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SEQUENCE STRATIGRAPHIC FRAMEWORK OF THE UPPER SAN ANDRES FORMATION AND EQUIVALENT BASINAL STRATA IN THE BROKEOFF MOUNTAINS, OTERO COUNTY, NEW MEXICO

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Abstract _____The upper San Andres Formation, upper Cutoff Formation and Cherry Canyon Tongue (Permian, Guadalupian) in the southern Brokeoff Mountains comprise two mixed siliciclastic-carbonate, intermediate-order (high-frequency) sequences on the basis of observed seismic-scale stratal geometries. integrated with detailed facies and high-order cycle stacking pattern analysis. These sequences are correlative to the two upper San Andres high-frequency sequences (GI2 and G13) of Kerans et al. (this volume) and can be traced throughout the Brokeoff Mountains and along the Algerita Escarpment. Each sequence contains a largely basinally restricted, siliciclastic-dominated lowstand to transgressive systems tract, the updip part of which can be correlated to one or more sandstone-based carbonate cycles on its respective platform. The transgressive systems tracts are downlapped along the slope by clinoformal carbonate and mixed carbonate-siliciclastic strata of their overlying progradational highstand systems tracts. The G I2 lowstand to transgressive systems tract onlaps the slope of the underlying G4 highstand and is provisionally correlated to the uppermost Brushy Canyon Formation on the basis of its stratigraphic position in the basin, i.e., within meters of the top of the Cutoff Formation, because its basal platform facies tracts are offset approximately 8 km basinward relative to similar facies tracts in the underlying sequence and due to the presence of a widespread karst profile that underlies the unit on the platform. The GI2 highstand systems tract is composed of sigmoidal carbonate clinoform cycles that can be traced from the peritidal ramp crest facies tract to the subtidal toe-of-slope facies tract. These cycles prograded the platform margin about 0.5 km. The sequence boundary at the top of GI2 is marked by minor erosional scour and stratal truncation along the outer shelf and slope. The G13 lowstand to transgressive systems tract onlaps the G12 highstand slope. It is definitively correlated to the lower two-thirds of the Cherry Canyon Tongue and provisionally correlated to the Lovington sandstones of the subsurface. The GI3 highstand is composed of sigmoid-progradational carbonate cycles that prograded the platform margin about I km and sigmoid- to oblique-progradational, mixed carbonate-siliciclastic cycles that prograded the margin an additional 5 to 6 km. The G I3 highstand is capped by a sequence boundary with minor erosion and stratal toplap along the outer 1-2 km of the platform and local karst development further landward. Paleocaverns and grikes within the karst profile extend downward as much as 30 m below the sequence boundary, which suggests a minimum relative sea level fall of similar magnitude.

INTRODUCTION

The broad stratigraphic relationships of lower Guadalupian platform and basin strata in the Guadalupe Mountains region have long been known (King, 1948; Boyd, 1958; Hayes, 1964; Wilde and Todd, 1968), but detailed correlation of these units has proved more difficult due to complex facies changes and the loss of critical marker beds in the platform to basin transition (Figs. 1, 2). Two stratigraphic problems in this region are the precise correlation of two basinal sandstone-dominated units, the Brushy Canyon Formation and the Cherry Canyon Tongue, with the carbonate-dominated, platformal San Andres Formation. The general paucity of sandstone within San Andres platform carbonates led several workers to conclude that the San Andres platform was an emergent area of siliciclastic sediment bypass during deposition of the basinal sandstone units (King, 1948; Sarg and Lehmann, 1986). However, the relative abundance of fusulinids and other carbonate allochems in the Brushy Canyon and Cherry Canyon Tongue seems to indicate the presence of some permanently or episodically flooded platform area that is coeval with deposition of these units (Wilde and Todd, 1968; Rossen, 1985; Wilde, 1986; New, 1988). If one accepts that each of these basinal units is represented by single or multiple closely spaced bypass surfaces on the platform, the challenge is to locate these surfaces.

Seismic-scale outcrops in the southern Brokeoff Mountains (Fig. 1) provide some key insights into the correlation of the Cherry Canyon Tongue and Brushy Canyon Formation with the upper San Andres Formation. The Brokeoff Mountains area is one of only two localities (Last Chance Canyon is the other) where the proximal onlap of these units can be examined and where their precise correlation to the San Andres platform can be determined. The Brokeoff Mountains section is further distinguished by its location between the Algerita Escarpment and the Western Escarpment, with nearly continuous outcrop exposure between these areas (Fig. 1).

This paper first discusses the development of various sequence stratigraphic correlation frameworks for the San Andres Formation and equivalent units, to provide some background to the present study and to establish the relationship between lithostratigraphic (formation) names and sequence names. Next, the facies tracts and stratigraphic relationships of the upper San Andres Formation, Cherry Canyon Tongue and upper Cutoff Formation in the study area are described and interpreted within the sequence stratigraphic framework of Kerans et al. (1992 and this volume'

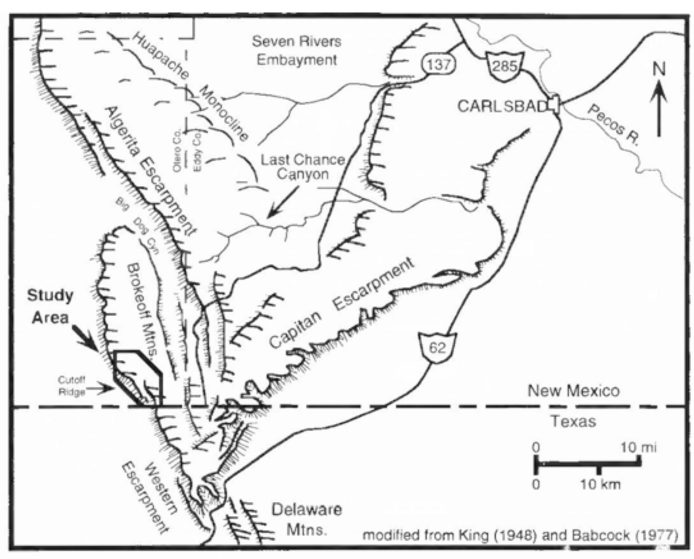

FIGURE 1. Pł ysiographic map of Guadalupe Mountains region, showing location of study area and other localities referred to in text.

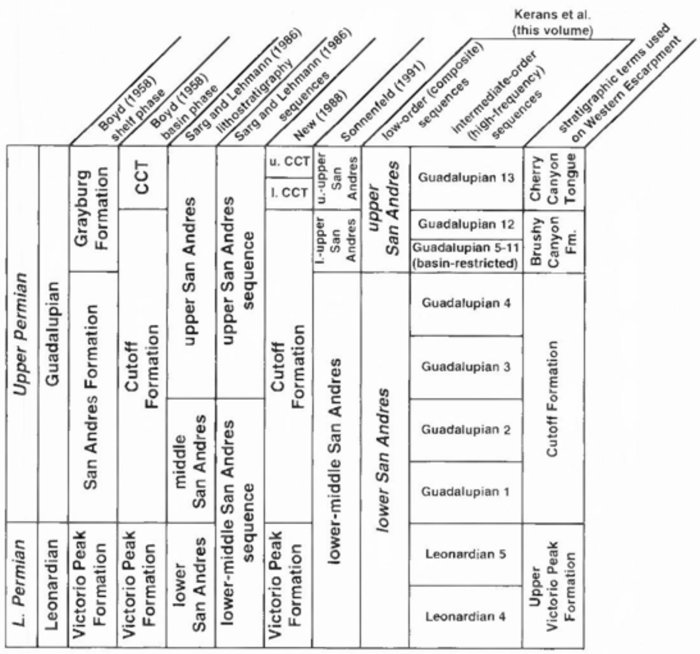

FIGURE 2. Stratigraphic chart showing evolution of correlation schemes for the San Andres Formation and coeval uppermost Leonardian and lower Guadalupian units. Note the correlation of upper San Andres intermediate-order sequences G12 and G13 to the uppermost Cutoff Formation, uppermost Brushy Canyon Formation and Cherry Canyon.

EVOLUTION OF THE SAN ANDRES SEQUENCE STRATIGRAPHIC FRAMEWORK

The pioneering sequence stratigraphic work of Sarg and Lehmann (1986) proposed a bipartite subdivision of the San Andres Formation and its basinal equivalents, based on correlation of the well-studied Western Escarpment basinal section (Harris, 1982; Kirkby, 1982; Rossen, 1985; Fekete et al., 1986; New, 1988) with more platformal sections in Last Chance Canyon and the Algerita Escarpment (Figs. 1, 2). Their model recognized a *lower-middle San Andres depositional sequence,* equivalent to the Cutoff Formation and an *upper San Andres depositional sequence,* which includes the Brushy Canyon Formation and Cherry Canyon Tongue as a basin-restricted lowstand systems tract (Fig. 2). In their model, a single bypass surface at the base of their upper San Andres sequence is the stratigraphic equivalent of approximately 500 m of basinal Brushy Canyon Formation and Cherry Canyon Tongue sandstone.

New (1988) recognized a prominent, horizontal to gently basinward-dipping downlap surface or zone within the Cherry Canyon Tongue of Boyd (1958) along Cutoff Ridge (Figs. I, 2). He subdivided the Cherry Canyon Tongue into a lower unit (lower Cherry Canyon Tongue), which he thought wedged out shelfward in Boyd's (1958) transition zone and an upper unit (upper Cherry Canyon Tongue), which he thought was gradational with the upper San Andres Formation. New (1988) concluded that the stratigraphic position and facies composition of these units is similar to that of the upper San Andres sequence described by Sarg and Lehmann (1986) in Last Chance Canyon. New (1988), however, stressed the transgressive nature of the lower Cherry Canyon Tongue, while Sarg and Lehmann (1986) implied that this unit was a progradational lowstand delta.

Recent work by Sonnenfeld (1991) in Last Chance Canyon led to the subdivision of Sarg and Lehmann's (1986) upper San Andres sequence into two sequences, the upper of which contains the Cherry Canyon Tongue at its base (Fig. 2). Sonnenfeld (1991) demonstrated that along the upper slope and outer shelf, the Cherry Canyon Tongue is composed of multiple landward-stepping, sandstone-based carbonate cycles and is thus the product of higher-frequency cyclic deposition. His data further demonstrates that in proximal slope positions, the Cherry Canyon Tongue is dominantly transgressive in nature; he speculated that the lowstand systems tract of this sequence is largely confined to deeper parts of the basin.

Kerans et al. (1991) significantly modified Sarg and Lehmann's (1986) framework by subdividing their upper San Andres depositional sequence into four high-frequency sequences (cf. Mitchum and Van Wagoner, 1991) separated by sequence boundaries with local karst development (Fig. 2). Kerans et al. (1992 and this volume) subsequently subdivided the entire uppermost Leonardian-Guadalupian section into 28 high-frequency sequences. Within the most recent sequence stratigraphic framework, the San Andres Formation is subdivided into two low-order sequences that are comparable to the third-order sequences of Goldhammer et al. (1991) and the composite sequence of Mitchum and Van Wagoner (1991). These sequences are termed lower San Andres and upper San Andres, respectively. The *lower San Andres low-order sequence* is composed of six intermediate-order or high-frequency sequences (comparable to fourth-order sequences of Goldhammer et al., 1991), of which the upper two were previously grouped within the upper San Andres low-order sequence (Kerans et al., 1991). This sequence is equivalent to the upper Victorio Peak Formation and the main body of the Cutoff Formation in the Brokeoff Mountains and Western Escarpment areas (Kerans et al., 1992 and this volume; Fig. 2). The *upper San Andres low-order sequence* is composed of nine intermediate-order sequences, of which the lower seven are entirely restricted to the Brushy Canyon Formation (see also Gardner, 1992). This sequence contains the Brushy Canyon Formation, uppermost Cutoff Formation, Cherry Canyon Tongue and upper San Andres Formations of King (1948) and Boyd (1958) (Fig. 2). The uppermost two intermediate-order sequences of the upper San Andres low-order sequence, termed GI2 and GI3 (previously G 11 and G12; Kerans et al., 1992) (Fig. 2), are the subject of this report.

This new subdivision of low-order sequences has greater genetic significance than previous schemes, because it better reflects the long-term fluctuation in accommodation and carbonate/siliciclastic sediment supply evident in the transgressive-regressive stacking pattern of intermediate-order sequences. The low-order sequence boundary that separates the sequences, which corresponds to the top of the G4 intermediate-order sequence of Kerans et al. (1992 and this volume), is marked by the most laterally extensive karst profile and the greatest basinward shift of the ramp crest facies tract. It is easily mapped along the outer 10-15 km of the platform and in the basin and forms a prominent reflection on seismic record sections (C. Kerans and W. M. Fitchen, unpubl. 1992).

STUDY AREA

The study area lies in the southern Brokeoff Mountains within the Panther Canyon 7.5 minute quadrangle, Otero County, New Mexico (Figs. 1, 3). The San Andres Formation, Cherry Canyon Tongue and Cutoff Formation are exposed along fault-bounded strike ridges and in canyon walls at an elevation of 4500 to 5000 ft. Pleistocene to Recent, northwest-trending faults associated with regional uplift are pervasive in the area and can hinder attempts at lateral tracing of units, but certain markers (sandstone beds, exposure/erosion and flooding surfaces) can be followed locally across fault zones. Key exposures within individual faulted blocks are located in the lower reaches of West Dog Canyon and along Cutoff Ridge (Figs. 3, 4).

The Brokeoff Mountains were originally mapped by Boyd (1958), who recognized three broad phases or zones within the San Andres Formation and coeval units (Fig. 4). These three phases trend northeast-southwest across the study area (Fig. 4). Boyd's shelf phase is composed of undifferentiated thick-bedded dolostones of the San Andres Formation; Boyd mistakenly mapped the upper San Andres Formation as the Grayburg Formation within his shelf phase, as pointed out by Wilde (1986). In the study area, this phase contains platform facies of the G12 and G13 sequences. Boyd's transition phase comprises a stratigraphically complex zone about 2-3 km in width that separates the shelf and basin phases. Boyd mapped the upper San Andres Formation, Cherry Canyon Tongue and Cutoff Formation separately within this

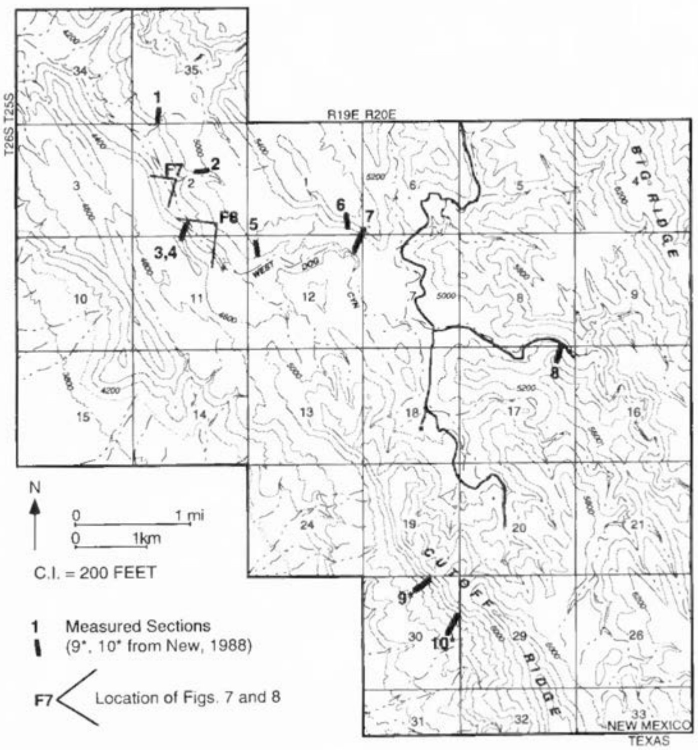

FIGURE 3. Topographic map of study area showing location of measured sections, schematic cross section (Fig. 5), facies cross section (Fig. 6) and photomosaics shown in Figs. 6 and 7.

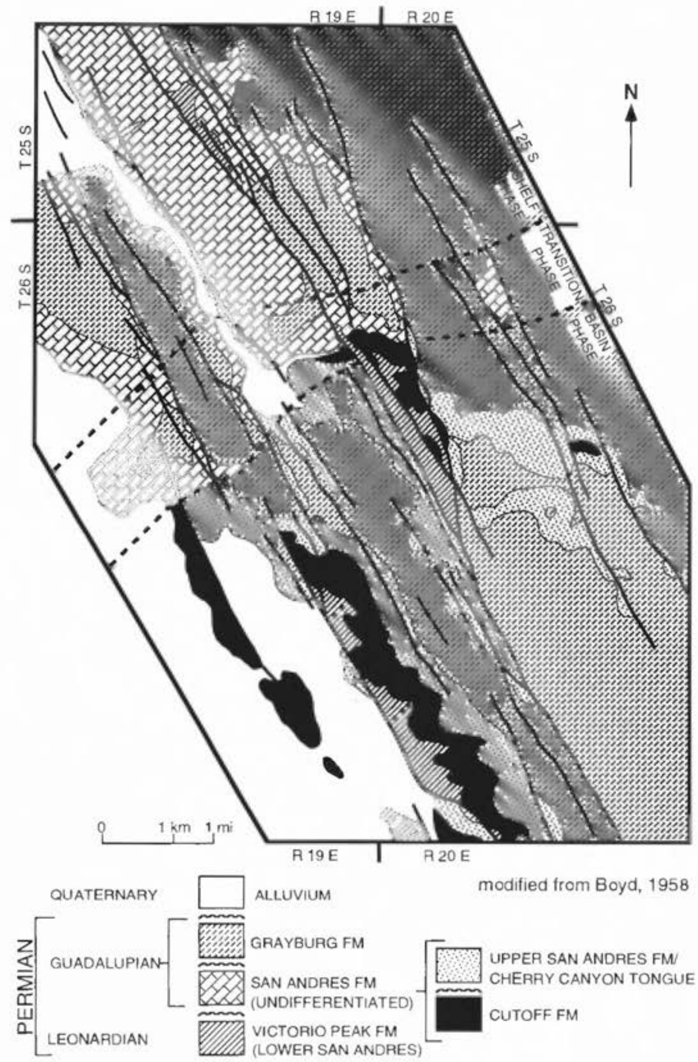

FIGURE 4. Geologic map of study area, showing trend of Boyd's shelf, transition and basin phases, and the location and trend of upper San Andres (sequence G12 and G13) terminal shelf margins.

zone. This phase contains an upward-shallowing succession of basinal to platform facies. Boyd's basin phase consists of the Cutoff Formation, which he correlated with the lower part of the San Andres Formation and the Cherry Canyon Tongue, which he thought spanned the San Andres/Grayburg boundary. This phase consists of an upward-shallowing succession of basinal to outer platform facies.

FACIES TRACTS

The G12 and GI3 platforms can be described as distally steepened ramps *(sensu* Read, 1985) with approximately 65-100 m of relief between the platform top and the toe-of-slope, as measured from a detailed cross section (Fig. 5). Their paleotopographic profile is characterized by primary ramp margin dips of 5°-18°, which are intermediate in magnitude between that of the more gently sloping (<1°-5°) ramp margins of the lower San Andres sequence and the steep slopes (35°—near 90°) of Goat Seep and Capitan rimmed shelves (Kerans et al., 1992).

Three broad facies tracts are recognized within these platforms (Fig. 5). The *ramp crest facies tract* consists of relatively horizontal strata composed of four general facies, which include fenestral peloid-pisolite packstone, burrowed to crossbedded ooid-peloid packstone to grainstone, burrowed peloid-dasycladacean algae wackestone to packstone and burrowed to crossbedded fine-grained quartz sandstone. These facies represent shallow subtidal to supratidal environments of deposition on the topographically highest part of the platform.

The *ramp margin facies tract* consists of gently to steeply dipping strata composed of five general facies, which include burrowed peloid-skeletal packstone to grainstone (outer ramp), fusulinid-peloid wackestone to packstone (upper slope), bryozoan-sponge-crinoid packstone to bafflestone (upper slope), chert-rich spicule-brachiopod wackestone to mudstone (mid- to lower slope) and massive bioturbated quartz sandstone (outer ramp to lower slope). These facies represent shallow to deeper subtidal environments of deposition along the outer ramp, ramp margin and slope.

The *toe-of-slope/basin facies tract* consists of gently basinward dipping strata composed of allodapic peloid, skeletal and ooid grainstone to packstone, carbonate breccia to megabreccia, parallel-laminated-to-ripple cross-laminated (Bouma B-C) or bioturbated quartz sandstone and carbonate mudstone. The former three facies contain allochthonous carbonate allochems from adjacent ramp crest and ramp margin facies tracts and exhibit textures and sedimentary structures indicative of transport by sediment gravity flow. This facies tract represents deep subtidal environments of deposition, but the presence of burrows in some of these facies indicate that the water column was aerobic to dysaerobic.

UPPER SAN ANDRES SEQUENCES

Introduction

Two intermediate-order or high-frequency sequences (G 12 and G 13; Fig. 2) are defined within the upper San Andres/Cherry Canyon Tongue/uppermost Cutoff Formation interval in the study area, based on data from seven measured sections, mapping of genetic units on photomosaics and correlation to sequences of Kerans et al. (1991) on the Algerita Escarpment. Exposures of the initial platform margins of both sequences permit the delineation and mapping of sequence boundaries, maximum flooding surfaces and systems tracts from ramp crest to toe-of-slope/basin facies tracts (Fig. 5).

Sequence boundaries are defined by the following criteria: stratal onlap, truncation and karst along the surface; stratal toplap below the surface on the platform; a basinward shift of facies tracts on the platform

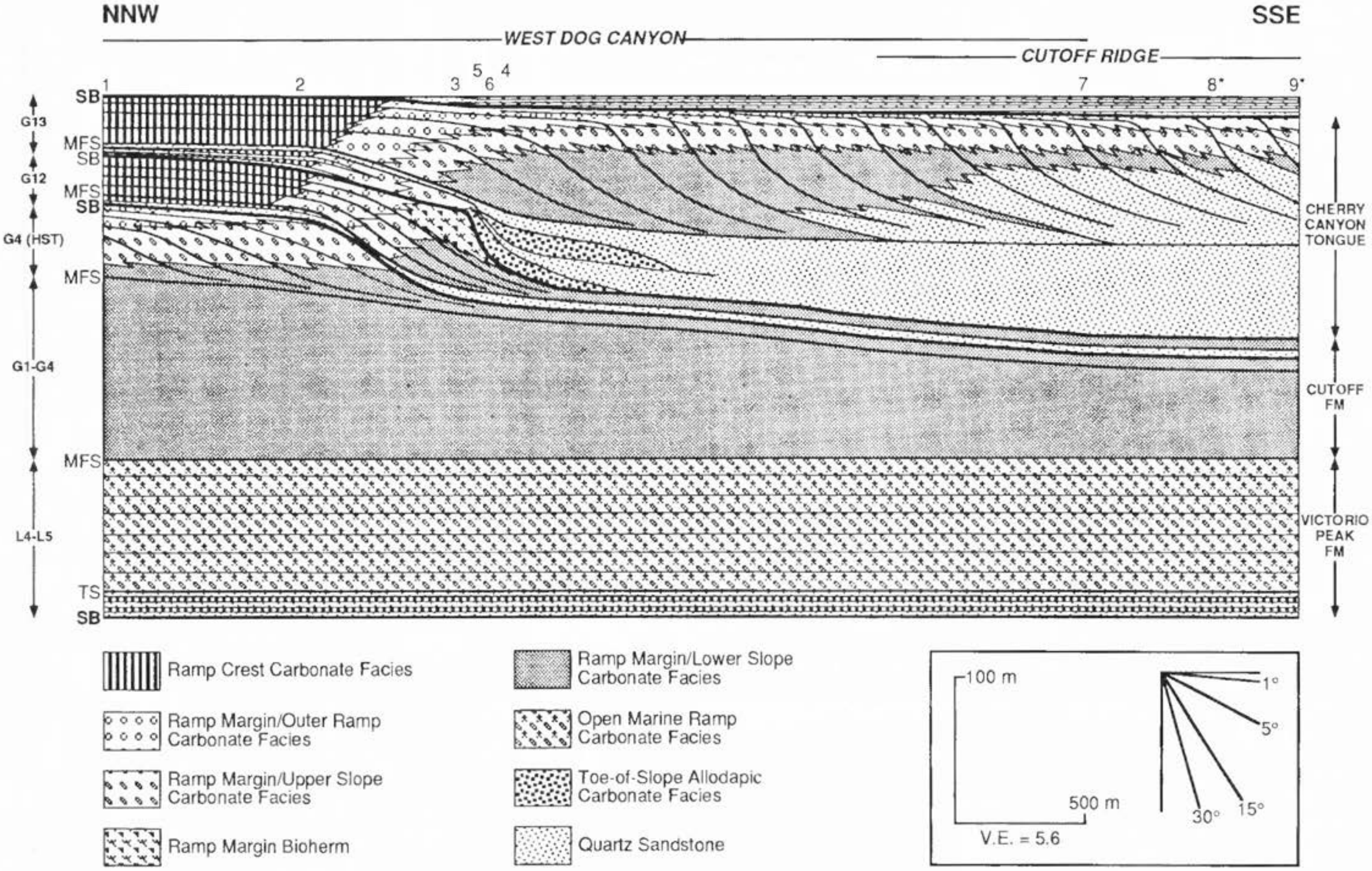

FIGURE 5. Schematic cross section of upper San Andres sequences in study area. Sections 8 and 9 are taken from New (1988). Stratigraphic relationships between measured sections 6 and 7 are supported by reconnaisance of existing exposures. The early highstand of the G13 sequence corresponds to the sigmoidal ramp crest and ramp margin carbonate strata that predate the first late highstand slope sandstones (note schematic cycle boundaries, which approximate time lines). Late highstand strata developed after aggradation of the ramp crest and consist of mixed carbonate-siliciclastic, sigmoid- to oblique-progradational strata.

relative to the underlying sequence; the occurrence of quartz sandstone above the surface along the platform and slope; and carbonate breccias with quartz sandstone matrix lying on the surface at the toe-of-slope (Mitchum et al., 1977; Sarg, 1988). Maximum marine-flooding surfaces are recognized by stratal downlap above the surface along the slope, a landward shift in facies tracts across the surface along the platform and upper slope and a change from mixed siliciclastic-carbonate cycles to carbonate cycles on the platform. As a result of the progradational character and low accommodation potential of upper San Andres sequences (relative to the older intermediate-order sequences of the lower San Andres), sequence boundaries are well expressed in all depositional settings, whereas maximum-flooding surfaces are best expressed where downlap is evident or where sandstones occur on the platform (Kerans et al., 1992).

Systems tracts are defined by their enclosing surfaces and by the stacking pattern of their component high-order cycles with respect to facies proportions, depositional geometries and the nature of their bounding surfaces (Van Wagoner et al., 1988; Goldhammer et al., 1991). Lowstand systems tracts cannot be unambiguously defined in the area, as it is difficult to differentiate potential lowstand strata from transgressive strata that onlap the toe-of-slope and that correlate to widespread, high-order siliciclastic-carbonate platform cycles (Figs. 5, 6). I propose that much of the lowstand stratal record of these sequences is confined to more basinward positons, whereas on the platform the record is represented by a hiatus associated with subaerial exposure and siliciclastic sediment bypass. Due to this difficulty in separating the two systems tracts within the area of study, they will be discussed together in the following sections. Highstand systems tracts are generally composed of sets of sigmoid-progradational, upward-shoaling (asymmetric) carbonate cycles. Within the G 13 sequence, these high-order carbonate cycles evolve into sigmoid- to oblique-progradational, mixed siliciclastic-carbonate symmetric cycles that are microcosms of the intermediate-order sequence (Sonnenfeld, 1991) (Fig. 5).

G12 sequence

The G 12 sequence (28-65 m thick) overlies the G4 sequence on the platform (Figs. 5, 6). Along the Algerita Escarpment, the uppermost several high-order cycles of the G4 sequence comprise a laterally extensive ooid-peloid grainstone complex that forms a conspicuous light-colored bench above underlying darker-colored fusulinid-peloid packstones and below thinner-bedded, more recessive peloid packstone and mudstone strata of sequence G12. A regionally extensive karst profile at the top of this grainstone complex marks the basal sequence boundary of the upper San Andres low-order sequence (Kerans et al., 1992 and this volume). This distinctive grainstone complex can be visually correlated across Big Dog Canyon to the Brokeoff Mountains, where it bears a similar relationship to enclosing strata. This unit was traced from Choisie Canyon (La Paloma Canyon 7.5 minute quadrangle) south to Panther Canyon, within 1 km of the area described in this report, in order to establish a correlation between the Algerita Escarpment and Brokeoff Mountains sections. In the study area, the terminal platform margin of sequence 04 is exposed on the west wall of West Dog Canyon, SW$^1/_4$ sec. 2, T26S, R19E (Figs. 5-7); excellent exposures of these sequences also occur on the east wall. Most of the relationships described below refer to this locality.

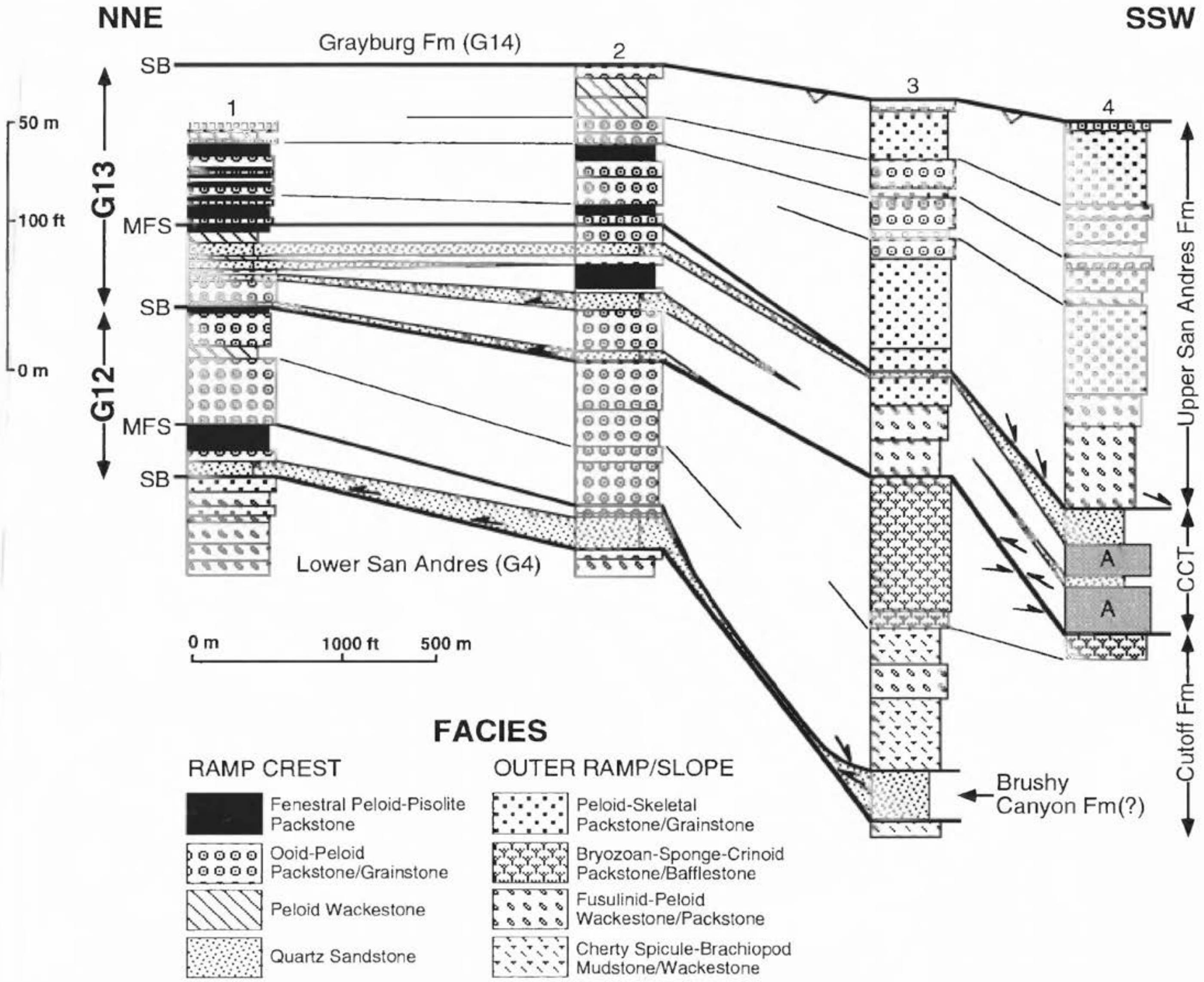

FIGURE 6. Detailed cross section of ramp crest to toe-of-slope facies transition and systems tracts of sequences G12 and G13. Note the correlation of quartz sandstone-based, ramp crest carbonate cycles to the toe-of-slope. These relationships demonstrate the transgressive nature of proximal onlapping slope wedges and establish the precise correlation of the Cherry Canyon Tongue and Brushy Canyon Formation(?) to the San Andres platform stratigraphy.

The sequence boundary above the G4 platform slopes about 1° bas-inward and is broadly channelized with up to 2 m of local erosional relief. No macroscopic evidence of subaerial exposure was noted along this boundary within the area of study. The sequence boundary is overlain by a 2 to 4.5-m-thick, fine- to very fine-grained quartz sandstone bed that thins toward the platform interior (Figs. 5, 6); this thinning is interpreted as an onlap relationship. The sandstone bed contains dune-to ripple-scale trough cross-stratification that becomes increasingly obscured by burrows towards its top. Burrow types include *Ophiomorpha, Diplocraterion, Rhizocorallium* and possibly *Muensteria,* which is consistent with a shallow marine to tidal flat environment (Ekdale et al., 1984). Skeletal fragments, peloids and ooids are present toward the top of the bed and in a downdip direction. Updip, this bed is overlain by quartz-rich ooid grainstone with a thick fenestral packstone cap. Down-dip, the bed is overlain by a thin ooid-peloid packstone capped by a burrowed horizon. This succession is interpreted as the lowstand to transgressive systems tract of the GI2 sequence (Figs. 5, 6). The maximum flooding surface that overlies this unit is characterized by erosion updip, where supratidal units are channelized by a 10-m-thick grainstone cycle containing intraclasts at its base and a burrowed horizon downdip, which is overlain by a 7-m-thick peloid-ooid packstone cycle containing abundant fusulinids at its base. These successions represent a basinward shift in facies tracts relative to uppermost G4 facies, which here are composed of peloid-skeletal packstone (updip) to fusulinid-peloid pack-stone (downdip) (Fig. 6). The lowstand to transgressive systems tract can be traced across the ramp margin and slope of the G4 highstand systems tract to the toe-of-slope, where it forms a 5 to 10-m-thick onlap wedge of carbonate-rich sandstone (Figs. 5-7). Sandstones and silt-stones equivalent to this unit are exposed at several other localities, including along the north and south walls of West Dog Canyon, $N^1/_2$ sec. 12, T26S, R19E and along the streambed on the south side of West Dog Canyon, $SW^1/_4$ sec. 8, T26S, R20E.

The G12 highstand systems tract thickens from 19 m on the platform to about 55 m at its terminal platform margin. On the platform, it is composed of at least two subtidal-dominated ramp crest cycles. These grade basinward into ramp margin facies that downlap the maximum

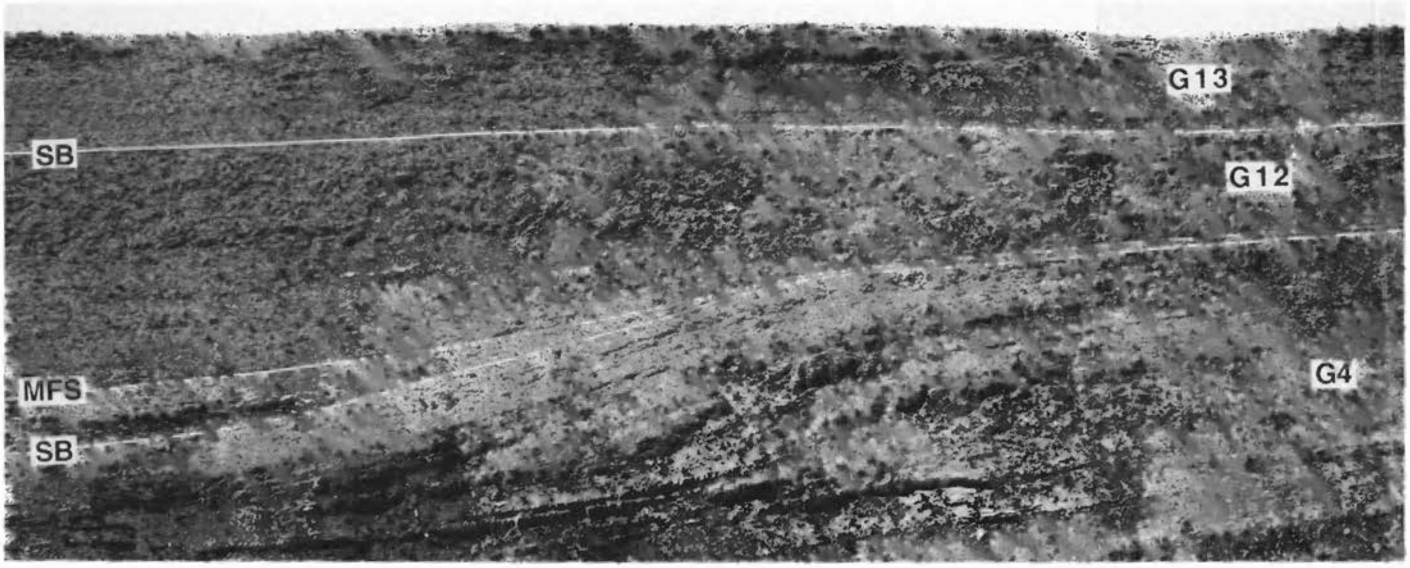

FIGURE 7. Photomosaic of west wall of West Dog Canyon, showing terminal ramp margin of sequence G4 and onlap of overlying G12 lowstand to transgressive systems tract strata at the toe-of-slope. Note the sigmoid-progradational geometry of G4 highstand strata and the low-angle downlap of G12 highstand strata (somewhat obscured by colluvium) onto the lowstand to transgressive systems tract. Upward-increasing bed thickness and resistance in sequence G12 corresponds to a facies change from chert-rich mudstone and wackestone to fusulinid-peloid packstone. Thin recessive intervals near the base of sequence G13 correspond to sandstones of the lowstand to transgressive systems tract, which are probable equivalents of the Lovington sandstones of the subsurface. The top of sequence G13 has been removed by Pleistocene-Recent erosion. Location of photomosaic is shown in Fig. 3; height of view is approximately 100 m.

flooding surface at a low angle and that prograded the ramp margin about 0.5 km (Figs. 4-6). A 25-m-thick bryozoan-calcareous sponge-crinoid bioherm is developed at the terminal margin of the highstand systems tract in the SE$^1/_4$ SE$^1/_4$ SW$^1/_4$ sec. 2, T26S, R19E (Figs. 5, 6). The seaward margin of this bioherm is steep (-30°), in part due to erosion along the overlying unconformity (sequence boundary) that truncates foreslope beds of the bioherm (Figs. 5, 6, 8). Basinward of the ramp margin, the G 12 highstand is represented by fusulinid-peloid wackestone and chert-rich spiculitic mudstone interbedded with laterally discontinuous planar-laminated allodapic peloid grainstone; these grainstones wedge out basinward within 2 km of the terminal highstand margin. At a more distal locality 4.5 km basinward of the terminal margin (SW$^1/_4$ sec. 8, T26S, R20E), the highstand systems tract consists of about 6 m of thin-bedded mudstone between the underlying lowstand to transgressive sandstone unit and the overlying sandstones of the Cherry Canyon Tongue. This outcrop demonstrates the equivalence of the G 12 sequence with the upper part of the Cutoff Formation as mapped by Boyd (1958).

In sections below Bush Mountain and 1.6 km north of Bush Mountain on the Western Escarpment, King (1948; pl. 5, sections 5 and 6) measured a 12-13 m thick sandstone or siltstone unit whose base lies about 21 m below the top of the Cutoff Formation. This observation, combined with inspection of panoramic photos of Cutoff Ridge and Cutoff Mountain (C. Kerans and W. M. Fitchen, unpubl. 1992), data presented in this report and sequence stratigraphic considerations outlined by Kerans et al. (this volume) has led to the hypothesis that the lowstand to transgressive systems tract of sequence G12 and the sequence boundary on which it lies may be correlative to the Brushy Canyon Formation. It should be noted that this sandstone unit does not appear in other Cutoff Formation sections of King (1948) and Harris (1982). This may be due to discontinuous deposition and preservation of the unit along the slope, the erosional removal of overlying G12 highstand strata such that the unit is amalgamated with sandstones of the Cherry Canyon Tongue, or complete removal of the entire sequence by erosion associated with Cherry Canyon Tongue siliciclastic (and carbonate) sediment bypass. Given the composite nature of the Cutoff Formation and the abundant evidence of a complex erosional history within the unit and along its top (Harris, 1982; New, 1988), this correlation hypothesis appears reasonable and warrants future field work along the Western Escarpment and Cutoff Ridge.

G13 sequence

The G13 sequence (30-152 m thick) overlies the G12 highstand on the platform (Figs. 5, 6) and is in turn overlain by the Grayburg Formation (G14 and G15 sequences of Kerans et al., this volume). The sequence boundary at the base of the G 13 sequence is relatively conformable and marked by low-relief, channel-form scours along the outer several hundred meters of the G12 platform. No evidence of subaerial exposure was noted along this surface in the area, although Kerans et al. (1991) documented karst features along the correlative surface on the Algerita Escarpment. At the platform margin the sequence boundary truncates biohermal strata, as discussed previously (Figs. 5, 6, 8). At the toe-of-slope (SE$^1/_4$ SE$^1/_4$ sec. 1, T26S, R19E), the sequence boundary occurs at the base of a 7 to 13-m-thick, 400-m-wide (parallel to depositional dip) carbonate breccia to megabreccia whose matrix contains fine-grained quartz sand. The unconformity is a relatively horizontal surface (as viewed from the southwest) that truncates approximately 10 m of underlying G12 highstand strata, here composed of gently southeast-dipping allodapic peloid grainstone interbedded with spiculitic mudstone. Farther basinward, the sequence boundary is a relatively conformable surface that separates distal slope mudstones of the G12 highstand (uppermost Cutoff Formation) from fine- to very fine-grained sandstones of the GI 3 lowstand to transgressive systems tract (lower Cherry Canyon Tongue) (Fig. 5).

The downlap (maximum-flooding) surface within the Cherry Canyon Tongue, first recognized by New (1988), can be traced landward along Cutoff Ridge and within West Dog Canyon into Boyd's (1958) transition phase. This surface represents the upper boundary of the G13 lowstand to transgressive systems tract along the slope. Just basinward of the terminal G12 highstand margin, the lowstand to transgressive systems tract is composed of interbedded fine- to very fine-grained sandstones and minor siltstones with interbedded allodapic ooid and skeletal grainstones and carbonate breccia/megabreccia that onlap the sequence boundary or overlying autochthonous slope strata (Figs. 5, 6, 8). Sandstone strata contain cut-and-fill structures with low-angle swaley lamination and rare channels filled with massive (slumped or liquified?) sandstone. Allodapic grainstones are parallel-laminated to trough cross-stratified. Carbonate breccias are massive to crudely bedded; bedding is accentuated by the presence of contorted sandstone lenses and stringers at (and above) bed contacts. In this proximal setting the unit is 25-30 m thick; 65-70% of this thickness consists of carbonate strata.

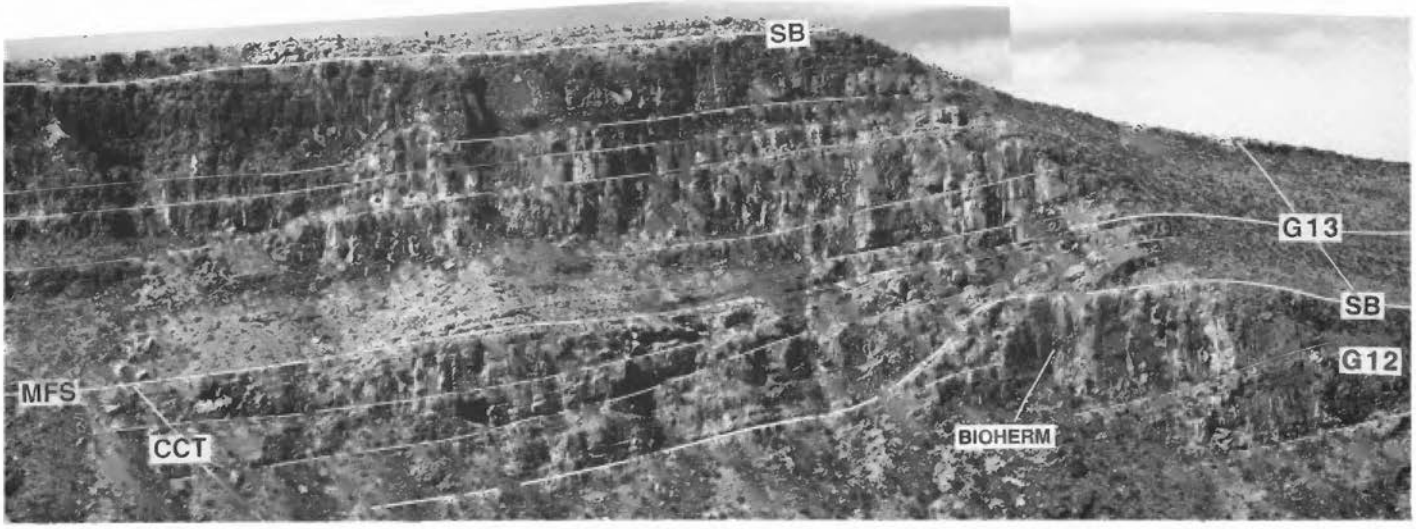

FIGURE 8. Photomosaic of west wall of West Dog Canyon (0.5 km south of location of Fig. 7), showing terminal ramp margin of sequence G12, which is here composed of a bryozoan-sponge-crinoid bioherm. Note clinoformal geometry of G12 highstand strata (relative to sequence boundary), truncation of bioherm-foreslope strata at the sequence boundary and onlap of overlying allodapic carbonates and quartz sandstones of the G13 lowstand to transgressive systems tract. G13 highstand strata are composed of upward-shallowing ramp margin to outer ramp crest cycles composed of spiculitic wackestones (light gray recessives), fusulinid-peloid wackestone and packstone (dark gray rubbly beds of intermediate resistance) and peloid/ooid packstone and grainstone (cliff-forming gray to light gray beds) that downlap the top of the lowstand to transgressive systems tract. Finer white lines mark prominent high-order cycle boundaries. Location of photomosaic is shown on Fig. 3; height of view is approximately 100 m.

Carbonate strata thin and wedge out basinward within 3 to 4 km of the toe-of-slope. Sandstone strata expand basinward to a maximum thickness of 70 to 80 m, as measured by New (1988) on Cutoff Ridge. Although no allodapic carbonates were noted in the lower Cherry Canyon Tongue along Cutoff Ridge, channelized carbonate breccias and associated grainstones occur in the unit at the basin margin on the Western Escarpment, about 20 km basinward of the platform margin (New, 1988).

The uppermost sandstone of the lowstand to transgressive systems tract at the toe-of-slope can be traced several tens of meters landward into the ramp margin facies tract, beyond which it is obscured by recent colluvium (Figs. 5, 6, 8). This sandstone bed is inferred to correlate to the uppermost of three sandstone beds on the ramp crest, which is exposed about 0.5 km to the north (landward). On the ramp crest, the lowstand to transgressive systems tract as defined consists of 3-4 sandstone-based carbonate cycles (Fig. 6). The systems tract thins landward (north-northeast) from 22 m to 12 m across the outer 0.8 km of the platform, possibly due to onlap against the sequence boundary. Ramp crest sandstones are typically very fine- to fine-grained (in contrast to dominantly very fine-grained slope sandstones) and contain ripple to megaripple cross-stratification. Fusulinids are present in some beds. Carbonate facies that cap these cycles consist of ooid-peloid packstone/grainstone and fenestral packstone in the seaward part of the ramp crest and peloid wackestone to ooid-peloid grainstone in the more landward part of the ramp crest. The maximum-flooding surface is tentatively placed at the top of the uppermost sandstone-based carbonate cycle (Figs. 5, 6). In the seaward part of the ramp crest, the surface is marked by minor erosion and is overlain by an ooid-peloid grainstone bed containing abundant fusulinids. The abundance of fusulinids in this bed reflects maximum flooding of the ramp crest and a shelfward encroachment of the ramp margin (upper slope) facies tract.

Platform sandstones of the G13 lowstand to transgressive systems tract occur within 25 to 47 m of the top of the San Andres Formation in the study area. This stratigraphic position is similar to that of the Lovington sandstones, which comprise a regionally persistent subsurface marker on the Northwest Shelf (Meissner, 1972). Correlations discussed herein equate the Lovington sandstones to the lower Cherry Canyon Tongue of New (1988).

The G 13 highstand systems tract concordantly overlies the maximum-flooding surface across the ramp crest and downlaps this surface along the slope (Figs. 5-8). The highstand is subdivided into early and late phases on the basis of variable cycle geometries, progradation/aggradation ratios and facies content. The early highstand consists of sigmoid-progradational cycles that aggraded the ramp crest 25 m and prograded the ramp margin about 1 km (Fig. 5). On the ramp crest, the highstand is composed of thin, relatively horizontal peritidal carbonate cycles (Fig. 6). These cycles grade seaward and topographically downward into clinoformal ramp margin cycles that downlap the lowstand to transgressive systems tract along the slope (Figs. 5, 6, 8). Aggradation of platform strata, coupled with basinward thinning of equivalent slope strata, resulted in an increase in the relief of the ramp crest above the distal slope during the early highstand. The relief on the maximum-flooding surface is about 65 m, whereas the youngest part of the early highstand platform has a relief of about 100 m (Fig. 5).

The late phase of the highstand systems tract is composed of mixed carbonate-siliciclastic cycles with sigmoid- to oblique-progradational geometries. These cycles developed subsequent to the full aggradation of the ramp crest and thus offlap with little net aggradation (Fig. 5). Late highstand cycles contain a (high-order) lowstand to transgressive wedge at their base that is composed of bioturbated, very fine-grained sandstone. This wedge onlaps the slope and outer ramp. This wedge grades upward into a (high-order) highstand unit composed of ramp margin carbonate facies that contain abundant quartz sand. Cycles are occasionally capped by high-order subaerial exposure surfaces that merge with the intermediate-order sequence boundary, or are truncated directly by the intermediate-order (upper G 13) sequence boundary (Sonnenfeld, 1991; Fitchen, 1992). The occurrence of sandstones in these late highstand cycles is inferred to be the result of low accommodation on the platform, which allowed sandstones to bypass the emergent ramp crest and be delivered directly to the ramp margin during high-order relative lowstand to transgressive phases. During high-order relative highstand phases, sandstones were limited to the shorezone and were reworked basinward during the subsequent relative lowstand. The relief of these clinoform cycles decreases from about 100 m to as little as 65 m during the development of the late highstand. This decrease may be the result of an intermediate-order relative fall of sea level, which is reflected in a basinward-sloping toplap surface and in the progressive development of oblique-progradational cycles, coupled with aggradation of the toe-of-slope and basin by sandstone wedges of high-order cycles (Sonnenfeld, 1991; Fitchen, 1992).

The sequence boundary at the top of the G13 highstand systems tract is concordant with uppermost early highstand strata. A karst profile is developed in early highstand strata below the sequence boundary in the NW 1/4 SE1/4 SE1/4 sec. 1, T26S, R19E. This profile consists of solution-widened fractures (grikes) and a southeast(?)-dipping paleocavern that appears to parallel clinoform bedding. Grikes and paleocaverns are filled predominantly by fine- to medium-grained sandstones similar to overlying transgressive sandstones of the Grayburg Formation (Premier sandstone of Meissner, 1972) together with rotated, angular breccia blocks of host dolostone. The base of the deepest paleocavern lies 30 m below the sequence boundary. This suggests that the sequence boundary and its associated karst formed during a relative sea level fall of at least 30 m. This does not account for sediment compaction or the apparent topographic fall of the sequence boundary towards the terminal platform margin, which would suggest a fall of greater amplitude. Kerans (personal comm. 1992) noted several beds composed of ramp crest facies in the lower Grayburg-equivalent Cherry Canyon Tongue at Cutoff Mountain, which is about 0.5 km basinward of the terminal G13 highstand ramp margin. If one uses a stratigraphic datum in the Grayburg Formation to relate the Cutoff Ridge sections of New (1988) to Kerans' Cutoff Mountain section, these peritidal beds appear to be about 60 m lower than the G13 margin, which suggests a minimum relative sea level fall of about 75 m(!). Further field work is required to support this hypothesis.

CONCLUSIONS

Two intermediate-order platform sequences can be defined in the upper San Andres, Cherry Canyon Tongue and uppermost Cutoff Formation in the Brokeoff Mountains on the basis of stratal geometries tied to facies distributions and high-order cycle stacking patterns. These sequences reflect mixed siliciclastic-carbonate, reciprocal sedimentation of both intermediate-order and high-order cyclic scales. Reciprocal sedimentation and the development of high-order cycles is inferred to be the result of high-order (low amplitude?) fluctuations in relative sea level, or accommodation. The development of high-order cycles appears to be modulated by intermediate-order (high-amplitude) accommodation changes. Intermediate-order accommodation changes determine the stacking pattern of high-order cycles with respect to geometry and site of deposition, thickness and facies proportions, as indicated by the physical stratigraphy of upper San Andres intermediate-order sequences described here.

The G12 sequence contains a lowstand to transgressive sandstone wedge that occurs within the upper part of the Cutoff Formation and is clearly distinct from the Cherry Canyon Tongue in the study area. On the platform, this unit contains a basal sandstone that lies 60-80 m below the top of the San Andres. I propose that this wedge is correlative to the uppermost Brushy Canyon Formation of the Delaware Basin. The sequence boundary at the base of the G12 sequence is thus a hiatal surface across which most of the Brushy Canyon sandstones were bypassed to the basin.

The G 13 sequence contains a lowstand to transgressive wedge that is correlative with the lower Cherry Canyon Tongue of New (1988) and to the upper-upper San Andres sequence lowstand and transgressive systems tracts of Sonnenfeld (1991). On the platform, this unit contains several sandstone beds, the lowermost of which lies 25-47 m below the top of the San Andres Formation. The stratigraphic position of these sandstones is similar to that of the Lovington sandstones; thus the Lovington sandstones and the sequence boundary upon which they rest appear to be equivalent to the lower Cherry Canyon Tongue.

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1907 guano mining in Bat Cave, later named Carlsbad Cavern. Photographer unknown. Courtesy of Southeastern New Mexico Historical Society of Carlsbad.

Cork Draw in southern Brokeoff Mountains. View is upstream, N65°E. The canyon is about 90–150 m deep. Cliffs and ridge consist of Grayburg Formation. Lower mostly covered slopes are upper San Andres Formation/Cherry Canyon tongue (Fitchens, this volume). The gravelly flood plain is occupied by an unidentified silvery white shrub. Creosote bush (medium gray shrub) is confined mainly to the low alluvial terrace and small alluvial fans at base of canyon walls. The two small trees beyond the tall yucca in the left foreground may be desert willow. Scattered trees on ridgecrests in distance are piñon pine. Camera station is in SW 1/4 sec. 17, T26S, R20E, about 10.5 km southwest of El Paso Gap. Altitude is approximately 1516 m. W. Lambert photograph No. 85L109. November 16, 1985, 9:41 a.m. MST.