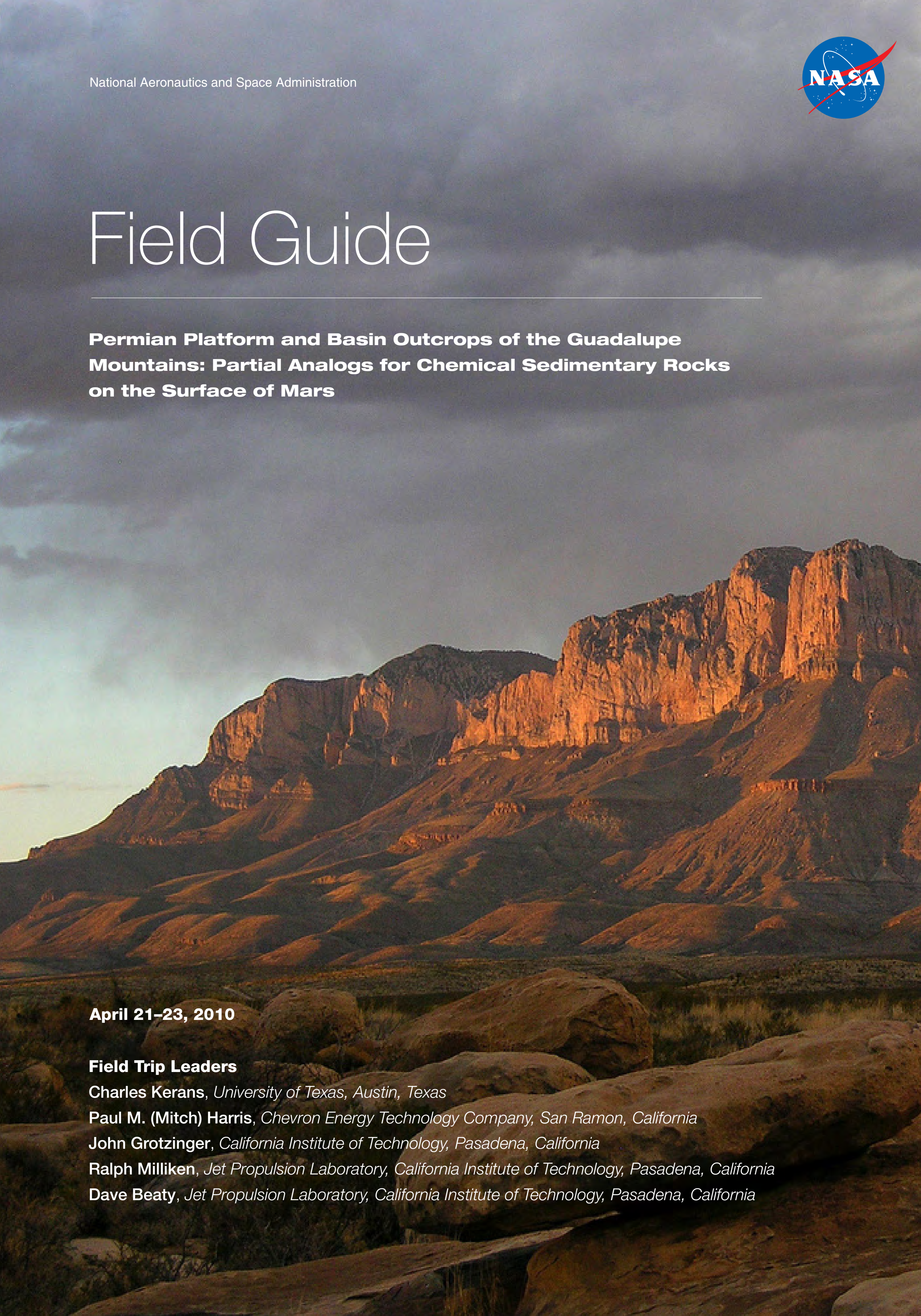

National Aeronautics and Space Administration

Field Guide

Permian Platform and Basin Outcrops of the Guadalupe Mountains: Partial Analogs for Chemical Sedimentary Rocks on the Surface of Mars

April 21–23, 2010

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Field Trip Agenda

Day 1: Wednesday, April 21

Overview and Delaware Basin Stops traveling from El Paso to Carlsbad

Day 2: Thursday, April 22

Shelf lagoon transect examining carbonate evaporite transition, and older clinoforms

Day 3: Friday, April 23

Carlsbad Caverns, Capitan reef, and deepwater sandstones

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Field Guide

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Society for Sedimentary Geology

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Preface

Mars Sedimentary Rocks, Terrestrial Analogs, and the Goals of the Field Trip

The exploration and interpretation of sedimentary rocks on the Martian surface requires a comparative approach, guided in part by insights acquired through analysis of analogous rocks on Earth. Mission results over the past decade have demonstrated that a diverse suite of sediments and sedimentary rocks exists on the surface of Mars that represents eolian, fluvial, and possibly lacustrine environments (Carr, 1996; Edgett and Malin, 2002; Greeley and Thompson, 2003; Grotzinger et al., 2005; Malin and Edgett, 2000; Squyres et al., 2004).These materials were formed during erosion of older basaltic rocks to form siliciclastic sediments and sedimentary rocks, deposited mostly as alluvial fans or eolian sand sheets. In areas affected by volcanism, reworking of volcanic deposits to form volcaniclastic sediments and sedimentary rocks may have occurred. Finally, where water was available and also charged with dissolved ions, evaporation of possibly shallow bodies of water (brine) to form chemical sediments appears to have occurred over relatively widespread regions. Formation of chemical sediments by evaporation of discharging spring waters may also have occurred. These deposits of chemical origin are dominated by sulfates, though the search for large carbonate reservoirs continues. Chemical and fine-grained siliciclastic sediments and sedimentary rocks are viewed as important targets for future in situ geobiological analysis or sample return.

Most recently (past 5 years), our understanding of the geologic history of Mars has taken a fresh turn as a result of the discoveries by recent missions, particularly Mars Express and Mars Reconnaissance Orbiter (MRO). Mars may have a distinct history of aqueous events that left distinct time-dependent patterns embedded within the rock record. The current hypothesis is that the long-term environmental evolution of the planet is delineated in the history of mineral assemblages, from a planet characterized by aqueous alteration of impact-brecciated ancient crust forming phyllosilicate minerals, to a planet marked by vast terrains of bedded sulfate minerals, and that this was followed by a terminal shift to the current dry state during which anhydrous iron oxide minerals accumulated (Bibring et al., 2005; Bibring et al., 2006; Gendrin et al., 2005; Mustard et al., 2008; Poulet et al., 2005). See Figure 1.

As applied to Mars, the methodologies of terrestrial stratigraphic analysis (Christie-Blick and Driscoll, 1995; Vail et al., 1977) developed over the past several decades offer much promise for efficient characterization of past surficial environments on Mars. This field trip attempts to study partial analogs for a subset of sedimentary rocks on Mars, particularly those vast, layered, sulfate-rich deposits that have accumulated over length scales greater than that of crater basins. We will explore ancient terrestrial surface processes, and the mechanisms by which hydrated minerals accumulated as thick sedimentary deposits, in addition to other aqueous and non-aqueous processes.

The field trip will specifically attempt to demonstrate the enormous importance of merging mineralogic/chemical attributes of sedimentary with the physical or geometric attributes of sedimentary rocks. The Guadalupe Mountains preserves what is

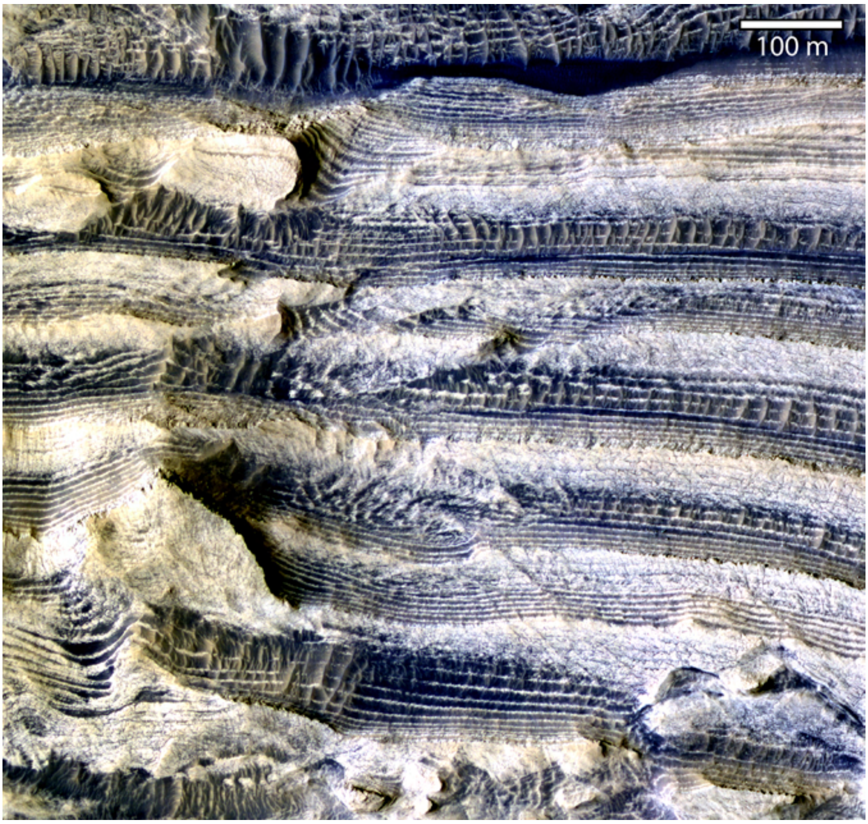


Figure 1. Cyclic stratification at Becquerel Crater. These rocks may represent accumulation of aeolian dust, possibly modulated by climatic cycles. From Lewis et al. (2009).

generally regarded as the one of the best examples in the world where complete integration of data sets provides high-resolution interpretation of depositional processes. The different stops will expose the participants to variations in models for sedimentation that involve sulfate, carbonate, and siliciclastic deposition.

These examples from the Guadalupe Mountains have been studied intensively, in some cases for over 50 years, and as such reveal the state of the art in stratigraphic and sedimentologic analysis. If we can capture even 10% of this understanding on Mars, we will be doing extremely well. The goal, therefore, cannot be to here emulate the level of understanding that is possible for Earth, but rather to absorb some of the techniques and approaches that would be applicable to extraterrestrial mapping, as well as obtaining insight into some of the processes that may be similar, and some that may be very different.

Field Trip Summary

The Guadalupe Mountains constitute an exquisite natural laboratory for studying the stratigraphy, depositional facies, and diagenetic overprint of Permian platform and basin carbonates, siliciclastics and evaporites. Well-studied outcrops from this classic locality have long served as important analogs for hydrocarbon reservoirs in the immediately adjacent Permian Basin and other areas worldwide where data are more limited. It is remarkable that these rocks may now constitute a partial analog for the sedimentary rocks that formed on Mars over 3 billion years ago.

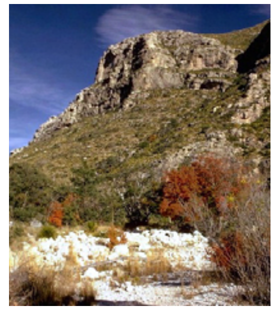
The Guadalupe and Delaware Mountain outcrops located 2.5 hours east of El Paso, Texas, represent one of the world's best exposed and best studied basin-fill successions. A remarkable spectrum of shallow and deep-water evaporites, eolian, shallow shelf and basinal sandstones, and shelf, slope, and basinal carbonate strata can be found in near-original depositional setting. These strata are both mineralogically diverse and exhibit a remarkable range of physical stratal geometries and stacking patterns. The 1700 m local relief produced by the Basin and Range–age normal fault system is on par with that observed in the Grand Canyon, making it possible to observe in one vantage point the entire shelf to basin Permian paleobathymetry.

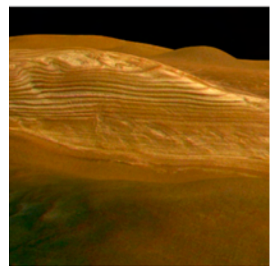
These outcrops present very useful partial analogs for what might be present in the sedimentary rock record of Mars. Many of the martian sedimentary rocks also fill large basins, and are either observed or are presumed to show systematic variations from basin margin to basin interior as well as from oldest to youngest unit. Both systems show a mixture of sulfate and phyllosilicate minerals, along with other sedimentary components. Part of the value of exploring this analog in the field is that there are key general lessons to be learned about how sedimentary strata in general are formed, and what techniques and approaches are used by terrestrial geologists to study them; how, for example, paleobathymetry could be reconstructed based on observation of specific types of stratal geometries. Indeed, the rocks that will be seen on this field trip are possibly the most visited on Earth for the purpose of education, so participants with less experience in sedimentology and stratigraphy will find the stops to be very instructive.

Our field trip will emphasize the stratigraphic framework and geomorphic features of an Upper Permian (Guadalupian) steep-rimmed platform of the Guadalupe Mountains. We invite questions and discussion at all field stops, as our group has diverse backgrounds and interests and any discussion will be beneficial to all. Stops on the field trip will be designed to highlight:

- Tectonic setting and overview of the shelf-to-basin profile of the Permian Basin (Salt Flat Graben)
- Style and occurrence of basinal sulfates (anhydrite) of the Castile Formation sitting in an estimated 600–700 m of paleo-water depth (Castile escarpment on Permian Basin floor)
- Mixed carbonate-evaporite-siliciclastic mudstone facies transitions of the restricted shelf, and their recognition through remote sensing using Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data (Rocky Arroyo–Seven Rivers Embayment transect)
- Stratal geometries of a mixed siliciclastic-carbonate prograding shelf deposit with well-exposed clinoforms (Last Chance Canyon)
- The world-famous Carlsbad Caverns to examine the geologic processes associated with cave formation in this environment
- Basinal sandstone turbidite slope channels of the Brushy Canyon and Cherry Canyon Formations (Guadalupe Canyon)

Contents





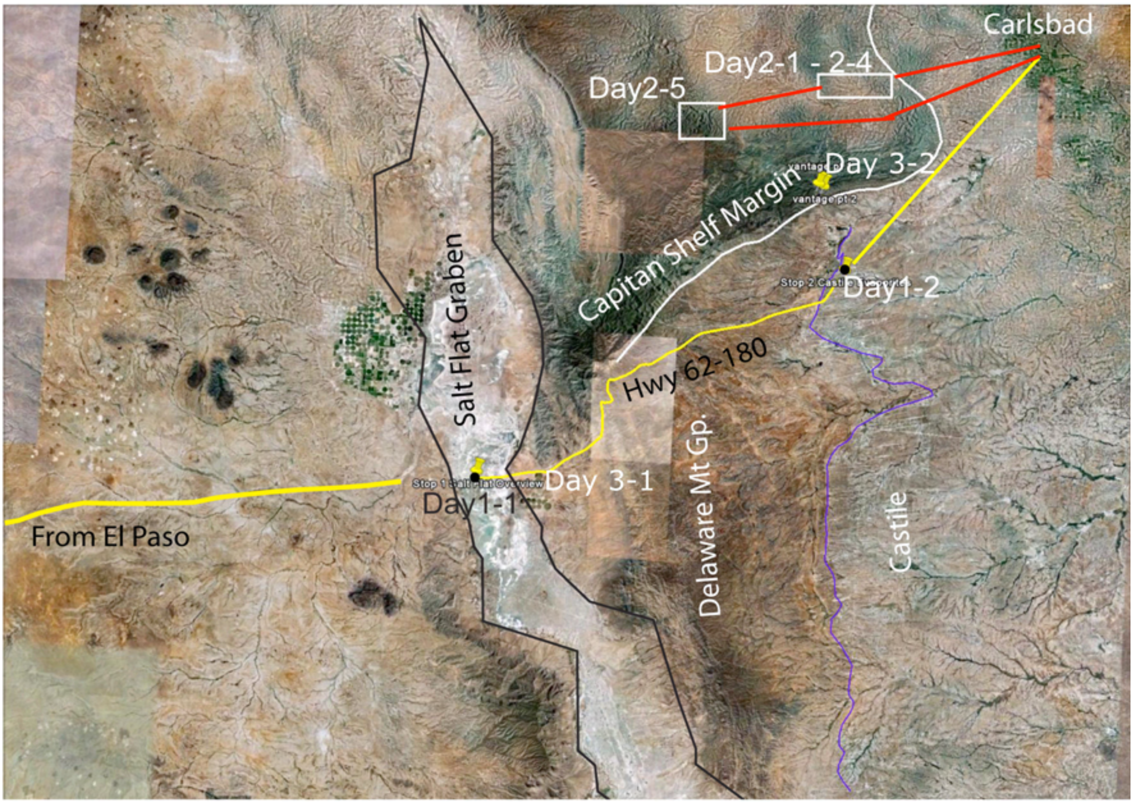


Figure 2. Overview of stops for our trip. Day 1 Stop 1-1 is in the Salt Flat Graben, providing an overview of the Guadalupe Mountains. Stop 1-2 is within the Castile evaporites on the floor of the Delaware Basin. Day 2 Stops 2-1 to 2-4 is a transect through the Seven Rivers Formation carbonate to evaporite transition. Stop 2-5 is Last Chance Canyon where spectacular clinoform geometries will be studied. Day 3 Stop 3-1 is Carlsbad Caverns, within the Capitan margin. Stop 3-2 is a final overview of the Delaware Basin sediment fill.

Field Trip Agenda

Refer to Figure 2 for an overview of stops on our trip.

April 21

Drive from El Paso, TX, to Carlsbad, NM, making two stops en route

Stop 1-1 — Salt Flat Graben Overview to examine regional setting and relevant Permian and Quaternary stratigraphy and geomorphology (Mars relevance: expression of chloride evaporites, and recognition of basin margin stratigraphy)

Stop 1-2 — Castile Evaporite Roadcut to examine basinal evaporite deposits (Mars relevance: how to recognize sulfates deposited in deep-water subaqueous setting)

Overnight at Stevens Inn, Carlsbad, NM

April 22

Morning stops along Rocky Arroyo to examine carbonate to evaporite facies transition within broad shelf behind the Capitan margin

Stop 2-1 — Rocky Arroyo Roadcut to examine nearshore carbonates of Seven Rivers Formation

Stop 2-2 — Rocky Arroyo Breccia Roadcut to examine mixed lithologies and diagenetic overprint of Seven Rivers Formation (Mars relevance: are some breccias related to dissolution of evaporites?)

Stop 2-3 — Seven Rivers Embayment Overview to discuss carbonate to evaporite facies transition in Seven Rivers Formation (Mars relevance: Do we see evidence for lateral transitions between different types of sedimentary rocks?)

Stop 2-4 — Seven Rivers Embayment Outcrop to examine evaporite facies in back-reef setting of Seven Rivers Formation (Mars relevance: how to recognize sulfate evaporites formed in a shallow water subaqueous setting)

Afternoon stops in Last Chance Canyon to examine stratigraphic architecture of Permian prograding marine shelf deposits

Stop 2-5 — Last Chance Canyon Overview to examine prograding carbonates and siliciclastics of the San Andres Formation (Mars relevance: recognition of inclined stratal geometries in Melas Chasma, Eberswalde crater, and other locations)

Overnight at Stevens Inn, Carlsbad, NM

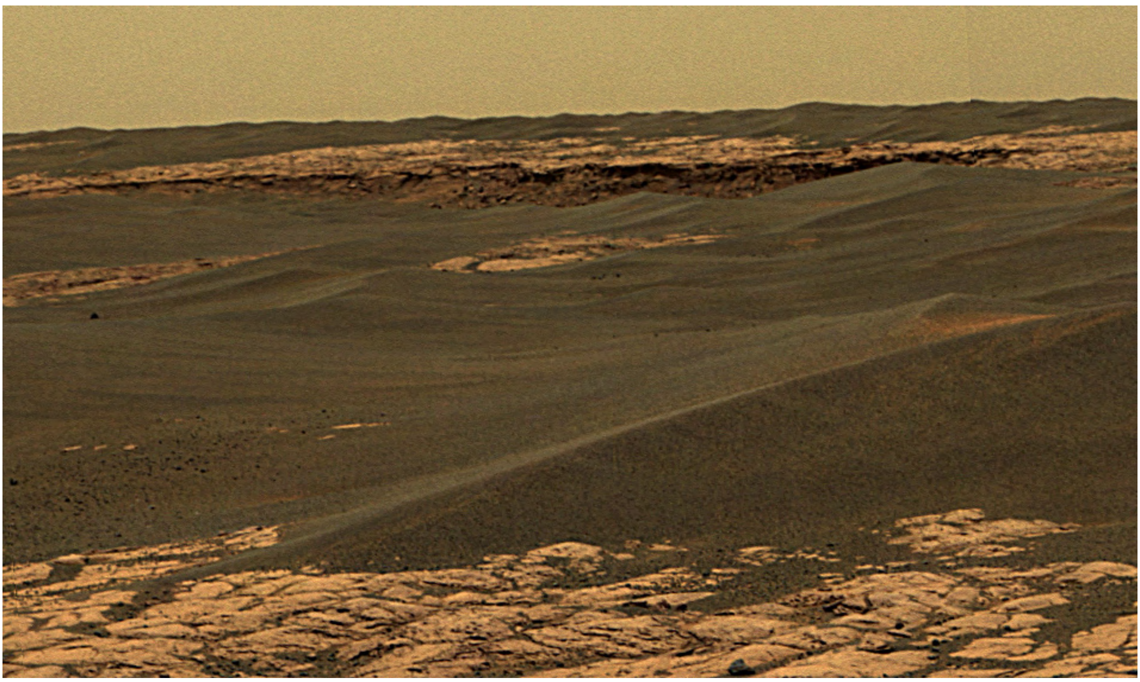
April 23

Drive from Carlsbad, NM, to El Paso, TX, making two stops en route

Stop 3-1 — Carlsbad Caverns to examine cavern formation and cave deposits

Stop 3-2 — Delaware Basin Overview to discuss sediment fill of Delaware Basin (Mars relevance: sublacustrine fan in Melas Chasma)

Return to El Paso Airport by 3:00 p.m. End of trip at El Paso International Airport or nearby hotel.



View of Meridiani Planum, Mars, showing typical outcrop and evidence of sedimentary processes.

Introduction

Guadalupe Mountains Geology Background

The Late Permian (Guadalupian) mixed carbonate/siliciclastic sequences of the Delaware Basin, one of the long-lived subbasins of the Permian Basin, are well known both for their classic outcrop exposures revealed by basin and range structuring in the Guadalupe Mountains and for their prolific hydrocarbon production. A large number of stratigraphic and sedimentologic studies have established the Capitan reef and associated facies as a model for the understanding of carbonate facies in a shelf margin setting and of reciprocal sedimentation relations between a shelf and basin. Early studies focused on biostratigraphy, lithostratigraphy, and early concepts of reciprocal sedimentation. Focus shifted in the 1970s and 1980s to analysis of depositional facies and processes and on the relatively new understanding of early diagenesis of reef margins. More recently, the outcrops have been analyzed from a cyclostratigraphy and sequence stratigraphy perspective.

Early Studies

Providing the initial interest in the area were the superb field studies and subsequent detailed reporting of the geology of the southern Guadalupe Mountains by King (1942, 1948). The book by Newell et al. (1953) on the Capitan did much to further enhance the outcrops as research models for sedimentary geologists. The critical treatment of the Capitan sedimentology by Dunham in the late 1950s and 1960s, culminating in his detailed 1972 guidebook (Dunham, 1972), 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.

Continuing Research

There was a major surge of research on the Capitan during the 1970s and 1980s. Published work focused on shelf-to-basin correlation (Kelley, 1972; Smith, 1973; Sneed, 1977), environments and cycles of shelf deposits (Motts, 1972; Smith, 1974), teepee structures (Assereto and Kendall, 1977), and 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 paleo-ecology. The first generation of Pray's students published their results along with the work of other authors in the Society of Economic Paleontologists and Mineralogists (SEPM) Permian Basin Section Publication 77-16 (Hileman and Mazzullo, 1977). That two-volume compilation and field trip guide discussed many aspects of the Capitan including: reef textures and paleo-ecology (J. A. Babcock, 1977; Toomey, 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 in the late 1980s and 1990s. SEPM Core Workshop Number 13 (Harris and Grover, 1989) was built around 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. That workshop volume contained many other excellent 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 (Bebout and Kerans, 1993) is another important collection of descriptions and interpretations of the Capitan margin. The guide focuses on McKittrick Canyon, which is unique in that it is possible to traverse in a single day's hike from the basin through the Capitan slope and reef into the outer shelf. An excellent and comprehensive review of most aspects of the Capitan is available in Hill's (1996) volume on the geology of the Delaware Basin. The most recent compilation on the Capitan (Saller et al., 2000) brings together the latest work on the stratigraphic framework, biostratigraphy, facies analysis, diagenesis, and subsurface data. In addition, a digital publication distributed by AAPG Datapages by Kerans and Kempter (2000) provides a unified stratigraphic model at a substantially higher resolution than previous syntheses, and also contains all the critical photomosaics and limited satellite imagery of the Guadalupe Mountain exposures.

Terminology

The focus of this part of our field trip is on the Capitan margin, which is synonymous with the Capitan reef complex of Pray or the Capitan depositional system of Saller et al. (2000). We will use the terms "reef," "forereef," and "backreef" in their positional sense.

A number of formation names have been applied to the rock units along a depositional profile across the Capitan margin. From the work of King (1948), Newell et al. (1953), and Hayes (1964), (a) the Capitan Formation includes both reef and slope; (b) shelfward equivalents are mixtures of carbonates, siliciclastics, and evaporites of the Tansill (youngest), Yates, and Seven Rivers Formations; and (c) basinward equivalents are siliciclastics of the Bell Canyon Formation, with carbonate interbeds along the basin edge designated Lamar (youngest), McCombs, Rader, Pinery, and Hegler members. Newell et al. (1953) further recognized a three-fold subdivision of the Yates Formation using major siltstone interbeds, designating these, from oldest to youngest, Yates A, B, and C.

Stratigraphic Framework

Kerans and Tinker (2000) interpret three composite sequences (CSs) within the Capitan system. Their interpretations are based on the large-scale stratigraphic framework developed for the Guadalupe Mountains by Kerans et al. (1992, 1993) and Kerans and Fitchen (1995) and the detailed work within McKittrick Canyon by Tinker (1996, 1998). The correlation between the shelf and basin edge carbonates within their scheme include:

1. A Seven Rivers CS to Manzanita, Hegler, and Pinery members of the Cherry Canyon and Bell Canyon formations;
2. A Yates CS to Rader and McCombs members of the Bell Canyon Formation, and
3. A Tansill CS to the Lamar member of the Bell Canyon Formation.

Detailed stratigraphic relationships for the Capitan margin generally suffer from the limited resolution of biostratigraphic control and the inability to trace beds or time lines from the shelf into the basin. A number of recent studies, however, are improving our understanding of the shelf-to-basin relations and inter-relationships between depositional facies. These include studies in McKittrick Canyon (Brown and Loucks, 1993a and b; Kerans and Harris, 1993; Borer and Harris, 1995; Brown, 1996; Tinker, 1996, 1998), Slaughter Canyon (Rankey and Lehrmann, 1996; Osleger, 1998), basin strata (Kerans et al., 1992, 1993; Borer and Harris, 1995), and regional comparisons (Osleger and Tinker, 1999; Kerans and Fitchen, 1995; Kerans and Tinker, 2000; Harris and Saller, 2000).

A primary control of the Capitan stratigraphy is inferred to be composite sea-level variation. Low-amplitude, high-frequency oscillations of relative sea level are suggested for much of the Permian shelf-top strata, including that of the Capitan margin (Neese and Schwartz, 1977; Hurley, 1989; Wheeler, 1989; Borer and Harris, 1991, 1995; Kerans and Nance, 1991; Lindsay, 1991; Sonnenfeld, 1991; Kerans and Harris, 1993; Osleger, 1998; Tinker, 1998; Osleger and Tinker, 1999). Longley (2000), however, proposes that small-scale sequences and cycles were partly controlled by differential compaction on the outer shelf of the Capitan. Ye and Kerans (1996) proposed a eustatic curve for the Leonardian and Guadalupian by picking highstand and lowstand shorelines for individual sequences and using lithologic data to remove effects of compaction and isostacy. They suggest amplitudes of approximately 10 m for Capitan composite sequence-scale eustatic cycles, which is consistent with that proposed by Borer and Harris (1995). Cyclicity in the different facies tracts of the Capitan-equivalent shelf profile, and suggested relations with sea-level change, will be emphasized during our field stops.

One important difference between carbonate and siliciclastic depositional systems that impacts stratal patterns is that high rates of in situ carbonate production can cause aggradation or even progradation during transgression. Also, in a pure carbonate system, a lowstand system tract may be poorly developed in the basin since this represents a time of no or only limited carbonate production on the shelf. The greatest shedding of fine carbonate debris into the basin occurs during transgressive to highstand times when the shelfal carbonate factory is widespread (Schlager, 1992; Brown and Loucks, 1993). In a mixed system like the Capitan, attributes of both carbonate and siliciclastic sequence stratigraphic approaches need to be considered, as do the important interactions between the two depositional styles.

Subsurface Relations

The subsurface stratigraphy of the Capitan margin is very similar to outcrop stratigraphy recognized in the Guadalupe Mountains (Borer and Harris, 1995; Osleger and Tinker, 1999; Harris and Saller, 2000). Seismic data of the Capitan margin (Harris and Saller, 2000) show characteristics that include (1) a massive prograding reef/slope, (2) backreef/shelf reflectors that dip and diverge basinward before disappearing into the massive reef, and (3) layered bottomset beds that thicken basinward by addition of younger reflectors. Wireline log cross sections (Garber et al., 1989; Harris and Saller, 2000) illustrate the stratigraphy in more detail than can be done using seismic data. Basinward dipping shelf strata are interbedded sandstones and carbonates that diverge and pass basinward into massive carbonate of the reef. Correlative markers within the massive reef are difficult to find. Slope carbonate beds thin and basinal siliciclastics thicken toward the basin. Bottomset beds in the basin consist of interbedded sandstones/siltstones and low-porosity carbonates.

The lithologic differences between outcrops of the Capitan margin and their subsurface equivalents are due largely to variations in dolomitization and evaporite dissolution on outcrops. Distribution of porosity in the Capitan margin in the subsurface is closely related to depositional facies (Ward et al., 1986; Harris and Saller, 2000). Shelf sandstones and some shelf carbonates adjacent to the reef have good porosity and moderate permeability, but porosity and permeability in those strata generally decrease landward. The subsurface Capitan reef has moderate porosity and high permeability and is a regional aquifer. Carbonate beds in the basin are generally not porous, but some basinal sandstone filling elongate channels have good porosity and moderate permeability.

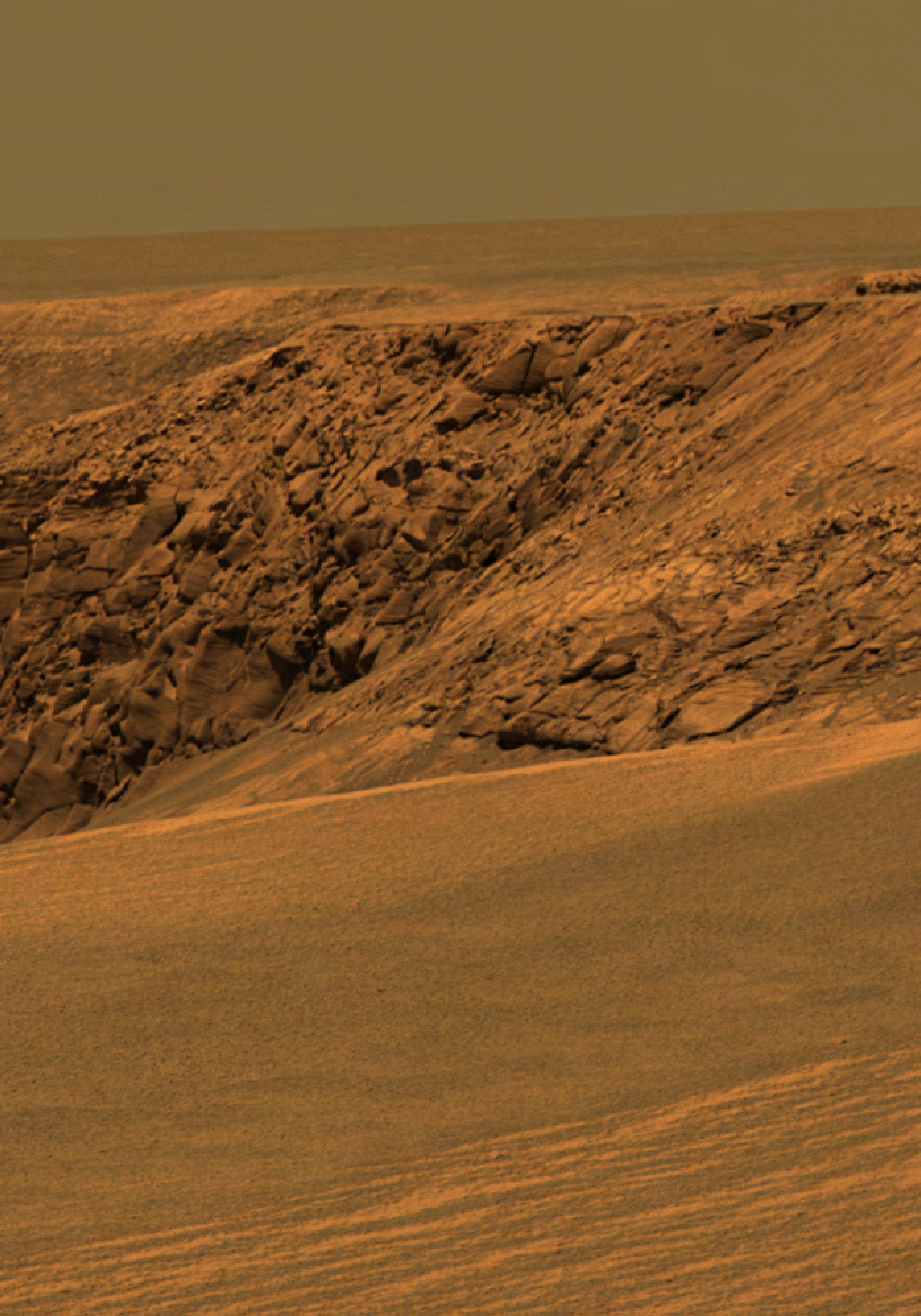
Hydrocarbon Production

Hydrocarbon reservoirs are present in shelf and basin equivalents to the Capitan margin (Galloway et al., 1983; Ward et al., 1986; Broadhead, 1993; Harris and Saller, 2000).

Hydrocarbon production on the shelf is primarily from sandstone beds of the Yates and Seven Rivers Formations, with minor production from dolomites (Galloway et al., 1983; Ward et al., 1986; Borer and Harris, 1991). The most widespread hydrocarbon reservoirs occur in relatively well-sorted sandstones with porosities of 15–30% and permeabilities of 10–100 mD (Borer and Harris, 1991). Individual siliciclastic reservoir zones show complex interfingering with carbonates in a downdip direction and evaporites in an updip direction (Borer and Harris, 1991). Some porosity also occurs in carbonate beds, especially grainstones near the reef (Ordonez, 1984). Hydrocarbon production from these shelf deposits generally occurs in stratigraphic traps caused by facies changes and evaporite cementation, but combination stratigraphic-structural traps occur in low-relief anticlines caused by compaction and draping over buried structures (Galloway et al., 1983; Ward et al., 1986; Broadhead, 1993).

A number of small oil fields occur in basin sandstones of the Bell Canyon Formation (Galloway et al., 1983; Ward et al., 1986; Williamson, 1977; Broadhead, 1993;

Harris and Saller, 2000). Cumulative production from these fields is generally less than 30 million barrels of oil. The fields tend to be very elongate (1.5–19 km long by <1 to 6 km wide) apparently reflecting accumulation of reservoir sands in deep-water channels (Bozanich, 1979; Williamson, 1977; Bashman, 1996). Average porosity and permeability in three Bell Canyon fields were estimated at 24–25% and 10–80 mD, respectively by Payne (1976). Basin carbonates that are interbedded with sandstones in the Bell Canyon Formation are generally not porous.



Day 1 Field Stops

Stop 1-1 — Salt Flat Graben
Overview of Guadalupe and Delaware Mountains

The main geomorphic features viewed from the floor of the Salt Flat Graben include the Western Escarpment of the Guadalupe Mountains, the Delaware Mountains, and the Salt Flat itself (Figure 3).

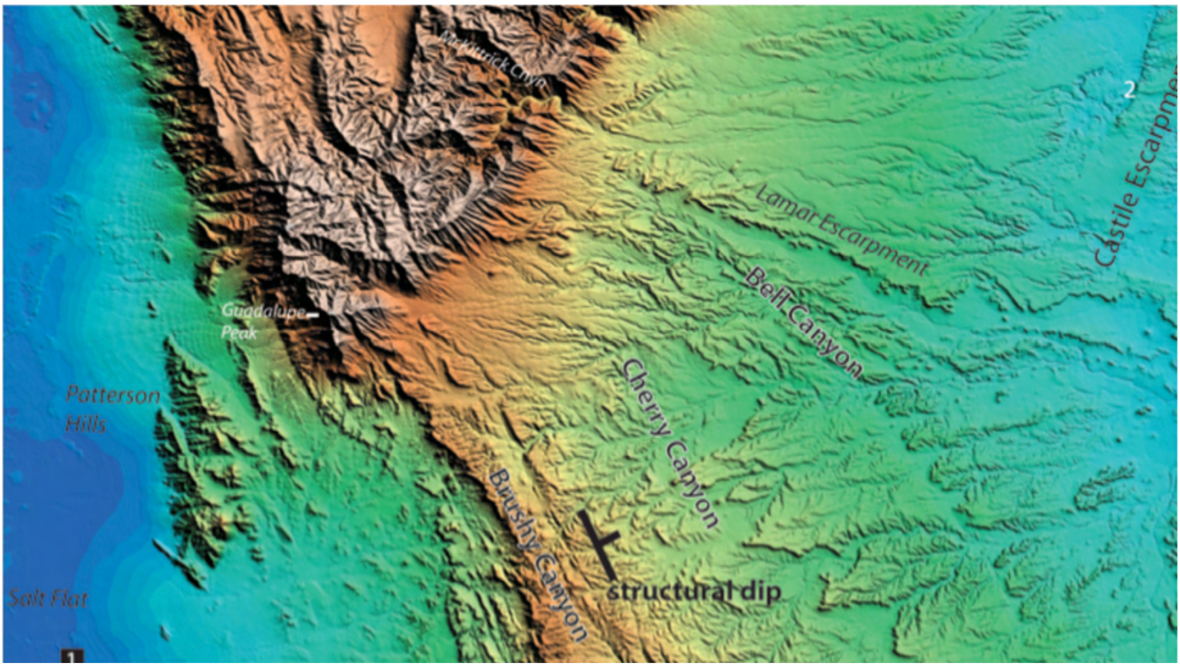


Figure 3. Digital elevation model (DEM) view of Guadalupe and Delaware Mountains on the eastern flank of the Salt Flat Graben. The easterly dip of the ranges is best shown in the Delaware Mountain group strata, including the Brushy Canyon, Cherry Canyon, and Bell Canyon sandstones.

The Western Escarpment of the Guadalupe Mountains is held up by Permian limestones, dolostones, and lesser sandstones of the “Permian Reef” complex. The Permian shelfal carbonates rim the Delaware Basin extending several hundred miles into the subsurface where they are major hydrocarbon producers. This view from the Salt Flat is particularly important to geoscientists to give a feeling of scale. The vertical relief from the floor of the Salt Flat to Guadalupe Peak at 8754 ft is 1.5 km, as much as from the floor to rim of the Grand Canyon. Features that should be apparent from our vantage point, still some 12 km away, are a lower set of carbonate cliffs that form an older carbonate platform margin, a bench of sandstones reflecting deeper water turbidite deposition, and the main prograding complex of the upper

Permian Capitan Reef itself. In this upper exposure you should be able to make out (particularly with the help of binoculars) the three main stratal architectural patterns of a carbonate platform, being the flat-bedded shelf, the massive reef, and the N to S dipping clinoforms of the slope (Figures 4–5). The total depositional relief of these clinoforms is 340 m, indicating that the upper parts of the reef developed a minimum of this high over the basin floor. We know that farther to the north the total relief is closer to 700 m (Figure 6).

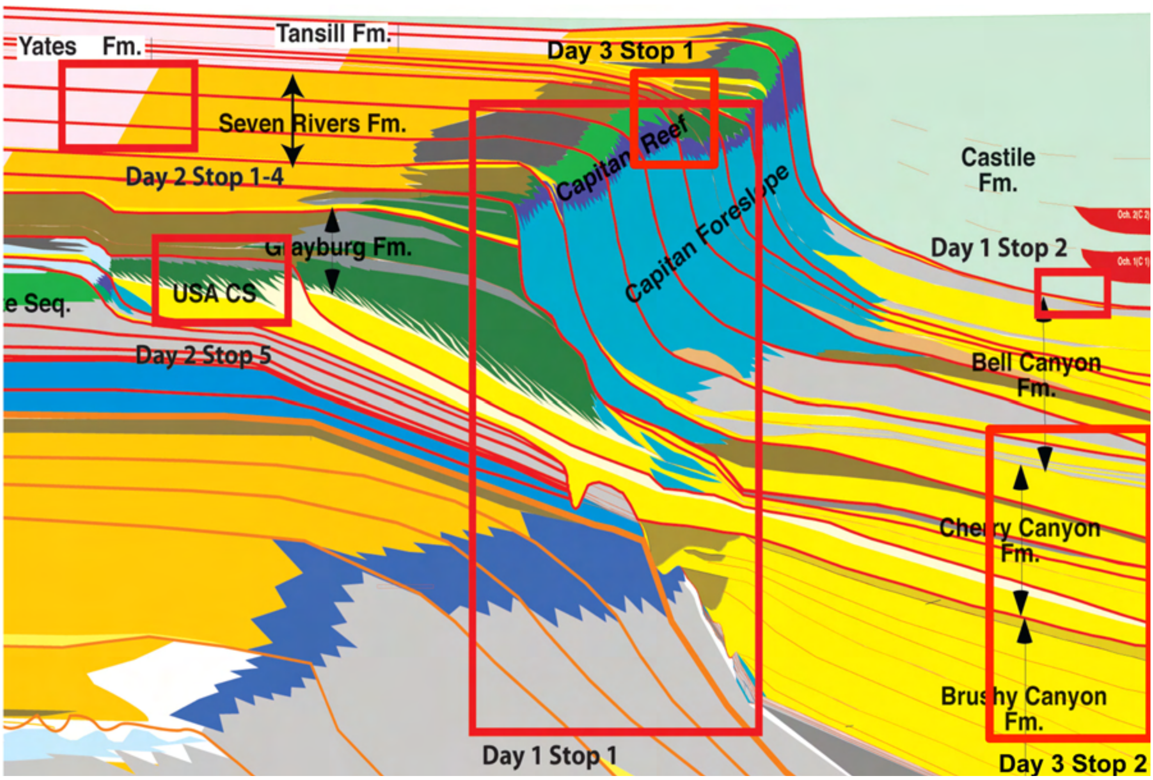


Figure 4. General stratigraphic position of field stops.

The Delaware Mountain range, which is marked by the distinct line of wind turbines, immediately to the south of El Capitan and Guadalupe Peak, is a significantly different rock suite. The Delawares are composed almost entirely of quartz-rich sandstones of deeper water turbidite origin. These sandstones were transported across the carbonate shelf and deposited on the floor of the Delaware Basin during lowstands of sea level. The Delaware Mountains are one of the best known exposures of deep-water sandstone deposition and have been studied extensively as an analog to deep-water sandstone production in the Gulf of Mexico and West Africa.

It is difficult to observe much detail from this distance, but as you drive past these outcrops on the way to our second stop, you will notice distinctly more massive sandstone bodies, commonly with concave bases and flat tops, which are deepwater channel systems formed on the slope of the basin margin.

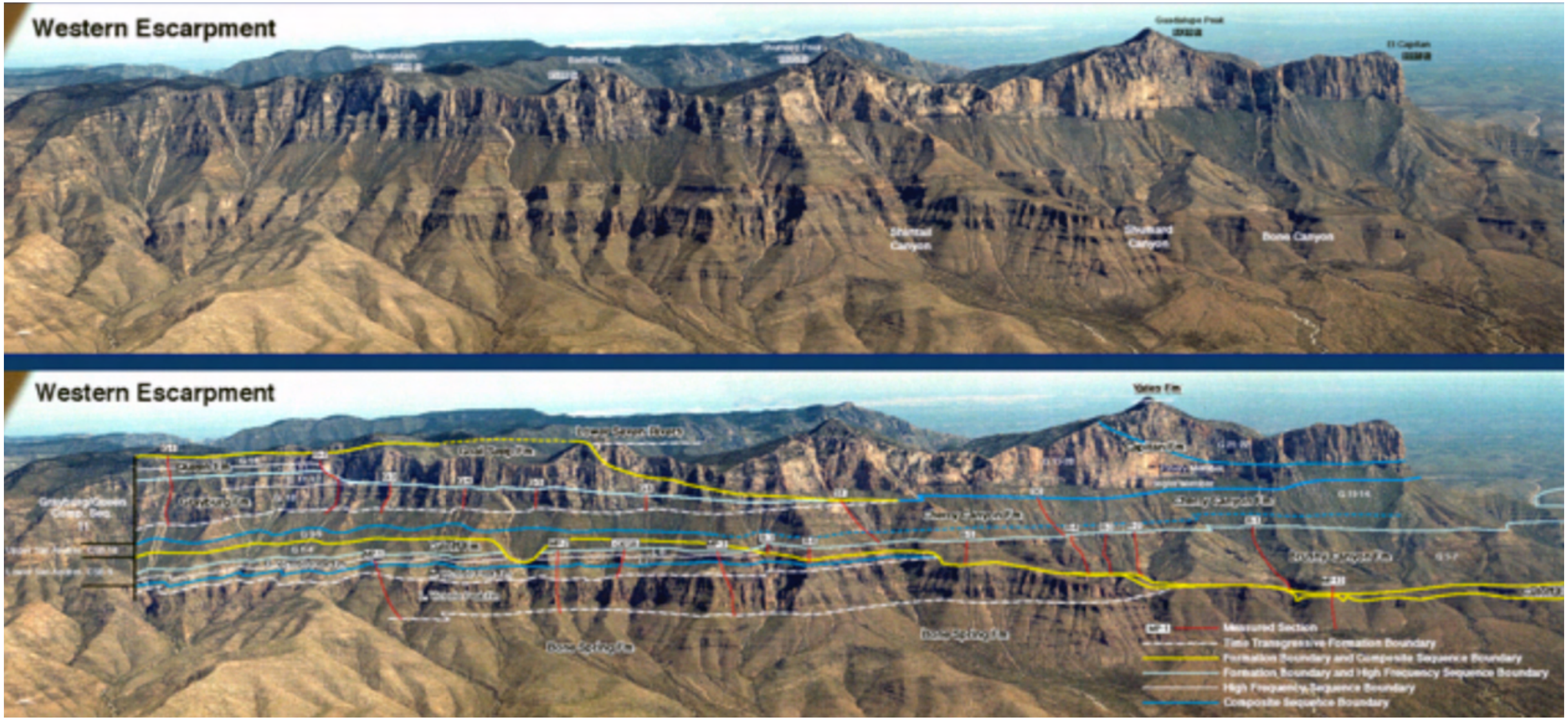


Figure 5. Geologic interpretation of stratigraphic units along the Western Escarpment of the Guadalupe Mountains.
From Kerans and Kempter (2002).

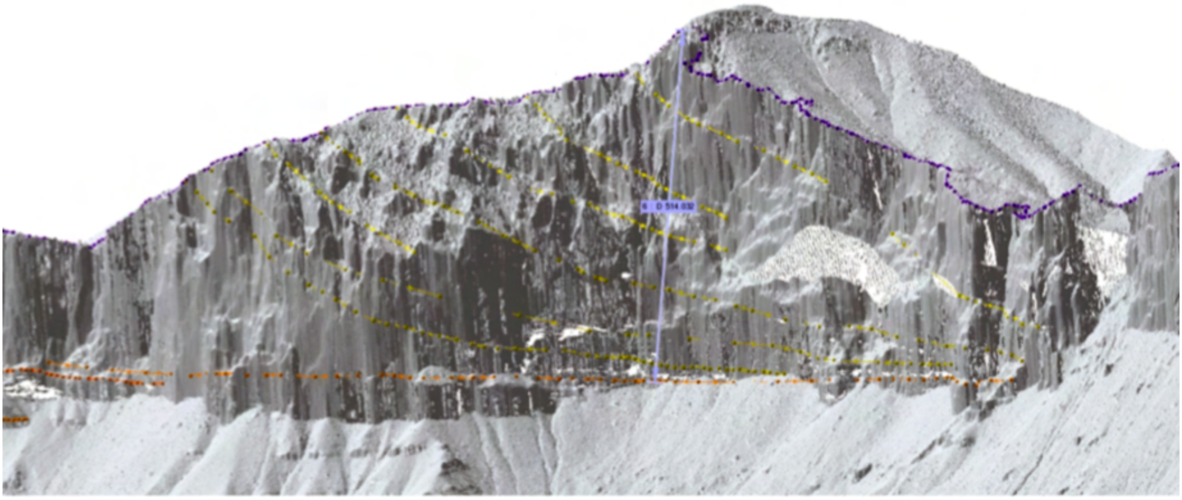


Figure 6. Airborne Lidar image of Guadalupe Peak showing the 514-m-high clinoform relief of the Capitan forereef slope. Clinoforms show characteristic asymptotic profile.

The third feature that we will discuss is the regional tectonic setting of the Salt Flat. The Salt Flat Graben is one of the most eastwardly developed features of the Basin-and-Range tectonic province. The graben, where our stop is situated, is floored by Pleistocene-Holocene gypsum, halite, and calcite/dolomite layers. The most recent layers of dolomite date at 4–5 ky. The graben fill is several hundred meters thick and is filled with Tertiary sandstones and minor evaporites. The maximum throw on rift-shoulder faults is 3 km, and excellent examples of rift transfer faults can be observed, as well as spectacular alluvial fans and playa lake deposits. It is this rift-shoulder fault system that provides our textbook seismic-scale cross section through the shelf-to-basin profile of Permian strata. The Guadalupes form the eastern shoulder of the Salt Flat Graben rift system, and as a result of this tectonic setting have a 5 degree NE dip away from the rift. The reason for the superb exhumation of this differential relief is not, however, a result of faulting. Rather, it is the reflection of differential weathering of the basinal Castile Formation, a cm to mm laminated gypsum/dolomite couplet deposit some 400–500 m in total thickness that filled in the basin at the end of reef growth. This sulfate is inherently more soluble than the reefal carbonates, or the basinal sandstones, and thus weathers recessively, effectively re-opening the Delaware Basin. From our vantage point on the floor of the Salt Flat, we will not be able to observe the Castile, but we will visit it on our next stop once we drive up across the Delaware sands and reach the terminal Permian basin floor surface.

Relevance to Mars

This stop provides a perspective of two important Mars analogs. The salt flat in the foreground is an example of the accumulation of chloride salts formed through evaporation of groundwater to form a surface deposit. Such processes have been involved in the accumulation of the Burns formation at Meridiani Planum (Grotzinger, et al. 2005; McLennan et al., 2005). Here in the salt flat, a variety of eolian-transport grains are being cemented by halite and possibly other salts such as gypsum.

The other important view is of the Western Escarpment of the Guadalupe Mountains, where inclined strata dip toward the interior of the basin, effectively defining the basin margin. These inclined strata, known as "clinoforms," represented the equilibrium geometry of the depositional surface of the earth at the time the sediments were accumulating. Mapping and modeling of these and other clinoforms in the terrestrial geologic record shows that they record the interplay between sediment flux, tectonic subsidence, and eustatic sea-level fluctuations. On Mars, these processes may have had different importance (Figure 7). Sediment flux must be considered, but it is possible that tectonic subsidence was negligible and that eustasy was irrelevant. If oceans were absent, then lake-level oscillations might have dominated; but where water was absent, eolian processes including wind speed, sediment flux, and ground topography might have been most important. Regardless of the specific combination of processes, the geometry of martian strata may hold important clues toward depositional mechanisms, including those that may be unique to Mars.

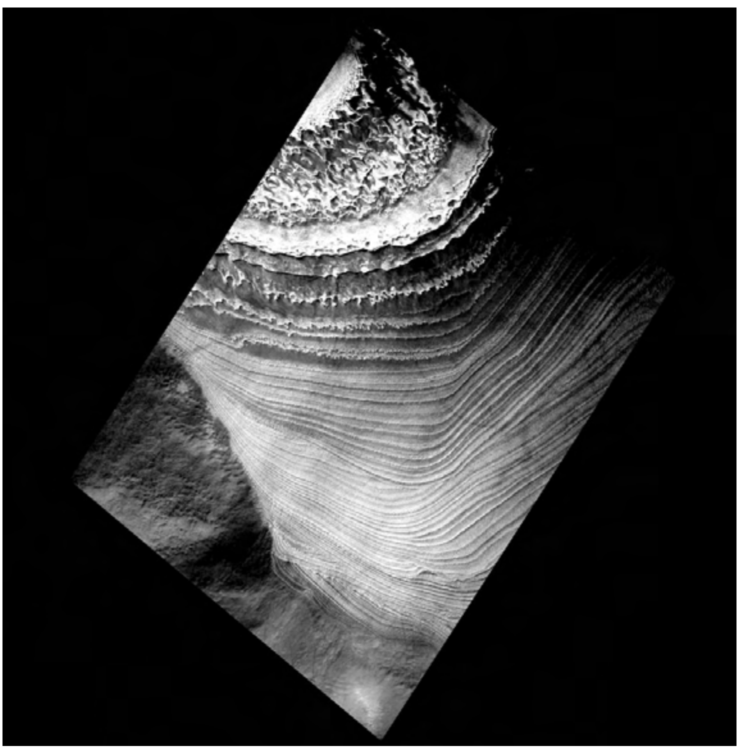


Figure 7. Sedimentary rocks deposited in Galle Crater preserve stratal geometries indicating episodic incision, development of unconformities, followed by onlap of younger strata.

Stop 1-2 — Castile Formation Roadcut
Evaporite Fill of the Permian Basin

One of the less studied and fairly controversial aspects of the Permian Basin history is the final stage infill of the basin by 600 m of mm-scale varved gypsum and calcite (and lesser halite) known as the Castile Formation (Figures 8–9). At the end of Late Permian Guadalupian time, the Delaware Basin was approximately 600 m deep, from the reef rim to the basin floor. At the onset of the Ochoan, reef growth and carbonate platform deposition ceased abruptly and the basin filled rapidly with cumulate deposits of gypsum in the space of approximately 250 ky. The most popular hypothesis is that reef growth cut off the inlets of normal marine water into the Delaware, forming a silled basin that then became supersaturated with respect to sulfate, and pelagic fall-out of gypsum and calcite began to fill the basin in, eventually to the brim.

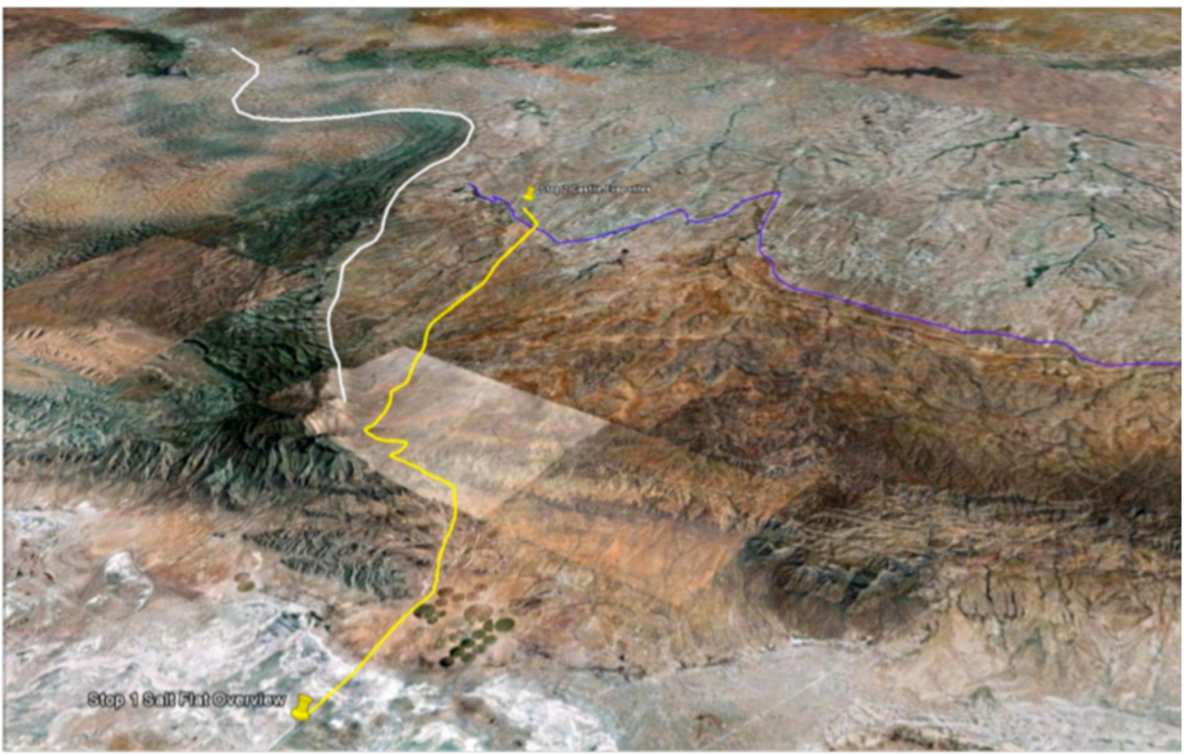


Figure 8. View to the northeast showing the route from the Salt Flat Graben Overview through the Delaware Mt Group sandstones to Stop 2 where we examine the Castile evaporites that filled in the Delaware Basin. The carbonate shelf strata that define the Northwest Shelf of the Permian Basin are outlined in white.

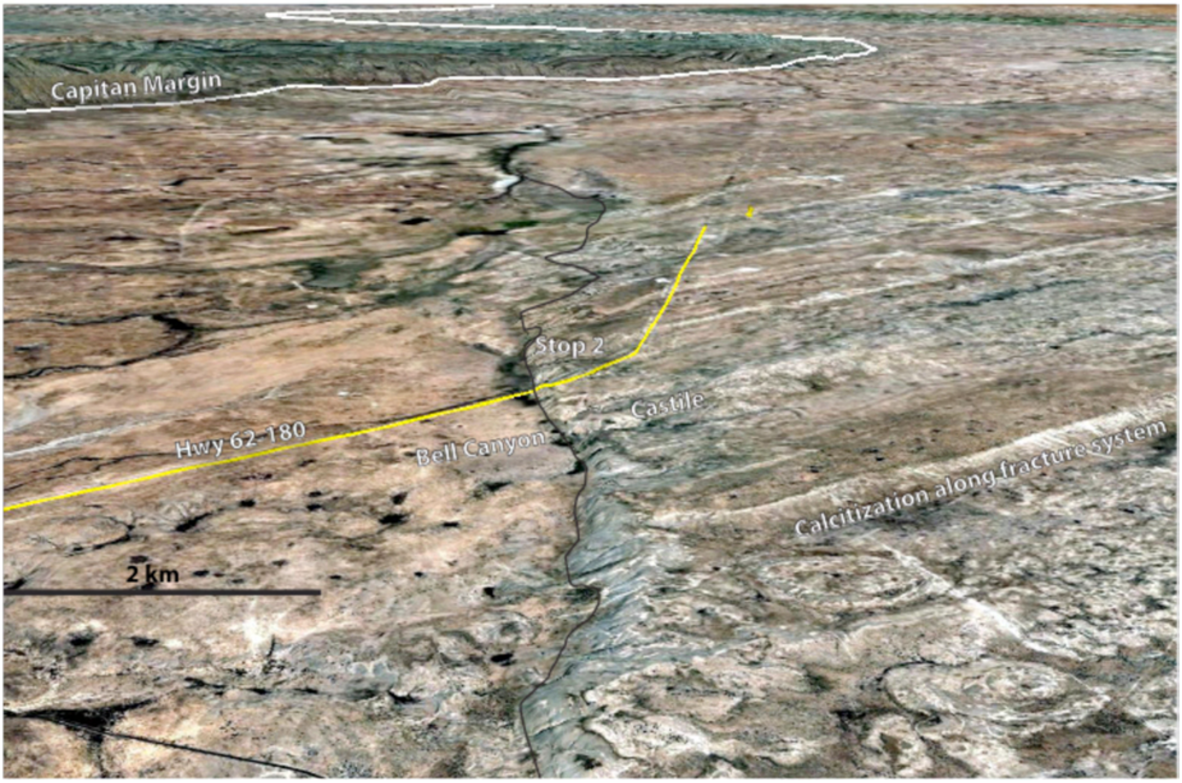


Figure 9. Perspective view of Stop 1-2, Castile Formation, Delaware Basin. This view from Google Earth shows the erosional escarpment formed by the Castile (to the right of view), as well as where we will view the Castile where Hwy 62-180 cuts the escarpment. N–S-oriented fractures are prominent and are a result of calcitization of sulfates by sulfur-reducing bacteria introduced by groundwater.

Anderson (numerous publications; 1982) and Kirkland et al. (2000) have shown that the Castile was derived from Permian seawater brine enriched some 225X over seawater. On the basis of spectral analysis, these workers suggested that the carbonate-gypsum couplets observed are annual in nature, with the gypsum layers being summer (high evaporation) and calcite layers being winter (low evaporation) deposits (Figures 10–11). A record of 260,000 varves has been counted and correlated extensively around the basin. If the interpretation of annual varves is correct, then this would make for a rapid accumulation rate of 1.5 m/ky (600 m in 260 ky). Varve counts and thickness variations show a distinct Milankovitch bundling in the 20 and 100 ky range, with a strong millennial signal at 2600 years (Kirkland et al., 2000).

Another common feature of the Castile and many other layered evaporate deposits is the intrastratal folding observed. Two possible explanations for the folding here are that (1) it is a result of anhydrite hydrating to gypsum in a near-surface setting causing layer-parallel extension and associated folding, or (2) regional tectonically driven shortening.

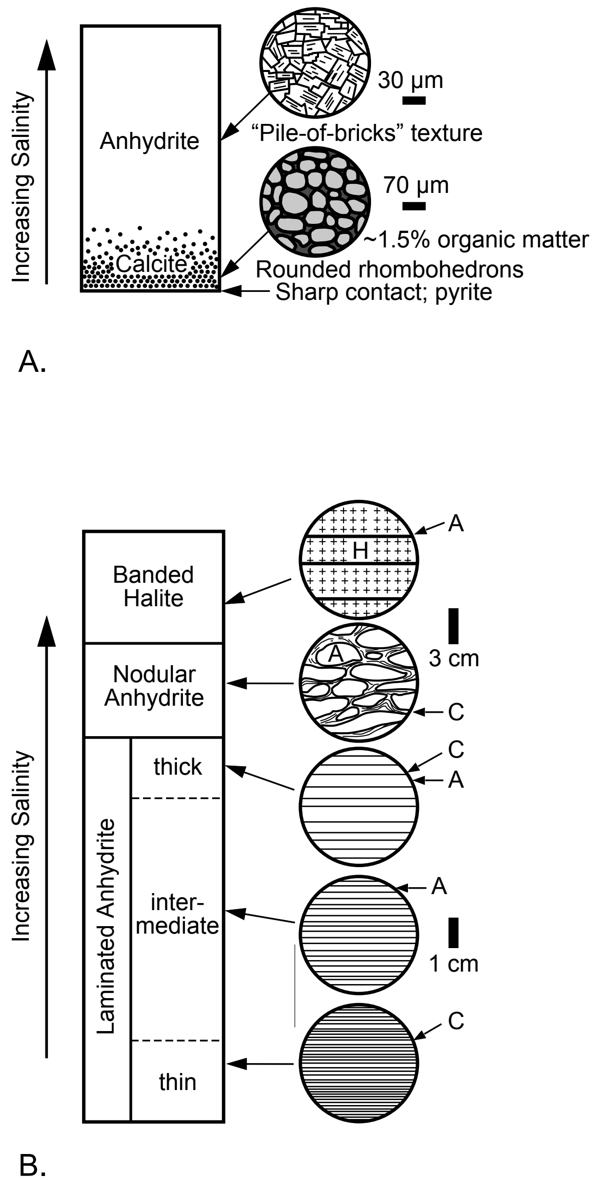


Figure 10. Geochemical/climate significance of carbonate-evaporite varve patterns. From Kirkland et al. (2000).

Figure 11. Calcite-gypsum couplets thought to be varves found at Stop 2. The periodicities observed are thought to be (1) annual varves of calcite to anhydrite, (2) bundles of thicker gypsum laminae to thinner laminae alternating on a 20 ky or 100 ky signals. Additional variants include those with halite.

One of the recent debates regarding the origin of the Castile evaporite is whether the basin witnessed a major draw-down similar to the Messinian crisis in the Mediterranean, or whether the basin remained near filled, and evaporites accumulated as pelagic cumulates. Kendall and Harwood (1989) argue for the draw-down model, suggesting that the bromide concentration in halites within the Castile were anomalously low for marine halites. Kirkland et al. (2000) have countered this argument, suggesting that the sulfur isotopes and Sr isotopes are consistent with a Permian seawater origin and do not support the shallow basin model that would have required significant meteoric modification of the sulfates. An important aspect that is generally not considered by proponents of the draw-down model is that no siliciclastic sediments enter the basin during evaporite deposition, as one might expect if sea level was held well below the shelf margin.

The classic Castile roadcut has fallen prey to the latest road project, and the quality of the exposure is now greatly reduced. We will have material on hand in case we are not able to see all the key features. The present-day surface terrain developed on the gypsum deposits is unique, with numerous karst sinks and caves having been documented throughout the gypsum outcrop belt. A second group of distinct features of the Castile geomorphology are the mound-like hills referred to as Castiles. These distinctive hills are a product of calcitization of sulfates that occurs as sulfate-reducing bacteria are introduced to the evaporites by meteoric waters carried along fracture systems.

Relevance to Mars

This stop provides access to a very thick succession of "layered" gypsum deposits. The gypsum contains some anhydrite, and the sulfates alternate at a mm to cm scale with carbonates (calcite, dolomite). As described above, there is some controversy over the water depth of deposition, however, most workers agree that these deposits record "basinal" water depths — on the order of 10s to 100s of meters.

It is possible that some of the thick, laterally extensive sulfate deposits on Mars formed in this way — due to evaporative drawdown of hypersaline water bodies. If so, none have yet been described. Note the fine lamination, and absence of depositional features suggestive of strong traction currents (e.g., cross-lamination). If we saw this with a rover, what observations would you make to arrive at a similar state of knowledge? In this case, the Mars Science Laboratory (MSL) payload would actually do a remarkably good job of obtaining a suite of observations/measurements similar to what could be done using analytical facilities on Earth.

Thick sulfate deposits are known to be especially well-developed in the Vallis Marineris, which may have formed an enormous sedimentary basin system. In particular, Juventae Chasma (see Figures 12a and b) and Candor Chasma are notable for their well-developed layered deposits formed of sulfates (Murchie et al., 2009), see Figures 12a and b.

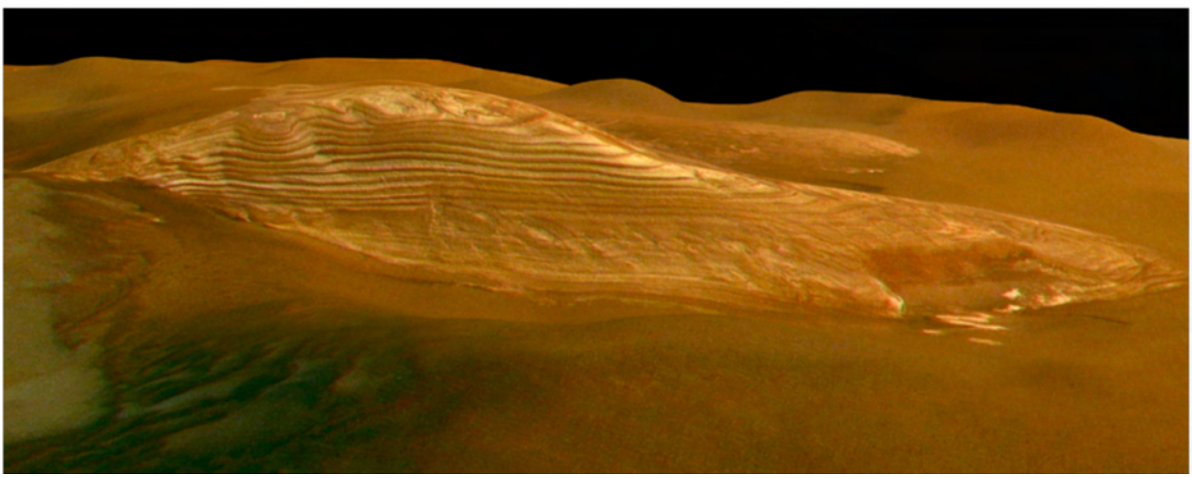


Figure 12a. Thick layered deposits in the center of Juventae Chasma. These deposits are over 2 km thick and have an unknown origin. Possibly they precipitated from an evaporating body of water. Other interpretations include: acidic alteration of volcanic ash to form sulfates as a weathering product; precipitation of sulfates as groundwater-supplied cements between grains of other composition; accumulation of windblown sulfate-rich sands or other sediments. (Image credit: ESA/DLR/FU Berlin, G. Neukum)

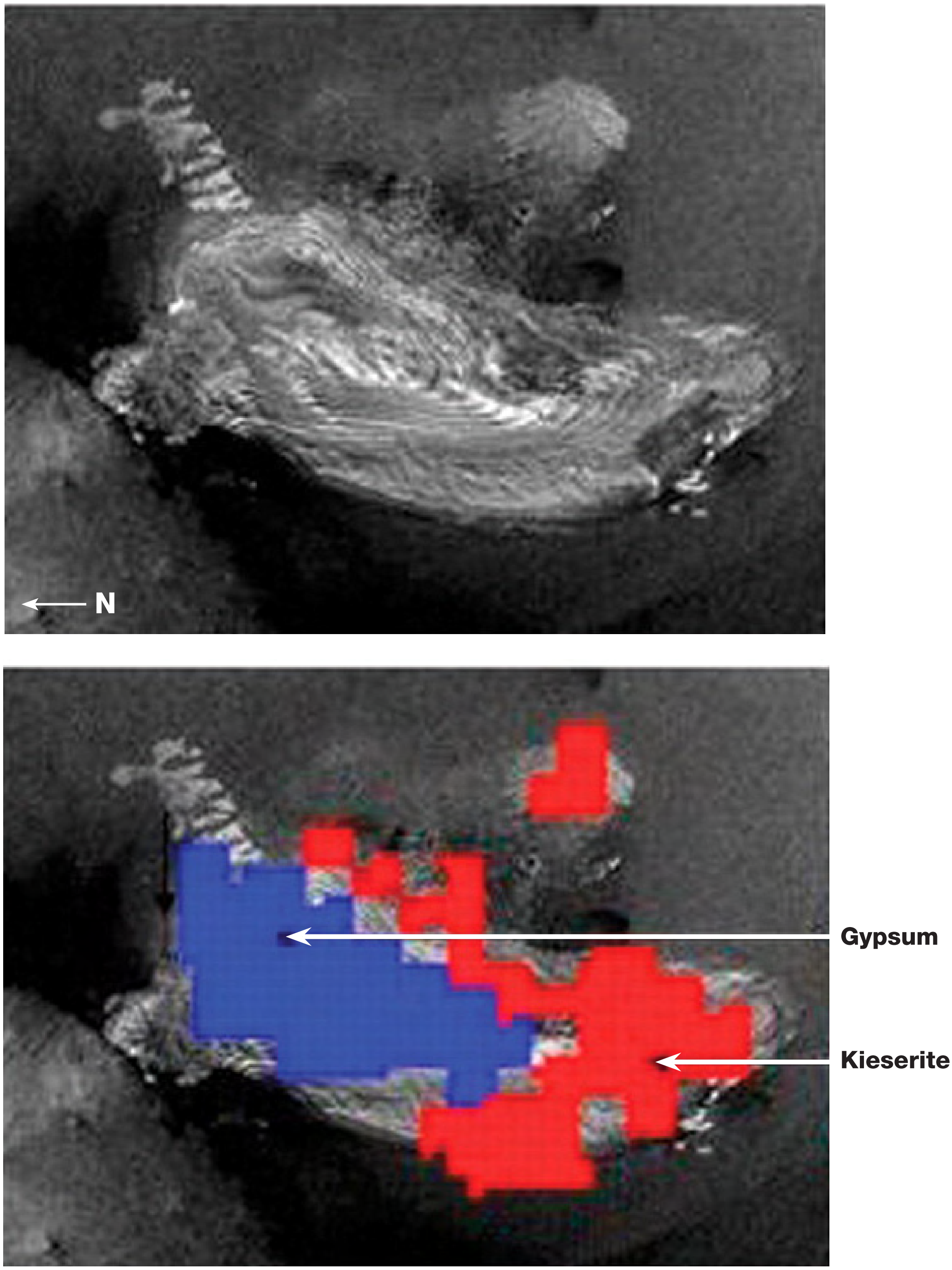


Figure 12b. OMEGA (Mars Express) data show compositional variation in the stratigraphy of the Juventae sulfate deposits. The lower deposits (colored in red) are thought to be composed of kieserite (monohydrated magnesium sulfate), whereas the upper deposits (blue) are thought to be composed of gypsum. From Bibring et al. (2005).

Day 2 Field Stops

Introduction

The Upper Permian Capitan formed as a reef-rimmed marine shelf attached to land, at 5–10 N latitude in a very arid setting. Thus, the association of reefal carbonates, siliciclastics, and sulfates is to be expected. The generalized facies scheme for the Capitan system consists, from landward to seaward, of an evaporite inner shelf, mixed carbonate-clastic middle shelf, and carbonate outer shelf/margin. The evaporite inner shelf is a transition from terrestrial clastics derived from further updip to the more marine portions of the shelf, and was perhaps a sabkha or an extremely restricted circulation portion of the innermost shelf. This inner shelf consists of interbeds of anhydrite, also halite further updip, siltstones, and dolomudstones. The mixed carbonate-siliciclastic middle shelf contains interbeds of dolomudstone and wackestone, siltstones, and sandstones. The carbonate-rich outer shelf and margin consists of diverse depositional settings consisting of muddy carbonate tidal flats, a tepee-pisolite shoal crest, shingled beach-foreshore grainstones, an outer shelf of subtidal carbonates, a reef rim, steep foreslope breccia complex, and basinal carbonate mudstones.

Yesterday, we visited this transect from the basin-side, driving through and stopping to examine strata of the Delaware Basin and discussing the imposing outcrops of the outer shelf and margin along the Reef Escarpment. At the stops in Rocky Arroyo and the Seven Rivers Embayment, we see the downdip portion of the evaporitic inner shelf and the transition into the mixed carbonate-clastic middle shelf (Figures 13–14). This morning, we will examine a seaward to landward facies transition from carbonates through carbonate-gypsum interbeds, and finally into carbonate-siliciclastic-gypsum interbeds. We will examine this transition using both outcrops, and hyperspectral data using two roadcut stops, an overview stop, and a hike up Tepee Hill at the end.

The main work published on this facies transition is by Sarg (1981) who used 7 measured sections through the 80-m-thick Seven Rivers Fm. section across a 4-km-wide outcrop belt. In simple terms, the more seaward deposits consist nearly entirely of dolostone with cyclic subtidal domal stromatolite to laminar and fenestral algal mat cycles. Moving landward, outcrops show cycles of algal mat carbonates, siltstones, and solution-collapse breccias that record the presence of removed gypsum. The most updip outcrops at Tepee Hill are of dolomudstone to gypsum to red siliciclastic mudstones cycles. These deposits are the record of initial marine transgression and “freshening” of the water column, followed by evaporation and precipitation of evaporites, and finally drying out of the sabkha and occupation of the shelf by wind and wadi-associated red mudstones.

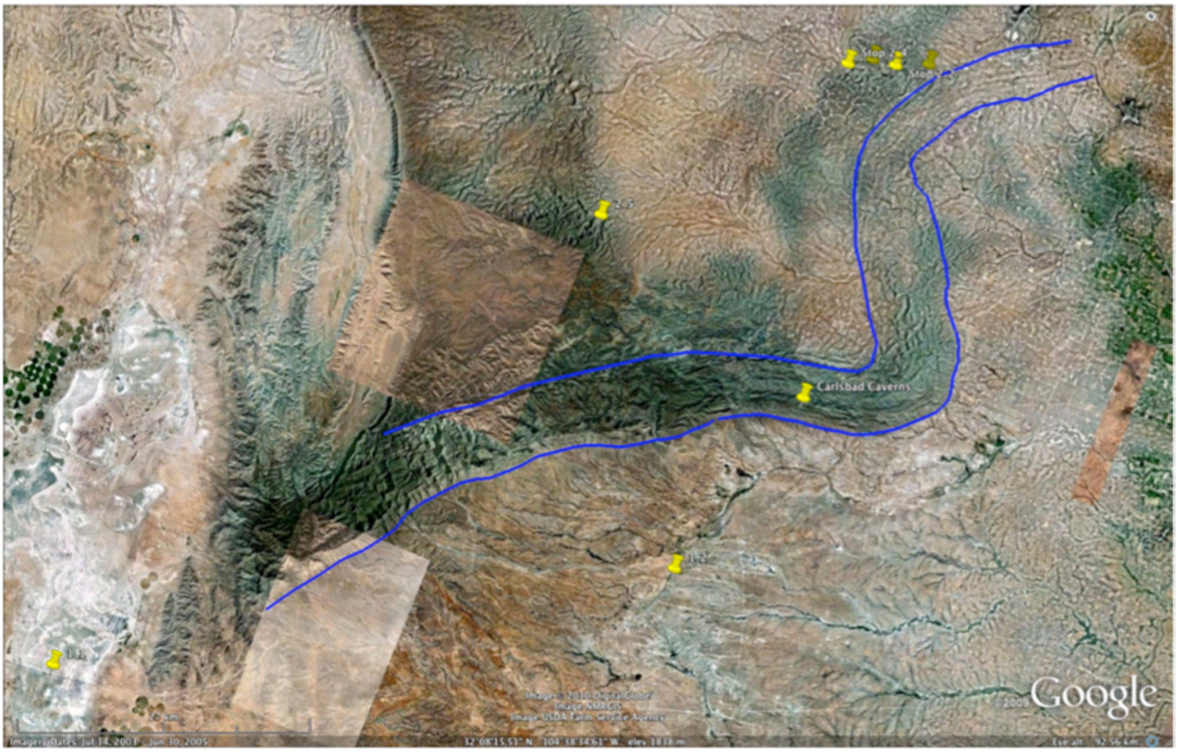


Figure 13. Overview of Guadalupe Mountains showing field trip stops. Rocky Arroyo–Seven Rivers Embayment transect stops in the NE part of the Guadalupe Mountains provide a seaward to landward progression into the shelf lagoon from the landward side of the reef margin, which is outlined in blue.

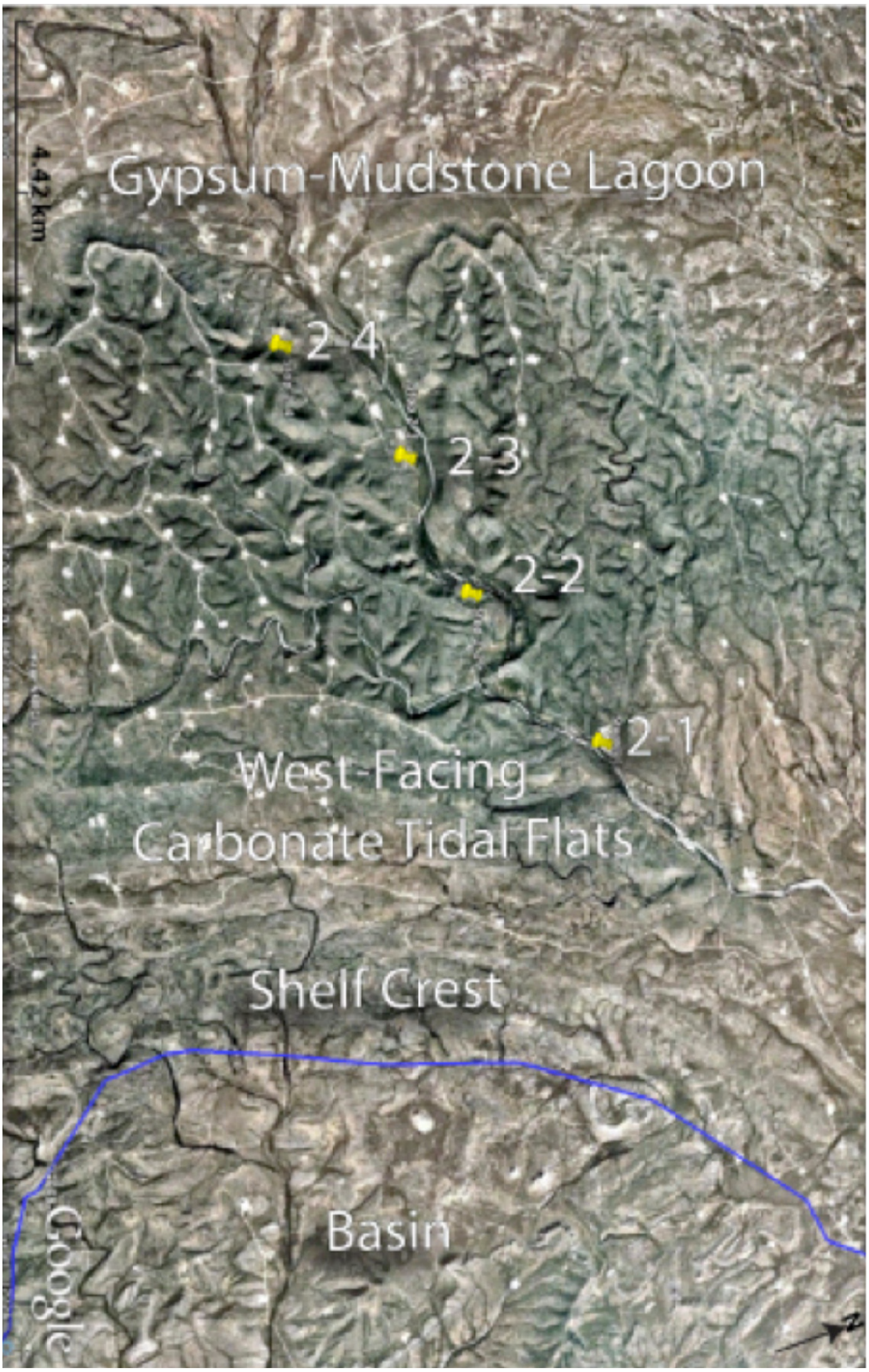


Figure 14. Regional setting of stops through the carbonate to evaporite transition along Rocky Arroyo. Stop 2-1 is of mud-dominated west-facing subtidal to intertidal carbonate cycles; Stop 2-2 is of intercalated carbonate/evaporite breccia to siltstone cycles; Stop 2-3 is an overview stop to view the large-scale evidence for the carbonate to evaporite facies transition; and Stop 2-4 is Tepee Hill, where we will examine dolomudstone-gypsum-siltstone cycles.

Stop 2-1 — Rocky Arroyo Roadcut
Nearshore Carbonates of Seven Rivers Formation

This stop illustrates typical meter-scale upward shallowing cycles composed of basal subtidal domal stromatolites and upper wavy to fenestral laminated microbial mats (Figure 15). This facies tract is dominated by carbonate muds that were likely generated locally or transported landward from the marine outer shelf crest 2–3 km seaward.

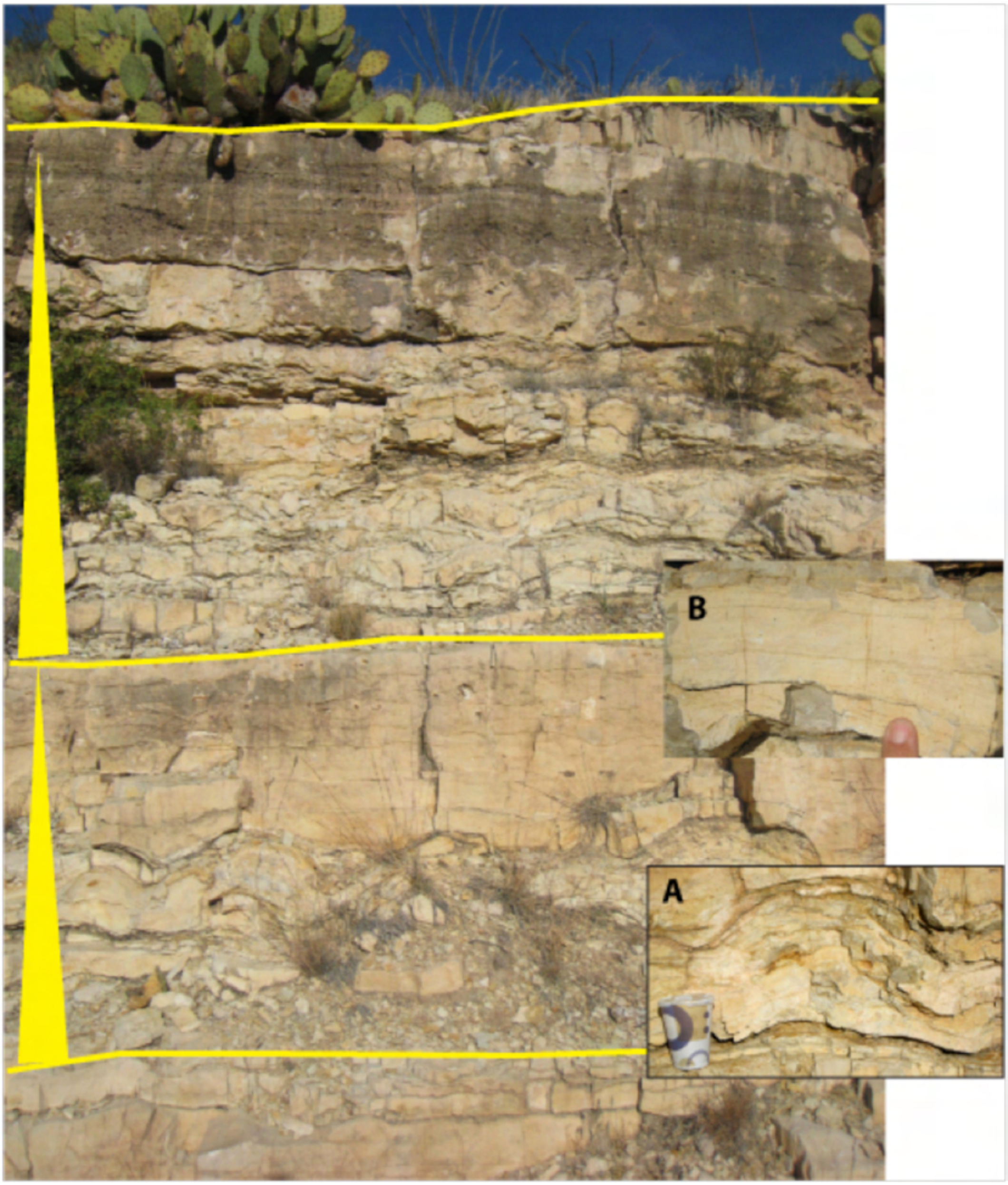


Figure 15. Carbonate peritidal cycles characteristic of the carbonate-dominated landward margin of the shelf crest. (A) Typical hemispherical subtidal stromatolite of cycle base. (B) Smooth microbial laminite of upper intertidal setting associated with cycle cap.

Relevance to Mars

The observation of stromatolites in sedimentary rocks on Mars would be considered by many to be prima facie evidence for the former presence of microbial mats on the ancient surface of Mars. Indeed, there is no single sedimentary texture that a rover could observe that would generate more excitement — and probably generate more debate.

Stromatolites are attached, lithified sedimentary growth structures, accretionary away from a point or limited surface of initiation. Though the accretion process is commonly regarded to result from the sediment trapping or precipitation-inducing activities of microbial mats, little evidence of this process is preserved in most ancient stromatolites (Grotzinger and Knoll, 1999); see Figure 16. The successful study and interpretation of stromatolites requires a process-based approach, oriented toward deconvolving the replacement textures of ancient stromatolites.

We know that stromatolites generally reflect a spectrum of interactions among microbial-mat communities, sedimentation, and carbonate/sulfate precipitation, but we remain in need of models and experiments that will enable us to deconvolve the sedimentary signals encrypted by each contributing process. The common wisdom is that stromatolites result from the trapping and binding of fine sediment by microbial-mat communities, and this does indeed provide the best explanation for a range of stromatolites seen in younger successions. As we go back farther in time, however, precipitated carbonates comprise a larger and larger proportion of the record, and the relationship between mat biology and lamination and microstructure becomes more difficult to interpret with confidence. At the extreme, in Archean rocks and (potentially) in sediments on Mars or other planetary bodies, the role, if any, played by biology can be difficult to ascertain. At no time in the last 3.5 Ga has Earth's surface been sterile, so all stromatolitic structures surely accreted in the presence of biology. The question, then, is not whether organisms were in site as stromatolites accreted, but what roles they played in development and how those roles can be understood from preserved morphology and microstructure (Grotzinger and Knoll, 1999). On a sterile Earth (or Mars), carbonates and sulfates would still be removed from chemically evolved water bodies, and they would likely form precipitated laminates in shallow water environments. Herein lies the caution in interpretation of potential stromatolites on Mars.

The conclusion that biology played a role in the accretion of most stromatolites does not equate to a statement that secular changes in stromatolite form or microstructure reflect changes in the mat-building biota. Testable hypotheses about the role of evolution in driving stromatolite morphology require that one must articulate the features of stromatolites that most directly reflect biology, and explain how evolution can account for observed changes through time. To date, this has not been accomplished. Whether longstanding interpretations of stromatolites as "evolutionary mileposts" can be sustained will require quantitative studies of stromatolite morphologies, to search for forms that can be shown to be uniquely biologic, coupled with detailed analyses of microfabric in which the influences of precipitation and diagenesis have been removed.

In contrast, we can be relatively confident in our assessment of how environmental change has contributed to the stratigraphic distribution of stromatolitic forms and textures. Thus, a promising avenue for continued research lies in the use of Proterozoic stromatolites as “environmental dipsticks”—as sensitive proxies for the evolution of ocean or lake water. Changing water chemistry undoubtedly contributed to the observed stromatolite record. The outstanding question is whether environmental change can account for all of the stratigraphic variation observed by geologists.

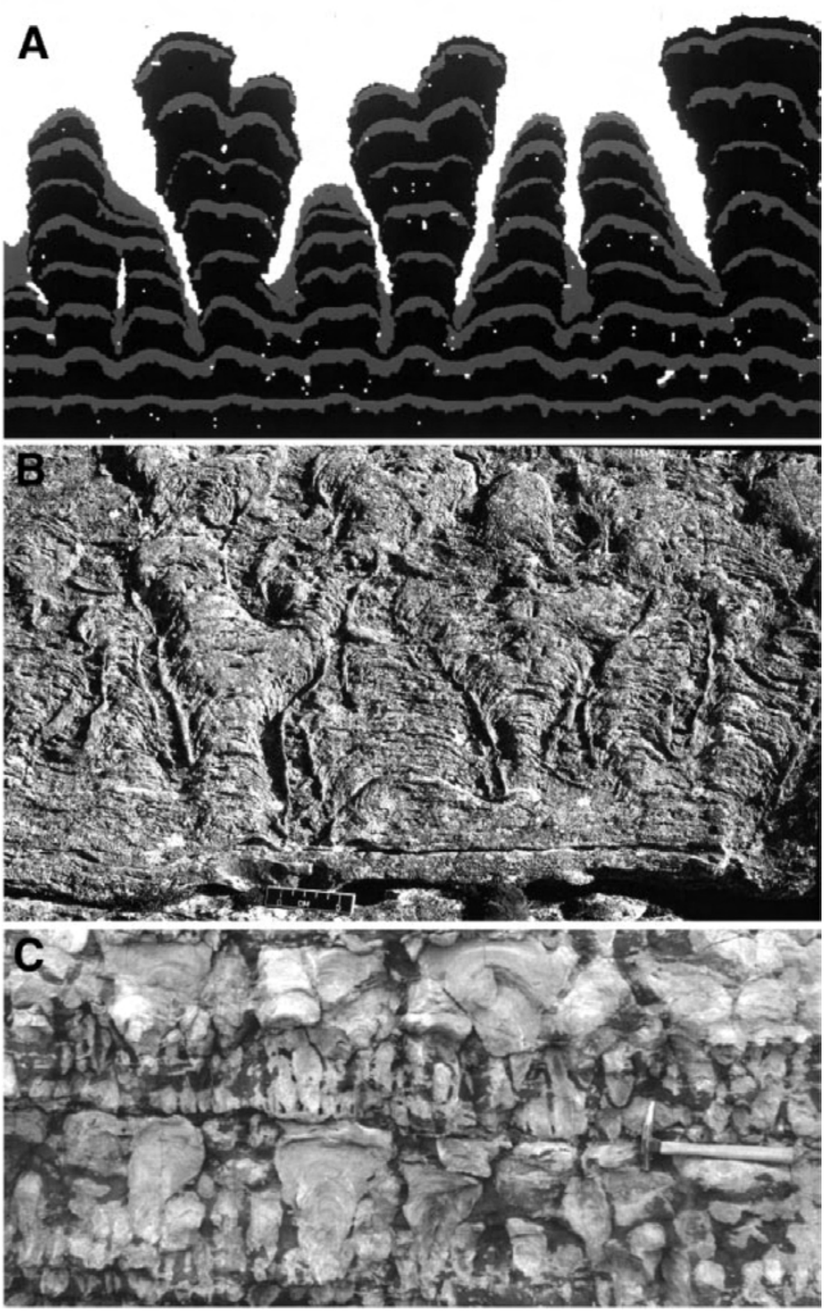


Figure 16. Stromatolite growth model from Grotzinger and Knoll (1999) and comparison to ancient stromatolites. (A) Growth model based on diffusion-limited aggregation and episodic sedimentation. Initially the interface is allowed to grow through diffusion-limited aggregation, which simulates the growth of either microbial mats or precipitating minerals (dark layers). After some time, the interface has become rough, and sediment is allowed to settle down onto the rough surface (light layers). It is assigned a lateral mobility and therefore can migrate into depressions; in doing so, it partially damps the preexisting topography. However, this process is incomplete, so the next interval of upward growth builds selectively on the remnant highs, reinforcing their topography. As long as the thickness of sedimentation events does not exceed some critical value, the growing interface eventually will produce branched columnar structures, similar to certain ancient stromatolites. Note that, in the late stages of growth, depressions are filled only by sediment. (B) Branching columnar stromatolites of the Paleoproterozoic Talthelei Formation, northwest Canada, showing strong similarity to model results. (C) Columnar stromatolites from Mesoproterozoic Debengda Formation, Siberia, also showing strong similarity to model results.

Stop 2-2 — Rocky Arroyo Breccia Roadcut
Mixed Lithologies and Diagenetic Overprint of Seven Rivers Formation

The first occurrence of relict evaporites is present in this outcrop, now 4 km landward of the shelf margin. Evidence for the former presence of evaporites comes from brecciated zones of dolostone that presumably collapsed when gypsum was dissolved from the unit during later diagenesis (Figure 17). In addition to the introduction of thin gypsum beds (breccias), we will observe siliciclastic sediments in significant abundance for the first time. These clastics are sourced from the platform interior and decrease in abundance in a seaward direction.

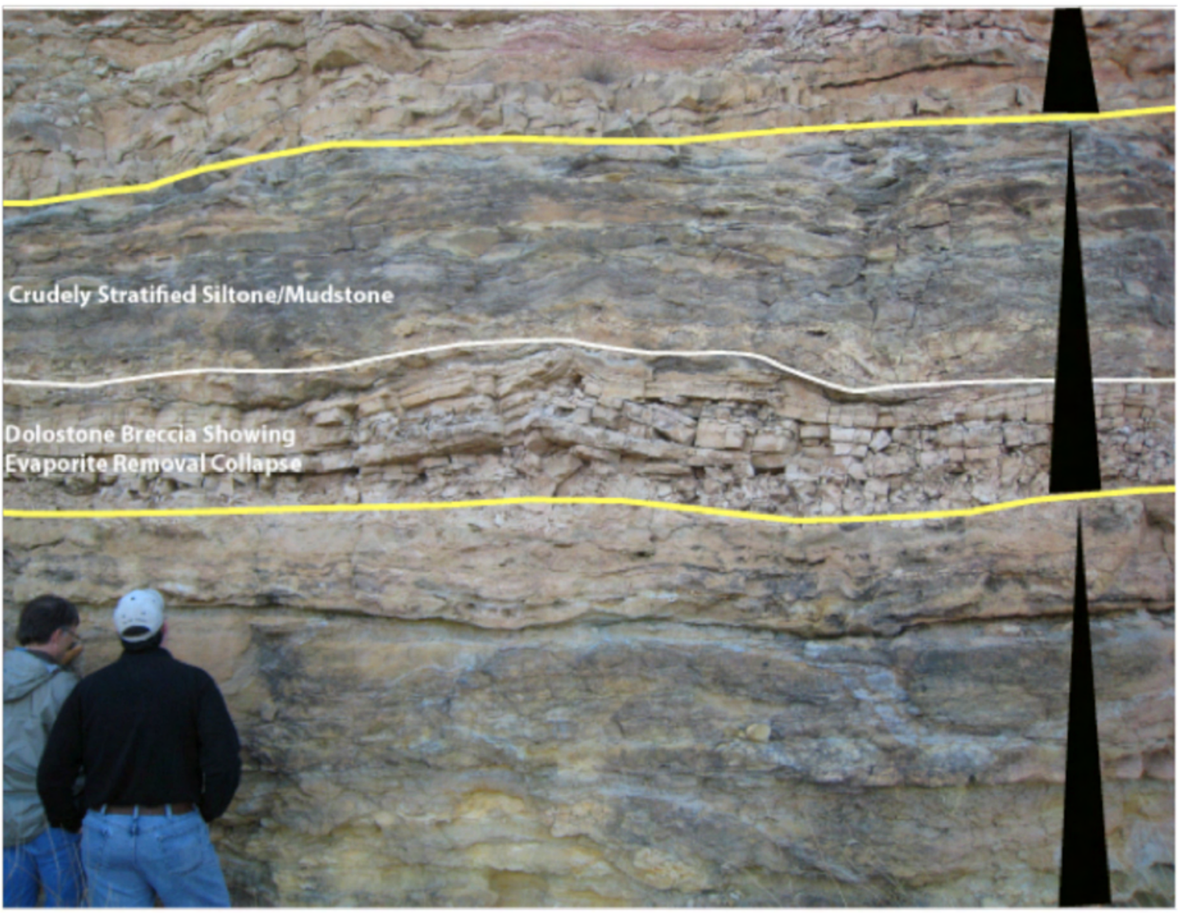


Figure 17. Mid-shelf cycles with carbonate-evaporite breccia basal units and siliciclastic caps. Brecciated dolomudstones are clear evidence for vanished gypsum.

Relevance to Mars

Breccias formed in association with sedimentary rocks are a common occurrence on Mars. It is likely that there are many distinct origins. However, there are some terrains (known as "chaos") for which dissolution of soluble minerals has been suggested, in addition to other, more conventional ideas such as the melting of water ice. Channeled surfaces often lead from these terrains, suggesting water was important in forming the breccias. See Figure 18. Crystal dissolution features have also been seen on the surface by the Opportunity rover (Figure 19).

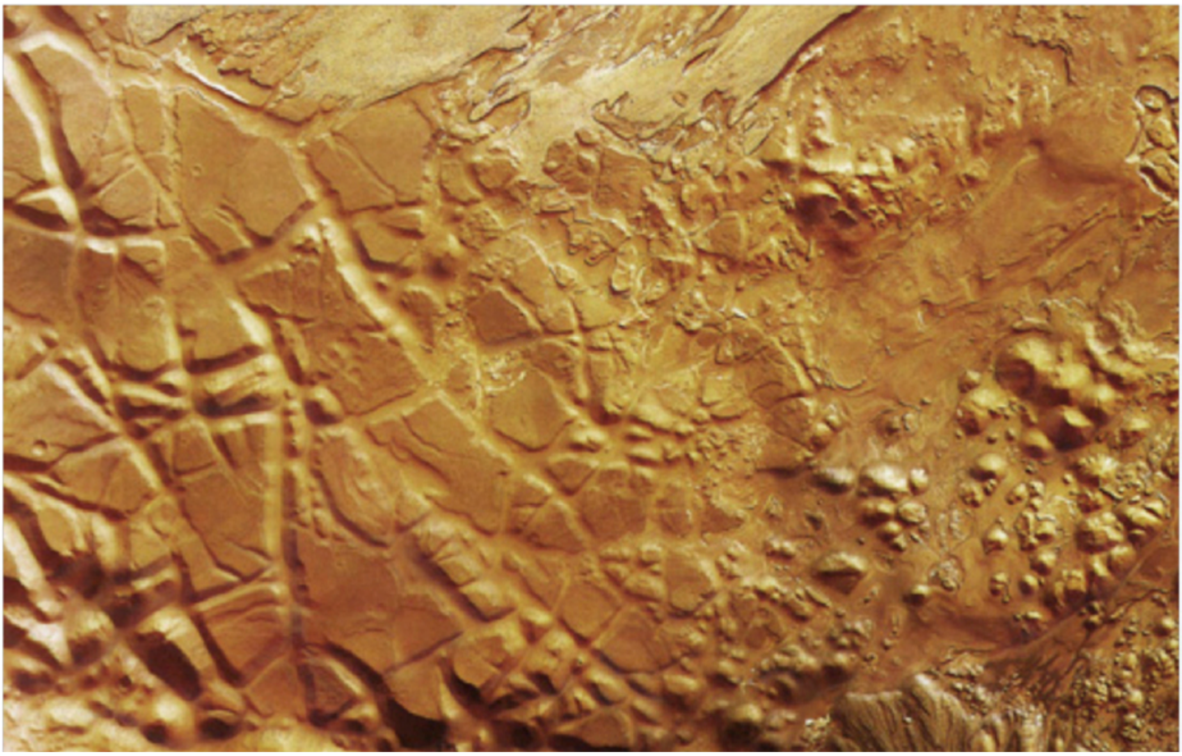


Figure 18. Aram Chaos. The top part of this Mars Express High-Resolution Stereo Camera (HRSC) color image is characterized by brighter material, which seems to be layered and could be the result of sedimentary deposition. Some scientists believe that the numerous chaotic regions located in the eastern part of Valles Marineris were the source of water or ice thought to have created the valleys that extend into Chryse Planitia. The origin of the breccias is debated, and may be related to discharge of ground water, accompanied by melting of ice, or dissolution of soluble minerals. Scale: image is 10 km in width. (Image credit: ESA/DLR/FU Berlin, G. Neukum)

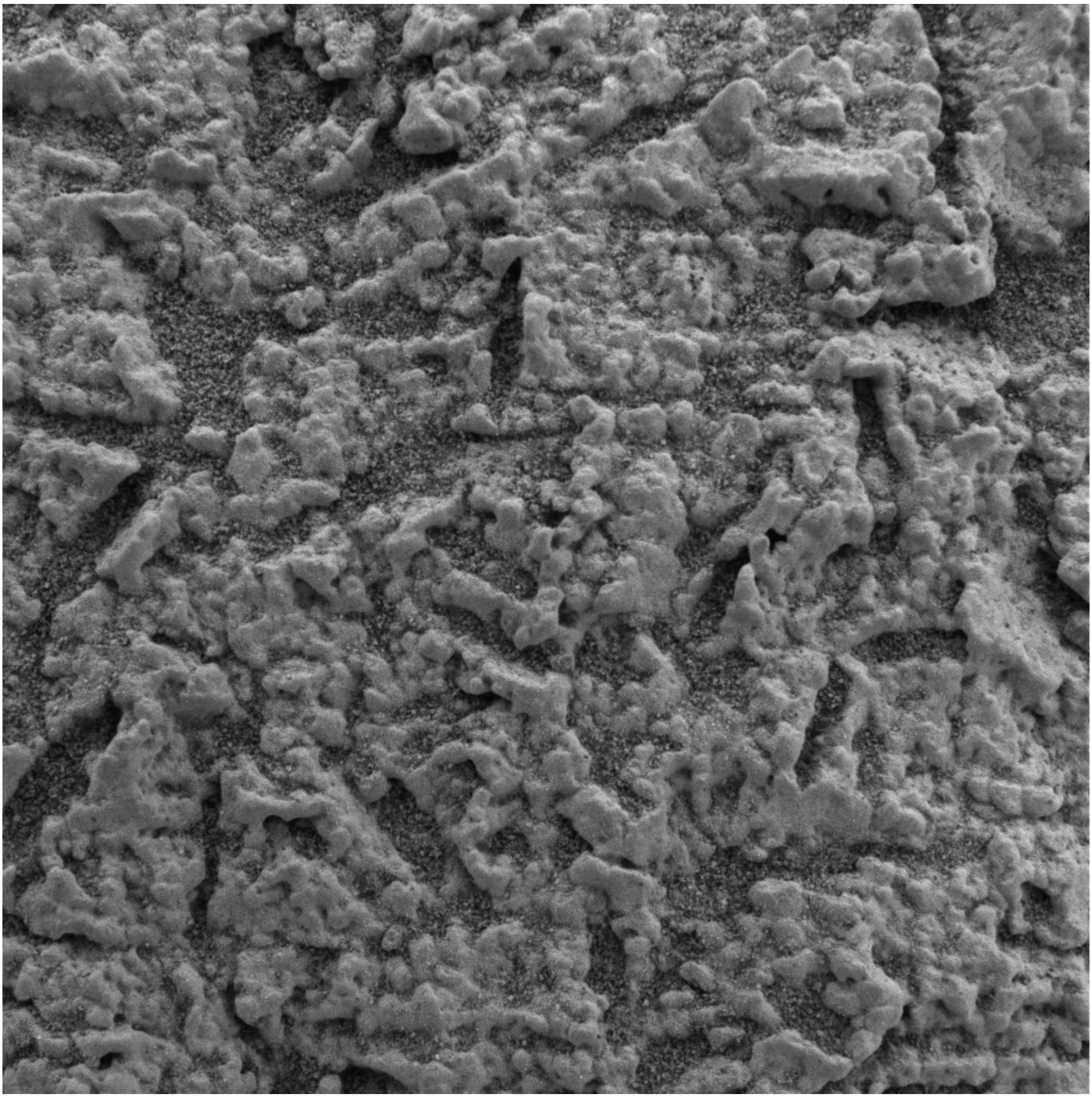


Figure 19. Opportunity Microscopic Imager view showing crystal dissolution features. From “El Capitan” at Eagle Crater, Mars. View is approximately 3 centimeters across.

Stop 2-3 — Seven Rivers Embayment Overview
Carbonate to Evaporite Facies Transition in Seven Rivers Formation

The Seven Rivers Formation consists of interbedded carbonates, evaporites (gypsum/anhydrite) and gypsum-rich silty red beds that capture the carbonate-evaporite facies change (Figures 20–21). The overall proportion of sulfates relative to carbonate minerals increases in the rocks as one moves back from the shelf edge to the back-reef environment. This change is quite abrupt and the mineral assemblage transitions from dolomite to gypsum-dominated over a lateral distance of only ~160 meters (Sarg, 1981). This transition runs parallel to the basin edge and occurs ~10–15 km

Figure 20. Carbonate-dominated exposure proximal to the shelf-crest. Note the dominance of cliff-forming dolostone beds, with thin siltstone parting planes. Sub-parallel undeformed layering indicates that no evaporite has been removed from this section. Thus, this location on the shelf was on the seaward side of the evaporitic lagoon.

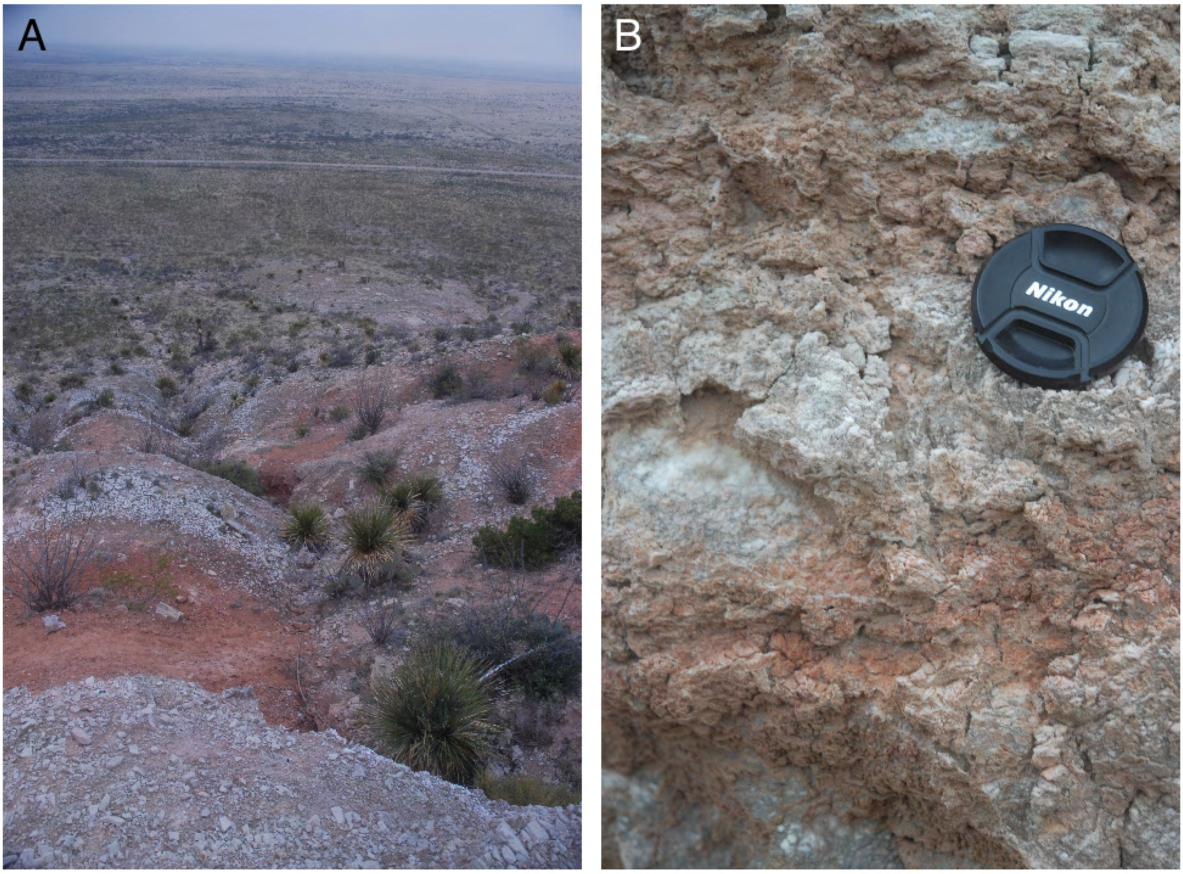


Figure 21. Interbedded sulfates (gypsum/anhydrite), carbonates and red beds of the Seven Rivers Formation. Note the differences in weathering texture between beds and the abundant red soil covering over much of the outcrops. The latter can obscure the presence of sulfates in AVIRIS and ASTER data, similar to the effects of dust covers on martian outcrops. (A) View from top of section used for MSL field test. (B) Close-up of sulfate weathering textures.

shelfward of the basin (Sarg, 1981; see map in Figure 22). The beds are 1–10 meters thick and the sulfate intervals often exhibit nodular and gypsum rosette textures. These rocks are interpreted to have been deposited in a stable, shallow, restricted marine environment, and the abundance of evaporite minerals suggests hypersaline conditions were achieved.

Reflectance spectra acquired by the AVIRIS airborne spectrometer are consistent with the presence of gypsum and dolomite, and ~4 m/pixel spatial resolution of the instrument also captures the interbedded nature of these phases (Figure 23). In addition, lower spatial and spectral resolution ASTER data can also be used to differentiate between these two rock types over the region as a whole (Figure 22). These data also highlight the appearance of evaporite facies in the backreef (Figure 22C) relative to the strong carbonate signatures along the shelf edge.

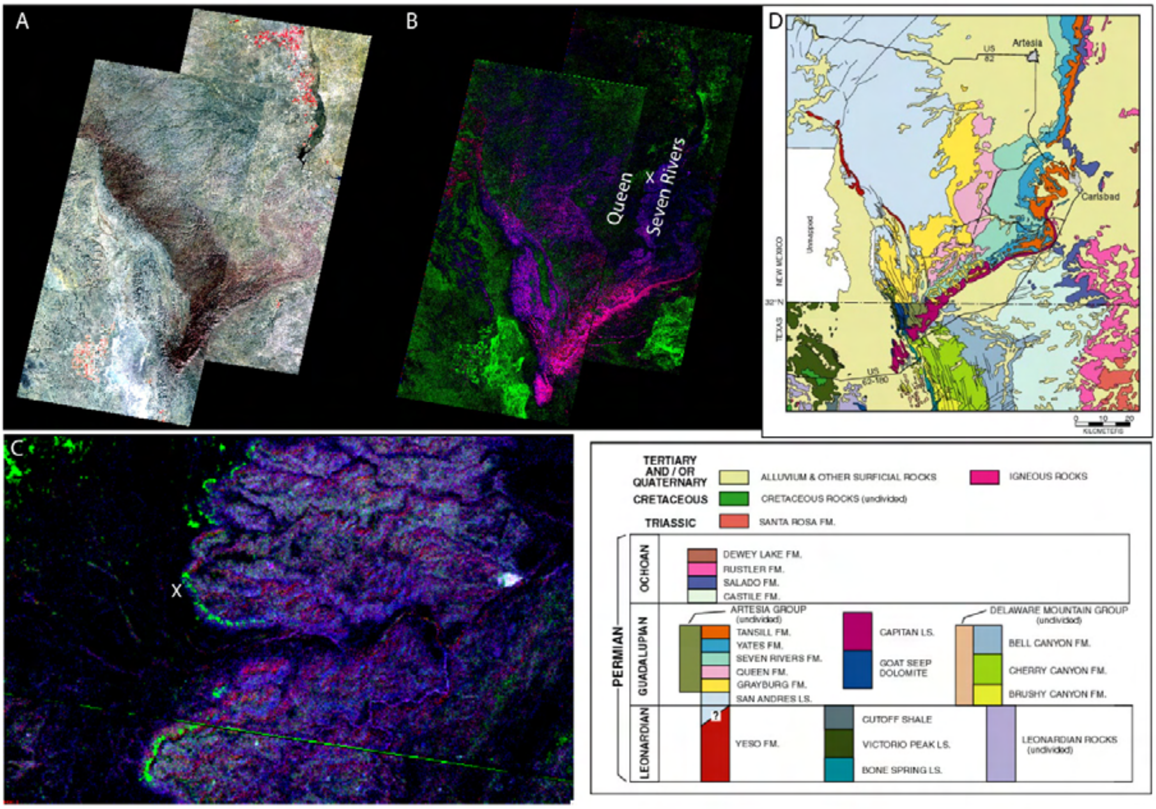


Figure 22. (A) ASTER false-color image of the Guadalupe Mountains. (B) Mineral parameter map derived from ASTER visible–near infrared data. Carbonates are in pink/blue tones and sulfates (gypsum) are bright green. The white "X" designates the location of the field stop (Figure 23). (C) Close-up of area around MSL field site ("X"). (D) Geologic map and legend compiled by Peter Scholle, 1992.

Relevance to Mars

Sulfates, carbonates, and clay-rich beds have all been observed on Mars from orbit (e.g., Gendrin et al., 2005; Poulet et al., 2005; Ehlmann et al., 2008), and in some locations, such as Gale Crater, there is strong evidence for interbedded sulfates and clays. Although there is no evidence for carbonate reefs on Mars (and thus this back-reef environment may not be a direct analog for martian deposits), evaporite facies such as these and their mineralogical and weathering trends can be quite informative. Indeed, interbedded sulfate and clay deposits on Mars may also have formed in lagoon/shallow environments and be laterally adjacent to deeper water facies. By studying these terrestrial deposits using remote-sensing techniques we can evaluate our ability to 1) detect specific minerals such as carbonate, gypsum, and clay, 2) estimate "true" modal abundances of those minerals for rocks and outcrops, and 3) detect lateral transitions in paleoenvironments. The latter can be particularly useful when

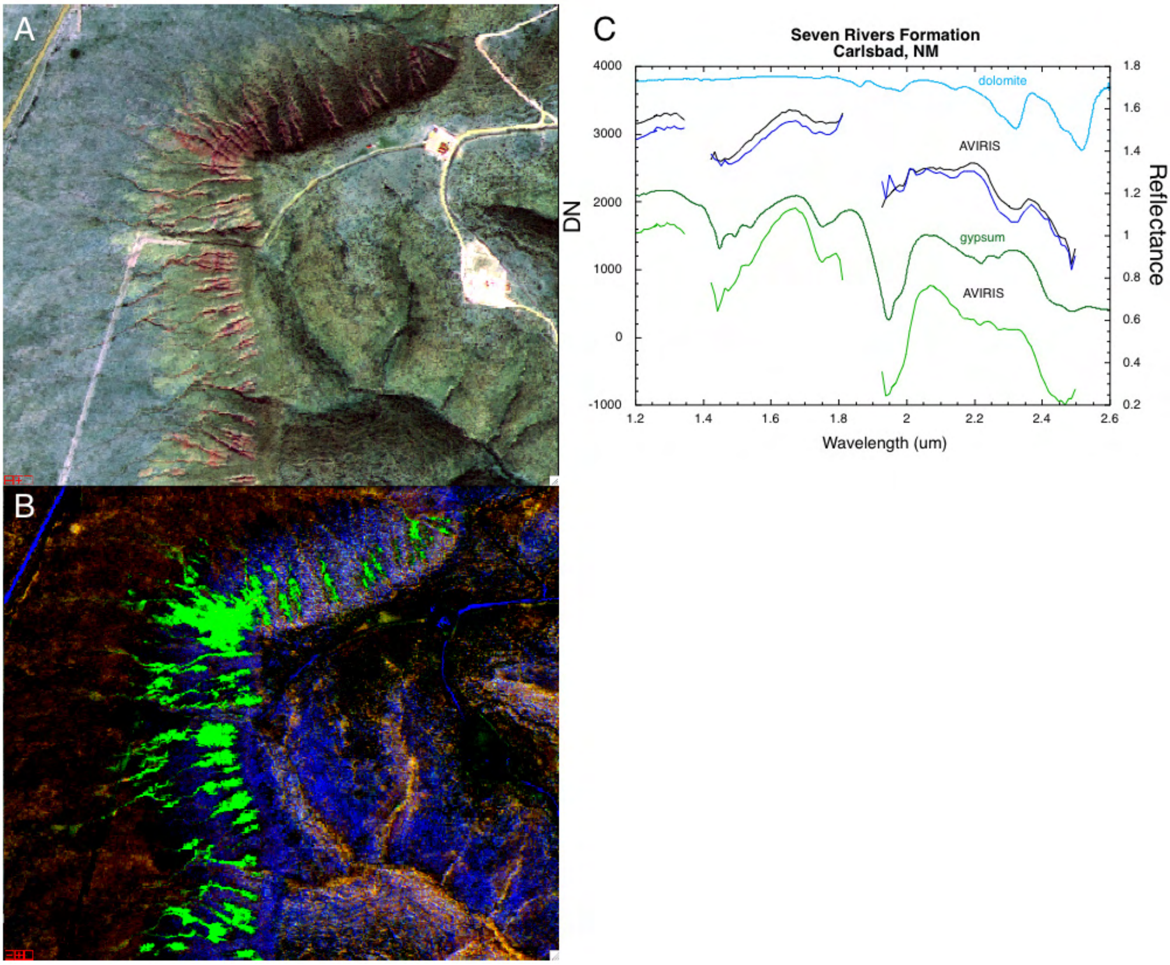


Figure 23. (A) Portion of an AVIRIS image over the Seven Rivers Formation; location is that used for the 2007 MSL slow motion field test. (B) Mineral parameter map highlighting the presence of vegetation (red channel), carbonate (blue channel), and gypsum (green channel). Note the interbedding of the dominant mineral phase and the strong signatures associated with the gullies (minimum soil cover). (C) Representative AVIRIS spectra for gypsum and dolomite beds.

limited to orbital data, as is the case for Mars, when attempting to infer a depositional system for outcrops in a given region. Because of its mineralogical relevance to Mars, this location was used as the site for the Mars Science Laboratory rover "Slow Motion Field Test" exercise in the spring/summer of 2007. Much of the gypsum/anhydrite is covered by soil and the weathered red beds and is not readily observed at the optical surface. However, note the weathering textures of the sulfates/red beds and classic "chicken-wire" texture observed in the gypsum/anhydrite beds; if such features were observed by a rover on Mars then they may indicate the presence of sulfates, even if remote mineralogical evidence is lacking due to dust/soil cover. Therefore, microscopic and macroscopic textural and weathering styles such as those observed here may also be important on Mars.

Stop 2-4 — Seven Rivers Embayment Outcrop Evaporite Facies in Back-Reef Setting of Seven Rivers Formation

Tepee Hill (Figure 24) lies on the landward side of the exposures of the carbonate-evaporite transition. Here the ratio of dolostone to gypsum to siliciclastic mudstone is 10-30-60. The surface weathering has transitioned from the cliff-forming dolostones to the soft-weathering slopes of the mudstone/gypsum succession.

Figure 24. Aerial view of Tepee Hill, where gypsum-red mudstone and dolomudstone-gypsum-red mudstone cycles characterize the evaporitic shelf lagoon. The section exposed is approximately 70 m, and shows distinct bundling of gypsum-dominated cycles (lower) passing into mudstone-dominated cycles (middle) and finally carbonate-dominated cycles.

Stop 2-5 — Last Chance Canyon Overview
Prograding Carbonates and Siliciclastics of the San Andres Formation

Last Chance Canyon is one of the most visited localities within the Guadalupe Mountains because it is possible to observe from a single vantage point all the key stratal geometries that are commonly associated with a single rise and fall of sea level, or depositional sequence. The stratal geometries of a classic depositional sequence include three basic packages of strata, associated with rising sea level (transgressive systems tract), slowly rising, stable, or slowly falling sea level (highstand systems tract), and rapidly falling sea level (lowstand systems tract). The history of this record of changing sea level has been read from the combination of detailed sedimentologic observations and from remote observations from across the canyon, as we will conduct. The importance of this approach is that general conclusions regarding changing base level can be derived solely on the basis of stratal architecture, without detailed rock information, regardless of whether the strata here are carbonates, sandstones, or evaporites. This explains the high level of interest in this approach from the oil and gas industry, which many times has to predict the nature of subsurface reservoirs entirely from remote data such as seismic reflection data or well bores.

The main stratal termination (lap) configurations that are observed here on the Wilson Canyon side canyon of Last Chance Canyon are onlap, toplap, and downlap. The single most important sediment object type is the clinothem, or rock-body bound by clinoforms (surfaces). These sigmoidal bundles of strata provide a record of a seaward-building shoreline systems and consist of undaform (flat-lying shelf), clinoform (seaward sloping sediment body), and fondoform (flat-lying basal portion of the clinothem) In some respects this sediment body is reminiscent of a “Gilbert delta,” but is not always a record of river-fed delta progradation, but may also record a prograding shallow marine shelf building into a basin.

In the case of Last Chance Canyon, the clinoforms and associated strata we will observe are part of an older succession than we have been dealing with, being Early Guadalupian in age rather than Late Guadalupian (such as the Capitan reef and associated strata) (Figure 25). These San Andres strata are exposed in Last Chance Canyon and its tributary canyons that allow rigorous examination of 3D stratal geometries of the prograding clinoforms (Figures 26–27). Last Chance Canyon lies 18 km landward of the Capitan shelf margin and whereas clinoform dips in the reef-forereef system of the Capitan are up to 60 degrees into the basin, the San Andres mixed siliciclastic-carbonate clinoforms are characterized by 6 and 15 degree dipping clinoforms.

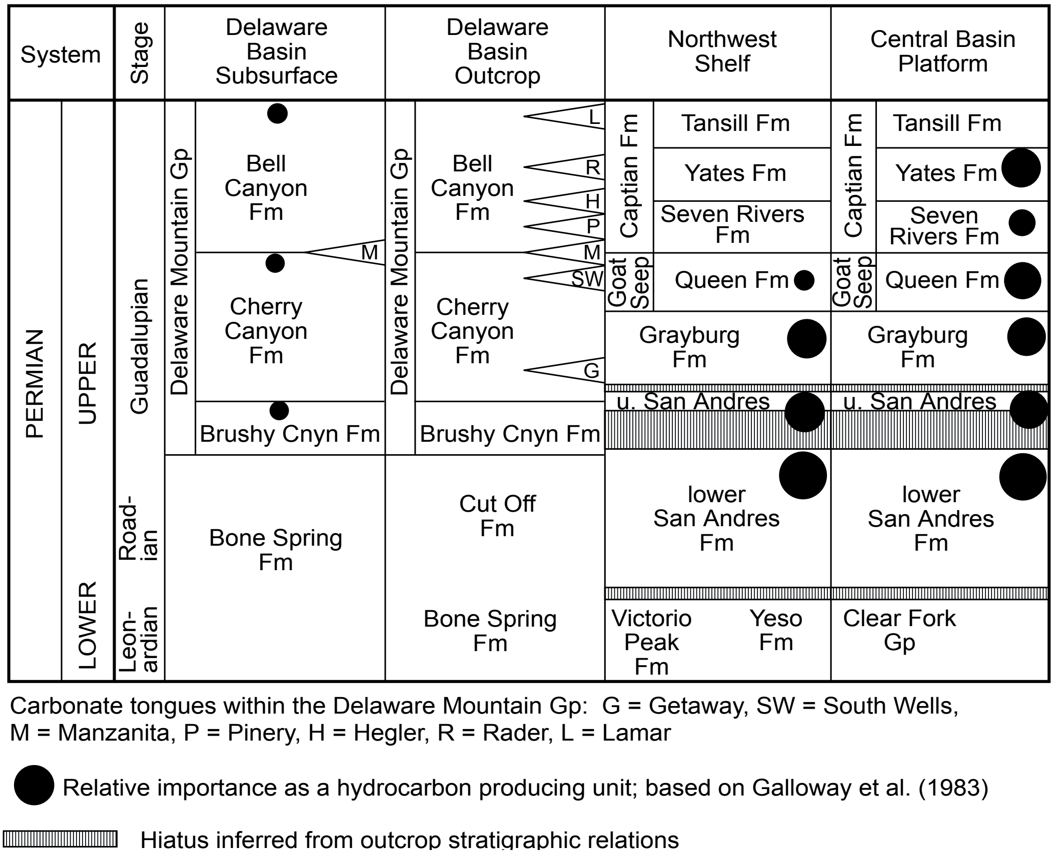


Figure 25. Stratigraphic setting of the San Andres Formation relative to the younger Permian Capitan system.

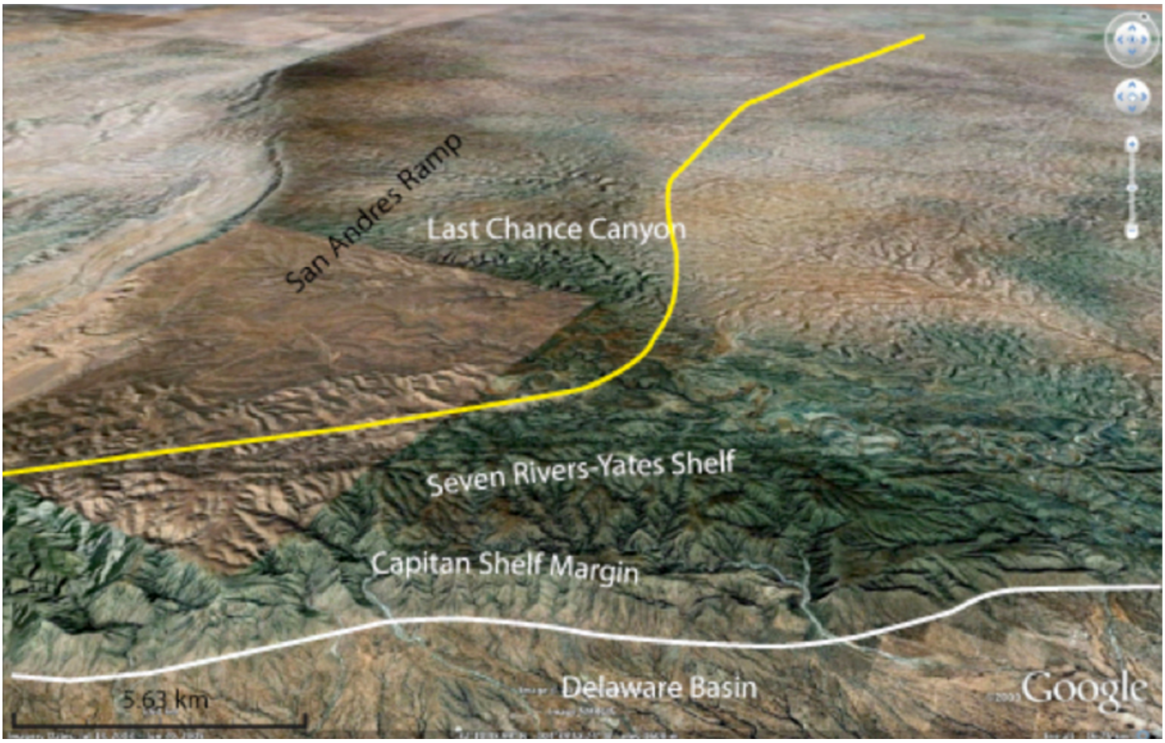


Figure 26. Regional setting of Last Chance Canyon exposures, within the older San Andres Formation carbonate ramp succession.

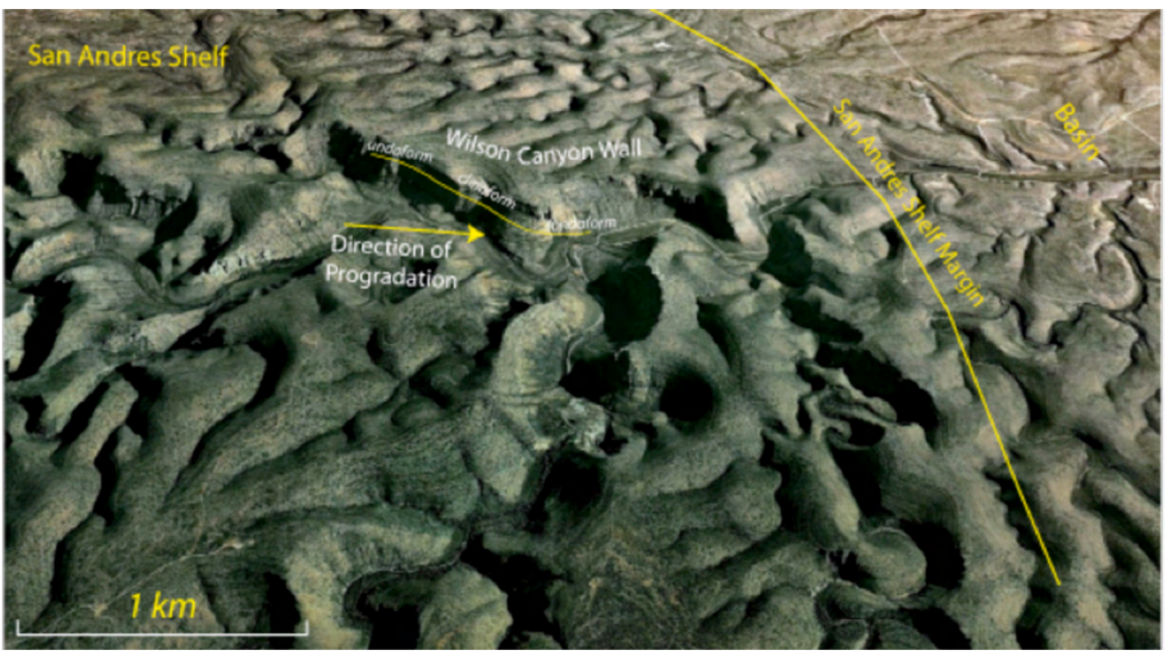


Figure 27. View looking NE at Wilson Canyon wall, within the Last Chance Canyon complex. We will examine the stratification styles associated with shelf-to-basin progradation of the upper San Andres Formation within this panoramic view.

Detailed mapping of the best exposure along the Wilson Canyon wall by Sonnenfeld (Sonnenfeld and Cross, 1993) (Figure 28) illustrates the complex architecture of this margin. Kerans and Phelps (2006) and Scott (2007) followed the work of Sonnenfeld, taking this 2D model into a 3D perspective using a combination of traditional field mapping and ground-based lidar-guided mapping and surface modeling (Figures 29–30). Fundamental changes in clinoform geometry and style of siliciclastic bypass were found to occur as clinoforms steepened due to decreasing accommodation on the shelf, with 2D linear clinoforms in the older lower angle profiles evolving into 3D cuspate forms in the steeper clinoform sets, implying channelization and bypass in younger clinoforms.

We will spend a majority of our time examining this prograding margin system and recognizing the fundamental stratal patterns.

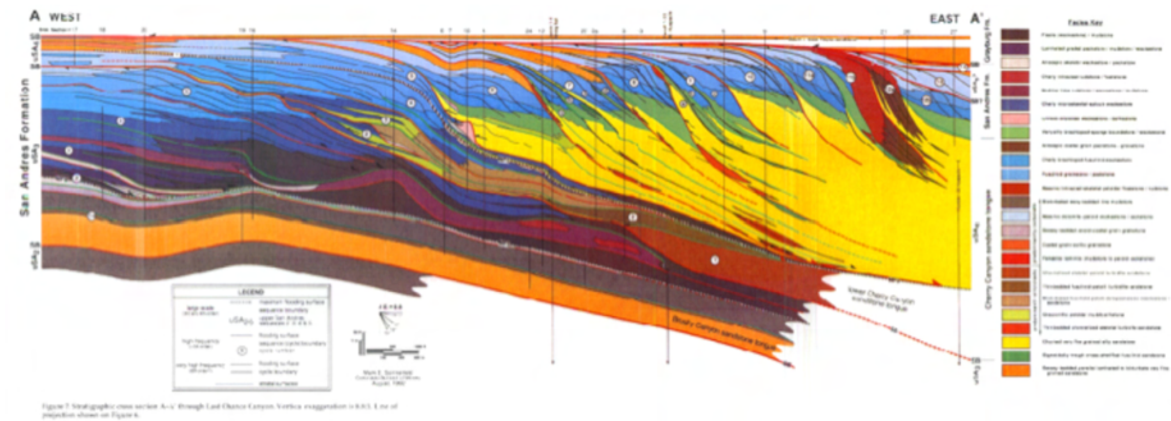


Figure 28. Detailed illustration of facies patterns within the San Andres clinoforms. Yellow is predominantly sandstones; light blue and orange are shelf-edge and shelf-top facies respectively. From Sonnenfeld and Cross (1993).

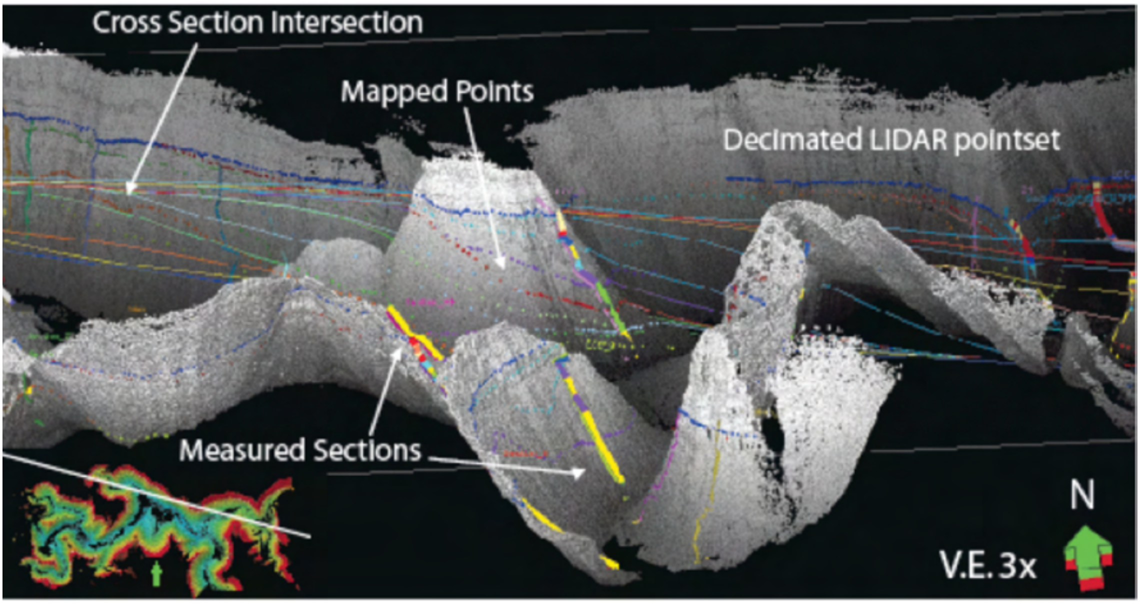


Figure 29. Interpretation of clinoform geometry in 3D space using outcrop mapping, ground-based lidar, and traditional measured sections.

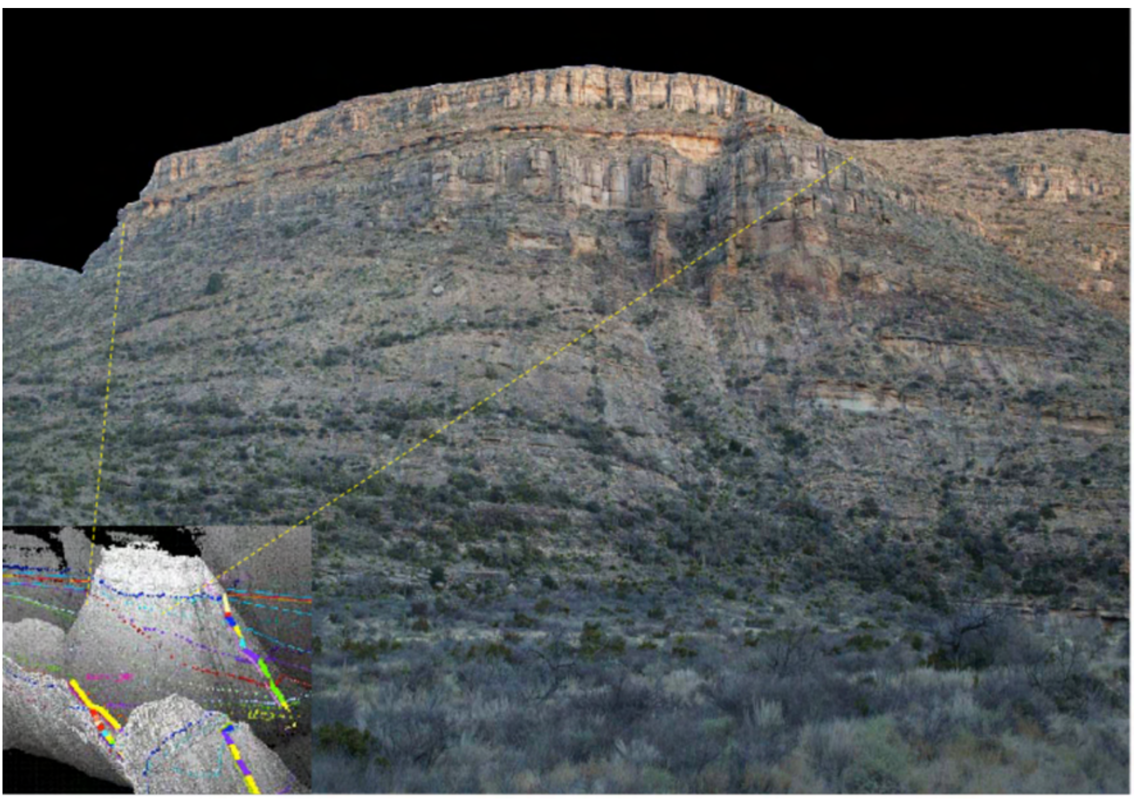


Figure 30. Clinoforms in upper San Andres Formation and linked model interpretation.

Relevance to Mars

The discovery of large-scale clinoforms in Melas Chasma by Dromart et al. (2007) represents a landmark in our understanding of the sedimentary geology of Mars (Figure 31). Deposited near the center of a small basin in northwest Melas Chasma, these clinoforms are interpreted to reflect either a Gilbert-type delta or a sublacustrine fan channel-levee complex (Dromart et al., 2007; Metz et al., 2009). Other clinoforms may be present in the Eberswalde delta, where delta foreslope deposits downlap against more basinal deposits (K. Lewis, pers. comm., 2009).

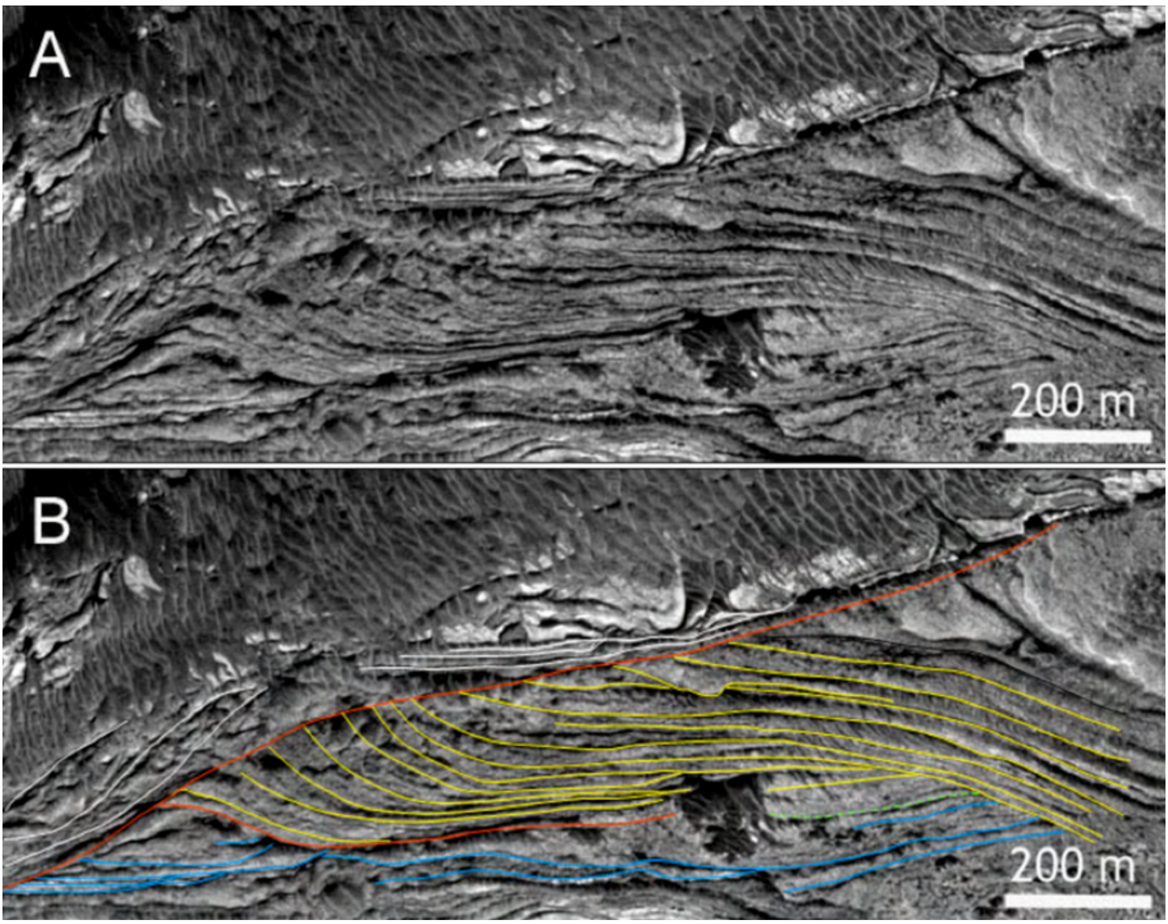


Figure 31. Prograding strata in Melas Chasma. From Dromart et al. (2007). Three distinct sequences shown in blue, yellow, and white tracings, separated by sequence boundaries shown in red.

The vast, layered, sedimentary terrains of Mars may also express inclined stratal geometries whose identity is only beginning to be appreciated. It is possible that sulfate and phylosilicate deposits of Terby Crater may contain complex stratal geometries, interpreted to record deltaic-lacustrine environments (N. Mangold, pers. comm., 2010). This approach holds much promise for the analysis of sedimentary rocks on Mars.

Sequence Stratigraphy, Clinoforms, and Application to Mars Stratigraphic Record

Beginning in the 1970s, the advent of high-resolution remote sensing of buried stratigraphic successions made it possible to visualize subsurface stratigraphy fully in 2D and 3D over broad regions, and this stimulated a revolution in process-based analysis of sedimentary rocks. This remote sensing capability was provided by reflection seismic imaging, which provided key information on ancient depositional environments through understanding the geometric attributes of sedimentary layers (Vail et al., 1977). During the 1980s and 90s, the geometric principles of stratigraphy derived from subsurface studies were applied to surface outcrops, where significant improvements occurred in understanding how sedimentary facies relate to stratal geometry (Miall, 1985; Osleger and Read, 1993). It is now routine to develop multiscale models of sedimentary basins that are built on outcrop and subsurface datasets, which allow observations at large scales to predict relationships at smaller scales and vice versa. This new, high-resolution, process-based approach to predicting facies distributions in sedimentary rocks is widely known as sequence stratigraphy (Christie-Blick and Driscoll, 1995).

The fundamental discovery of sequence stratigraphy was that genetically-related sets of strata are bounded by unconformities that are revealed as discordances in stratal geometry. These discordances are gentle enough that they are commonly not recognized in terrestrial outcrops except where outcrop is excellent and laterally extensive. Therefore, they are most commonly expressed in subsurface reflection seismic datasets where continuous data coverage allows subtle discontinuities to be shown clearly. These discontinuities (“sequence boundaries”) are the attribute that allows for correlation of strata within sedimentary basins. The organization — or “architecture” — of strata that are bounded by these stratal discontinuities provides the key to facies recognition. It is noteworthy that even where recognizable fossils are absent, for example the Precambrian record on Earth, this approach offers a reliable methodology for constraining both the relative chronology and the general distribution of facies within the observed strata (Christie-Blick et al., 1988). Therefore, it makes the method ideally suited for application to Mars’ stratigraphic record.

The principles of sequence stratigraphy also are applicable to Mars (e.g., Grotzinger et al., 2005). For example, the High-Resolution Imaging Science Experiment (HiRISE) camera on MRO provides a powerful imaging capability to map sedimentary successions based on their stratal geometries (and see Branney and Kokelaar, 2002, for an application to volcanic successions). Proof that high-resolution stratal geometries are present and can be mapped using sequence stratigraphic principles is provided by images acquired since the start of the MRO mission, as well as in earlier Mars Orbiter Camera (MOC) images from the Mars Global Surveyor (MGS) mission (see Figure 2 in Dromart et al., 2007). HiRISE, MOC, and MRO Context Camera (CTX) imagery will permit detailed mapping of this particular succession of strata, and others like it; the results will likely shed light on the origin of the strata and facies distributions within the succession (see below).

A remarkable amount of information regarding process may be gleaned from a first-pass interpretation of the strata shown in Figure 31: 1) There is an inclined bundle of strata sandwiched between two stratal discontinuities (colored red and blue in

Figure 31 (B). These discontinuities must represent unconformities; 2) the inclination of the strata themselves provides evidence for progradation. Progradation is the progressive advance of an inclined depositional surface, for example, a delta foreslope. All depositional systems have slopes, which can be measured for information regarding depositional process, and therefore environment of deposition; and 3) the strata not only are inclined but they also show convergence in the direction of progradation. This indicates downslope thinning of strata due to spatially-dependent changes in bedload transport rate ($\delta Q/\delta x = -ve$; Kenyon and Turcotte, 1985). This is significant because on Earth, for subaqueous strata, organics might be concentrated where strata are thinnest because suspended materials will tend to accumulate when bedload transport is reduced. This observation on Mars can lead to recognition of which parts of a sedimentary succession might be most favorable for study by future landed missions aimed at analysis of possible organic compounds (Ehlmann et al., 2008; Golombek and Grotzinger, 2006; Grotzinger, 2009). The foregoing discussion is intended to illustrate what high-resolution observations can be made independent of their interpretation.

Day 3 Field Stops

Stop 3-1 — Carlsbad Caverns

Numerous caves are present in the Guadalupe Mountains, with Carlsbad Cavern and Lechuguilla Cave being the most spectacular (Figure 32). The theories of local cave formation have changed over the last 50 years. Dissolution was initially attributed to "normal cave processes" of carbonic acid occurring in rainwater (Bretz, 1949). During the last 20 years, a more complex model has evolved for development of caverns in the Capitan system (Jagnow, 1979, 1989; Hill, 1989, 2000; DuChene and McLean, 1989). Based on cave geometries and the geochemistry of the cave fill, Hill (1987, 1995, 1996, and 2000) postulated four stages of cave development. The last and volumetrically most important dissolution event was "sulfuric acid karst" associated with basinal hydrogen sulfide mixing with oxidizing freshwater during the last 15 million years (Figure 33). This model has been substantiated and is now being considered for other cave systems around the world.

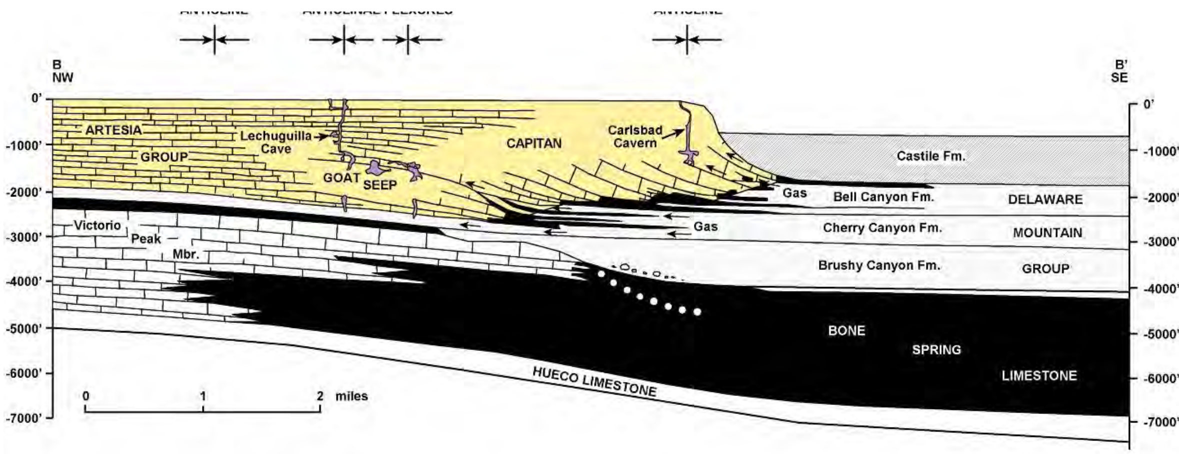


Figure 32. Cross section showing location of cave systems relative to Permian stratigraphy.

The Carlsbad Caverns Visitor Center is situated directly above the Capitan reef and along what is termed the Reef anticline (Figure 34). The cavern is developed primarily along a series of joints that are parallel or perpendicular to the reef front. Passages are confined to the limestone reef, being sandwiched between backreef and forereef deposits.

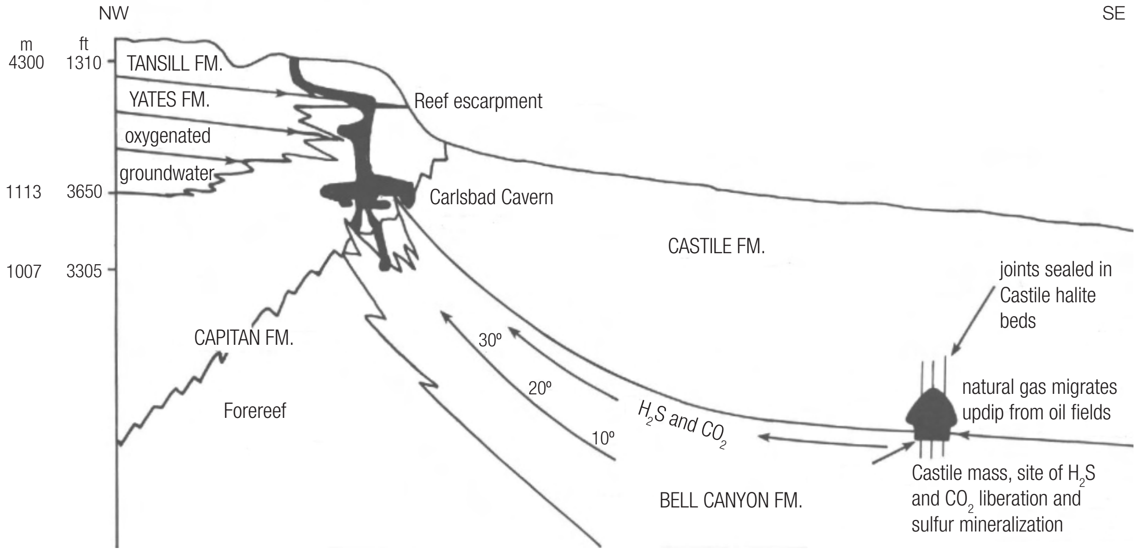


Figure 33. Schematic cross section summarizing the sulfuric acid karst model for cave development in the Guadalupe Mountains.

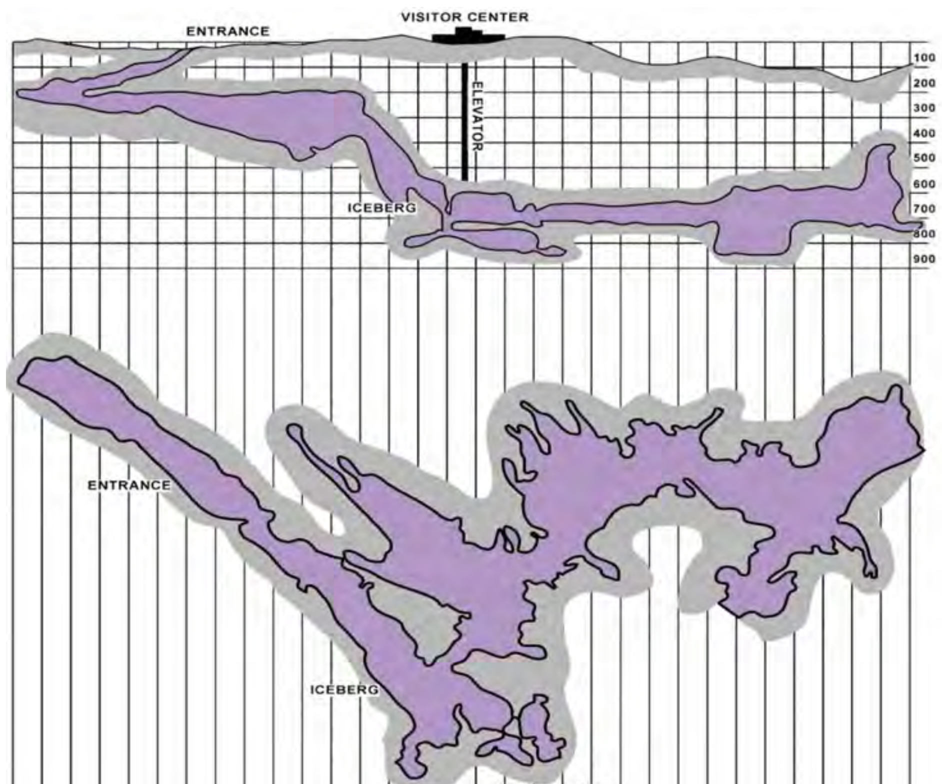


Figure 34. Generalized cross section and map view of Carlsbad Caverns.

The natural entrance to the cavern (Figure 35) is a paleospring developed in the Tansill formation. According to the work of Hill (1987), the entrance paleospring was operative ~1 Ma ago, but had ceased functioning by the time the Big Room level was being excavated (~0.75–0.85 Ma). With the lowering of regional base level, horizontal levels of cave passage were developed at new water table positions. Potential cave openings have been observed on Mars (Figure 36).

Figure 35. Natural entrance to Carlsbad Cavern.

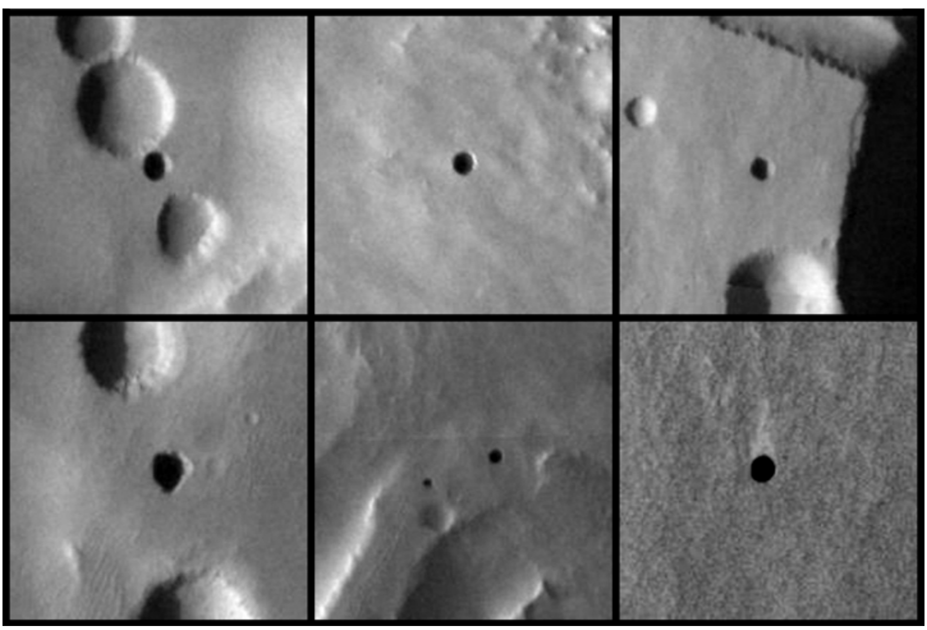


Figure 36. Possible cave skylights on Mars. Images taken in visible-wavelength light by the Thermal Emission Imaging System camera on NASA's Mars Odyssey orbiter.

Stop 3-2 — Overview of Delaware Basin

A thick succession of siltstones, sandstones, and minor carbonates fills the Delaware Basin (Figure 37). Only Bell Canyon, which is the uppermost portion of the Delaware Mountain Group, is age-equivalent to the Capitan margin. Ideas on the deposition of these basinal deposits have evolved over time. King (1948) and Newell et al. (1953) initially proposed deposition of the Brushy Canyon (older than the Capitan) 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 has led most subsequent workers to invoke deeper water depositional environments (Payne, 1976; Bozanich, 1979; Williamson, 1977, 1979). Harms (1974) and Harms and Williamson (1988) proposed deposition by density currents created when high-salinity shelf waters flowed down into the less saline basin. Mazzullo et al. (1985) and Fischer and Sarnthein (1988) proposed deposition of sands and silts in the basin largely by eolian processes during base-level falls when the adjacent shelves were exposed above sea level. In this model, sands were carried across the shelf in dunes before deposition in subtidal environments at the basin margin. Those sands were episodically carried down slope and into the basin by gravity flows. In

Figure 37. Outcrops of basinal siliciclastics sitting directly below the prominent edifice of El Capitan.

contrast, silts were transported largely as airborne dust. Although concentrating on the Brushy Canyon, stratigraphic and depositional analyses by Gardner and Sonnenfeld (1996) have clarified depositional processes that are also probably applicable to the Bell Canyon.

The source for the siliciclastics of the Delaware Basin is still being debated. Kocurek and Kirkland (1998) proposed that the basinal siliciclastics were derived from eolian systems in the Whitehorse Group of the Anadarko Basin. Previous workers hypothesized on a more northerly or northwesterly source. The timing and nature of siliciclastic bypass into the Delaware Basin is also arguable. Is sand and silt being transported to the basin across a few major surfaces, i.e., 3rd-order sequence boundaries? Or, are the numerous high-frequency exposure surfaces apparent in outcrops important times of sand bypass?

Relevance to Mars

The siliciclastic turbidite sandstones that fill the Delaware basin formed a submarine fan. Very recently, Metz et al., (2009) reported what is the first possible sublacustrine fan on Mars. Thus, the Bell Canyon and Brushy Canyon depositional systems may form a partial analog for what could be present in the center of Melas Chasma.

Two depositional fan complexes have been identified on the floor of southwest Melas Chasma (Metz et al., 2009). The western fan complex is located near the center of an enclosed basin in southwest Melas Chasma and is composed of multiple lobes with dendritic finger-like terminations (see Figure 38). These fans are very flat and have a morphology unlike any other fan that has been previously identified on Mars. Based on the morphologic similarity of the western fan complex to the Mississippi submarine fan complex, Metz et al. (2009) suggest that it may be a subaqueous fan. The surface of the western fan complex is covered with numerous channels, and measurements of channel length, width, and sinuosity are consistent with channels observed on terrestrial submarine fans.

The analysis by Metz et al. concludes that a sublacustrine fan is most probable, but a deltaic origin can not be excluded. Analysis of plan-view morphology and slopes provides broad constraints on interpretations of depositional fans, but does not uniquely constrain their origin. The observed facies, as well as their stacking pattern, would allow discrimination conclusively whether deposits were formed as part of a delta or a submarine fan.

Distinctive features that could be observed in a deltaic environment, but would not be expected in a submarine fan environment, include point bar deposits, floodplain deposits, paleosols, and mudcracks. Submarine fans are largely composed of the deposits of turbidity currents. The outcrops of the Brushy Canyon and Bell Canyon formations provide the opportunity to examine turbiditic sedimentary features at a scale that could be conducted by a rover. This outcrop provides an excellent chance to observe the features that would allow discrimination of a fluvial delta from a sublacustrine fan.

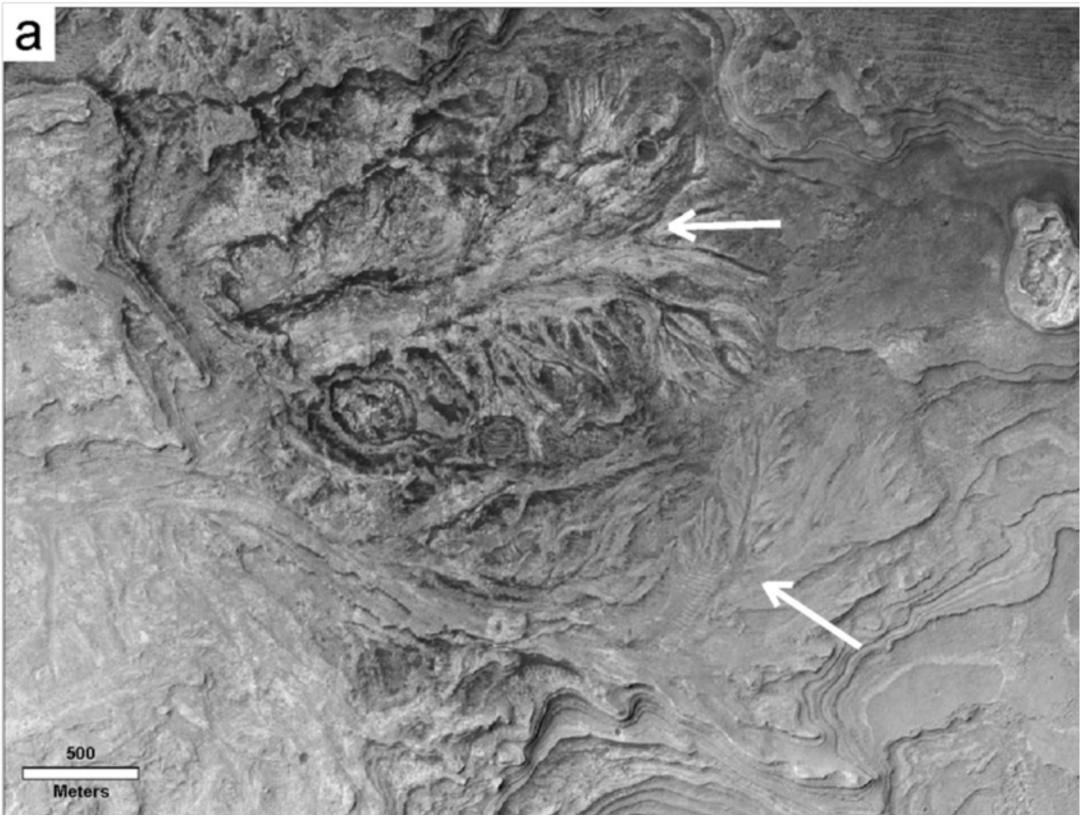
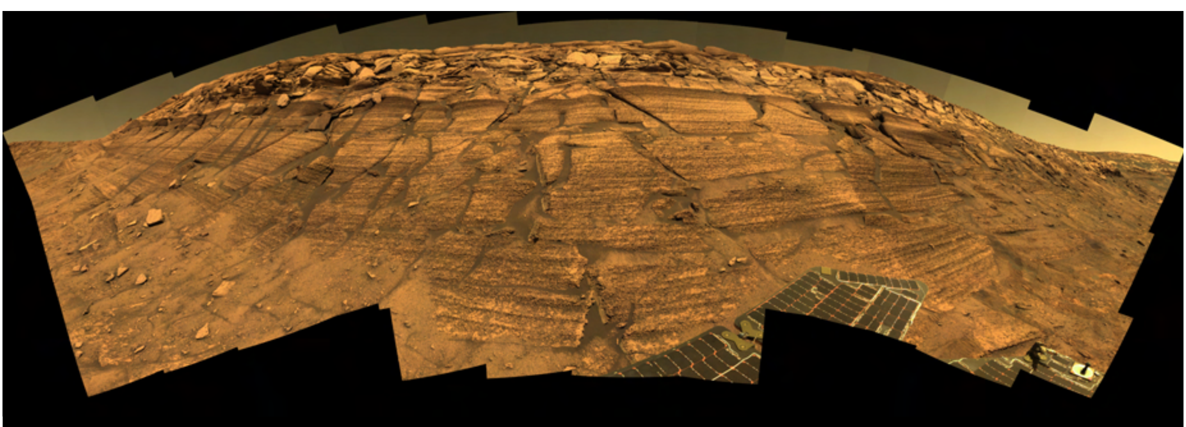
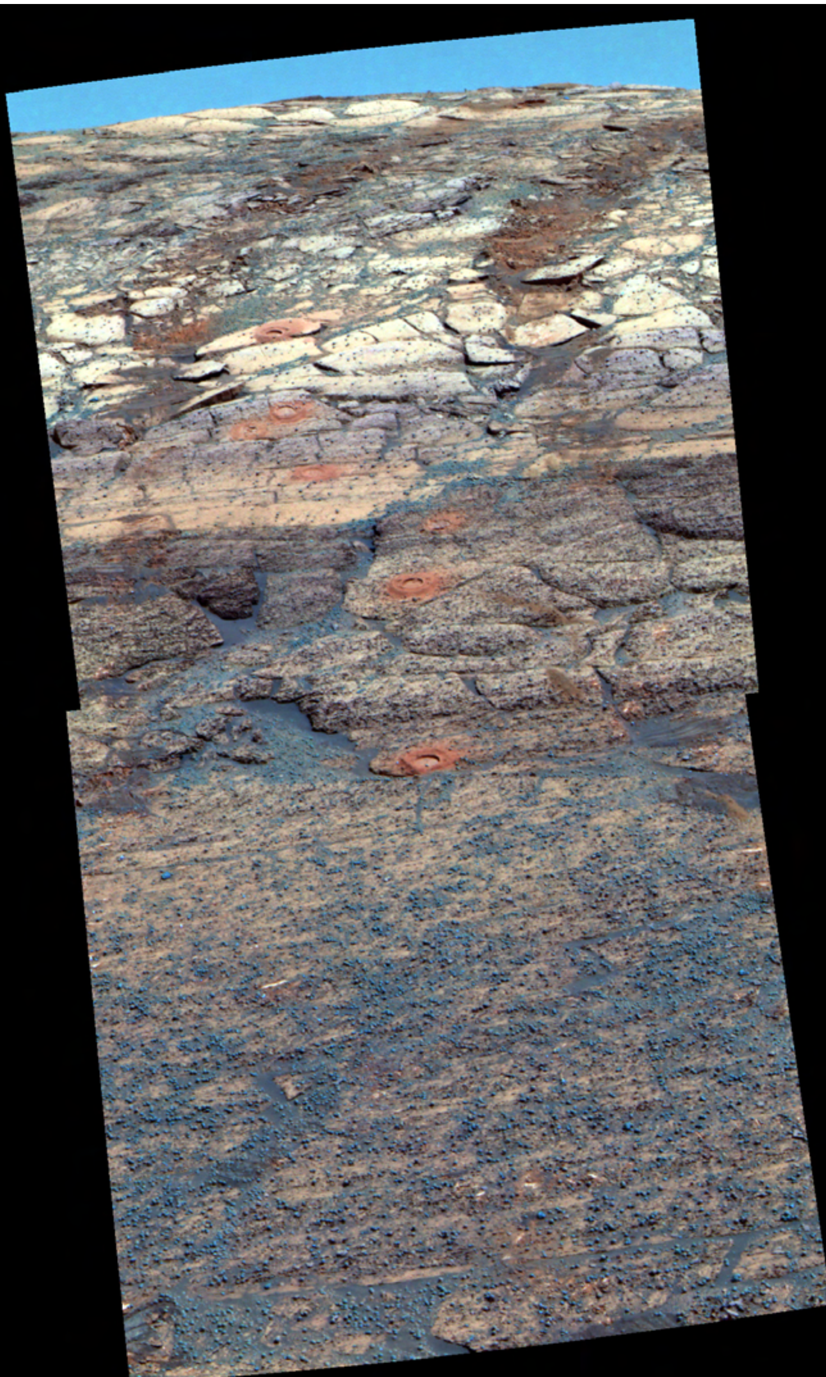


Figure 38. Portion of HiRISE image PSP_007667_1700 with white arrows showing the location of the two likely sublacustrine fans intercalated within the topographically lowest strata in Southern Melas Basin. From Metz et al. (2009).



Burns Cliff in Endurance Carter, Meridiani Planum, Mars. This shows one of the best explorations to date of sedimentary outcrops on the surface of Mars.



False-color composite rendering of the first seven holes that the Opportunity rover's rock abrasion tool dug on the inner slope of "Endurance Crater." This is the most complete "sampled" section on the surface of Mars.

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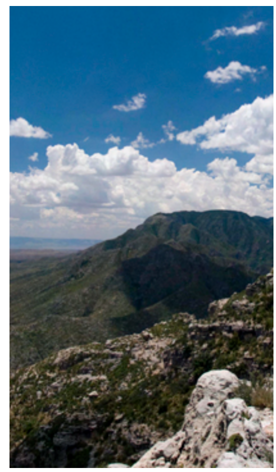

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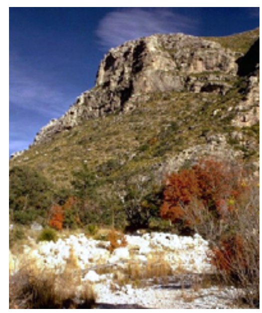

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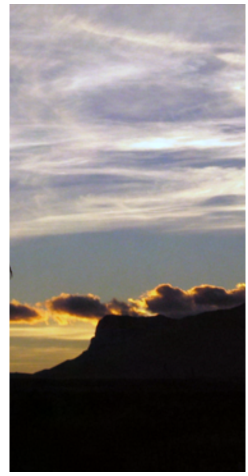

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