[PS] High-Resolution Core Studies of Wolfcamp/Leonard Basinal Facies, Southern Midland Basin, Texas*

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Abstract

Recently, lower Leonard and upper Wolfcamp (operational Wolfcamp A and B) strata have become targets for horizontal drilling and hydraulic fracturing in the southern Midland Basin. High-resolution hand-held XRF, CT scan, and rebound hammer (unconfined compressive rock strength) analyses were collected from core from these intervals. These basinal rocks can be divided into four facies: (1) siliceous mudrock, (2) calcareous mudrock, (3) carbonate-clast conglomerate, and (4) skeletal wackestone/packstone. These facies are interpreted as hemipelagic deposits and sediment density-flow deposits reworked, locally, by bottom currents. Facies thickness ranges from inches to feet. Three scales of cyclicity are observed: (1) cycles of alternating sediment density-flow and hemipelagic deposits defined by 3-inch-spaced XRF elemental data (Ca, Al) (1-5 ft thick), (2) sets of repeating cycles defined by gamma ray log (low gamma = high carbonate, high gamma = high clay) (10s of ft thick), and (3) megacycles of dominantly calcareous or siliceous (defined by facies) cycle sets (10s-100s of ft thick).

The dominant facies, siliceous and calcareous mudrock, have few sedimentary structures, contain relatively high total organic carbon (TOC) (up to 6.3 percent), rare burrows, and common phosphatic nodules and pyrite framboids. Coarser-grained conglomerates and wackestone/packstones have current-related structures, locally, contain low TOC, few phosphatic nodules, and rare pyrite framboids. TOC varies widely by facies over small vertical distances, varies directly with geochemical proxies for marine productivity (Ni, Cu, Zn) and siliciclastic sediment (Al, Si, Ti), and varies inversely with carbonate (Ca, total inorganic carbon). Collectively, these factors indicate that fine-grained sediments accumulated slowly over long periods under

anoxic conditions, but carbonate-rich, coarse-grained sediments were deposited rapidly on the basin floor and did not include significant marine or terrestrial organic matter.

In the northern Reagan County study area, conglomerates up to 9 ft thick are common in the upper Wolfcamp, but absent in the lower Leonard, where thinner, finer-grained wackestone/packstones prevail. The difference in thickness of carbonate-rich beds in these two formations may affect vertical fracture propagation. Measurements of unconfined compressive strength show that most wackestone/packstones are stronger than almost all mudrocks. Even so, mineralized natural fractures are present in all facies. Close vertical proximity of mature organic matter (Type II-III kerogen, calculated Ro = 0.67-1.07, Tmax>438) in mudrock and thin, more brittle beds (brittle-ductile couplets) may explain the appeal of basinal Wolfcamp and Leonard strata as targets for horizontal well completion and fracture stimulation. S2/TOC data from the study cores identify zones of potential hydrocarbon production, which correlate with horizons that have produced 179-460 barrels of oil equivalent/day (30-day initial production) in nearby fields.

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Part 1: Context of High-Resolution Study

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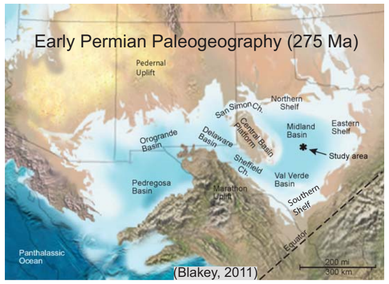
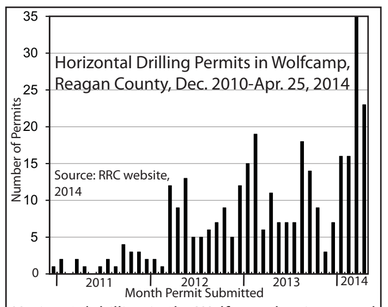
Background

As the use of horizontal drilling and hydraulic fracturing has increased in the Permian Basin, lower Permian basinal rocks in the southern Midland Basin have become drilling targets. In this study, cores were analyzed with a variety of techniques to characterize the facies, geochemistry, and rock strength of these economically important rocks.

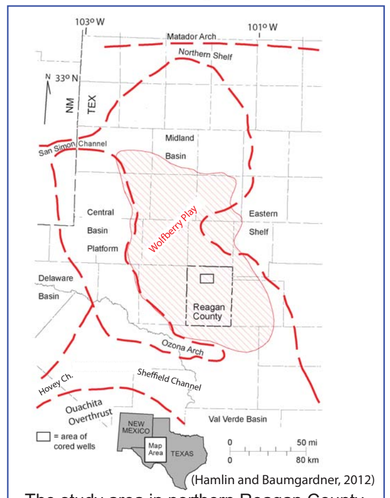
Regional Setting, Stratigraphic Context, and Drilling Activity



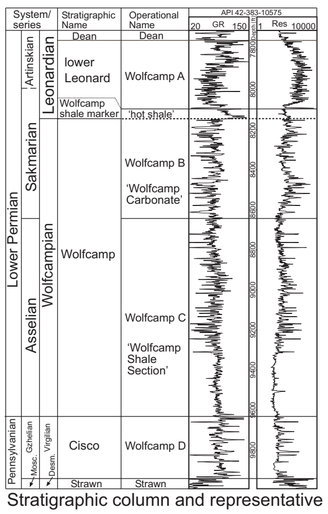
During early Permian time, the Midland Basin was separated from open ocean by several intervening basins and interconnecting channels, which restricted water circulation and fostered basin anoxia.



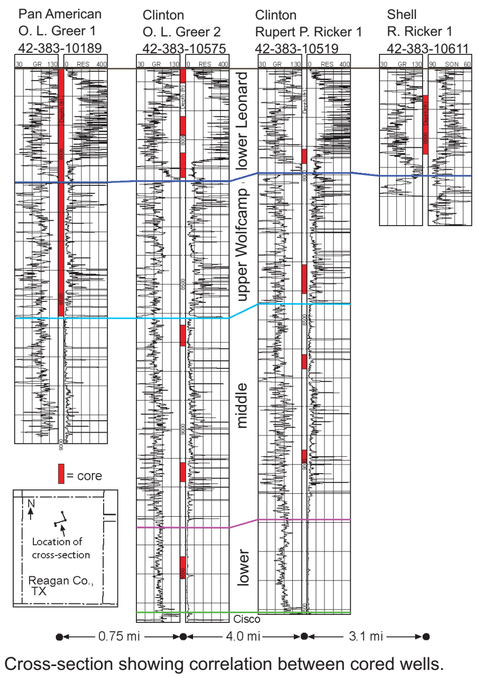
Horizontal drilling in the Wolfcamp has increased dramatically in Reagan County since Feb. 2012.



The study area in northern Reagan County is located near the center of the southern Midland Basin, an area of recent horizontal drilling and hydraulic fracturing.

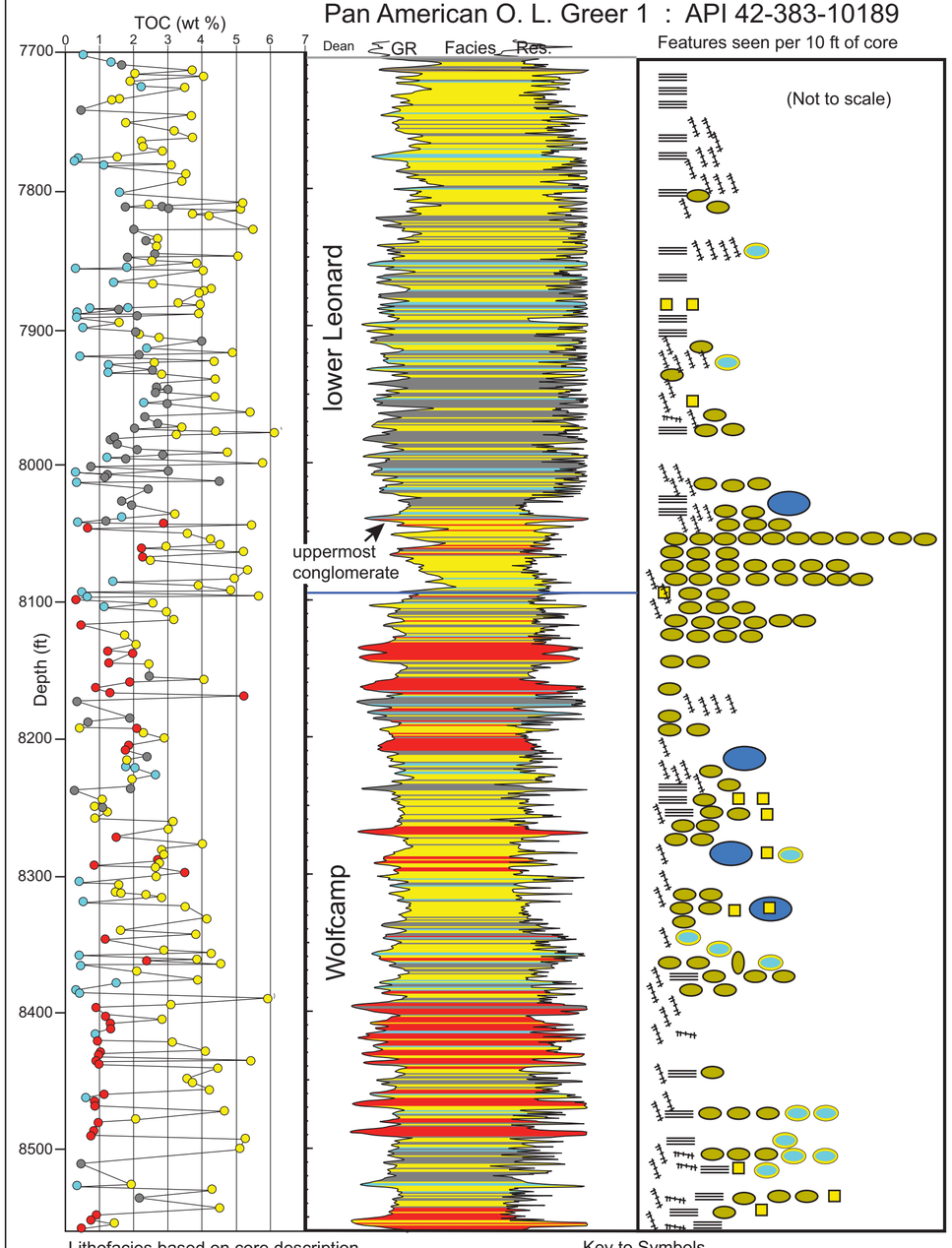


Stratigraphic column and representative wireline logs from O. L. Greer 2 well show divisions of Wolfcamp Formation and lower Leonard, along with operational names.



Cross-section showing correlation between cored wells.

Core Description, Lithofacies, and Total Organic Carbon (TOC)

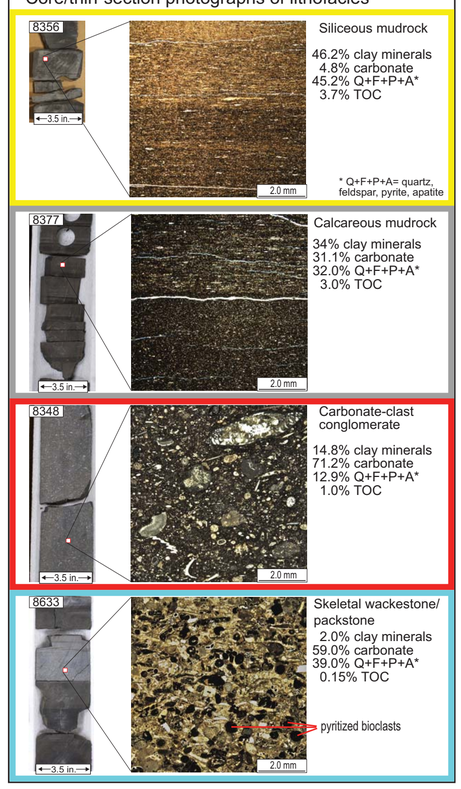


Lithofacies based on core description
- Siliceous mudrock
- Calcareous mudrock
- Carbonate-clast conglomerate
- Skeletal wackestone-packstone

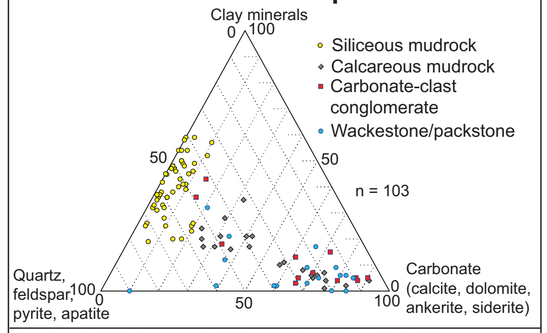
Key to Symbols
- Laminations
- Pyrite accumulation
- Fractures (vertical, horizontal)
- Carbonate concretion
- Phosphatic nodule
- Chert lens with pyrite rim

- High GR responses generally correlate with siliceous mudrocks and high TOC content.
- TOC is highest in siliceous mudrocks, which are interbedded with low-TOC, high-carbonate facies.
- Laminations, phosphatic nodules, pyrite, and lack of burrows in fine-grained deposits indicate prevalence of anoxia in accumulating sediment.
- End of conglomerate deposition in early Leonard (uppermost conglomerate) suggests change in distance to source (relative sea-level change) or in carbonate production, compared to late Wolfcamp time.
- Conglomerates and wackestone/packstones are interpreted as debrites and turbidites.
- Mineralized natural fractures are present throughout the cored interval, even in mudrocks.

Core/thin-section photographs of lithofacies



Mineralogy Based on XRD Data. Facies from Core Description.



Quartz = 9-90%, feldspar 0-19%, pyrite 0-13%,apatite 0-9%.
Calcite = 0-85%, dolomite = 0-70%, ankerite = 0-20%, siderite = 0-18%.
Clays = illite 0-40%, mixed ill/smec = 0-12%, chlorite = 0-15%, kaolinite = 0-5%.

Mean Values for Mineralogy of Lithofacies

Lithofacies	XRD Mineralogy (wt %)			TOC
	Clays	Carb	Q+F+P+A	
Siliceous mudrock	38.8	5.8	52.4	3.0
Calcareous mudrock	13.7	51.9	32.3	2.1
Carbonate-clast conglomerate	12.9	61.3	24.7	1.2
Skeletal wackestone/packstone	8.0	59.8	31.9	0.4

Q+F+P+A = quartz, feldspar, pyrite, apatite 103 samples from 3 wells

Clay, siliciclastics, and TOC highest in siliceous mudrock.
Carbonate highest in conglomerate and wackestone/packstone.

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Part 2: Mineralogy, Chemofacies, and Cyclicity Defined by XRF and Rock Strength Data

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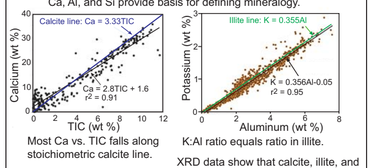
Objectives of High-Resolution XRF Study

Lithofacies in the Wolfcamp/lower Leonard have been identified on the basis of megascopic description of core and mineralogy derived from XRD. Chemofacies were defined using XRF data. High-resolution XRF and rock strength data were used to address questions regarding cyclicity, mechanical properties, and relationships between paleoreducing conditions, terrigenous sediment, and marine paleoproductivity.

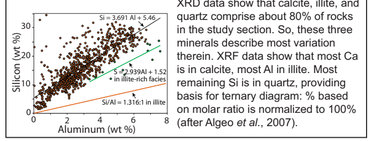
Mineralogy, Chemofacies Defined with XRF

Ca, Al, and Si provide basis for defining mineralogy.



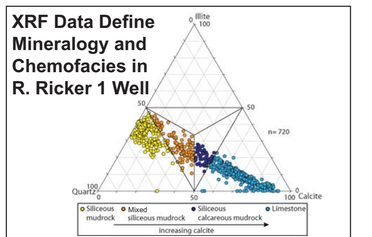
Most Ca vs. TIC falls along stoichiometric calcite line.

K:Al ratio equals ratio in illite.



XRD data show that calcite, illite, and quartz comprise about 80% of rocks in the study section. So, these three minerals describe most variation therein. XRF data show that most Ca is in calcite, most Al in illite. Most remaining Si is in quartz, providing basis for ternary diagram: % based on molar ratio is normalized to 100% (after Algeo *et al.*, 2007).

XRF Data Define Mineralogy and Chemofacies in R. Ricker 1 Well



(Ternary diagram subdivisions after Nance, personal communication, 2013.)

On the basis of data from handheld XRF, we define facies mostly by variation in carbonate content. Siliceous mudrocks are >50% quartz. Mixed siliceous mudrocks are dominated by quartz, with varying amounts of illite and calcite. Siliceous calcareous mudrocks are dominated by calcite. Limestones (>50% calcite), are skeletal wackestone/packstones and calcareous mudrocks, based on core description and XRD data (SEE PART 1). Illite is <50%, so no argillaceous mudrocks are present in this core.

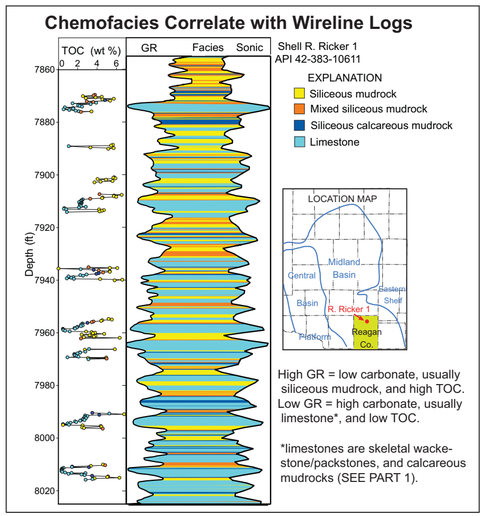
Principal Geochemical Proxies from XRF Data:

Sedimentology
- Al, K = illite
- Si = quartz (Si not in illite)
- Ti = terrigenous sediment
- Ca = calcite

Paleoredox, paleoproductivity
- Cu, Ni, Zn = marine productivity
- Mo = reducing conditions

Others
- TOC (total organic carbon) = result of productivity, reducing conditions, and sedimentation rate/dilution

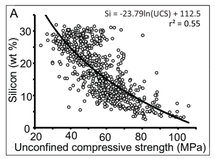
Chemofacies Correlate with Wireline Logs

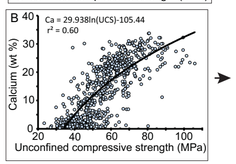


High GR = low carbonate, usually siliceous mudrock, and high TOC. Low GR = high carbonate, usually limestone*, and low TOC.

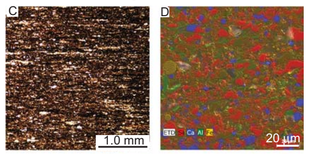
*limestones are skeletal wacke-stone/packstones, and calcareous mudrocks (SEE PART 1).

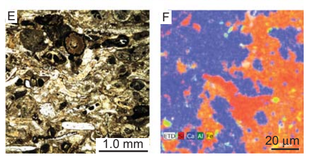
Rock Strength: Strength Depends Directly on Ca Content





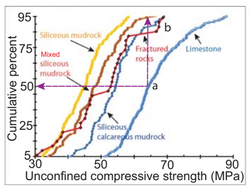
A: Rock strength (unconfined compressive strength) decreases with Si content, unlike Barnett shale (Jarvie, *et al.* 2007), because much Si is in, or associated with, clay minerals.
B: Rock strength increases with Ca content, like Haynesville shale (Buller, *et al.*, 2010).





C. Photomicrograph of siliceous mudrock. Discontinuous laminae composed of calcite and quartz grains.
D. SEM image of siliceous mudrock shown in C. Quartz (red) and calcite (blue) grains in clayey (green) matrix.

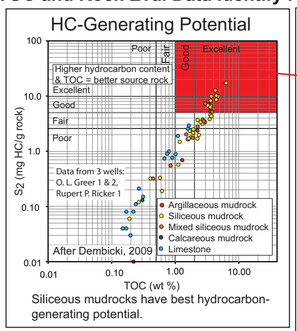
E. Photomicrograph of limestone (skeletal packstone) showing grain-to-grain contact and little clay.
F. SEM image of limestone in E shows replacive quartz (red) interlocking with calcite bioclast (blue).



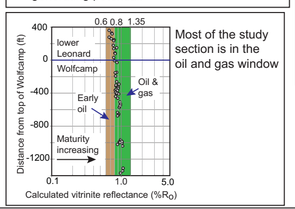
50% of limestones (a) are stronger than 85-100% of other facies (b). Naturally fractured rocks (red line) have intermediate strength.

In comparison, rock strength in black shales ranges from 27-47 MPa, in tight grainstones ranges from 40-86 MPa (Zahm and Enderlin, 2010).

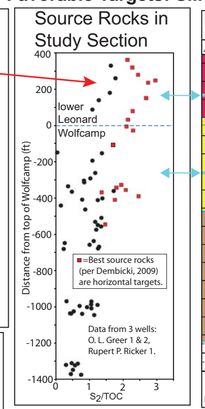
TOC and Rock Eval Data Identify Favorable Targets: Siliceous Mudrocks

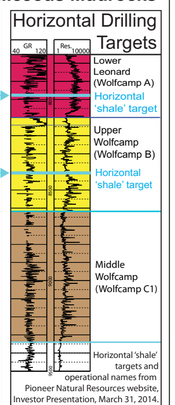


Siliceous mudrocks have best hydrocarbon-generating potential.

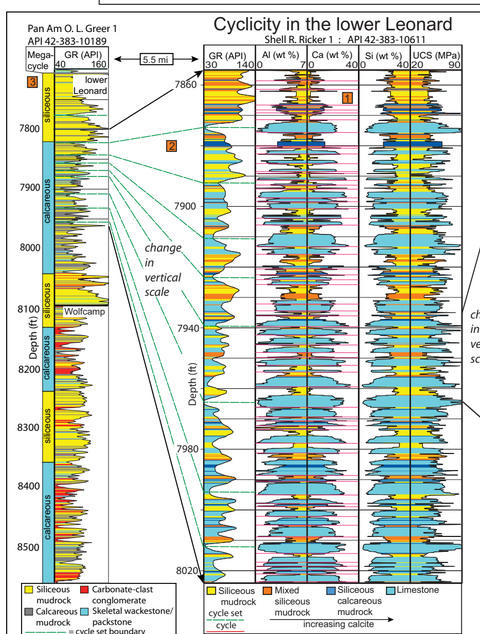


Most of the study section is in the oil and gas window

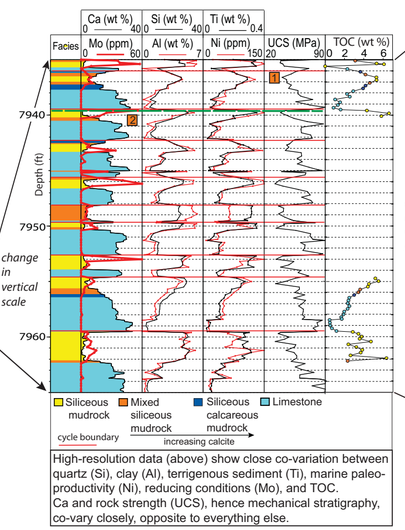




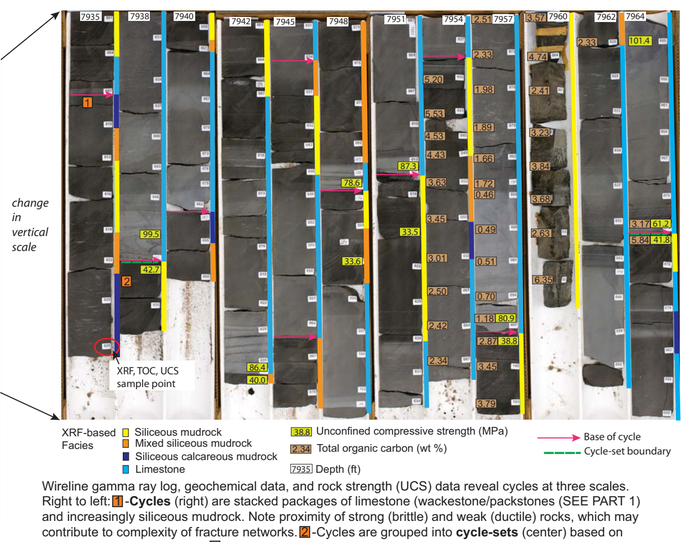
Cyclicity in the lower Leonard



Three Levels of Cyclicity are Evident in Wireline Logs, Elemental Profiles, and Rock Strength (UCS)



High-resolution data (above) show close co-variation between quartz (Si), clay (Al), terrigenous sediment (Ti), marine paleo-productivity (Ni), reducing conditions (Mo), and TOC. Ca and rock strength (UCS), hence mechanical stratigraphy, co-vary closely, opposite to everything else.



Wireline gamma ray log, geochemical data, and rock strength (UCS) data reveal cycles at three scales. Right to left: **1-Cycles** (right) are stacked packages of limestone (wackestone/packstones (SEE PART 1) and increasingly siliceous mudrock. Note proximity of strong (brittle) and weak (ductile) rocks, which may contribute to complexity of fracture networks. **2-Cycles** are grouped into **cycle-sets** (center) based on correlation with nearby wells. **3-Megacycles** (left) are cycle-sets of predominantly calcareous or siliceous facies.

Conclusions

XRF data provide detailed information about facies and controls on accumulation and preservation of organic matter.

Cycles represent repeated deposition of limestones (carbonate-rich wackestone/packstones) followed by upward-waning carbonate deposition, and finally, a return to 'background' siliciclastic deposition.

Limestone (wackestone/packstone) deposition interrupted deposition of detrital quartz, clay minerals, terrigenous sediment, and marine organic matter.

Molybdenum concentrations suggest that redox conditions at the Permian seafloor were largely anoxic, favoring preservation of organic matter, but redox conditions within limestones were less reducing. Consequently, TOC levels change abruptly between limestones (low TOC) and hemipelagic sediments (high TOC).

Rock strength (brittleness) is largely a function of calcite content. Most limestones are stronger than all other facies.

Recent horizontal drilling has targeted zones having high S2/TOC ratios, primarily siliceous mudrocks.

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