aforementioned siliciclastic shoreline facies. This facies would be located in the subtidal internal shelf, very close to the shoreline.

Moving away from the siliciclastic assemblages, a subtidal intrashelf facies assemblage mainly consists of an oyster wackestone to floatstone, with subordinated mudstone, wackestone, floatstone, and rudstone. Bioclasts or skeletal particles consisting of molluscs are mostly present in the mudstone and wackestone. The characteristics of the mud-dominated matrix suggest a deposition in a very low energy environment of the shelf interior, possibly in the lagoon setting (Read, 1985; Phelps, 2011; Wilson, 2012). Annelid-burrowed beds are also found in this intrashelf environment. The molluscan floatstones of this assemblage contains glauconitic grains. Oysters and rudists comprise most of the larger allochems observed in the floatstone and rudstone facies. Mud matrix and allochems indicate a low energy, back reef environment ranging from a proximal shoreline to a lagoon located in an intrashelf setting. Rudist floatstone to rudstone dominate the most distal area of this lithofacies. Dolomite, iron-oxide and evidence

of glauconite are also found in this assemblage which is characteristic of a backreef environment of the shelf interior of a carbonate platform setting (Wilson, 1974).

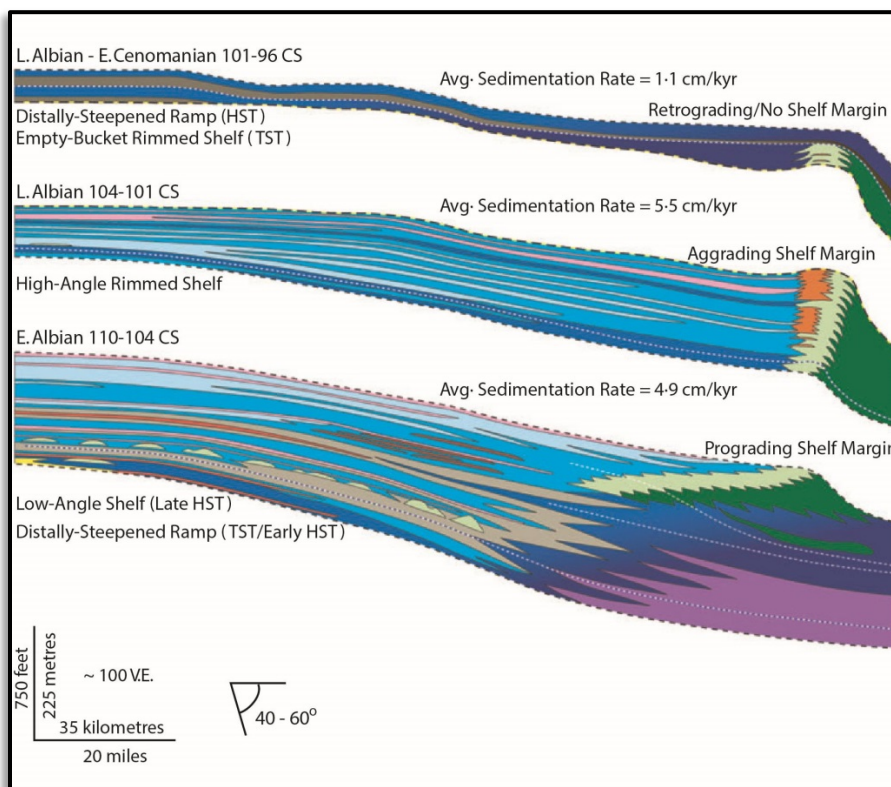


Figure 31. Separated view of composite sequences through the Albian age showing the evolution of the margin architecture of the Comanche Platform that developed on the northern margin of the ancestral Gulf of Mexico (modified from Phelps et al., 2014). The Glen Rose Formation in BBNP corresponds to a distally-steepened ramp (Transgressive System Tract/Early Highstand System Tract) followed by the low-angle shelf (Late Highstand System Tract).

The next facies assemblage is being referred to as a subdued or low-profile reef facies assemblage due to lack of evidence of a substantial reef structure: the Glen Rose in BBNP is interpreted as gently sloping, lacks a high angle rim and is most likely a distally steepened ramp which was common during the early Albian as shown in Figure 31 (Phelps et al., 2014). Corals are present in hand samples and molluscan, echinoderm and gastropod bioclasts are found in these wackestones. However, the thickness of the beds would not suggest the presence of a prominent reef.

As shown in Figure 32 bioclastic samples began to transition from packstone to grainstone between the subdued reef and the more distal external open shelf. Gastropods, rudists, bivalves and some crinoid parts are present in this external distal subdued reef slope area.

The most distal and deepest facies assemblage of the Glen Rose Formation in BBNP corresponds to the upper portion of an open shelf facies. A small amount of bioclasts characterizes this mudstone. Included in this assemblage, a highly stratified friable layer contains large allochems of echinoderms and bivalves, and microscopic allochems including crinoid remains and foraminifera. These friable beds transition to very competent, cliff building, and massive beds at the base of which ammonites and large gastropods are identified. The allochems and the matrix of these samples indicate an open-shelf setting (Boggs, 2006).

The next assemblage in BBNP is found at Santa Elena Canyon. This facies consists of a dark lagoonal intrashelf deposits. This mudstone displays few allochems (e.g., gastropods, bivalves) and lacks lamination. It is interpreted as being deposited in a very low energy intrashelf environment in the lagoonal portion of a shallow carbonate ramp system (Phelps, 2011; Wilson, 2012).

To synthesize, the most proximal depositional environment corresponds to terrestrial, fluvial setting where siliciclastic deposits are represented by conglomerates at the base of the section. They grade into coastal beach sandstone deposits and, moving away from the shore, to a low energy subtidal environment characterized by mudstones, floatstones to rudstones with molluscan grains. A subdued reef system is interpreted from the occurrence of scarce corals within a mudstone; this environment transitions into the proximal open shelf where bioclasts, echinoderms, bivalves, ammonites and gastropods in mudstone were deposited. The last facies, at Santa Elena Canyon, is a low energy intrashelf lagoon. Based on the description of facies

assemblages, it is determined that the depositional environment is a low profile carbonate shelf margin with quiet to moderate energy levels (Wilson, 1974; Read, 1985; Handford and Loucks, 1993).

Such a low-profile carbonate shelf depositional environment was common during the Early Cretaceous in Texas (Read, 1985; Phelps et al., 2014). The shelf-to-basin profile of the Glen Rose supersequence model is characterized by low-angle fore-reef slopes that range from 3° to 15° in dip (Phelps, 2011). An idealized lithologic column derived from the study of the Shell Tomasek #1 well (Phelps, 2011) through the Glen Rose Formation exhibits similar facies as those described in BBNP: peloid-miliolid wackestone/packstone, caprinid bafflestone/floatstone, coral framestone, bioclastic grainstone/rudstone, mixed fauna boundstone, peloid-skeletal wackestone/packstone, and a black gastropod-rudist floatstone/wackestone. Related to depositional environment, there was thorough work completed on an outcrop at Canyon Lake Gorge in central Texas which exhibits some slight differences, including a siliciclastic-influenced shelf facies assemblage, open-marine subtidal assemblage, shallow subtidal and peritidal assemblage and a restricted inner shelf assemblage (Ward and Ward, 2007). However, all of these facies also belong to a shallow low-angle carbonate slope environment (Wilson, 1974; Handford and Loucks, 1993). Research on the Glen Rose Formation at the Canyon Lake Gorge suggests that this area was more influenced by siliciclastic material, and that an open-marine subtidal, shallow subtidal and peritidal assemblages could be defined (Ward and Ward, 2007). Based on the similarities of the depositional settings, facies and assemblages, we can assume that climate, ocean chemistry, sea-level, water depth, platform structure and provenance remain similar between the BBNP, the Shell Tomasek #1 location and Canyon Lake Gorge.

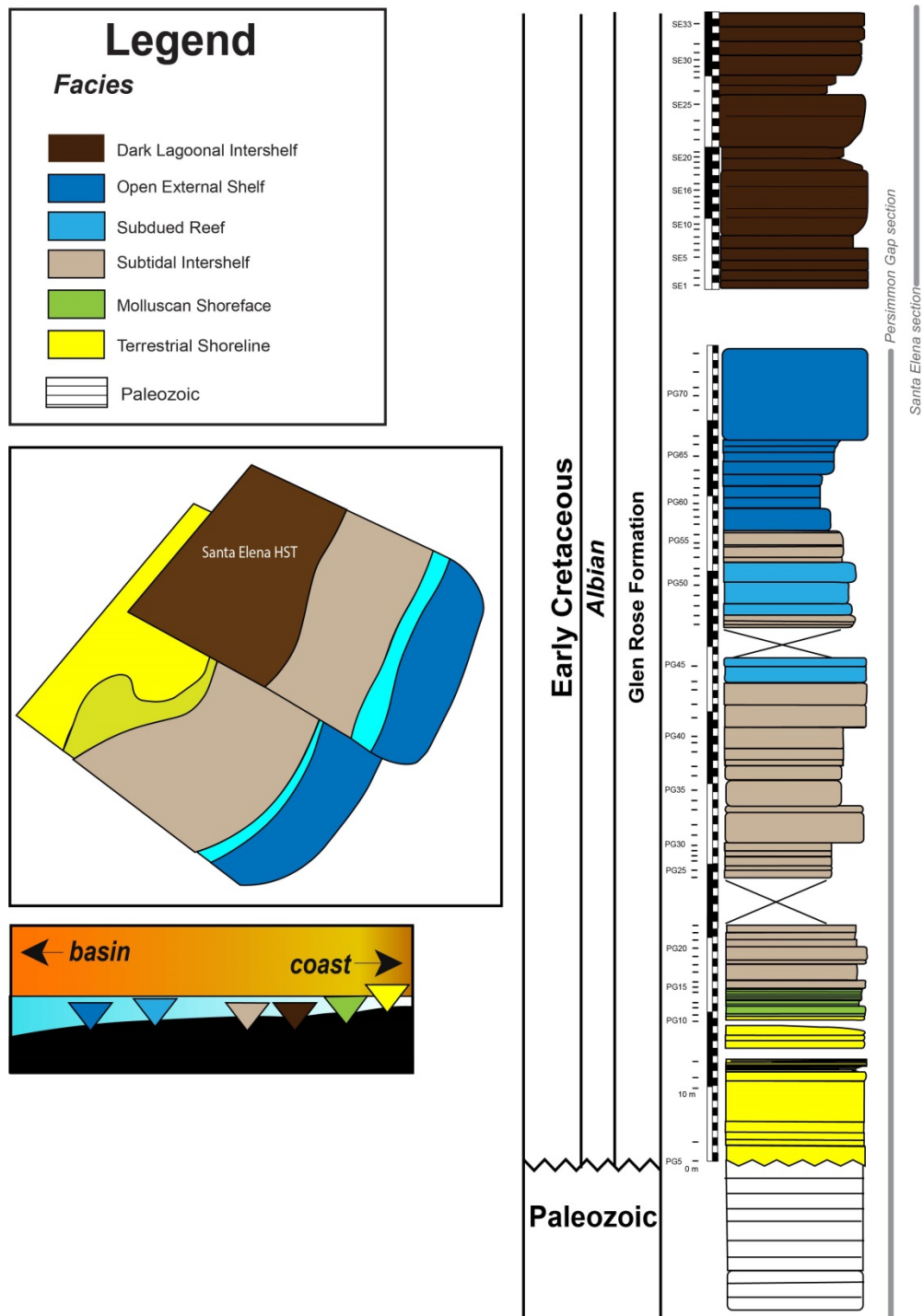


Figure 32. Lithological column that illustrates stratigraphic evolution of facies and interpreted depositional environments. Shore to near shore facies at the base of the Glen Rose Formation transition into lagoonal intertidal facies, and then into proximal open shelf depositional environment. Finally at Santa Elena Canyon, a proximal intrashelf lagoon depositional environment is interpreted. Overall depositional environment is a shallow shelf low angle carbonate ramp as illustrated by the schematic profile in the bottom left corner of the figure.

Stable Isotopes

Carbon isotope chemostratigraphy is a powerful tool to perform local to global correlations of both marine and continental sedimentary successions (Scholle and Arthur, 1980; Herrle et al., 2004; Suarez et al., 2009; Jenkyns, 2010). However, diagenetic overprint of isotope systems constitutes a major pitfall and must be properly assessed before correlations are performed (e.g., Weissert and Erba, 2004; Follmi et al., 2006; Godet et al., 2016). Constructing a cross plot of $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ values constitutes a quick data quality investigation for diagenetic alteration: in Figure 33, results from BBNP are compared to estimate seawater composition (ESC) for the Albian stage derived from data from Herrle et al. (2004). This figure also captures meteoric and burial trends (Choquette and James, 1987; Herrle et al., 2004; Knoerich and Mutti, 2006). $\delta^{18}\text{O}$ values are suspect, and may have possibly been exposed to excessive precipitation events and have been altered diagenetically. The more negative $\delta^{18}\text{O}$ trends have been interpreted as increased fluid temperature during burial diagenesis (Knoerich and Mutti, 2006). Another possibility is lab error, during micro sampling collection, the helium flush, or the phosphoric acid reaction. Resampling and further analysis may be required to completely confirm no errors during lab analysis. Moving forward the $\delta^{13}\text{C}$ results seem suitable for further chemostratigraphic correlation.

The variation of diagenetic trends of the two sample locations, even though locations are only 70 mi apart, can be attributed to the difference of geological processes experienced. Meteoric waters have a slight negative effect on the subtidal intrashelf samples deposited after the siliciclastic facies assemblage, which directly overlays the sequence boundary, depleting the $\delta^{13}\text{C}$ of this section of the Glen Rose Formation at Persimmon Gap (Lohmann, 1988). There is only a slight variation of the $\delta^{13}\text{C}$ at Santa Elena Canyon, despite being deposited during a

highstand system tract. The $\delta^{13}\text{C}$ values can be effected by the mixing of marine and meteoric fluid (Lohmann, 1988), during regression in a highstand systems tract (HST) due to increased erosion and chemically altered run-off being deposited in shoreline and subtidal environments, the HST is likely to be exposed subaerially.

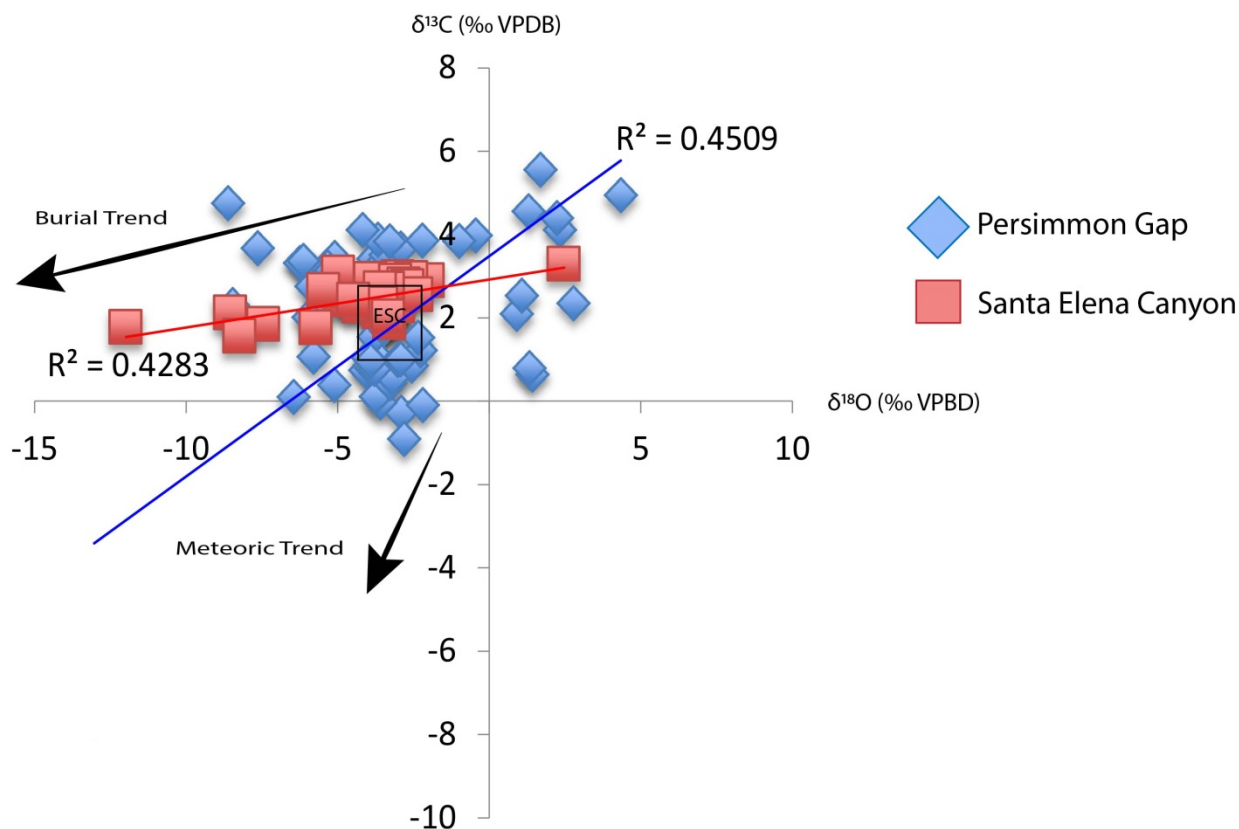


Figure 33. $\delta^{13}\text{C}/\delta^{18}\text{O}$ cross plot for samples of the Glen Rose Formation in BBNP including Albian Estimated Seawater Composition (ESC) data from Herrle et al. (2004).

Phelps et al. (2015) provide a $\delta^{13}\text{C}$ composite profile from the Comanche Platform in south Texas that represents a continuous secular carbon isotope curve through the Aptian to the Albian strata (Figure 34). When comparing this reference curve with the present study, it is important to note that the range of $\delta^{13}\text{C}$ values from BBNP is higher than that reported by Phelps et al. (2015). However, BBNP results still display strong similarities with an overall trend to

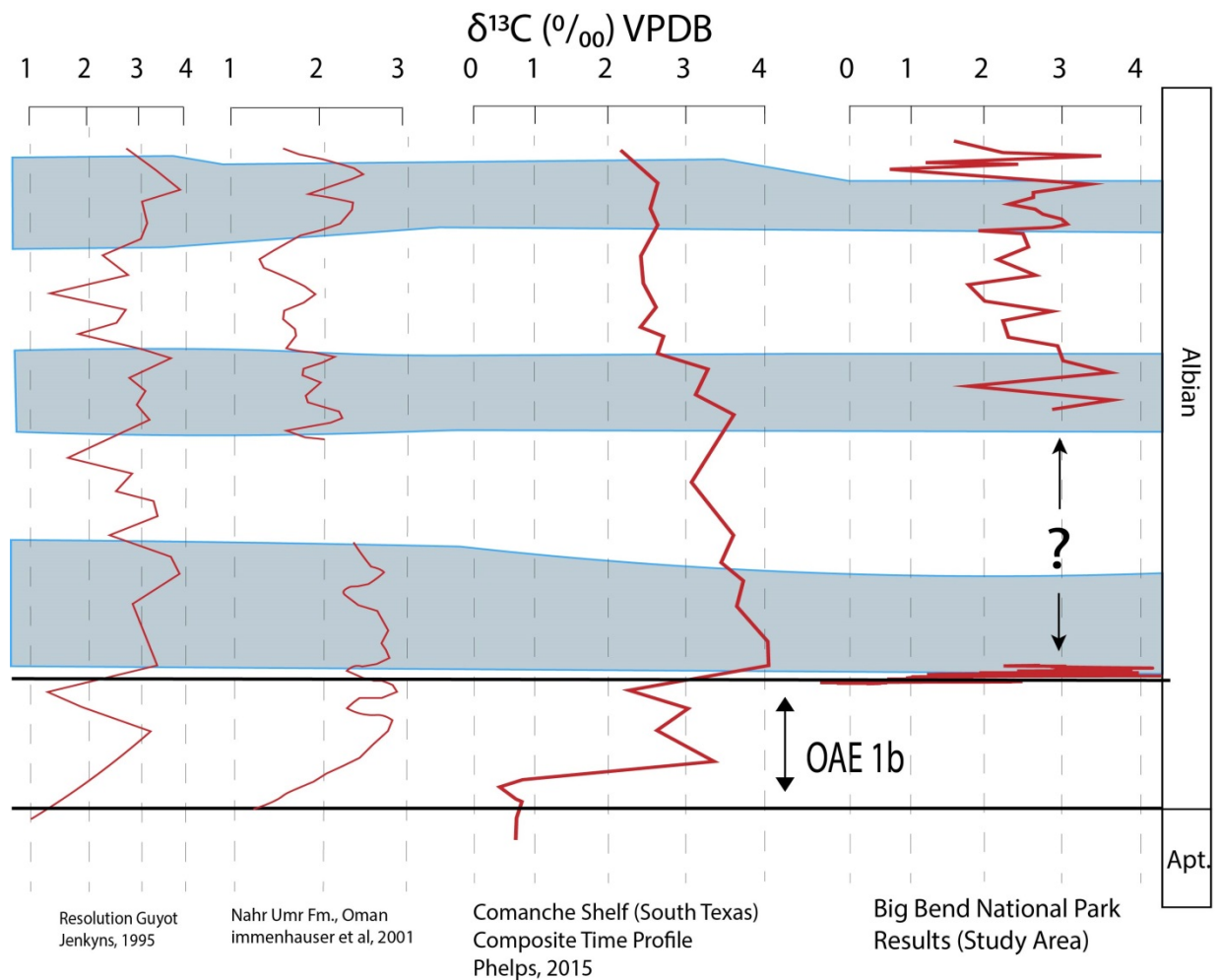


Figure 34. $\delta^{13}\text{C}$ correlation of the $\delta^{13}\text{C}$ curve for BBNP to the reference isotope record for the Comanche shelf (South Texas) and other global locations. Modified from Phelps et al. (2015).

slightly more negative values: a key feature that can be correlated is the OAE 1b at the base of the Albian.

The correlation displayed in Figure 33 is supported by the USGS map of BBNP, which reports that the base of the Glen Rose Formation crops out at Persimmon Gap, whereas the top of the Glen Rose Formation is found at Santa Elena Canyon. Initially the resulting data was anchored to the top and bottom of the Glen Rose Formation to make the correlation to the Comanche Shelf in south Texas apparent. However, after further analysis and comparing the sequence stratigraphy of the two locations, discussed more in the next section, the base of the

Glen Rose Formation isotope data was anchored at the base of Phelps' (2011) Glen Rose Sequence boundary.

Discounting major diagenetic effects on carbon isotope composition, several factors could explain fluctuations in $\delta^{13}\text{C}$ values: surface water temperature changes, faunal or floral alterations, fertility and production variations, and modifications in the carbon isotopic composition of the oceanic carbon reservoir—local, regional, or global (Scholle and Arthur, 1980; Swart and Eberli, 2004).

The $\delta^{13}\text{C}$ data at Persimmon Gap of the Glen Rose Formation correlates to the end of OAE1b. The carbonates at the base of the Glen Rose Formation exhibit the most negative values of all collected samples, however the values increase abruptly matching other trends that identify the OAE1b in this portion of the Albian (Leckie et al., 2002; Herrle et al., 2004). The OAE1b represents an extended interval of dysoxia and deposition of black shales in the ocean during this part of the Cretaceous (Leckie et al., 2002). Other positive excursions that may represent times of higher productivity and warmer climate are highlighted in Figure 33 and support the chemostratigraphic correlation of the BBNP $\delta^{13}\text{C}$ data correlates to the Comanche Shelf reference curve.

Unfortunately, isotope analysis can't be done below this point of the Glen Rose Formation due to the unconformity, however collecting the samples between these two sites from a third site or sampling above the Glen Rose Formation in Santa Elena Canyon, would improve the data and lead to a more confident interpretation.

Sequence Stratigraphy

At Persimmon Gap, the base of the Glen Rose Formation overlies an unconformity that cuts into the Paleozoic shales and on top of which shoreline siliciclastic sediments were

deposited. This type of boundary agrees with the definition of a sequence boundary (Vail et al., 1977; Van Wagoner et al., 1988; Catuneanu et al., 2011) is critical in correlating strata and identifying chronostratigraphic relationships related to sequence deposition (Van Wagoner et al., 1988). Since the unconformity is interpreted as a sequence boundary and because younger deposits describe an overall deepening-upward trend the overlying siliciclastic terrigenous shoreline facies indicates the beginning of a transgressive systems tract (TST) in a composite sequence or 3rd-order sequences as stated by Vail et al. (1977). Composite sequence boundaries are defined by sudden shallowing-upward facies trends across the shelf and subaerial regional exposure surfaces (Van Wagoner et al., 1988; Catuneanu et al., 2011). After the deposition of the facies deposited in a shoreline environment, transgression during the Albian led to the deposition of a lagoonal facies assemblage, a back reef facies, and eventually reached a maximum flooding surface (mfs), which marks the most rapid rise of sea level (e.g., Catuneanu et al., 2009 and references therein) allowed the deposition of mudstone in a proximal open shelf and onto a subdued reef facies assemblage. Sea-level is interpreted to remain constant for the last 7-10 meters at Persimmon Gap before regression begins. The (mfs) therefore represents the boundary between the transgressive systems tract (TST) and the highstand systems tract (HST) (Vail et al., 1977; Sarg, 1988; Van Wagoner et al., 1988; Handford and Loucks, 1993). The beginning of the HST often results in a short aggradation of deposits followed by a progradation towards the basin; the lack of accommodation space induces a regression until the next sequence boundary (Van Wagoner et al., 1988; Handford and Loucks, 1993). The molluscan bioclastic mudstone described at Santa Elena is interpreted as being deposited in an intrashelf lagoonal environment, its occurrence in the upper part of the Glen Rose Formation confirms the regression of a HST that was initiated at Persimmon Gap (Figure 35). Again, regarding the

missing section, it is inferred it would display facies environments representative of regression until the lagoonal intrashelf facies of Santa Elena Canyon.

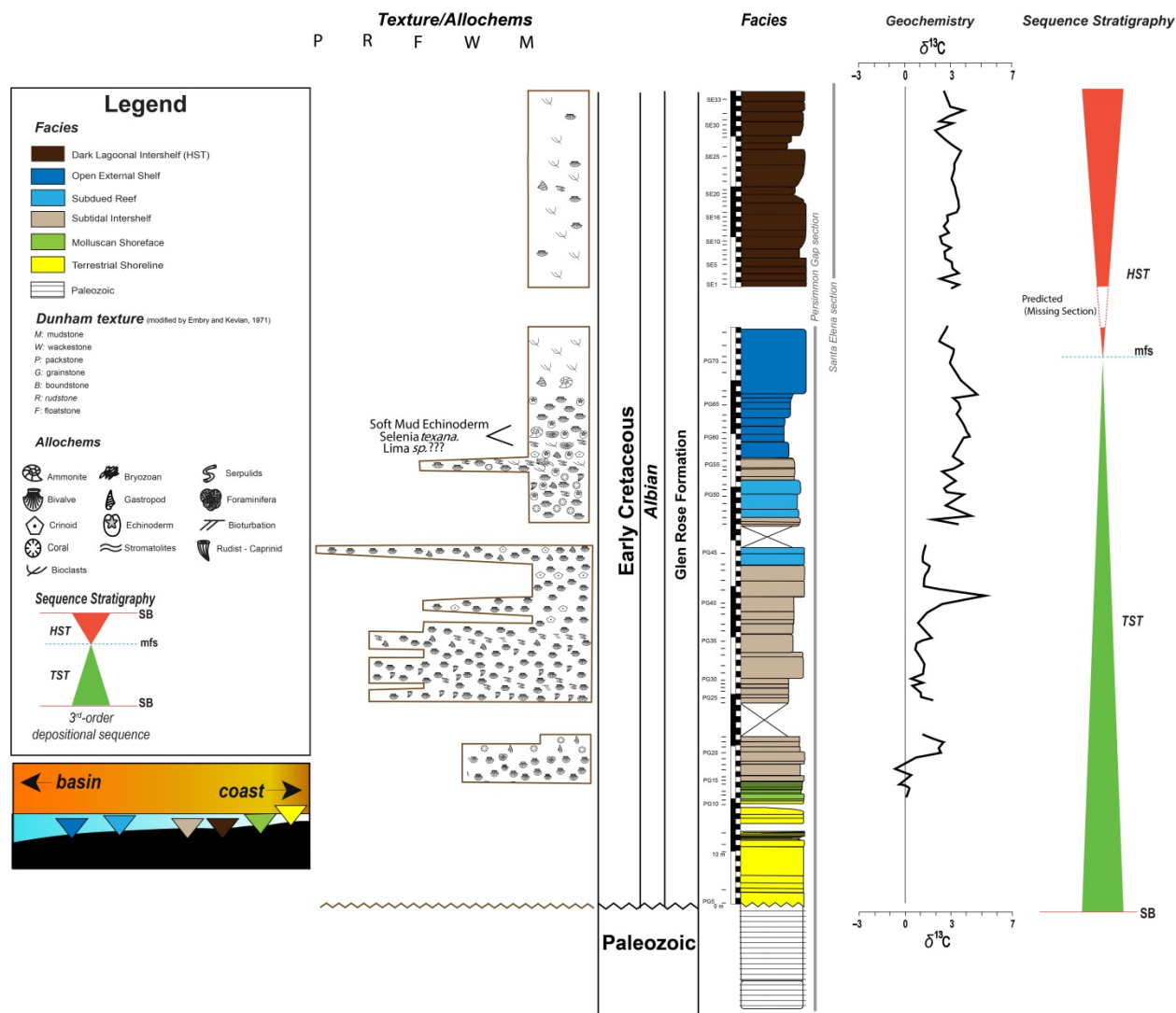


Figure 35. Geological column of the Glen Rose Formation in BBNP with texture, allochems, facies, stable isotope values and composite (3rd-order) sequence. Starting at the siliciclastic facies at the base, a transgression leads to deposition of proximal open shelf facies, then a regression occurs, and dark muddy lagoonal facies deposited at the top of the Glen Rose Formation in BBNP at Santa Elena Canyon outcrop.

This composite sequence in BBNP can be correlated to the general sequence stratigraphic framework defined for the Comanche Platform (Figure 36); and thus facilitates the regional chronostratigraphic correlation of the succession at BBNP. Such chronostratigraphic

relationships allows to embed other data (e.g., reservoir characteristics, diagenetic data) into a comprehensive sequence and systems tract models, in order to predict the occurrence of specific facies, texture or petrophysical properties of carbonate platforms (Handford and Loucks, 1993).

The sequence boundary and base of the Glen Rose Formation in BBNP has been correlated to Phelps' (2011) Glen Rose Sequence boundary picked above the regressive Hensel Formation sand. However, the initial deposits in BBNP may not be chronologically correlative. It is possible the onset of deposition initiated in BBNP before or after deposition in south Texas, the unconformity below the clastics make this difficult resolve without radiometric dating or possibly biostratigraphy. As sequence boundaries are refined or disputed in south Texas, the chronological equivalent according to sequence stratigraphy principles will be the erosional surface at Persimmon Gap.

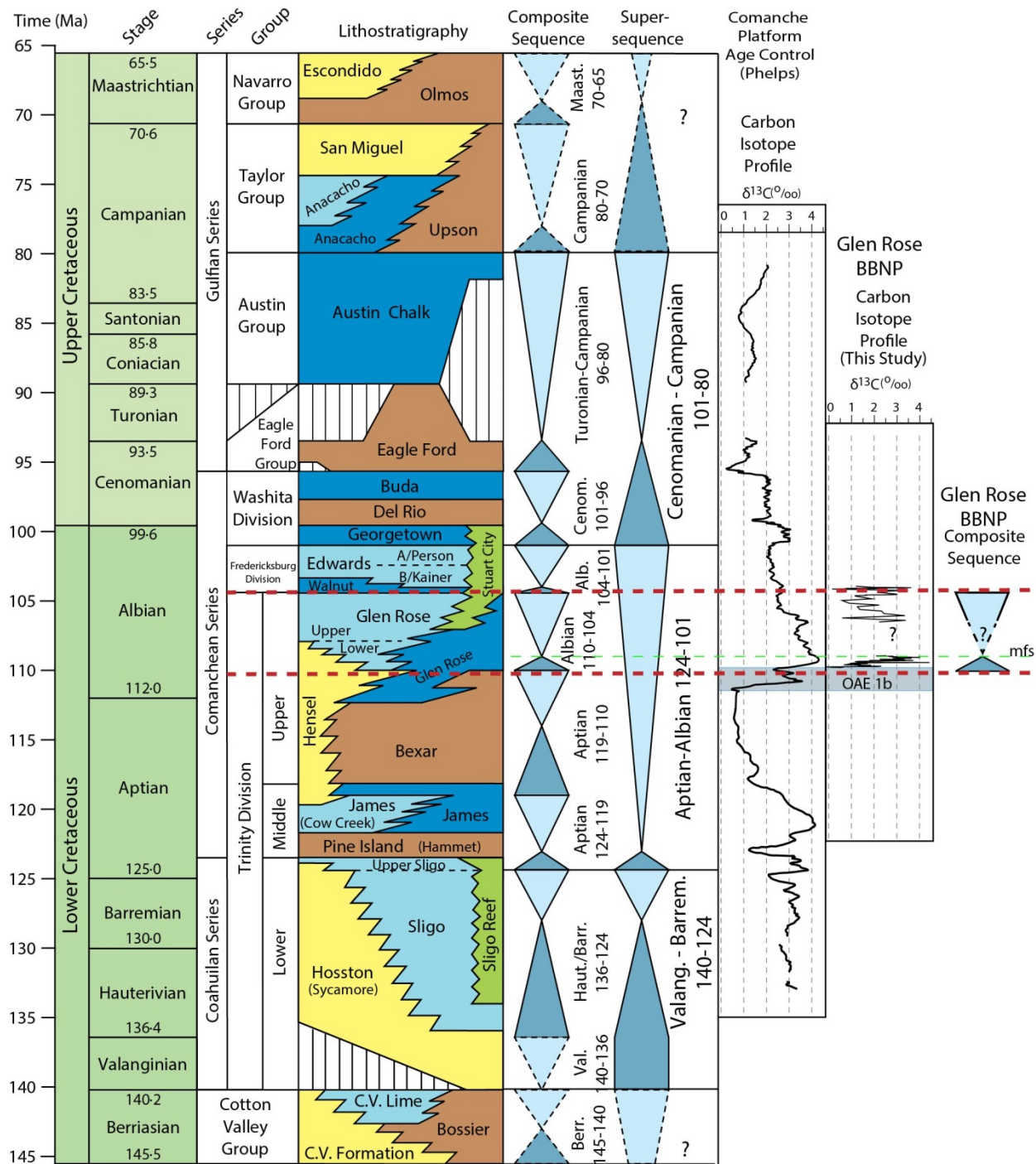


Figure 36. Composite sequence correlation. Modified from (Phelps et al., 2014). Inside light blue rectangle BBNP $\delta^{13}C$ isotope curve on the far right of figure allows for composite sequence comparison.

CONCLUSION

The stratigraphy of the Glen Rose Formation in Big Bend National Park has been compared with the Glen Rose Formation in the Comanche shelf of central Texas. Samples collected of Glen Rose Formation in BBNP at two locations, Persimmon Gap and Santa Elena Canyon, were described and based on facies assemblages their depositional environment was determined. The Glen Rose Formation in BBNP possesses microfacies and facies assemblages that are consistent with a low-profile ramp in a shallow carbonate shelf depositional environment. According to other research (e.g., Pittman, 1989; Scott, 1993; Ward and Ward, 2007; Phelps et al., 2015) this low-profile ramp system is similar to what occurred in central and southern Texas during the Albian age of the Early Cretaceous. Deposition of shoreline siliciclastic rocks, sub-tidal intrashelf deposits, fossil bearing mudstones and open shelf deposits are represented in both locations during comparatively the same time according to stable isotope analysis and sequence stratigraphy.

According to the stable isotope analysis of the Glen Rose Formation in the BBNP, $\delta^{13}\text{C}$ values were determined to match the Glen Rose Formation $\delta^{13}\text{C}$ trend of the Comanche shelf of central Texas, as well as other global locations (Scholle and Arthur, 1980; Jenkyns, 1995; Phelps et al., 2015). The $\delta^{13}\text{C}$ trend assisted in the identification of the end of OAE1b near the base of the Glen Rose Formation in BBNP and other excursions during the Albian age according to $\delta^{13}\text{C}$ trends of previous research (e.g., Scholle and Arthur, 1980; Leckie et al., 2002; Herrle et al., 2004; Phelps et al., 2015).

Sequence stratigraphy is a vital tool for correlation and evaluation of carbonate systems. After identifying the boundary of the composite sequence at the unconformity at the base of the Glen Rose Formation at Persimmon Gap outcrop, a TST, mfs and HST were identified. From

the base of the sequence, sea-level began to rise, this transgression ended with the deposition of sediments in a proximal open shelf representing the maximum flooding surface followed by the highstand systems tract finally depositing a subtidal intrashelf mudstone. Further sampling above the Glen Rose Formation at Santa Elena Canyon may reveal the base of the next sequence boundary.

Based on these new constraints, the comparison of the Glen Rose Formation in BBNP with other studies in Texas can be more easily accomplished. The Glen Rose Formation in BBNP was not described sufficiently prior to this research. Sampling of the section between the highest collection point at Persimmon Gap location and the base of Santa Elena Canyon, at Telephone Canyon and/or at the end of the Marufo Vega trail, would further improve our understanding of the Glen Rose Formation stratigraphy at BBNP. Facies interpretation, stable isotope analysis, sequence stratigraphy were all integral tools linking BBNP to the central Texas Comanche Shelf in south Texas.

APPENDIX

Table 1. Glen Rose Formation stable isotope data from Big Bend National Park at Persimmon Gap and Santa Elena Canyon.

PERSIMMON GAP								SANTA ELENA CANYON			
Sample	d13C VPDB	d18O VPDB	Meters	Sample	d13C VPDB	d18O VPDB	Meters	Sample	d13C VPDB	d18O VPDB	Meters
PG 13	-0.280445667	-2.9011476	21.15	PG 45	0.9570292	-3.8912906	67.1	SE 01	2.48411547	-3.2978802	0.55
PG 14	-0.099437867	-2.1767932	22.72	PG 46	4.10216667	2.341	72.45	SE 02	2.96633227	-3.0155711	1.47
PG 15	-0.905371933	-2.79400545	23.5	PG 47	1.79028207	-3.5077845	73.65	SE 03	1.84274053	-7.4491988	2.38
PG 16	-0.0341679	-3.569239489	24.55	PG 48	4.54960237	1.320164501	73.65	SE 04	2.91870333	-3.9070448	3.3
PG 17	-1.084606089	-3.101531	25.91	PG 49	2.65025836	-4.7821786	75.57	SE 05	2.6057632	-3.4354352	4.21
PG 18	-0.371919413	-3.859778567	26.72	PG 50	3.973673	-0.431629178	77.75	SE 06	2.54156173	-3.22233	5.13
PG 19	-0.371919413	-3.859778567	27.42	PG 50	2.9128676	-5.113337733	77.75	SE 07	2.15401427	-3.62283155	6.04
PG 20	2.147102978	-3.676469733	29.2	PG 51	2.60243091	-2.769756056	79	SE 08	2.12408413	-8.5303096	6.96
PG 21	2.017305689	-5.9406554	30.15	PG 52	3.40888173	-3.808629925	80.07	SE 09	2.43780858	-4.911022133	7.87
PG 22	2.344666667	2.796166667	31.16	PG 53	2.531	1.088888889	81.96	SE 10	1.8833443	-3.273028867	8.79
PG 23	1.06678965	-5.7729119	32.5	PG 54	3.18761791	-2.3192991	82.69	SE 11	1.76968631	-5.6986408	9.7
PG 24	1.7415809	-3.456887778	38.95	PG 55	3.8419712	-0.973614917	83.45	SE 12	2.31220167	-3.056250083	10.61
PG 25	0.733214667	-4.075410556	39.82	PG 56	3.21748765	-2.55818306	84.64	SE 13	2.1265565	-3.330789867	11.53
PG 26	0.642333333	1.436777778	40.65	PG 57	3.37685307	-3.4432276	86.75	SE 14	2.3125423	-3.498821867	12.45
PG 27	0.105385067	-3.718467011	41.5	PG 58	3.50867067	-3.4073056	87.01	SE 15	2.29329652	-2.997351367	13.36
PG 28	0.78625	1.341833333	42.2	PG 59	3.65315467	-2.9109728	87.94	SE 16	2.90354113	-2.008238	14.27
PG 29	0.786833689	-3.8738424	42.2	PG 60	4.39516667	2.2435	88.75	SE 18	2.94765315	-2.559417967	16.1
PG 30	0.096027022	-6.4325207	42.85	PG 61	3.87197747	-3.6522672	90.48	SE 19	2.8899158	-3.095545067	17.01
PG 31	0.939963911	-3.531919433	44.3	PG 62	3.8491006	-2.189809756	91.15	SE 20	2.79147277	-2.807790267	17.42
PG 32	1.046203378	-3.996981033	45.9	PG 63	3.43073068	-5.08479135	92.76	SE 21	2.7517018	-2.678909933	18.54
PG 33	0.423025378	-3.242545067	48.25	PG 64	3.82969518	-3.26497458	94.28	SE 22	2.55711703	-2.384384633	20.06
PG 34	0.378838122	-5.094691756	49.45	PG 65	3.2077728	-5.327349922	95.5	SE 23	2.6855358	-3.316087067	21.59
PG 35	1.55	-3.8	50.4	PG 66	4.93466667	4.349666667	96.65	SE 24	2.6924917	-3.584885208	22.5
PG 36	0.85	-2.55	52.5	PG 67	4.10330853	-4.153752633	98.01	SE 25	3.08362618	-4.976802533	24.79
PG 37	0.552661267	-3.18457365	53.68	PG 68	3.32092373	-6.221224	101.15	SE 26	2.27711643	-4.284371467	26.47
PG 38	1.2190312	-2.245752283	55.35	PG 69	3.04767347	-6.608040533	102.2	SE 27	1.56704222	-8.217954956	28.45
PG 39	2.086666667	0.921111111	56.78	PG 70	3.30538739	-6.035659492	103.1	SE 28	2.6633206	-5.471381417	29.97
PG 40	5.541023367	1.689605366	58.45	PG 71	3.35554745	-6.110481883	104.71	SE 29	1.77570417	-11.98058713	29.97
PG 41	0.977771	-3.001578275	60.4	PG 72	2.3	-8.45	106.28	SE 30	2.33025523	-3.536629067	30.88
PG 42	1.004168	-2.912791233	61.93	PG 73	2.75	-5.85	108.76	SE 31	3.29133333	2.474333333	31.9
PG 43	1.528197333	-2.331425467	64.01					SE 32	2.43585157	-4.473757533	32.86
PG 44	0.764592867	-3.7674592	64.95					SE 33	2.0274322	-3.320637933	35.61

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VITA

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