PS Geological Controls on Evaporite – Carbonate Facies Transition in Permian Seven Rivers Formation, SE New Mexico*

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Abstract

Regional evaporite-carbonate transitions control stratigraphic trapping in many carbonates, yet basin-scale controls on the position of evaporite-carbonate facies changes are not well understood. The Seven Rivers Formation changes from a carbonate near the Delaware Sea to evaporite on the shelf to the north and northwest. The objectives of this study are to describe the nature of this lateral facies change and interpret its geological controls.

In the subsurface of eastern Eddy Co., NM, the Seven Rivers sulfate-dolomite transition is a fine-scale interfingering of southerly thickening dolomite beds and northerly thickening anhydrite beds within a narrow (< 1.5 km) E-W striking transition zone. On outcrop near Rocky Arroyo, NM, the Seven Rivers sulfate-dolomite transition is also abrupt. In both areas, the position of the lower Seven Rivers evaporite transition is relatively stable as the contemporaneous shelf margin aggrades. The evaporite transition shifts landward (N and NW) in the upper Seven Rivers as the shelf margin progrades seaward.

Shelf-interior dolomitized carbonates are salinity-restricted, subtidal, marine deposits with no evidence for intertidal or supratidal deposition except near major siliciclastic units. Carbonates are interbedded with thin (2 – 30 cm) siltstones that are subaerial sheet-flow and eolian sand-flat deposits. The carbonate – siltstone couplets are therefore meter-scale parasequences controlled by minor, high-frequency sea level changes on the shelf.

Gypsum and carbonate are synchronous, subaqueous deposits from a salinity-stratified water column. Carbonate was deposited in mildly hypersaline marine water at shallow depth whereas gypsum was precipitated from brine deeper in the water column. Both carbonate and evaporite accumulation rates decrease near the pycnocline, and the paleobathymetry therefore steepens near the facies contact. The steeper bathymetric gradient at the transition narrows the transition zone width so that minor water-balance or sea-level changes do not significantly shift the facies boundary. The longer-term position of the facies boundary is controlled by accommodation space creation. When vertical accommodation space creation is low, carbonate produced on the shelf-interior progrades into the adjacent evaporite basin and carbonate produced on the shelf margin progrades into the Delaware basin.

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Introduction

The Seven Rivers Formation is a "saline giant" evaporite deposited on an evaporite shelf that is separated from the Delaware sea by a narrow rim of carbonate. Seven Rivers evaporites are laterally extensive (>100,000 km^2 or 38,000 mi^2), moderately thick (~150 m or 500 ft), and voluminous (>15,000 km^3 or >3600 mi^3). Evaporite facies are predominantly calcium sulfate near the shelf margin (gypsum on outcrop; anhydrite in the subsurface). Halite facies predominate in the shelf interior.

This study focuses on the carbonate-calcium sulfate facies boundary. The facies transition is exposed on outcrop and closely penetrated in the shallow subsurface. Thin, persistent sandstone beds within the Seven Rivers Formation provide a stratigraphic framework between the subsurface and outcrop. The combination of outcrop and subsurface control allows an almost unique opportunity to examine the detailed facies transition from carbonate to evaporite over the sill that is responsible for isolating a shelf saline giant from its seawater source.

The carbonate - evaporite facies boundary is abrupt. There are no apparent depositional barriers such as thickened carbonate bars or banks to provide local sills at the carbonate-evaporite facies transition. Questions to be addressed include: Why is the carbonate-anhydrite facies transition so abrupt? What controls the position of the evaporite facies relative to the shelf margin in the absence of persistent tectonic control? Why does the Seven Rivers Fm. (and other shelf evaporites in the northern Permian basin) show a predominantly lateral evaporite facies zonation whereas other major evaporites show predominantly vertical evaporite facies zonation within the silled basin?

Regional Seven Rivers Setting and Deposition

Age and Geological Setting

Seven Rivers Formation straddles the Wordian - Capitanian boundary in the Guadalupian Stage of the Permian (Figure 1). It is the shelf equivalent of the lower part of the shelf-margin Capitan Formation. At this time, the northern shelf area near the Delaware basin was subsiding but tectonically quiescent, and the shelf margin aggraded and prograded towards the south and southeast.

The Seven Rivers Formation extends from the northern shelf of the Delaware Basin north to the Palo Duro basin and east to the Eastern Shelf of the Midland Basin, where it forms part of the Whitehorse Group. The Seven Rivers Formation was also deposited along the southern and western margins of the Delaware basin where it is now absent due to Mesozoic-Cenozoic erosion. The northern Seven Rivers limit is depositional (although modified by salt dissolution, Presley 1987). Based on regional facies patterns, the Seven Rivers Formation probably originally extended to the Pedernal Uplift - Diablo Uplift west of the Permian Basin and to at least the Bend Arch on the Eastern Shelf to the east.

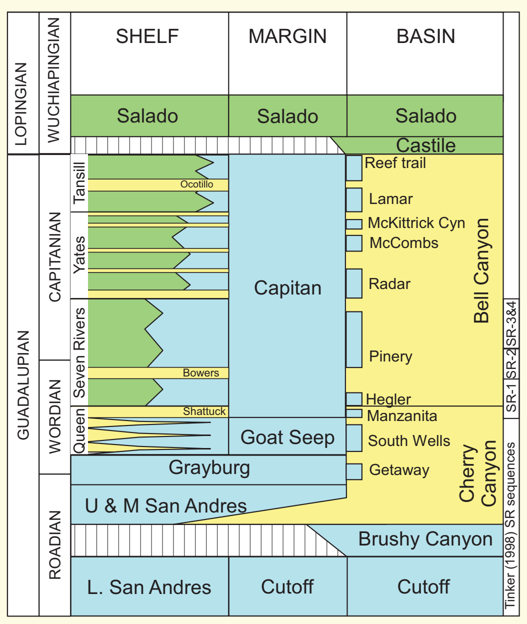


Figure 1. Chronostratigraphic chart for Guadalupian strata of the Guadalupe Mountains area. Yellow is siliciclastic, blue is carbonate, and green is evaporite. Vertical hatch indicates major hiatuses. Modified from Garber et al. (1989) using Tyrrell and Diemer (2003) correlations and other data.

Regional Facies Patterns

The Seven Rivers Formation is an exclusively shelf deposit formed behind the shelf-margin Capitan Formation. Near the shelf margin, the Seven Rivers Formation is entirely carbonate. About 5 To 20 km from the shelf margin, carbonate grades abruptly into evaporite.

The Seven Rivers evaporite shows systematic lateral compositional changes (Figure 2). Evaporites closest to the shelf margin are thin-bedded anhydrite with minor dolomite and sandstone beds. Anhydrite gradually grades landward into a predominantly halite facies. The halite facies comprises mostly halite with interbedded anhydrite, halitic anhydrite, and siliciclastics (Figure 3). Thin (<2 ft), high gamma-ray beds within the halite facies have been interpreted on some logs as bittern evaporites, but this has not been confirmed by core.

Near the north and east landward edges of the Seven Rivers Formation, halite facies grade into evaporitic sandstones and mudrocks (Ward et Al. 1986; Presley 1987). East of the dashed line on Figure 2 on the Eastern Shelf, evaporitic facies become predominantly anhydrite (e.g., Galley 1958). This is probably related to salt dissolution due to proximity to outcrop.

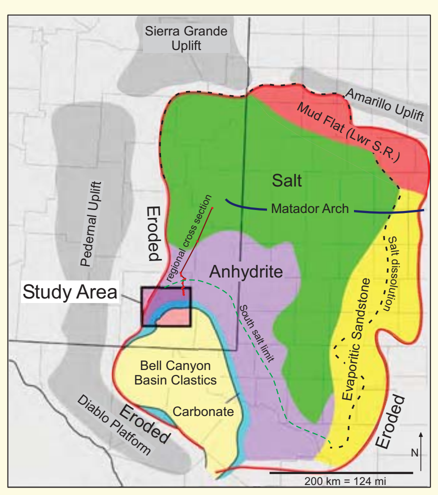


Figure 2. Regional depositional facies in the Seven Rivers and equivalent formations. Red line is current landward limit of the Seven Rivers Formation. Seven Rivers salt has been extensively dissolved east and north of the black dashed line. The anhydrite-salt limit is where approximately half of the evaporites are halite. The green dashed line is the southern limit of salt interbedded with anhydrite. This is a new compilation from data in Presley (1987), Ward et al. (1987), Galley (1958), and well log control.

Stratigraphic Subdivisions in the Seven Rivers Formation

Thin, siliciclastic beds occur within the Seven Rivers Formation. They increase in number and extent along the northern shelf towards the east. Some of these are remarkably correlative, whereas others abruptly thin or disappear. The most correlative of these is the Bowers Sandstone, which is used here to subdivide the Seven Rivers Formation.

In this study, the Seven Rivers Formation is subdivided into three units. The lower Seven Rivers Formation extends from the top of the Shattuck (Queen Sandstone) to the base of the lower Bowers Sandstone. The Bowers Sandstone occurs near the middle of the Seven Rivers Formation. It includes two regionally persistent sandstone beds and intervening lithology. Bowers Sandstone rarely exceeds 60 ft (20 m) in thickness. The upper Seven Rivers Formation includes all strata above the second Bowers sandstone to the base of the Yates Formation. It is the thickest Seven Rivers subdivision.

The Bowers Sandstone as used here follows usage by DeFord and Wahlstrom (1932) at the type area in Hobbs Field. The Bowers Sandstone includes the two lowest of 3 regionally correlative siliciclastic zones. The uppermost sandstone (which was included in the Bowers Sandstone by Tyrrell and Diemer 2003) is referred to here as the third Bowers Sandstone. It is less laterally persistent and in many wells consists of two or more separate sandstone beds.

Another correlative sandstone occurs near the middle of the Lower Seven Rivers Formation. It is referred to here as the Rocky Arroyo Sandstone (new name) and is the siliciclastic associated with the "R" gamma ray marker discussed by Tyrrell and Diemer (2003). Another less persistent sandstone bed occurs near the top of the Seven Rivers Formation, but it is so thin that it rarely shows quartz composition on lithodensity logs.

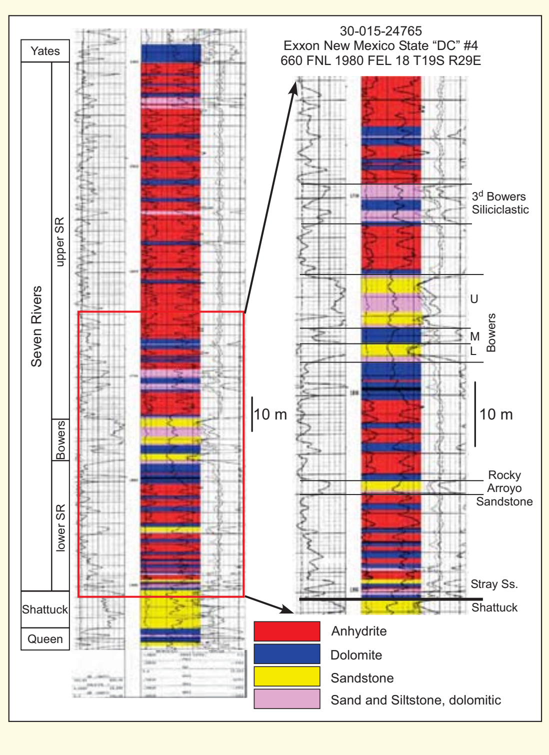


Figure 3. Stratigraphic subdivisions used for subsurface studies and a detail (right) showing other correlative sandstone units in the Seven Rivers Fm. Lithologies are interpreted from density, neutron, gamma ray, and Pe logs. This example is from the anhydrite lithofacies.

Regional Facies Tracts

The subsurface carbonate facies is nearest the shelf margin. It is predominantly dolomite, anhydritic dolomite, and a few anhydrite beds near its updip limit. It abruptly grades into the anhydrite facies with a transition zone less than 2 km wide.

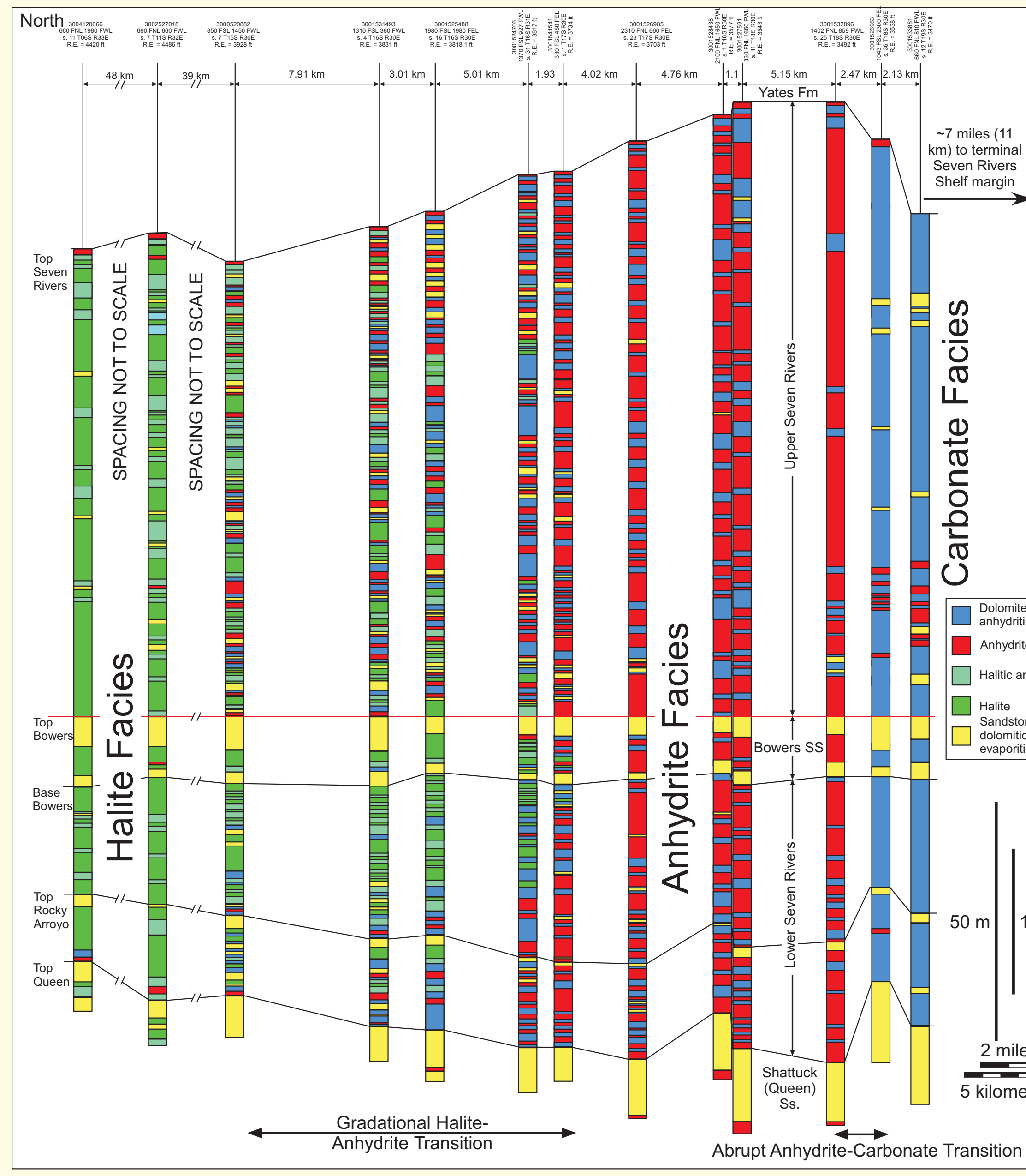
The anhydrite facies is anhydrite with about 20% thin anhydritic dolomite beds. The northern part of the anhydrite facies contains minor halite beds. Its southern limit is about 5 to 20 km north of the Seven Rivers transition into the Capitan Formation and about 8 to 22 km north of the contemporaneous shelf margin.

The halite facies is predominantly thin-bedded halite with thin halitic anhydrite beds. Its has a wide (10 km +) transition into the anhydrite facies about 40 - 50 km from the contemporaneous shelf margin. Relatively pure halite does not develop until about another 30 - 40 km north. Anhydritic dolomite beds are rare and most common in the transition to the anhydrite facies.

Siliciclastics are sandstone, dolomitic sandstone, anhydritic sandstone, and halitic sandstone. Most siliciclastics are in thin, stratigraphically continuous named beds: the two sandstones in the Bowers Sandstone, the Third Bowers sandstone, and the Rocky Arroyo Sandstone. Thin (<1 m or 3 ft), discontinuous sandstones occur elsewhere in the Seven Rivers formation, especially near its top, in an interval above the Third Bowers Sandstone, and near the contact with the Shattuck Sandstone. Wireline spectral gamma ray logs indicate numerous thin (<1 ft) siliciclastic-rich layers throughout the Seven Rivers Formation. These beds are too thin to be resolved by the porosity logs. Marginal siliciclastic-rich Seven Rivers facies were not examined in this study.

Figure 5. Regional north-south stratigraphic cross section showing fine-scale lithology changes from the carbonate facies (blue, south) through the anhydrite facies (red, middle) to the halite facies (green, north). Change from dolomite to anhydrite is abrupt (over about 1.5 km) and at approximately the same position in the upper and lower Seven Rivers. In contrast, the transition from anhydrite to halite is gradational (tens of km) with the lower Seven Rivers and Bowers transition distinctly farther south than the transition in the upper Seven Rivers.

Most of southern part of the cross section is to scale, but northern two wells are not to horizontal scale due to their great distance from the shelf margin.



Study Area

Outcrops were studied in the Rocky Arroyo area, west of Carlsbad, NM. Subsurface Seven Rivers facies relationships were examined in northeastern Eddy County, NM. One regional dip section, a strike section (1), and four detailed dip sections (2 - 5) were constructed across the anhydrite-dolomite facies transition.

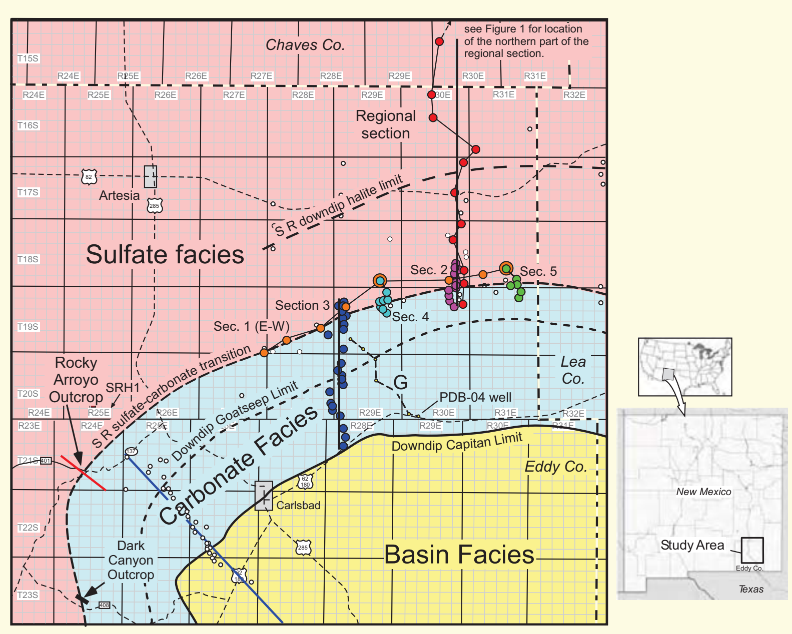


Figure 4. Eastern Eddy County New Mexico, showing locations of subsurface cross sections (numbered) relative to regional facies boundaries and other features. The regional cross section (red dots) does not show the two northern wells, which are over 40 km north of this map. See Figure 2 for location of northern wells on the regional section. Cross section G is location of Garber et al. (1989) NW dip section. Red line is outcrop cross section for Rocky Arroyo; blue line is well section. Outcrop SRH1 location is labeled. Reef limits from Garber et al. (1989). Seven Rivers facies transition near outcrop modified slightly from Cox (1967).

Methods

Subsurface Lithology Identification

Subsurface lithologies are interpreted from rastered wireline-log images of lithodensity, density-neutron, and sonic logs. Because digitized data are not available, lithologies are binned into the lithofacies shown on cross-section keys. Wireline-log cross sections with interpreted lithologies are available upon request to the senior author.

Halite is identified from caliper, sonic, and density logs. Anhydrite and dolomite are identified from density, neutron, and photoelectric logs. Anhydrite is separated from anhydritic dolomite using a density porosity of -12% (limestone matrix and 1.1 g/cc fluid) combined with Pe > 4 b/e. Siliciclastics are interpreted from spectral gamma ray, photoelectric, density, and neutron logs.

Outcrop Methods

Seven new sections were measured, six near Rocky Arroyo and one in the northern Seven Rivers Hills. New measured sections and lithofacies descriptions were integrated with measured sections from previous studies. Most sedimentological interpretations are based on outcrop-observed fabrics with support by thin sections, especially in the carbonate section. No geochemical data were collected.

Focus is on placing sedimentological data into the siliciclastic correlation framework. Positions of siliciclastic units were determined in the new and literature sections. Siliciclastic unit correlations were confirmed by tracing on canyon walls and Google Earth between sections. Minimum thickness of carbonate above the measured sections (Azotea dolomite) was estimated by measuring elevation from the top of measured sections to the ridge crest.

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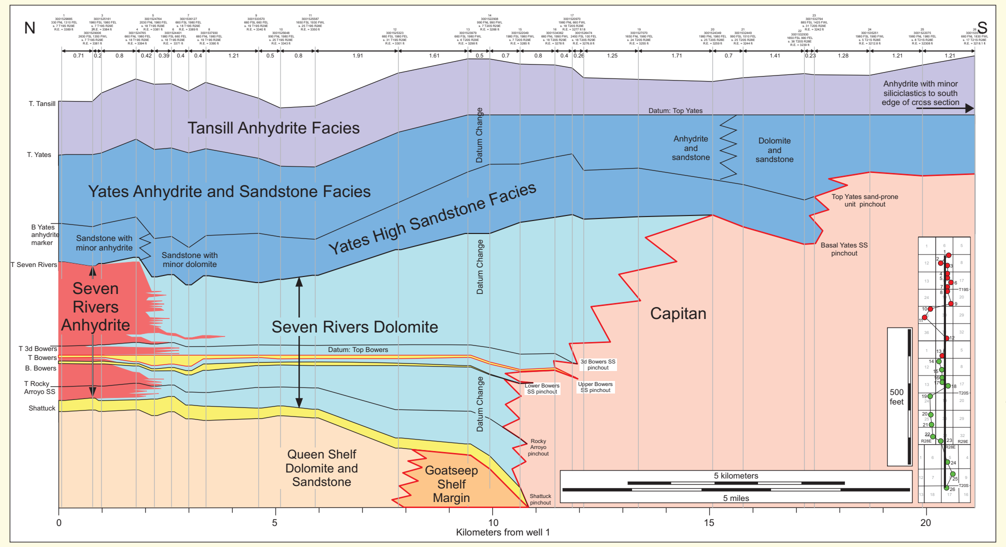
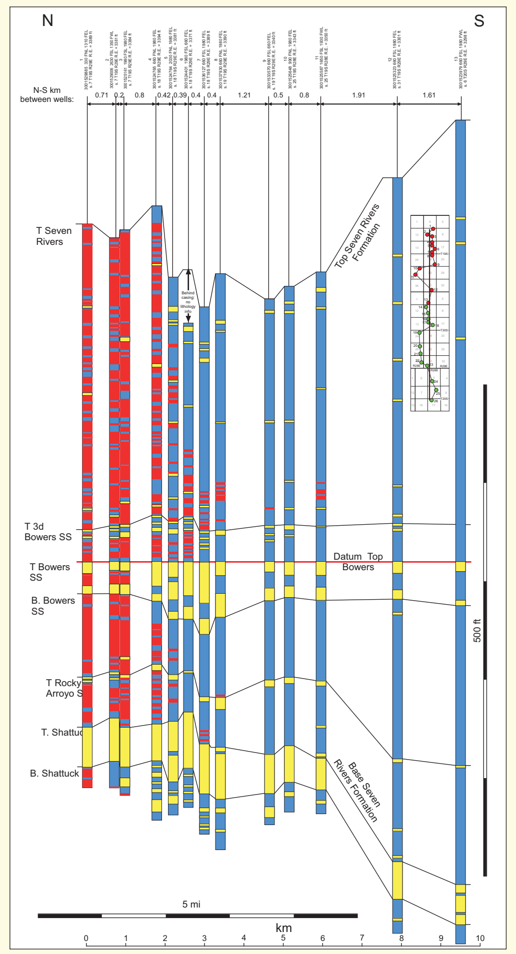


Subsurface Anhydrite to Capitan Transition

Figure 6. North-south stratigraphic cross section 3 showing position of the Seven Rivers anhydrite - dolomite transition relative to transition from Seven Rivers into shelf-margin Capitan Formation, Queen transition into Goatseep Fm., and anhydrite - dolomite transitions in the overlying Yates and Tansill Formations.

Subsurface Carbonate-Anhydrite Transition



Anhydrite Lithofacies

Subsurface anhydrite lithofacies comprises about 70% anhydrite and 30% anhydritic and siliciclastic dolomite (Figure 7). Dolomite is probably overestimated due to thin-bed effects on logs. Anhydrite forms beds about 10 ft (3 m thick), but these beds contain thin impure anhydrite (or very thin dolomite or siliciclastic beds) about every 3 - 5 ft (1 -1.5 m; blue arrows on Figure 9). Thin siliciclastic beds are indicated by minor GR peaks; however, these beds are either exceptionally thin or actually sandy anhydrite.

Carbonate Lithofacies

The carbonate lithofacies comprise dolomite with minor anhydritic dolomite, sandy dolomite, and thin siliciclastics. It lies closest to the shelf margin. Most of the thickness is relatively pure dolomite with 3 to 5% porosity (Figure 9), but thin zones are tight (Figure 9) and other zones are anhydritic (not figured). Silty dolomite can be identified by convergence of density and neutron porosity curves due to decreasing grain density.

Transition Lithofacies

The transition lithofacies occur between the anhydrite and dolomite lithofacies. It comprises about 10% to 50% thin anhydrite beds in predominantly dolomite. The thin dolomitic beds in the anhydrite lithofacies thicken as anhydrite beds thin and split along horizons of impure anhydrite (Figure 9).

The transition occurs at about the same position, but there are subtle shifts. In the lower part of the upper Seven Rivers Fm., the transition shifts to the south (seaward) about 2 km (Figure 7). The overlying upper Seven Rivers anhydrite-dolomite transition shifts slightly to the north up section back to a position similar to that in the lower Seven Rivers Fm.

Thickness Changes

The Seven Rivers Formation thins from the Anhydrite to the Transition Lithofacies, and then it thickens as it approaches the shelf margin (Figures 6, 7, and 8). Thinning is caused by Permian-aged subsurface sulfate dissolution in the Transition Lithofacies.

Times of dissolution can be identified by comparing thicknesses of Seven Rivers and Yates units (Figure 8). Bowers sandstone thickens as Lower Seven Rivers thins, indicating shallow-subsurface sulfate dissolution during Bowers deposition, especially during or preceding Upper Bowers sandstone deposition.

The Yates Formation thickens where the Upper Seven Rivers Formation thins. The lower, sandstone-rich lower Yates thickens over the southern part of the upper Seven Rivers thin zone, whereas the anhydrite-rich upper Yates Fm. unit thickens close to the modern transition in the upper Seven Rivers. This indicates progressive dissolution from south to north during Yates deposition.

Thinning of Seven Rivers units and thickening of Yates units extends into the carbonate lithofacies (Figures 7, 8). Thinning helps define the depositional width of the transition. Prior to dissolution, the transition was approximately 4.5 km wide. The depositional anhydrite-carbonate transition is still much narrower than the halite-anhydrite transition (see Figure 4).

Apparently, calcium sulfate beds interbedded with carbonate selectively dissolved relative to the massive sulfate farther north. Selective dissolution was probably caused by the higher surface area to mass ratio in Transition Lithofacies sulfate beds. Anhydrite beds are typically not preserved near the sandstones in the Seven Rivers formation in the transition zone. This may indicate selective early dissolution near the most permeable beds.

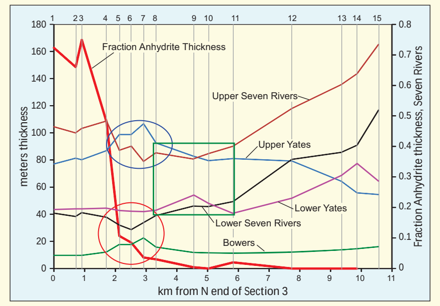
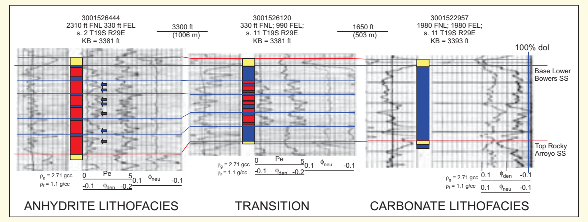
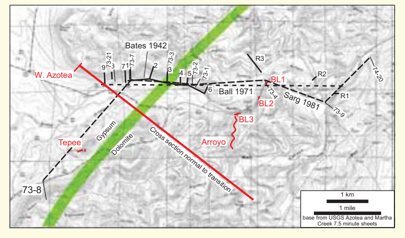


Figure 8 (Right). Thickness changes in cross section 3 near the transitional lithofacies.

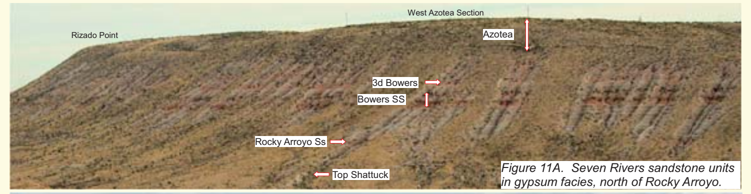


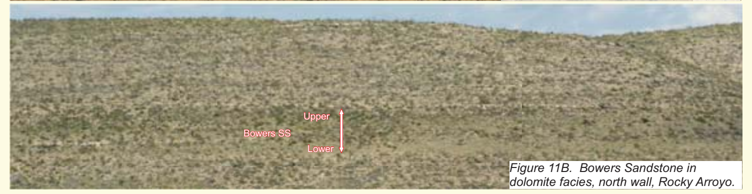
Outcrop Study Area and Stratigraphic Framework

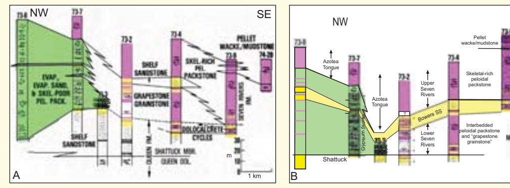
Outcrop Study Area



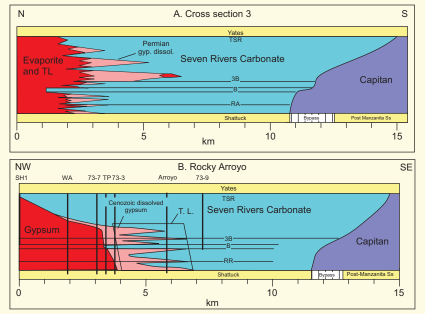
Outcrop Stratigraphic Framework







Outcrop vs. Subsurface Transition Patterns



Outcrop Gypsum-Dolomite Transition Geometry

As in the subsurface, Evaporite, Transition, and Carbonate Lithofacies are evident on outcrop. However, geometry of the transition is somewhat different from that in the subsurface (Figure 13).

- The "Azotea Tongue" (Upper Seven Rivers carbonate overstepping gypsum to the NW) is about 4.5 km wide, wider than in the subsurface (Figure 13, Figure 14). The outcrop transition is mostly depositional except its southeastern end where abrupt thinning is caused by gypsum dissolution.
- Lower Seven Rivers transition is southeast (seaward) of the upper Seven Rivers transition.
- The width of the outcrop Transition Lithofacies is much narrower than that in the subsurface (Figure 13, 14). Both upper and lower Seven Rivers thin more over the transition, indicating that the narrow transition width is caused by gypsum dissolution in the Transition Lithofacies. Dissolution converts Transition Lithofacies to Carbonate Lithofacies with interbedded evaporite collapse fabrics. Dissolution is Cenozoic in age.
- Total Seven Rivers thickness near the SE end of Rocky Arroyo is similar to Carbonate Lithofacies thickness farther southeast (Figure 13). Little or no sulfate was deposited at or southeast of section 73-8.

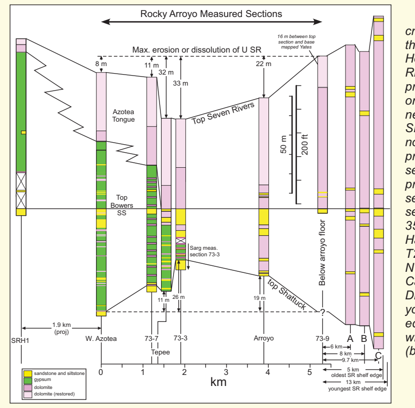


Figure 13. Stratigraphic cross section projected onto the red line of Figure 10. Horizon marked "top Seven Rivers" is line of highest

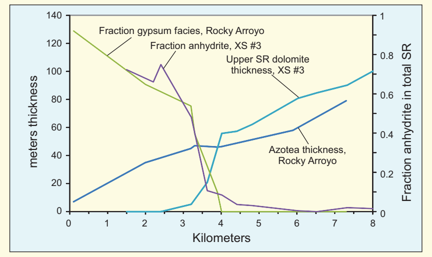


Figure 14. Sulfate (gypsum and anhydrite) fraction in the Seven Rivers Formation and thickness of the upper dolomite (Azotea equivalent) at Rocky Arroyo and at cross section 3. Subsurface and outcrop sulfate show similar thinning, the outcrop pinchout is more abrupt due to sulfate dissolution near the gypsum pinchout. The subsurface upper Seven Rivers dolomite (Azotea Tongue equivalent) thickens more abruptly and shows less landward shift than at Rocky Arroyo.

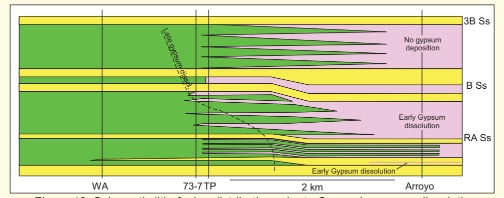
Original Gypsum Distribution at Rocky Arroyo

The former presence of gypsum is identified by brecciation, convoluted siltstone, and anomalous thinning of stratigraphic intervals. Former distribution of gypsum can be reconstructed from these features (Figure 18). Late gypsum dissolution (LED on Figures 16 and 17) is identified by brecciation in overlying units. Pre-lithification gypsum dissolution (EED on Figures 16 and 17) is identified by convoluted bedding in siltstones and soft-sediment deformed dolomite nodules.

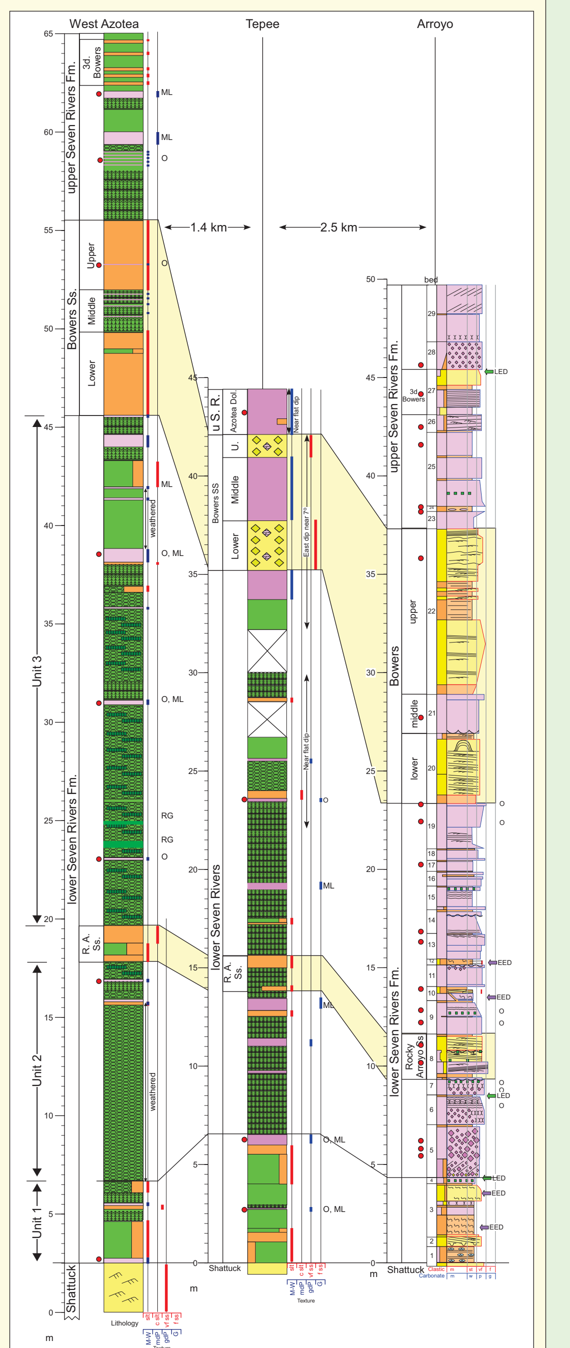
Unit 1 and most of Unit 3 show evidence for pre-lithification gypsum dissolution in the Transition Lithofacies (Figure 16 and 17). Minor pre-lithification gypsum dissolution is also present in Unit 2 at BL1 and BL3. The Bowers sandstone at the Arroyo section is anomalously thick. This indicates that the pre-lithification dissolution is probably of Bowers age.

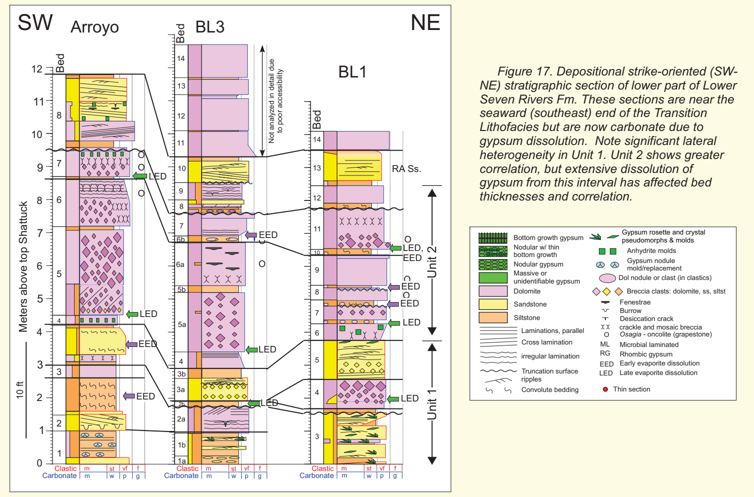
Gypsum was dissolved after lithification in Transition Lithofacies Unit 1 at BL1, all carbonate sections in Unit 2, below the Bowers Sandstone at the Tepee, and in the middle Bowers member at Sarg's (1976) section 73-7. Post-lithification gypsum dissolution is probably Cenozoic-aged.

Gypsum was probably not deposited in the interval between top of Bowers sandstone and third Bowers marker at the Arroyo section. However, the dolomite immediately above the third Bowers is brecciated at the Arroyo section, indicating both former gypsum presence and its Cenozoic-aged dissolution.



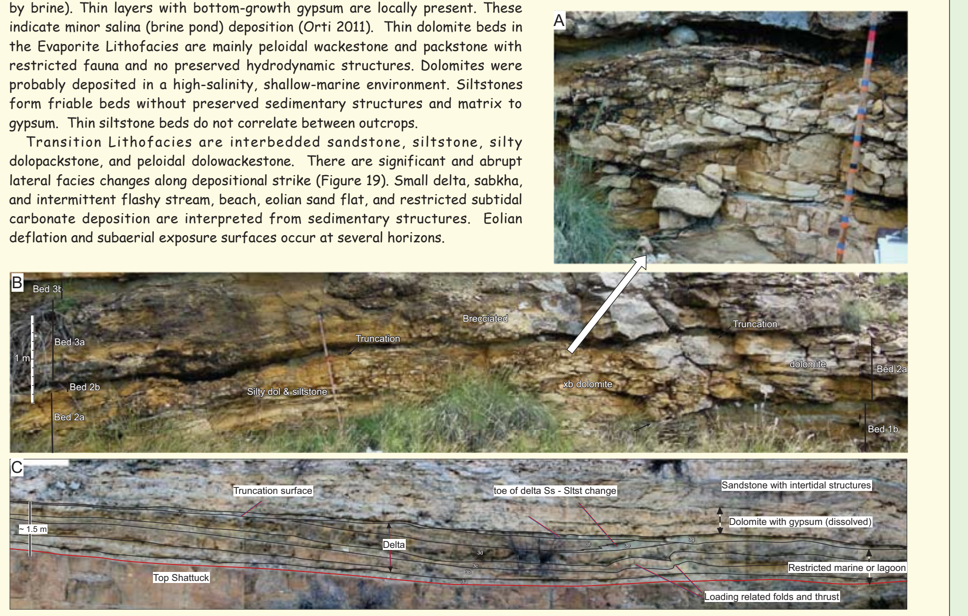
Detailed Transition, Lower Seven Rivers



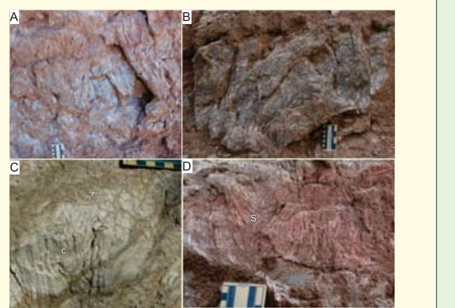


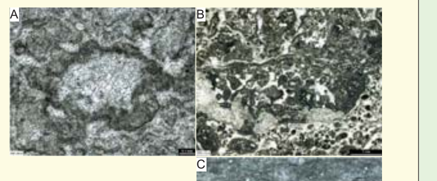
Lower Seven Rivers Depositional Interpretations

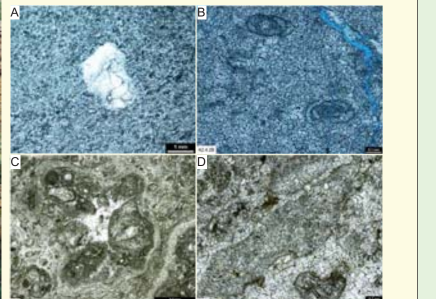
Unit 1



Units 2 and 3







Presented at AAPG ANNUAL MEETING, Calgary, 2016

Geological Controls on Evaporite – Carbonate Facies Transition in Permian Seven Rivers Formation, SE New Mexico

Siltstones in Units 2 and 3

Siltstone beds separating the dolomite beds in units 2 and 3 Transition Lithofacies are from about 1 to 20 cm thick. There are two and possibly three siltstone types. One is a parallel-laminated siltstone grading locally to ripples (Figure 24A, B, C). These are nonmarine sheetwash deposits. The second siltstone type is a convoluted siltstone with thin, soft-sediment deformed dolomite or silty dolomite clasts (Figure 24D). These are interpreted as pre-lithification gypsum dissolution zones (EED on Figures 16 and 17). Some of these convoluted layers show disturbance of underlying dolomite beds (Figure 24E). These may be sabkhas formed prior to gypsum deposition.

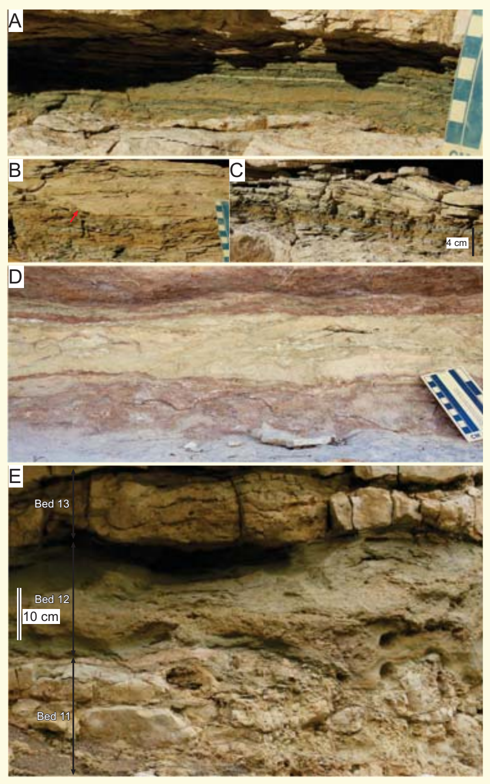


Figure 24. Unit 2 & 3 Transition Lithofacies siltstones. (A) Laminated siltstone, lower Unit 10. (B) Scour (red arrow) into siltstone below vf Ss., upper unit 10. (C) Small dune showing vf sandstone accretion to right, upper unit 10. (D) Convoluted siltstone showing small deformed doloclasts and absence of distinct bedding. Top of Unit 6. (E) Poorly bedded siltstone (Bed 12) with clasts of underlying dolomite (Bed 11). All photos from Arroyo Section.

Bowers Sandstone and Rocky Arroyo Sandstone

In the evaporite lithofacies, Rocky Arroyo Ss. is siltstone interbedded with gypsum and silty gypsum beds deposited in salar and salina environments. Siltstone is friable and lacks sedimentary structures (Figure 25A). The Transition Lithofacies Rocky Arroyo Sandstone grades from intertidal dolomitic siltstone with desiccation cracks, fenestra, and microbial mats near its base to nonmarine stream and sand-flat deposits near its top (Figure 25B). It is overlain by a laminated sheetwash siltstone.

Lower Bowers siltstone in the Evaporite Lithofacies is friable siltstone with thin bottom-growth gypsum layers, indicating at least intermittent salina deposition. In the Arroyo section, lower Bowers sandstones are non-marine, intermittent, flashy steam deposits and associated sand flats. The lower Bowers grades into the middle Bowers through intertidal sediments (Figure 25F).

The medial Bowers member in the Evaporite Lithofacies is salina-deposited gypsum (Figure 20A) with very thin dolomite beds. In the Transitional Lithofacies it is a restricted marine dolopackstone similar to that of Unit 3 (Figure 25E) with no evidence for former gypsum beds. No evidence for subaerial exposure was observed in either lithofacies.

The upper Bowers siliciclastic member in the Evaporite Lithofacies in the Seven Rivers Hills is an haloturbated siltstone with gypsum rosettes (sabkha) interbedded with layers of bottom-growth gypsum (salina) near its base (Figure 25C). Fluvial and eolian ripples characterize the middle to upper parts respectively (Figure 25D). At West Azotea, the upper Bowers contains thin *Osagia*-bearing dolopackstone in weathered siltstone. In the Transition Lithofacies, upper Bowers deposition is mainly restricted shallow-marine sandstone and siltstone with abrupt lower and upper contacts and no dolomite.

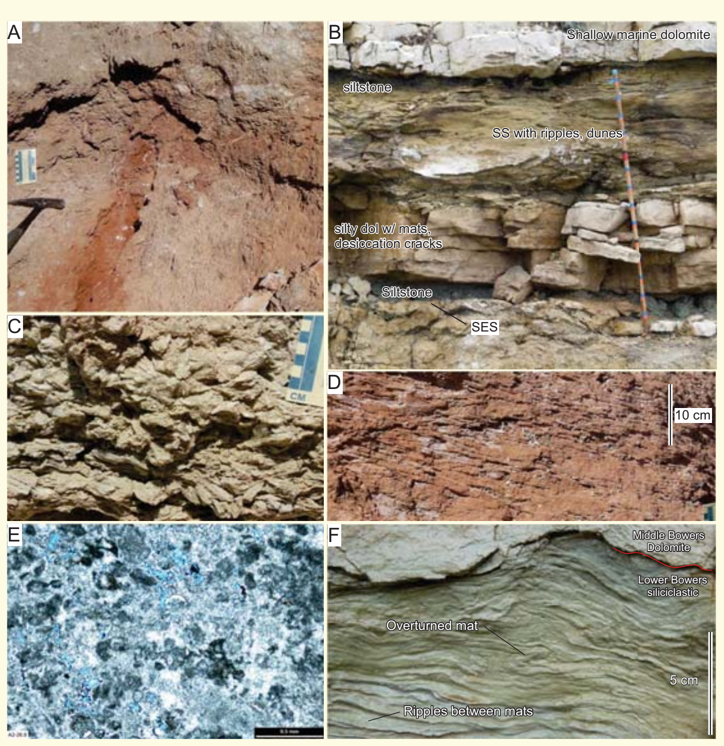


Figure 25. Bowers and Rocky Arroyo Ss. (A) Poorly exposed, friable Rocky Arroyo Ss., West Azotea section. (B) Rocky Arroyo, BL3 and associated features. SES: subaerial exposure surface. (C) Small gypsum rosettes in Third Bowers Ss, northern Seven Rivers Hills. (D) Low-relief eolian ripples, upper Bowers Ss, northern Seven Rivers Hills. (E) Peloid grainstone, middle Bowers at Arroyo section. (F) Contact, lower to middle Bowers showing intertidal matting and ripples. Arroyo section.

Presented at AAPG ANNUAL MEETING, Calgary, 2016

Lower Seven Rivers Facies Models

Unit 1

Unit 1 was deposited along an irregular, rapidly shifting, evaporitic shoreline during transgression at the base of the Seven Rivers Formation (Figure 26). Beach ridges and minor deltas separated evaporite deposition from shallow-marine carbonate and siliciclastic deposition to the southeast. Salars and ponds were common but of small to moderate size.

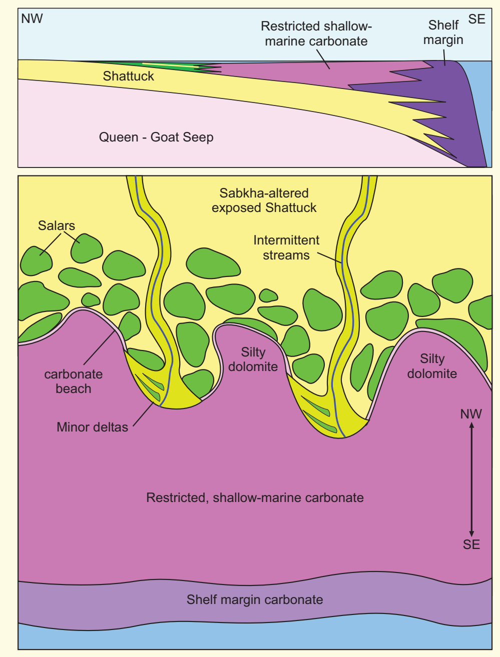


Figure 26. Schematic cross section (upper) and map (lower) interpretation of Unit 1 depositional environments during a high-frequency high stand. Unit 1 Low stand was entirely subaerially exposed and locally deflated by eolian processes.

Unit 2, Unit 3, and Medial Bowers

Transition Lithofacies carbonates are almost entirely shallow-water, restricted marine deposits, whereas interbedded siltstones are subaerial fluvial or sabkha deposits. Dolomite-siltstone couplets therefore represent meter-scale, high-frequency relative sea-level changes. Carbonate and gypsum were deposited during high stand (Figure 27). Sheetwash siltstone and silty gypsum was deposited during low stand - transgression (Figure 28). The thin carbonate beds in the evaporite facies may represent early highstand deposits or periodic freshening of the salina. Absence of consistent vertical facies successions within the carbonate part of each cycle indicates a facies mosaic (i.e., autocycles). Abrupt subaqueous carbonate to subaerial siliciclastics indicates an external control on carbonate-siliciclastic deposition (i.e., allocycles).

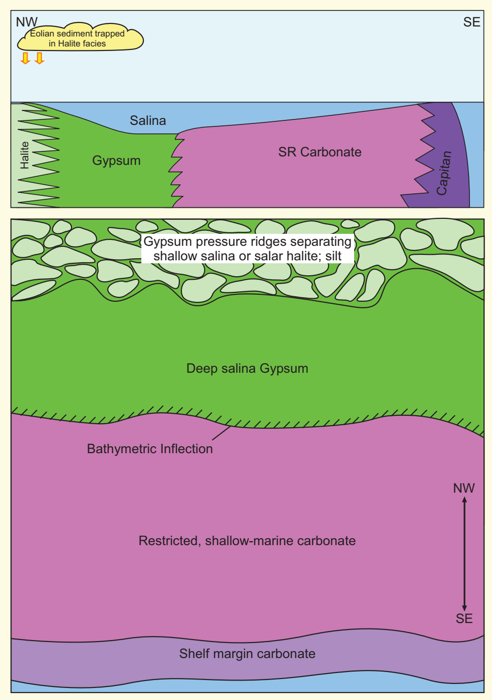
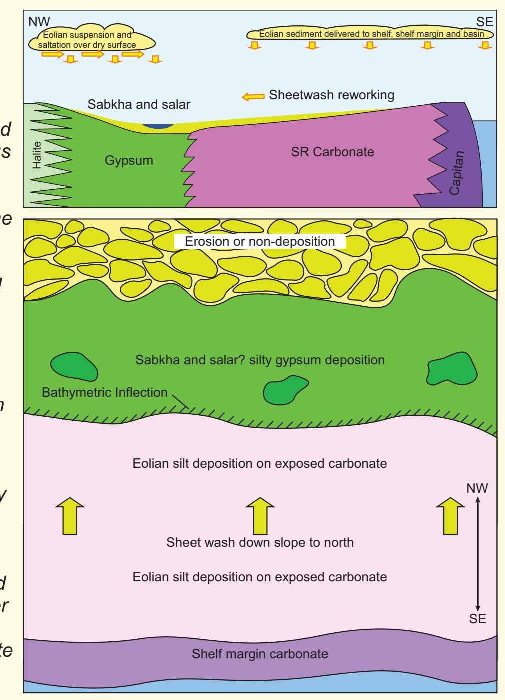


Figure 27 (left). Cross section (upper) and map (lower) of interpreted depositional facies during high frequency high stand deposition of Unit 2, Unit 3, and medial Bowers. Both carbonate and gypsum deposition was subaqueous with no physical barrier between. Brines were generated to the NW and settled to the deep axis near the gypsum-carbonate transition. Sea water was delivered over the shelf margin (SE). Halite was deposited in smaller salinas separated by gypsum ridges.

Figure 28 (right). Cross section (upper) and map (lower) interpretation of Unit 2 and Unit 3, depositional environments during high-frequency low stand and early transgression. Most areas were subaerially exposed sheet-wash, eolian flat, and sabkha environments. Eolian silt and sand could be transported onto the outer shelf and basin. Small salinas persisted near the gypsum-dolomite transition.



There is no evidence for a physical barrier separating restricted marine carbonates from salina gypsum. Brine density contrast is too great for a lateral hydrodynamic barrier (e.g., Scruton 1953). Deposition was probably in a continuous, salinity-stratified brine pool (Figure 29). Denser brines settled to the deep parts of the salina where gypsum precipitated. Carbonates were deposited in modified seawater in shallower water depth closer to the shelf-margin sea-water source.

Carbonate production decreases as salinity increases, and gypsum precipitation rate decreases as salinity decreases. This results in lower sediment accumulation near the pycnocline which causes a bathymetric inflection (Figure 29). This stabilized the position of the gypsum-carbonate transition both within and between high-frequency sea-level cycles. Position of the inflection shifts in response to changes in pycnocline depth, which is controlled by the balance between sea-water recharge (sea level) and brine generation (climate).

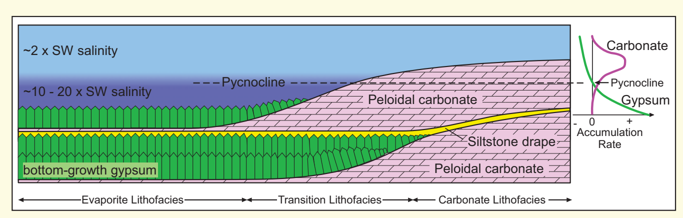


Figure 29. Conceptual model for carbonate-gypsum transition in a density-stratified salina. Stratification develops due to influx of sea water from the margin and brine from the inner shelf. Gypsum precipitated in the deeper, more saline part of the salina as carbonate was deposited in the shallower, less saline part of the water column above the pycnocline. Potential carbonate accumulation rate decreases while gypsum accumulation rate increases downwards. Near the pycnocline, total accumulation rate is less, so bathymetric slope steepens. The slope provides a feedback stabilizing position of the transition during minor sea-level and climatic variations.

Rocky Arroyo Sandstone; Lower and Upper Bowers

Major siliciclastic units in the Evaporite Lithofacies are salina, salar, and sabkha siltstones mixed with gypsum. In the Transition Lithofacies, Rocky Arroyo and Lower Bowers siliciclastics are intermittent fluvial and eolian flat siltstone and sandstone. Upper Bowers is a restricted marine deposit. Near the shelf margin, siliciclastic units correlative to the Bowers and Rocky Arroyo units are siltstone interpreted by Tinker (1998) as eolian and sabkha deposits. This pattern of shelf siltstone to sandstone to shelf margin siltstone is similar to that in the Yates Formation (e.g., Borer and Harris 1991).

Selective fluvial deposition near the Transition Lithofacies surrounded by predominantly eolian flat deposition both seaward and landward of the fluvial system indicates predominantly strike-oriented, intermittent fluvial systems in an area low to both the shelf margin and inner shelf (Figure 30). The streams probably cut across the shelf margin to provide point sources for sand delivered to the basin.

Rocky Arroyo and lower Bowers fluvial, eolian sand flat, and sabkha deposition interrupts shallow-water deposition and therefore represents low stand or transgression after a low stand, as proposed for the Yates siliciclastics (Borer and Harris 1991). The upper Bowers siliciclastic member was a greater transgression than the lower member, which may explain the absence of gypsum between top Bowers and third Bowers in the Arroyo section.

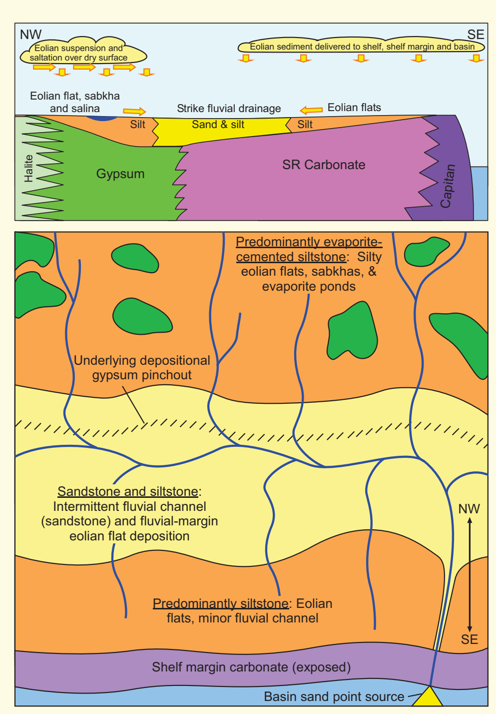


Figure 30. Cross section (upper) and map (lower) interpretation of Rocky Arroyo and lower Bowers depositional environments. Poorly integrated drainage seaward and landward of the transition zone leads to primarily eolian flat and sabkha deposition. These drain into a strike-oriented fluvial system near the evaporite transition that reworks eolian-derived siliciclastics into sands. Isolated small salinas persist in the Evaporite lithofacies. Sand is ultimately delivered to the basin at point sources that cross the shelf margin.

Discussion and Conclusions

Causes of Abrupt Evaporite - Carbonate Transition

The gypsum-carbonate transition is abrupt for two reasons:

(1) Gypsum selectively dissolves from interbedded gypsum-dolomite lithofacies near their transition, thereby reducing the width of the transition. Permian-aged dissolution affects both surface and subsurface; Cenozoic-aged dissolution affects outcrops and shallow subsurface.

(2) The stratified salina model provides a mechanism for developing bathymetric relief at the carbonate-gypsum transition. Abrupt bathymetric change reduced lateral shifts of the gypsum-carbonate transition as sea level and climate changed. This is the reason that the carbonate-sulfate transition is narrower than the halite-sulfate transition.

Synchronous Subaqueous Gypsum and Carbonate Deposition

The proposed stratified salina model is similar to the Sloss (1969) layered-water model, only salinity in the surface water mass is sufficiently high to restrict carbonate fauna. In stratified salinas, brine is generated where wind stress locally thins the upper water mass to expose brine at the surface where it evaporates (Stuart 1973). The dense brine then flows toward the deeper area near gypsum-carbonate transition where it is overridden by modified sea water flowing from the shelf margin (Figure 31).

Based on lack of fine-scale bed correlation in the halite facies, water depth was very shallow where brine was generated in the halite facies (~1 m?). The salina deepened towards the gypsum-carbonate transition. Maximum water depth near the transition is not specified in this model, but it was probably on the order of ten meters.

Control on Position of Sulfate-Carbonate Transition

The transition did not shift during times of shelf-margin aggradation. It shifted landward as the shelf margin prograded (Figure 15). Landward shift during shelf margin progradation indicates that the position of the transition is controlled by sediment production on the shelf interior and not by transported shelf-margin material.

The pattern of transition shifts can be interpreted in terms of accommodation space creation vs. sediment accumulation. Shelf-margin aggradation corresponds to low-frequency relative sea-level rise (Figure 32). Shelf-interior carbonate production balanced accommodation space, so no excess carbonate was available for landward shifting of the sulfate-carbonate transition. Shelf-margin progradation corresponds to times of lower low-frequency relative sea-level rise. With lower vertical accommodation space creation on the shelf interior, carbonate was available for landward (down paleoslope) transport. Landward carbonate transport shifted the sulfate-carbonate transition landward (Figure 32).

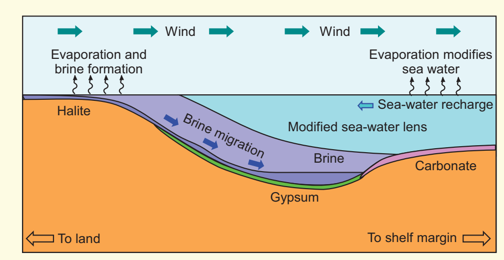


Figure 31. Generalized stratified brine model. A modified sea-water lens forms by evaporation over the carbonate facies. Wind prevents spread of sea water over entire shelf. Near halite-saturated brines form in the halite facies. The brine flows due to density towards the deepest part of the salina near the gypsum-carbonate transition. Excess halite-saturated brine sinks into the sediment, where it dolomitizes underlying carbonates.

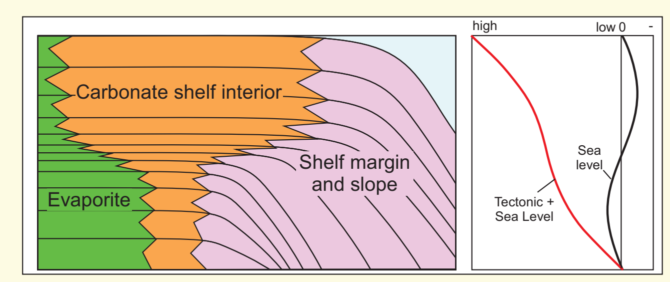


Figure 32. Stratal patterns and shelf lithofacies distribution (left) in response to long-term accommodation space creation (right). Accommodation space is created by low-frequency sea-level cycles superimposed on tectonic subsidence. Lines are equally spaced in time.

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