

Expression of Low- to Intermediate-Frequency Cyclicity in Siliciclastic Intervals of the Paradox Formation, Paradox Basin, Utah*

Jennifer Eoff¹, Katherine Whidden¹, Russell Dubiel¹, Sarah Hawkins¹, Kristen Marra¹, Ofori Pearson¹, and Janet Pitman¹

Search and Discovery Article #50777 (2013)**

Posted March 18, 2013


*Adapted from oral presentation given at AAPG Rocky Mountain Section meeting, Grand Junction, Colorado, 9-12 September 2012

**AAPG©2013 Serial rights given by author. For all other rights contact author directly.

¹United States Geological Survey, Denver, Colorado (jeoff@usgs.gov)

Abstract

The U.S. Geological Survey (USGS) completed a geology-based assessment of the undiscovered, technically recoverable oil and gas resources in the Paradox Basin. Ongoing research includes revised description of core from the Shafer-1 well, drilled in the northwestern part of the basin in San Juan County, Utah. Whereas only two scales of cyclicity were described previously, changes in mineralogy and depositional fabric actually reveal at least five scales of nested cyclicity. Recent paleogeographic reconstructions place the Paradox Basin at low latitudes during the Middle Pennsylvanian, within about 15 deg of the paleoequator. At the scale of tens of meters, the lowest-frequency cycles consist of alternating salt and non-salt strata, with the latter comprised of dolomitic siltstones and organic carbon-rich shales. Subdivisions of each lithology are defined by crystal size and texture or by the presence and type of sedimentary structures, including bioturbation, for salt and siliciclastic intervals, respectively. High-frequency cycles in evaporite successions that record freshening of the saline basin contrast with those cycles that document periods of increasing basin restriction, and most of the finest-scale cyclicity within each likely resulted from local to regional variations in climatic conditions. Alternatively, retrogradational and progradational stacking of siliciclastic packages document the effects of intermediate-frequency, regional variations during eustatic flooding and highstand. The distribution of hydrocarbon source rocks within the siliciclastic intervals was controlled primarily by the varying supply of silt-sized and coarser sediment by active basinward transport processes and by the degree of bioturbation. A preliminary microstratigraphic framework aids in characterization of shales as potential source rocks or as potential self-sourcing shale reservoirs, which has important implications for exploration strategies and production techniques.



Expression of low- to intermediate-frequency cyclicality in siliciclastic intervals of the Paradox Formation, Paradox Basin, Utah

U.S. Geological Survey
Central Energy Resources Science Center :
Jennifer D. Eoff, Katherine J. Whidden, Russell Dubiel,
Sarah Hawkins, Kristen Marra, Ofori Pearson,
and Janet Pitman



Rocky Mountain Section
American Association of Petroleum Geologists
Grand Junction, CO
September 9-12, 2012

Presenter's notes: These are the observations and preliminary interpretations from a team core research study at the U.S. Geological Survey (USGS) in Denver to supplement the Paradox Basin hydrocarbon resource assessment that was made available to the public this year as a USGS Fact Sheet (Whidden and others, 2012, Assessment of undiscovered oil and gas resources in the Paradox Basin Province, Utah, Colorado, New Mexico, and Arizona, 2011: U.S. Geological Survey Fact Sheet 2012-3031, 4 p., <<http://pubs.usgs.gov/fs/2012/3031/>>).

Delhi-Taylor Oil Company Shafer No. 1 Core, USGS

Rocky Mountain Section American Association of Petroleum Geologists abstracts, September, 2012:

- Eoff, Jennifer D., Whidden, Katherine J., Dubiel, Russell, Hawkins, Sarah, Marra, Kristen, Pearson, Ofori, and Pitman, Janet, 2012, Expression of low- to intermediate-frequency cyclicity in siliciclastic intervals of the Paradox Formation, Paradox Basin, Utah: American Association of Petroleum Geologists Rocky Mountain Section Meeting, Grand Junction, CO, September 9-12, 2012, American Association of Petroleum Geologists Search and Discovery Article #90156, <http://www.searchanddiscovery.com/abstracts.html/2012/90156rms/abstracts/eoff.htm>.
- Marra, Kristen, Dubiel, Russell, Pitman, Janet, Pearson, Ofori, Whidden, Katherine, Eoff, Jennifer, and Hawkins, Sarah, 2012, Interpreting small-scale cyclicity of halite-anhydrite precipitation within Cycle 13, Shafer No. 1 core, Paradox Basin, Utah: American Association of Petroleum Geologists Rocky Mountain Section Meeting, Grand Junction, CO, September 9-12, 2012, American Association of Petroleum Geologists Search and Discovery Article #90156, <http://www.searchanddiscovery.com/abstracts.html/2012/90156rms/abstracts/marra.htm>.
- Pearson, Ofori, Dubiel, Russell, Eoff, Jennifer, Hawkins, Sarah, Marra, Kristen, Pitman, Janet, and Whidden, Katherine, 2012, Quantitative Color Analysis of Evaporites from the Middle Pennsylvanian Paradox Formation, Paradox Basin, Utah: American Association of Petroleum Geologists Rocky Mountain Section Meeting, Grand Junction, CO, September 9-12, 2012, American Association of Petroleum Geologists Search and Discovery Article #90156, <http://www.searchanddiscovery.com/abstracts.html/2012/90156rms/abstracts/pear.htm>.
- Whidden, Katherine, Dubiel, Russell, Eoff, Jennifer, Hawkins, Sarah, Marra, Kristen, Pearson, Ofori, and Pitman, Janet, 2012, Expression of high-frequency cyclicity in different lithofacies of the Paradox Formation, Paradox Basin, Utah: <http://www.searchanddiscovery.com/abstracts.html/2012/90156rms/abstracts/whid.htm>



Presenter's notes: The project is introduced in this report, but team members presented several oral talks and posters on the Paradox Basin at this meeting of the Rocky Mountain Section of the American Association of Petroleum Geologists. Each covered different aspects of our work on the Delhi-Taylor Oil Company Shafer No. 1 corehole. The reader is also directed to the websites provided above.

Introduction

- Continued research to supplement recent hydrocarbon assessment of the Paradox Basin (Whidden and others, 2012, USGS Fact Sheet 2012-3031)
- Shafer No. 1 core, San Juan County, Utah
 - 2,160' – 4155.8'
 - Penetrated Honaker Trail and Paradox Formations of the Hermosa Group
- Paradox Basin, Ancestral Rocky Mountains
 - Uncompahgre and San Luis bordering uplifts
 - Basin fill of evaporites, carbonates, and siliciclastics (including petroleum source rocks)



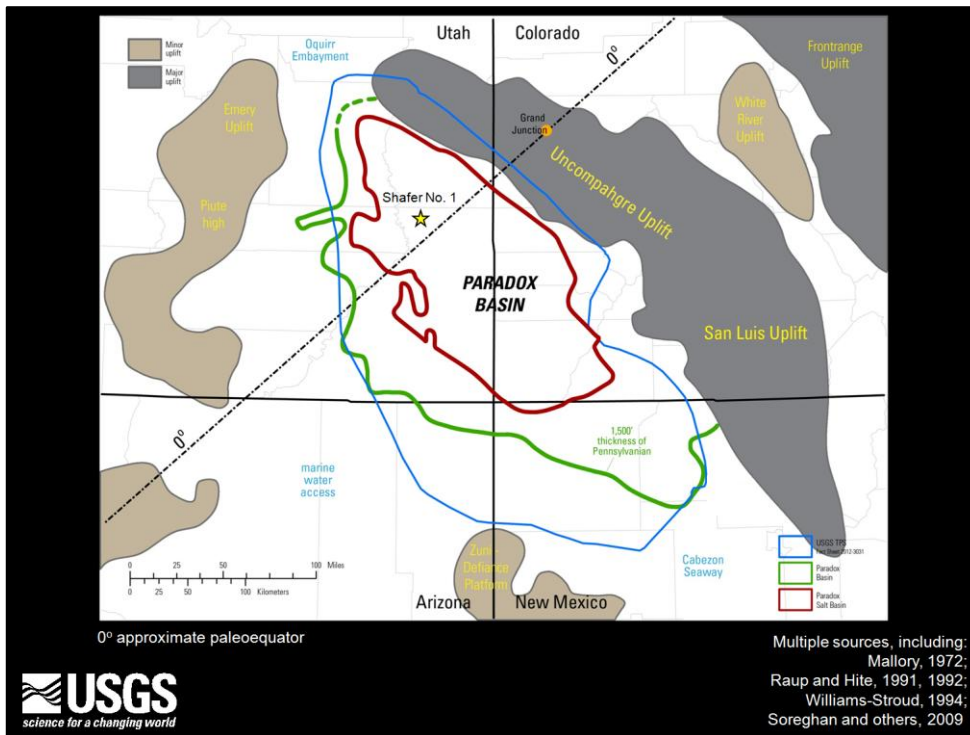
U.S. Geological Survey
Fact Sheet 2012-3031

<http://pubs.usgs.gov/fs/2012/3031/FS12-3031.pdf>

Presenter's notes: These are observations of an ongoing core study.

The Paradox Basin records Pennsylvanian-Permian accommodation in the Ancestral Rocky Mountains. The Ancestral Rockies resulted from latest Mississippian-Permian intraplate orogeny from far-field effects of Ouachita-Marathon collisional tectonics (Soreghan and others, 2012).

The Shafer No. 1 core in San Juan Co., Utah, penetrates sequences of evaporites, carbonates, and shales.



Presenter's notes: As currently defined, boundaries of the Paradox Basin correspond to the extent of Paradox salt (in red) (Williams-Stroud, 1994). The Paradox Basin was an asymmetrical basin that resulted from thrusting and uplift to the east (Williams-Stroud, 1994). The green boundary corresponds to 1,500 feet of thickness of Pennsylvanian strata (Mallory, 1972), the greater Paradox depositional basin, and records the location of accommodation generated as a result of the adjacent tectonism of the San Luis and Uncompahgre uplifts. The Total Petroleum System for the USGS assessment of the Paradox Basin is in blue (Whidden et al., 2012).

In the latest Mississippian to Early Pennsylvanian, deformation of the craton in the Four Corners area of Utah-Arizona-New Mexico-Colorado resulted from far-field effects of the early deformational phases of the Ouachita and Marathon orogenies along the southern margin of Laurentia (Soreghan and others, 2012). As Laurasia and Gondwana sutured (Kluth and Coney, 1981), deformation spread westward from the Anadarko Basin toward the southeast end of the Uncompahgre uplift (i.e., the San Luis uplift) (Kluth and Coney, 1981; Soreghan and others, 2012). Basin accommodation in the Paradox developed rapidly (Hite et al., 1984; Williams-Stroud, 1994). This intracratonic orogenesis, characterized by rapid uplift, peaked in the Middle Pennsylvanian (Desmoinesian) to earliest Permian (Kluth and Coney, 1981; Soreghan and others, 2012).

Introduction

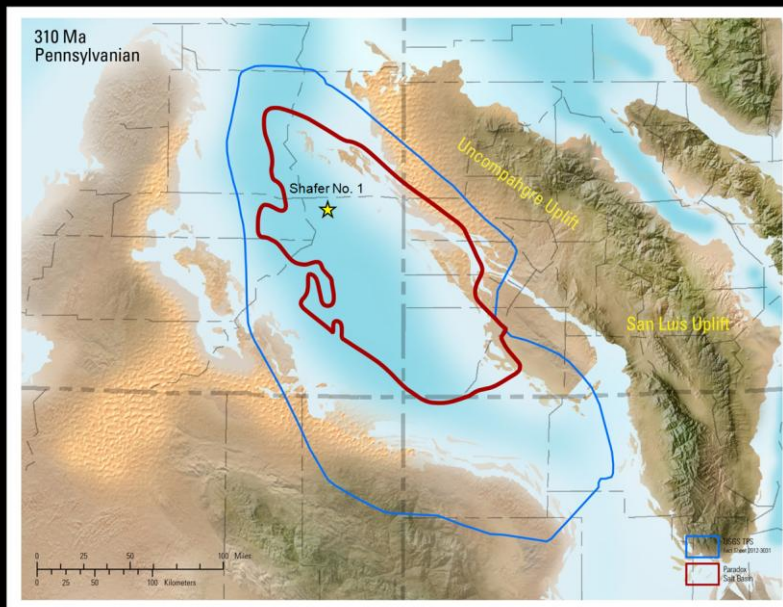
Agenda

- Stratigraphy & geologic setting
- Low-frequency depositional cycles
 - Idealized evaporite model
 - Simplified Paradox Basin model
 - Gross depositional setting
- Intermediate-scale cycles
- High-frequency cycles
- Concluding remarks



Presenter's notes: The stratigraphy and general geologic setting are discussed first.

STRATIGRAPHY & GEOLOGIC SETTING



Blakey, 2011



Sea Level : High

Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012). All paleogeographic maps are courtesy of Blakey (2009) and Ron Blakey and Colorado Plateau Geosystems (2011 DVD series). The Four Corners area was in an equatorial position during deposition in the Paradox Basin.

Uplift of the San Luis began, at the earliest, in the latest Mississippian, and faulting of the greater Uncompahgre area appears to have ceased in the Late Pennsylvanian to earliest Permian (Soreghan and others, 2012).

Agenda

- Stratigraphy & geologic setting
- Low-frequency depositional cycles
 - Idealized evaporite model
 - Simplified Paradox Basin model
 - Gross depositional setting
- Intermediate-scale cycles
- High-frequency cycles
- Concluding remarks

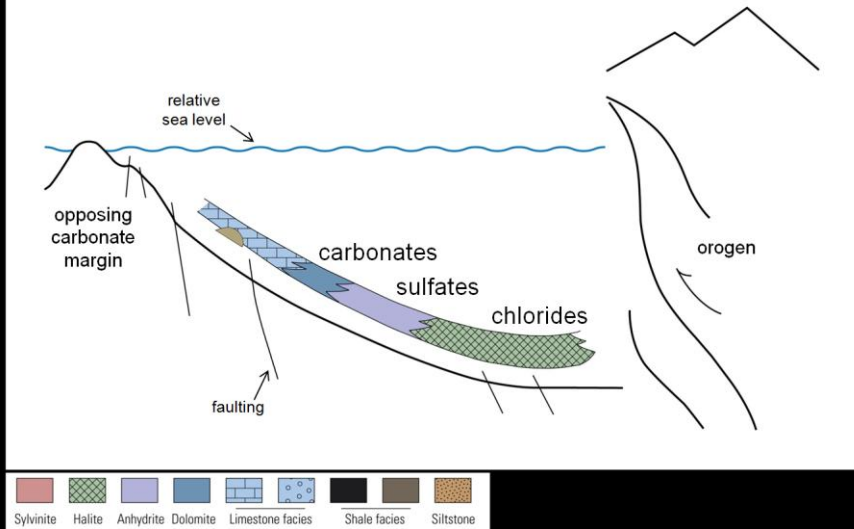
} *Alternation of salt and non-salt strata*

Models (Idealized & Simplified)

LOW-FREQUENCY CYCLES

Eustasy : Lowstand
 Global climate : Glacial
 Deposition : Precipitation

global climate
 Arid
 Humid

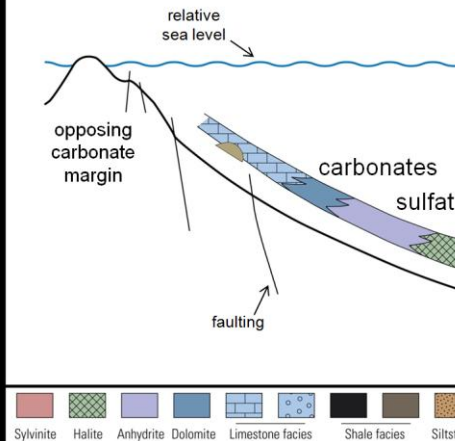


Presenter's notes: This is a general model of evaporite precipitation during deposition/precipitation of the Paradox Formation. The ideal evaporite cycle documents the expected order of solubility products from evaporated seawater (Hite and others, 1984) (see below). Water in the Paradox Basin underwent many cycles of increased salinity and dilution (Hite and others, 1984). Both marine incursion through the opposing platform and seepage of meteoric groundwater adjacent to the orogen affected salinity in the basin (Williams-Stroud, 1994). In the example shown here, the global climate was likely glacial and eustatic sea level correspondingly low.

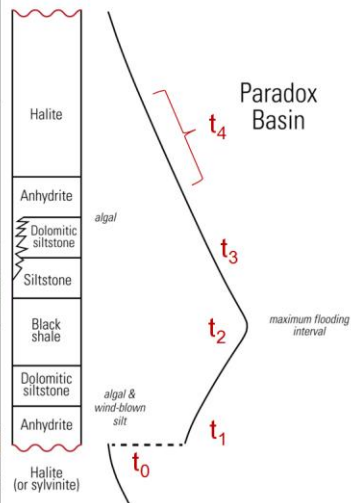
Lateral transition from carbonates to sulfates and then to chlorides occurs with increasing basin restriction and increasing salinity. In an interval of decreasing basin restriction and incursion of normal marine water, reverse transitions are characteristic.

In each of the following figures, Paradox Formation deposition is discussed in context of approximate basin center and the Shafer No. 1 core location, while keeping orogen and opposing carbonate platform static. Furthermore, the model is meant to represent one cycle of deposition in the basin, not the entire basin fill.

Eustasy : Lowstand
Global climate : Glacial
Deposition : Precipitation



Global setting	Low	←	→	High	Eustasy
	Cool	←	→	Warm	Climate
	Dry	←	→	Wet	Precipitation
	Brine	←	→	Marine	Seawater Chemistry



Modified from:
Hite and others, 1984

Presenter's notes: For the following slides, the global setting is noted in the text or box at the top. Using cores, Hite and others (1984) and Williams-Stroud (1994) developed a local model for deposition in the Paradox Basin, in which lateral transitions among evaporite precipitates can be understood in terms of regional to local climate variation and relative sea level change.

In the following slides, times " t_0 " through " t_4 " begin at the top of the previous cycle and finish near the top of the new salt cycle:

t_0 = top of previous cycle (halite or sylvinite).

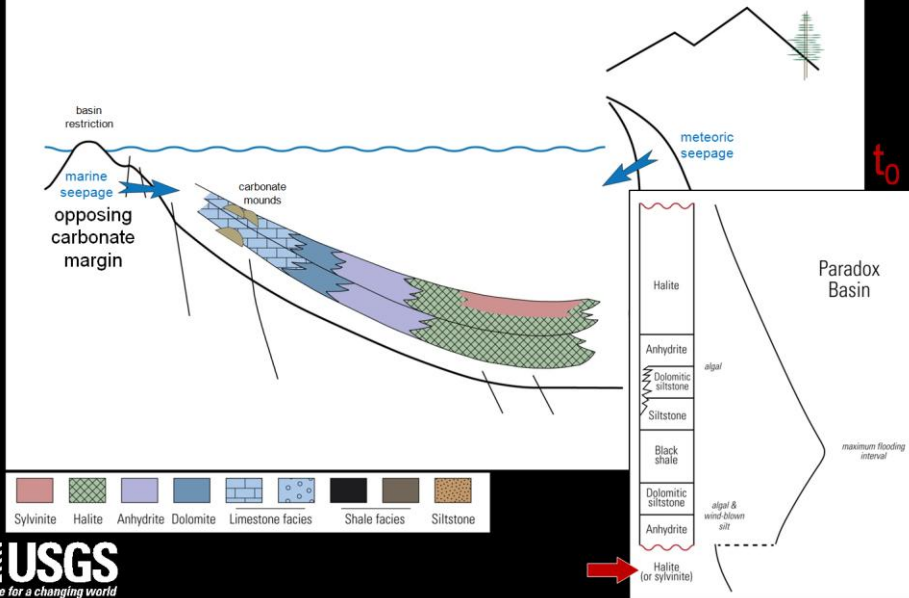
t_1 = basal contact of new salt cycle.

t_2 = black shale deposition.

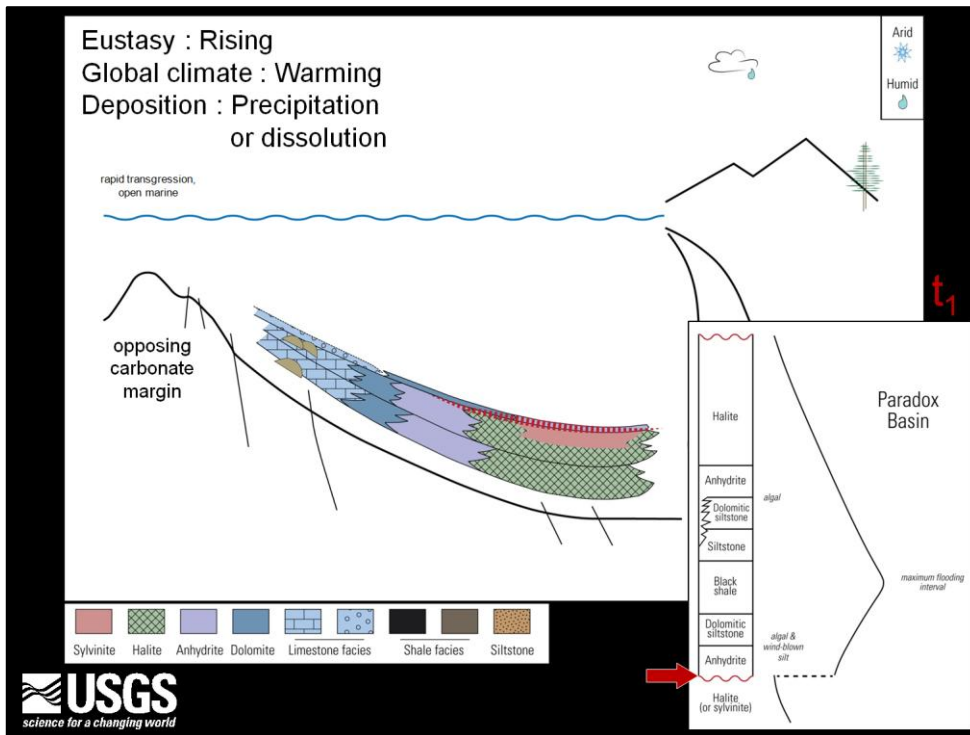
t_3 = deposition of siltstone.

t_4 = transition back into evaporite facies.

Eustasy : Lowstand
 Global climate : Glacial
 Deposition : Precipitation

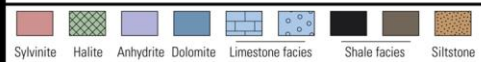
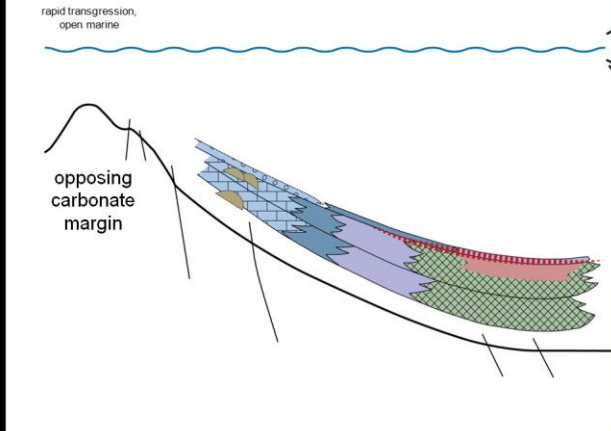


Presenter's notes: The following slides will step through modeled facies for one salt cycle in the Paradox Basin, starting at the top of the previous salt cycle (t_0). At a basic level of observation, this is the expected transition among evaporite minerals in a restricted basin during lowstand, from carbonates to sulfates and finally to chlorides. Deposition in the basin center was dominated by precipitation of evaporite mineral assemblages, and Williams-Stroud (1994) noted possible inflow of marine water from the west through the exposed platform and meteoric groundwater from the east. Carbonates were only contemporaneous with salt precipitation if the carbonate margin was not fully exposed (Williams-Stroud, 1994). If present, exposure surfaces of carbonates are correlative with salts in the basin (Williams-Stroud, 1994).

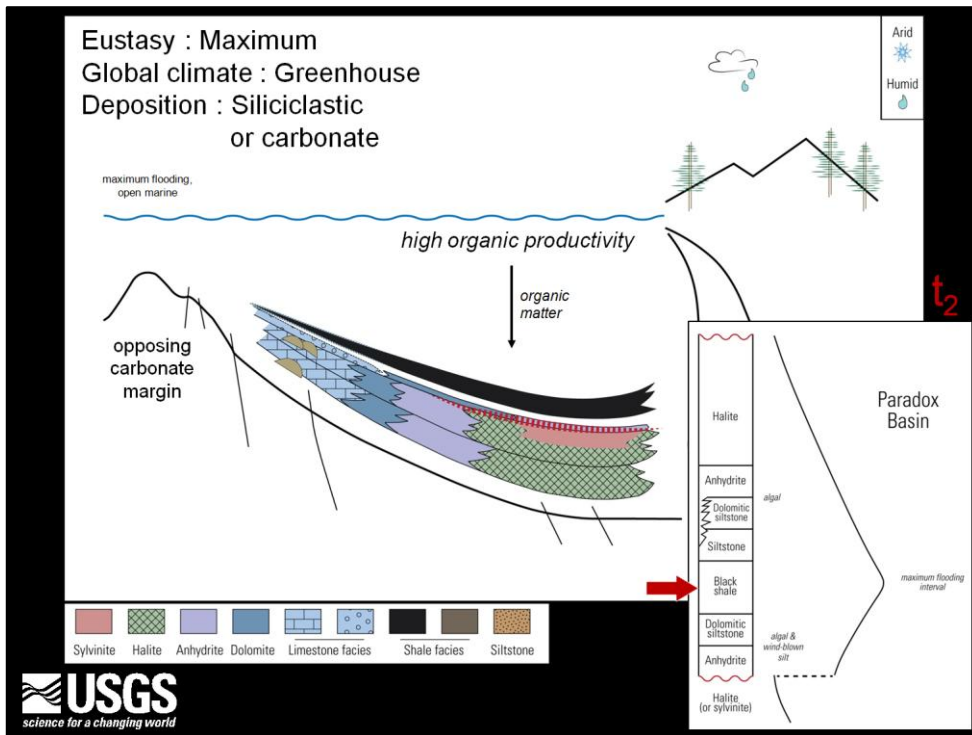


Presenter's notes: An erosional or dissolution contact (red hashing) between anhydrite and the underlying halite marks the base of an idealized cycle (t_1) (Williams-Stroud, 1994). The base of this cycle records the initial rise in sea level, likely due to a combination of global tectonics and climate. Precipitation of sulfates occurred, preserved as anhydrite in core. Anhydrite may also be associated with silty dolomite in parts of the basin.

Eustasy : Rising
 Global climate : Warming
 Deposition : Precipitation
 or dissolution



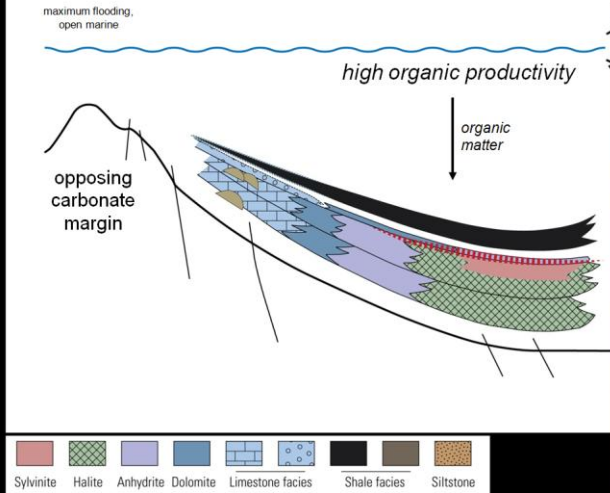
Presenter's notes: Example of a cycle base (t_1) in core. The contact is sylvinite to wavy-laminated anhydrite (red arrow). Vertical scale bar 2 in. This may be associated with algal features and silty dolomite. Williams-Stroud (1994) identified that a "cap facies" of pelletal-foraminiferal limestone unconformably overlies mound facies near the basin margin. These are transgressive carbonate deposits.



Presenter's notes: During t_2 , deposition was dominated by clastic or carbonate sedimentation during continued transgression and flooding that were due to warming and global greenhouse conditions. Once sea level reached its maximum landward extent, deposition of organic-rich shale was common. Coarser siliciclastics were trapped inboard along the uplift margins or in peripheral foredeep accommodation. Enhanced supply of terrestrial organic detritus promoted increased activity of microorganisms in shallow water. Accumulation of this organic matter was not diluted by clastics.

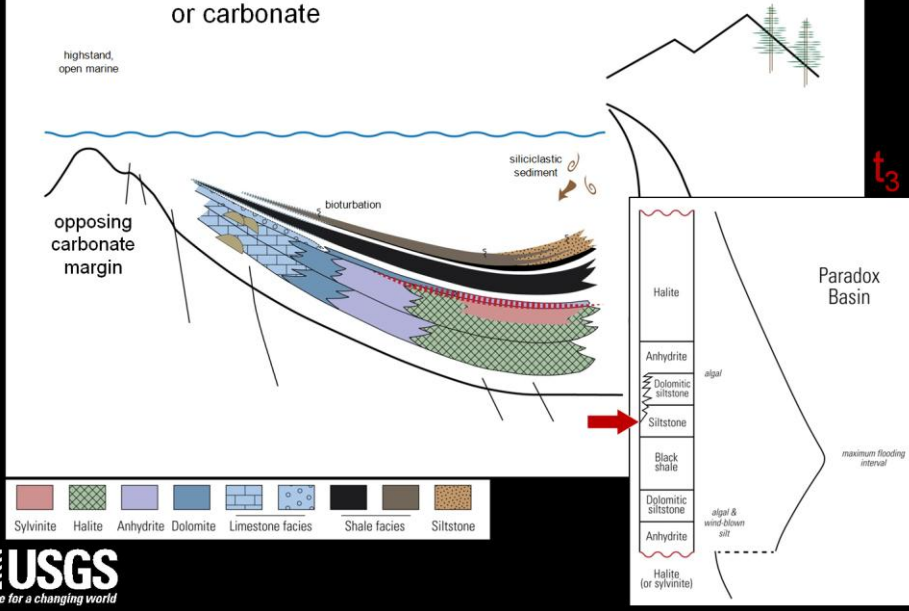
Black shale units document the highest and freshest (i.e., normal marine) sea (Williams-Stroud, 1994). The largest volume of organic matter accumulated and was preserved during high sea level (Hite and others, 1984).

Eustasy : Maximum
Global climate : Greenhouse
Deposition : Siliciclastic
or carbonate



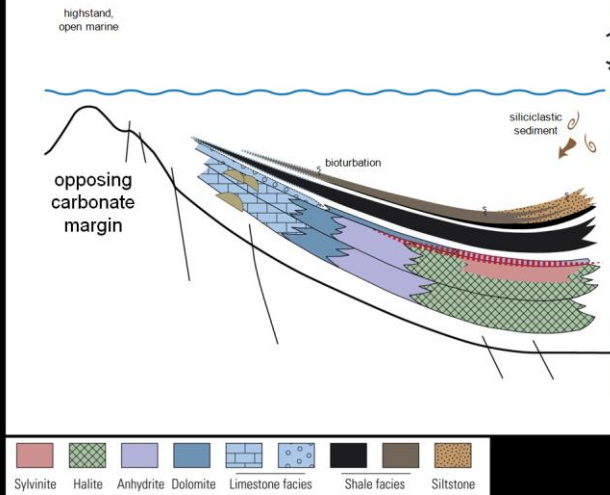
Presenter's notes: Dark shale contains abundant organic matter. Scale bar 2 in. Shale is infrequently pyritic. Shale is associated with siltstone in some parts of the section and can also be associated with nodular anhydrite. Organic-rich shale correlates with carbonate deposition on the platform opposite the orogen (Hite and others, 1984) or with a drowned platform.

Eustasy : Falling
 Global climate : Cooling
 Deposition : Siliciclastic
 or carbonate



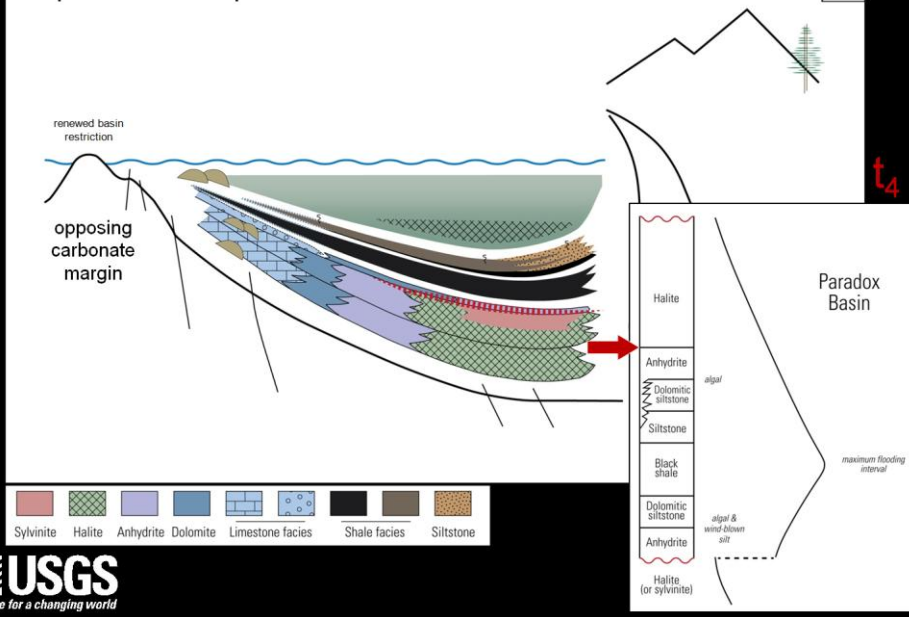
Presenter's notes: Initial (global) cooling and lowering of sea level (during t_3) caused progradation of coarser siliciclastics from the building orogen. While still associated with thinner organic-rich shale, dilution of organic matter was more common. Because substrates were more stable due to greater influx of silt, bioturbation increased and (or) its preservation was greater. Consumption of accumulating organic materials by benthos increased.

Eustasy : Falling
 Global climate : Cooling
 Deposition : Siliciclastic
 or carbonate



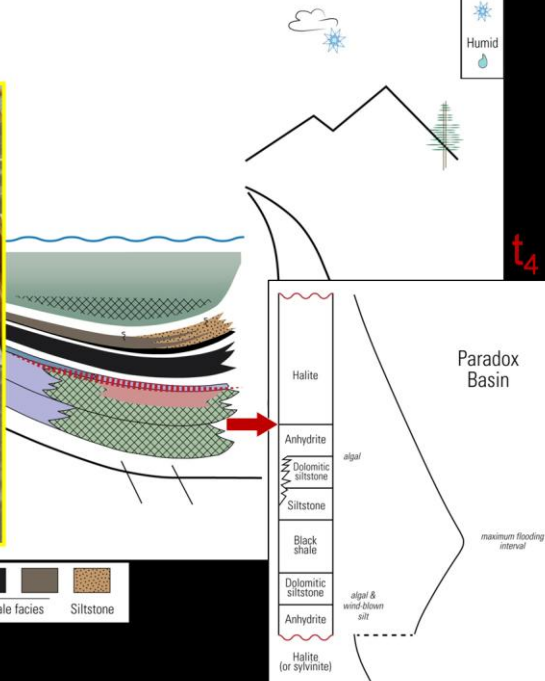
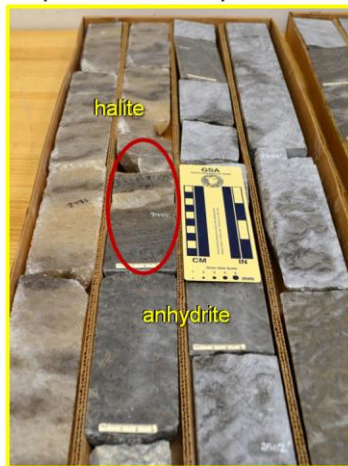
Presenter's notes: This is an example of an intensely burrowed siltstone. Scale bar 2 in. Bioturbation is most apparent in the siltstones as compared to the other facies. In the Shafer No. 1 core, one can frequently identify parasequences among the various shale units and siltstones.

Eustasy : Lowstand
 Global climate : Glacial
 Deposition : Precipitation

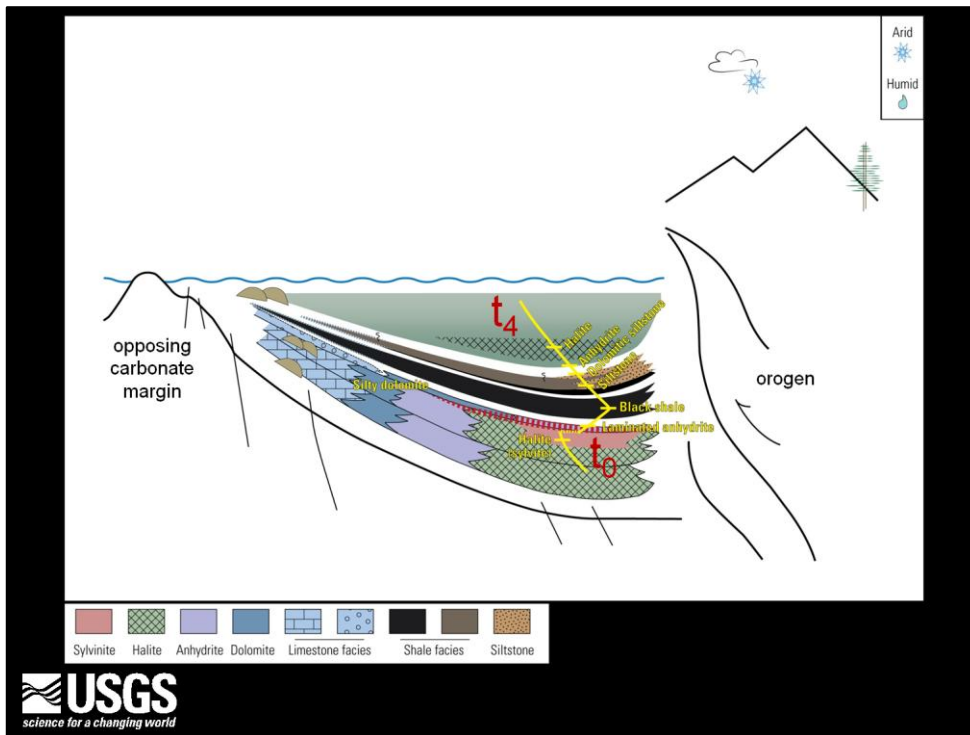


Presenter's notes: During global lowstand (t_4), which was likely due to a return to glacial conditions, sea level again dropped below the sill opposing the orogen. Precipitation of evaporites recommenced through carbonate to gypsum/anhydrite and to halite transitions.

Eustasy : Lowstand
 Global climate : Glacial
 Deposition : Precipitation



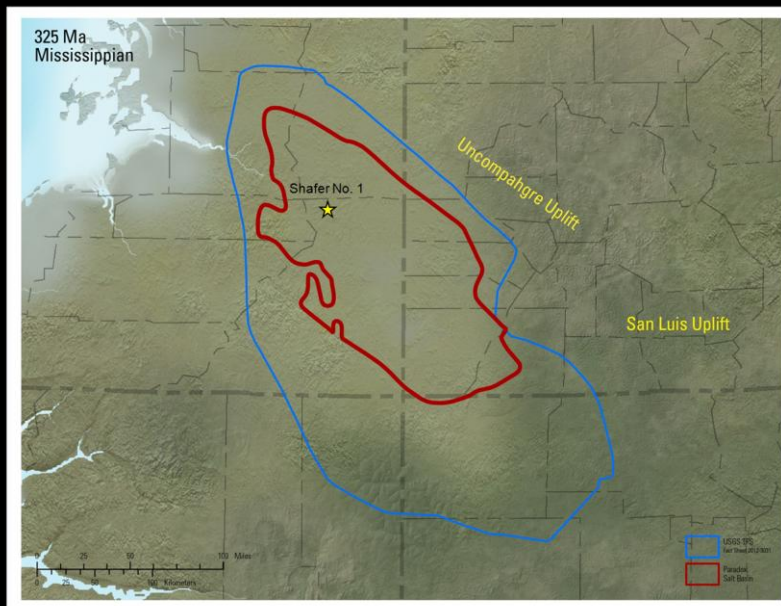
Presenter's notes: In this section, the cycle top is expressed as a long transition through sulfides (anhydrite) to the next package of halite.



Presenter's notes: This is the basic salt cycle developed by Hite and others (1984), plotted on the depositional model. The top of the underlying cycle (t_0) is halite, with or without sylvite. Initial transgression and freshening (t_1) from brine to normal-marine water partially dissolved the halite, and the salt succession reversed direction. Flooding (t_2) permitted the deposition of organic-rich shale, the thickness of which was dependent on amount of accommodation and the degree of dilution by clastic or biogenic grains. During initial lowering of sea level after maximum flooding (t_3), progradational siltstones were deposited proximal to the orogen. More stable substrate, as compared to the underlying shale, permitted abundant infauna and epifauna, so marine organic matter was both diluted and consumed more than during deposition of the underlying shale unit. Transitions upsection from siliciclastic units back into evaporite precipitation (t_4) were complex, but often preserved "drying upward" parasequences. Renewed basin restriction (t_4 continued) resulted in salt precipitation in depocenters.

Gross Depositional Setting

LOW-FREQUENCY CYCLES



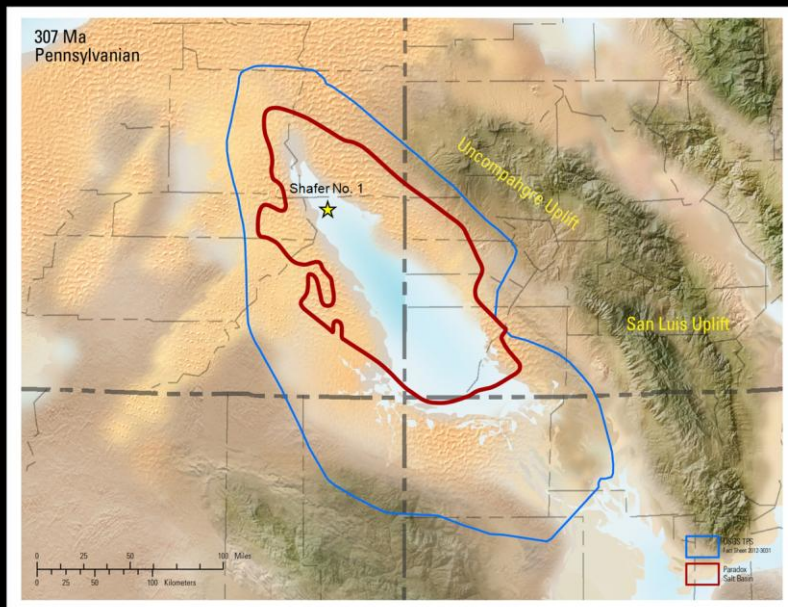
Blakey, 2011



Before development of accommodation of the Paradox Basin

Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox Salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

The depositional model for a salt cycle in map view will now be discussed. The Mississippian paleogeography (Blakey, 2011), prior to creation of the Paradox Basin, is shown.



Blakey, 2011

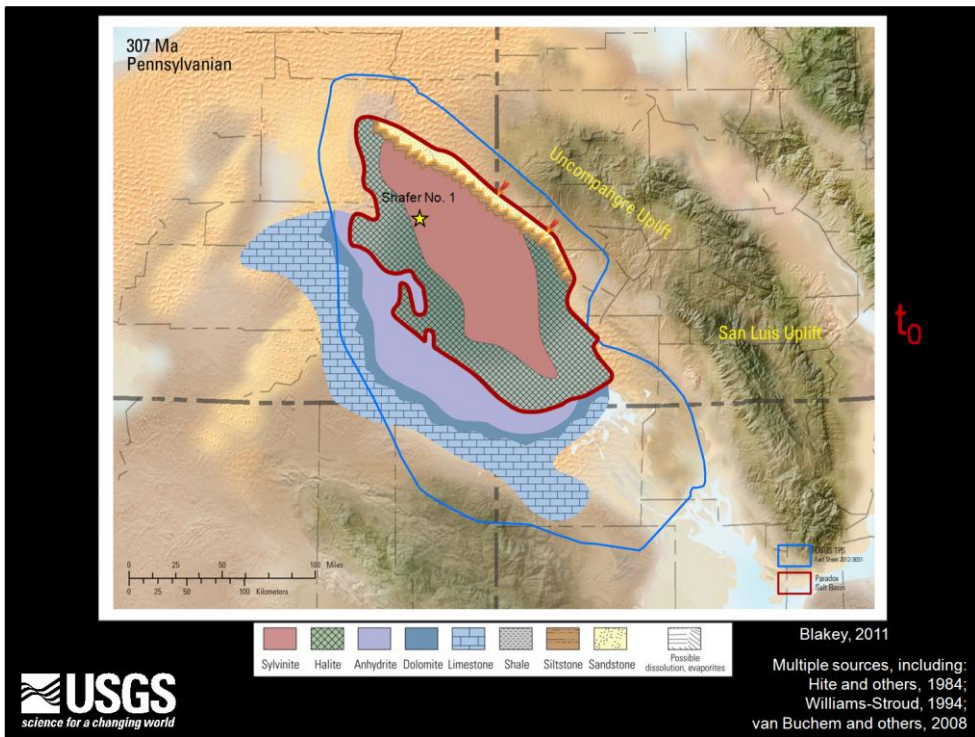


Sea Level : Low

Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox Salt Basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

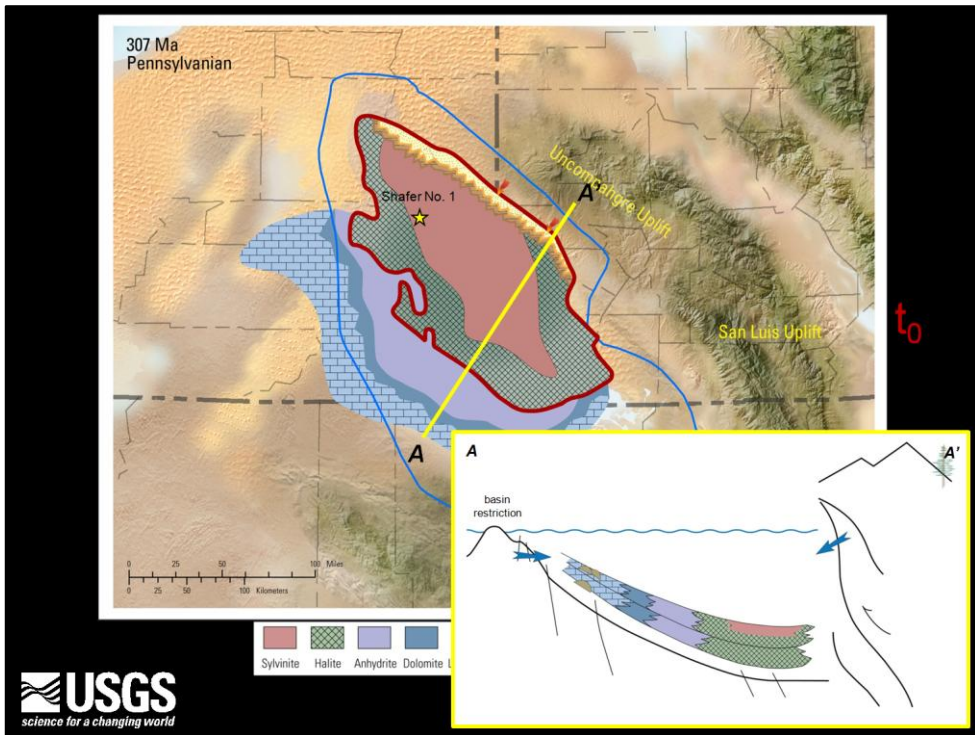
This map from the Pennsylvanian (Blakey, 2011) shows lowstand conditions similar to those during salt precipitation (t_0 or t_4).

Note that for the following slides, facies polygons do not correspond exactly to the newer interpretations of paleogeography provided by Blakey (2011). Facies polygons were minimally modified from their original published versions.



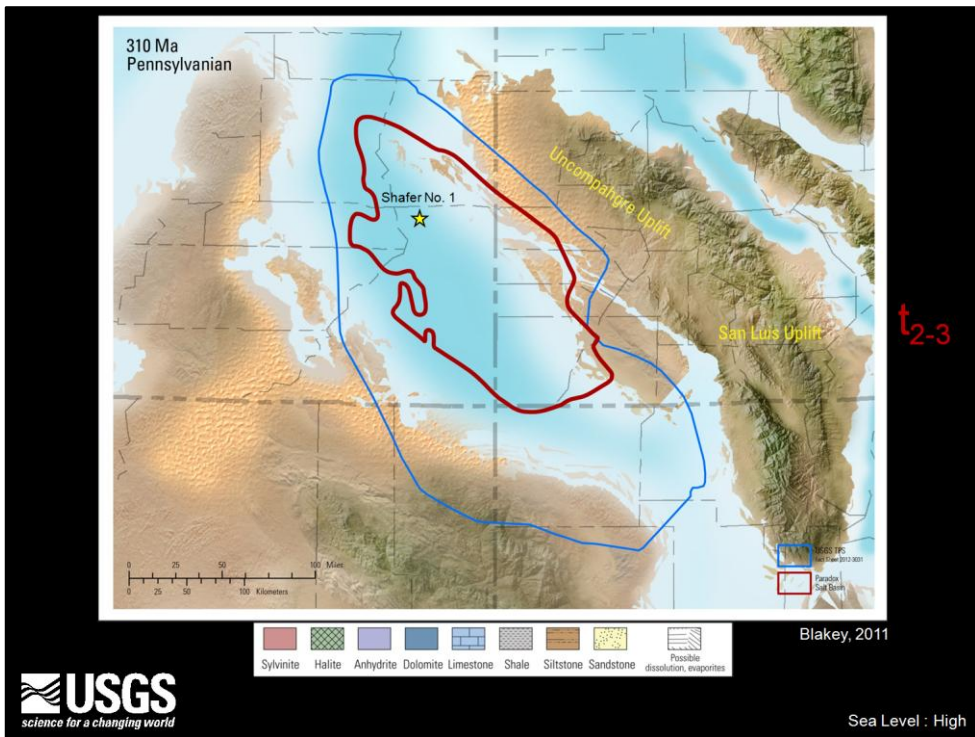
Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox Salt Basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

Salt precipitated in the depocenter was associated with silty units, anhydrite, and black shale (Hite and others, 1984; Williams-Stroud, 1994). Contemporaneous with salt precipitation, silty biostromal-biohermal carbonates and gray shales were deposited on the shelf to the southwest (Williams-Stroud, 1994). Anhydrites (or dolomites) are frequently laminated, often algal (Williams-Stroud, 1994). Silt content in the basin was due to reworking and redistribution of sediment from basin margins or eolian transport. Along the San Luis and Uncompagre uplifts, sand and silt were trapped in and near foredeep accommodation.



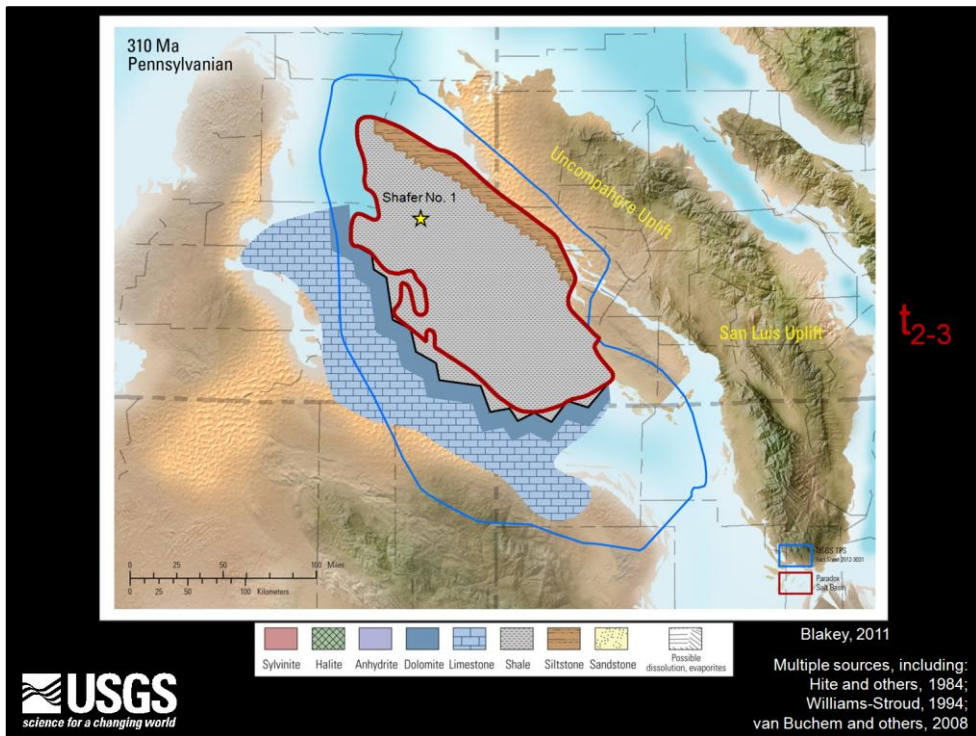
Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

This depositional setting corresponds to the first stage, t_0 , of the model discussed earlier, which is represented by the top of the underlying salt cycle.



Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

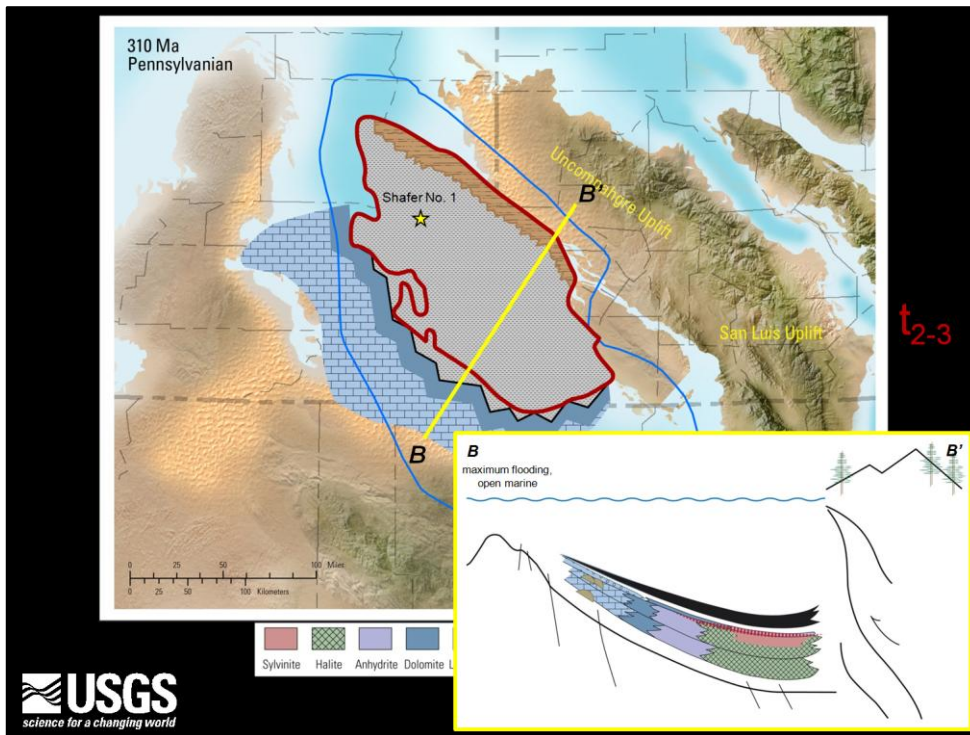
This is an example of a highstand event during the Pennsylvanian (Blakey, 2011) Paradox Basin deposition. There was more open communication with marine sources than during lowstand precipitation of evaporite minerals, permitting normal marine deposition.



Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

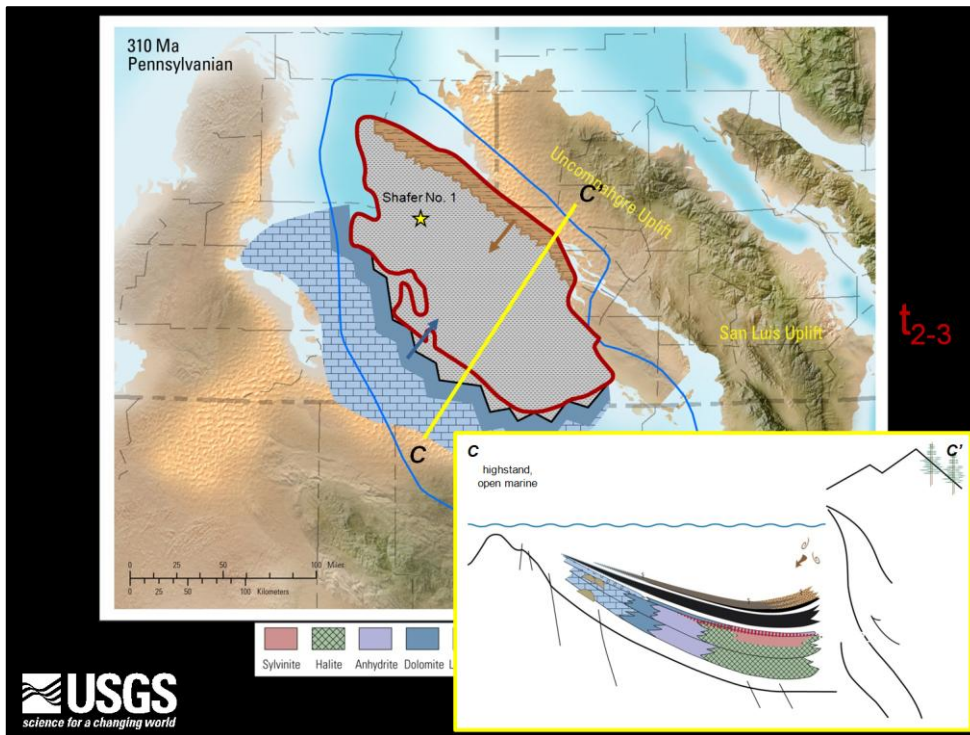
No polygon for shale deposition is available in the literature, so one could extrapolate the location of the shale boundary by using the extent of sylvinitic (i.e., the salt basin polygon) to approximate the broadest depocenter. Shale deposition may have been, and was likely, more laterally extensive than salt deposition, as shown here. Platform carbonates were positioned to the west and southwest, and fine clastic deposition occurred to the northeast.

Shale contains mixed Type II-III kerogen, but Type II dominated early in the basin's history while Type III dominated later cycles of shale deposition as the basin filled (see Hite and others, 1984).



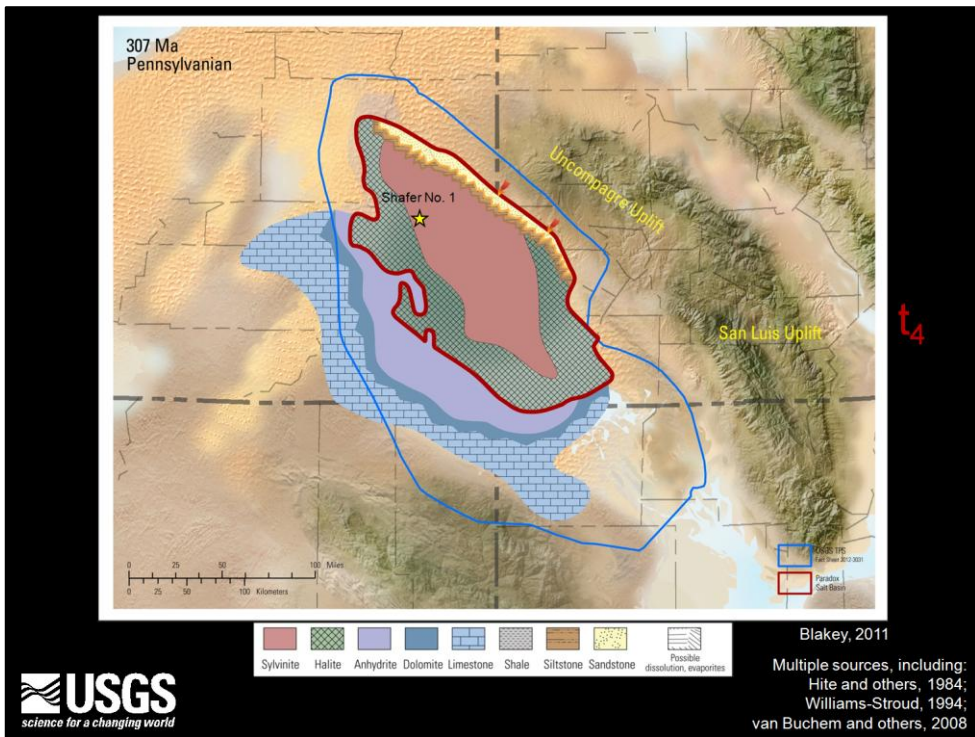
Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

This diagram corresponds to the third stage of the model, t_2 , introduced earlier. Widespread deposition of organic-rich shale occurred when primary organic productivity in the water column was high and coarser siliciclastics were trapped proximal to the orogen by flooding.



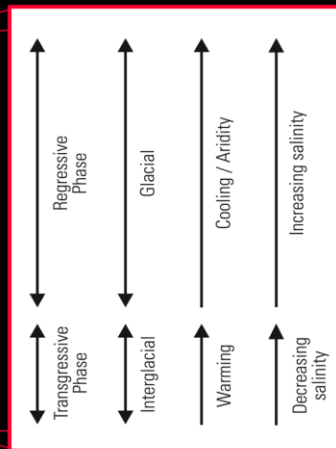
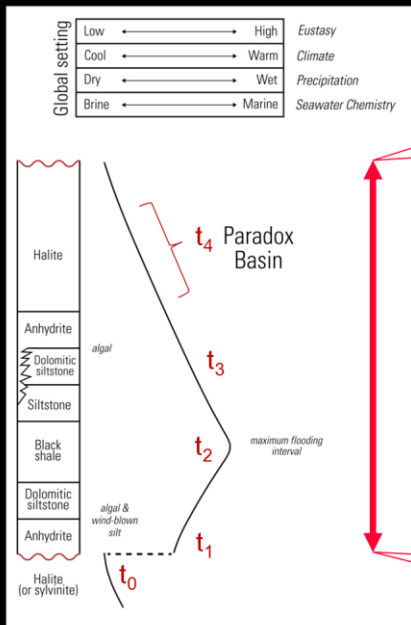
Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

As sea level lowered and coarser detritus began to fill the basin from the margins, organic matter in shales was diluted. Silty sediment migrated into the basin, and progradational stacking of parasequences is documented in core.



Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

Finally, basin restriction during the subsequent lowstand permitted return to precipitation of evaporites in the basin.



Presenter's notes: From the cycle base at t_1 , the initial succession of facies documents a transgressive, "freshening" phase that is likely related to an interglacial interval and global warming. After maximum flooding, the transition back to evaporite precipitation documents a regressive phase in which salinity increased. Global cooling was likely responsible for increased aridity at the low-latitude position of Paradox deposition.

Agenda

- Stratigraphy & geologic setting
- Low-frequency depositional cycles
 - Idealized evaporite model
 - Simplified Paradox Basin model
 - Gross depositional setting
- **Intermediate-scale cycles**
- High-frequency cycles
- Concluding remarks

} *Sedimentary structures,
bioturbation; textures
of associated salts*



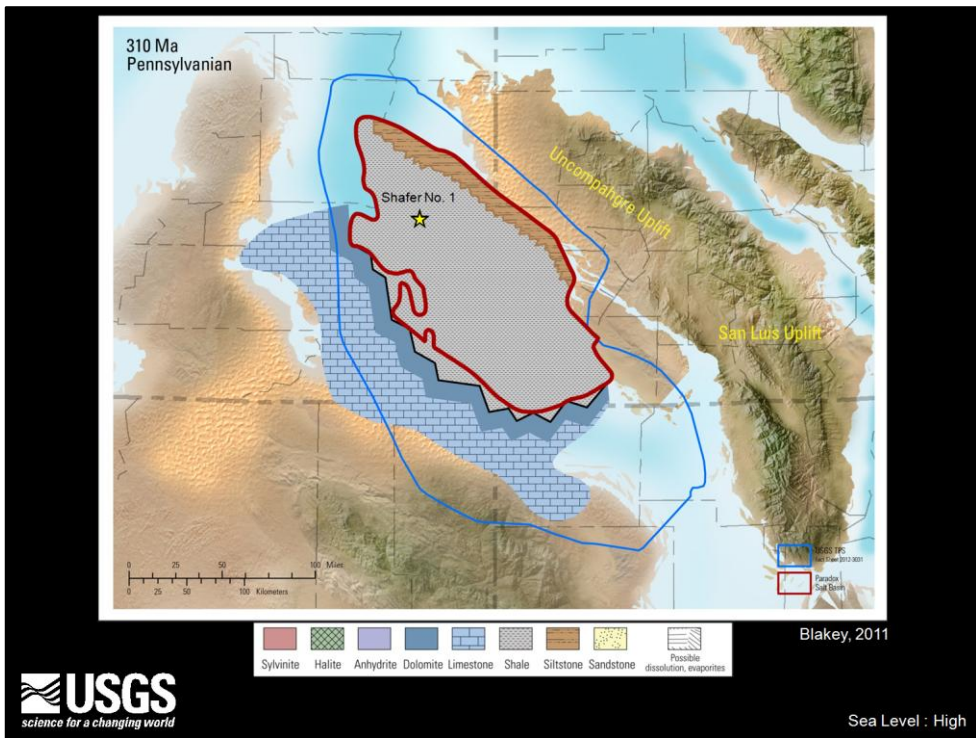
Presenter's notes: Intermediate-scale and higher-frequency cycles are documented in core by sedimentary structures, including bioturbation, and textures of associated salts (when present).

Variability

INTERMEDIATE-SCALE CYCLES

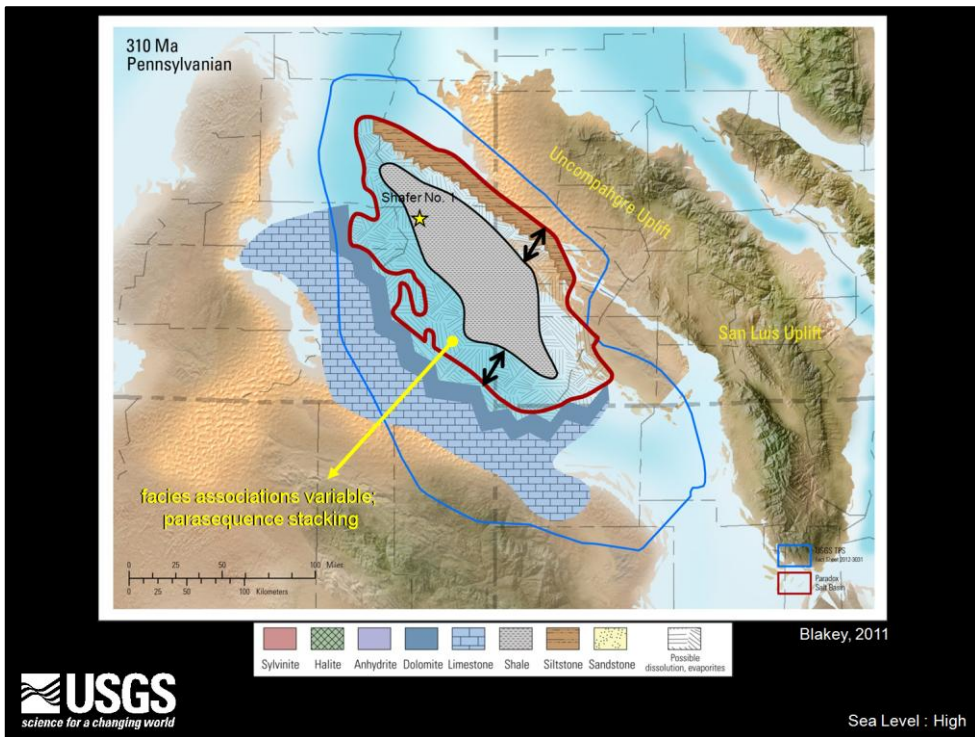


Presenter's notes: The greatest variability in deposition in the Paradox Basin was during intermediate-scale changes in tectonics, sea level, or climate.



Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

For any of the shale intervals, deposition of mud may have extended across the basin. However, there may have also been areas of nondeposition or bypass. Those areas may be documented by the presence of evaporites in otherwise siliciclastic sections.



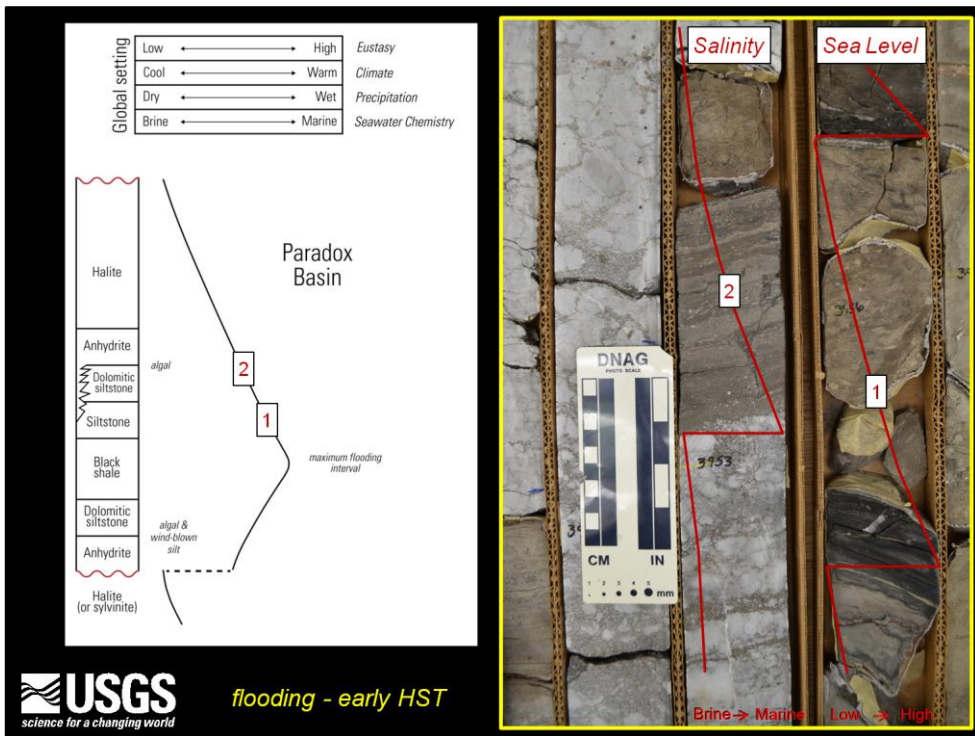
Presenter's notes: The star denotes the location of the Shafer No. 1 core in the northwest part of the Paradox salt basin (in red). The USGS total petroleum system for the Paradox Basin is in blue (Whidden and others, 2012).

The polygon for shale deposition here is from the sylvinitic polygon (Williams-Stroud, 1994), which approximates the basin center. Between shale deposition in the depocenter and carbonate deposition near and on the platform to the southwest, facies associations appear to have been variable. In addition, this variability permits recognition of parasequence stacking patterns in the early highstand part of the depositional cycle. (See following slides).

Salt precipitation during predominantly siliciclastic intervals may be by localized increases in salinity that occurred in areas of nondeposition or bypass. Local dissolution of exposed evaporite strata along the basin floor or erosion and transport from marginal evaporites may have created local brines. These brines, however, did not reside in the stability field of sulfates or halite long enough to establish separate cycles. Local brines may have permitted precipitation of evaporite minerals at the seafloor or within unconsolidated clastic sediment, and those minerals may have been preserved, rather than dissolved, if buried rapidly by renewed clastic input.



Presenter's notes: Complex relations among shale or mudstone, siltstone, anhydrite, and halite are shown. All scale bars represent 2 in.



Presenter's notes: As mentioned, the highstand (HST) interval displays the most variability in composition, facies, and stacking patterns.

1. Early highstand (HST) parasequences with basal shale, grading upward into bioturbated siltstone.
2. During HST, progradational parasequence tops are marked by anhydrite after siltstone. The deposition of siltstone at the base of the following parasequence marks freshening during overall drying conditions (increasing aridity).

Agenda

- Stratigraphy & geologic setting
- Low-frequency depositional cycles
 - Idealized evaporite model
 - Simplified Paradox Basin model
 - Gross depositional setting
- Intermediate-scale cycles
- High-frequency cycles
- Concluding remarks

} *Sedimentary structures,
bioturbation; textures
of associated salts*



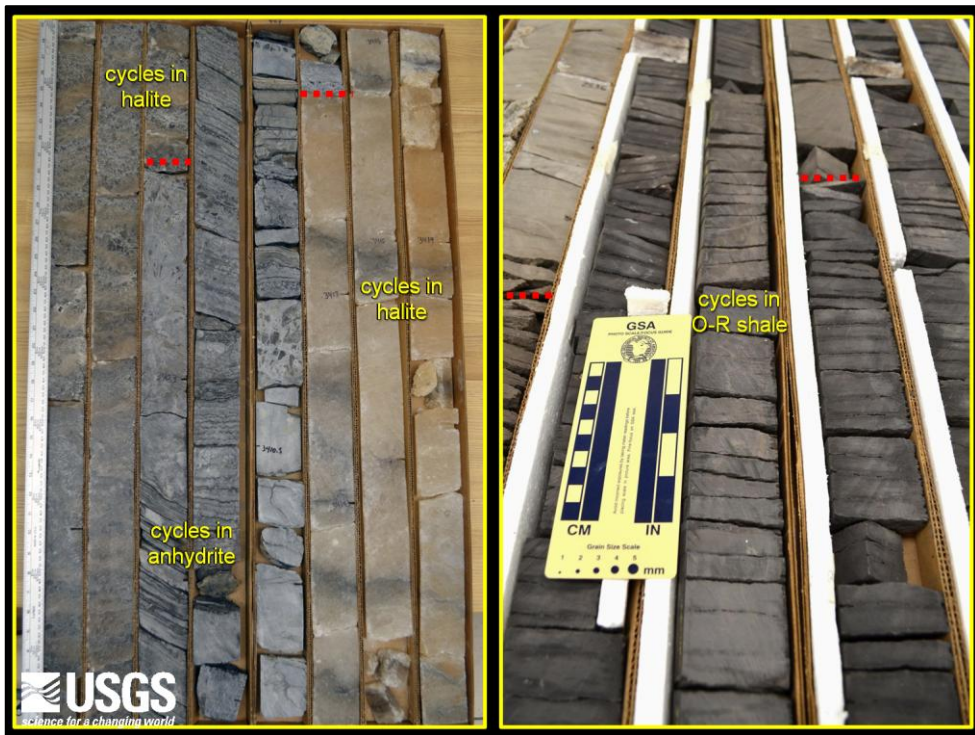
Presenter's notes: High-frequency cyclicity is beyond the scope of this report but is addressed in associated abstracts (Slide 2). The appearance of finer cyclicity is shown on the following slide.

Fine cyclicity

HIGH-FREQUENCY CYCLES



Presenter's notes: In this report, we have been using the term "cycles" more loosely in a regional context. Finer, true cyclicity in siliciclastic successions can be easily overprinted by bioturbation, whereas preservation of cyclic bedding is better in evaporite units.



Presenter's notes: Cyclicity:

1. Smaller or limited cycles: Halite to gypsum/anhydrite to halite, without siliciclastic input (left image).
2. High-frequency cycles documented within each facies (yellow text on both images).

Dashed lines mark various contacts.

[Left image: Ruler on left is 39.25" in length]

Source Rocks

REMARKS



Presenter's notes: A couple of brief remarks about source rock potential follow.

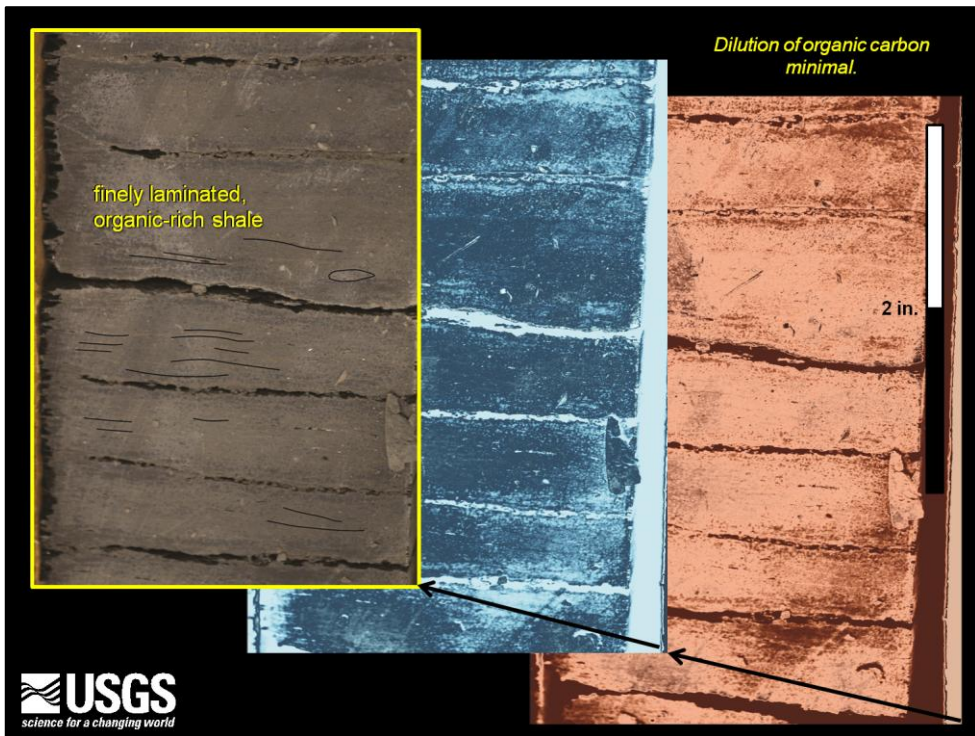
Remarks

- Source rock vs. shale resource play :
 - Thickness, richness, maturity, etc...
 - Dilution by clastics

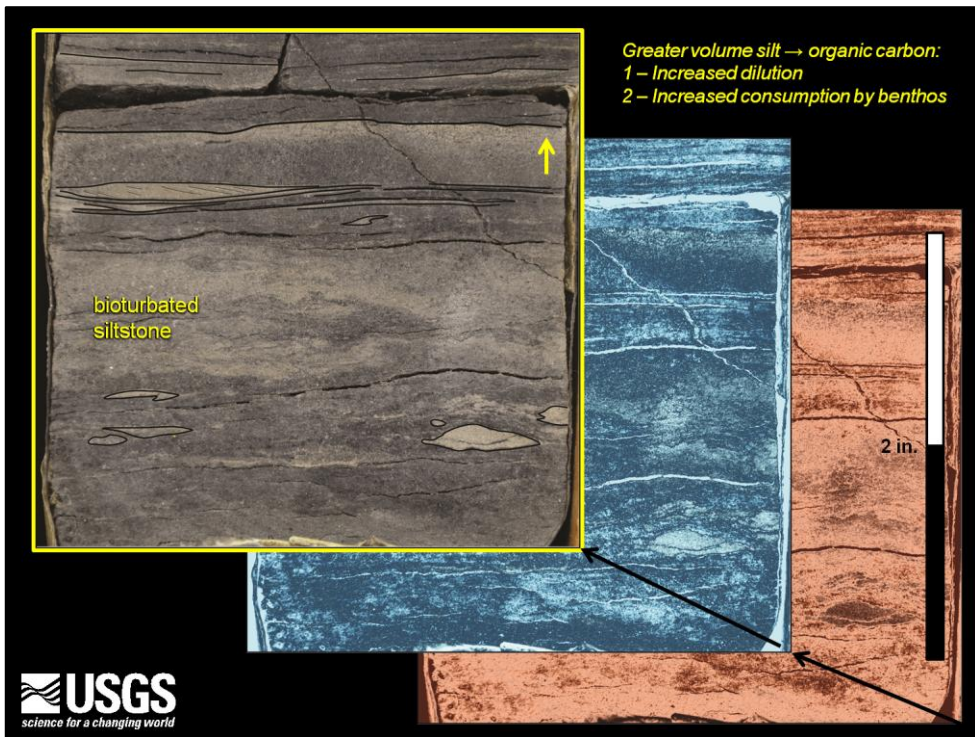
Thick accumulations of marine organic carbon can be preserved as “black” shale or mudstone if not diluted by coarser siliciclastics or biogenic or inorganic carbonate detritus.



Presenter's notes: The shale unit from the earlier slide is shown. Identifying continuous hydrocarbon accumulations as shale resource play targets requires discrimination between petroleum source rocks that only source conventional (or tight) reservoirs and those that can also self-source. Several parameters, such as thickness, organic-richness, and thermal maturity, are usually quantified for source rocks in general. An important consideration, however, is also that of dilution of organic matter by coarser clastic material or by biogenic or inorganic carbonate debris.



Presenter's notes: Core images were manipulated in several stages and stacked with varying transparencies in order to trace out the microstratigraphy of shale in the Shafer No. 1 core. Organic-rich shale is finely laminated, and only subtle features are identified.



Presenter's notes: Silt content allows the identification of scours, ripple bedforms, sediment grading, and burrows.

A higher supply of coarser siliciclastics, such as at the tops of progradational parasequences, predicts at least two things for source rock potential. First, dilution of organic carbon increased. Second, the consumption of organic materials increased because silt-sized and coarser grains provided more stable substrates/habitats for efficient benthonic consumers.

Units with greater volume of silt-sized and coarser grains may still generate hydrocarbon compounds if rich enough in organic carbon, but the dilution by clastics prevents its use as a "shale" play in the current economic setting.

Conclusions

- Low-frequency cycles of siliciclastic successions record the effects of tectonics, eustasy, and global climate
 - Stratigraphic distribution of source rocks
- Intermediate-frequency cycles document regional variations
 - Source rock / shale play exploration
 - Parasequence stacking patterns
 - Dilution of organic matter
- Contrast with high-frequency cycles in evaporite sections that record local variations in climate



Presenter's notes: Low-frequency cycles in the Shafer Dome - 1 core in the Paradox Formation record the effects of tectonics, eustasy, and global tectonics, even in this tropical setting. Intermediate-frequency cycles superimposed on larger trends document the effects of regional controls. Higher-frequency cycles in evaporitic sections likely document local variations in climate.

One of the most important controls on the lateral and temporal distribution of source rocks, especially those that can be exploited as self-sourcing shale reservoirs, is dilution of organic matter by coarser siliciclastic material. The intermediate-scale cyclicity, therefore, warrants as much attention and impacts the presence of certain types of source rocks as much as the low-frequency cyclicity identifies the presence of source rocks.

References Cited

- Blakey, Ronald C., 2009, Paleogeography and geologic history of the western Ancestral Rock Mountains, Pennsylvanian-Permian, southern Rocky Mountains and Colorado Plateau, in W.S. Houston, L.L. Wray, and P.G. Moreland, eds., *The Paradox Basin revisited—New developments in petroleum systems and basin analysis*: Rocky Mountain Association of Geologists Special Publication, p. 2–20.
- Blakey, Ronald C., 2011, Paleogeography of the southwestern United States and Colorado Plateau: Colorado Plateau Geosystems, Inc., DVD series.
- Hite, Robert J., Anders, D.E., and Ging, T.G., 1984, Organic-rich source rocks of Pennsylvanian age in the Paradox Basin of Utah and Colorado, in J. Woodward, F.F. Meissner, and J.L. Clayton, eds., *Hydrocarbon source rocks of the greater Rocky Mountain region*: Rocky Mountain Association of Geologists, 1984 Field Conference, p. 255–274.
- Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the Ancestral Rocky Mountains: *Geology*, v. 9, p. 10–15.
- Mallory, William Wyman, ed., 1972, *Geologic Atlas of the Rocky Mountain Region, United States of America*: Rocky Mountain Association of Geologists, Denver, CO, 331 p.
- Raup, Omer B., and Hite, Robert J., 1991, Preliminary stratigraphic and lithologic data from the Delhi-Taylor Oil Company, Shafer No. 1 corehole, San Juan County, Utah: U.S. Geological Survey Open-File Report 91-373, 34 p.

References Cited

- Raup, Omer B., and Hite, Robert J., 1992, Lithology of evaporite cycles and cycle boundaries in the upper part of the Paradox Formation of the Hermosa Group of the Pennsylvanian age in the Paradox Basin, Utah and Colorado: U.S. Geological Survey Bulletin 2000-B, 37 p.
- Soreghan, G.S., Keller, G.R., Gilbert, M.C. Chase, C.G., and Sweet, D.S., 2012, Load-induced subsidence of the Ancestral Rocky Mountains recorded by preservation of Permian landscapes: *Geosphere*, v. 8, p. 654-668.
- Stevenson, Gene M., and Wray, Laura L., 2009, History of petroleum exploration of Paleozoic targets in the Paradox Basin, in W.S. Houston, L.L. Wray, and P.G. Moreland, eds., *The Paradox Basin revisited—New developments in petroleum systems and basin analysis*: Rocky Mountain Association of Geologists Special Publication, p. 1-23.
- van Buchem, F.S.P., Huc, A.Y., Pradier, Bernard, and Stefani, Marco M., 2008, Stratigraphic patterns in carbonate source-rock distribution: Second-order to fourth-order control and sediment flux: *Society for Sedimentary Geology Special Publication*, v. 82, p. 191-223.
- Whidden, K.J., Anna, L.O., Pearson, K.M., and Lillis, P.G., 2012, Assessment of undiscovered oil and gas resources in the Paradox Basin Province, Utah, Colorado, New Mexico, and Arizona, 2011: U.S. Geological Survey Fact Sheet 2012-3031, 4 sheets.
- Williams-Stroud, S., 1994, The evolution of an inland sea of marine origin to a non-marine saline lake: The Pennsylvanian Paradox Salt, in R.W. Renaut and W.M. Last, eds., *Sedimentology and geochemistry of modern and ancient saline lakes*: *Society for Sedimentary Geology Special Publication* 50, p. 293-306.