Shale Velocity and Density as Functions of TOC and Thermal Maturity: Upper Devonian Woodford Shale, Permian Basin, Texas*

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Abstract

The Woodford Shale is an Upper Devonian organic-rich black shale and potential gas and liquid reservoir in the Permian Basin, west Texas. It is widespread and thick (up to 200 meters) and represents the longest continuous record of black shale deposition in North America. Detailed sedimentological and geochemical studies have been carried out on two Woodford cores, from 8300 feet and 12900 feet, equivalent to 0.71% and 1.48% Ro, based on Rockeval Tmax values. The geochemical data, combined with extended modern log suites, provides an opportunity to examine the impact of varying total organic carbon (TOC) content and thermal maturity on acoustic velocities and density. By correlating the gamma log to core TOC, a complete record of organic carbon content through the well is obtained; the log-estimated TOC is then compared to Vp, Vs, and density logs. Vp and Vs decrease systematically with increasing TOC, by 20 to 25% as TOC increases from 0% to 10%. Because density also decreases with increasing TOC, the effect on acoustic impedance is substantial, as much as 30% in the range of 0 to 10% TOC. Velocity is affected because organic matter is relatively soft material, while density is affected because organic matter is composed primarily of the light elements carbon and hydrogen. Although organic matter is relatively ductile, particularly in lower maturity rocks, and would be expected to transmit shear waves relatively poorly, a decrease in Vp/Vs ratios is evident with increasing TOC; this may be because high TOC is accompanied by high volumes of quartz cement, which would provide a stiff framework to the shale. The effect of thermal maturity is significant. The velocity of both P waves and S waves is approximately 20% higher in the higher maturity well than in the lower maturity well. Acoustic impedance is also substantially higher. This may result from loss of organic carbon during oil and gas generation and expulsion, or it may result from changes in the physical properties of kerogen related to thermal maturation. These results suggest that it may be possible to map isomaturity lines in a

source rock formation based on acoustic velocities, and where seismic resolution is sufficient, it may be possible to identify intervals of high TOC based on impedance maps. However prediction of shale TOC may have to be accompanied by an independent interpretation of thermal maturity such as basin modeling.

References Cited

Hemmesch, N.T., N.B. Harris, C.A. Mnich, and D. Selby, 2014, Electrical and Flow Properties of Highly Heterogeneous Carbonate Rocks: AAPG Bulletin, v. 98/1, p. 23-48.

Mnich, C.A., 2009, Geochemical Signatures of Stratigraphic Sequences and Sea-level Change in the Woodford Shale, Permian Basin: MS Thesis, Colorado School of Mines, Golden, CO, 89 p.

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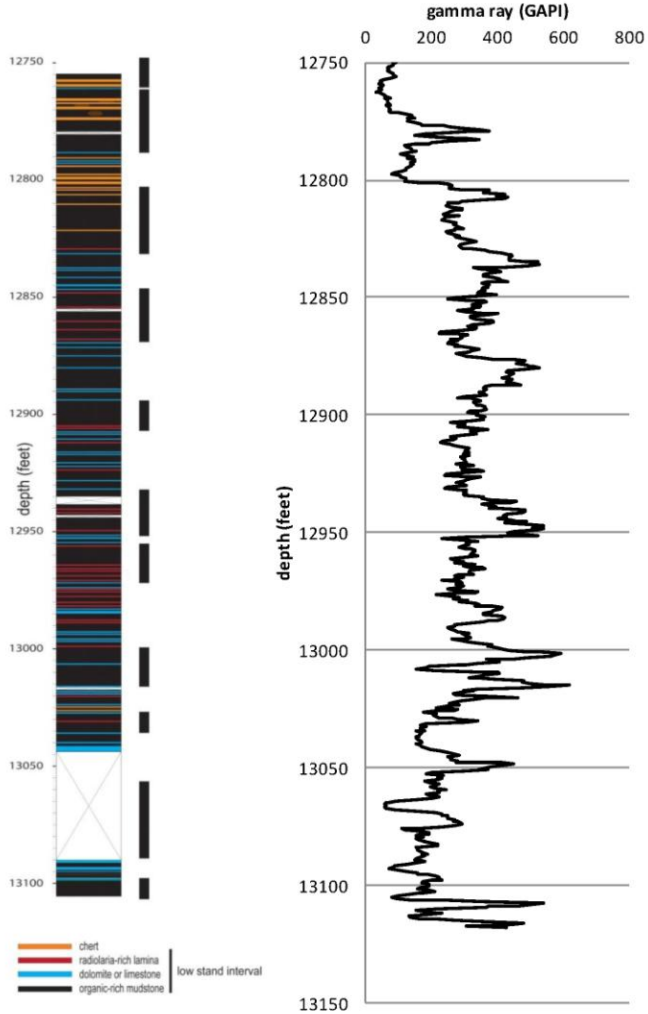
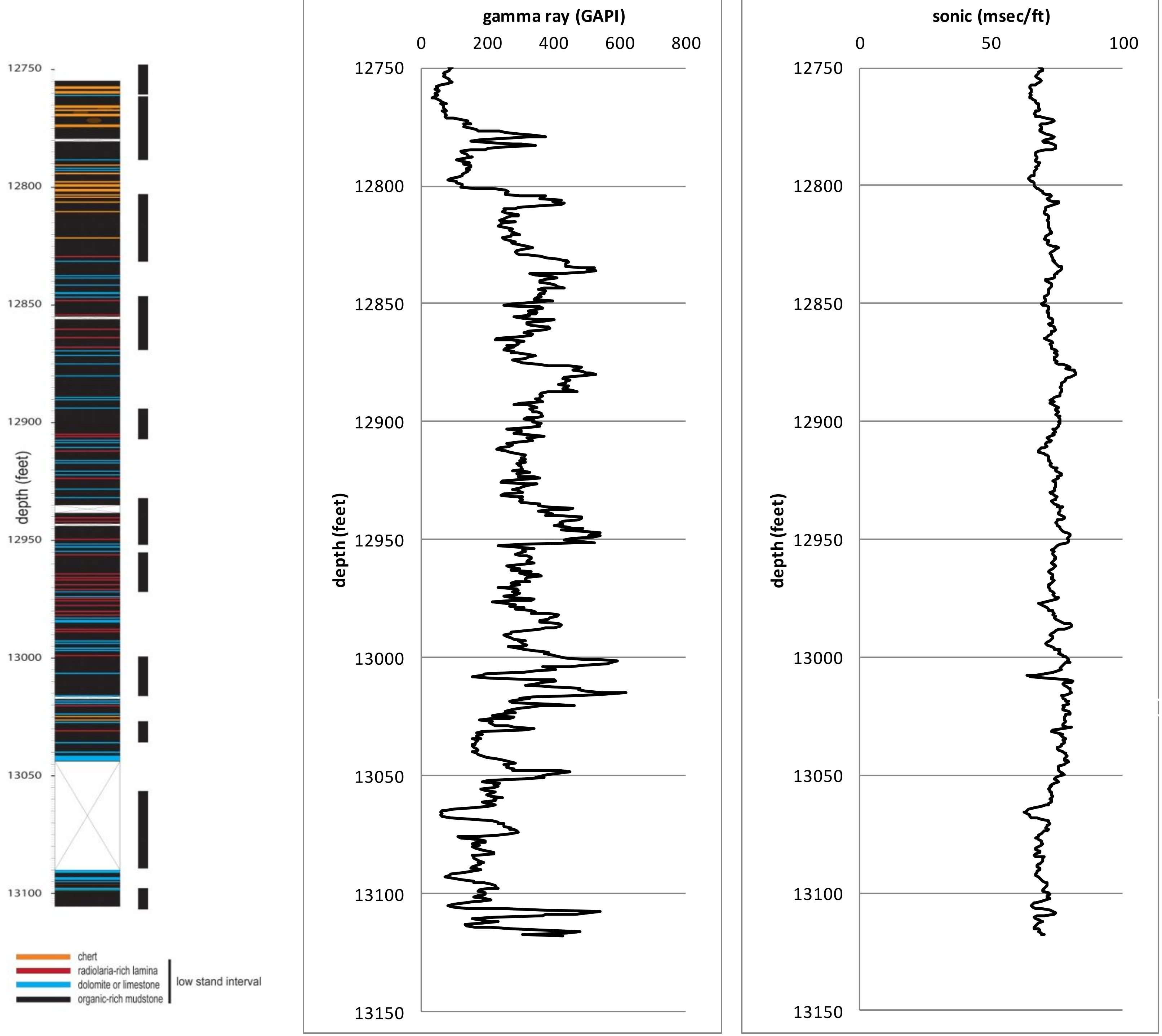


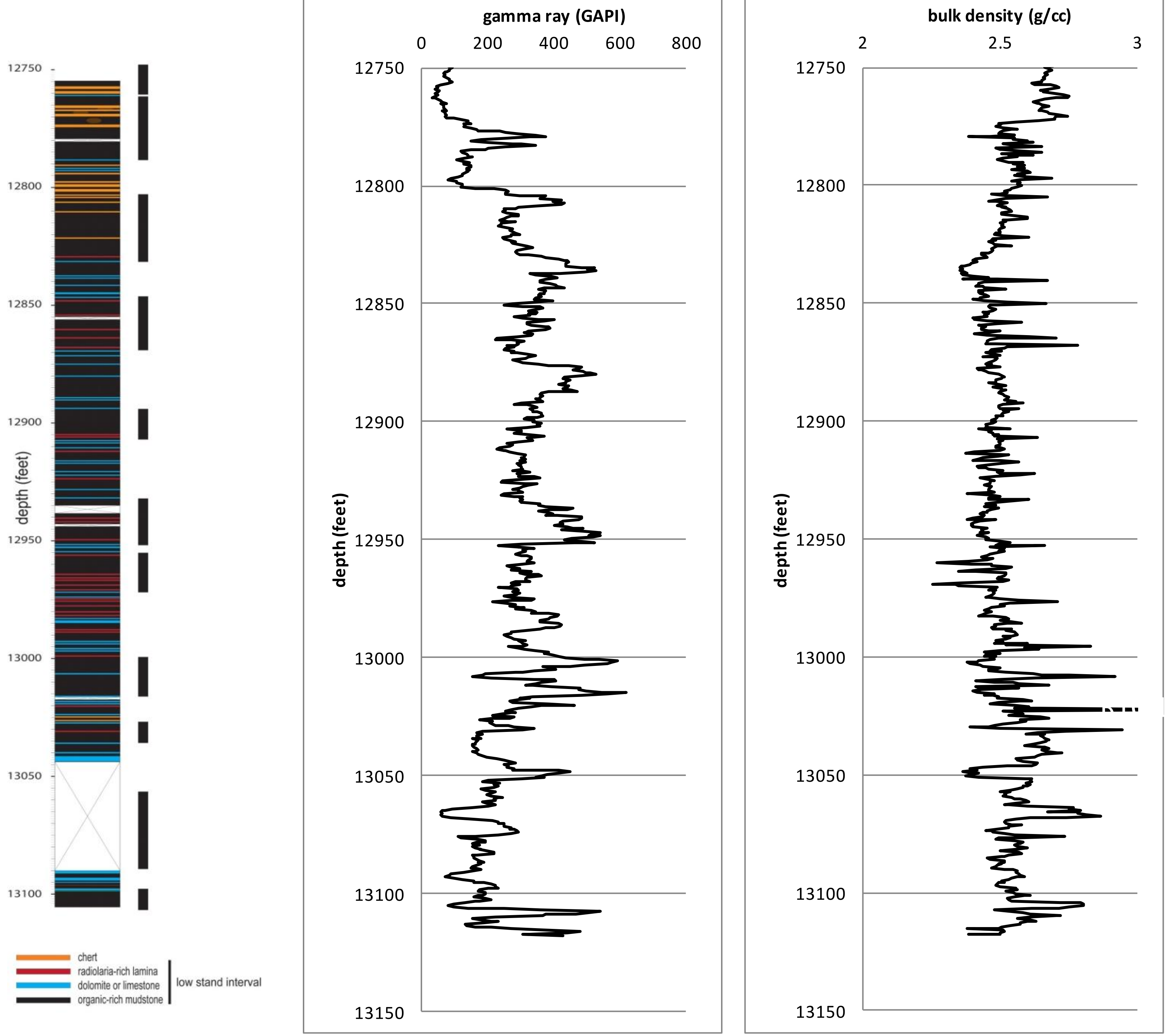
Shale formations are heterogeneous

- A variety of lithofacies (black shale, chert beds, dolomite beds, phosphate nodules)
- A range of shale mineralogy (quartz, carbonate and clay content)
- A range of total organic carbon content (TOC)

Core description from Hemmesch et al., 2014

Presenter's notes: So what did we see in the core? This is the PH.D. work of Nikki Hemmesch. Black shale, the classic laminated organic-rich dark rock, is the dominant lithology. That's the black rock in the facies column on the left hand side, and it amounts to more than 90% of the section.


depth (feet)
chert
radiolaria-rich lamina
dolomite or limestone
organic-rich mudstone
low stand interval
gamma ray (GAPI)
0
200
400
600
800
sonic (msec/ft)
0
50
100
12750
12800
12850
12900
12950
13000
13050
13100
13150



depth (feet)
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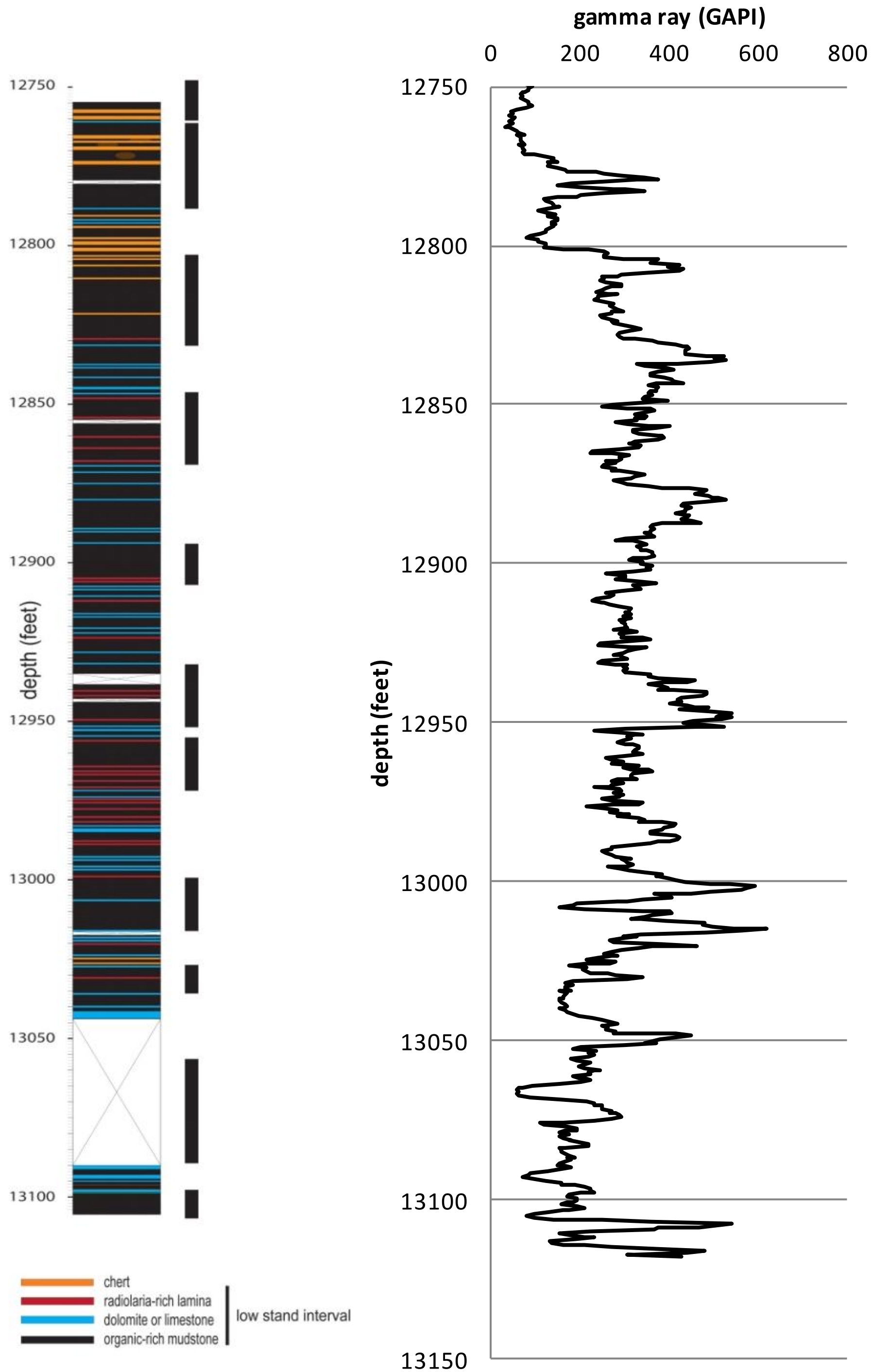
dolomite or limestone
organic-rich mudstone
low stand interval
gamma ray (GAPI)
0
200
400
600
800
depth (feet)
13150
bulk density (g/cc)
2
2.5
3
depth (feet)



How can we use the variability in density and sonic velocity?

- Can we get obtain source rock information (TOC, thermal maturity)?

- What is the stratigraphic meaning of contrasts in physical properties?

– How do we interpret seismic reflectors in a shale sequence?

Core description from Hemmesch et al., 2014

Geologic Setting

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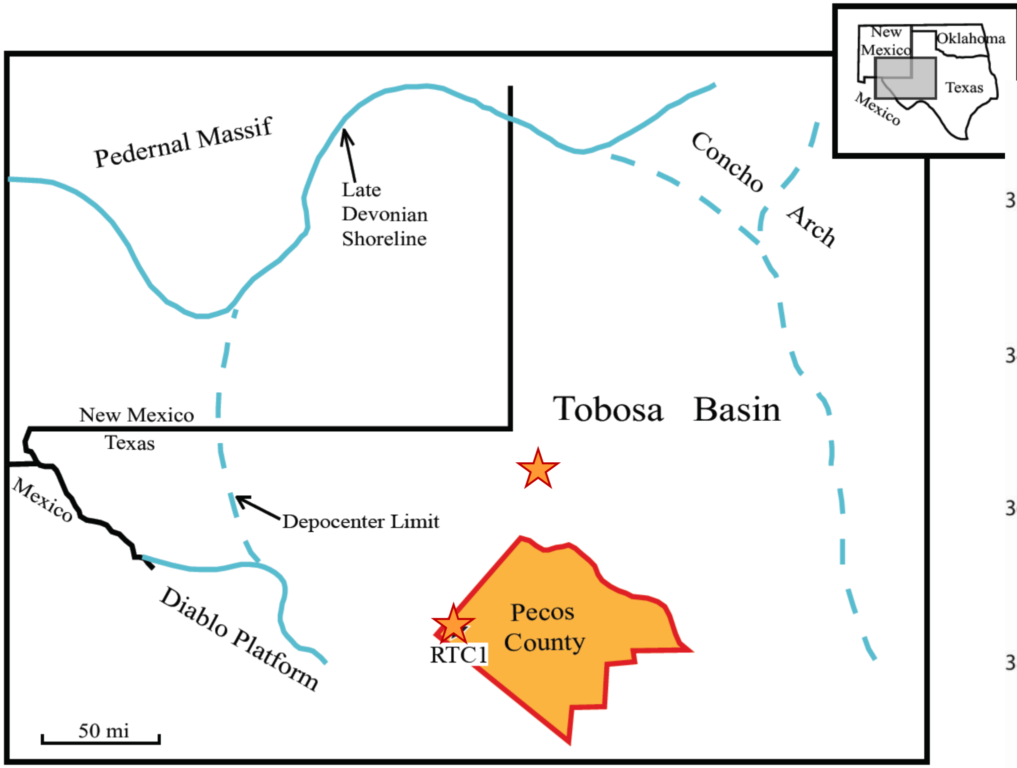
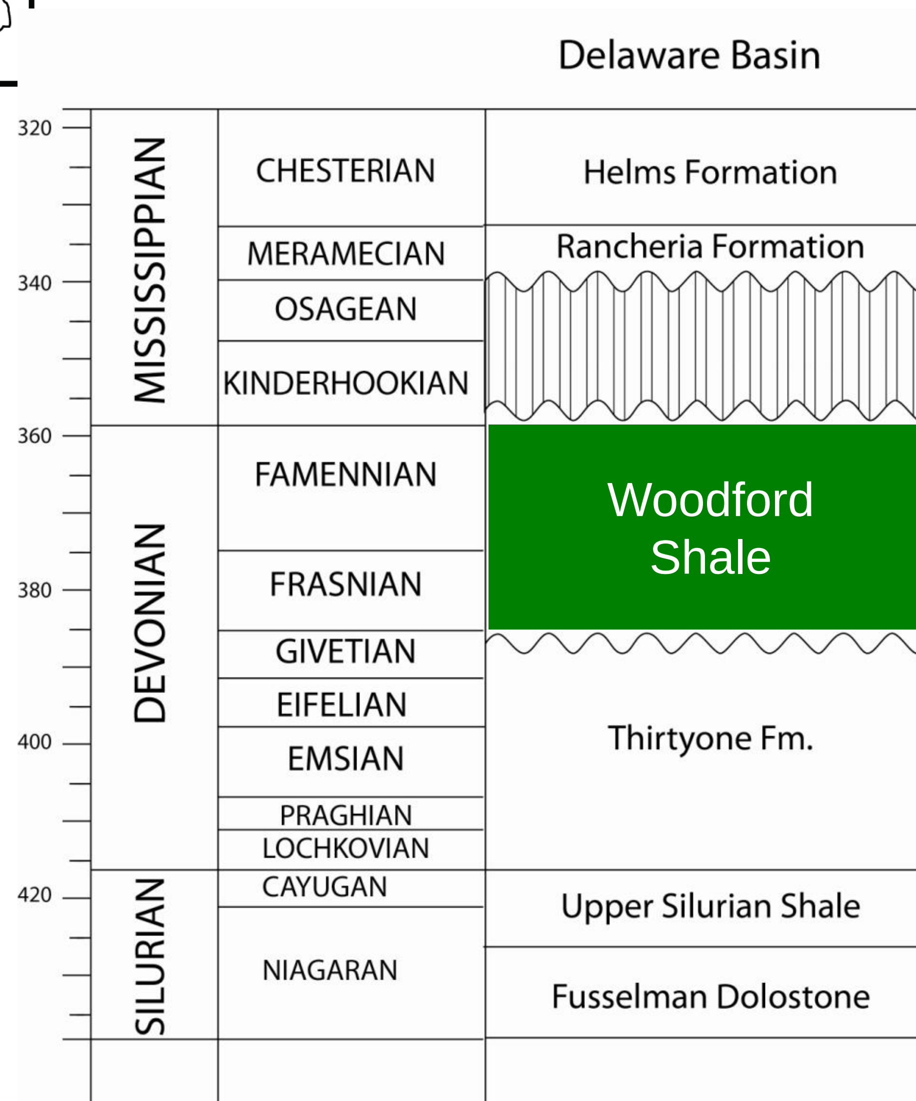
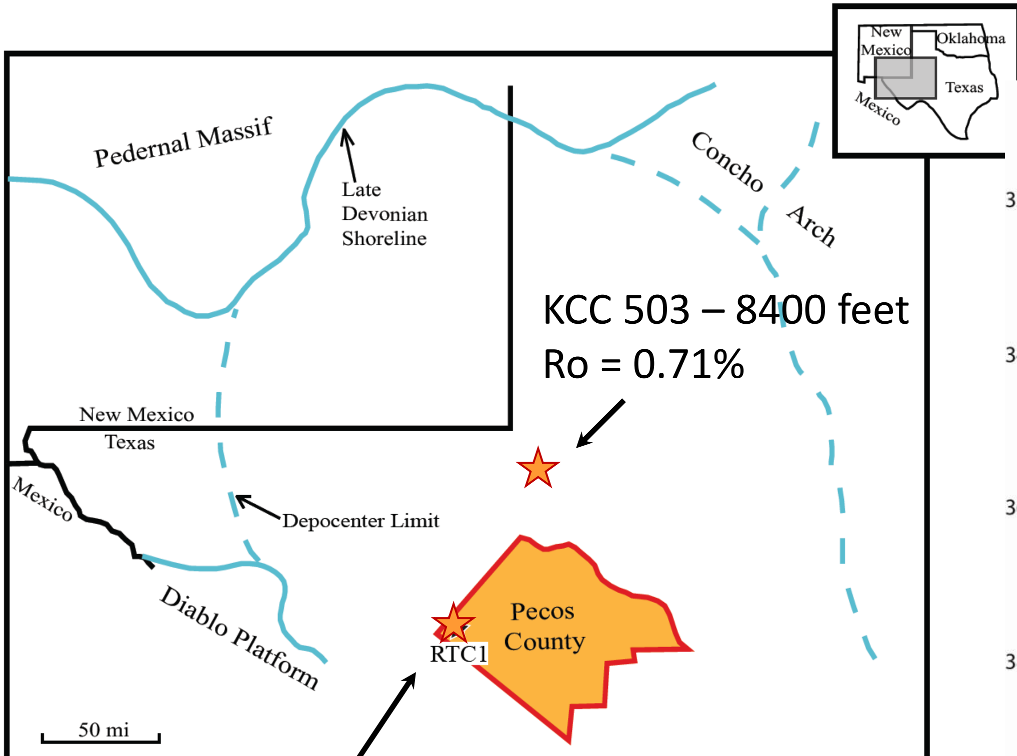
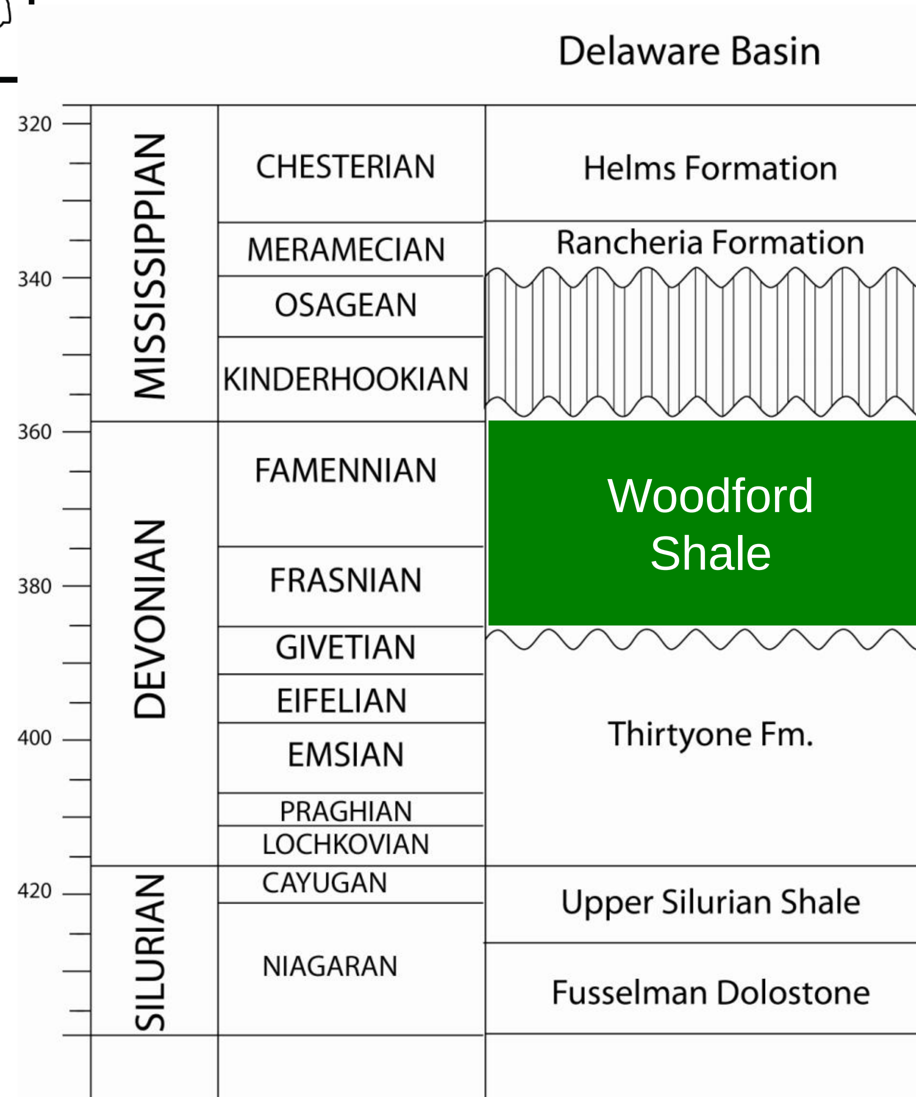




Geologic Setting



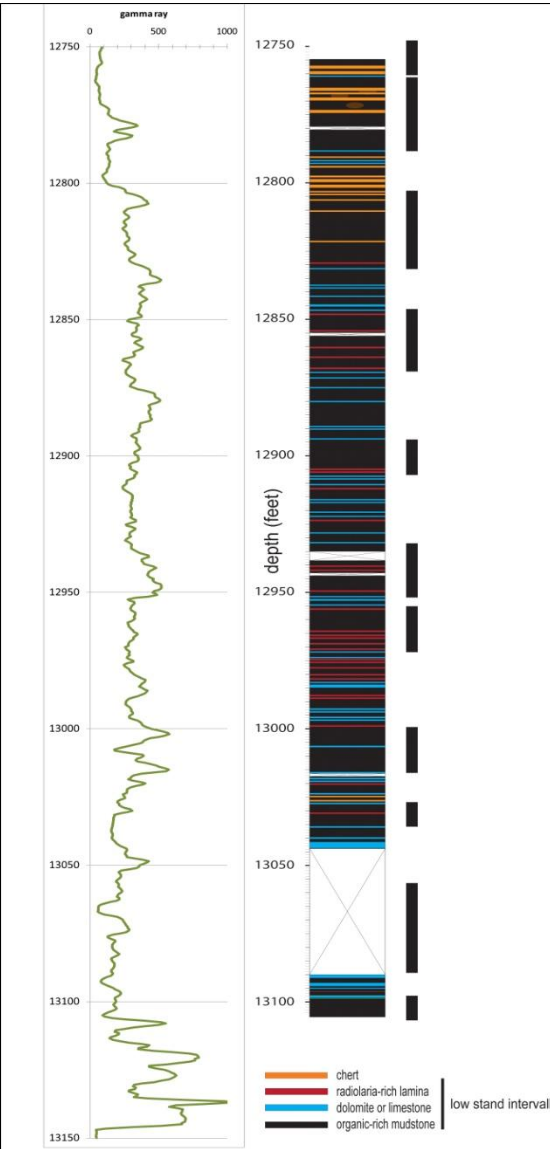
RTC 1 – 13,000 feet
Ro = 1.48%

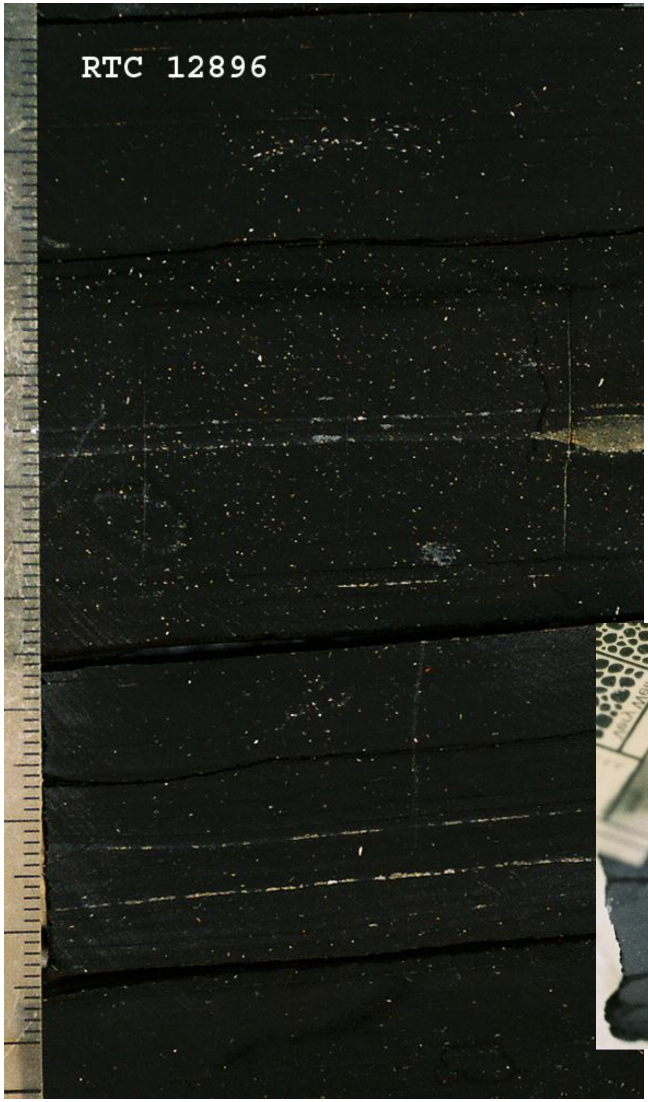


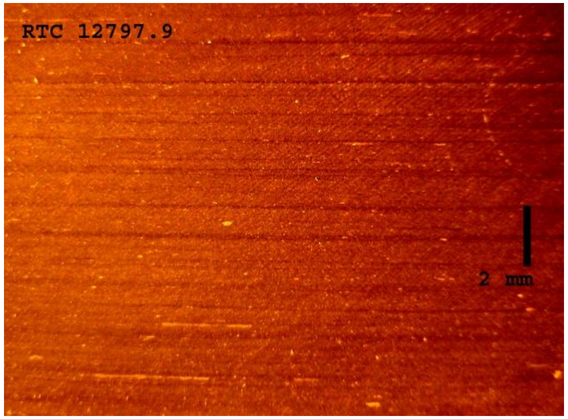
Reliance Triple Crown #1

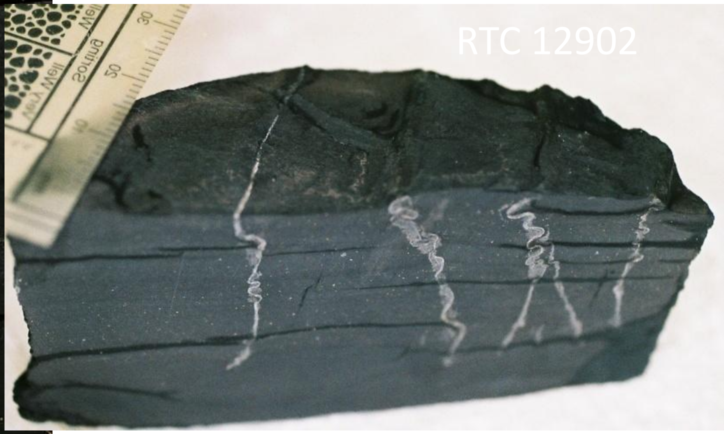
Woodford Shale Consortium

Black Mudstone Lithofacies

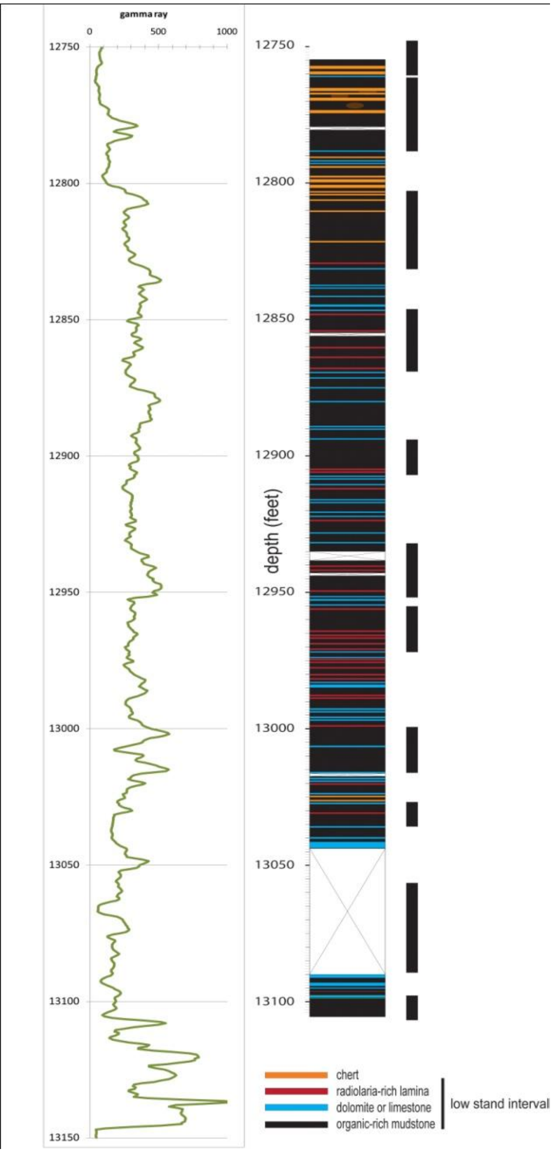


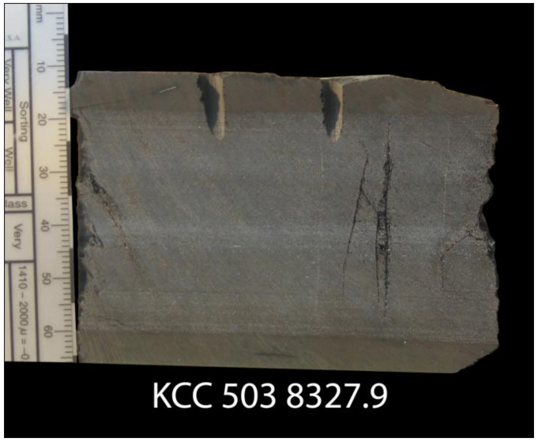






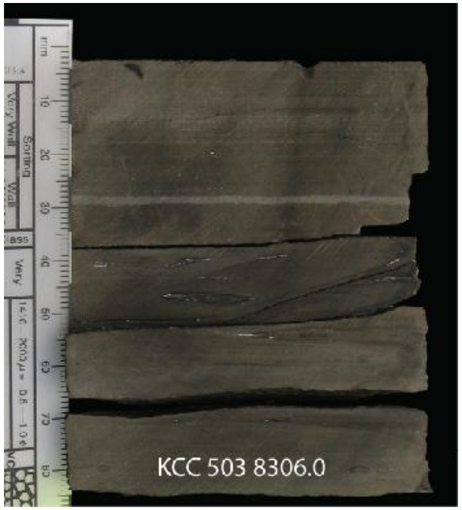
Minor lithofacies within the organic mudstone



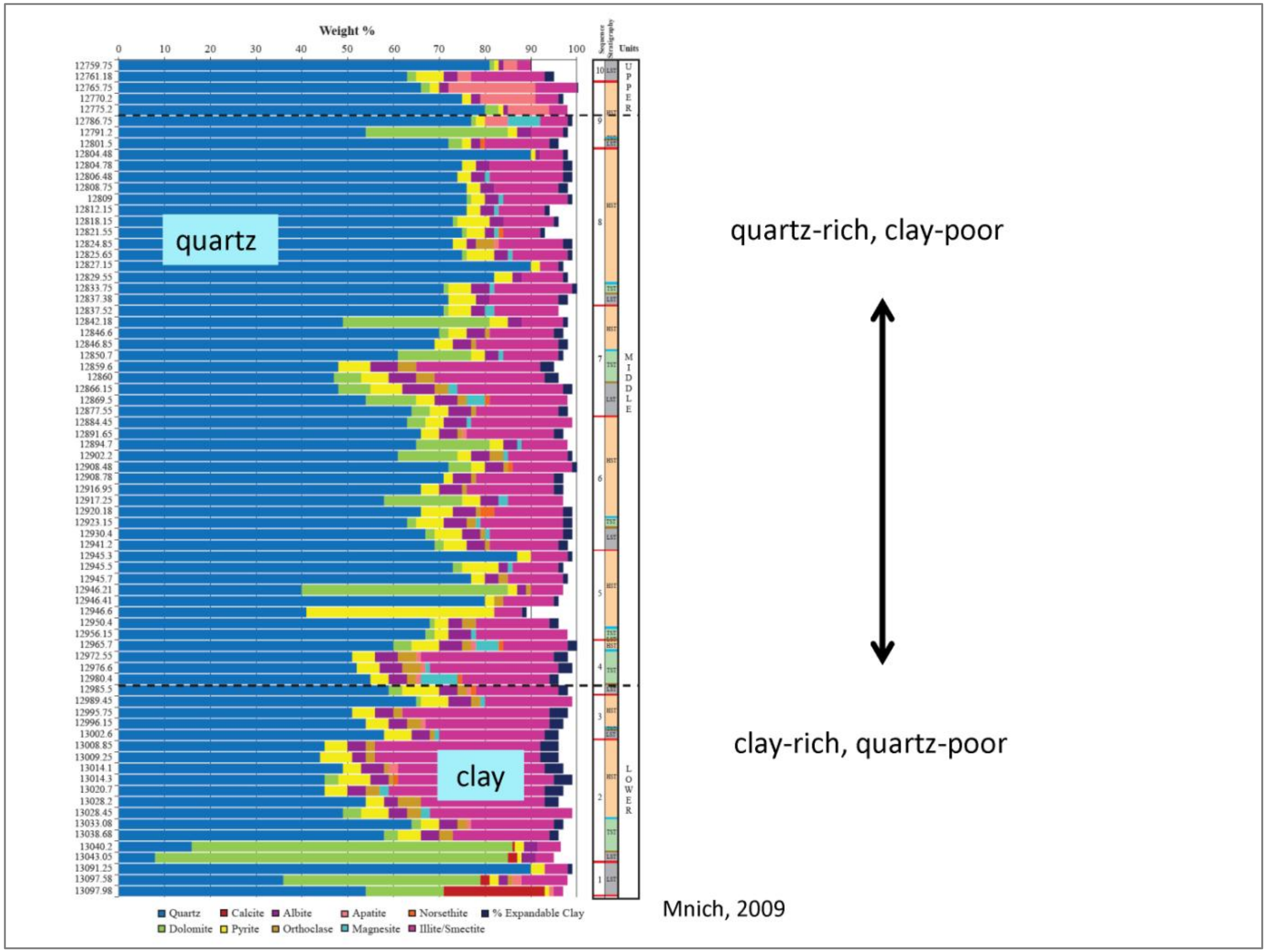


Chert beds (orange)

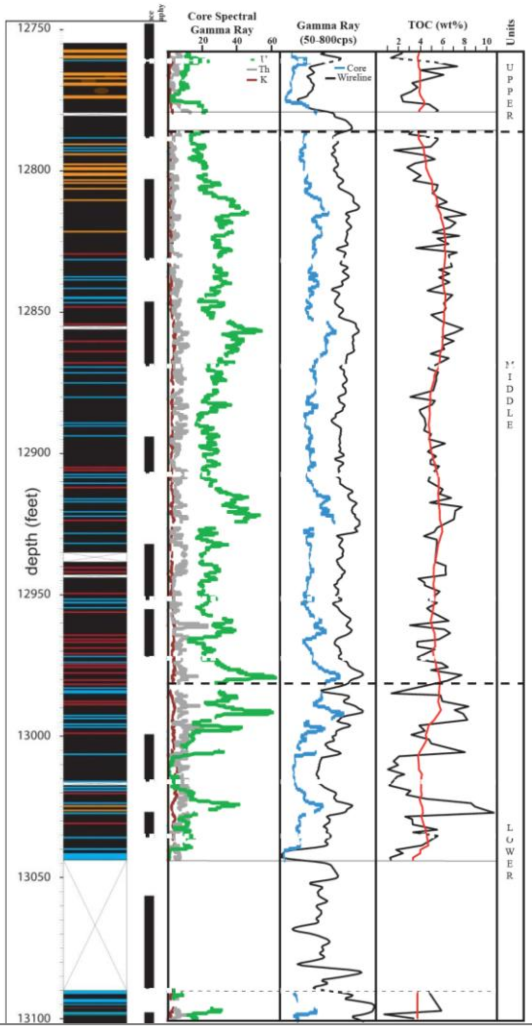
Dolomite beds (blue)



Radiolarian laminae (dark red)



Presenter's notes: There is one other expression of the 2nd order sea level fall that's important to mention. That's the ratio of quartz to clay. In the lower part of the Woodford section, quartz is about 50 weight% of the rock, but that increases upward to about 75% of the rock in the Upper Woodford. We know that this is biogenic silica, not detrital quartz, because our geochemical data show that silica is decoupled from other elements associated with siliciclastic minerals, like Al, K, and Ti.



Close relationship between gamma ray (U) and TOC enables us to build a transform between gamma log and TOC

Steps:

1) Calibrate TOC to gamma ray for log-based prediction of TOC.

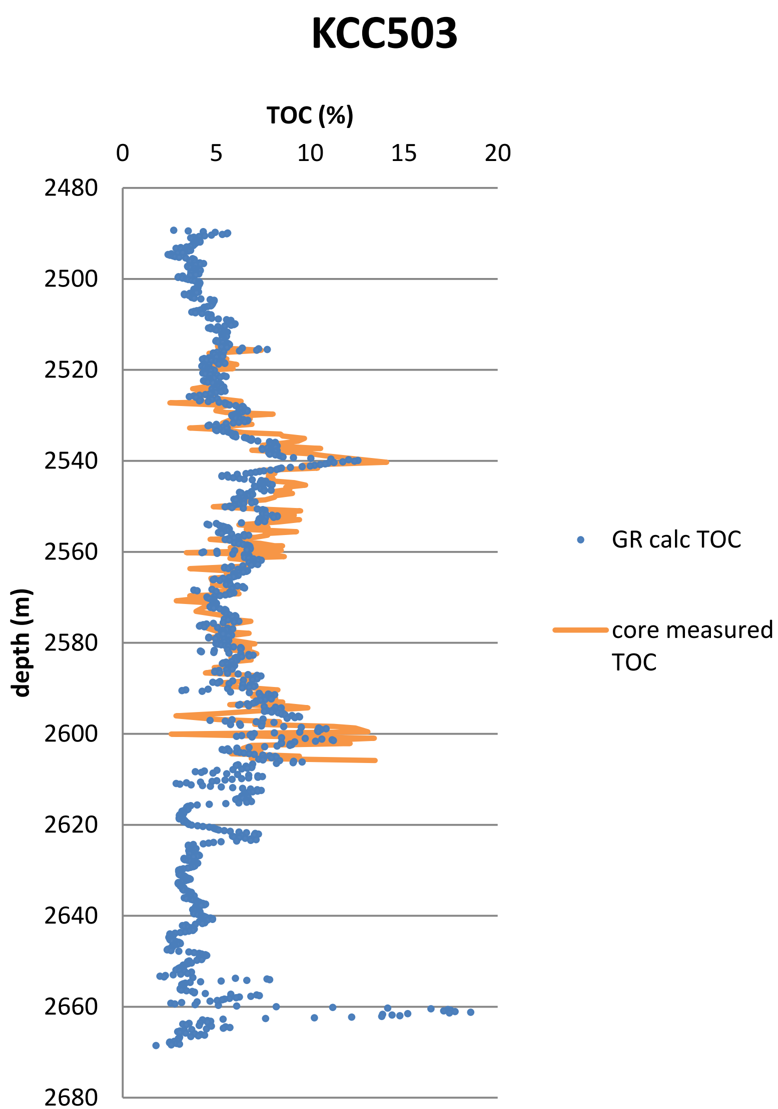
2) Compare GR-derived TOC to Vp, Vs, density, Vp/Vs.

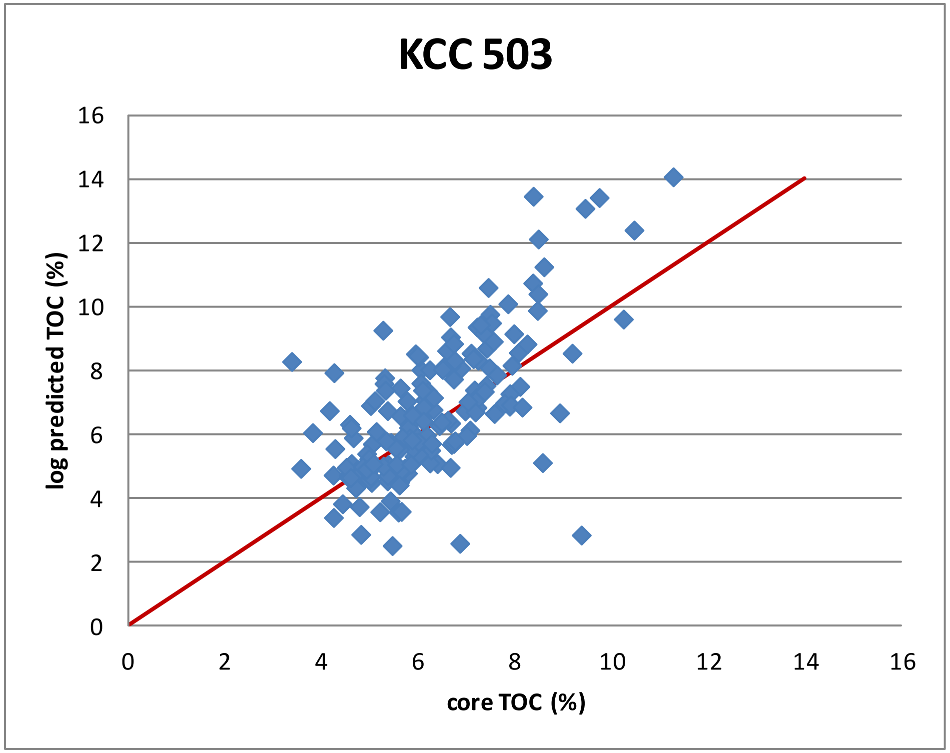
   - effects of TOC, maturity on rock physics response

3) Are any features thick enough to resolve with seismic?

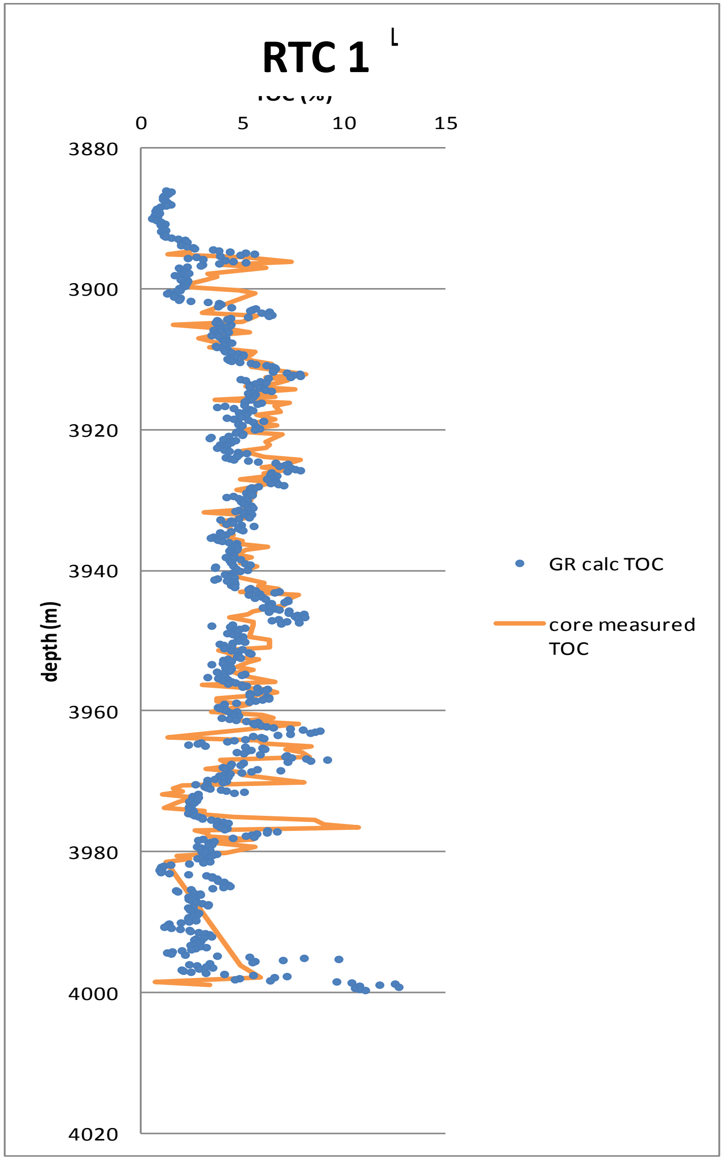
Presenter's notes: We see at least 10 of these cycles in the RTC core. Given that the overall age span of the Woodford was something like 20 million years, these cycles represent periods of time on the order of 2 to 3 million years, so these would then be 3rd and 4th order sea level cycles.

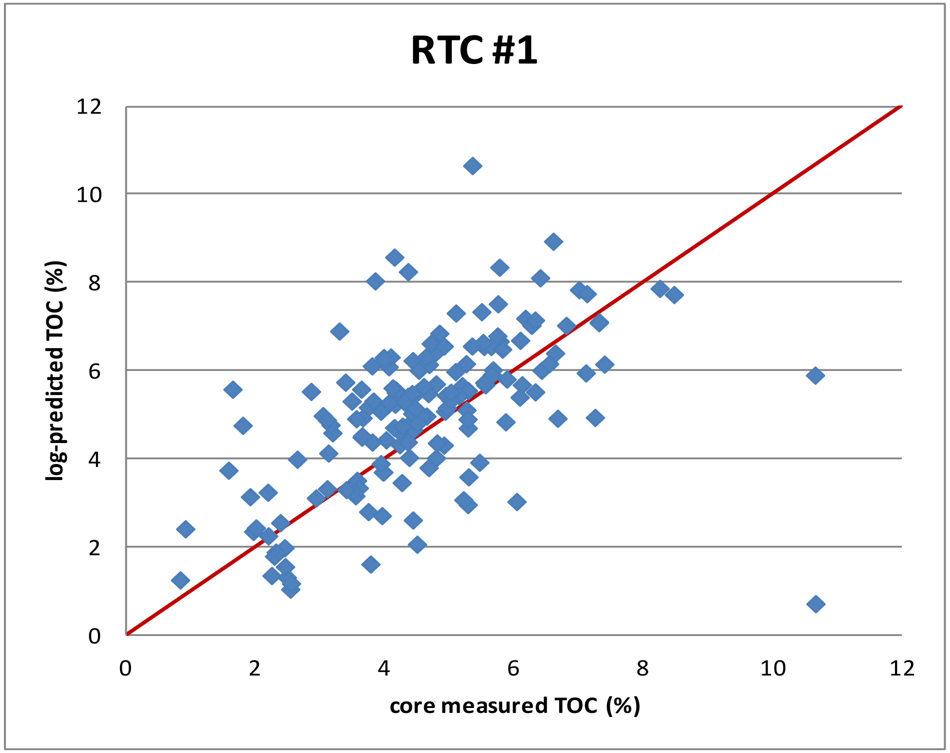
TOC versus gamma ray in the low maturity well





TOC versus gamma ray in the high maturity well





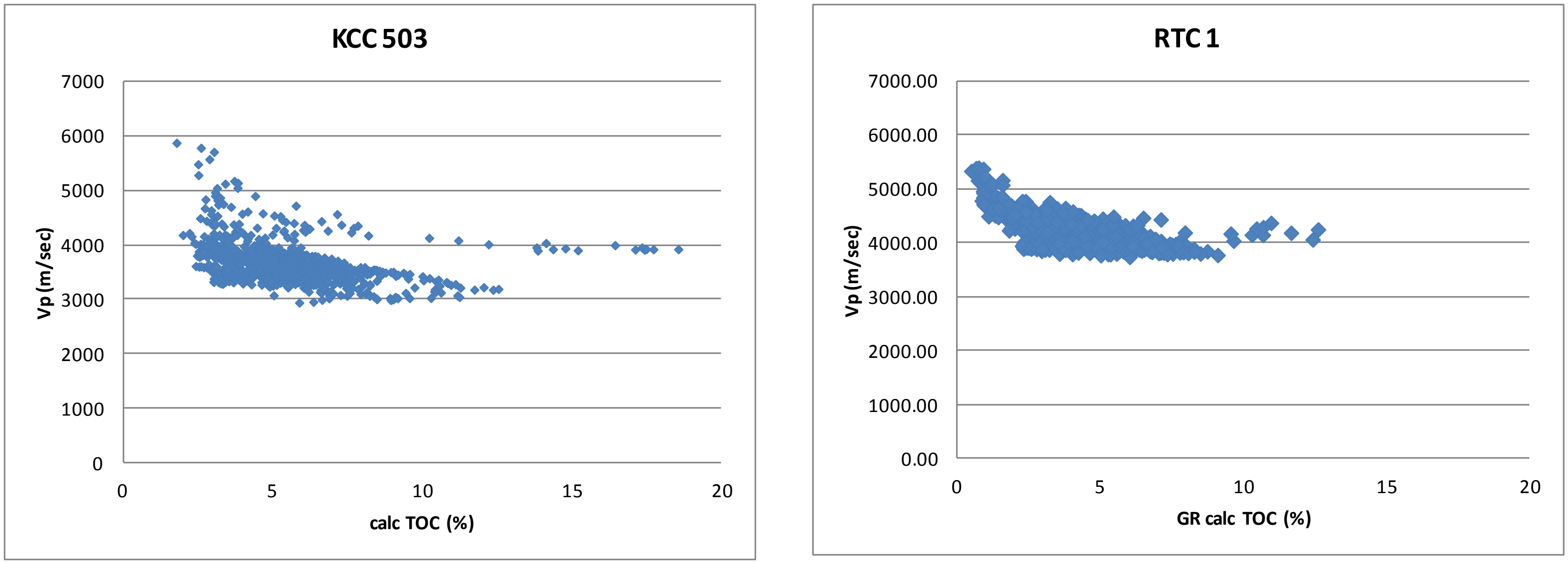
P-wave velocity decreases with TOC, increases with maturity

maturity →

Ro = 0.71%

Ro = 1.48%

Vp (m/sec)

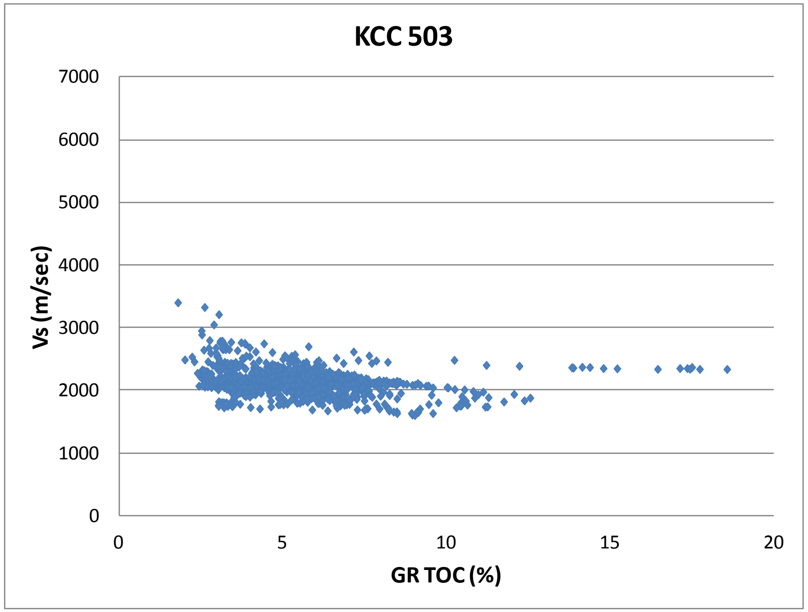


calculated TOC (%)

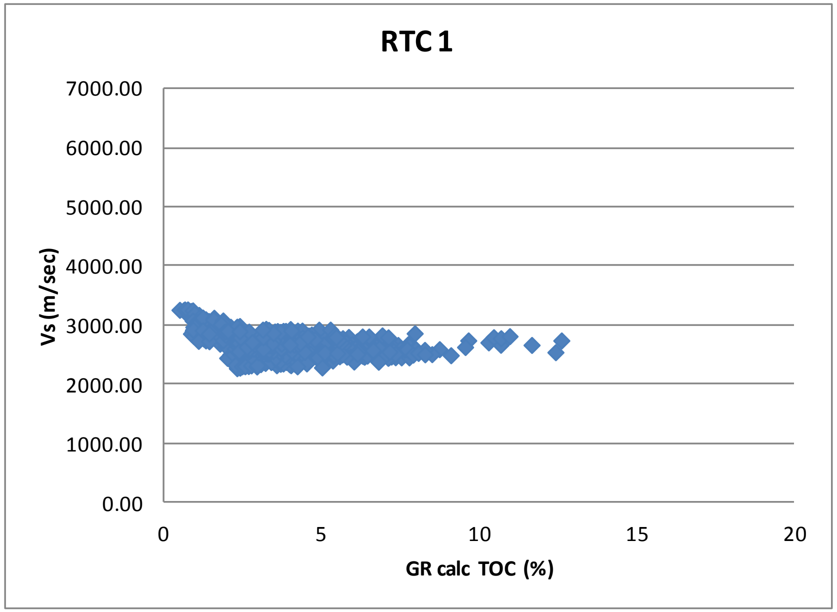
S-wave velocity decreases with TOC, increases with maturity

maturity →

Ro = 0.71%



Ro = 1.48%



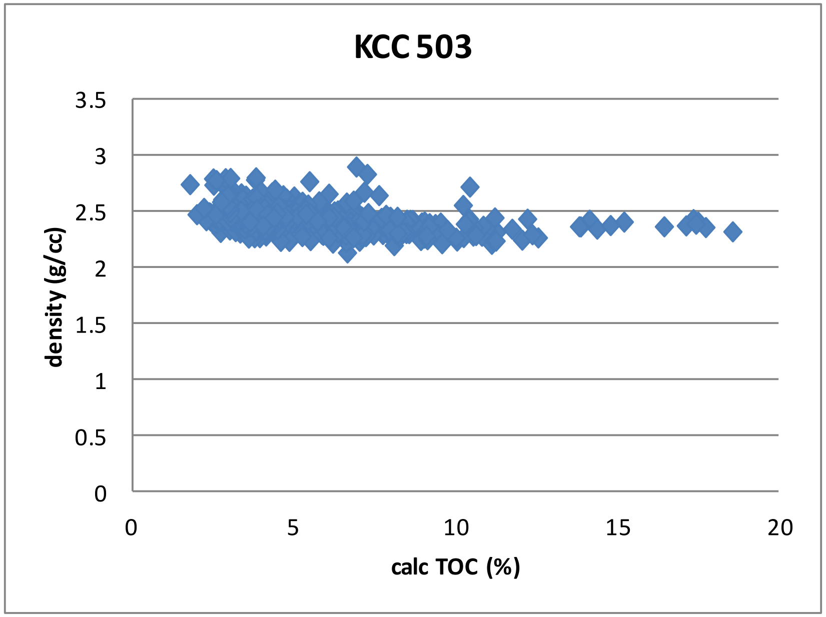
Vs (m/sec)

calculated TOC (%)

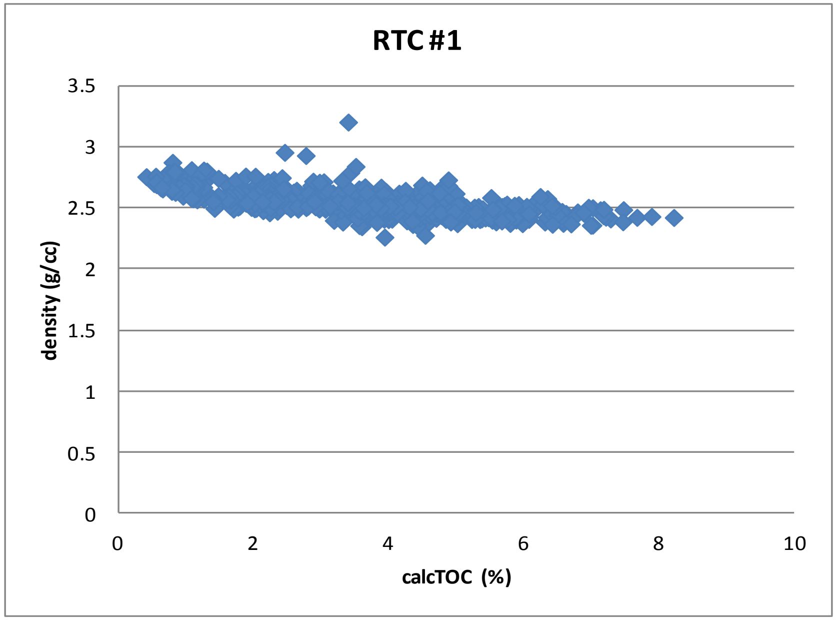
Density decreases with TOC, increases with maturity

maturity →

Ro = 0.71%



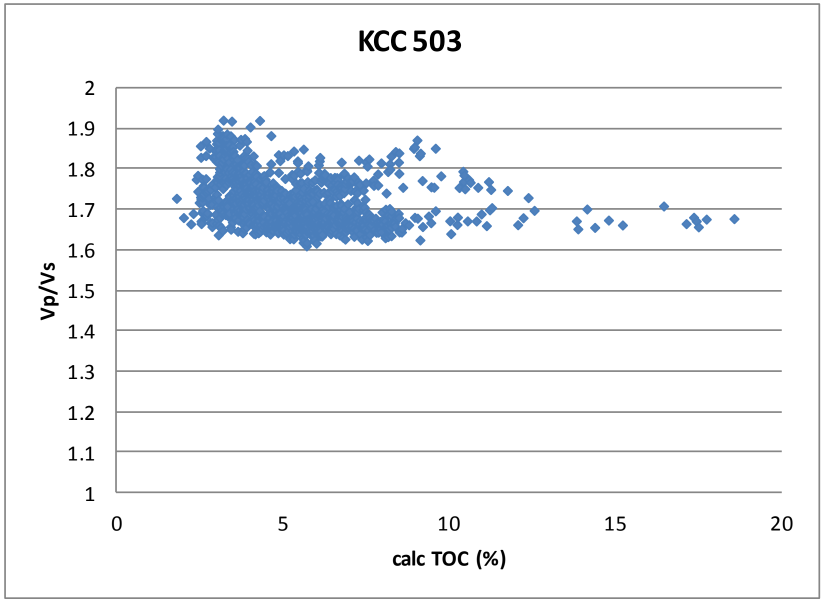
Ro = 1.48%



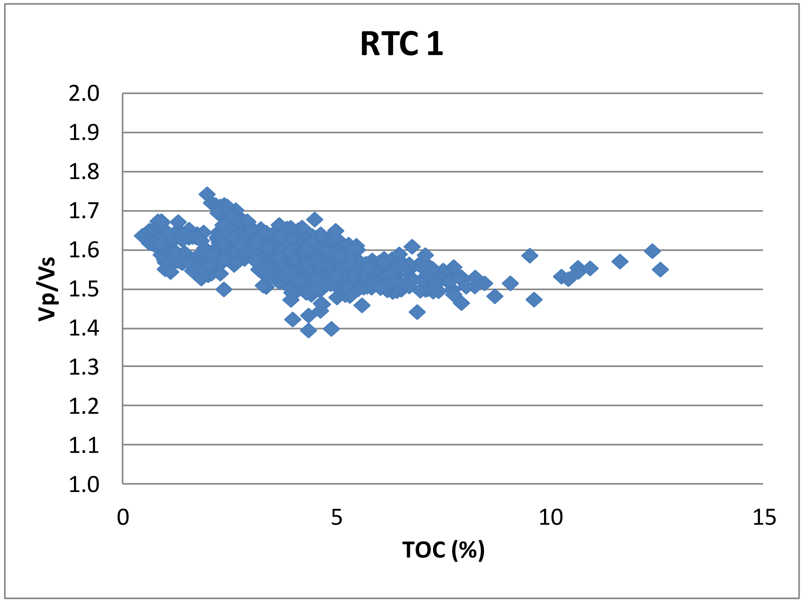
Vp/Vs decreases with TOC, decreases with maturity

maturity →

Ro = 0.71%



Ro = 1.48%

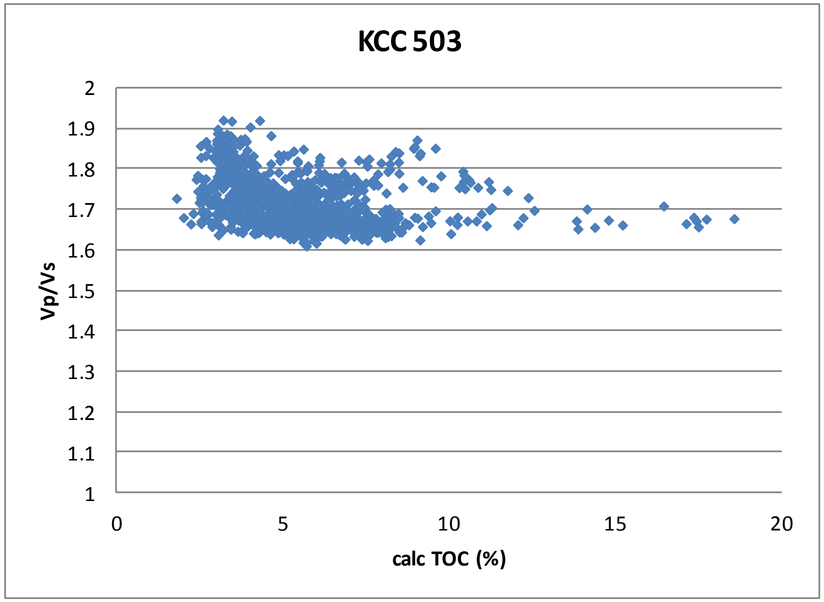


Decrease in maturity associated with expulsion of hydrocarbons, collapse or hardening of kerogen

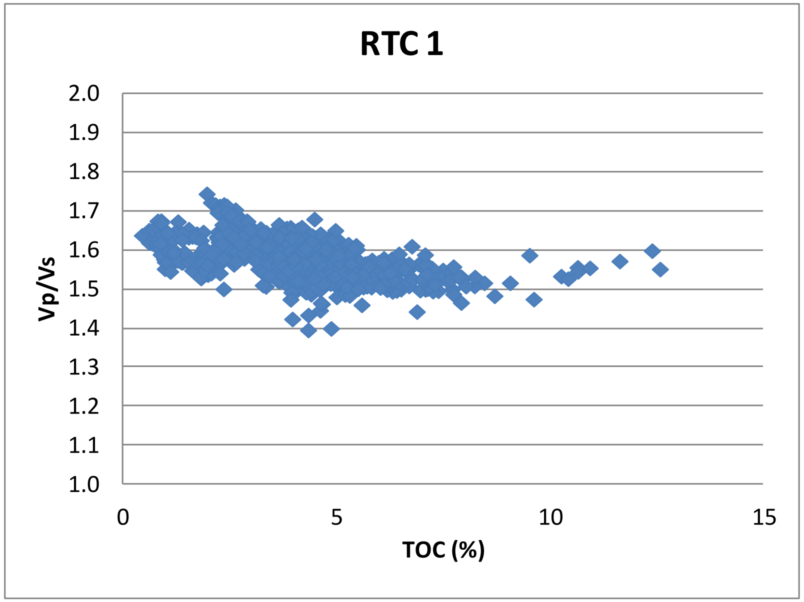
Vp/Vs decreases with TOC, increases with maturity

maturity →

Ro = 0.71%

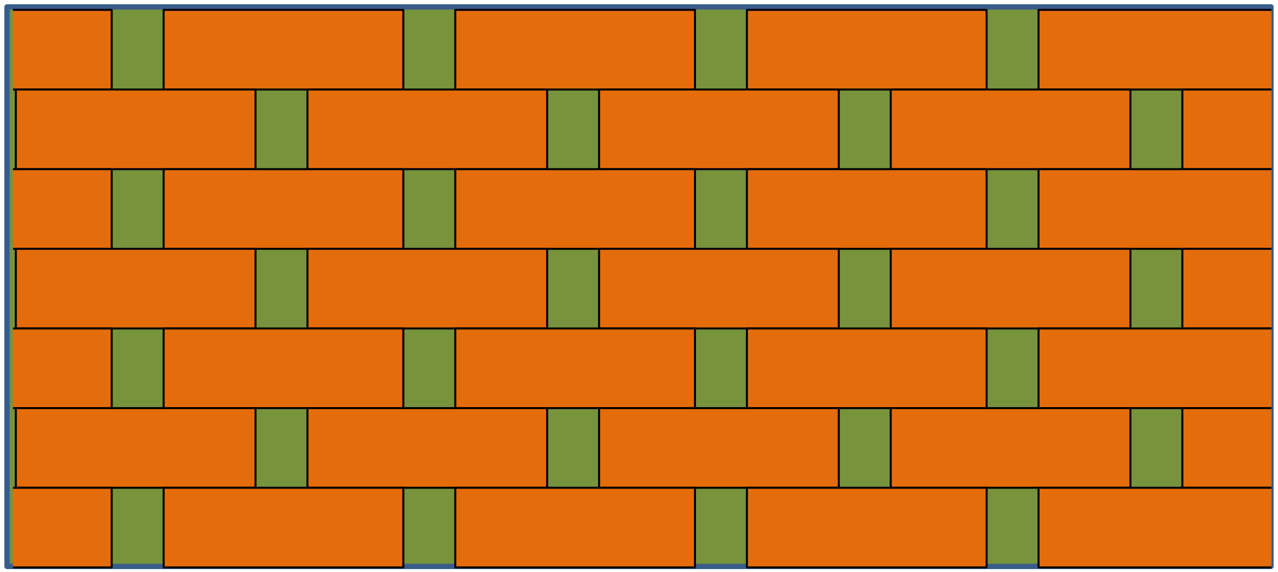


Ro = 1.48%



If organic matter is soft, why should the difference between Vp and Vs decrease with TOC?

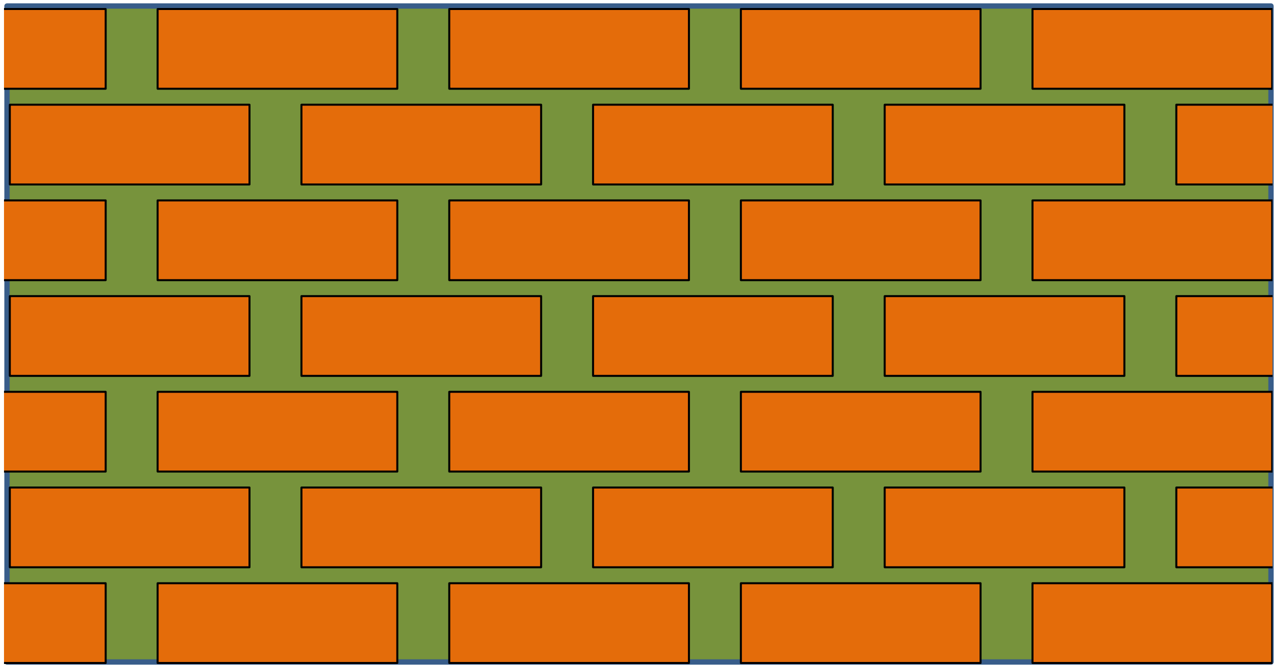
In a low(er) TOC shale, hard grains are in point-to-point contact, so both P and S wave are transmitted



→ Relatively low Vp/Vs ratios

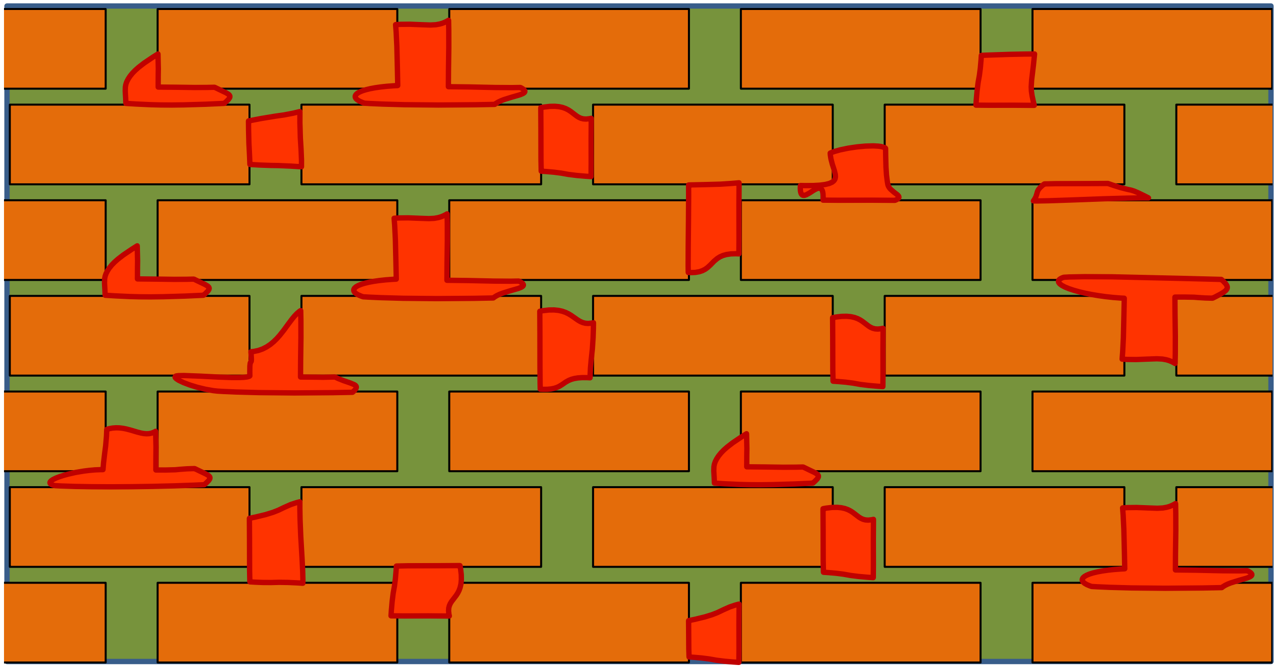
In high(er) TOC shale, few hard grains are in point-to-point contact, and sonic energy has to be transmitted through the organic matter.

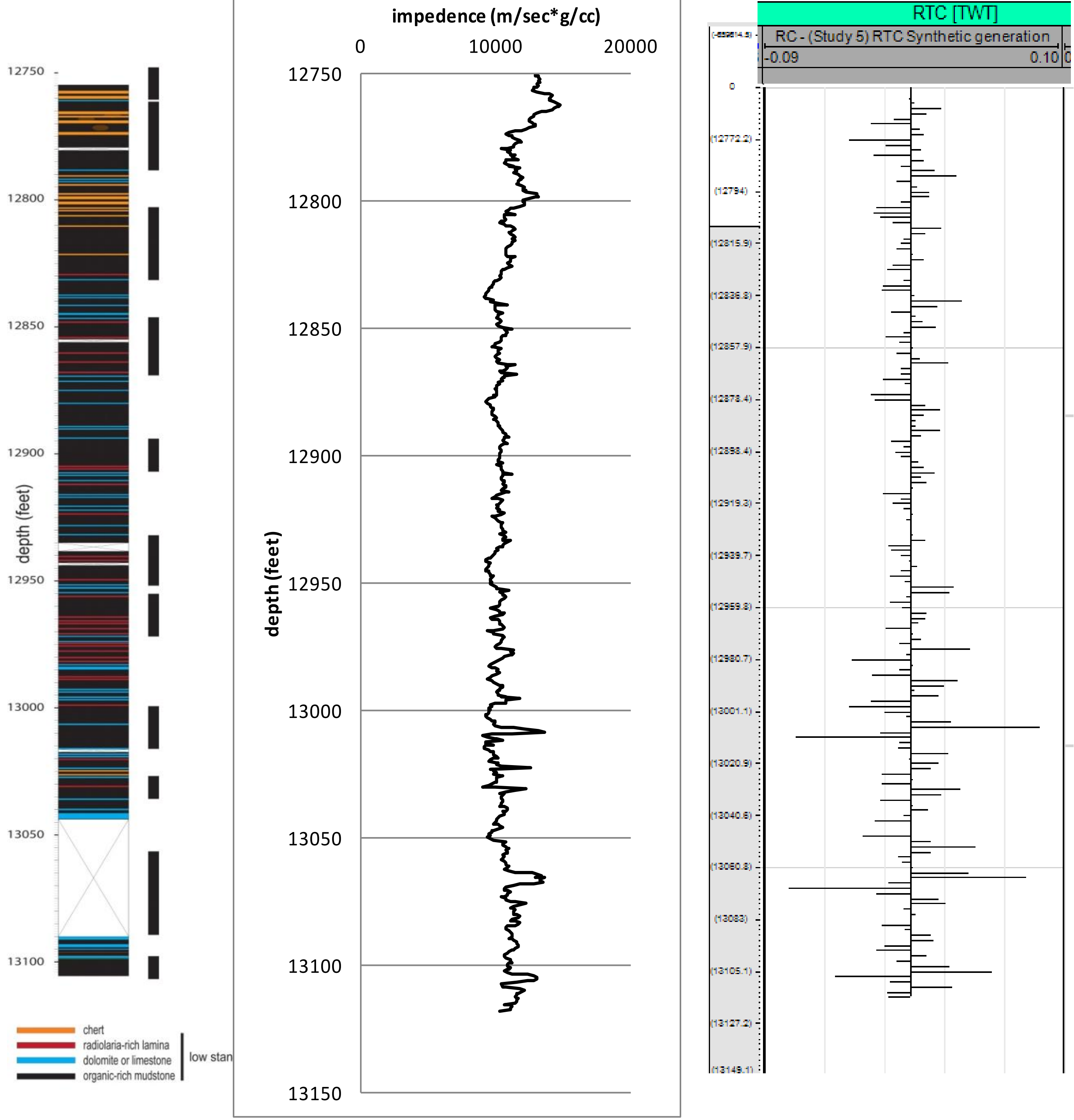
Organic matter is ductile → shear wave energy is attenuated



→ Relatively high Vp/Vs ratios

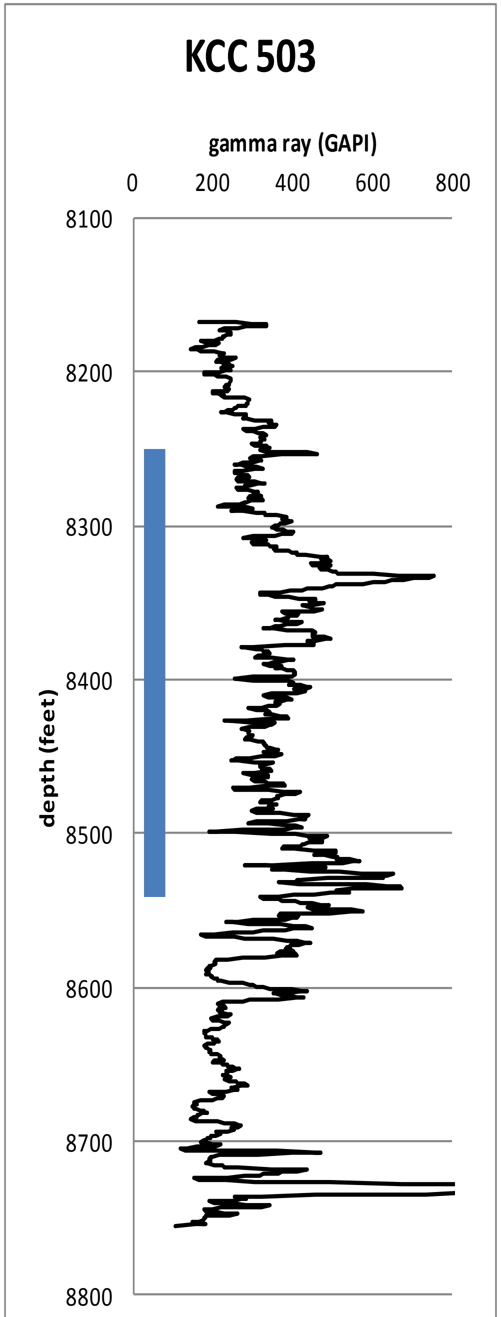
Does quartz cementation create a more rigid framework?

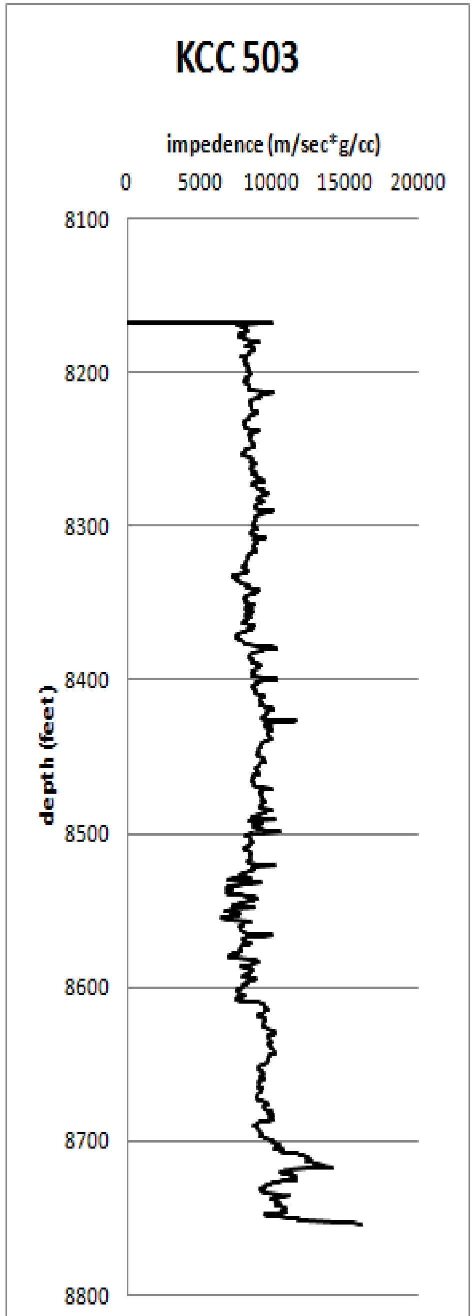


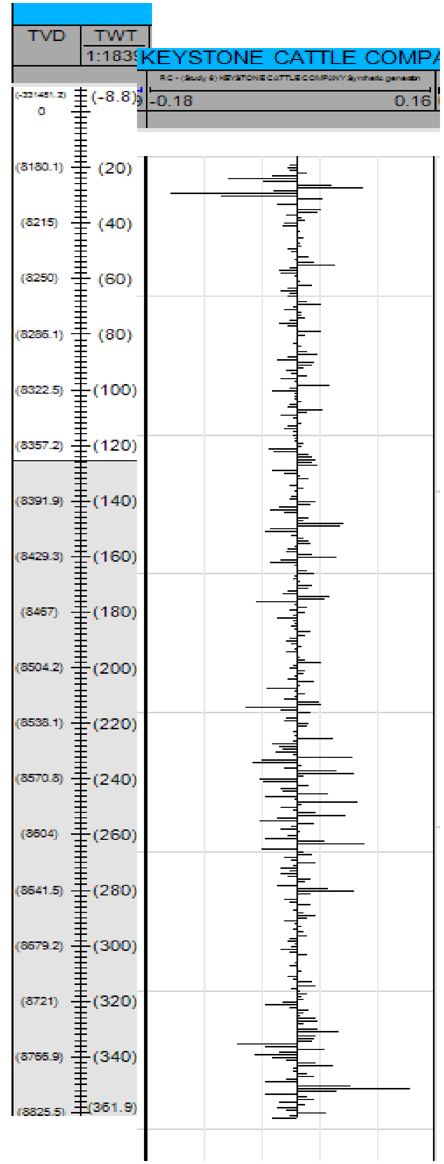


λ/4 at 50 hz

21 m = 69 feet

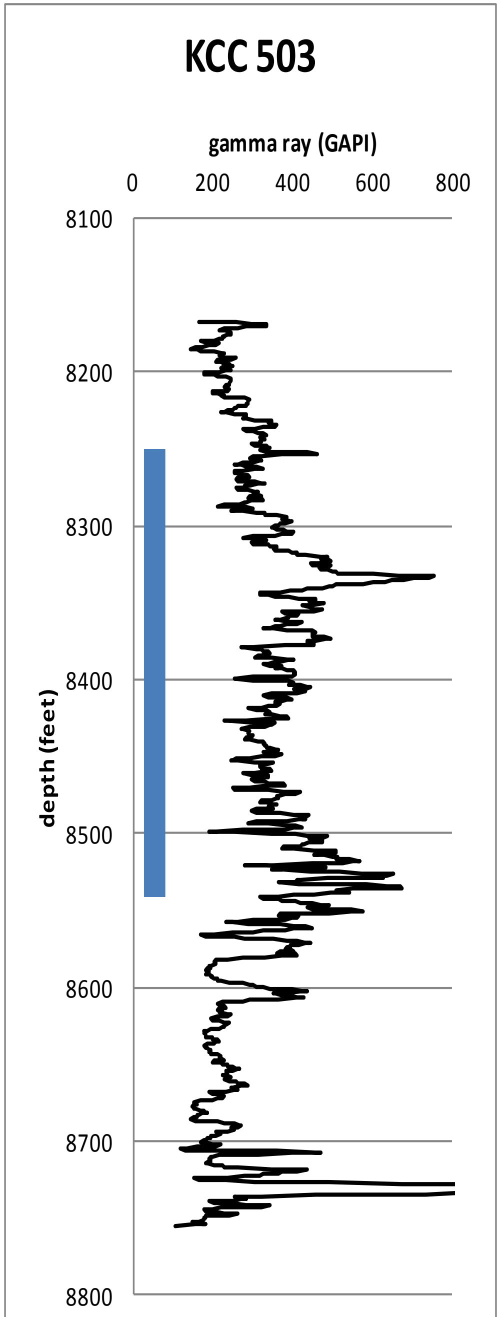


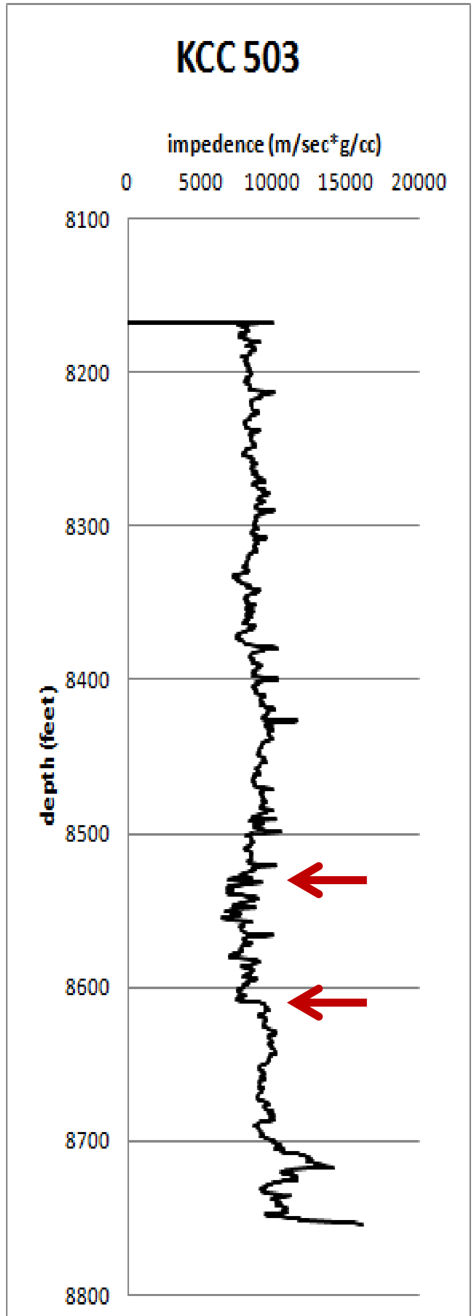


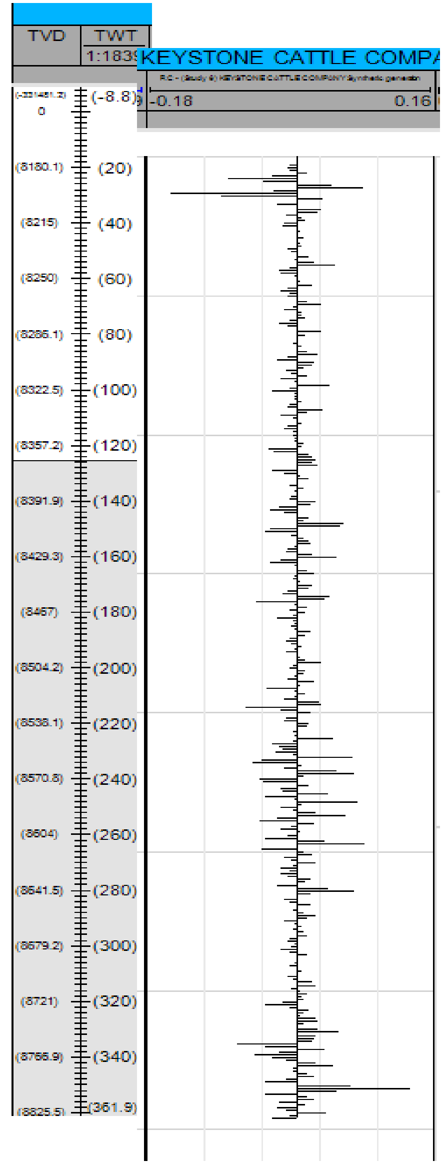


λ/4 at 50 hz

18 m = 59 feet







λ/4 at 50 hz

18 m = 59 feet

RTC 12797.9

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SOME CONCLUSIONS AND OBSERVATIONS

Velocities, density decrease systematically with increasing TOC in shales; carbonate content also affects density.

Velocities, density increase with increasing thermal maturity

Vp/Vs decreases with increasing TOC, possibly a cementation effect

2 mm

Much of the heterogeneity is at a finer scale than reasonable λ/4, so would likely be unresolvable at normal seismic frequencies. So seismic response will average TOC over most intervals.