Anatomy of offlap: Upper San Andres Formation (Permian, Guadalupian), Last Chance Canyon, Guadalupe Mountains, New Mexico

Mark D. Sonnenfeld

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ANATOMY OF OFFLAP: UPPER SAN ANDRES FORMATION (PERMIAN, GUADALUPIAN), LAST CHANCE CANYON, GUADALUPE MOUNTAINS, NEW MEXICO

MARK D. SONNENFELD
Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado 80401

Abstract—San Andres Formation outcrops in Last Chance Canyon are interpreted to contain two large-scale depositional sequences, upper San Andres sequence 3 and upper San Andres sequence 4. Facies associations, volumetric proportions of carbonate and siliciclastic strata and depositional topography change progressively through the course of the upper San Andres sequence 4. These aspects change in a predictable fashion and correspond to position within the lowstand, transgressive and highstand systems tracts. Units within the lowstand to transgressive systems tracts record a progressive decrease in sedimentation rate, depositional energy and siliciclastic content. This reflects a long-term transition from detrital, siliciclastic-dominated, point-sourced slope sedimentation to increasingly autochthonous, carbonate-dominated, line-sourced slope sedimentation. Within carbonate strata of the transgressive systems tract, long-term relative sea level rise is interpreted from thick outer-shelf deposits, highly aggradational to mounded fusulinid shoals and net stratigraphic rise of the fusulinid facies tract. The most carbonate-rich and bioherm-bearing interval of the entire sequence overlies a distinctive maximum flooding surface capping the transgressive systems tract. Ensuing high-frequency sequences of the middle to late highstand systems tract show pronounced progradational offlap and record a progressive increase in the volume of siliciclasts accumulated on the outer shelf. A karsted toplap surface represents a subaerial unconformity and sequence boundary capping upper San Andres sequence 4. Embedded within upper San Andres sequence 4 are numerous high-frequency sequences that show the following similarities to larger, seismic-scale depositional sequences: (I) stratal geometries; (2) the nature of bounding surfaces; (3) the timing of bioherm development; (4) siliciclastic to carbonate facies evolution; and possibly (5) point-source to line-source evolution. One of the most important aspects of stratigraphic self-similarity, best documented within the highstand systems tract of upper San Andres 4, involves the seaward transition from asymmetric shallowingupward hemicycles at the toe-of-slope and seaward. Each symmetric cycle includes an inferred deepening-upward phase or "transgressive hemicycle," characterized by a waning siliciclastic influence, succeeded by a shallowing-upward phase, or "regressive hemicycle," characterized by flourishing, prograding carbonates. The concept of qualified stratigraphic self-similarity does not diminish the importance of facies variation or "differentiation" within and among sequences; it merely emphasizes that the physical stratigraphy of a sequence reflects spatial and temporal variations in accommodation/sediment supply ratios but is relatively independent of absolute duration.

INTRODUCTION AND GEOLOGIC SETTING

Last Chance Canyon lies 20 km northwest of the upper Guadalupian Capitan escarpment that separates the Permian Delaware Basin province from the Northwestern Shelf province (Figs. 1, 2). The Huapache fault zone obliquely crosses the eastern edge of the Last Chance Canyon area and is expressed on the surface as the Huapache Monocline of probable Tertiary age (McKnight, 1986). This fault zone was also active in Pennsylvanian to earliest Permian (Wolfcampian) times and defines the northeastern margin of an ancestral Huapache Uplift (Fig. 3; Meyer, 1966).

The northwestern margin of the Permian Delaware Basin was an arid region ±5° of the paleoequator (Scotese et al., 1979; Fischer and Sarnthein, 1988). The arid climate limited fluvial runoff while pro-

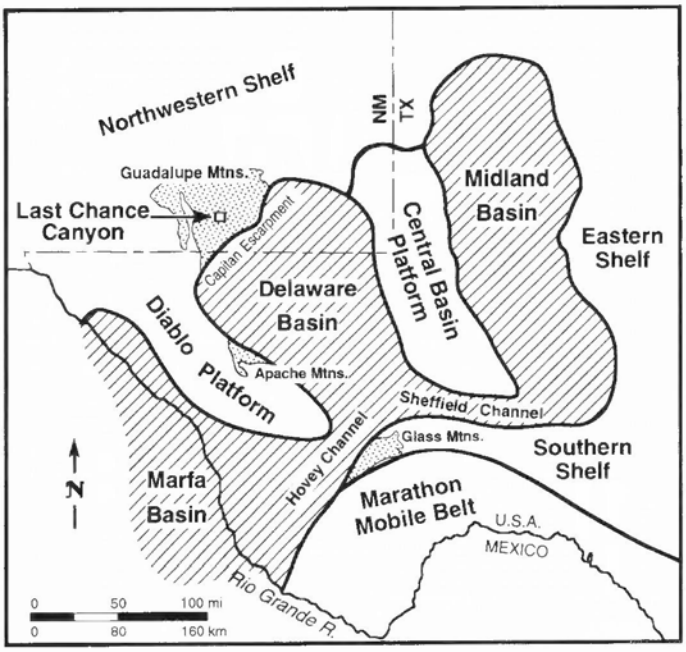


FIGURE 1. Regional paleogeographic setting during the late Guadalupian (Permian). Modified from King (1948).

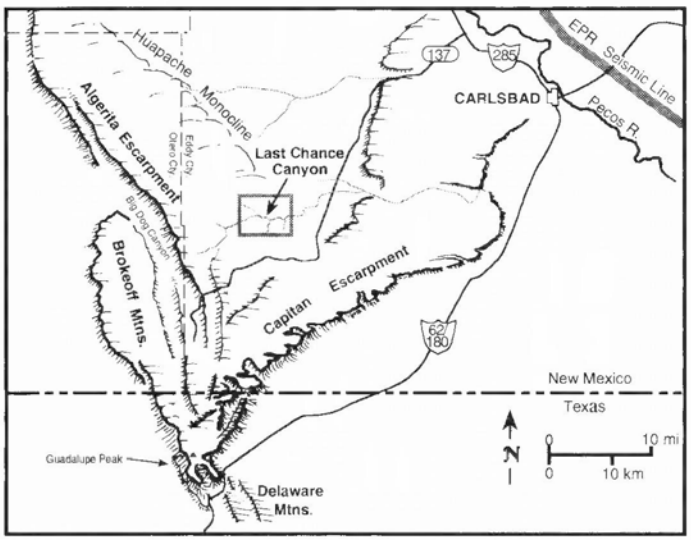


FIGURE 2. Location of Guadalupe Mountains region and Last Chance Canyon study area. Modified from King (1948) and Babcock (1977).

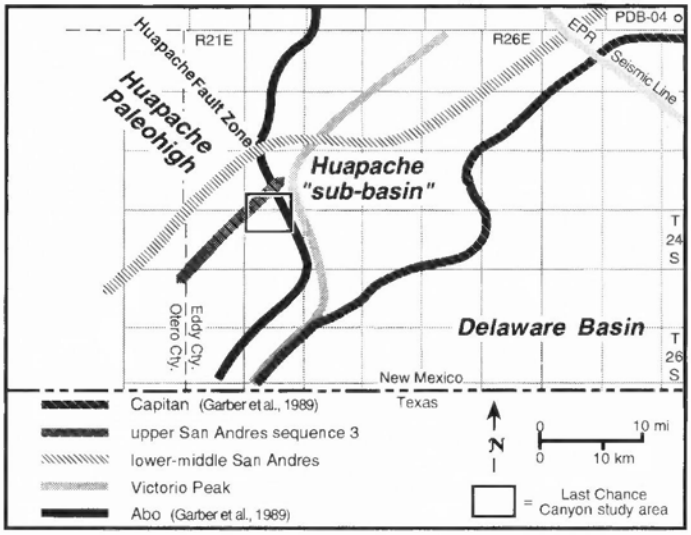


FIGURE 3. Terminal shelf-margin trends for several Leonardian and Guadalupian units. Note the pronounced bend of the lower Leonardian Abo Reef trend in response to the remnant paleohigh formed by Pennsylvanian through Wolfcampian activity along the Huapache fault zone. The lower-middle San Andres margin's trend records a subdued yet evident expression of the Huapache sub-basin and was derived from author's observations, Rossen and Sarg (1988) and Fitchen et al. (1992).

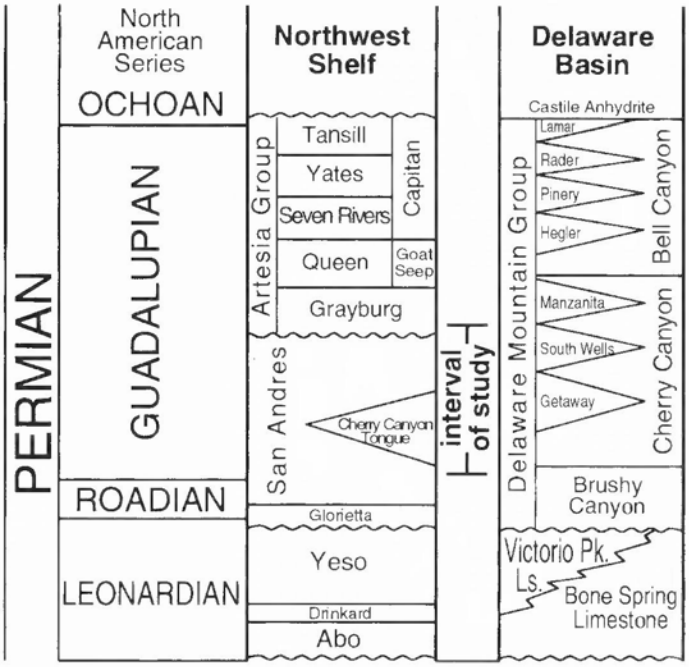


FIGURE 4. Generalized early to middle Permian stratigraphic columns. After Hills and Kottlowski (COSUNA), 1983.

moting the development of inferred aeolian dunefields during episodic subaerial exposure of carbonate-dominated shelves (Fischer and Sarnthein, 1988). The low paleolatitude, the arid climate and the lack of turbid, terrestrial runoff promoted the growth of basin-rimming carbonate banks and reefs. Negligible volumes of hemipelagic clay, coupled with the absence of calcareous and siliceous planktonic organisms prior to the Jurassic, led to the development of a sediment-starved basin during relative highstands of sea-level. By contrast, siliciclastics bypassed the shelves in a "reciprocal" fashion during relative lowstands of sea-level, resulting in the accumulation of predominantly siliciclastic basinal deposits of the Delaware Mountain Group (Meissner, 1967, 1972).

Early stratigraphic studies in Last Chance Canyon focused on the nature and distribution of rock types and fossils within the context of correlating formations and their boundaries (Fig. 4; Darton and Reeside, 1926; King, 1942, 1948; Skinner, 1946; Boyd, 1958; Hayes, 1959). More recent studies of Last Chance Canyon emphasized the interpretation of shelf through slope environments of deposition (Harrison, 1966; Jacka et al., 1968; Williams, 1969; Naiman, 1982; McDermott, 1983). The regional studies of Meissner (1967, 1972) and Silver and Todd (1969) refined shelf-to-basin temporal correlations and pioneered the application of sequence stratigraphy in the Delaware Basin by applying the concept of "reciprocal sedimentation" (Van Siclen, 1958; Wilson, 1967). These workers recognized the cyclic alternation of basin-centered siliciclastics with carbonate-dominated shelf and slope deposits, and presumed that eustasy was responsible for basinwide late Wolfcampian through Guadalupian depositional cycles. Meissner (1967, 1972) and Silver and Todd (1969) interpreted the lower San Andres Formation as the product of a long-term, punctuated transgression commencing in the late Leonardian to Guadalupian Epochs. Relatively deep-water lower Guadalupian strata were deposited upon flooded Leonardian platforms, resulting in paleo-water depths at the toe-of-depositional-slope of 40-100+ m, rather than the 200-500+ m water depths inferred for Delaware Mountain Group sandstones in the center of the Delaware Basin proper (Fig. 5). This transgression was followed by long-term, punctuated regression during deposition of the middle to upper San Andres Formation. Multiple episodes of siliciclastic bypass across the upper San Andres shelf resulted in deposition of Brushy Canyon and lower Cherry Canyon sandstones in the Delaware Basin (Meissner, 1972).

More recently, Sarg and Lehmann (1986a, b) described depositional facies, large-scale stratal geometries and sequence boundaries within the framework of seismic-scale sequence stratigraphy (Vail et al., 1977). They proposed a temporal correspondence between two seismically resolvable San Andres sequences in the subsurface (location of Exxon Production Research seismic section shown on Figs. 2, 3) and two sequences recognized within the San Andres of Last Chance Canyon.

In Last Chance Canyon, Sarg and Lehmann (1986a) interpreted two genetically distinct stratigraphic units within the complex transitional strata between shelf and slope carbonates of the San Andres Formation and slope and basinal siliciclastics of the Cherry Canyon Formation. The lower unit is an onlapping, predominantly siliciclastic unit termed the "lower Cherry Canyon sandstone tongue." The upper unit consists of offlapping, mixed siliciclastic/carbonate strata of the uppermost San Andres Formation and "upper Cherry Canyon sandstone tongue." These strata downlap the upper surface of the lower Cherry Canyon sandstone tongue (Fig. 5).

Studies of the San Andres Formation by Fitchen (1992), Kerans et al. (I 992a, b), Sonnenfeld (1991a, b) and Sonnenfeld and Cross (in press) emphasized facies arrangements within and among numerous high-frequency sequences embedded within the San Andres formation. Recent outcrop studies have subdivided the San Andres Formation into at least eight sequences of similar spatial scales (Fig. 5; Fitchen et al., 1992; Kerans et al., 1992a, b; Kerans et al., 1993). Additionally, most if not all sequences within the Brushy Canyon Formation lack shelfal equivalents (M. **H.** Gardner, personal comm. 1992; Kerans et al., 1993, this volume); thus up to sixteen large-scale sequences may be embedded within the two seismic-scale, third-order sequences of Sarg and Lehmann (1986a; Fig. 5). Estimates of the duration of the entire San Andres Formation range from 5 to 10 Ma, depending on the absolute time scale used (Fig. 6). Assuming equal durations, each of the eight to sixteen San Andres sequences could range from 310 ky to 1250 ky, below the 1-5 Ma duration of Leonardian and Guadalupian biostratigraphic zones (Ross and Ross, 1987; Harland et al., 1989; Wilde, 1990). Because estimates of temporal duration remain so imprecise, a site-specific terminology is used instead. Probable fourth-order cycles (0.1-1.0 Ma) are informally termed "large-scale" (rock) and "long-term" (time) and probable fifth-order cycles (<0.1 Ma) embedded within the two large-scale San Andres sequences exposed in Last Chance Canyon are termed "high-frequency sequences" or simply "cycles."

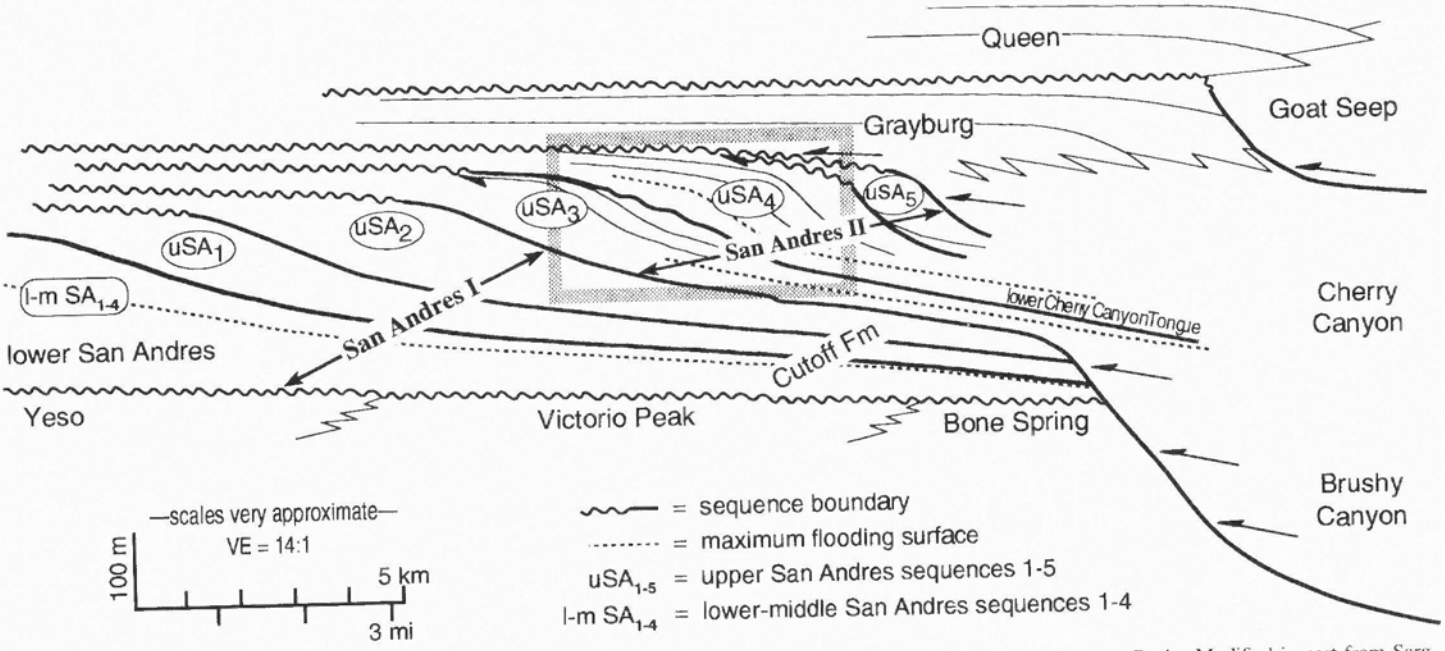


FIGURE 5. Schematic stratigraphic setting of Leonardian and Guadalupian strata along the northwestern shelf of the Delaware Basin. Modified in part from Sarg and Lehmann (1986a), Pray (1988) and Kerans and Nance (1991). Box represents area of Last Chance Canyon cross section A-A′ (Fig. 8). San Andres "I" and "II" correspond approximately to the seismic-scale third-order sequences defined by Sarg and Lehmann (1986a). Upper San Andres sequences 3 and 4 correspond to Guadalupian sequences 12 and 13 of Kerans et al. (1993, this volume).

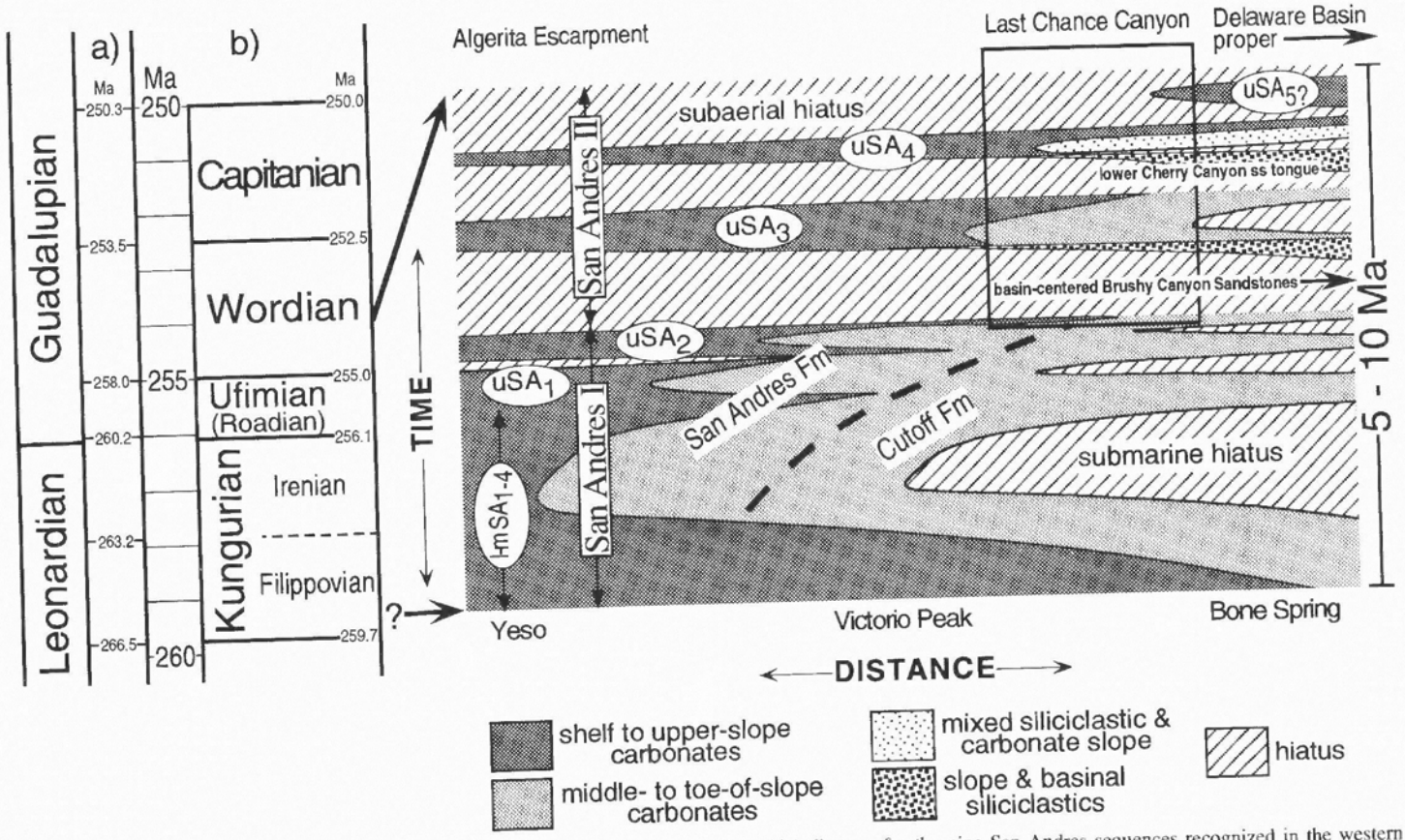


FIGURE 6. Absolute time scales, geochronologic units and Wheeler (chronostratigraphic) diagram for the nine San Andres sequences recognized in the western Delaware basin and Guadalupe Mountains region. Time scale "a" of Ross and Ross (1987) and Wilde (1990) differs from time scale "b" of Harland et al. (1989), particularly with respect to the duration ascribed to the Roadian and Wordian stages. These discrepancies impart a potential range in duration of 5 to 10 Ma for the San Andres Formation. Note that Kerans et al. (1993, this volume) document that the lower-middle San Andres is late Leonardian in age. Box denotes Last Chance Canyon outcrops.

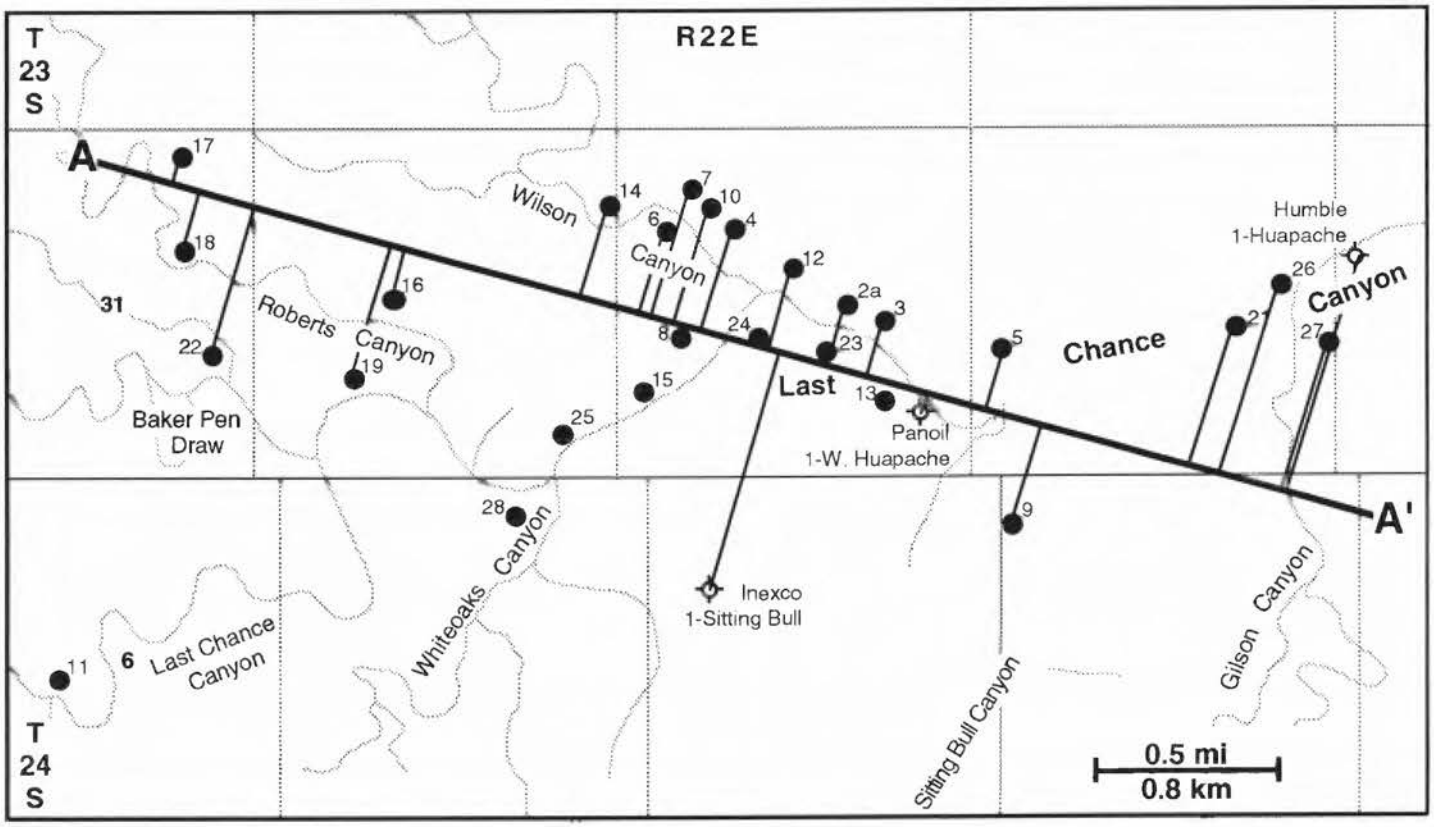
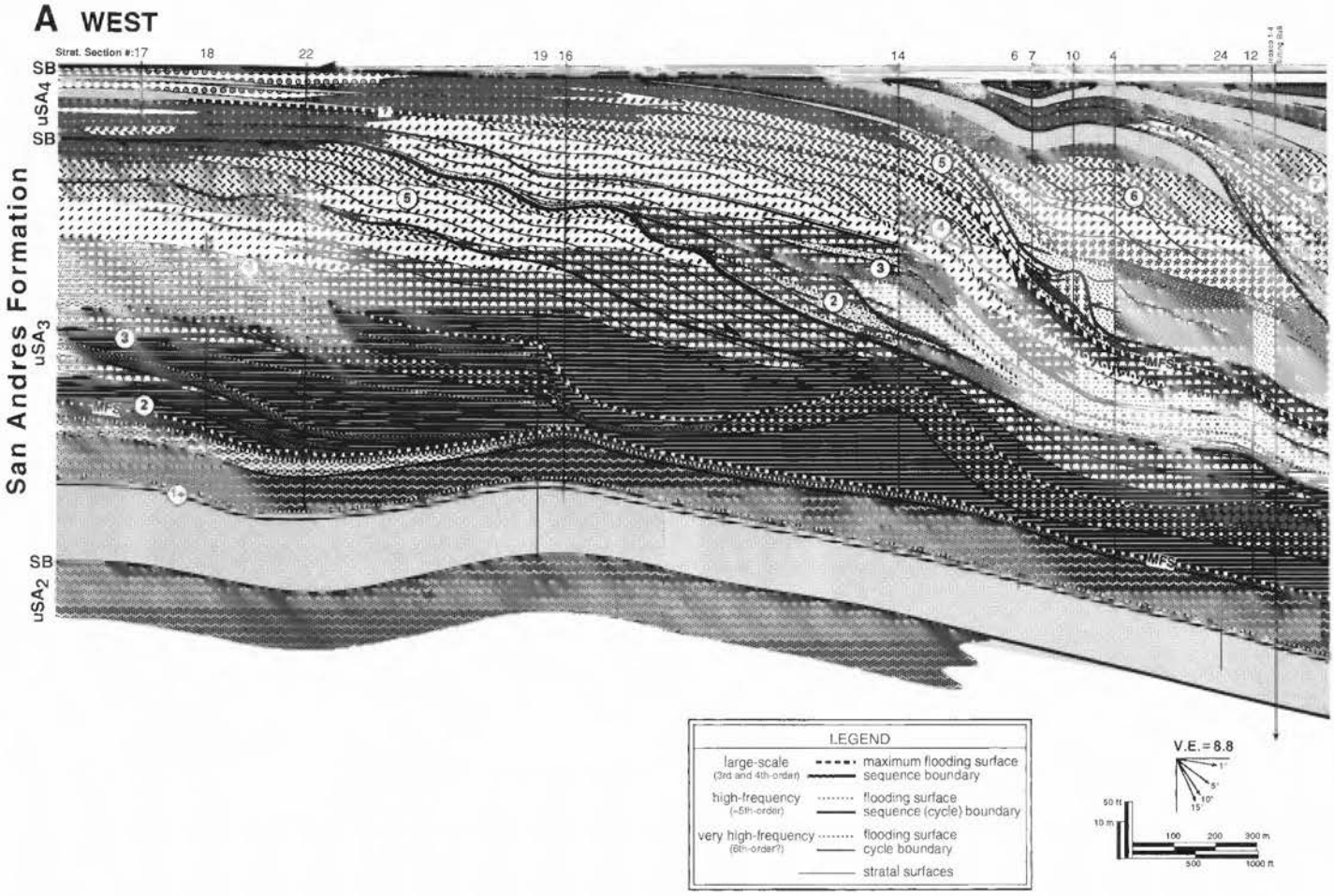


FIGURE 7. Geographic map of Last Chance Canyon area showing locations of measured sections and projection lines used to construct depositional-dip cross section A-A′ (Fig. 8).



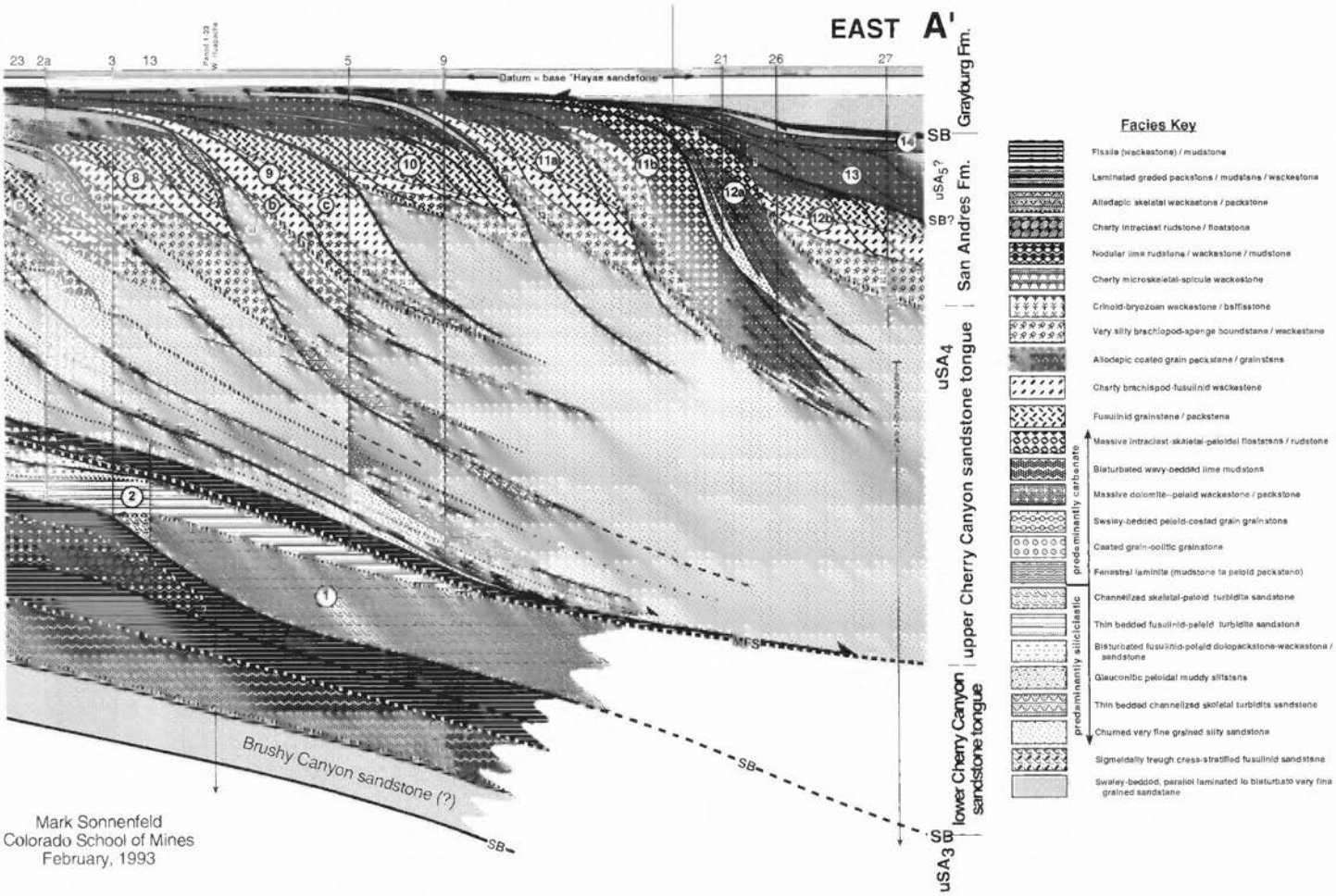
SUMMARY OF STRATIGRAPHIC RELATIONS

Last Chance Canyon is noted for its spectacular exposures of offlapping strata. Observation of stratal geometries exposed in Last Chance Canyon enhances one's appreciation and "eye" for stratal geometries most commonly observed on seismic lines. Clinoform morphologies varying from sigmoidal to complex sigmoid-oblique to oblique have been used on both outcrop and seismic profiles to infer long-term accommodation trends (e.g., Barrell, 1912; Cotton, 1918; Sarg, 1988; Bosellini, 1989), yet premises concerning the significance, genesis and likely facies associated with different clinoform geometries have remained quite general (Brown and Fisher, 1977; Mitchum et al., 1977; Sangree and Widmier, 1977; Bosellini, 1984; Sarg, 1988). Last Chance Canyon's outcrops permit physical examination of strata and bounding surfaces continuously from the outer shelf to the basin margin. This allows relationships between seismic-scale clinoform geometries and coeval depositional facies to be directly observed, thereby enhancing description and understanding of the relations among facies, stratigraphic geometries and time-significant stratigraphic bounding surfaces.

Twenty-six stratigraphic sections were measured for this study, eight of which are located on the north wall of Last Chance Canyon (Figs. 7, 8, 9). These sections facilitate detailed correlations between and within high-frequency sequences. Measured sections are projected onto depositional dip oriented cross section A-A' (Fig. 8). San Andres Formation outcrops in Last Chance Canyon are interpreted to contain two large-scale, fourth-order depositional sequences, upper San Andres sequence 3 and upper San Andres sequence 4 (Figs. 5, 6). Facies associations, volumetric proportions of carbonate and siliciclastic strata and depositional topography change progressively through the course of the 199 upper San Andres sequence 4 (Sonnenfeld, 1991a, b; Sonnenfeld and Cross, in press). These aspects change in a predictable fashion and correspond to position within the lowstand, transgressive and highstand systems tracts. Units within the lowstand and transgressive systems tracts (uSA_4, cycles 1-4) record a progressive decrease in sedimentation rate, depositional energy and siliciclastic content. This reflects a long-term transition from detrital, siliciclastic-dominated, point-sourced slope sedimentation to increasingly autochthonous, carbonate-dominated, line-sourced slope sedimentation. Within carbonate strata of the transgressive systems tract (uSA_4 cycles 3-4), long-term relative sea level rise is interpreted from thick outer-shelf deposits, highly aggradational to mounded fusulinid shoals and net stratigraphic rise of the fusulinid facies tract. The most carbonate-rich and bioherm-bearing interval of the entire sequence overlies a distinctive maximum flooding surface capping the transgressive systems tract (measured section 10, Fig. 8). Ensuing high-frequency sequences of the middle to late highstand systems tract (uSA_4, cycles 6-12) show pronounced progradational offlap and record a progressive increase in the volume of siliciclastics accumulated in the basin with a concomitant decrease in the volume of siliciclastics accumulated on the outer shelf. A karsted toplap surface represents a subaerial unconformity and sequence boundary capping upper San Andres sequence 4. Peritidal cycles within the overlying Grayburg Formation exhibit a significant seaward shift in coastal onlap across this sequence boundary (Sarg and Lehmann, I 986a, b).

Published sequence stratigraphic models for carbonates have been based on the simplifying assumption that carbonate and siliciclastic responses to accommodation changes are analogous (Sarg, 1988; Vail, 1988). Within the transgressive systems tract of the upper San Andres

FIGURE 8. Stratigraphic cross section A-A′ through Last Chance Canyon. Vertical exaggeration is 8.8:1. Line of projection shown on Fig. 7. High-frequency cycles 1–2 internal to uSA_4 are interpreted as the landward limit of the lowstand systems tract; uSA_4 cycles 3–4 are interpreted as the transgressive systems tract; and uSA_4 cycles 6, 7–10 and 11–12 are interpreted as the early, middle and late highstand systems tracts, respectively.



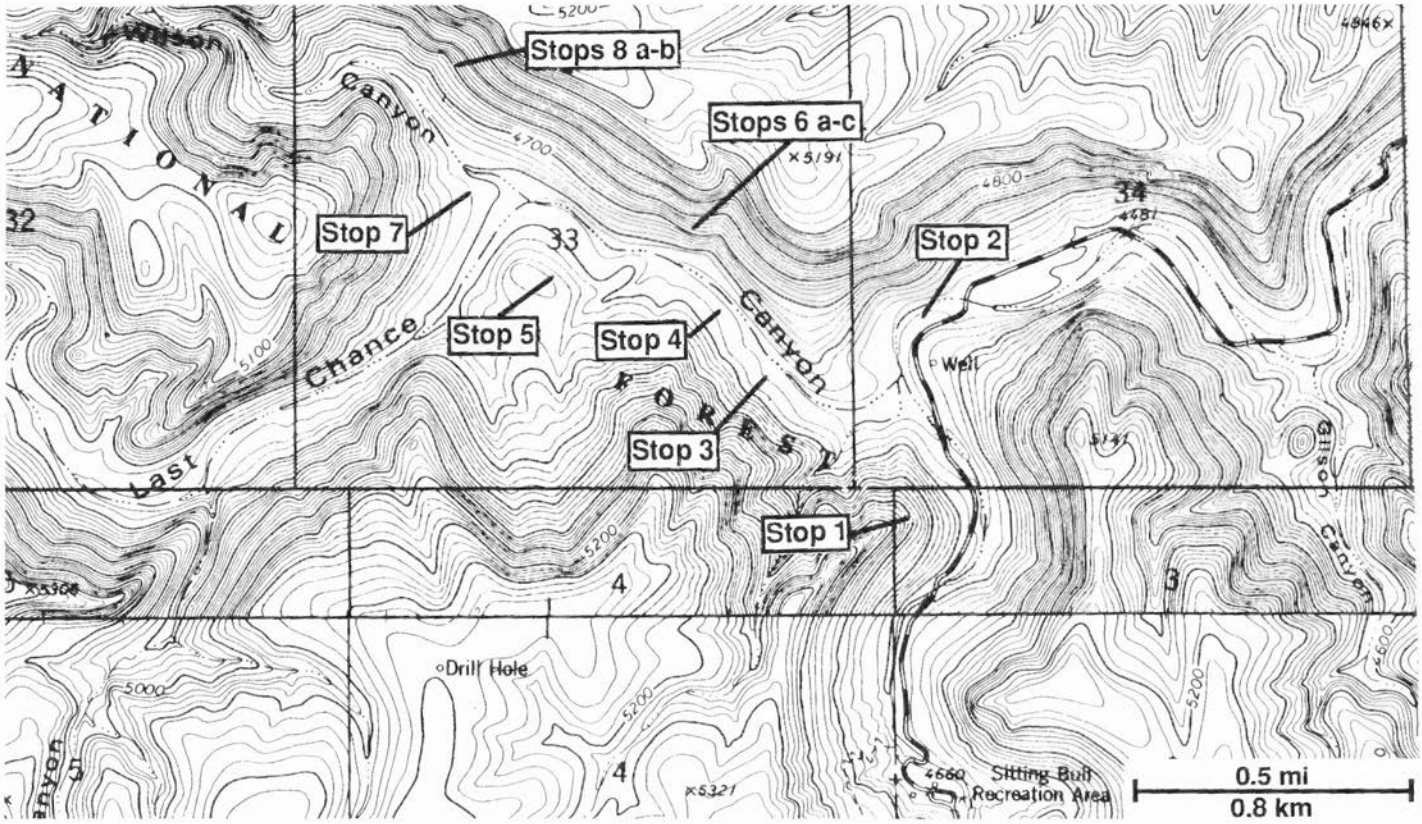


FIGURE 9. Topographic map showing stops described in detailed field guide to Last Chance Canyon (Sonnenfeld, 1991b). Today's field trip is limited to overview Stop 1 (= "Panorama Point") and outcrop Stops 2 and 6.

4, carbonate strata of successive cycles show net offlap *concurrent with* landward-stepping siliciclastic domains. These contrasting strata] patterns reflect the contrasting nature of carbonate versus siliciclastic sediment supply. Carbonate production occurs across a wide range of subtidal environments, whereas siliciclastic sediment supply to the slope is directly tied to shoreline position.

Embedded within upper San Andres *sequence* 4 are numerous higher-frequency sequences. Reciprocal siliciclastic/carbonate sedimentation patterns enhance the recognition of cyclicity within both large-scale sequences and within the many higher-frequency sequences. The internal components of several high-frequency cycles embedded within upper San Andres sequence 4 are especially apparent from field trip stops 1 ("Panorama Point") and 5 (Figs. 9, 10, 11). Erosional surfaces and isolated turbidite- and/or storm-deposit filled channels form the basal portion of slope to toe-of-slope siliciclastic transgressive hemicycles. Channelized deposits are succeeded gradationally by bioturbated and basin-restricted sandstone wedges representing waning rates of siliciclastic sedimentation, predominantly from suspension. These high-frequency strata/ relationships are similar to those generally ascribed to lowstand through transgressive systems tracts within larger-scale sequences. Sandy slope wedges are capped by transgressive surfaces sporadically colonized by sponge-brachiopod communities that are high-frequency analogs to the larger crinoid-bryozoan bioherms and brachiopod-sponge reefs developed on the large-scale, fourth-order maximum flooding surface of upper San Andres 4. Prograding fusulinid shoals downlap the siliciclastic wedges and are capped by regressively accumulated shelf sands, forming carbonate-dominated regressive hemicycles that are high-frequency analogs to highstand systems tracts.

Fourth- and fifth-order sequences in Last Chance Canyon show remarkable similarities to third-order, seismic-scale depositional sequences (Fig. 12). Scale-independent similarities include: I, stratal geometries; 2, the nature of bounding surfaces; 3, the timing of bioherm development; 4, siliciclastic to carbonate facies evolution; and possibly 5, point-source to line-source evolution. This *qualified* "stratigraphic self-similarity" probably results from the fact that changes in shelfal accommodation, siliciclastic transport to the shelf margin, elastic poisoning effects on autochthonous carbonate generation and basin hydrographic criteria critical to carbonate production (water depth, temperature, nutrient flux and storm regime) were controlled similarly by third-, fourth- and fifth-order relative changes in sea level.

Stratigraphic self-similarity emphasizes that the physical stratigraphy of a sequence reflects spatial and temporal variations in accommodation/ sediment supply ratios but is relatively independent of absolute duration. One of the most important aspects of stratigraphic self-similarity, best documented within the highstand systems tract of upper San Andres 4, involves the seaward transition from asymmetric shallowing-upward hemicycles commonly observed on shelves, to symmetric cycles on slopes, to asymmetric hemicycles at the toe-of-slope and seaward. Each symmetric cycle includes an inferred deepening-upward phase or "transgressive hemicycle," characterized by a waning siliciclastic influence, succeeded by a shallowing-upward phase, or "regressive hemicycle," characterized by flourishing, prograding carbonates. Regressive asymmetric hemicycles on the shelf and transgressive asymmetric hemicycles in the basin each record approximately half the time spanned by an entire high-frequency base-level rise and fall cycle; only within symmetric cycles of slope settings is a relatively complete proportion of the time recorded by rock of significant thickness. In the shelf and basin, by contrast, surfaces and/or relatively condensed rock intervals represent approximately half the time spanned by a cycle of base-level change. Though infrequently documented in the literature, symmetric cycles may be a common feature in slope settings.

The concept of qualified stratigraphic self-similarity does not diminish the importance of facies variation or "differentiation" (Sonnenfeld, 1992; Sonnenfeld and Cross, in press) within and among sequences. Indeed, facies models abstracted from multiple facies successions taken from various portions of larger-scale sequences are apt to be over gen-

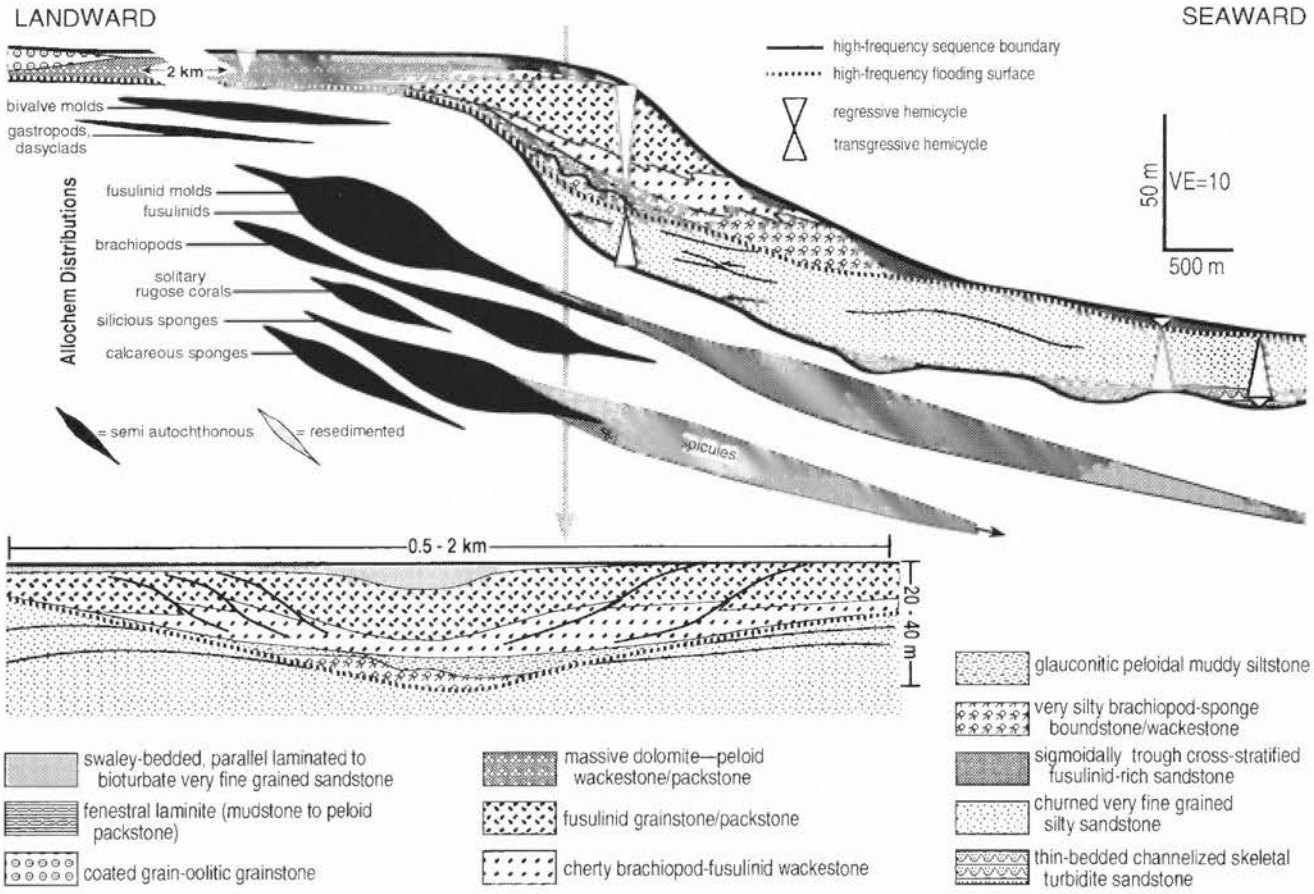


FIGURE 10. Schematic strike and dip cross sections through a high-frequency cycle typical of the uSA_4 middle highstand systems tract, showing the distribution of facies and skeletal allochems.

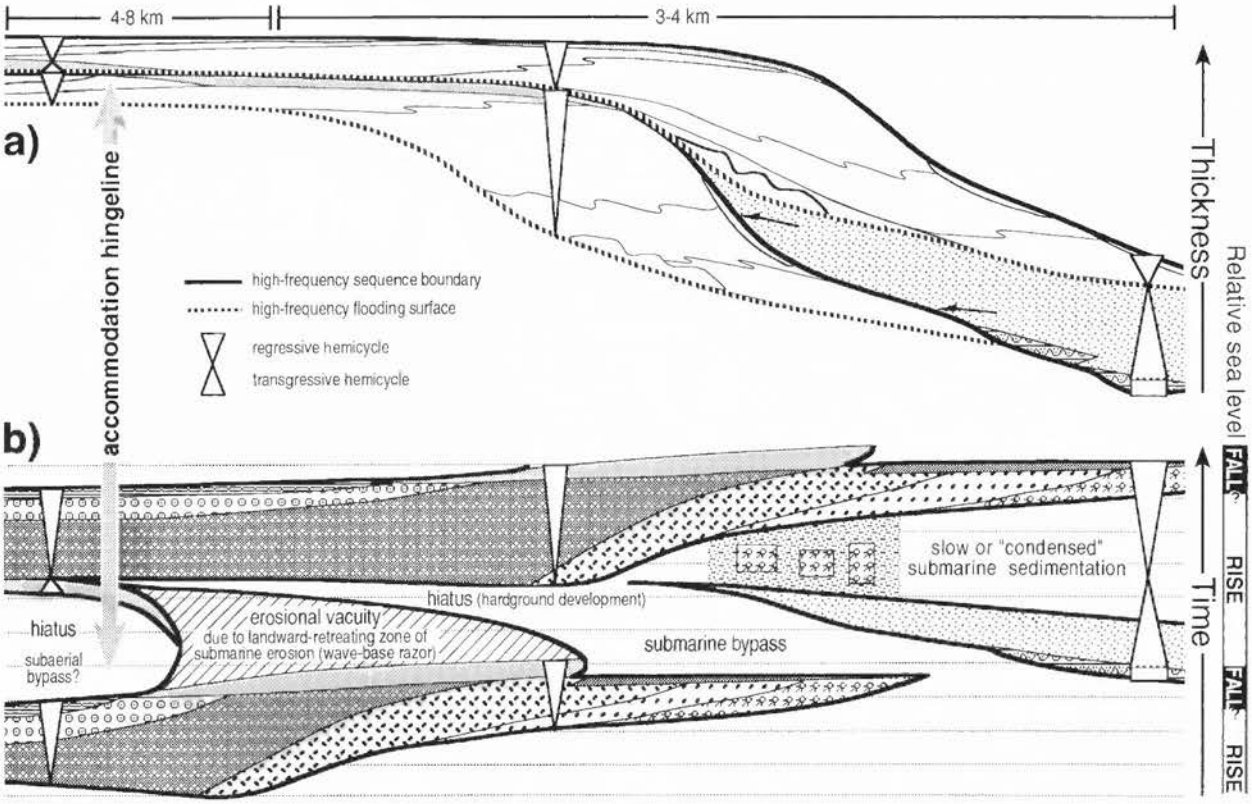


FIGURE 11. a) Schematic cross section through a high-frequency cycle typical of the uSA_4 middle highstand systems tract, with siliciclastics patterned and carbonates left white to emphasize reciprocal sedimentation patterns. b) Wheeler (chronostratigraphic) diagram of a). Key to facies patterns on Fig. 10.

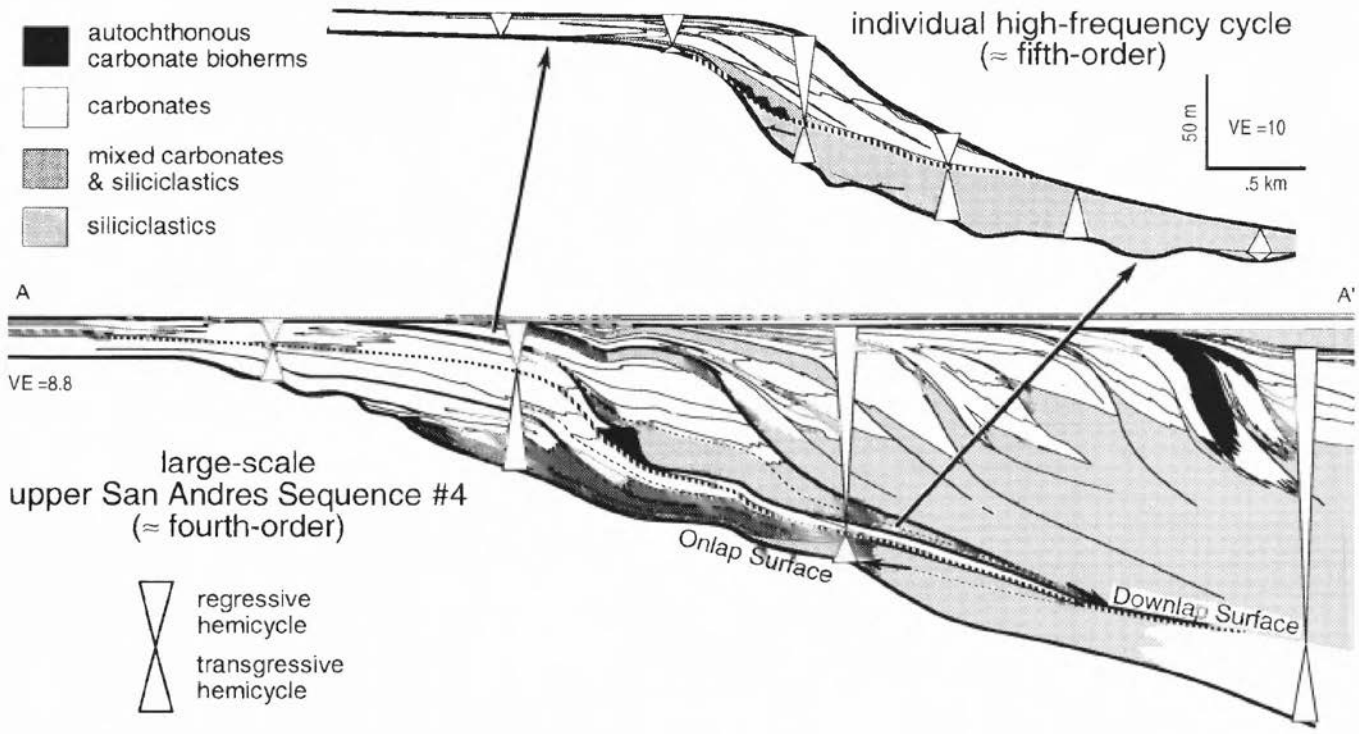


FIGURE 12. Stratigraphic self-similarity—note the similar nature of stratal geometries, lithofacies partitioning and preservation of transgressive versus regressive hemicycles within base-level transit cycles at these two spatial and temporal scales. a) Simplified version of depositional dip cross section A-A' (Fig. 8) emphasizing large-scale geometries and lithofacies relationships for the upper San Andres sequence #4. b) Simplified version of Fig. 11, showing large-scale geometries and lithofacies for an idealized high-frequency cycle within the middle highstand systems tract of upper San Andres #4.

eralized. Facies model predictability can be significantly refined by recognizing that high-frequency cycles form fundamental units for application of Walther's Law.

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South Tank Canyon in southern Brokeoff Mountains. View is upstream N65°W. High cliffs and ridge on right are Grayburg Formation; lower slopes are transitional San Andres and faulted Cherry Canyon tongue. Lowest cliff and slope in middle distance is Cutoff Formation (Boyd, 1959; Fitchen, this volume). Camera station is in NE¼ sec. 7, T26S, R20E, about 10.5 km west-southwest of El Paso Gap. Altitude is approximately 1846 m. W. Lambert photograph No. 85L115. November 16, 1985, 3:06 p.m. MST.