Stratigraphic Hierarchy and Shelf-to-Basin Architecture of Aptian-Albian Mural Shelf, Cerro Caloso Range, Sonora, Mexico

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ABSTRACT

The Mural-Caloso Shelf in Sonora, Mexico is one of only a limited number of outcrops that provide continuous shelf-to-basin profiles of reef-rimmed carbonate platforms with well-defined lowstand deposits and documentable downward shifts in coastal onlap. This paper examines the shelf-to-basin transition across three third-order sequences at the Cerro Caloso outcrop. Four parameters: reef framestone lateral and vertical dimensions, fore-reef slope lateral and vertical dimensions, evolution of platform interior facies, and presence or absence of lowstand systems tract siliciclastic wedges with or without mixed oolitic grainstone were used as the basis for the characterization of the shelf to basin profile evolution. The lower two sequences (S3 and S4) are mostly aggradational with broad coral-rudist reef rimmed margins and thick platform interiors dominated by carbonate facies. The uppermost sequence (S5) is progradational and downstepping with a narrow coral-rudist reef rimmed margin and a thin siliciclastic-rich platform interior. A lowstand wedge of fine-medium grained sandstone and cross-bedded oolitic grainstones that onlaps the S4 coral-rudist margin documents downstepping and a minimum of 20 m of downward shift in coastal onlap. The lower sequence wedge is relatively thin compared to the thickness of the S5 wedge. The long-term progradation and increased clastic component observed in the latter stages of shelf evolution indicate a large second order relative sea level fall during the deposition of the Lower Albian age Mural-Caloso Shelf. The continuous outcrop provides a good reference model for facies patterns and stratigraphic architecture for the time equivalent Cretaceous platforms that develop similar geometries such as the Shuiba shelf in the Middle East.

INTRODUCTION

The Mural Limestone extends from southeastern Arizona into northeastern Mexico and is an extension of the Comanche Shelf; a broad carbonate platform that rimmed the northwest Gulf of Mexico during Albian time (Scott and Warzeski, 1993) (Figure 1). The Mural-Caloso Shelf is one of only a limited number of outcrops that provide continuous shelf-to-basin profiles of reef rimmed carbonate shelves during Cretaceous Greenhouse settings in the northern Gulf of Mexico region. During the Lower Cretaceous, several low angle shelves developed during the 2nd order highstand (Yurewicz et al, 1993; Scott, 1993). The continuous exposure of the Mural Shelf allows detailed investigation of similar shelf architecture, especially the nature of the shelf-to-basin transition in terms of its lateral facies distribution and extent, slope angles and margin trajectory, and response of the platform margin to siliciclastic input across the shelf into the Chihuahua Trough.

The principal objective of this study was to establish a modern sequence stratigraphic framework by outlining the facies transitions and stratal geometries associated with third-order sequences proximal to the platform margin for the upper portion of the Lower Albian age Mural-Caloso Shelf system. Furthermore the data and analysis of facies transitions and stratal geometries associated with third order sequences on the Caloso Shelf margin may be used for subsurface geometric and facies comparisons with similar Aptian/Albian-age reservoirs including examples from the Shuiba Formation in Abu Dhabi (Yose et al, 2006; van Buchem et al, 2010).

PREVIOUS WORK

Lower Cretaceous formations in Arizona were first studied by Dumble (1900) and Ransome (1904). The equivalent rocks in Sonora, Mexico were subsequently examined by Dumble (1902). The Mesozoic structures of the region were described by Taliferro (1933), Gilluly (1956), Viveros (1965), and Hayes (1970). Scott (1979) studied the lower Cretaceous patch -reef developments on the shelf interior in Arizona.

Warzeski (1983) provided the most extensive study on the upper Aptian to Albian outcrops in both southern Arizona and Northern Mexico. He collected detailed measured sections for the Montes Canova and Cerro Caloso ranges in northern Sonora as well as for the Grassy Hill-Paul Spur area in southeastern Arizona (Figure 1). Warzeski (1983) described seven depositional facies and measured seven vertical sections at the Cerro Caloso outcrop (Figure 2). Scott and Warzeski (1993) later developed a regional depositional model for the Mural Shelf that serves as the basis for the present study. The most recent work of Lawton and Gonzalez (2004), and Gonzalez and Scott (2008) have focused on improving the stratigraphy of the Mural Shelf mostly in Arizona.

REGIONAL SETTING

The Mural Limestone that crops out in northeastern Sonora and southern Arizona was deposited on a broad carbonate shelf with land to the north and west (Warzeski, 1983). During Early-Middle Cretaceous time northeastern Sonora was at the northern edge of the Chihuahua Trough which curved east and southeast through the modern Mexican states of Chihuahua and Durango to join the ancestral Gulf of Mexico (Cordoba et al, 1970; Rangin and Cordoba, 1976). The Mural Limestone is one of the four formations that comprise the Bisbee Group.

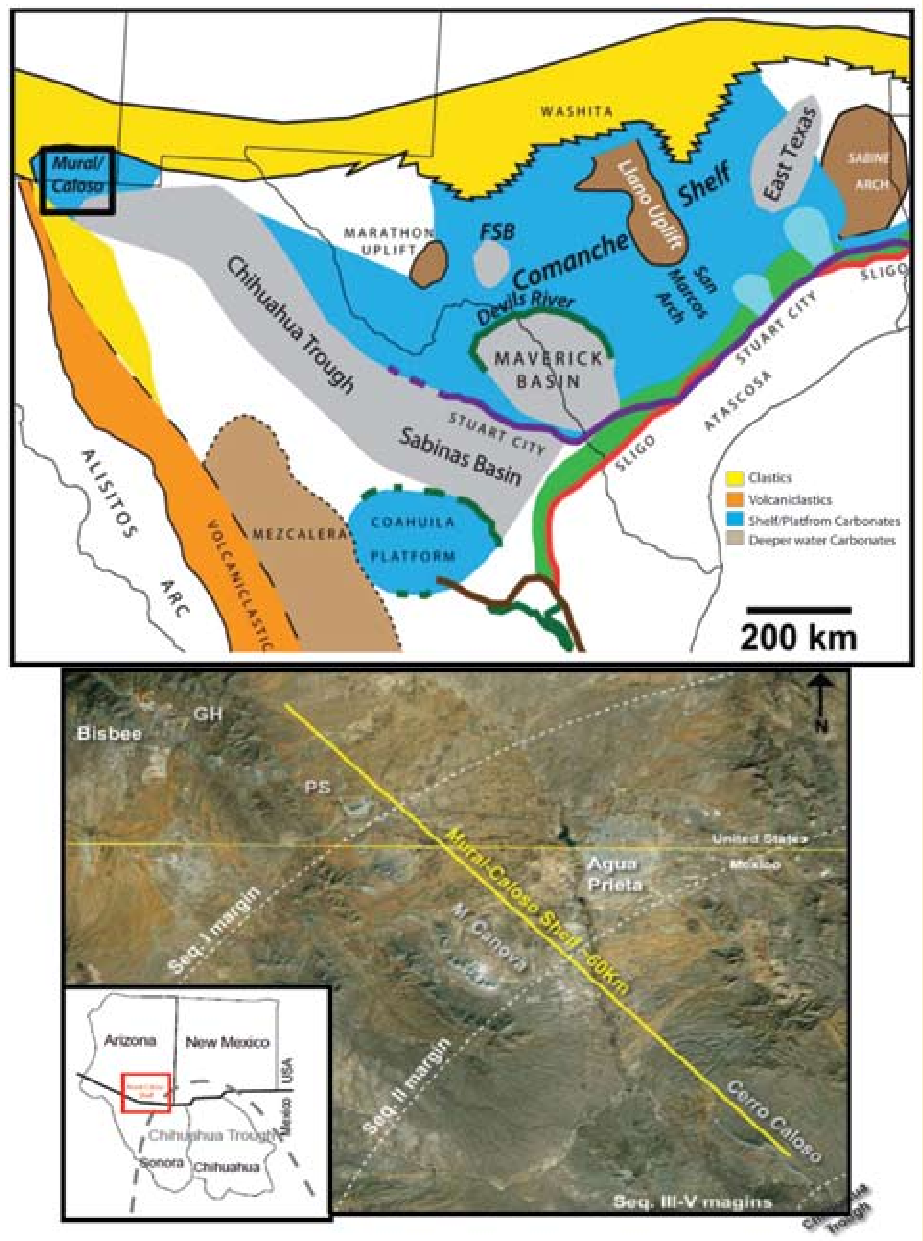

Figure 1: Top Paleogeographic map showing the Mural-Caloso Shelf as an extension of the expansive Comanche Shelf located to the southeast. During Albian time the deepwater Chihuahua Trough ran southeast through present day northern Mexico to the open ocean. Highlands to the north of the Mural-Caloso Shelf are the likely source of the lowstand sand wedges mapped at the outcrop. After Winkner and Buffler (1988), Goldhammer and Johnson (2000), McFarlan and Menes (1991), and Kerans (pers. Comm.). Bottom Google Earth image shows Mural Caloso Shelf and regional outcrop pattern including the position of the main outcrop areas, GH-Grassy Hill, PS-Paul Spur, M.Canova-Montes Canova, and Cerro Caloso the focus of this study. Progressive shelf margins are dashed in white. Inset is the regional location map.

The oldest formation of the Bisbee Group is the Glance Conglomerate which is overlain by the Morita Formation, Mural Limestone, and Cintura Formation respectively (Figure 2). The age of the Bisbee Group extends from the lower Aptian through the Albian. It is time-equivalent to the Trinity and Fredericksburg Groups of the Comanche series in Texas (Hayes, 1970) and corresponds to the Albian sequences 6-8 of Loucks and Kerans (2003). Regional northwest-southeast thrust faults strike in the direction of Mural Limestone depositional dip to expose large thicknesses of the Mural-Caloso Shelf (Scott and Warzeski, 1993).

DATA AND METHODS

Three vertical sections were measured and tied to aerial photopans in order to link stratal geometries observed on photopans and in the field with small-scale facies variability. Ten facies were identified that describe depositional environments ranging from low-energy shelf interior, through reef core, fore reef, and deeper-water slope/basin. Facies tract dimensions are quantified using the measured sections, lateral tracing of units, and qualitative assessment of bedding patterns on aerial photopans.

FACIES AND DEPOSITIONAL MODEL

The ten depositional facies identified at the Cerro Caloso outcrop are detailed in Table 1. Figure 3 shows the vertical facies organization along section 1-1 located at the shelf margin. Based on the vertical and lateral facies transitions mapped on the outcrop we developed a conceptual depositional model the 3 sequences observed in the outcrop (Figure 4).

SEQUENCE DEFINITION

Vertical stacking patterns, stratal geometries, and changes in dip-parallel facies tract dimensions were used to define the depositional sequences and the progradational versus aggradational long term evolution of the Mural-Caloso Shelf. Sequence boundaries are placed at the base of basin-restricted sand wedges that onlap the slope and shelf margin. The turnaround from increasing to decreasing accommodation corresponds to the furthest landward position of the lowest energy facies (Figures 4 and 5) (Cantuneanu et al. 2009). Only sequences 3-5 were detailed in this study. Sequences 1-3 in the Bisbee/Paul Spur area were recently studied in detail by Aisner (2010).

SEQUENCES: S3 AND S4

The thin LST of S4 consists of a sandstone (F10) wedge that onlaps the S3 outer shelf facies (F1-4). Following established sequence stratigraphic convention (Vail et al, 1977; Cantuneau et al. 2009) a sequence boundary is placed at the base of the sand wedge (Figures 4 and 5). The transgressive systems tracts in S3 and S4 are relatively thick successions of low energy open shelf and deep water facies (F9, F1-4). The maximum flooding surface is placed at the surface that marks the furthest landward position of the deeper water low energy facies.

The early highstand system tracts of S3 and S4 are characterized by strongly prograding successions of middle shelf facies (F3,F4) that grade upward into a broad aggradational coral-rudist boundstone rimmed margins (F6, F7, F8). During the S3 and S4 highstands there was sufficient accommodation to develop a broad aggradational shelf interior dominated by carbonate facies.

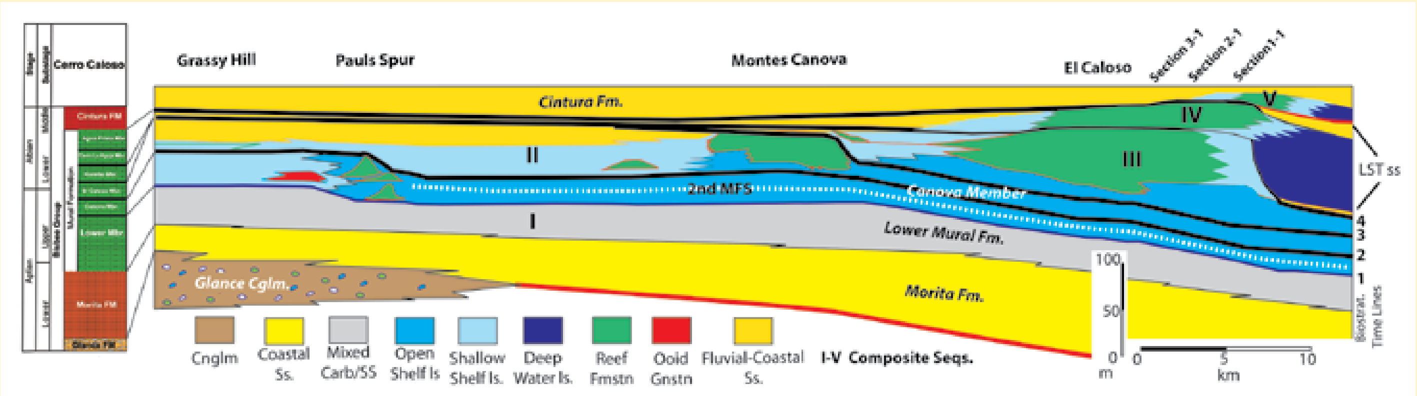

Figure 2: Generalized sequence stratigraphic model of the Mural-Caloso Shelf succession of the latest Aptian through early Albian age. Locations of measured sections of this study are identified. Figure adapted from Kerans (pers. Comm.).

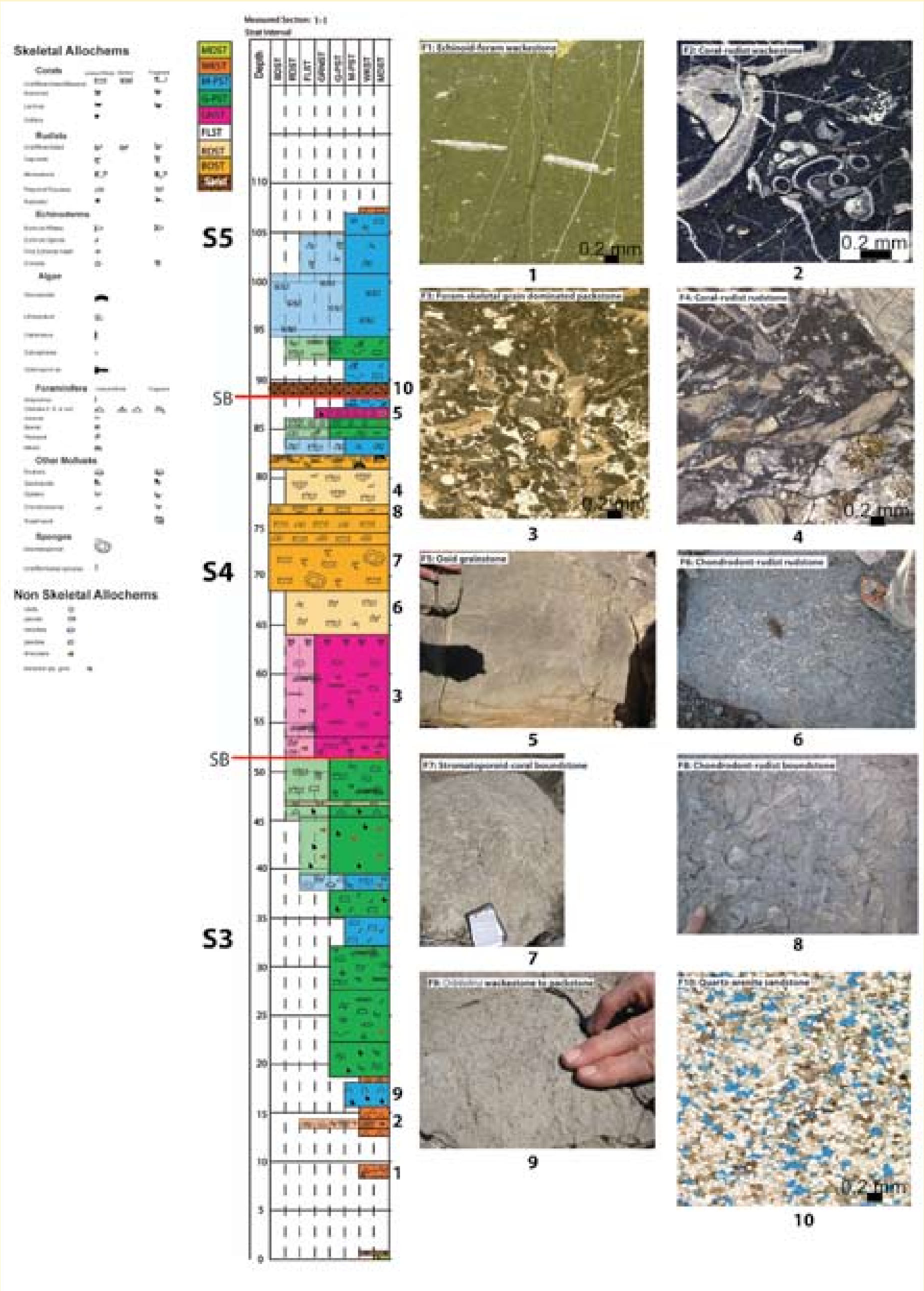

Figure 3: Measured section 1-1 (see figure 2 for location) and photomicrographs and outcrop images of depositional facies identified at the Cerro Caloso outcrop.

SEQUENCE: S5

The S5 lowstand sand wedge is significantly thicker than the lowstand wedge of S4 indicating increased lowstand shelf margin bypass during S5. The sequence boundary is placed at the base of the wedge. During the ensuing transgression a beautiful cross bedded oolitic grainstone belt (F5) develops on top of the sand wedge. The grainstone belt onlaps the coral-rudist boundstone margin of sequence IV. The geometric facies relationship observed at this surface is an example of a downward shift in coastal onlap.

The early highstand system tract of S5 contains a thin progradational belt of middle shelf facies (F3, F4) that quickly evolves to the narrow progradational coral-rudist boundstone rimmed margin (F6, F7). The thin siliciclastic-rich shelf interior of S5 reflects a decrease in accommodation from the highstands of S3 and S4 to the ensuing S5.

DISCUSSION

The measured sections were used in conjunction with the aerial photopans to determine facies belt dimensions for the lowstand sand wedges, the forereef, reef margins, and shelf interiors (Table 2). The lowstand sand wedge of S4 is significantly thinner and laps out farther downdip relative to the shelf margin facies compared to the S5 wedge (Figure 5). The fore reef slope of S3 and S4 have similar dimension, and the S5 fore reef slope is considerable less expansive and thinner. The S3 and S4 reef margins have similar dimensions while the S5 reef margin is narrower and slightly thicker. The shelf interiors of S3 and S4 are significantly thicker and more expansive compared to the thin narrow interior of S5. The difference in dimension

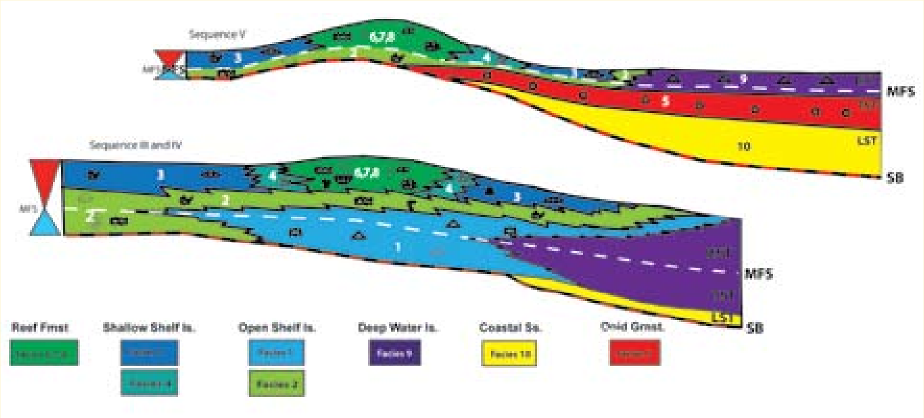

Figure 4: Conceptual depositional models for sequences three through five showing facies tract geometry and thickness variability between sequences. See symbol key of Figure 3 for reference.

and facies association between the lower 2, mostly aggrading sequences, and the uppermost sequence is interpreted as being the result of a regional decrease of accommodation that not only limited the space available to build vertically aggrading robust shelf margin buildups, but also brought more siliciclastics onto the carbonate shelf resulting in sand rich shelf interior and thicker slope and basin sand accumulation during the LST. The increasing influx of siliciclastics also probably prevented the full development of the reef margin buildups.

The best evidence for measurable downward shift in coastal onlap is the cross bedded ooid belt of the early highstand in S5. In modern settings, cross-bedded ooid grainstone belts are found in high-energy shallow water environments with water depths generally less than 5m (Rankey ad Reeder 2011). This well-developed ooid belt onlaps the S4 reef margin. The top of the S4 reef margin lies ~15m above the lapout termination of the coastal wedge. This stratal geometry as well as the facies relationship is not possible without shifting the shoreline down towards the basin at the end of S4 deposition.

This outcrop-based facies tract dimensional analysis can be applied as a predictive reference for subsurface exploration in similar time equivalent Cretaceous reservoirs. If lowstand sands are a desirable target, this work has found the thicker lowstand sand wedge associated with the transition from a more aggradational margin trajectory to a strongly to downstepping progradational margin trajectory. Conversely, if prospecting for the thicker shelf interior and margin accumulations the earlier S3 and S4 aggradational margin morphology would be a key feature to look for.

CONCLUSIONS

This field-based analysis of the continuously exposed shelf-to-basin profile of the greenhouse Lower Albian Mural-Caloso Shelf has documented the stratigraphic response of a low-angle reef-rimmed shelf to base-level forcing. The mostly aggradational reef-rimmed shelf margin with a aggradational carbonate shelf interior during S3 and S4 shifted to a strongly progradational reef-rimmed margin with a thin siliciclastic dominated shelf interior associated with a baselevel (eustatic?) fall of a minimum 20-30m. The geometric and facies evolution observed at the Cerro Caloso outcrop are consistent with a long-term second order fall during the deposition of the Lower Albian age Mural-Caloso Shelf. This fall is coeval with less-well-constrained Glen Rose 2nd order fall observed in the Gulf of Mexico margin. This study is one of only a few that can document a minimum estimate of likely eustatic fall associated with a greenhouse 2nd-order sequence.

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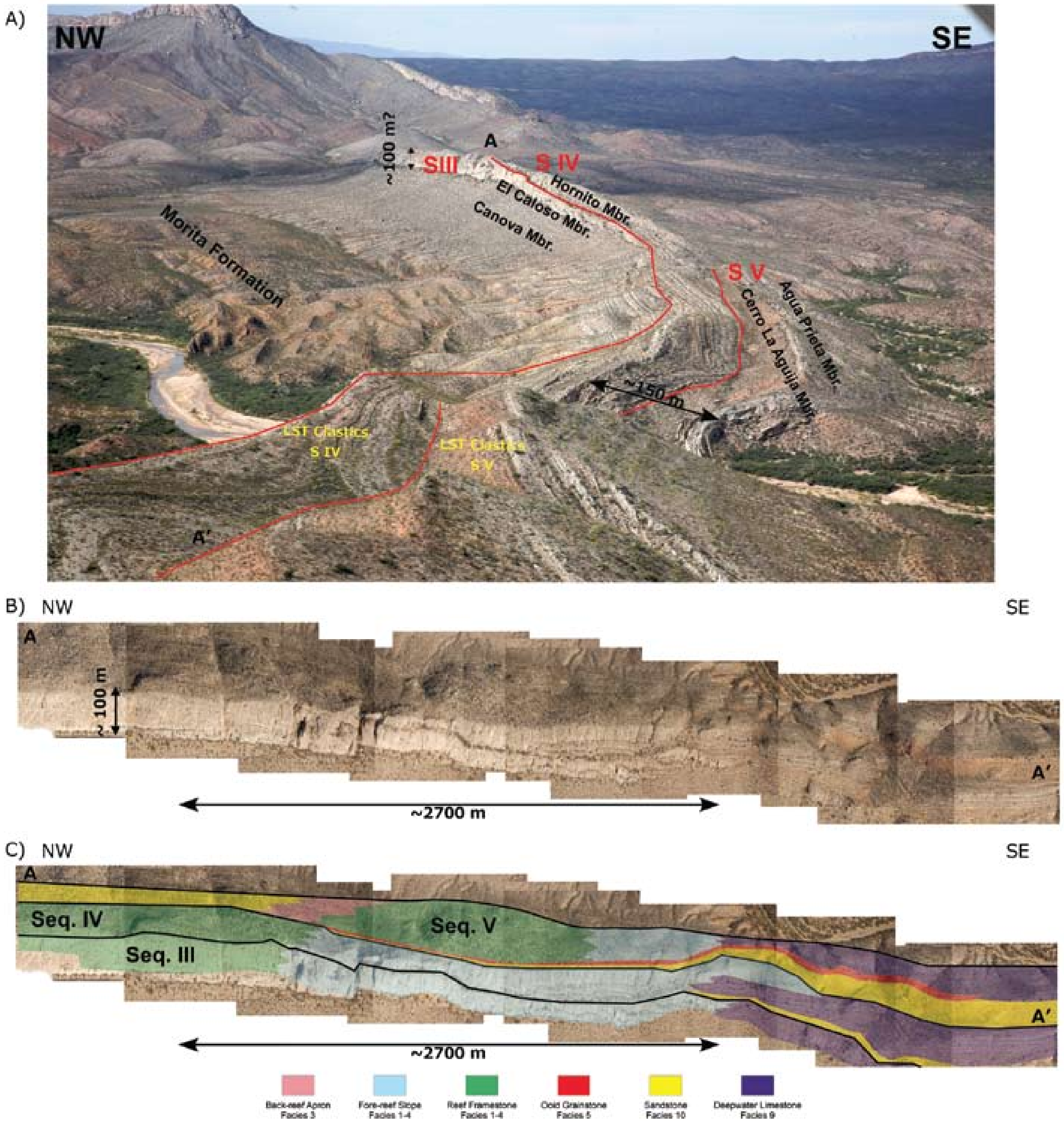

Figure 5: A: Aerial photo looking north showing sequences three through five tied into the Bisbee Group stratigraphic nomenclature. Sequence boundaries are marked in red. B: Aerial oblique photo the studied outcrop. C: Interpreted aerial photo from B showing the shelf margin facies tract geometry.

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#	Facies Name	Texture	Grain-size	Sorting	Composition	Depositional Environment
F1	Echinoid-foram wackestone	Pervasively bioturbated, mud rich, rare oyster shell fragments to 2.0cm.	Fine grained matrix with oyster shell fragments 2.0cm	Poorly sorted	Disarticulated irregular echinoid fragments along with both uniserial and biserial forams are common. Type A Orbitolina are rare.	Open Shelf
F2	Coral-rudist wackestone	This mud rich facies is extensively bioturbated and devoid of sedimentary structures	Fine grained matrix with rudist shell fragments to 0.8cm	Poorly sorted	Abundant coral and rudist fragments with minor echinoid and oyster fragments. Miliolid, uniserial, biserial, and type A *Orbitolina* are present.	Open Shelf
F3	Foram-skeletal grain-dominated packstone	Parallel current stratified to weakly developed parallel lamination. *Thalassinoides* galleries.	Upper fine to lower medium sand sized matrix	Moderately-well sorted	Moderate mud component with prevalent echinoid plates and spines, thin valve oyster shell fragments, and forams: miliolids, biserial, type A *Orbitolina*, and rare *Dictyoconus*.	Shallow Shelf
F4	Coral-rudist rudstone	Minor mud component, beds are structureless, and successive beds exhibit depositional dips that define foreset geometries	Matrix is medium to coarse sand size with coral fragments to 5cm.	Moderately sorted	Caprinid and requinid rudists along with corals are dominant. Peloids, calcispheres and type B *Orbitolina* are common.	Shallow Shelf
F5	Ooid grainstone	Trough cross-stratified	Medium sand sized grains	Well sorted	Prevalence of superficial ooids with dominantly quartz nuclei. Rare oncoids and lithoclasts.	Shallow Shelf
F6	Chondrodont-rudist rudstone	Large skeletal fragments are coated with *Lithocodium*. Depositional mud, as well as microbial micrite is present.	Medium to coarse grain matrix with rudist shell fragments >2cm.	Poorly sorted	Dominant skeletal allochems include caprinid and requinid rudists, undifferentiated corals, and oysters. Non-skeletal components include oncoids, peloids, and calcispheres.	Reef margin
F7	Stromatoporoid-coral boundstone	Corals and stromatoporoids are bored. *Lithocodium* is the dominant binder. The red algae *Solenopora* is present.	Individual corals reach 35cm length.	No sorting	Massive irregular in situ *Actinastraea* and platy *Microsolena* corals are dominant. Miliods and type B Orbitolina are present.	Reef Margin
F8	Chondrodont-rudist boundstone	Massive 1x1 meter clusters of chondrodont oysters and requinid rudists are bored and algal bound	Individual chondrodont oysters may reach 20cm.	No sorting	*Lithocodium* is the dominant binder of massive chondrodont oysters and requinid rudists. Minor faunal elements include monoplurid rudists and undifferentiated corals.	Reef Margin
F9	*Orbitolina* wackestone to packstone	Thinly bedded with moderate bioturbation.	Matrix if fine grained with type A *Orbitolina* to 1.5cm.	Poor	This facies is predominantly fine grained mud with moderately abundant type A *Orbitolina* and other pelagic microfossils.	"Deepwater"
F10	Quartz-arenite sandstone	Overall upward coarsening with poorly-defined horizontal and cross laminations	Very fine lower to fine sand	Well sorted	This mud free sand has 10-20% interparticle porosity and rare undifferentiated rudist fragments.	Shallow Shelf

Table 1: Facies description table

	Lowstand System Tract	Fore Reef	Reef Margin	Platform Interior
S3		Lateral Dimensions: 750m Thickness: ~35m Facies: F1, F2, F3, F4	Lateral Dimensions: 400m Thickness: 40m Facies: Facies 6,7, and 8	Lateral Dimensions: >1000m Thickness: ~35-50m Facies: F3,F4
S4	Lateral Dimensions: >1000m Thickness: ~5-10m Facies: F10	Lateral Dimensions:800m Thickness:40m Facies:F1, F2, F3, and F4	Lateral Dimensions:350m Thickness:35m Facies: F6, F7, and F8	Lateral Dimensions: >1000m Thickness: ~35-50m Facies: F3, F4
S5	Lateral Dimensions: >1000m Thickness: ~70-100m Facies: F10	Lateral Dimensions: 100m Thickness: 25m Facies: F2, F3, and F4	Lateral Dimensions: 100m Thickness: 45m Facies: F7 and F8	Lateral Dimensions: 100m Thickness: 15m Facies: F3

Table 2: Systems tract dimension table