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

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Abstract

Evolving studies of the Permian stratigraphy of the Guadalupe Mountains have established these mixed carbonate and siliciclastic rocks, particularly those relate to the Capitan shelf margin, as “analogs” for numerous similar rocks around the world. In so doing, these exposures played a key role in the development of general conceptual models for carbonate shelf margins. Examples to highlight this importance are: Nature of the reef – the ongoing debate on whether the Capitian is a reef, and if so what type, has somewhat abated with results from more recent outcrop studies. A look back at the discussions reemphasizes the need for diagnostic criteria for recognizing reef textures and for the appreciation of the role of microbes in reef construction, a current hot topic. Shelf margin profile – The notion from facies associations, geopetal measurements, and fall-in bed geometry of a reef developing between 15 and 60 m of water depth is countered by the concept of syndepositional differential compaction to explain the seaward dip of outer shelf beds. The ongoing discussion has provided important characteristics to examine in other outcrop and stratal geometries as seen in seismic. Sequence stratigraphic models– Building upon the concept of reciprocal sedimentation, the interplay between a carbonate-dominated shelf and margin with a siliciclastic-dominated basin was placed into context using sequence stratigraphy, with the outcrops remaining one of the principle natural laboratories for investigating different approaches of applying sequence stratigraphy at all scales. Dolomitization – most ideas on dolomitization of the shelf strata are still consistent with the seepage reflux model, although there remains some divergence of opinion on the extent of evaporation needed to instigate reflux and the relationship of the reflux process to changing sea level. The spatial patterns and detailed petrographic and geochemical studies have provided well-constrained models for interpreting dolomite occurrences elsewhere. Nature of faults and fractures – 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 with syndepositional fractures in the margin facies as well as in the inner to middle shelf.

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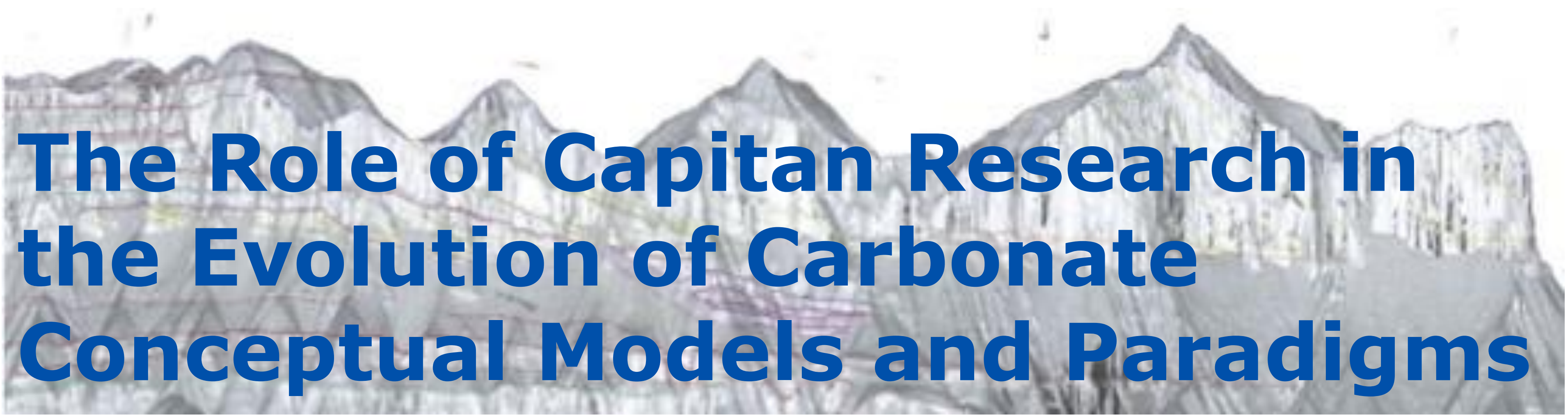

The Role of Capitan Research in the Evolution of Carbonate Conceptual Models and Paradigms

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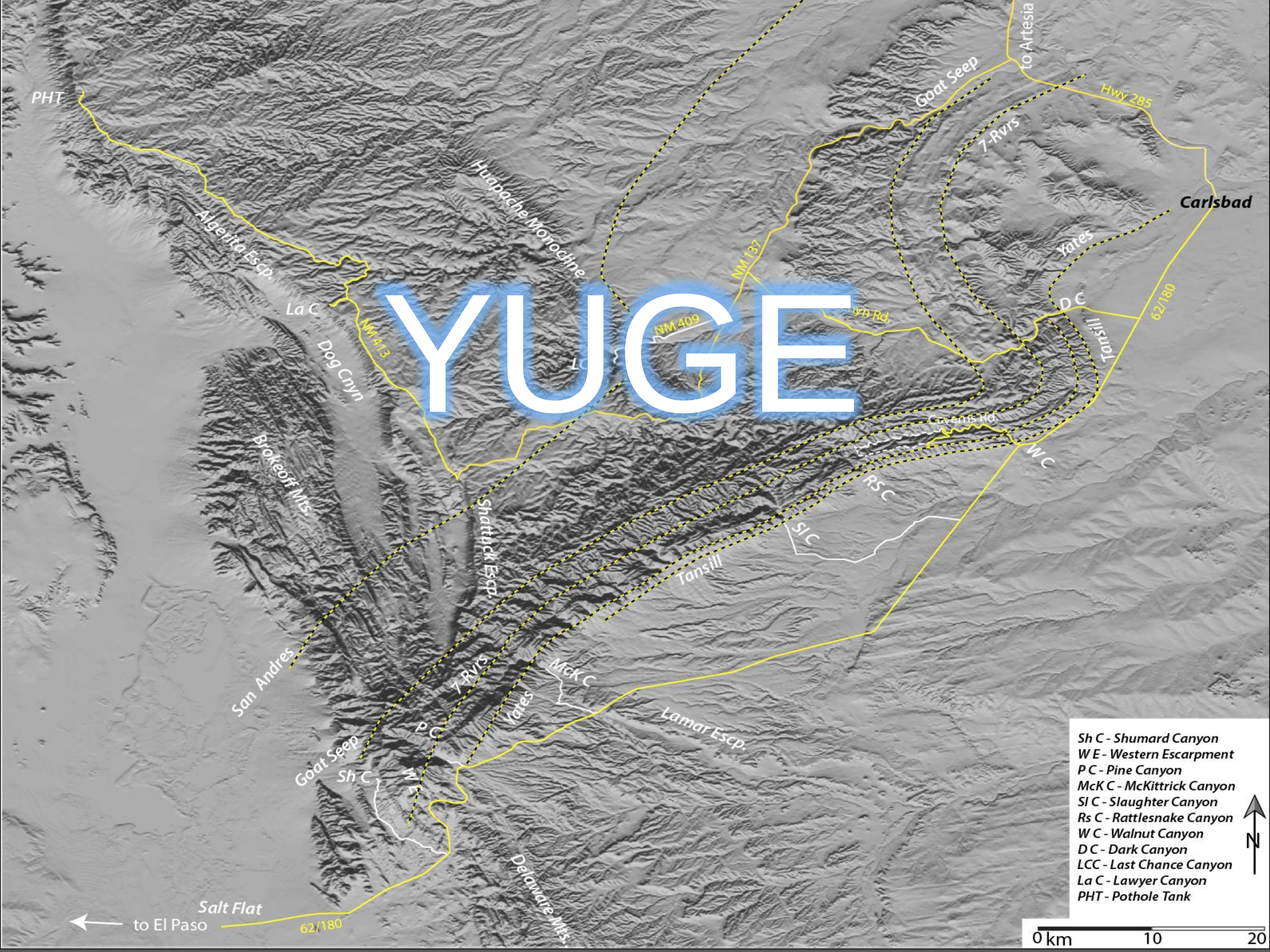
YUGE
PHT
Algerita Escp.
La C
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NM 413
Huapache Monocline
NM 409
NM 137
Goat Seep
to Artesia
Hwy 285
7-Rvrs
Carlsbad
Yates
D C
Tansill
62/180
Caverns Rd.
W C
RS C
Sl C
Tansill
Brokeoff Mts.
Shattuck Escp.
San Andres
7-Rvrs
Yates
McK C
Lamar Escp.
P C
Goat Seep
Sh C
W E
Delaware Mts.
Salt Flat
to El Paso
62/180
Sh C - Shumard Canyon
W E - Western Escarpment
P C - Pine Canyon
McK C - McKittrick Canyon
Sl C - Slaughter Canyon
Rs C - Rattlesnake Canyon
W C - Walnut Canyon
D C - Dark Canyon
LCC - Last Chance Canyon
La C - Lawyer Canyon
PHT - Pothole Tank
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0 km
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20

Continuing Importance of Capitan Research

The Capitan shelf margin has played a major role in developing universal conceptual models for carbonate shelf margins.

- 1940’s to 1970’s – Geology investigated from the view of biostratigraphy, lithostratigraphy, depositional models and concepts of reciprocal sedimentation.
- 1970's and early 1980's – Focus shifted to analysis of depositional facies and processes and early diagenesis of reef margins.
- 1980’s to today – Outcrops analyzed from a cyclostratigraphy and sequence stratigraphy perspective, with this stratigraphic framework now serving as a template in which many aspects of the geology are being further evaluated.

Continuing Importance of Capitan Research

HILEMAN, M.E., and MAZZULLO, S.J. (eds.), **1977**, Upper Guadalupian Facies, Permian Reef Complex, Guadalupe Mountains, New Mexico and West Texas (1977 Field Conference Guidebook, v. 1: Permian Basin Section-SEPM Publication 77-16, 508 p.

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Conceptual Models and Discussion Points

Examples of the major role that previous studies of the Capitan margin have played in developing models for carbonate shelf margins, and in the process sometimes leading to paradigms.

- **Nature of the Reef**
- **Shelf-Margin Profile**
- **Sequence Stratigraphic Models**
- **Models for Dolomitization**
- **Nature of Faults and Fractures**

In all cases, the examples can be viewed as starting points for additional discussions that will prompt a variety of opinions.

Nature of the Reef

Nature of the Reef

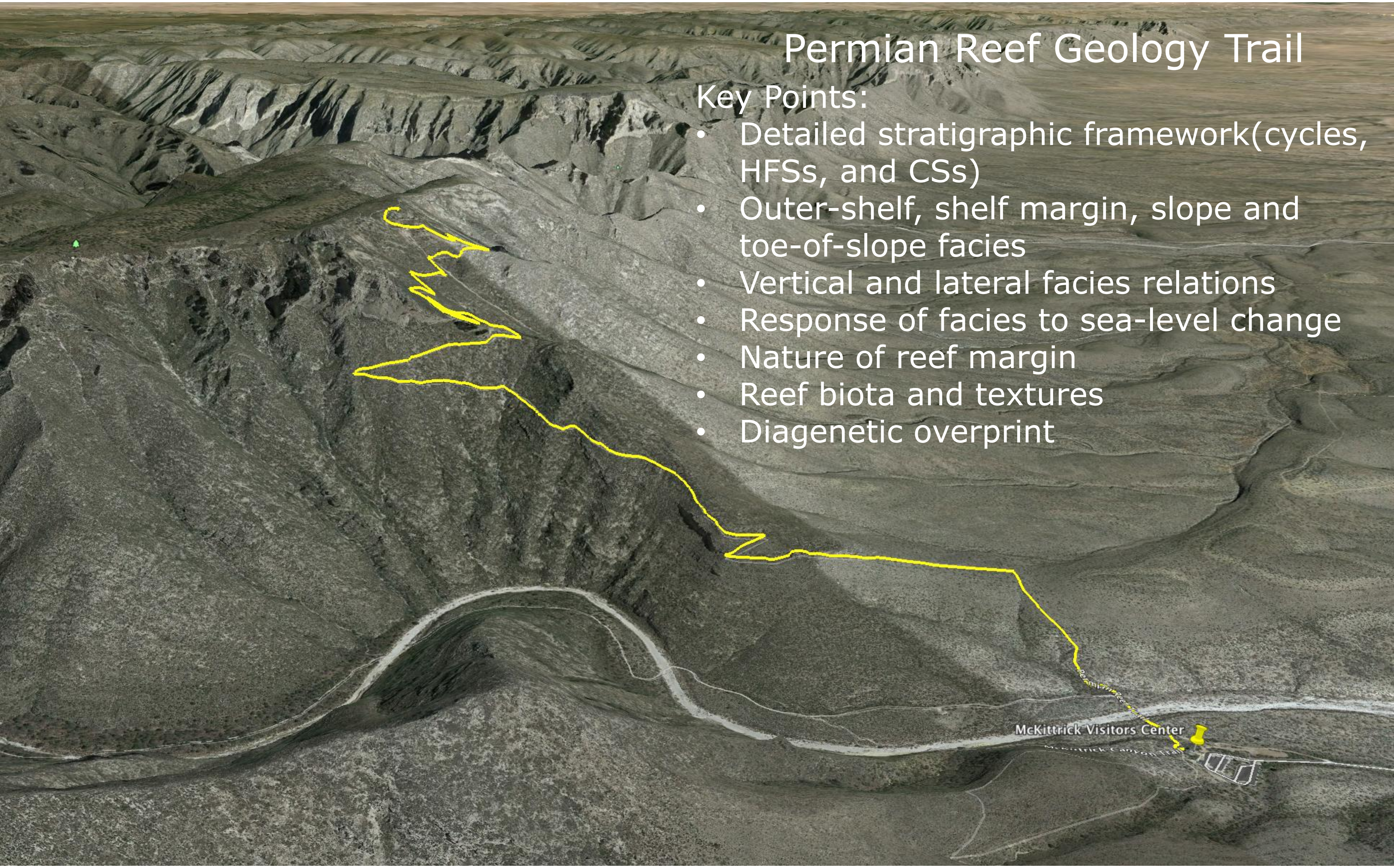
Debate on whether the Massive Member of the Capitian Formation is a reef, and if so, whether it is an ”ecologic reef”, ”diagenetic reef”, or ”stratigraphic reef.”

Baars (1964) Dunham (1969) Achauer (1969) Tyrrell (1969) Cronoble (1974) Schmidt (1977) Mazzullo and Cys (1977, 1978) J. A. Babcock (1977) Yurewicz (1977) Cys *et al*. (1977) Scholle and Halley (1980) Toomey and Babcock (1983) Grotzinger and Knoll (1995)

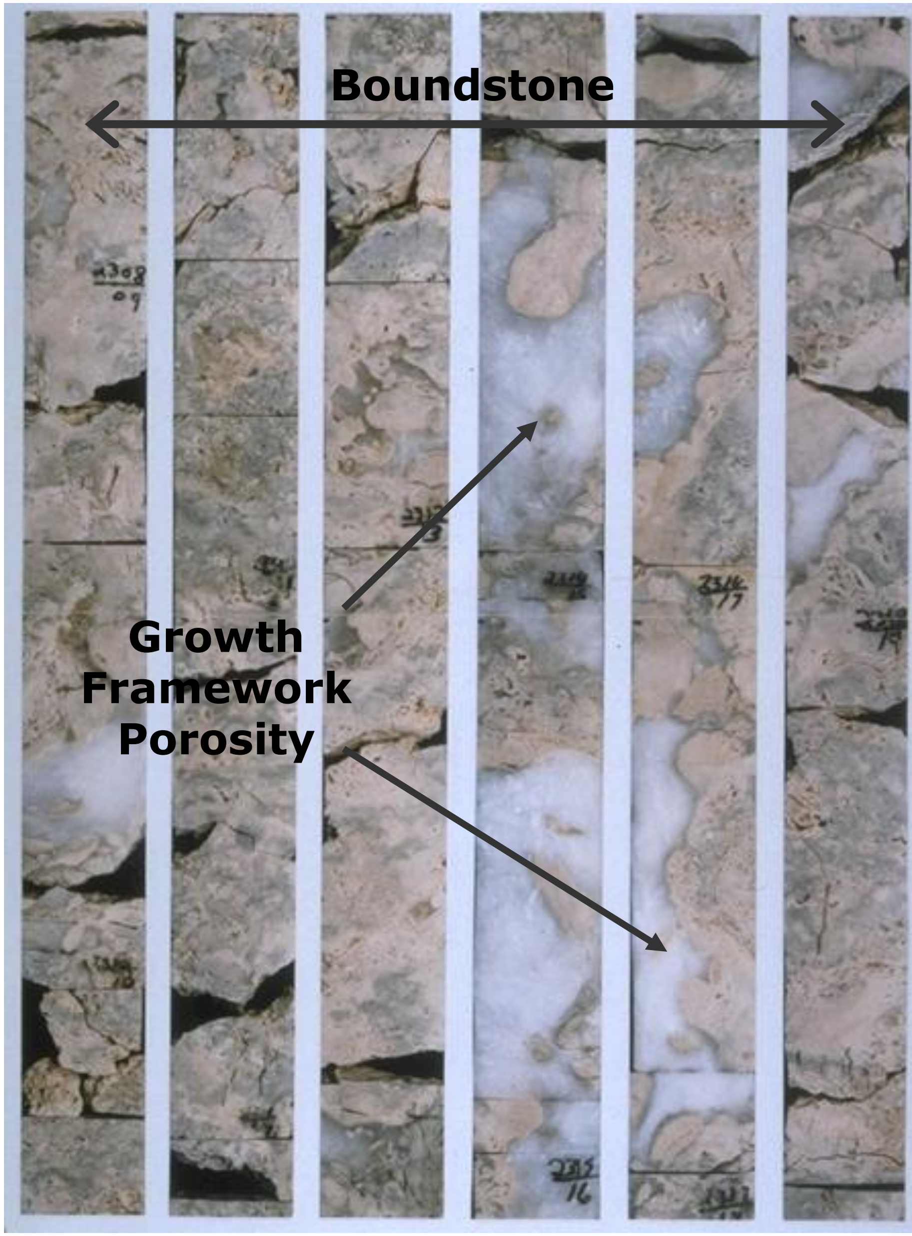
Key outcrops showed that much of the Capitan: 1) has an organic reefal framework with bryozoans, calcareous sponges and other organisms in growth position, 2) is bound by a variety of microbial coatings and marine cements, and 3) contains abundant internal cavities.

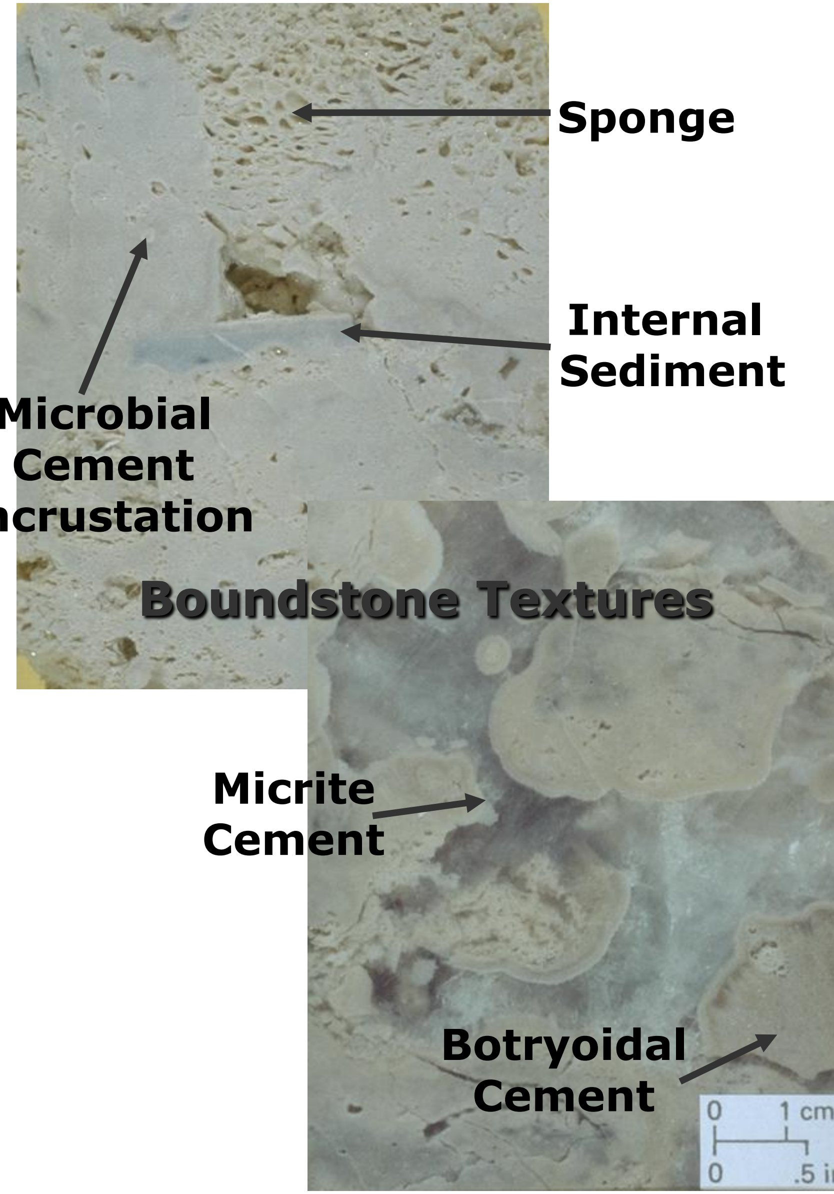
Mazzullo (1977) Schmidt (1977) Schmidt and Klement (1977) Mazzullo and Cys (1978) Garber *et al.* (1989) Mruk (1989) Noè and Mazzullo (1992) Kirkland *et al*. (1993, 1998, 1999) Wood *et al*. (1994, 1996) Senowbari-Daryan and Rigby (1996) Noè (1996) Wood (1999) Rahnis and Kirkland (1999) Weidlich and Fagerstrom (1999) Kenter *et al*. (2005) Harris (2012)

Nature of the Reef



Nature of the Reef





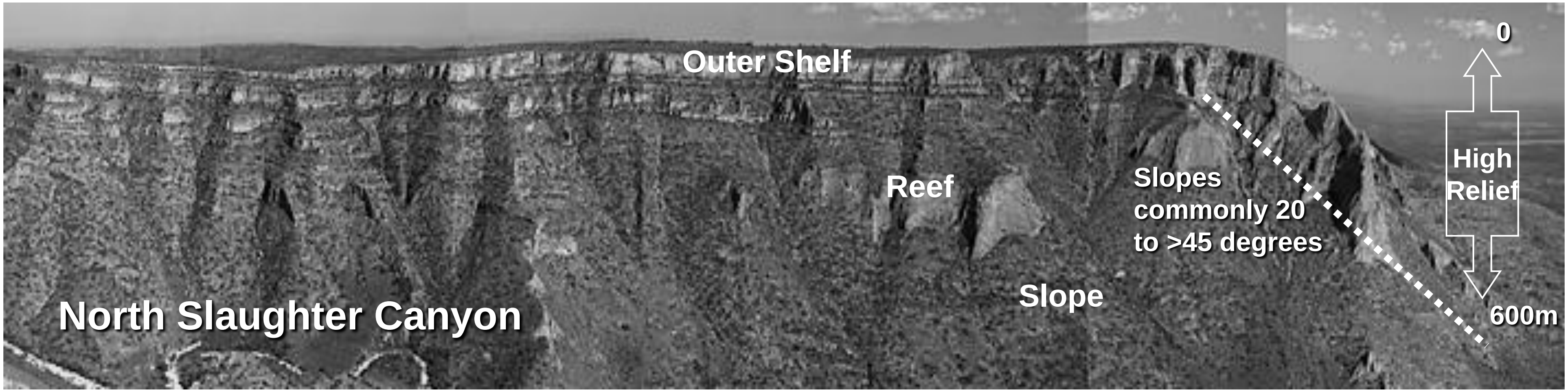
(modified after Garber et al,1989)

Nature of the Reef

What we have learned:

- The ongoing debate on whether the Capitian is a reef, and if so what type, has somewhat abated with results from more recent outcrop studies.
- The diagnostic criteria to recognize reef textures (framebuilders, binders and encrusters, growth framework porosity, internal sediment) have been identified.
- A growing appreciation of the role of microbes in reef construction.

Shelf Margin Profile (Depth of Reef)



5 km of progradation

Shelf Margin Profile

Debate whether the Capitan is a raised barrier-reef profile or or a deep-reef-rimmed margin.

King (1948) Newell *et al.* (1953) Dunham (1972) Pray (1977) Cys *et al.* (1977) Hurley (1978) Kirkland and Moore (1990) Kerans and Harris (1993) Harris and Saller (1999) Kerans and Tinker (1999)

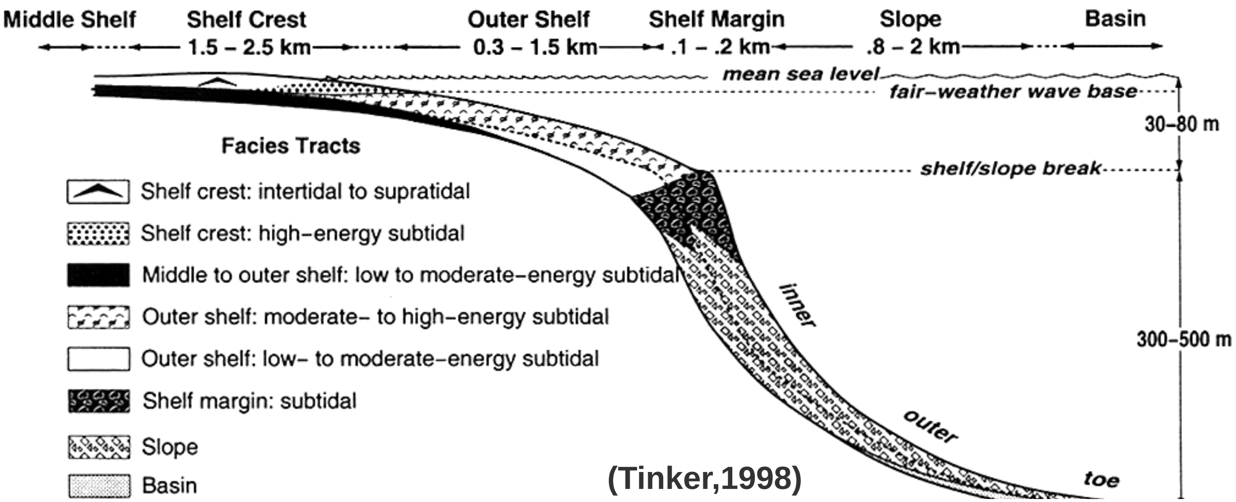
Counter to this ”depositional profile” model is the concept of syndepositional differential compaction.

Saller (1996, 2012) Hunt *et al.* (1996, 2002) Longley (1999) Hunt and Fitchen (1999)

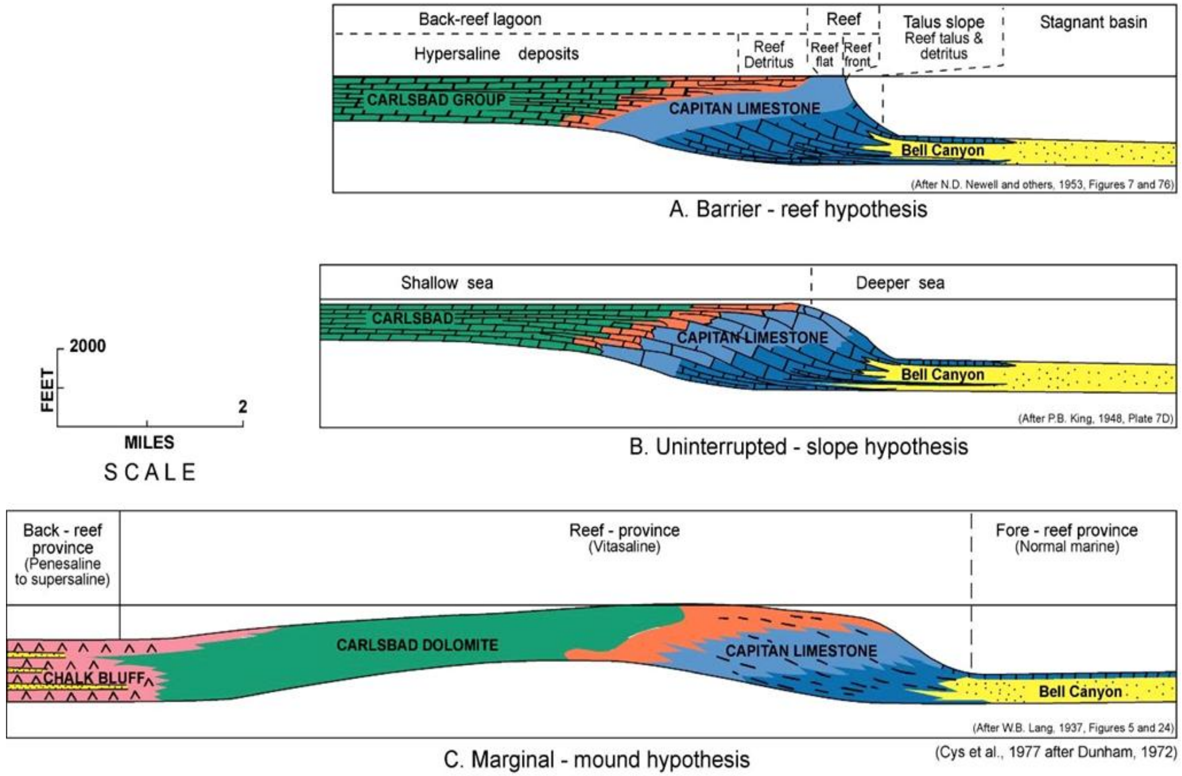
Integration of static sedimentologic models with sequence stratigraphic analysis adds clarity to the debate.

Osleger (1998) Tinker (1998) Osleger and Tinker (1999) Kerans and Tinker (1999) Weidlich and Fagerstrom (1999) Harman (2011)

Shelf Margin Profile

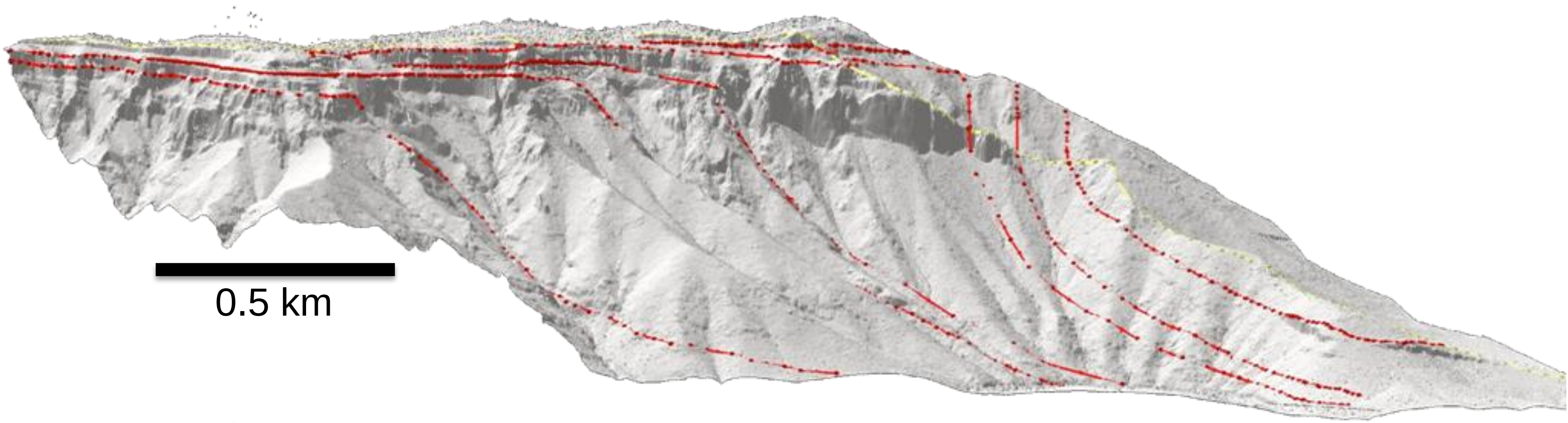


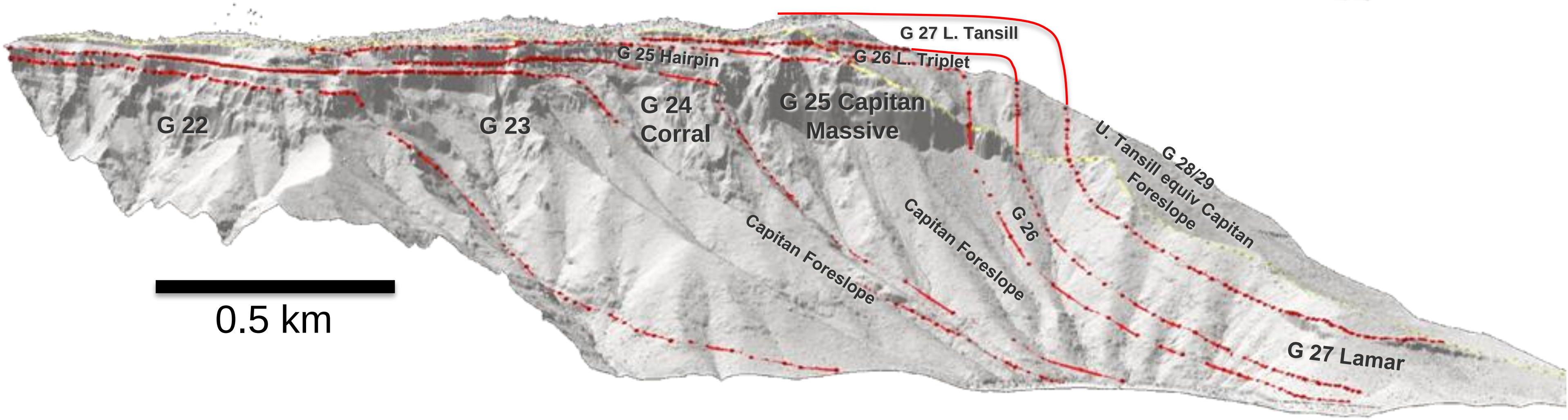
(Tinker,1998)



(Cys et al., 1977 after Dunham, 1972)

Shelf Margin Profile





Shelf Margin Profile

What we have learned:

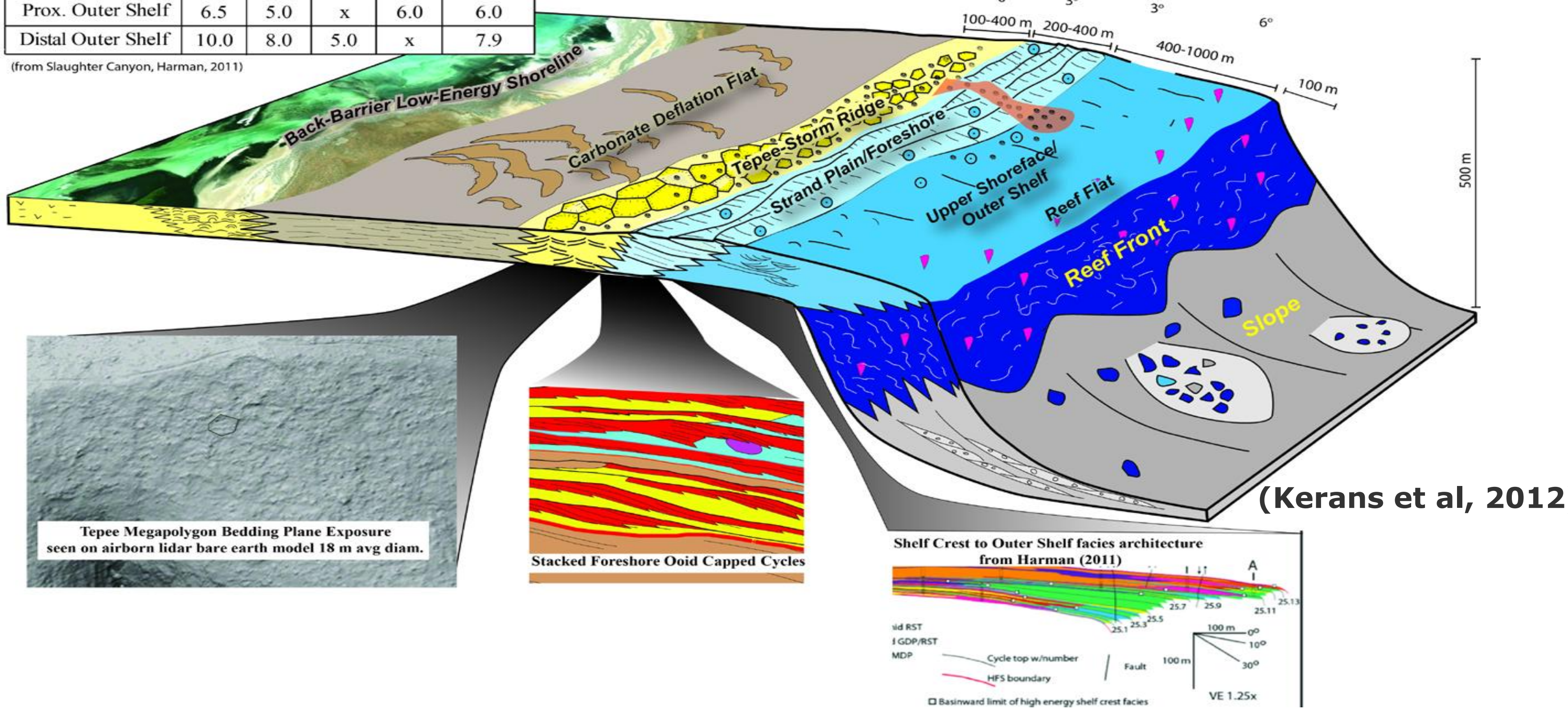
- The notion from facies associations and fall-in bed geometry of a reef developing between 15 and 60 m of water depth -- is countered by the concept of syndepositional differential compaction to explain the seaward dip of outer shelf beds.
- Exposures along the north wall of McKittrick or Slaughter canyons demonstrate that the shelf profile and depth of water over the reef clearly varied significantly during the evolution of the Capitan margin.
- The ongoing discussion has provided important characteristics to examine in other outcrop and stratal geometries as seen in seismic.

Nature of the Reef and Shelf Margin Profile

What more is needed:

Present-Day Dip	G23	G24	G25	G26	Overall Average
Tepee-Storm Comp.	2.5	2.3	1.7	1.3	1.7
SP/Foreshore	3.8	4.0	6.9	6.0	5.8
Prox. Outer Shelf	6.5	5.0	x	6.0	6.0
Distal Outer Shelf	10.0	8.0	5.0	x	7.9

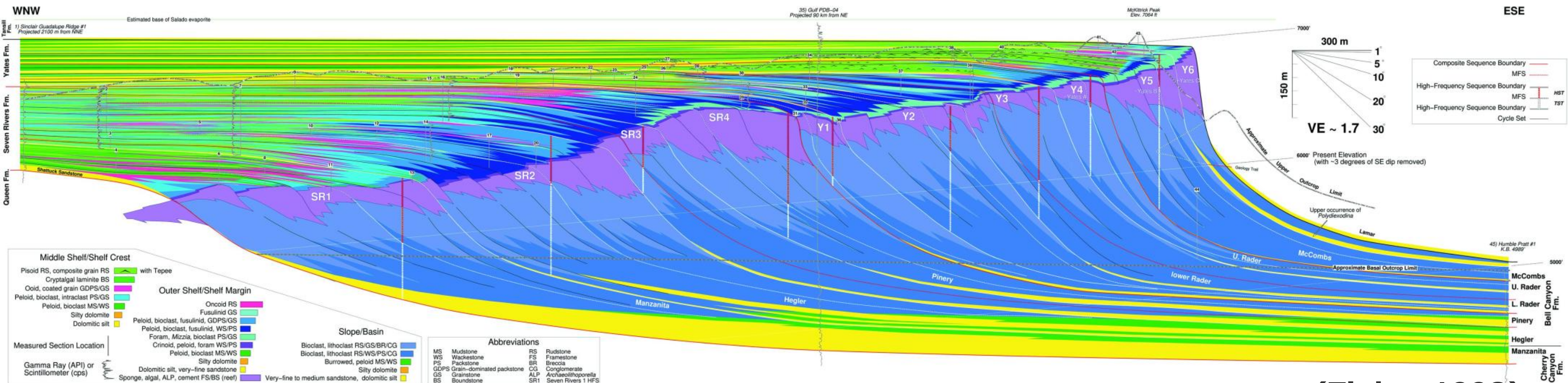
(from Slaughter Canyon, Harman, 2011)



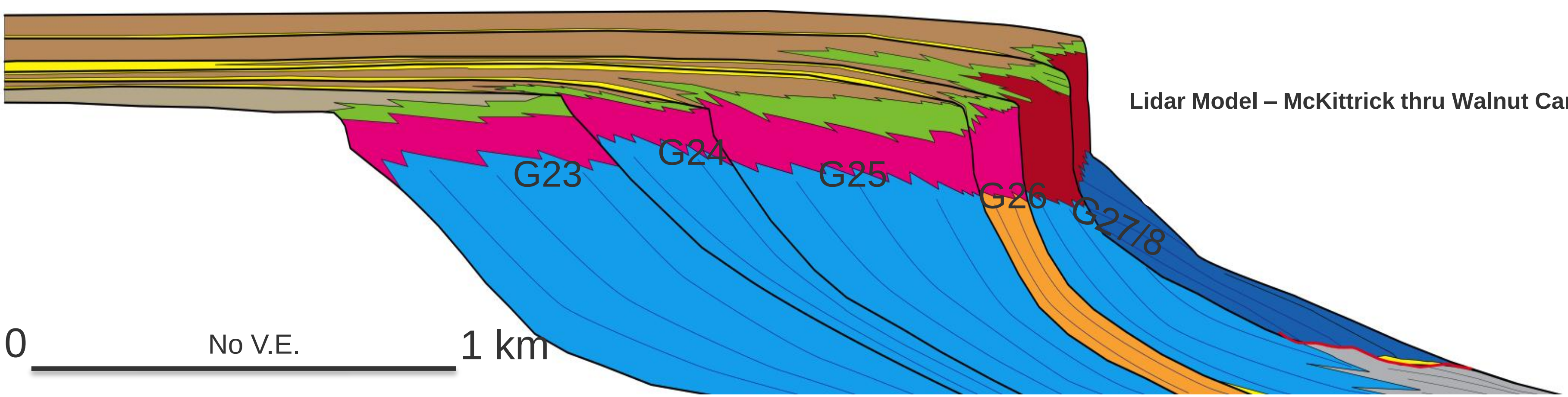
(Kerans et al, 2012)

Further **studies better constrained by stratigraphic framework** to more fully evaluate reef composition and zonation, the syndepositional profile, and role of differential compaction in explaining fall-in bed geometry.

Sequence Stratigraphic Models



(Tinker,1998)



Lidar Model – McKittrick thru Walnut Canyon

(Kerans, 2011)

Sequence Stratigraphic Models

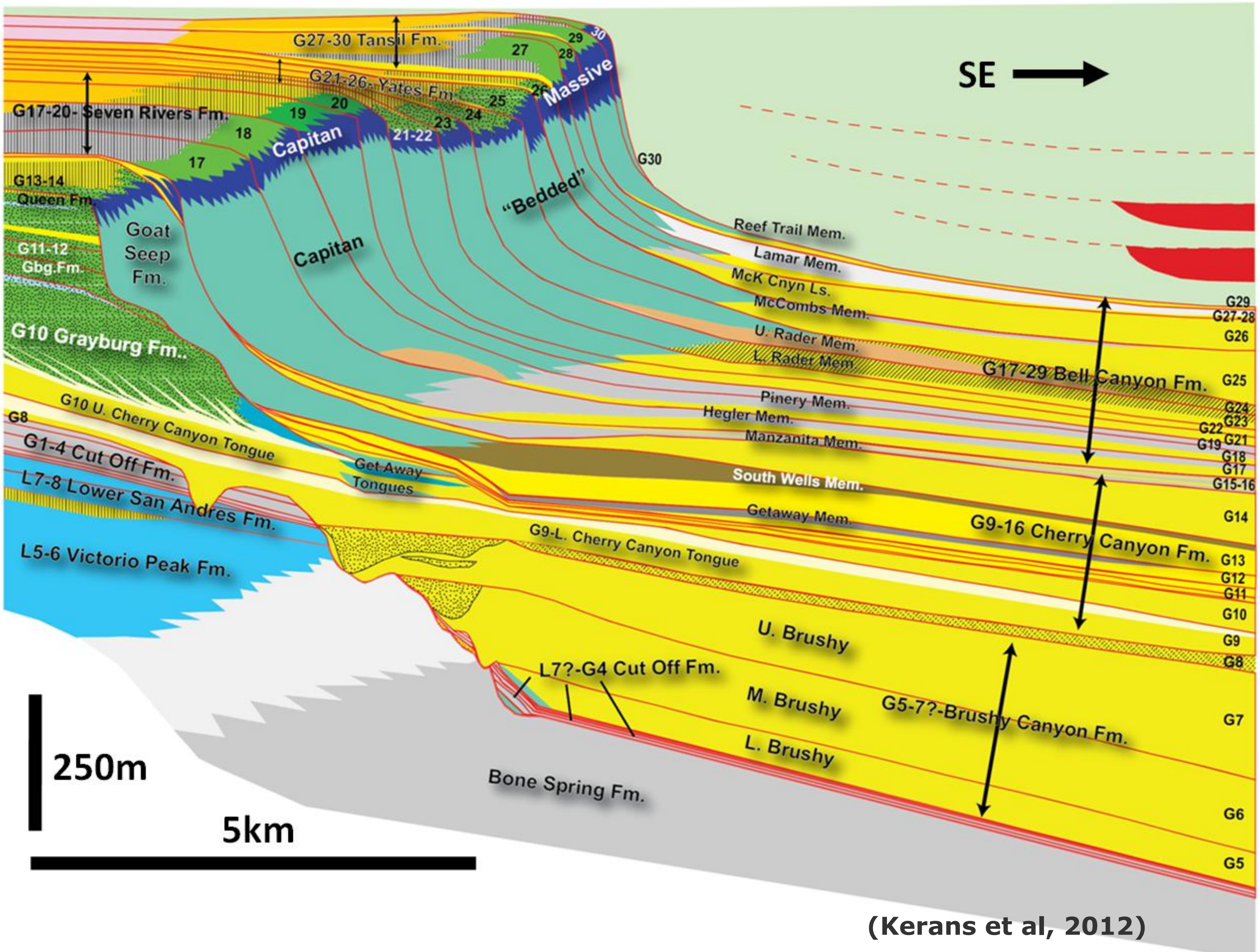
Building upon the concept of reciprocal sedimentation the interplay between a carbonate-dominated shelf and margin with a silicilastic-dominated basin was better put into context.

Silver and Todd (1969) Wilson (1972) Meissner (1972) Mazzullo *et al*. (1985) Sarg and Lehmann (1986) Sarg *et al.* (1988) Borer and Harris (1991, 1995) Keran *et al.* (1992, 1993, 2012) Kerans and Harris (1993) Osleger (1998) Tinker (1998) Osleger and Tinker (1999) Longley (1999) Harman (2011) Kerans *et al.* (ongoing)

Semiquantitative approaches and sequence geometries linked to facies partitioning showed a way forward in prediction of reservoir-scale stratigraphic architecture on the platform.

Borer and Harris (1991) Sonnenfeld and Cross (1993) Tinker (1998) Kerans and Tinker (1999) Osleger and Tinker (1999) Harman (2011) Kerans *et al.* (2012)

Sequence Stratigraphic Models



(Kerans et al, 2012)

Sequence Stratigraphic Models

What we have learned:

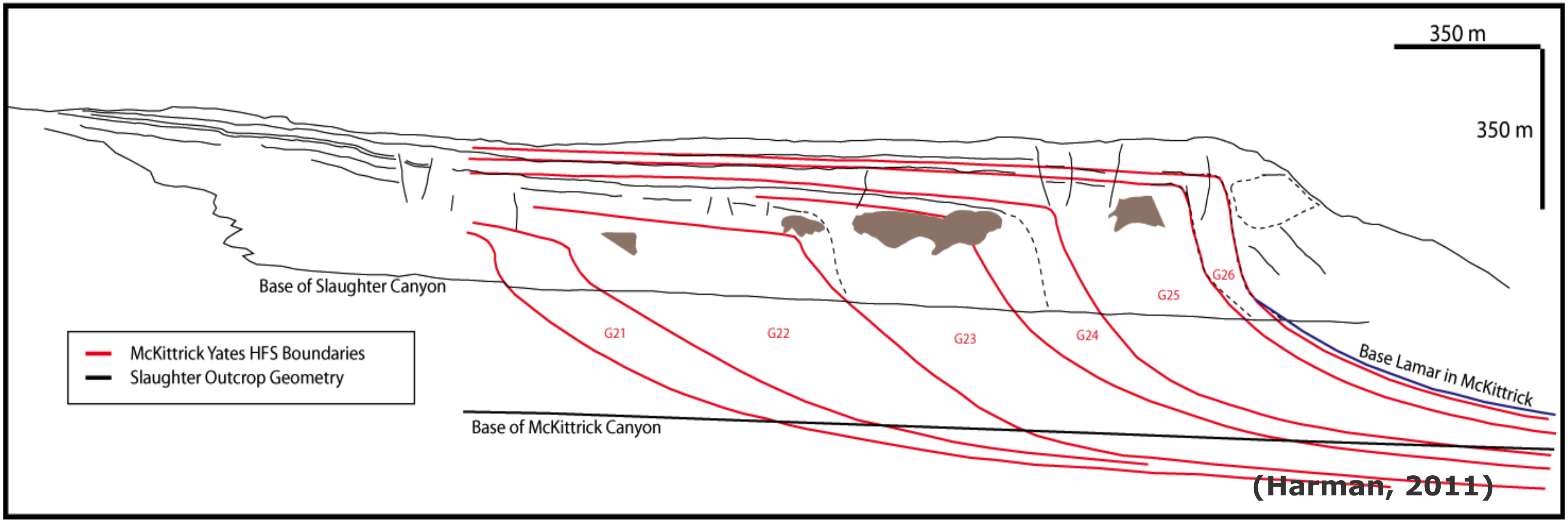
- A sequence stratigraphic approach has better clarified the relation between shelf, shelf margin, and basin.

- Lateral variation and stacking patterns show there is substantial variation in the nature of a cycle, albeit a carbonate or a mixed carbonate-siliciclastic one, depending on position along the depositional profile, within a sequence, and along strike.

- The outcrops remain one of the principle natural laboratories for investigating different approaches of applying sequence stratigraphy at all scales.

Sequence Stratigraphic Models

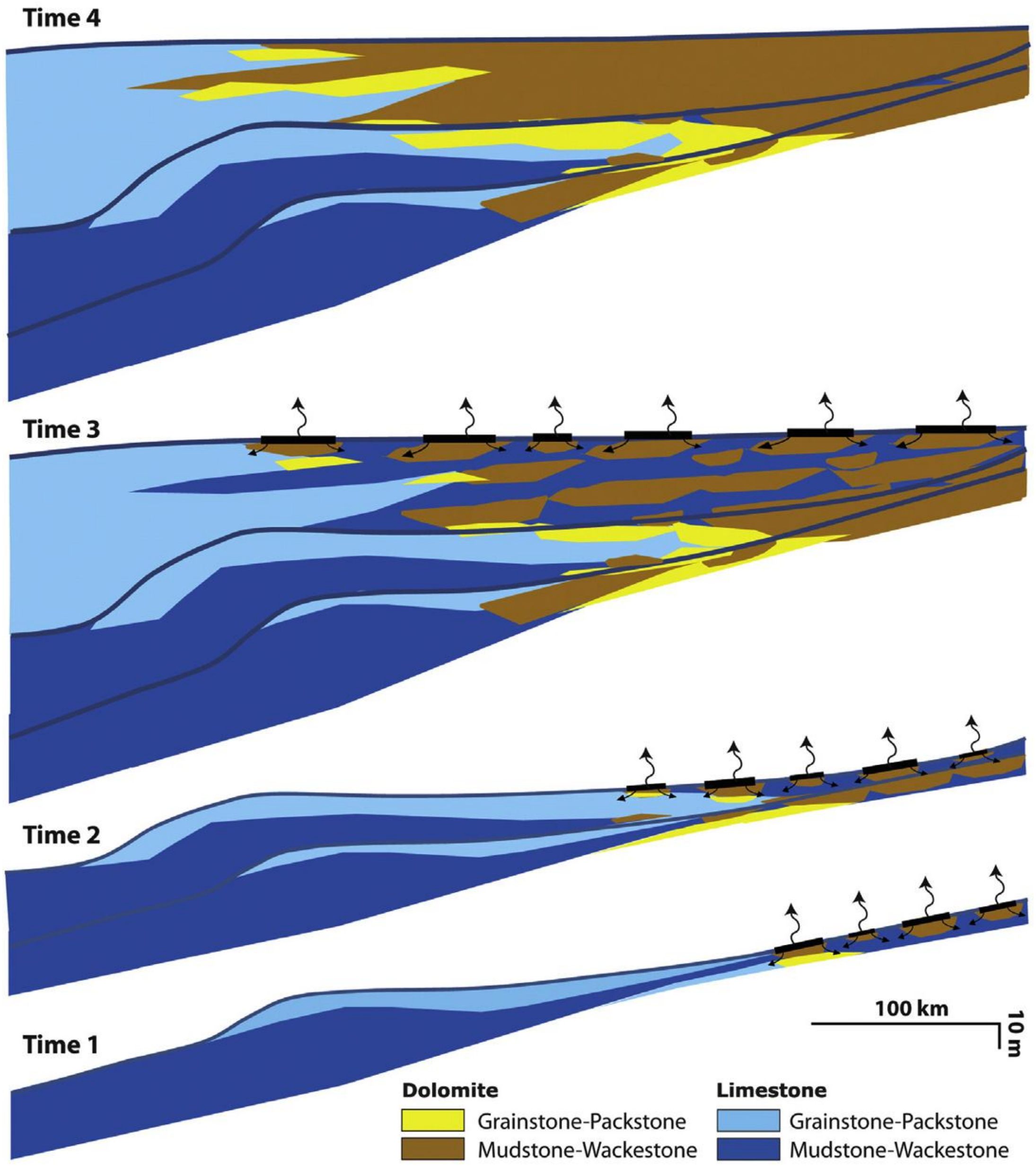
What more is needed:



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.

Models for Dolomitization



(Gabellone et al, 2016)

Models for Dolomitization

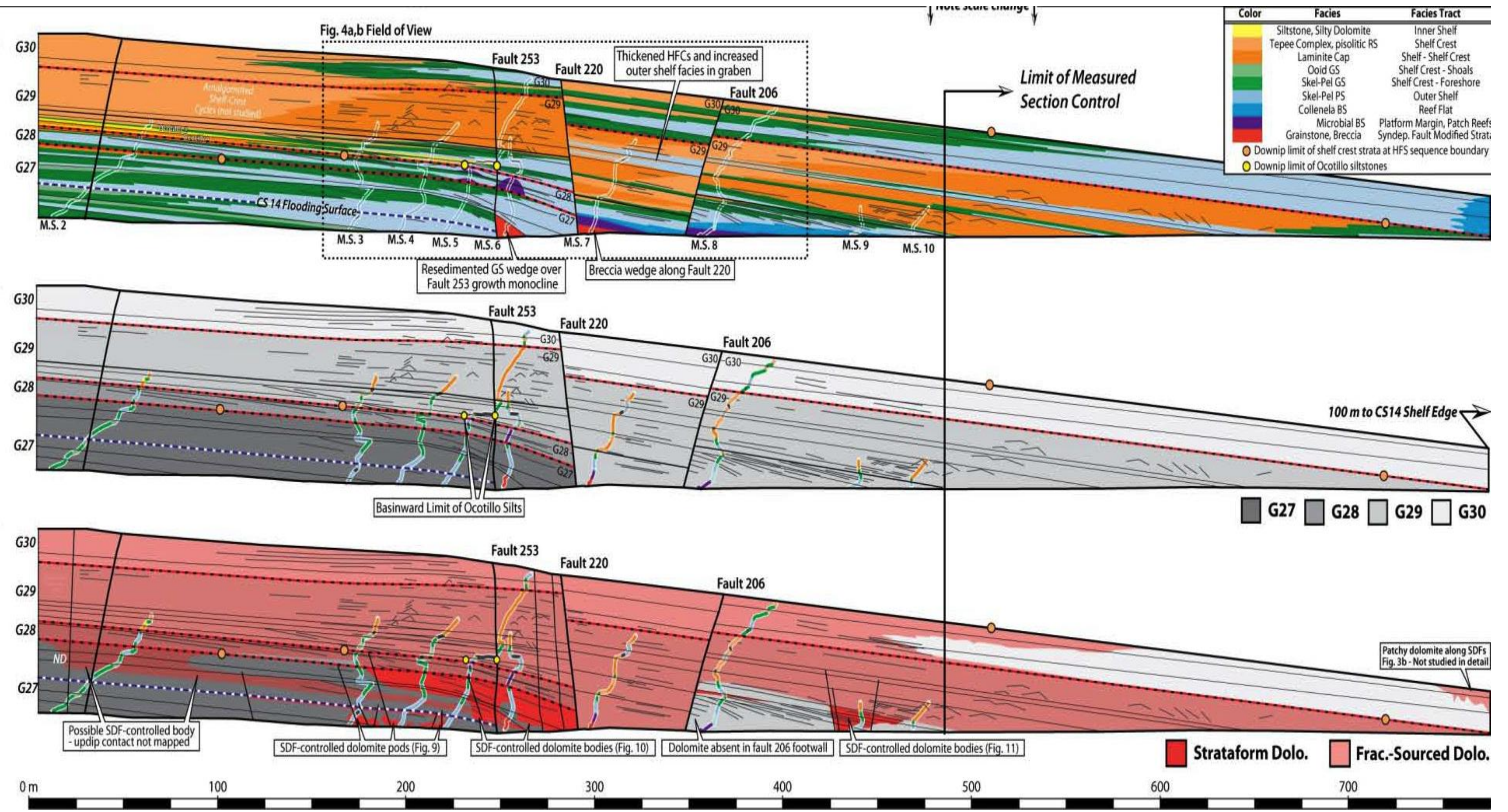
Pervasively dolomitized shelf beds consistent with seepage reflux model related to evaporitic inner shelf, whereas localized dolomitized reef and slope are problematic as far as origin of the fluids (from shelf or basin, or both) and timing.

Adams and Rhodes (1960) Kendall (1969) Silver and Todd (1969) Meissner (1972) Sarg (1977, 1981) Garber *et al.* (1989) Mruk (1989) Kendall and Harwood (1989) Darke and Harwood (1990) Melim (1991) Melim and Scholle (1992, 1995, 1999) Mruk and Bebout (1993) Mutti and Simo (1994) Hill (1996) Garcia-Fresca and Jones (2011) Frost *et al.* (2012)

Mesohaline rather than hypersaline brines may have been the reflux fluid, with the fluid source being the near-reef backreef mesohaline lagoon instead of the far-backreef, hypersaline evaporative lagoon.

Melim (1991)

Models for Dolomitization



(Frost et al, 2012)

Models for Dolomitization

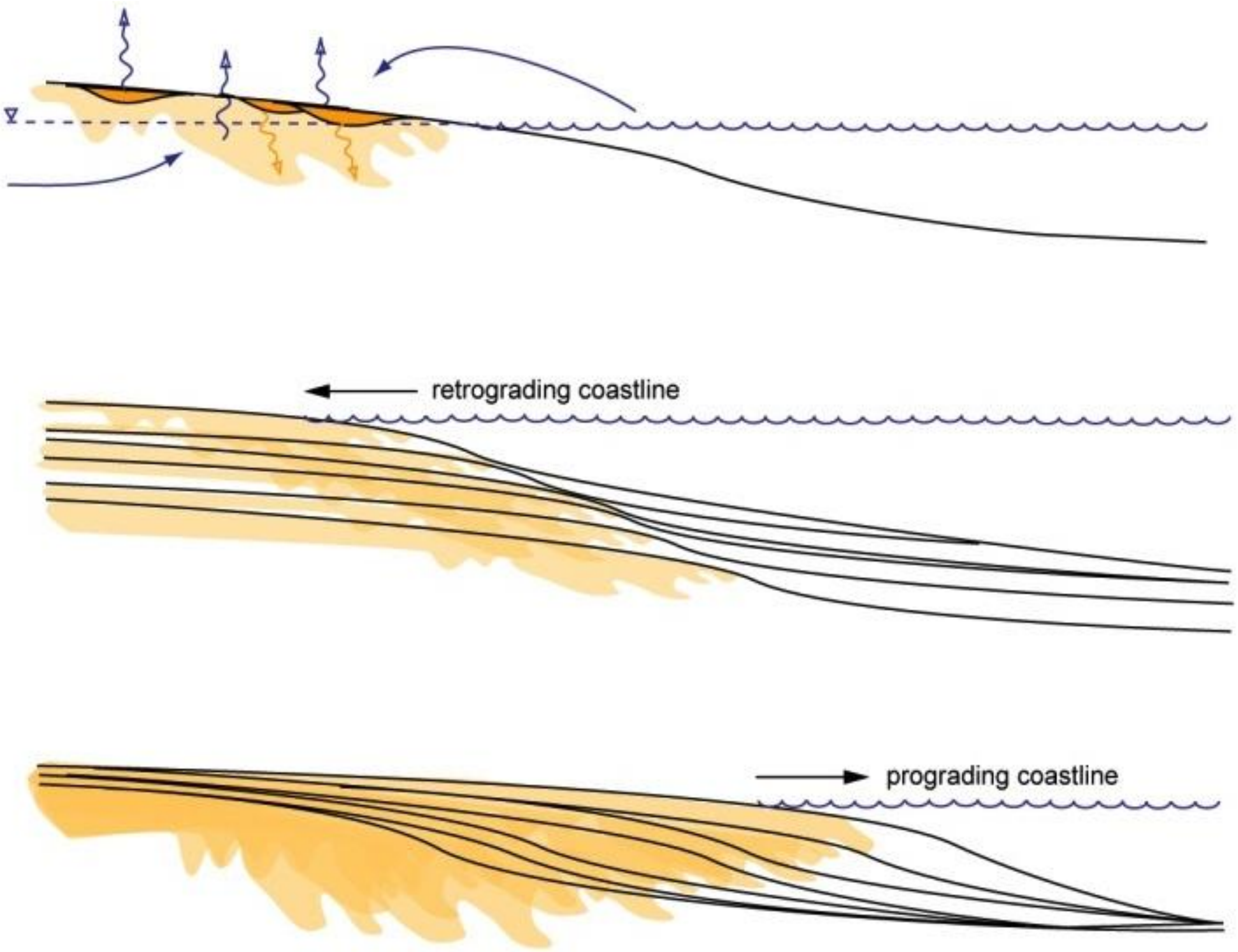
What we have learned:

- Most ideas on dolomitization of the shelf strata are still consistent with the seepage reflux model, although there remains some divergence of opinion on the extent of evaporation needed to instigate reflux, the relationship of the reflux process to changing sea level, and the role of early-formed fractures and faults.

- The spatial patterns and detailed petrographic and geochemical studies have provided well-constrained models for interpreting dolomite occurrences elsewhere.

Models for Dolomitization

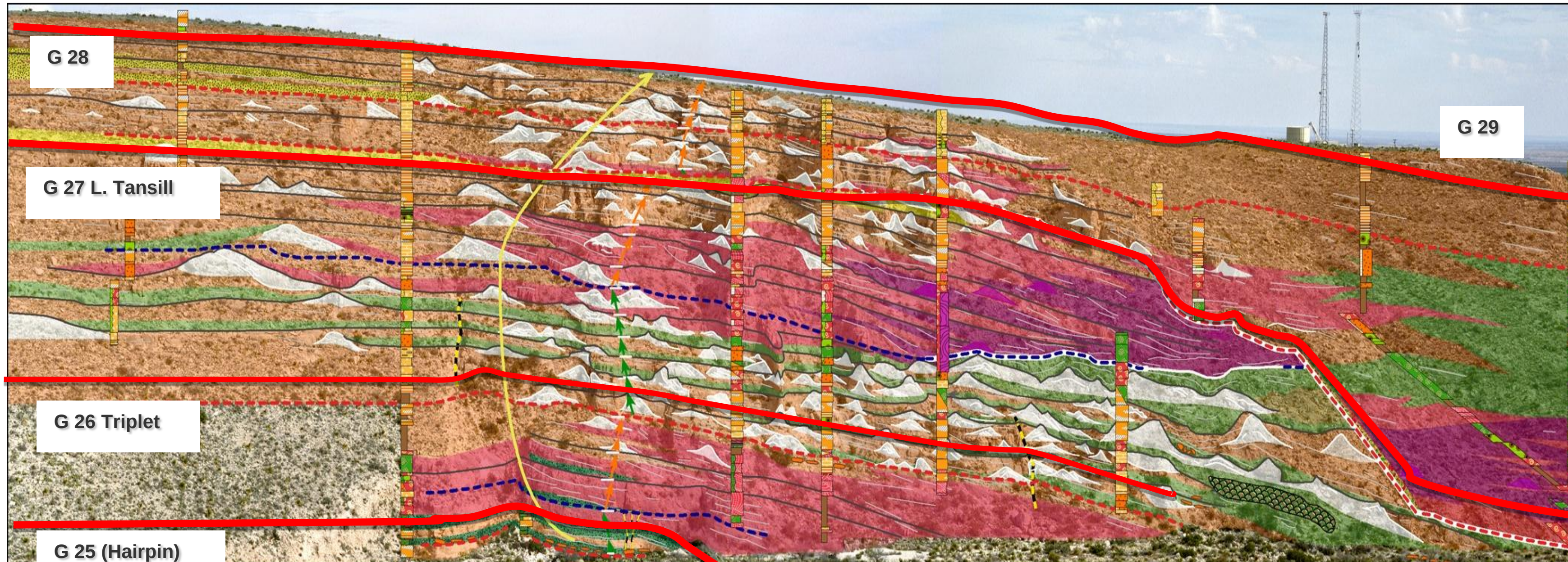
What more is needed:



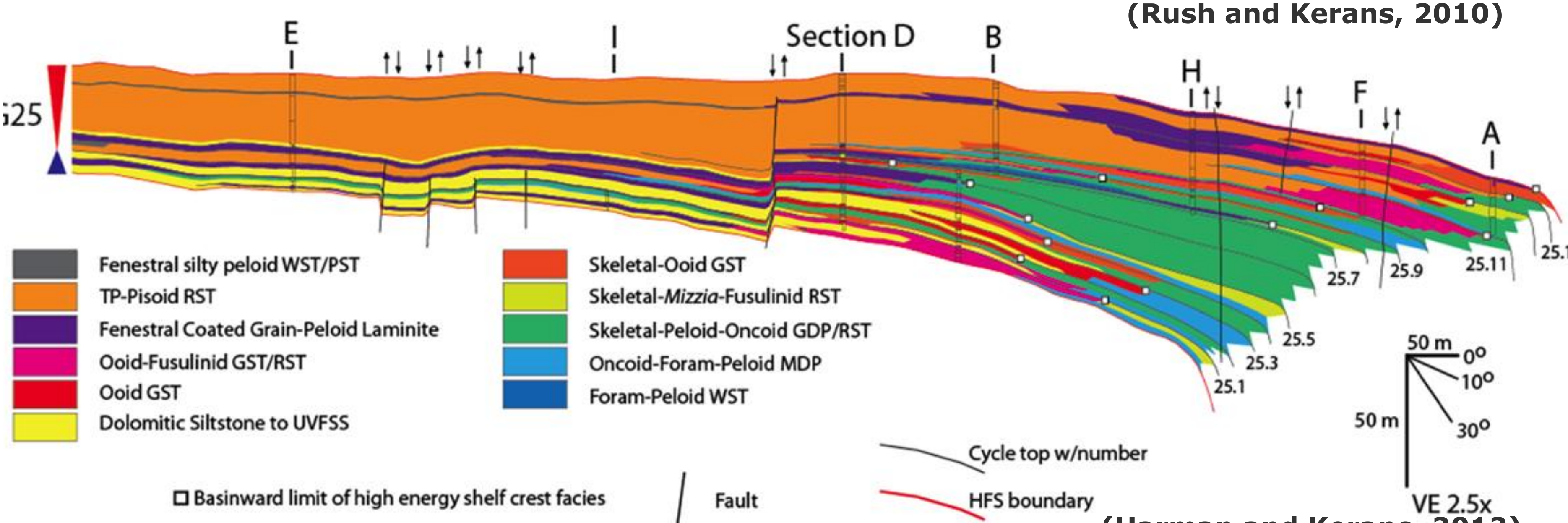
(Garcia-Fresca and Jones, 2011)

Establish stratigraphic context, spatial distribution, and **trends of dolomite stages** and their characteristics

Nature of Faults and Fractures



(Rush and Kerans, 2010)



(Harman and Kerans, 2012)

Nature of Faults and Fractures

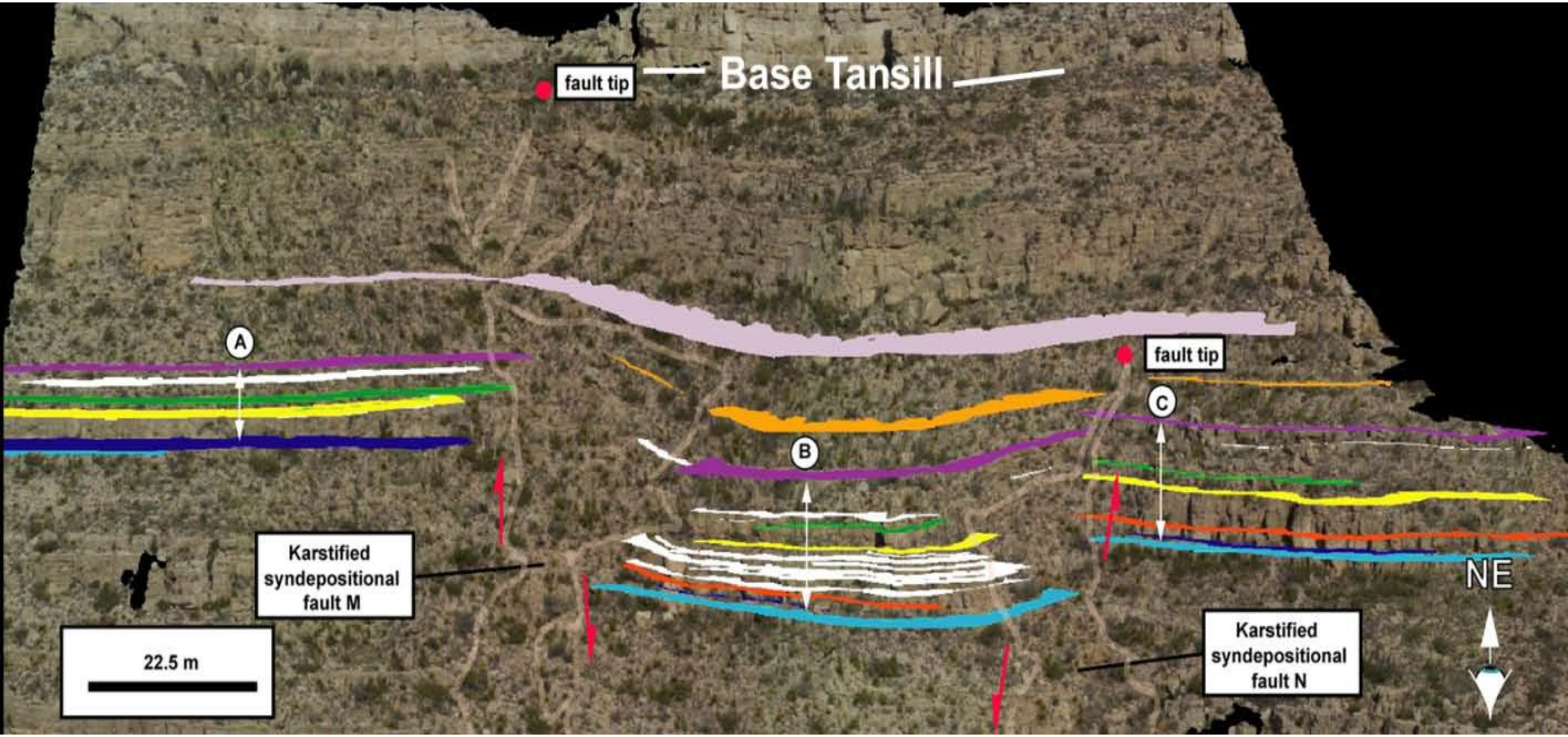
Steep rimmed margin characterized by collapse with syndepositional fractures in the margin and shelf.

Toomey and Babcock (1983) Fekete *et al.* (1986) Hunt *et al.* (2002) Kosa *et al.* (2003) Kosa and Hunt (2005, 2006a, 2006b) Rush and Kerans (2010) Resor and Flodin (2010) Harman (2011) Harman and Kerans (2012) Hunt *et al.* (2012)

The fractures play an important role in controlling early depositional patterns, such as growth faults with up to 30 m of active growth, meteoric diagenesis, karstification, and dolomitization.

Kosa *et al.* (2003) Kosa and Hunt (2005) Kosa and Hunt (2006a, 2006b) Rush and Kerans (2010) Zahm *et al.* (2011) Frost *et al.* (2012) Harman and Kerans (2012) Hunt *et al.* (2012)

Nature of Faults and Fractures



Shelf crest pisolite facies thicken from 9.6 m in the fault M footwall (A) to 20.4 m in the graben (B) and are 17.9 m thick in the fault N footwall (C) **(Hunt et al, 2012).**

Nature of Faults and Fractures

What we have learned:

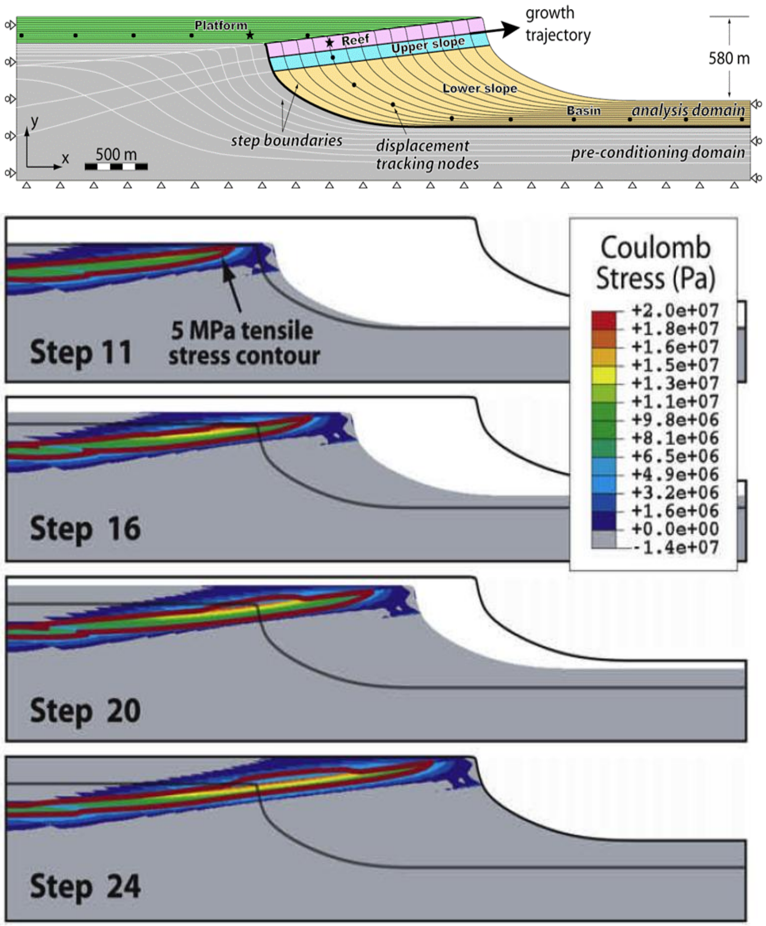
As the Permian carbonate profile evolved from low-relief ramp to the steep-rimmed Capitan margin, the shelf margin changed:

- From one characterized by gradual low-angle slopes lacking brittle failure and significant sediment gravity flows
- To one with steep margin collapse and with syndepositional fractures in the margin as well as in the middle to inner shelf facies

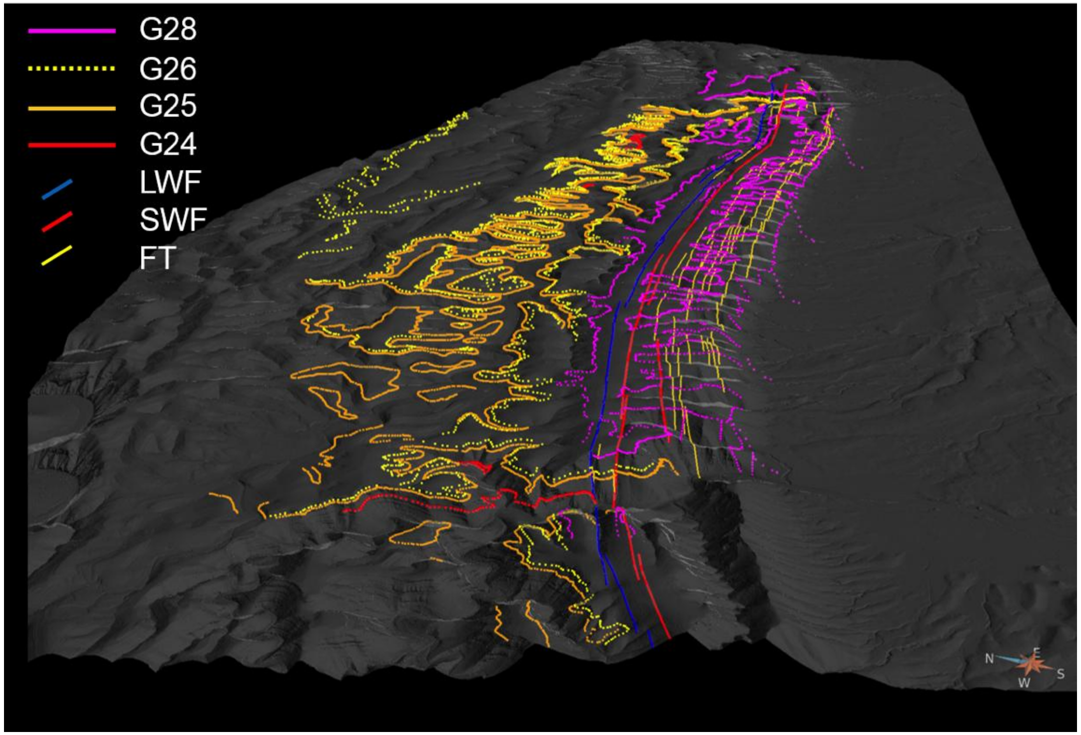
These fractures impacted subsequent deposition (thickness and facies changes) and diagenesis.

Nature of Faults and Fractures

What more is needed:



(Resor and Flodin, 2010)



(Zahm et al, ongoing)

Refine **stratigraphic context, spatial distribution and trends, and timing** of fractures and faults.

Conceptual Models and Discussion Points

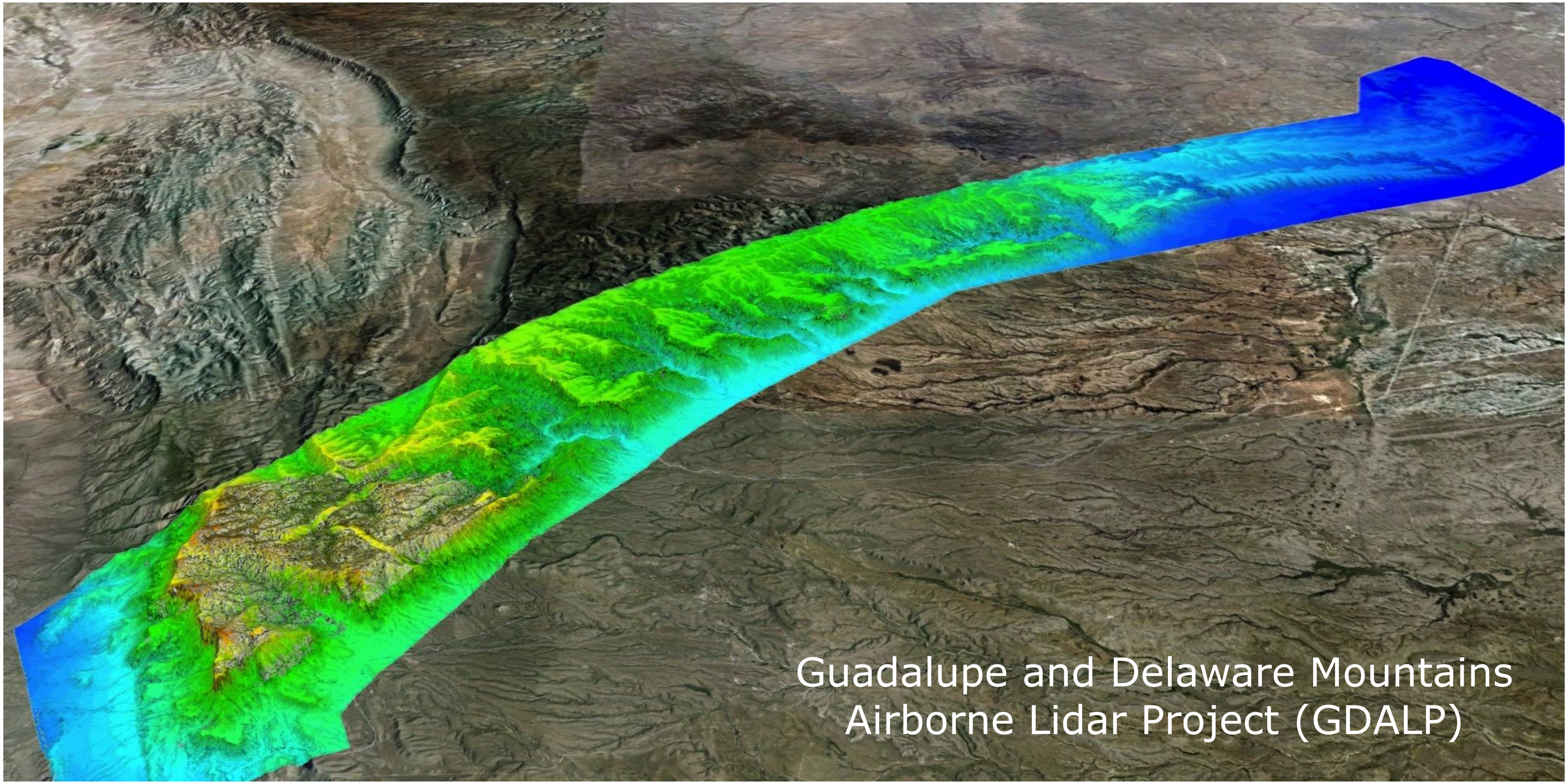
Examples of the major role that previous studies in the Guadalupe Mountains have played in developing models for carbonate shelf margins, and in the process sometimes leading to paradigms.

- **Nature of the Reef**
- **Shelf-Margin Profile**
- **Sequence Stratigraphic Models**
- **Models for Dolomitization**
- **Nature of Faults and Fractures**

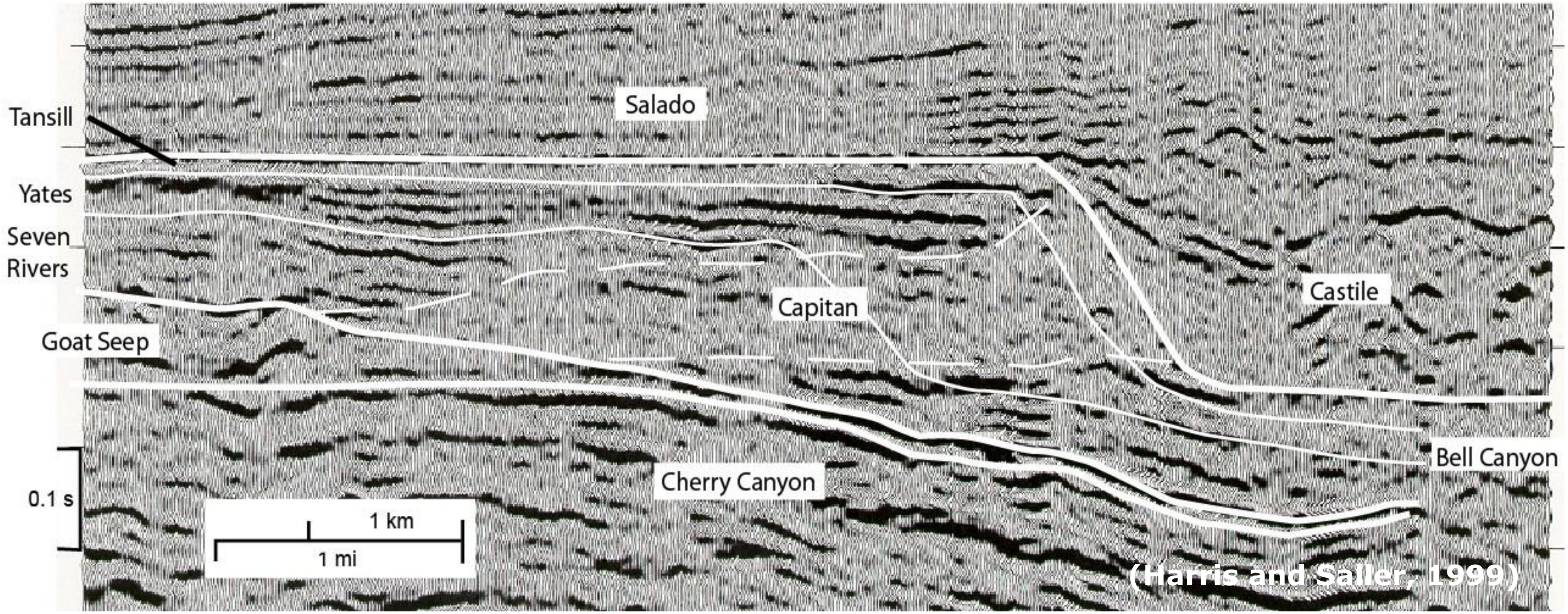
In all cases, the examples can be viewed as starting points for additional discussions that will prompt a variety of opinions.

Looking Forward

The Capitan margin will continue as a natural laboratory for 3-D interrogation of stratigraphic, depositional, diagenetic, and structural models.



Looking Forward



Enhanced interrogation will further clarify:

- 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 and basin
- The **spatial distribution of diagenetic overprint** including dolomitization and syndepositional fracturing.

Lloyd's Part in All of This

Nature of the Reef

Babcock (1974, 1977) Yurewicz (1976, 1977) Babcock and Yurewicz (1989)

Shelf-Margin Profile

Pray (1977) Esteban and Pray (1977, 1983) Esteban *et al.* (1983) Neese and Schwartz (1977) Hurley (1978, 1989) Neese (1979, 1989) Schwartz (1981) Fekete *et al.* (1986) Pray and Harris (1989)

Sequence Stratigraphic Models

Wheeler (1985) Sarg *et al*. (1988) Candelaria (1989) Sarg (1989) Lawson (1989)

Models for Dolomitization

Sarg (1977, 1981), Crawford (1981)

Nature of Faults and Fractures

Stanton and Pray (2004)