The Role of the Guadalupe Mountains and Capitan Research in the Evolution of Carbonate Conceptual Models and Paradigms*

Paul (Mitch) Harris[1] and Charles Kerans[2]

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[1]Chevron Energy Technology Company, San Ramon, CA; currently Center for Carbonate Research, University of Miami, Miami, FL (pmitchharris@gmail.com)
[2]Department of Geosciences, Jackson School of Geosciences, University of Texas at Austin

Introduction

Evolving studies of the Permian stratigraphy of the Guadalupe Mountains have established these mixed carbonate and siliciclastic rocks, particularly those of the Capitan shelf margin, as "analogs" for numerous similar rocks around the world. In so doing, these exposures have played a key role in the development of general conceptual models for carbonate shelf margins. From the 1940s and earlier to the 1970s the geology of the Guadalupe Mountains was investigated from the view of biostratigraphy, lithostratigraphy, depositional models and concepts of reciprocal sedimentation. Focus shifted in the 1970s and early 1980s to analysis of depositional facies and processes and on the relatively new understanding of early diagenesis of reef margins. Starting in the 1980s and continuing to today, the outcrops have been analyzed from a cyclostratigraphy and sequence stratigraphy perspective, with this stratigraphic framework now serving as a template in which many aspects of the geology, including origin of reefal fabrics, slope carbonate depositional styles, and syndepositional faults and fractures, are being evaluated.

Stratigraphic and Sedimentologic Pioneers 1940s-Early 1970s

Providing the initial interest in the area to the carbonate community were the field studies and subsequent detailed reporting of the geology of the southern (Glass Mountains), western (Sierra Diablo Mountains), and ultimately the northwestern margin (Guadalupe Mountains) of the Delaware Basin by King (1930, 1942, 1948, 1965). King's maps and descriptions provided such an accurate starting point for subsequent studies that they are still in wide use today.

Newell et al.'s (1953) Capitan Reef did much to further enhance the outcrops as research models for sedimentary geologists, introducing the barrier reef model and refining the stratigraphic framework of the shelf system. The critical treatment of Capitan sedimentology by Dunham in the late 1950s and 1960s, culminating in his detailed 1972 guidebook, stimulated interest and added new understanding. Dunham's work, plus the overall increase in sedimentary geology research in both academia and industry, provided impetus for additional research by many geologists. The Guadalupian Series, particularly the San Andres and Grayburg formations and Carlsbad Group, provided understanding to the precursors of modern-day sequence stratigraphy. These mixed carbonate and siliciclastic depositional systems forced an evaluation of the interplay between the shelf and the basin with regard to sea-level change and led to the concepts of reciprocal sedimentation. The regional subsurface analyses of Silver and Todd (1969) and Meissner (1972) at Exxon and Shell, respectively, though founded in subsurface data, were inspired by the Guadalupian exposures and became the heart of company field trips and outcrop research efforts.

Carbonate Facies Analysis – Importance of the Preserved Depositional Profile

The Capitan system became the training ground for both industry and academic carbonate sedimentologists during the 1960s through the present day, becoming an integral part of the ”ancient carbonates” segment of the modern/ancient trips of Humble/Exxon, Shell, and other companies. Those of us who frequent the Guadalupes forget the impressions we first had when it became possible to observe a full spectrum of shallow to deep-water carbonate and siliciclastic facies laid out in their original depositional geometric position. This exceptional, though non-unique, setting encouraged important early facies analyses including those of tepee structures (Assereto and Kendall, 1977), pisolites (Dunham, 1969; Esteban and Pray, 1977), and a generation of comprehensive field guide overviews (Scholle and Halley, 1980; Toomey and Babcock, 1983). Graduate students, under the supervision of L. C. Pray at the University of Wisconsin-Madison, studied Capitan sedimentology, stratigraphy and paleoecology. The first generation of Pray's students published their results along with other authors in SEPM Permian Basin Section Publication 77-16 (Hileman and Mazzullo, 1977). This two-volume compilation with field trip guide discussed many aspects of the Capitan including: reef textures and paleoecology (J.A. Babcock, 1977; Toomey and Cys, 1977; Yurewicz, 1977; Schmidt and Klement, 1977); backreef sedimentology and stratigraphy (Neese and Schwartz, 1977; Esteban and Pray, 1977; Sarg, 1977); reef and backreef diagenesis (Mazzullo, 1977; Mazzullo and Cys, 1977; Schmidt, 1977); and basinal carbonates and clastics (L. C. Babcock, 1977; Williamson, 1977).

Studies of the Capitan continued unabated in the late 1980s and 1990s. SEPM Core Workshop Number 13 (Harris and Grover, 1989) was built upon descriptions of the Gulf PDB-04 well which continuously cored the Bell Canyon, Capitan, Seven Rivers, Yates and Tansill formations. The descriptions (Garber et al., 1989) are a unique documentation of lithologies, facies, and diagenesis of the Capitan in the subsurface. The workshop volume contained many other articles on depositional features of the reef (Babcock and Yurewicz, 1989; Harwood, 1989), backreef and shelf equivalents (Parsley and Warren, 1989; Mazzullo et al., 1989; Neese, 1989; Borer and Harris, 1989; Candelaria, 1989; Hurley, 1989; Sarg, 1989; Wheeler, 1989), and diagenesis (Mruk, 1989; Melim and Scholle, 1989). The Guide to the Permian Reef Geology Trail (PRGT) (Bebout and Kerans, 1993) is another important collection of descriptions and interpretations of the Capitan system. The guide focuses on the mouth of McKittrick Canyon which is exceptional in providing a trail with fresh exposures from the basin through the Capitan slope and reef, and ending in the outer shelf and shelf crest. An excellent and comprehensive review of most aspects of the Capitan is available in Hills (1996) volume on the geology of the Delaware Basin. The most recent compilation on the Capitan (Saller et al., 1999) emphasized the stratigraphic framework (Kerans and Tinker, 1999; Lehrmann and Rankey, 1999; Mazzullo, 1999), facies analysis (Wood, 1999; Weidlich and Fagerstrom, 1999; Kirkland et al., 1999; Longley, 1999), diagenesis (Rahnis and Kirkland, 1999; Melim and Scholle, 1999; Hill, 1999), biostratigraphy (Wilde et al., 1999), and subsurface data (Harris and Saller, 1999).

Conceptual Models and Discussion Points

Below we provide some examples of the major role that previous studies in the Guadalupe Mountains have played in developing universal conceptual models for carbonate shelf margins and in the process sometimes leading to paradigms. In all cases, the examples can be viewed as starting points for discussions that will prompt a variety of opinions.

What Constitutes a reef?

Starting with Dunham (1969), the debate on whether the Massive Member of the Capitian Formation is even a reef, and if so, whether it is an ”ecologic reef”, ”diagenetic reef”, or ”stratigraphic reef” continues. Workers who saw a dominance of wackestone concluded that the Capitan was a massive carbonate buildup (“stratigraphic reef”) but not an ecologic reef (Baars, 1964; Achauer, 1969; Dunham, 1970; Tyrrell, 1969). Others saw a dominance of syndepositional cement and concluded that inorganic cement was the critical binding agent in the reef (Schmidt, 1977; Mazzullo and Cys, 1977, 1978; Grotzinger and Knoll, 1995). Still others (Cronoble, 1974; J. A. Babcock, 1977; Yurewicz, 1977; Cys et al., 1977; Scholle and Halley, 1980) observed substantial amounts of organic boundstone and concluded that much of the Capitan was an organic reef. Construction of the PRGT provided many rock faces with naturally etched surfaces, and along with further studies of outcrops in the mouth of Walnut Canyon and Dark Canyon, provided convincing arguments that much of the Capitan (1) has an organic reefal framework with bryozoans, calcareous sponges and other organisms in growth position, (2) is bound by a variety of microbial coatings and marine cements, and (3) contains abundant internal cavities. Capitan reef paleoecology remains the subject of active research, including Noè and Mazzullo (1992), Wood et al. (1994, 1996), Senowbari-Daryan and Rigby (1996), Noè (1996), Wood (1999), Weidlich and Fagerstrom (1999), and Kirkland et al. (1993, 1998, 1999). The role of microbial fauna in carbonate margins has expanded and been extrapolated to similar systems that include the Triassic of the Dolomite Alps (Keim and Schlager, 2001) and the Carboniferous in the Cantabrian Basin of Spain and the subsurface of Kazakhstan (Kenter et al., 2005).

Shelf Margin Profile (or Depth of Reef); Depositional, Compactional or Both?

Beginning with King (1948) and Newell et al. (1953), a debate was set-up focusing on whether the Capitan is a raised barrier-reef profile or a deep-reef-rimmed margin. Some authors propose a shallow barrier and relatively flat-lying back-reef beds based on facies associations and geopetal measurements, e.g. Kirkland and Moore (1990), whereas others argue for a shelf profile with water depth increasing steadily in a seaward direction away from the shelf-crest tepee complexes (fall-in bed geometry), placing the reef margin in 15-40 m water depth (Pray, 1977; Hurley, 1978; Kerans and Tinker, 1999). The counter to this ”depositional profile” model is the concept of syndepositional differential compaction to explain the seaward dip of outer shelf beds, with rotational subsidence seaward of the older margins causing the ”fall-in” as a secondary effect (Saller, 1996; Hunt et al., 1996, 2002; Hunt and Fitchen, 1999). Integration of **static** sedimentologic models with sequence stratigraphic analysis adds to the debate by illustrating that the question - of whether the reef margin was shallow or deep - hinges on which part of the Capitan is being considered (Kerans and Tinker 1999; Harman, 2011). One needs only to examine exposures along the north wall of McKittrick or Slaughter canyons to demonstrate that the shelf profile and depth of water over the reef clearly varied significantly during development of the Capitan margin (Osleger, 1998; Osleger and Tinker, 1999; Kerans and Tinker, 1999; Weidlich and Fagerstrom, 1999).

Further studies constrained by this stratigraphic framework are needed to more fully evaluate the relative importance of a syndepositional profile and differential compaction in explaining the fall-in bed geometry (see Figure 1).

Deposition of Basinal Siliciclastics

King (1948) and Newell et al. (1953) initially proposed deposition of the Brushy Canyon (older than the Capitan) in the adjoining Delaware Basin as a shallow-marine environment, based on the abundance of sand and abundant ripples. The recognition of graded beds in the basinal deposits (Hull, 1957; Jacka et al., 1968) suggested deposition as deep-water turbidites. The stratigraphic position of the basin-fill led most subsequent workers to invoke deeper water depositional environments, and during the 70s work, was initiated into the nature and timing of reciprocal sedimentation (Wilson, 1972; Meissner, 1972) and the style of deep-water sedimentation (Payne, 1976; Bozanich, 1979; Williamson, 1977, 1979). The concept of reciprocal sedimentation, wherein basinal siliciclastics are deposited during times of relative lowstands and shelf exposure and carbonates are deposited on the shelf and less so in the basin during relative highstands, set the stage for the application of sequence stratigraphy to the Guadalupe Mountains and, in so doing, provided many aspects regarding the timing and mechanisms of this reciprocity for debate. Harm's (1974) and Harms and Williamson (1988) hallmark papers dealt with the character of deep-water turbidites and channel systems in the Brushy Canyon Formation. This area became the focus of several of Pray's students, including Rossen (1985), who extended the studies of the Brushy Canyon at Exxon's research lab (Rossen and Sarg, 1987; Sarg et al., 1988). Brushy Canyon studies by Exxon (Beaubouef et al., 2000) and the CSM group (Gardner and Sonnenfeld, 1996; Gardner and Borer, 2000; Gardner et al., 2003) have played a key role in developing global deep-water exploration models.

Depositional models for Capitan-equivalent basinal sandstones and siltstones of the Bell Canyon Formation are still being debated. Stratigraphic position and sedimentologic criteria cause most, but not all, to invoke deeper water deposition of sediment transported through or over the carbonate margin into the basin, but the exact mechanism and relative timing of bypass remain uncertain. Some have proposed deposition by density currents created by high-salinity shelf waters flowing into the basin, i.e., during highstand flooding of the shelf; whereas most others suggest transport of sands and silts from the shelf to the basin by eolian process during lowstands and exposure of the shelves. Borer and Harris (1995) argued for repeated input of siliciclastic sands into the basin during high-frequency subaerial exposure and bypassing of the shelf. Mruk and Bebout (1993) and Brown and Loucks (1993a, 1993b) documented high-frequency siliciclastic input toward the basin within the slope and toe-of-slope at McKittrick Canyon outcrops. A distinct small-scale cyclicity is readily apparent in the basinal strata (Meissner, 1972; Kerans et al., 1992, 1993; Borer and Harris, 1995; Gardner and Sonnenfeld, 1996),. including the Bell Canyon Formation. Refinement of our understanding of this interplay over time between the shelf deposition or bypassing and basin deposition is still needed.

Sequence Stratigraphy Application and Relationships

The Capitan remains one of the principal natural laboratories for investigating different approaches of applying sequence stratigraphy, and many remaining contentious points are the result of the Leonardian-Guadalupian being a complex mixed carbonate – siliciclastic system. Building upon the concept of reciprocal sedimentation of Silver and Todd (1969), Wilson (1972) and Meissner (1972), the interplay between a carbonate-dominated shelf and margin with a silicilastic-dominated basin has been put into a regional context using sequence stratigraphy.

Undoubtedly the paper by Sarg and Lehmann (1986) highlighted the use of a sequence stratigraphic framework for carbonate and mixed carbonate/clastic systems. On the platform, Borer and Harris (1991), Sonnenfeld and Cross (1993), Tinker (1998), Kerans and Tinker (1999), Osleger and Tinker (1999), and Harman (2011) developed semiquantitative approaches and linked sequence geometries to facies partitioning that showed a way forward in prediction of reservoir-scale stratigraphic architecture. Remaining questions involve which sands or surfaces on the shelf correlate with which sands or surfaces in the basin, in what manner do basinal carbonates correlate with the shelf, and how did this interplay occur across the reef margin. Most solutions, but not all, have converged on an interpretation of shelf cyclicity in which most shelf sands occur immediately above an exposure surface that represents the time when most sands were carried across the shelf to the basin (Mazzullo et al., 1985; Fischer and Sarnthein, 1988; Borer and Harris, 1991, 1995; Osleger, 1998; Osleger and Tinker, 1999); these sands are the transgressive portion of the shelf cycles and carbonates form the top of the cycles (Borer and Harris, 1991; Kerans and Harris, 1993; Tinker, 1998; Osleger, 1998; Osleger and Tinker, 1999). These authors, along with Longley (1999) and Harman (2011), examine the lateral variation and stacking patterns of cycles on outcrop in McKittrick and Slaughter canyons. Their work shows there is substantial variation in the nature of a cycle, albeit a carbonate cycle or a mixed carbonate-siliciclastic cycle, depending on its position along the depositional profile, within a sequence, and along strike (see Figure 2).

Capitan Pisolites: Soil or Shoreline? (Figure 3)

Varied ideas for the origin of pisolites, ranging from vadose soil profile to marine versus vadose microbial precipitates (Thomas, 1968; Dunham, 1969; Jacka et al., 1972), have converged in the model proposed by Esteban and Pray (1977, 1983). These authors suggest the pisolites form in current-agitated subtidal to peritidal settings, commonly occurring in inter-tepee depressions, and additional coatings may form in these same settings or even in a vadose environment. The intimately associated tepees remain somewhat enigmatic in a way similar to the dolomite problem, being volumetrically significant in the ancient (Capitan, Canning Basin Devonian, Dolomites Triassic, Morocco Jurassic) yet rare and substantially less robust in the modern (Assereto and Kendall, 1977; Warren, 1983; Kendall and Warren, 1985). Compression, force **of crystallization**, thermal expansion and contraction, and desiccation have been suggested as the mechanism for tepee formation; but discharging groundwater and associated pressure have emerged as an equally viable cause for tepees and related precipitates. Timing of tepee formation relative to exposure of the shelf (i.e., most agree that tepees form during exposure, but related cements are marine whereas crack-filling siliciclastics are a lowstand event) and whether tepees form during transgressive or highstand portions of sequences (thicker tepee intervals occur during transgessive systems tracts – Kerans and Kempter, 2002) still represent points of contention. Kerans and Tinker (1999) suggest that during times of high aggradation several factors occur that would promote tepee formation. The shoreline position of each successive cycle or sequence is offset only slightly, thus causing the hydrologic system of repeated desiccation/cementation required for tepee formation to be stacked. The high accommodation also favors steep-rimmed margins and narrow outer shelf facies-tract widths, bringing the shelf-crest complex closer to open ocean circulation and enhancing marine **cementation.**

Dolomitization and Relationship to Evaporites (Figure 4)

Most ideas on dolomitization of the pervasively dolomitized shelf beds are still consistent with the seepage reflux model (Adams and Rhodes, 1960), although there remains some divergence of opinion on the extent of evaporation that was needed to instigate reflux, and the relationship of the reflux process to changing sea level and intemittent shelf exposure. Dolomitization of the reef and slope is more localized and there is

some difference of opinion as to the origin of the fluids (from shelf or basin, or both) and the timing of dolomitization (Garber et al., 1989; Mruk, 1989; Mruk and Bebout, 1993; Melim and Scholle, 1992, 1995, 1999).

Carbonates of the Captian shelf margin give way to evaporites in a shelfward direction, which Sarg (1977, 1981) interpreted based on his studies of the Seven Rivers outcrops, as a shelf lagoon where the evaporites precipitated dominantly under subaqueous conditions. In contrast, Kendall (1969), Silver and Todd (1969), and Meissner (1972) proposed that the evaporites and dolomites of the Seven Rivers were of sabkha origin. In general, the seepage reflux model envisions that shelf carbonate-evaporites and shelf-margin carbonates were dolomitized syndepositionally and during shallow burial by relatively cool, basinward-refluxing brines originating in the shelf lagoon and sabkha. Melim (1991) favored mesohaline rather than hypersaline brines as the reflux fluid, with the fluid source being the near-reef backreef mesohaline lagoon instead of the far-backreef, hypersaline evaporative lagoon. The profound implication of this idea is that any area with a restricted carbonate lagoon may be dolomitized by refluxing brines even if no evaporites are present.

Mutti and Simo (1994) placed the timing of dolomitization of back-reef strata during deposition and subaerial exposure of each depositional cycle and related it to Permian seawater of normal to elevated salinity. A sharp contrast in timing was proposed by Kendall and Harwood (1989) and Darke and Harwood (1990) who suggested that the brine reflux occurred in the Ochoan as formational waters migrated down section during initial desiccation of the basin and deposition of the Castile Formation anhydrites. Hill (1996) presents a thorough discussion of the petrography and geochemistry of different stages of dolomite recognized in the Capitan-related and older strata, but a clearer picture of the spatial distribution and trends of these stages and their characteristics are still needed.

Origin of Caves (Figure 5)

Theories of cave formation in the Guadalupe Mountains have evolved from early ideas of more ”normal” dissolution involving rainwater and carbonic acid, to a now widely agreed upon model of sulfuric acid karst, a model which has been substantiated and is now being considered for other cave systems around the world. (Jagnow, 1979, 1989; Hill, 1987, 1989, 1999; DuChene and McLean, 1989). The sulfuric acid karst model involves gas ascension from the basin into the slope and reef through permeable Bell Canyon basinal sandstones. Natural gas migrated updip from the oil fields to the east and encountered anhydrite at the base of the Castile Formation, where reactions between the gas and the anhydrite solutions produced hydrogen sulfide, carbon dioxide, and coarse replacement calcite. Hydrogen sulfide moved updip along beds of the Bell Canyon and where this gas mixed with oxygenated ground water moving downdip along backreef beds, sulfuric acid formed and dissolved the large cave passages, such as Carlsbad Caverns and Lechuguilla Cave. Most cave formation occurs within the reef facies where this mixing of ground waters occurred and where fractures are most common, and these fractures influenced the spatial distribution of the caves.

Nature of Faults and Fractures (Figure 6)

As the Permian carbonate profile evolved from low-relief ramp to steep-rimmed margin, the foreslope/margin interface changed from one characterized by gradual low-angle slopes lacking brittle failure and significant sediment gravity flows to one with steep margin collapse

(Fekete et al., 1986; Rush and Kerans, 2010) with syndepositional fractures in the margin facies (Toomey and Babcock, 1983; Kosa et al., 2003) as well as in the inner to middle shelf (Hunt et al., 2002, Kosa and Hunt, 2005, 2006a, 2006b; Kosa et al., 2003). Although nowhere near as extensive as those observed in the classic Canning Basin complexes (Playford, 1980; Frost and Kerans, 2009), the role of syndepositional fracturing has been shown to play an important role in controlling early depositional patterns, such as growth faults with up to 30 m of active growth (Kosa and Hunt, 2005) and meteoric diagenesis and karstification (Kosa et al., 2003; Kosa and Hunt, 2006a, 2006b). Finite element modeling of the prograding margin (Resor and Flodin, 2010) demonstrates the physical basis for this fracturing, but heterogeneities and controls on localization are yet to be entirely understood. Differential compaction over preexisting margins seems a likely control in Slaughter Canyon (Harman, 2011).

Final Thoughts

The examples discussed above, although far from complete, illustrate the major role played by the Guadalupe Mountains, and especially the Capitan margin, in developing universal conceptual models for carbonate shelf margins. Suffice to say, discussions about any of the examples will quickly point out the remaining issues and what types of additional data are needed to add clarity. The newly developed high-resolution lidar-based point cloud, combined with other digital mapping techniques, is creating a field laboratory for the 3-D interrogation of stratigraphic, depositional facies, and structural models (see Figure 7). This enhanced interrogation is likely to help answer some of the questions raised by the examples cited above, especially with regard to:

- changes in the depositional and compactional profile of the Capitan margin through time,
- the interplay between shelf and basin deposition over time,
- stratigraphic correlations between the shelf, margin, slope, and basin, and
- the spatial distribution of diagenetic overprint, including dolomitization and syndepositional fracturing.

We expect this type of enhanced perspective to greatly increase our understanding in all respects, and with that, the Guadalupe Mountains and Capitan research will continue to play an important role in the evolution of carbonate conceptual models.

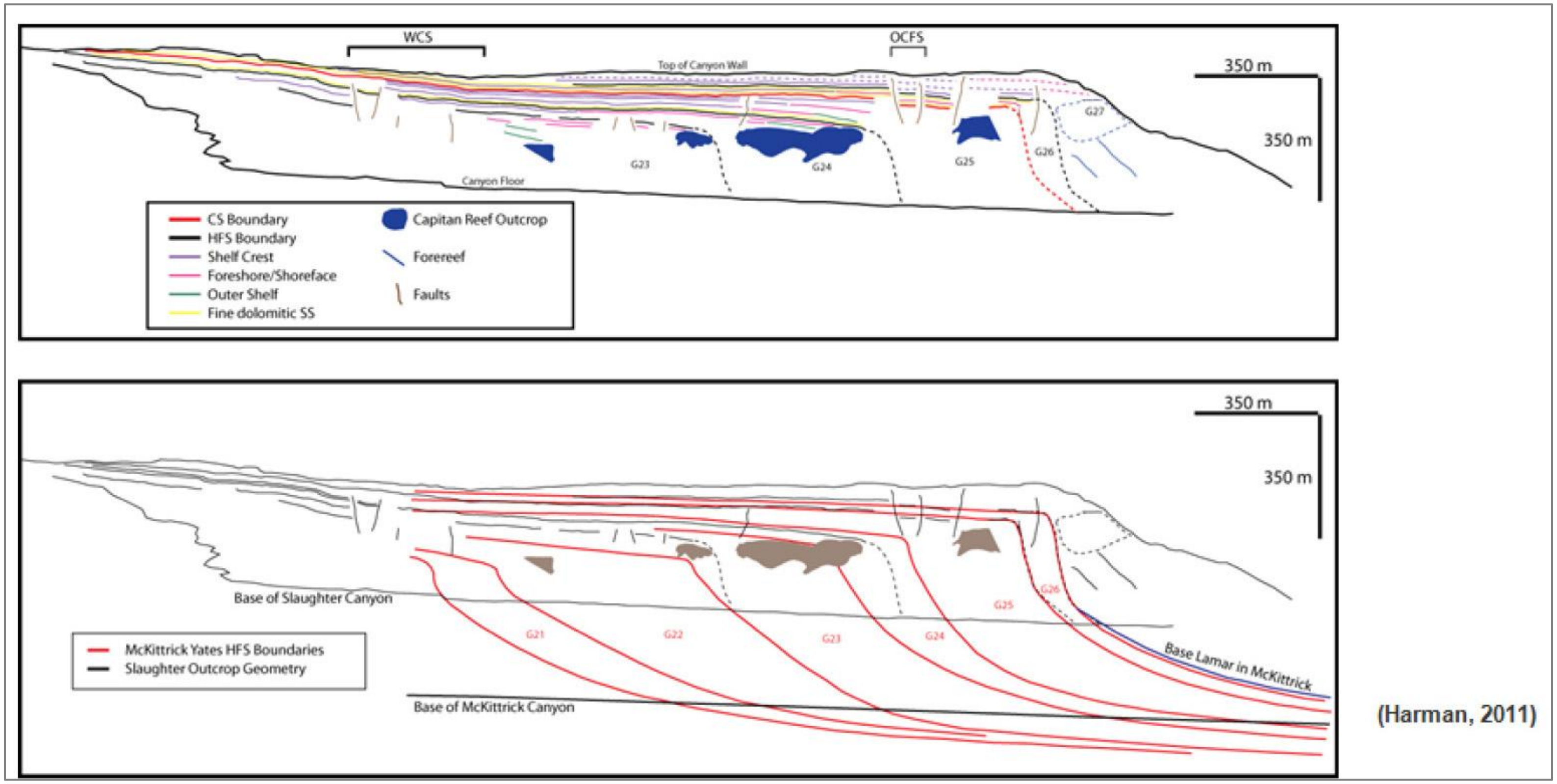

Figure 1. What more is needed? Further studies constrained by stratigraphic framework to more fully evaluate reef composition and zonation, the syndepositional profile, and role of differential compaction in explaining the fall-in bed geometry.

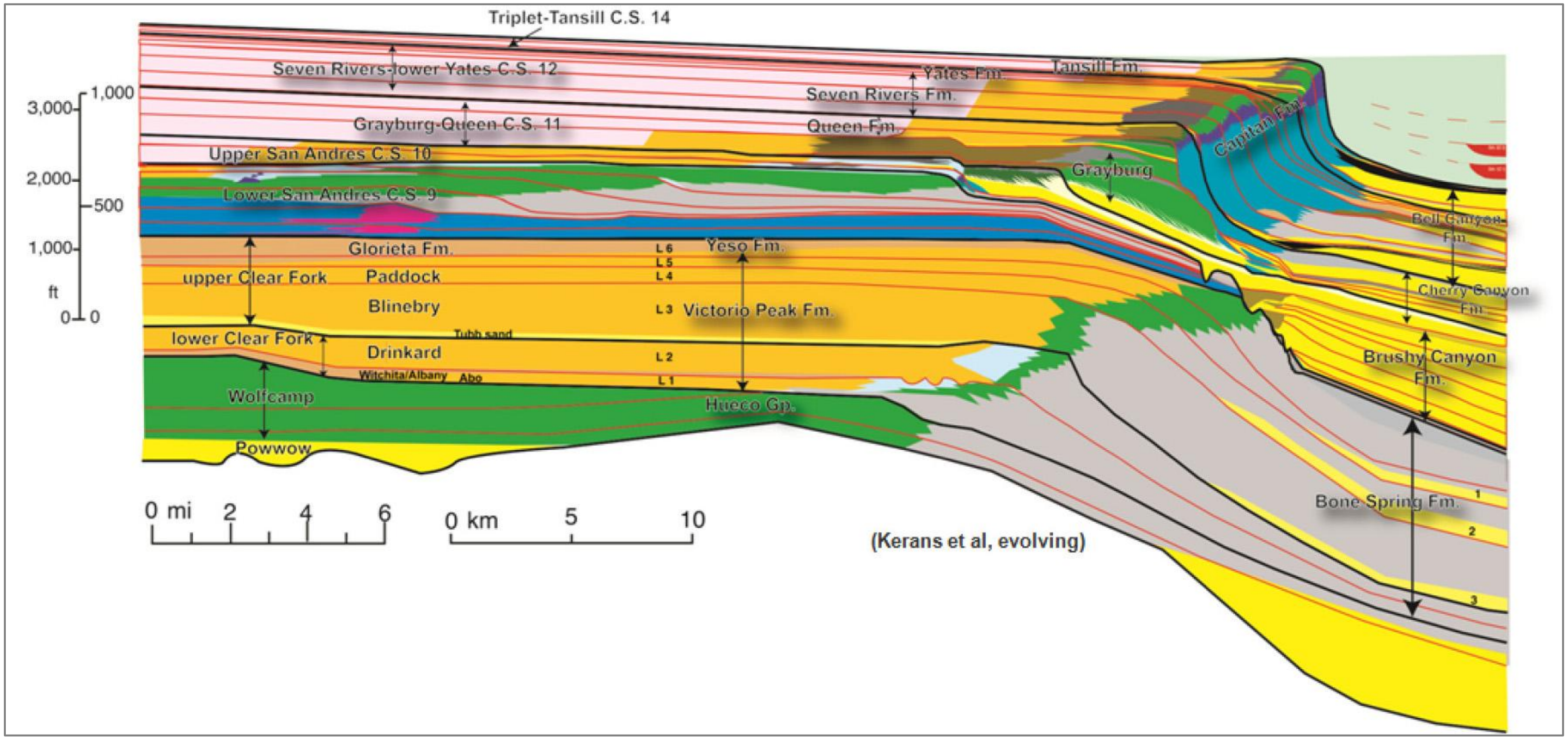

Figure 2. What more is needed? Refinement of our understanding of interplay over time between shelf deposition or bypassing, nature of the margin, and basin deposition. Calibrate variation in the nature of a cycle (shelf, outer shelf, reef, slope, basin), depending on position along the depositional profile, within a sequence, and along strike.

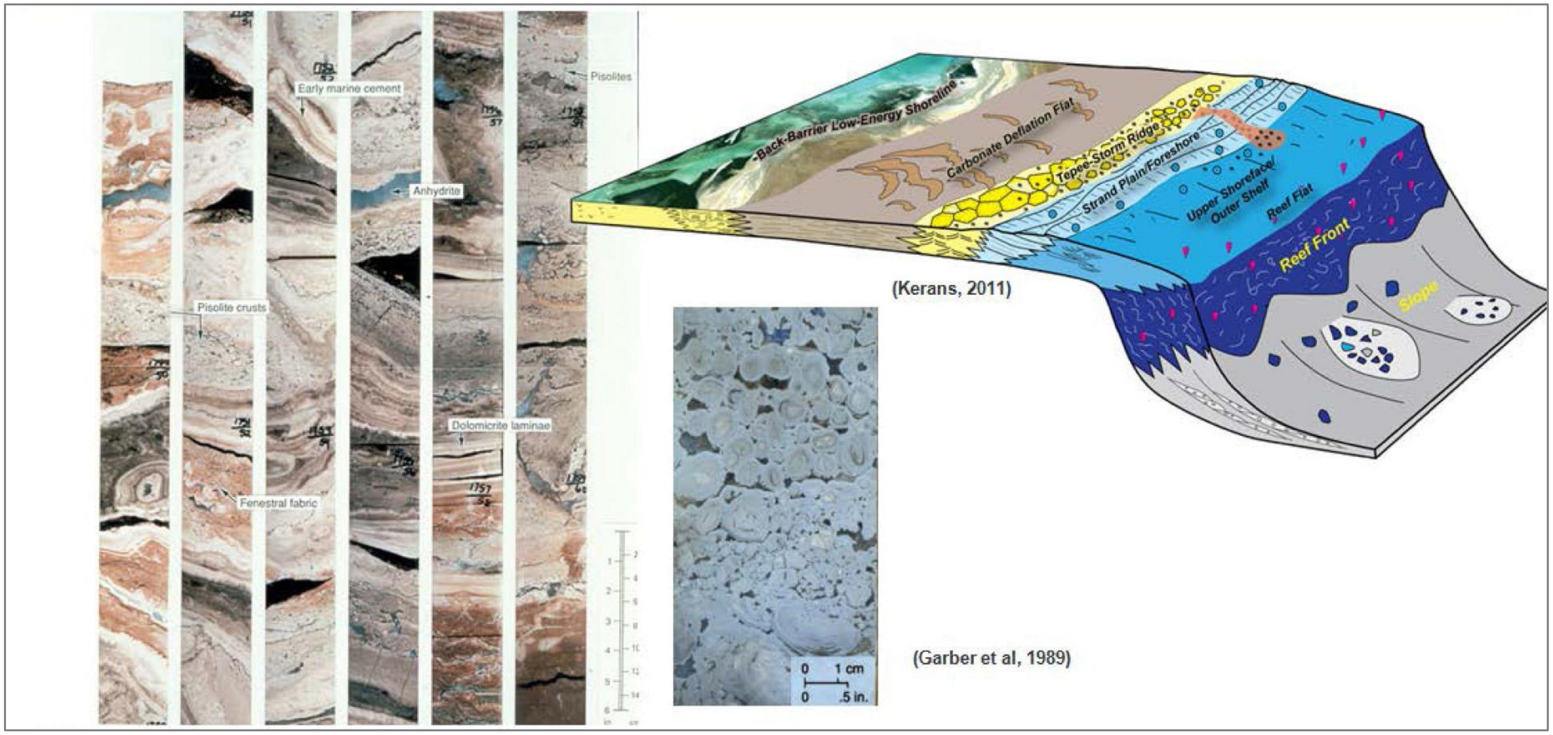

Figure 3. Capitan pisolites and tepees. What's needed: Refine timing of pisolite and tepee formation relative to exposure of the shelf and whether robust tepees form during transgressive or highstand portions of sequences.

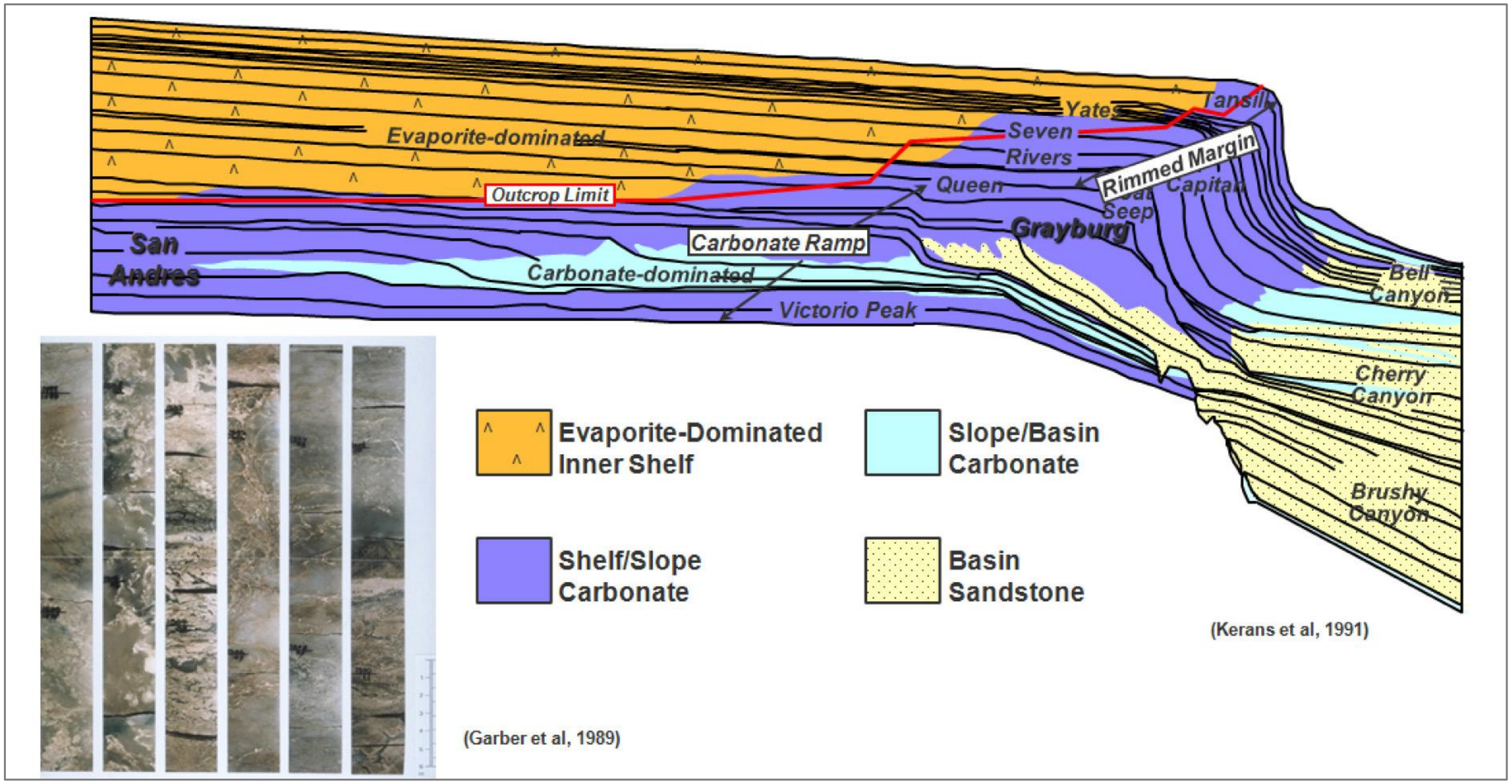

Figure 4. Dolomitization and relationship to evaporites. What's needed: Establish stratigraphic context, spatial distribution, and trends of dolomite stages and their characteristics.

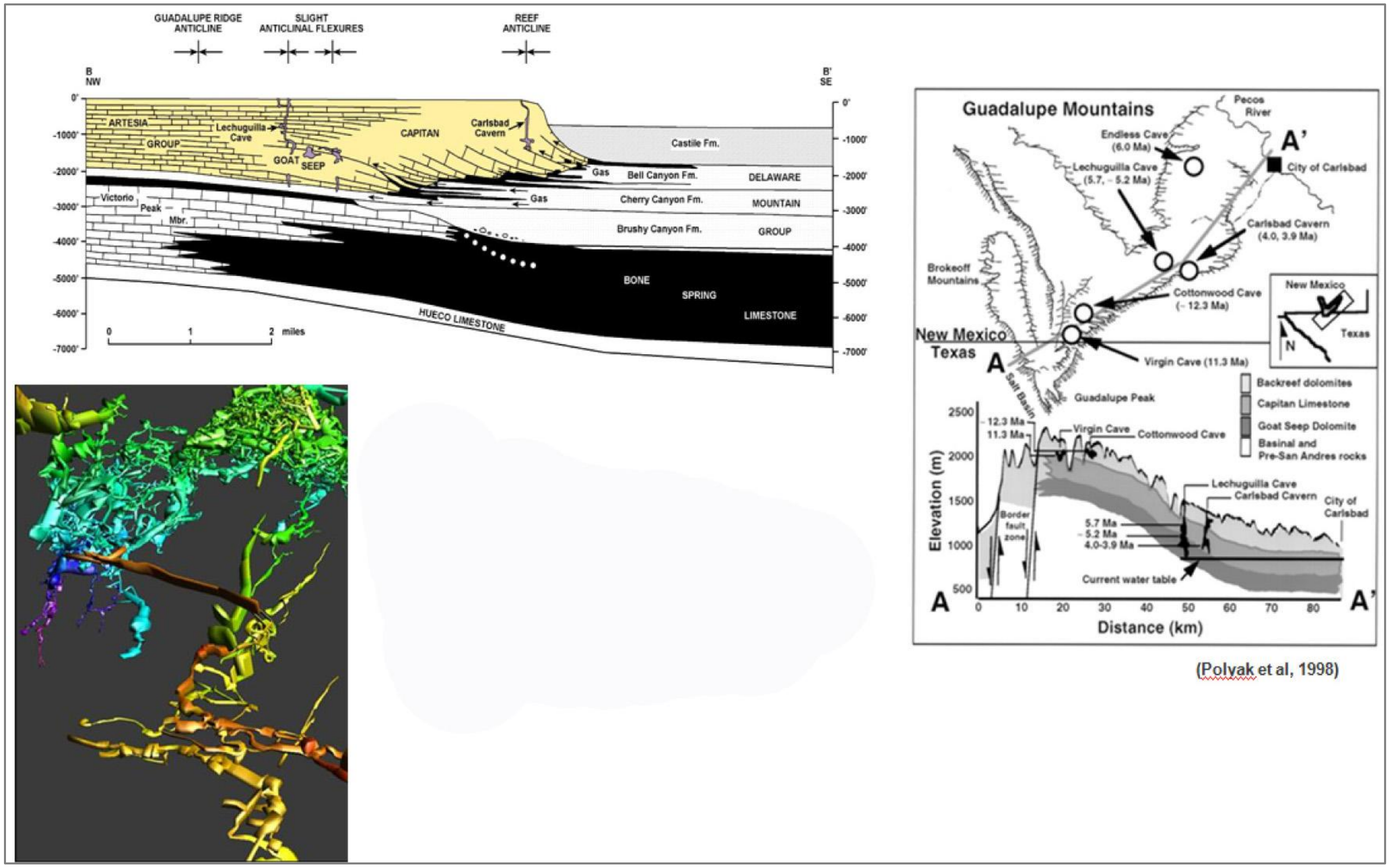

Figure 5. Origin and attributes of caves. What's needed: Refine stratigraphic context, spatial distribution, and timing of caves.

Figure 6. Nature of faults and fractures. What's needed: Refine stratigraphic context, spatial distribution and trends, and timing of fractures and faults.

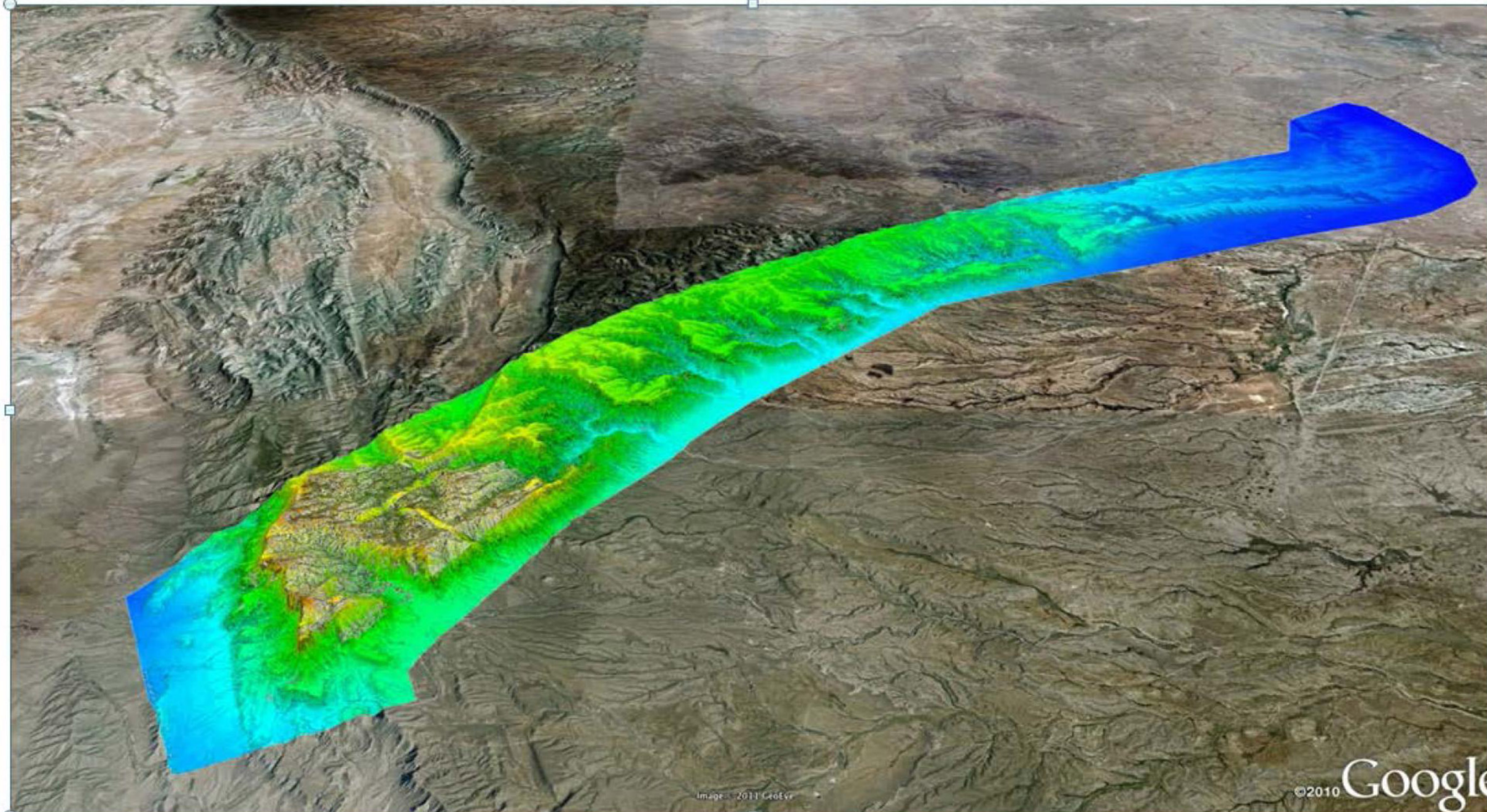

Figure 7. Natural laboratory for 3-D interrogation of stratigraphic, depositional facies, and structural models.

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