Geomechanical Heterogeneity in the Lower Cotton Valley Shelf System—Applications to Completion Design

Craig D. Hall

Core Laboratories, 6316 Windfern Rd., Houston, Texas 77040

GCAGS Explore & Discover Article #00338*
http://www.gcags.org/exploreanddiscover/2018/00338_hall.pdf
Posted September 29, 2018.

*Article based on an extended abstract published in the *GCAGS Transactions* (see footnote reference below), which is available as part of the entire 2018 *GCAGS Transactions* volume via the GCAGS Bookstore at the Bureau of Economic Geology (www.beg.utexas.edu) or as an individual document via AAPG Datapages, Inc. (www.datapages.com), and delivered as an oral presentation at the 68th Annual GCAGS Convention and 65th Annual GCSSEPM Meeting in Shreveport, Louisiana, September 30–October 2, 2018.

EXTENDED ABSTRACT

Completion design simulators require data on rock mechanical properties to successfully predict fracture propagation and proppant pack density. Those mechanical properties are derived from the downhole sonic curves that may or may not be calibrated with benchtop data on Young's Modulus and Poisson's Ratio. The sonic tools typically used collect and average data over several feet of stratigraphic section and may not have the ability to fully measure the properties of mechanical units less than twelve to eighteen inches thick. However, some formations are composed of layers with substantially different mechanical properties, with thicknesses that are below the resolution of the sonic tools. Based on work in other formations this architecture may impart a mechanical heterogeneity that could impact the vertical propagation of hydraulic fractures. This mechanical stratigraphy and heterogeneity can be expressed in terms of amplitude (magnitude of the mechanical contrast between one layer and another) and frequency (roughly thickness or vertical distance between the layers). The zones with greater heterogeneity would be characterized by high amplitude and high frequency, while lower heterogeneity would be characteristic of formations with either low amplitude or low frequency changes. We have used a rebound hammer device to measure the hardness of the Lower Cotton Valley in conventional core to determine the mechanical stratigraphy and mechanical heterogeneity of the formation on a six-inch spacing. We converted the hardness data to unconfined compressive strength (UCS), Young's Modulus, and Poisson's Ratio using in-house algorithms to create high-resolution, geomechanical properties curves for the Lower Cotton Valley. Our analysis indicates variable mechanical heterogeneity in the formation that is controlled by diagenesis (particularly the volume of calcite cement) and the clay volume. This heterogeneity is not evident in the sonic logs, and can be used to refine fracture height growth models.

The zone that has been analyzed is from a conventional core in Lincoln Parish, Louisiana. The core recovered 275 feet of Lower Cotton Valley, interbedded calcite-cemented, very fine-grained sandstones, argillaceous very fine-grained sandstones, and silty to sand shale. The cored interval broadly coarsens upward from mostly sandy to silty shale in the lower third of the interval, to a mostly sandstone-dominated facies comprising approximately 175 feet. The uppermost 35 feet of the interval is composed pre-

Originally published as: Hall, C. D., 2018, Geomechanical heterogeneity in the Lower Cotton Valley shelf system—Applications to completion design: Gulf Coast Association of Geological Societies Transactions, v. 68, p. 589–590.

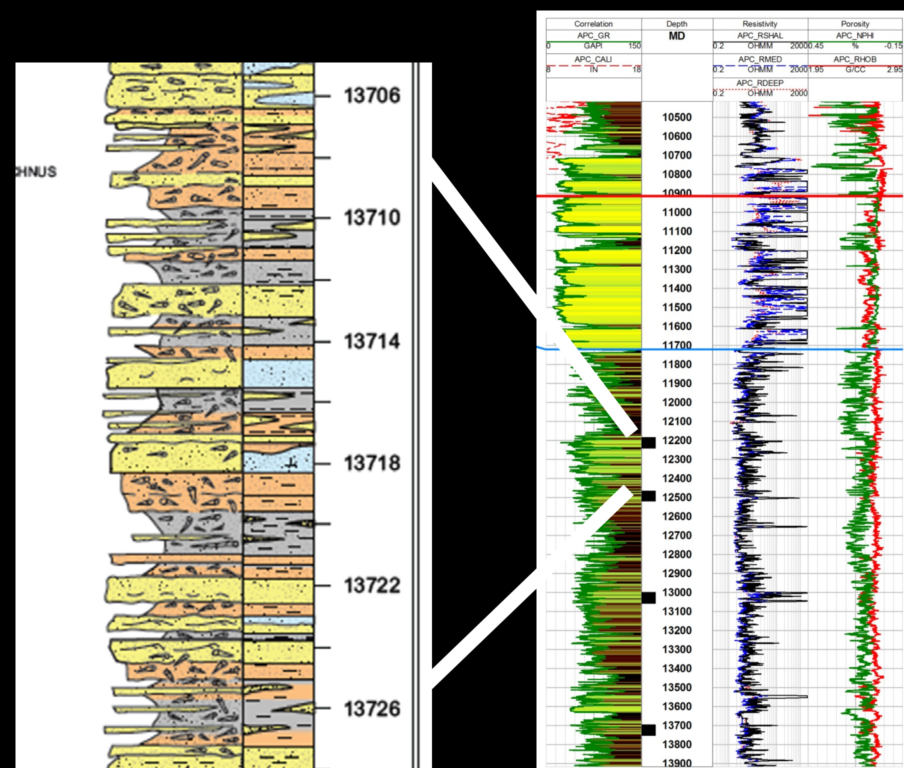
dominantly of sandy shale and argillaceous, very fine-grained sandstones similar to the basal facies. Measured hardness data indicates that clay volume is a first-order control on hardness with a negative correlation between clay volume and hardness. Thin, scattered, calcite cemented beds result in a higher frequency, second-order control on hardness, and result in increased geomechanical heterogeneity.

Two frac-design simulations were run with and without a Reservoir Geomechanical Heterogeneity Index (RGHI) derived from the hardness data. A hypothetical landing point was placed in the middle portion of the core within the thick interval of higher sand content. Using a surrogate Poisson' Ratio curve derived from the downhole logs in one modeling run, and a separate Poisson's Ratio curve derived from the hardness data in a second run, the formation displays a tendency for greater frac height growth with total height of 175 feet. When the high-frequency geomechanical heterogeneity of the formation is factored into the simulation, the total height is reduced to 105 feet with the lost height being in the upper portion of the cored interval, and more of the energy being directed downward. The formation also tends to place more proppant close to the wellbore.

This work indicates that high-frequency, vertical changes in geomechanical properties of a reservoir can influence frac height growth and proppant concentrations in the Lower Cotton Valley. Running multiple simulations swapping out various carrier fluids, and trying different pump rates and proppant calibers may be able to mitigate the effects of the geomechanical heterogeneity and contact greater volumes of the reservoir.

Geomechanical Heterogeneity in the Lower Cotton Valley Shelf System – Applications to Completion Design

Craig D. Hall Ph.D.
Feiyan Chen Ph.D.
Core Laboratories
Houston, TX



Outline

- Introduction
  - Key Question
  - Methods
  - Reservoir Geomechanical Heterogeniety Index concept
- Lower Cotton Valley Geology
- Results
- Summary and Conclusions

Outline

I would like to thank my employer - Core Laboratories, and Range Resources for allowing me to present this work to you today.

Key Question

- **What impact do vertical changes in rock mechanical properties (the mechanical stratigraphy) have on frac height growth?**

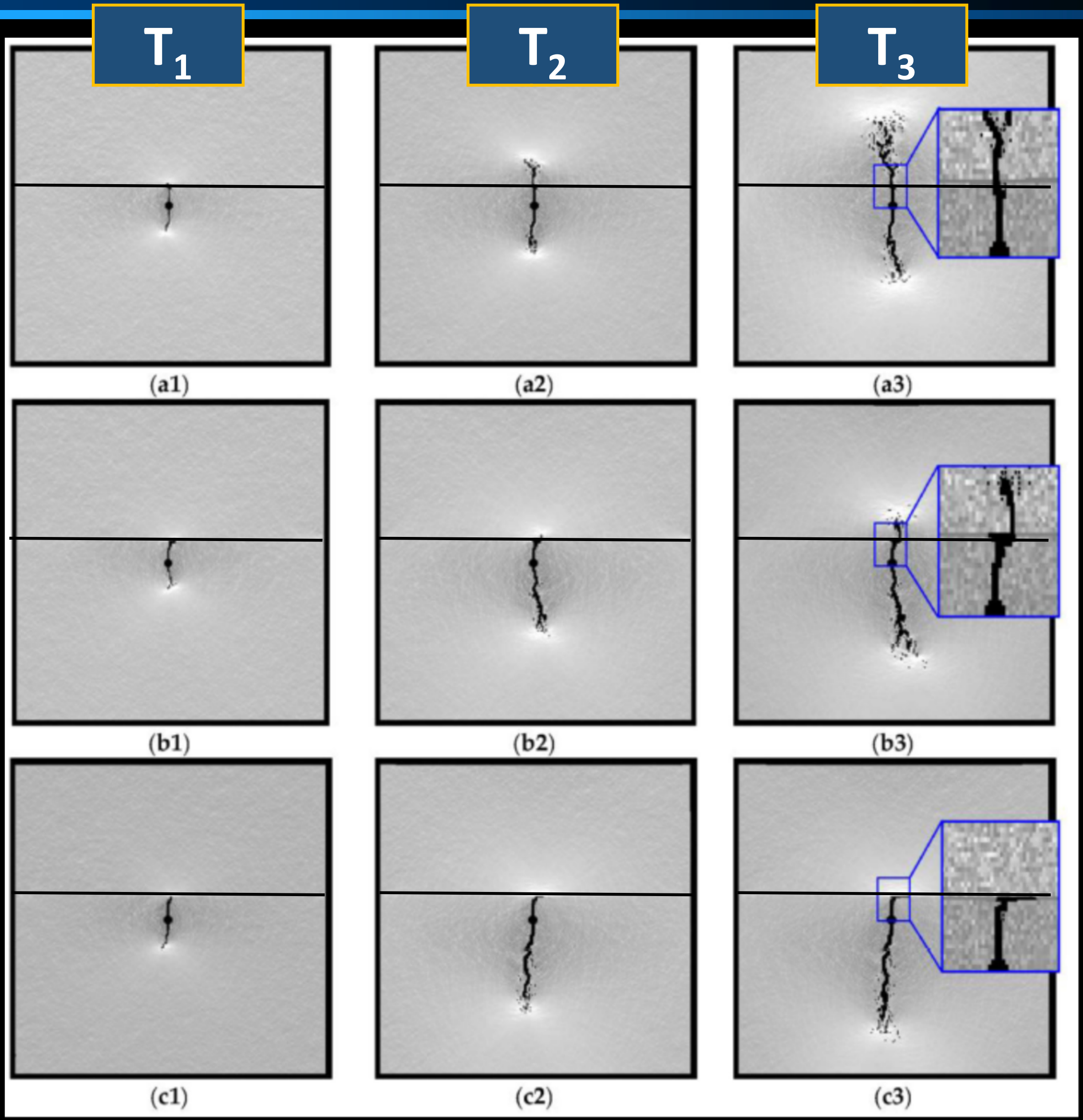
Key Question

$S_{Upper} = S_{Lower}$

$S_{Upper} > S_{Lower}$

$S_{Upper} >> S_{Lower}$

Li et al, 2016



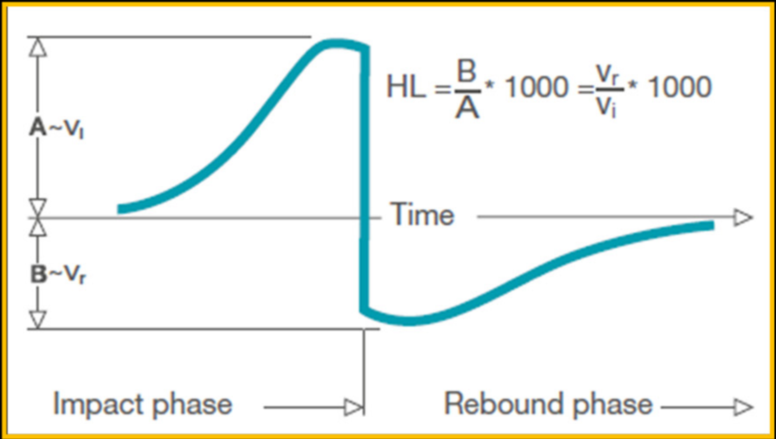
Key Question

- Some thinly bedded reservoirs exhibit significant bed-scale changes in rock mechanical properties.
- Downhole sonic tools have limited ability to resolve bed-scale changes in rock mechanical properties.
- How can we economically and accurately determine the sub-sonic log-scale mechanical stratigraphy of these formations and account for them in a frac design simulator?

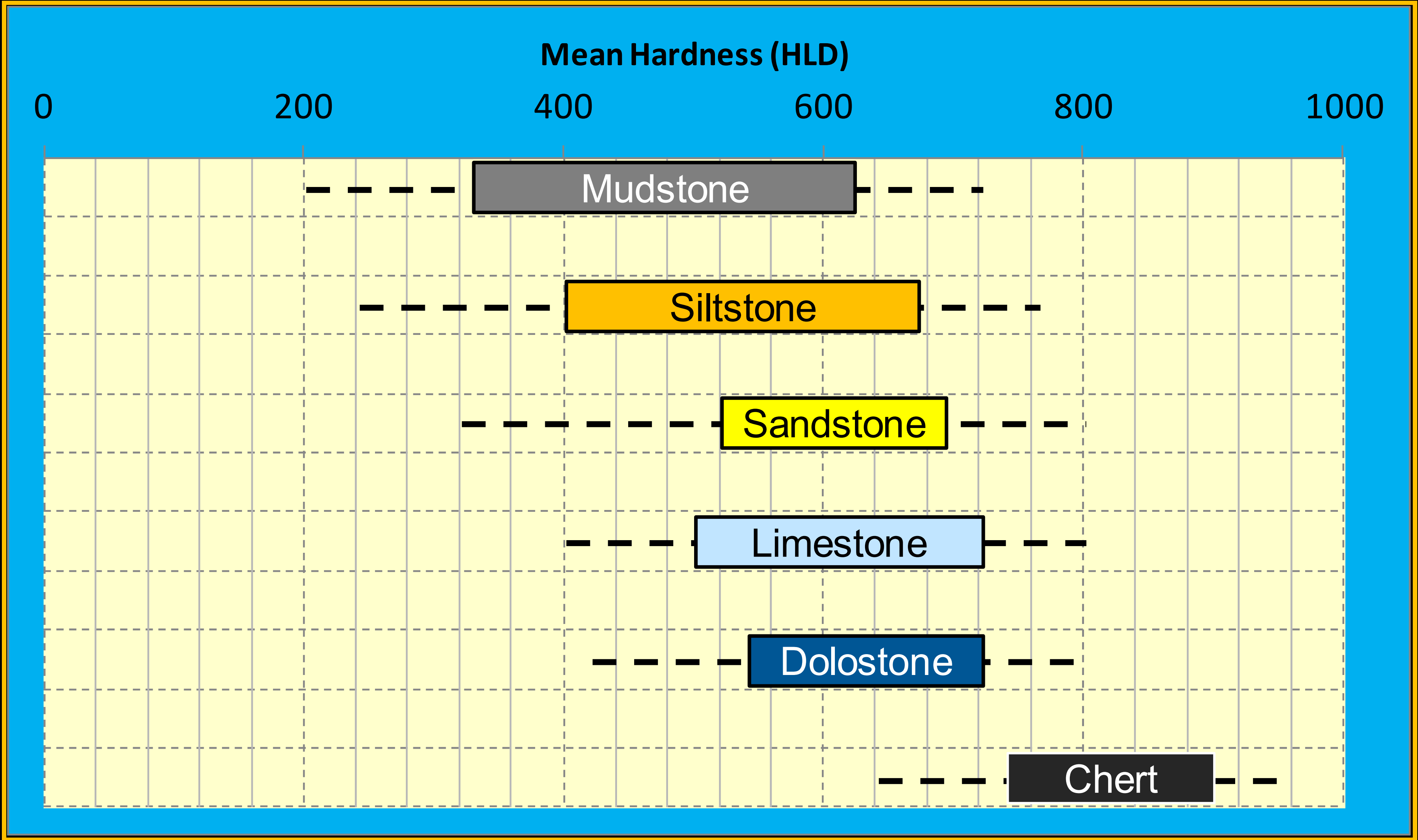
Methods

- Procedure based on that developed by Dietmar Leeb (1978) essentially determining elasticity.
- Fast, non-destructive brittleness profile based on ratio of impact to rebound velocity of a magnetic “hammer”.
- Half-foot spacing.
- Average of ten (10) measurements at each depth.
- Hardness reported as H_{LD} for Leeb Hardness – Impact Device type D.

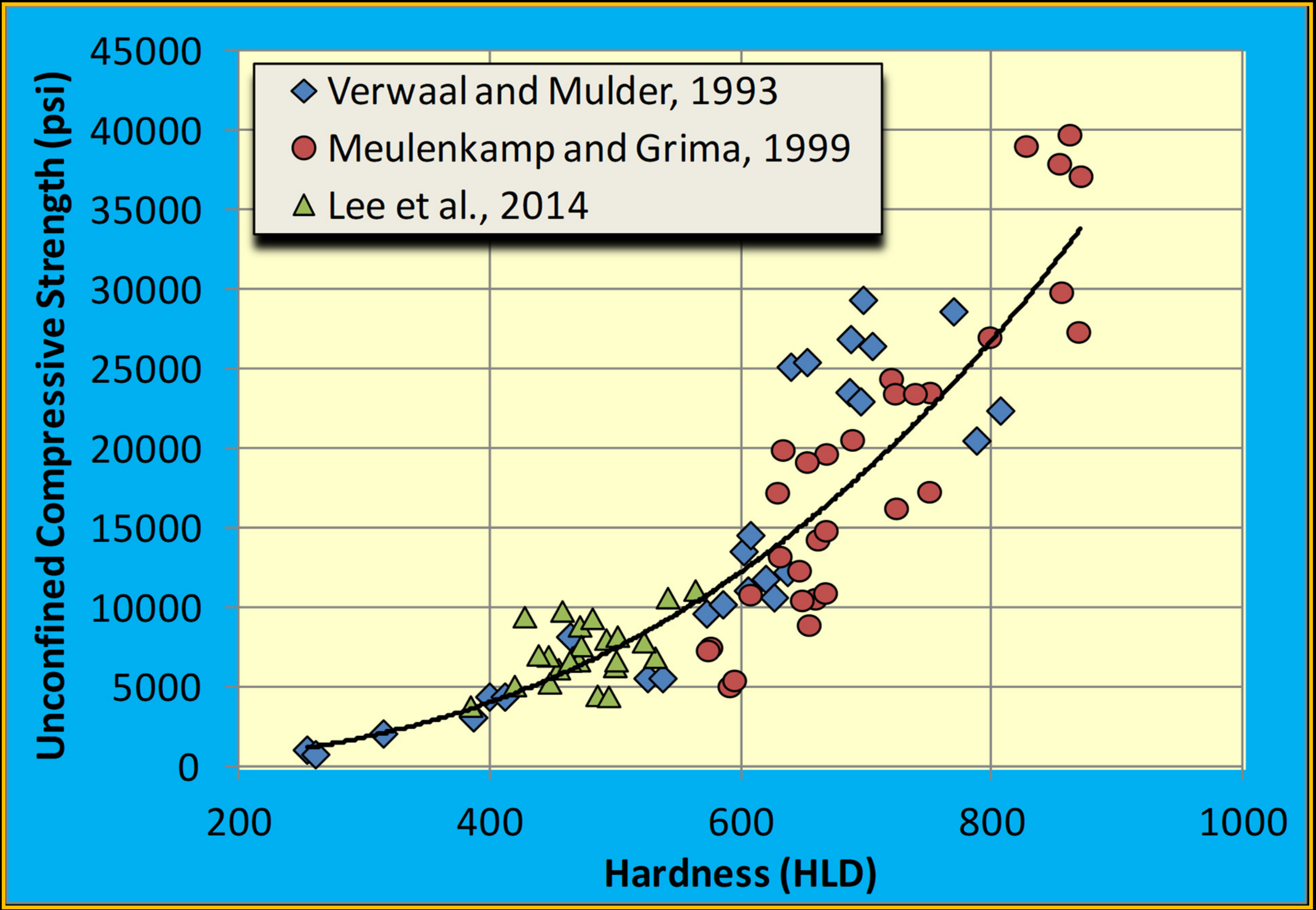
Equotip 550 Leeb



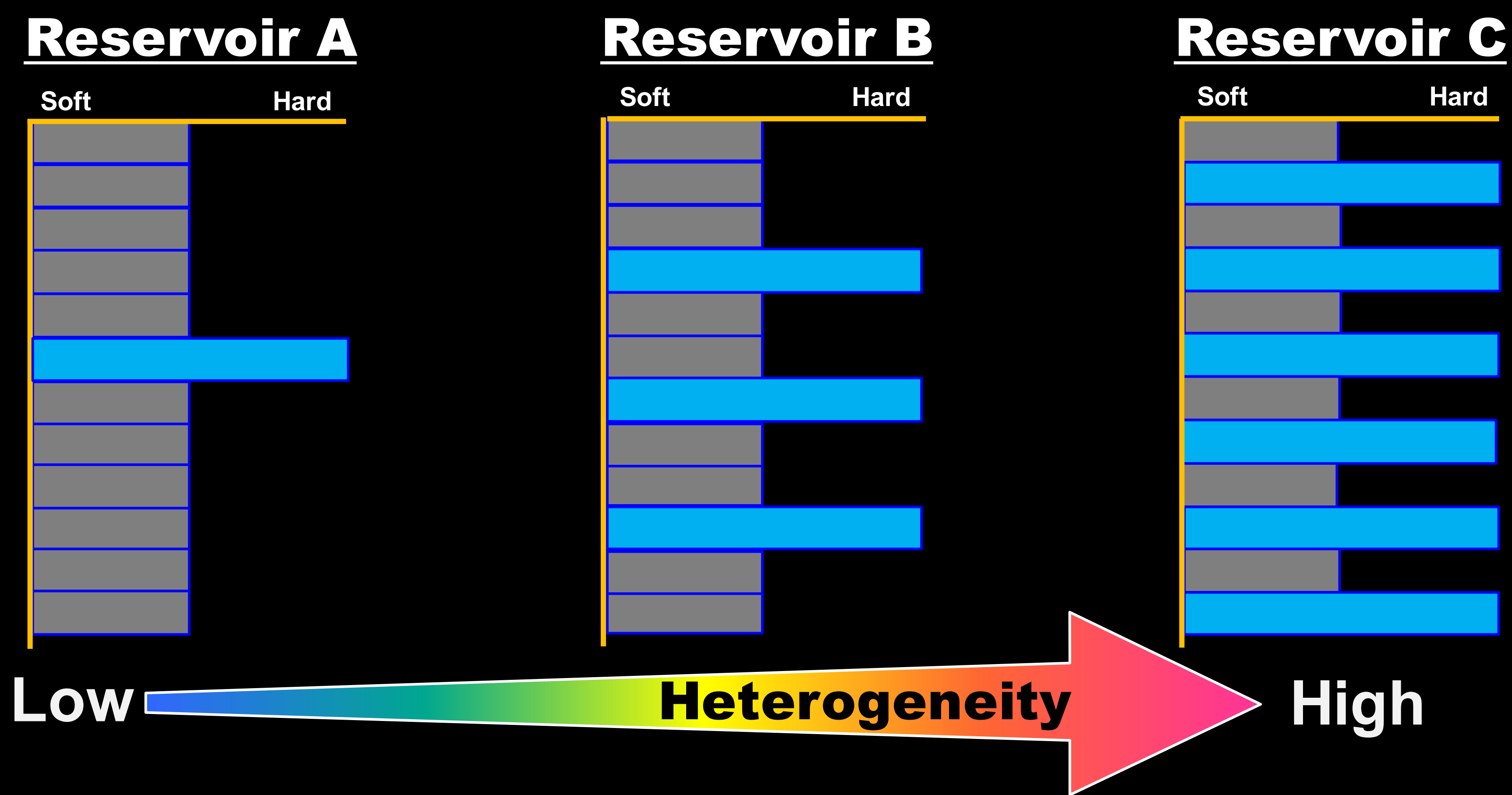
Reservoir Geomechanical Heterogeneity



Reservoir Geomechanical Heterogeneity



Reservoir Geomechanical Heterogeneity Index

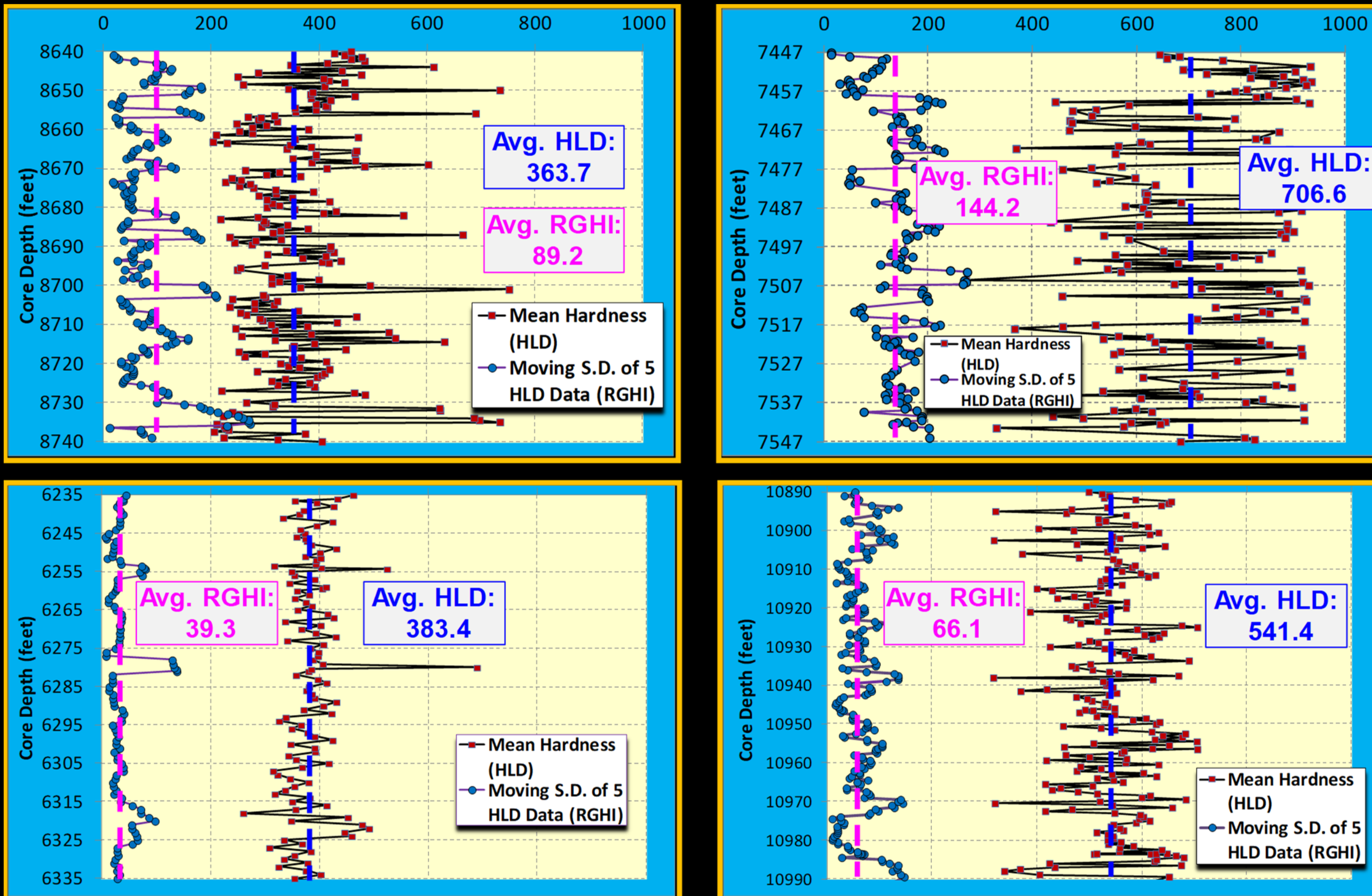


From the observations of core, we know that reservoir heterogeneity varies from formation to formation, which is one of the key parameters controlling hydraulic frac height, but how to quantitatively evaluate it?

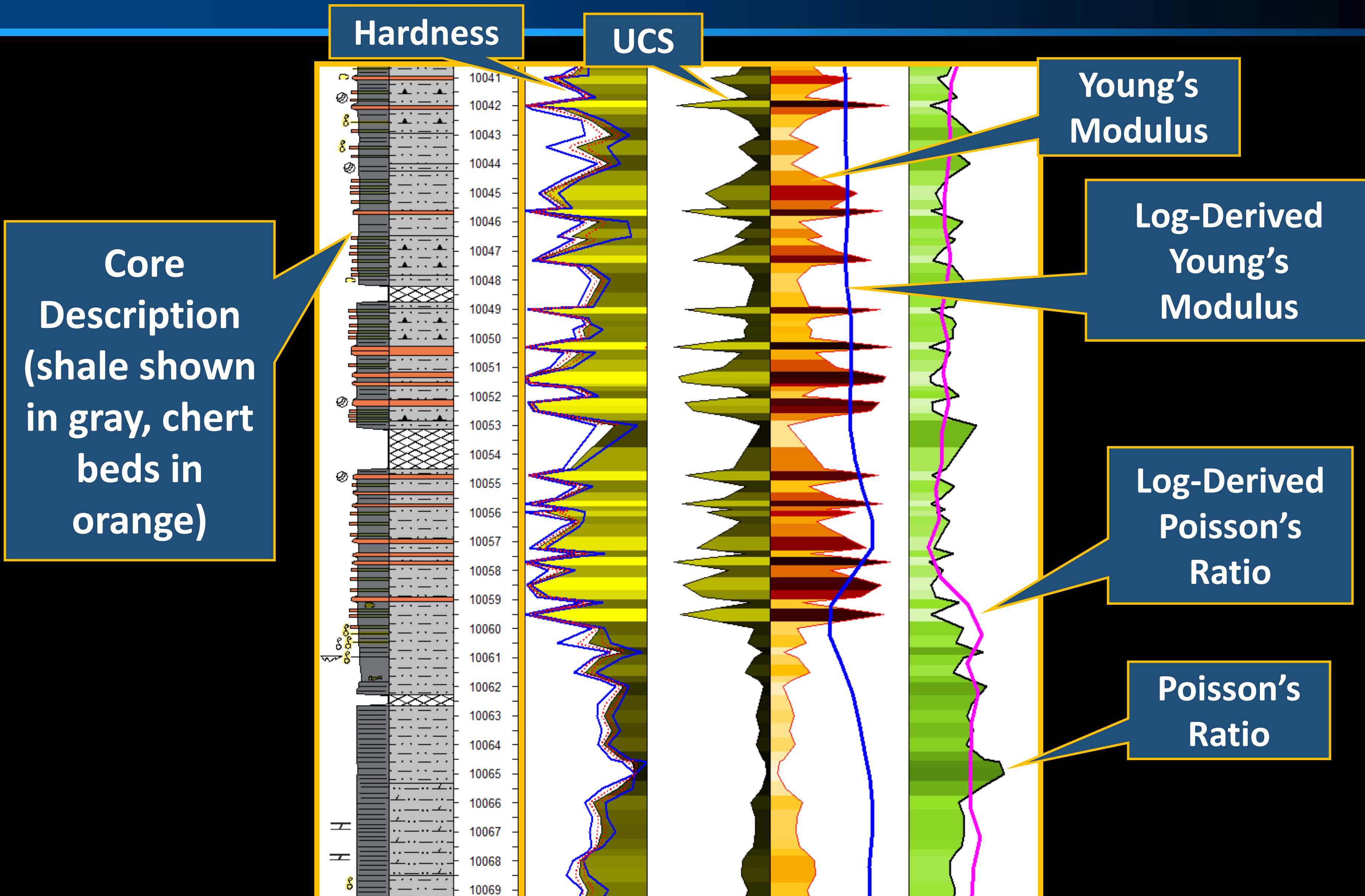
Reservoir Geomechanical Heterogeneity Index

- The mean value of 10 measurements at each depth is calculated.
- The Reservoir Geomechanical Heterogeneity Index (RGHI) is the moving Standard Deviation across 2 vertical feet of the mean values.
- It is essentially a portrayal of the vertical frequency and magnitude of the changes in geomechanical properties of the formation.

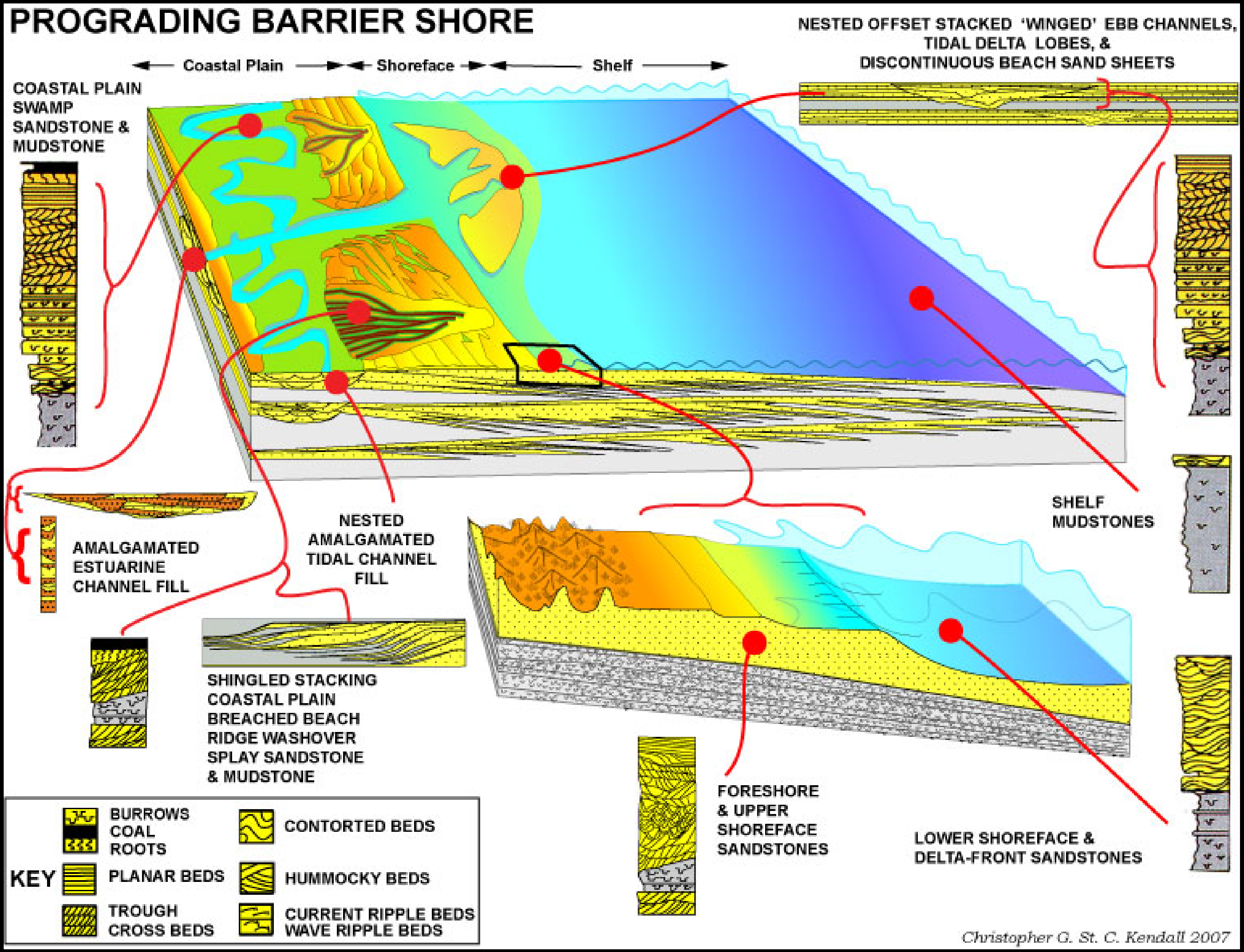
Reservoir Geomechanical Heterogeneity Index



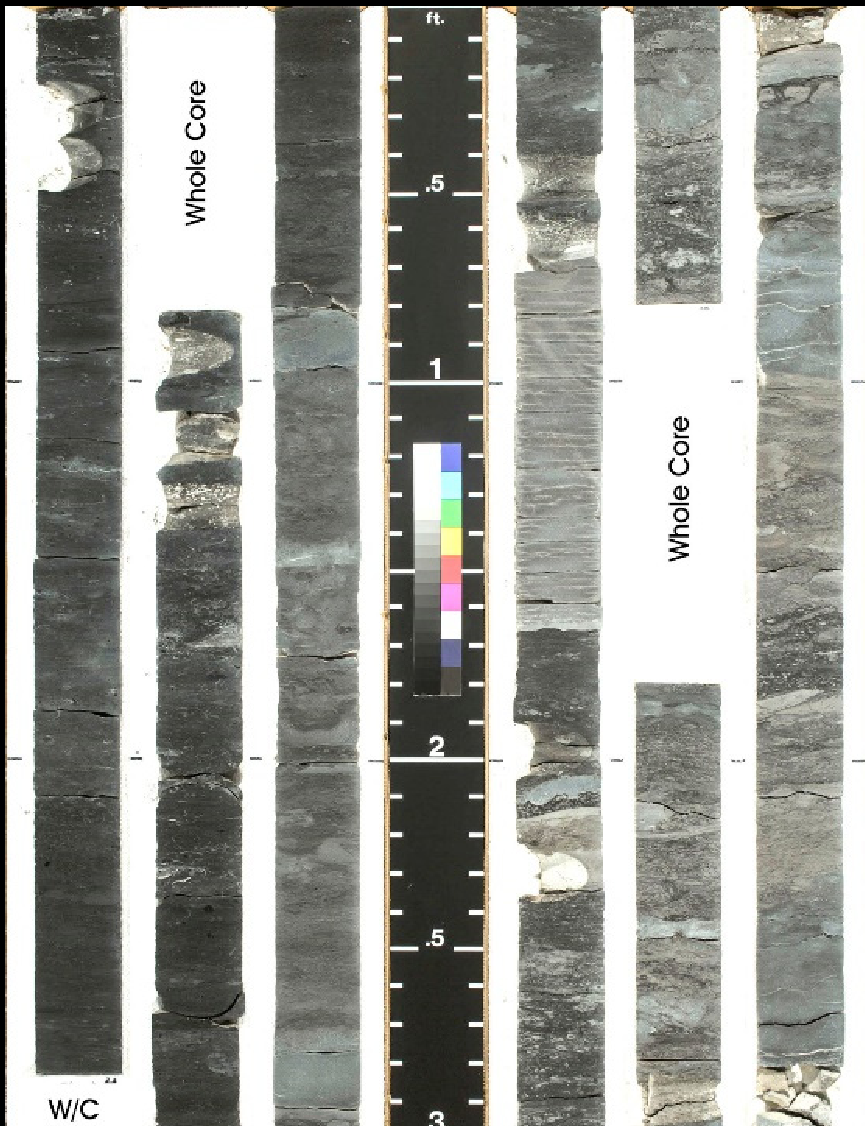
Reservoir Geomechanical Heterogeneity Index

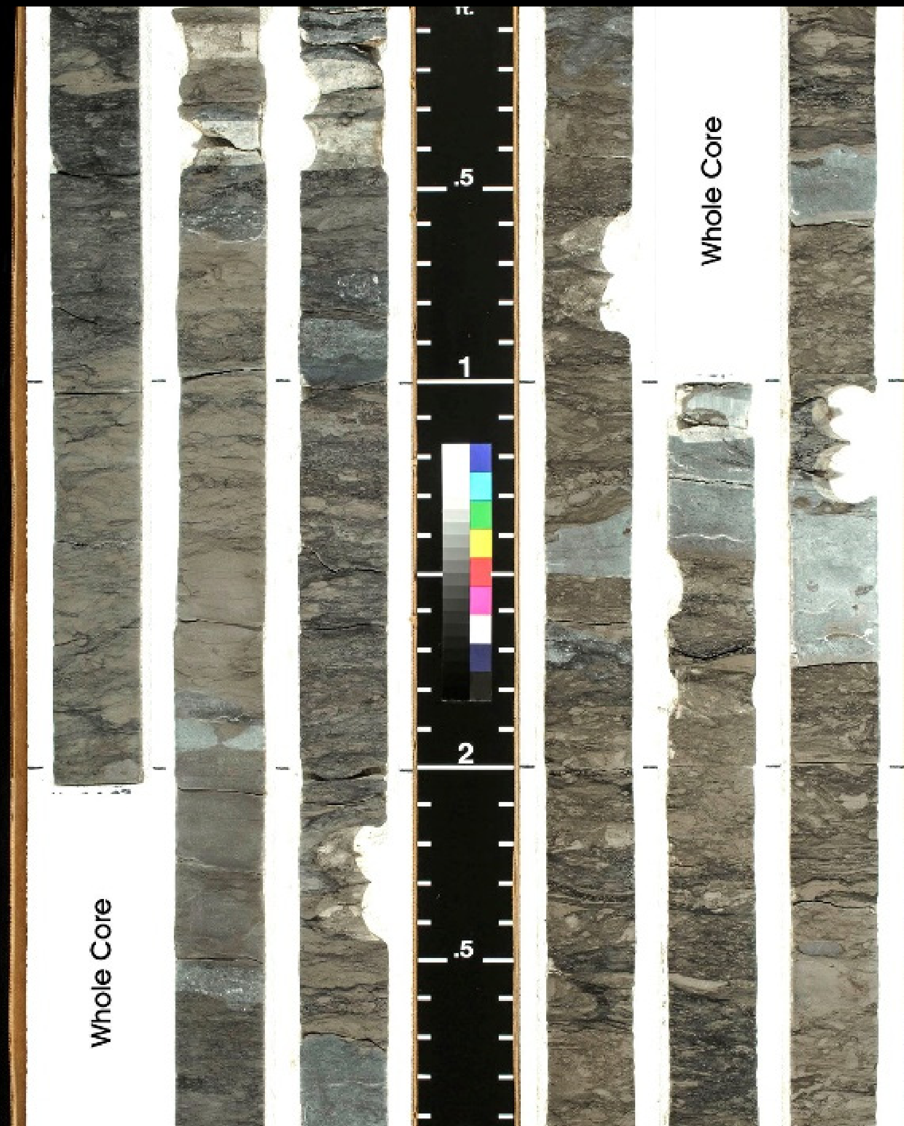


Lower Cotton Valley Geology



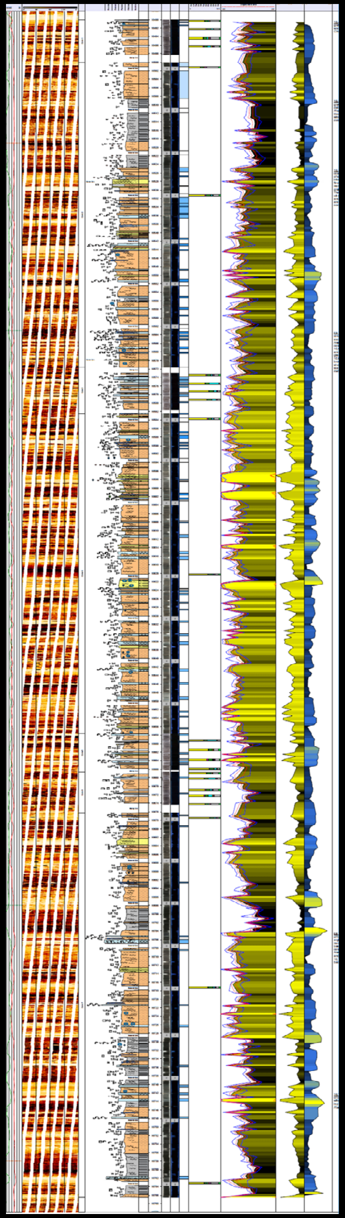
Lower Cotton Valley Geology





Results

Lower
Cotton
Valley Sands

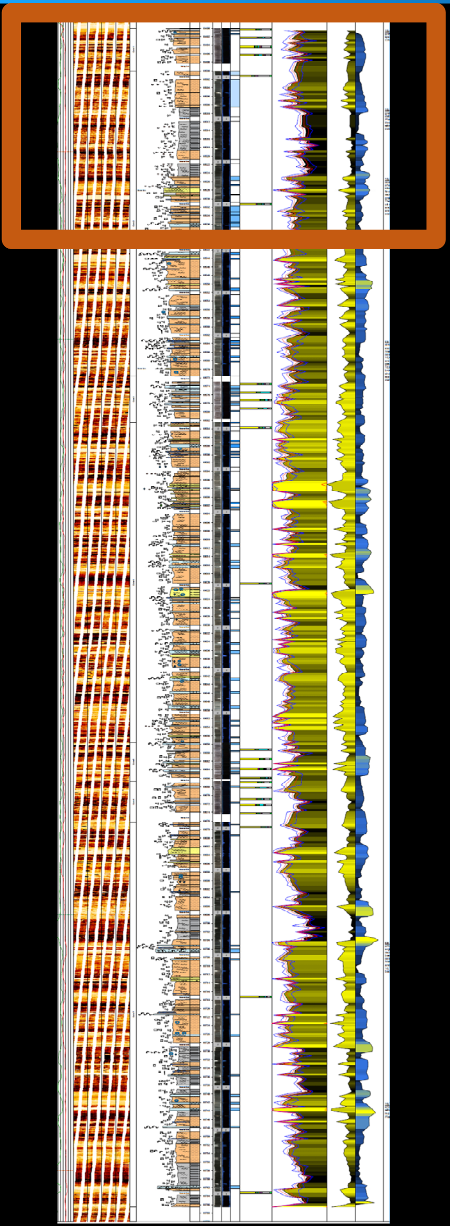


Cored Interval
= 276 Feet

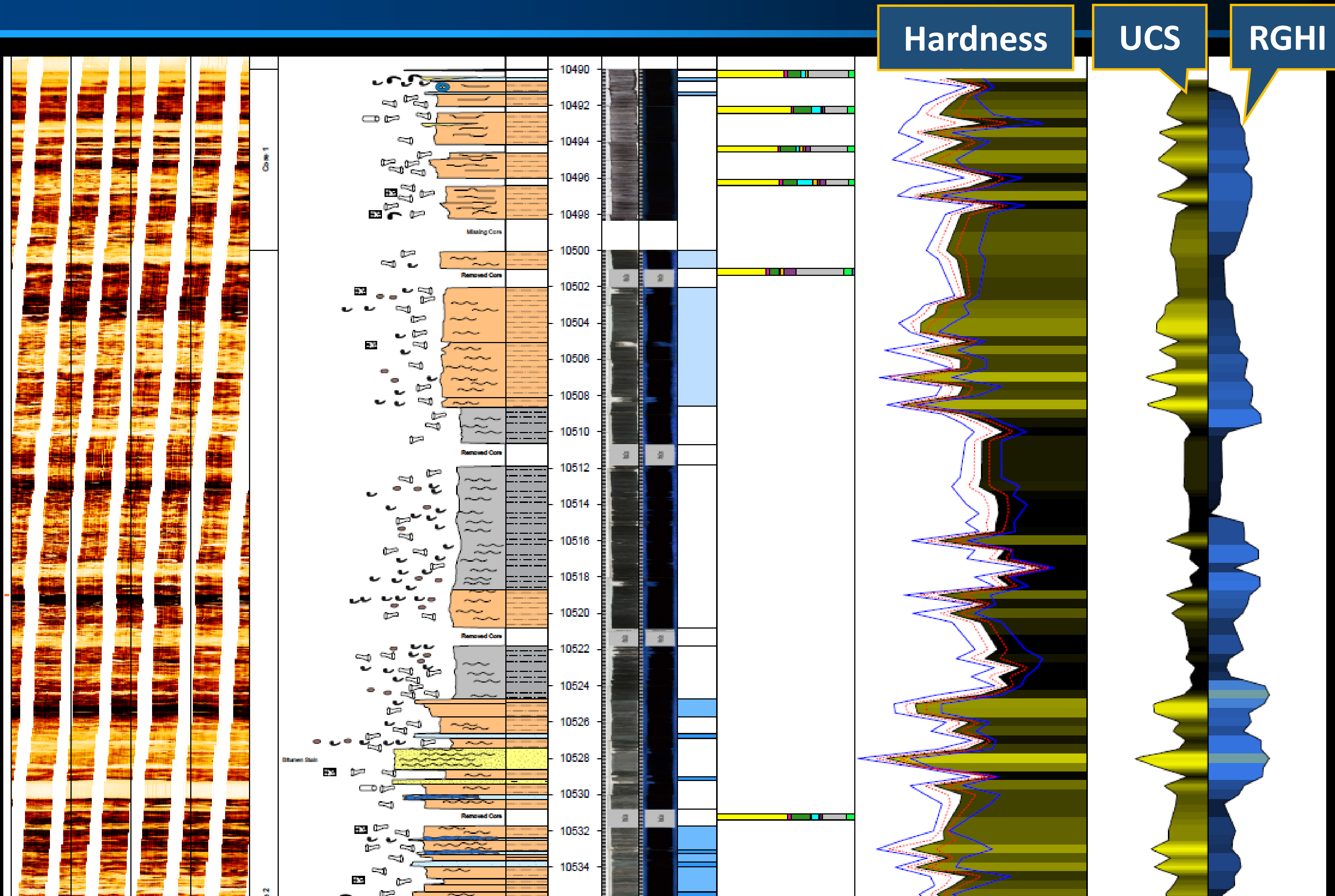
(~ 550 depths, ~ 5500 measurements)

Results

Lower Cotton Valley Sands

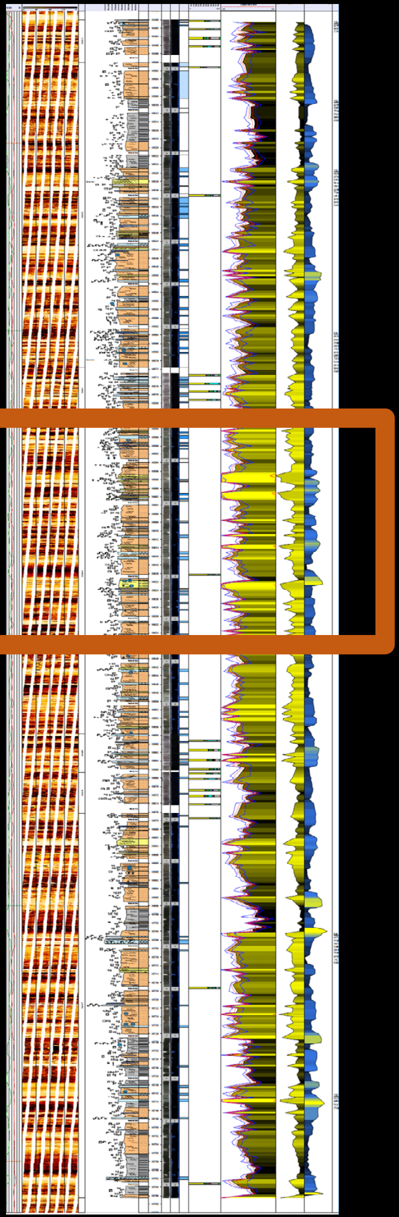


Results

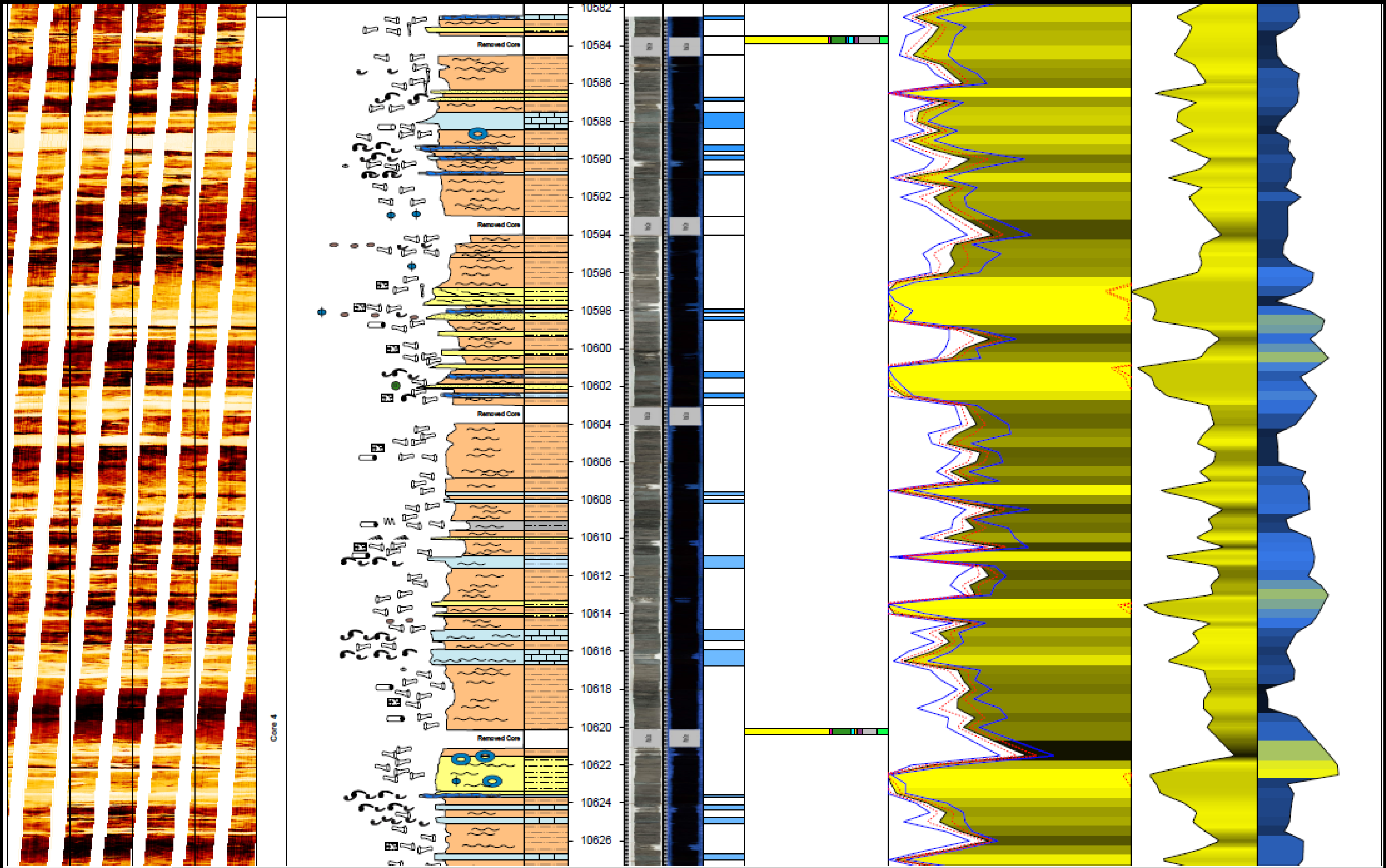

Hardness
UCS
RGHI
10490
10492
10494
10496
10498
Missing Core
10500
Removed Core
10502
10504
10506
10508
10510
Removed Core
10512
10514
10516
10518
10520
Removed Core
10522
10524
10526
10528
Bitumen Stain
10530
Removed Core
10532
10534

Results

Lower Cotton Valley Sands

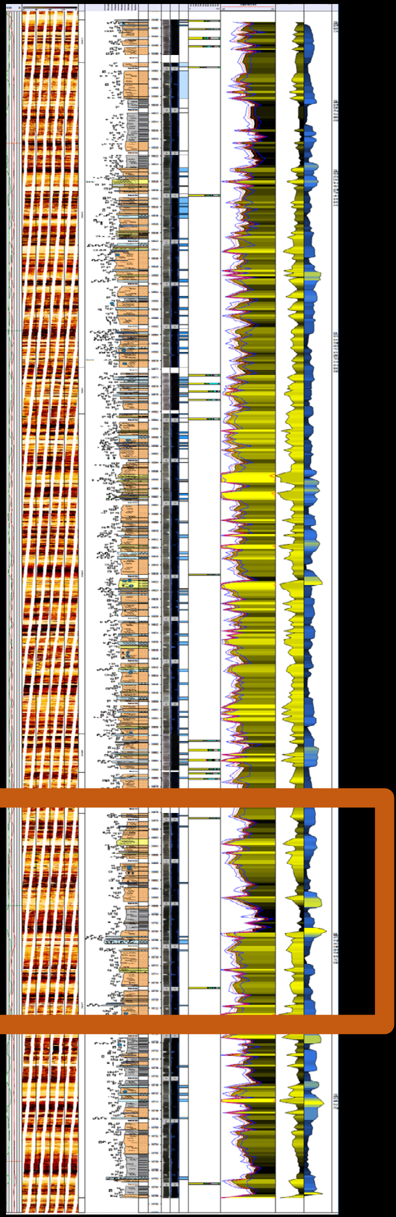


Results

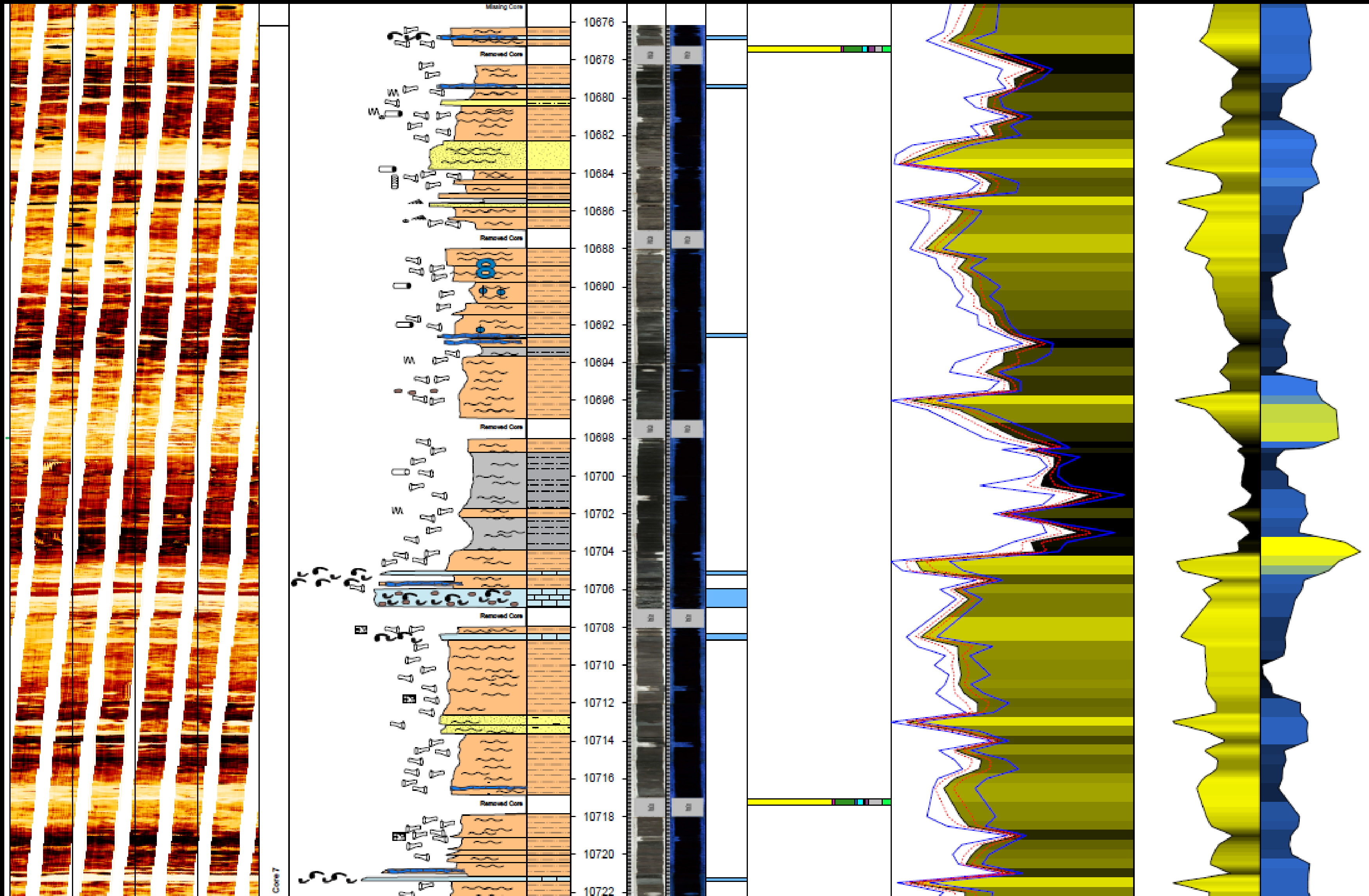

10582
10584
10586
10588
10590
10592
10594
10596
10598
10600
10602
10604
10606
10608
10610
10612
10614
10616
10618
10620
10622
10624
10626
Removed Core
Removed Core
Removed Core
Removed Core
Core 4

Results

Lower Cotton Valley Sands

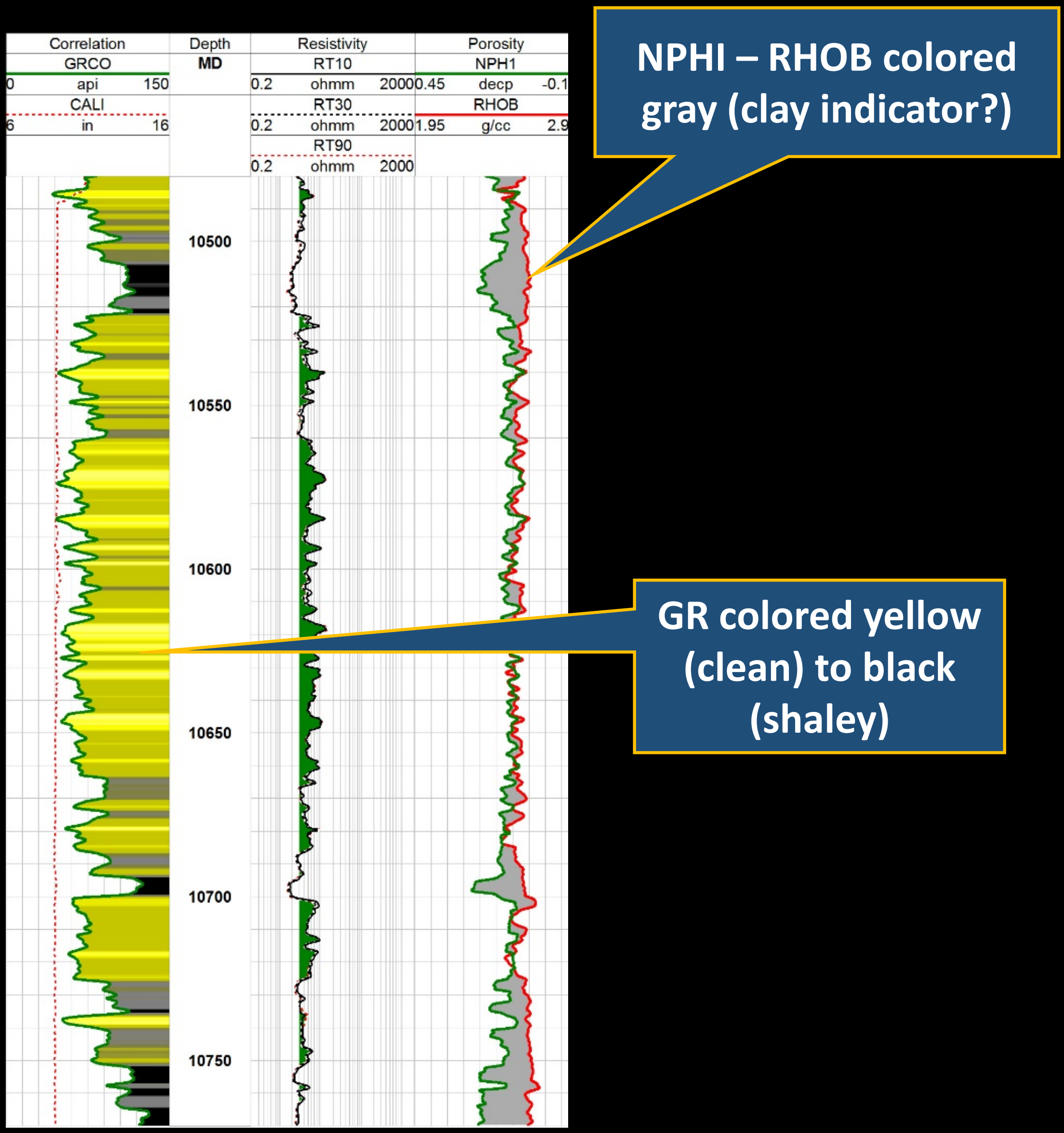


Results

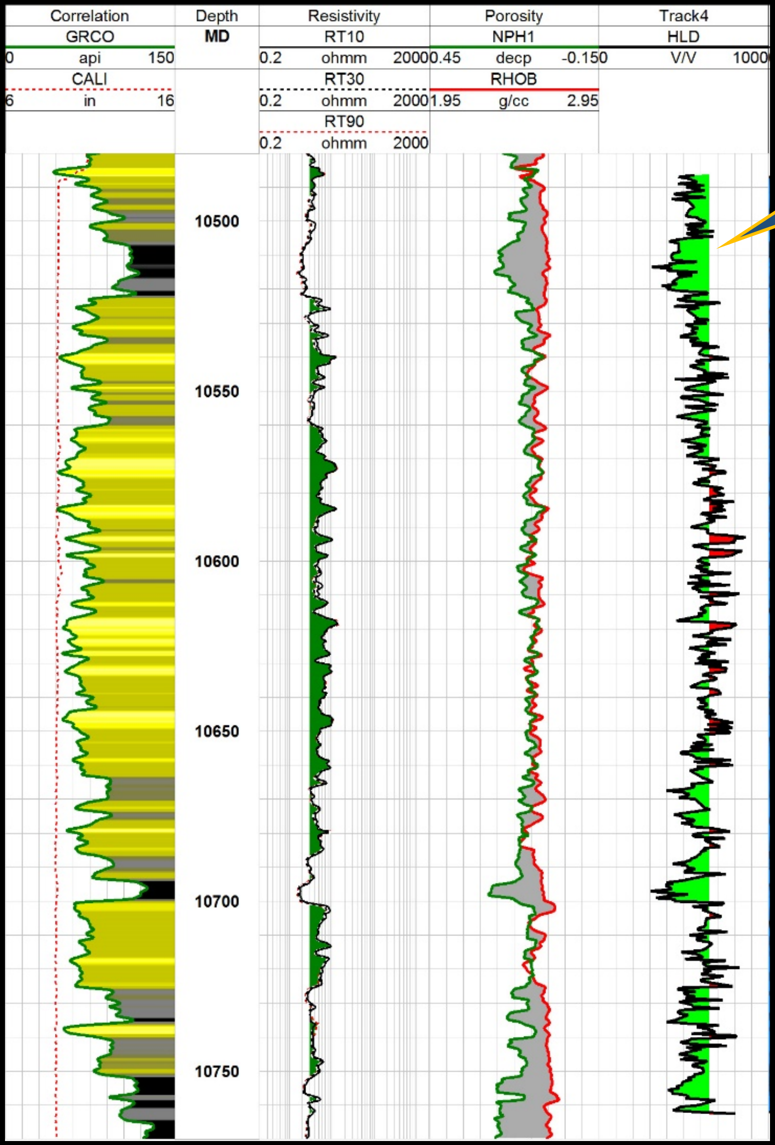


Missing Core
Removed Core
10676
10678
10680
10682
10684
10686
10688
10690
10692
10694
10696
10698
10700
10702
10704
10706
10708
10710
10712
10714
10716
10718
10720
10722
Core 7

Results

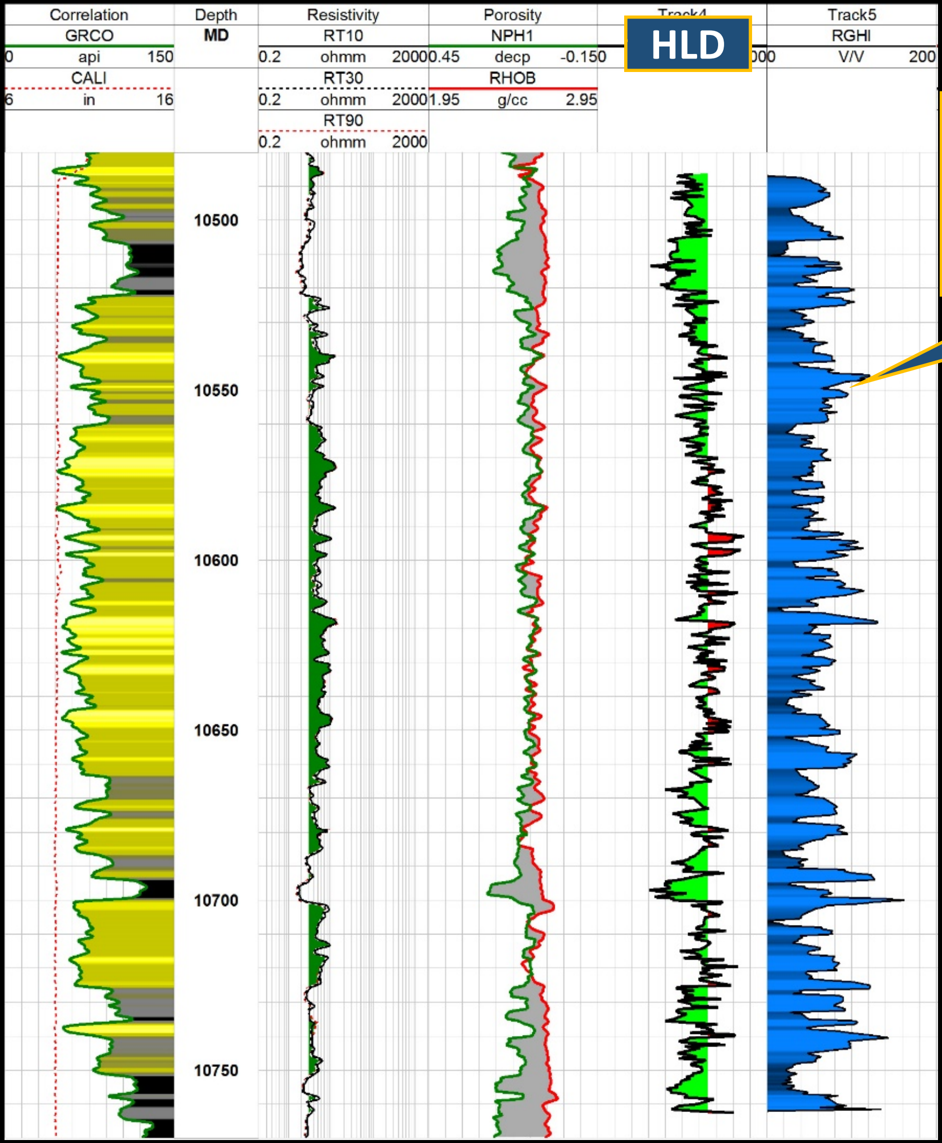

Correlation
GRCO
0 api 150
CALI
6 in 16
Depth
MD
Resistivity
RT10
0.2 ohmm 2000
RT30
0.2 ohmm 2000
RT90
0.2 ohmm 2000
Porosity
NPH1
0.45 decp -0.1
RHOB
1.95 g/cc 2.9
10500
10550
10600
10650
10700
10750
NPHI – RHOB colored gray (clay indicator?)
GR colored yellow (clean) to black (shaley)

Results



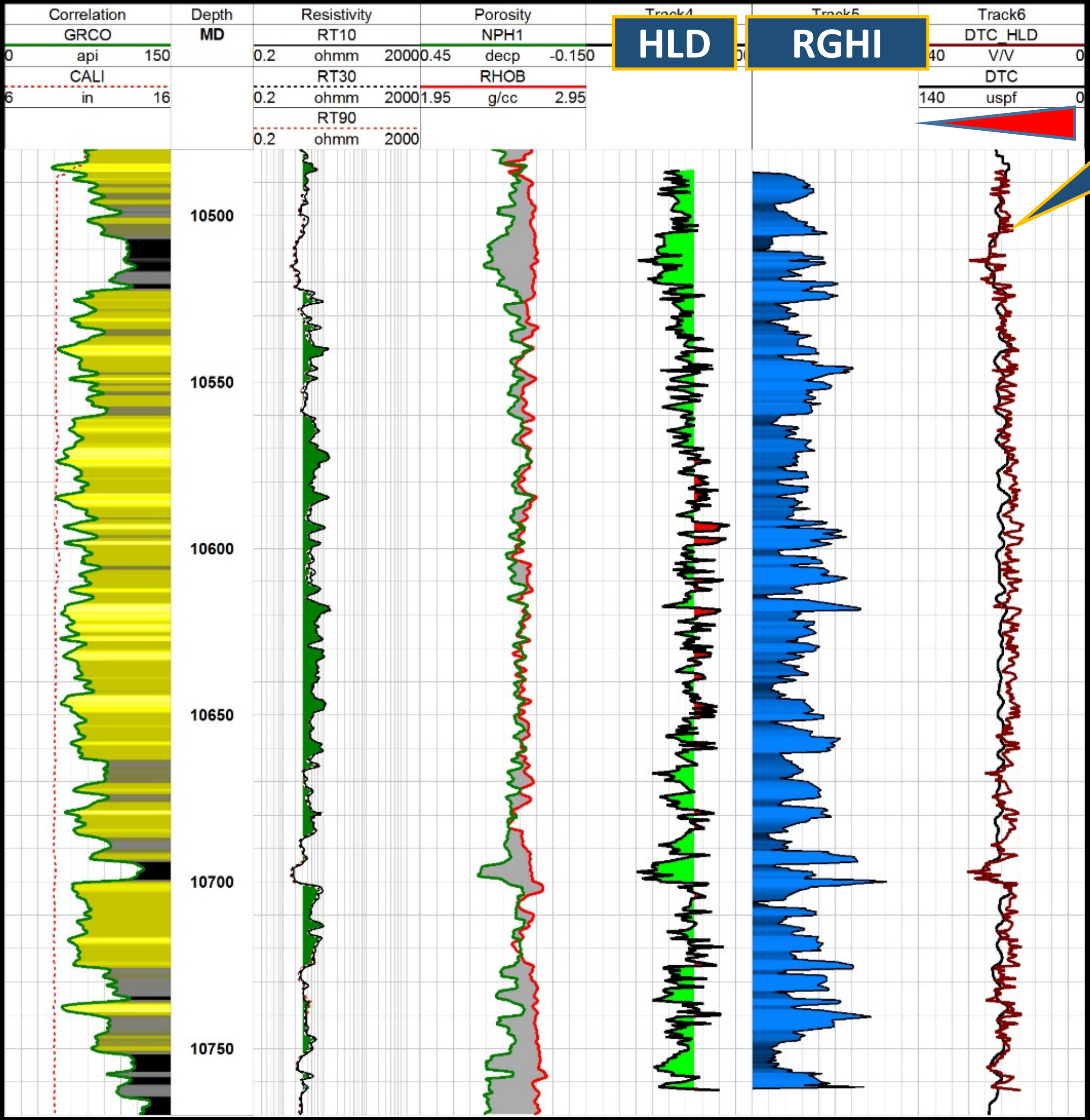
Hardness scaled increasing to the right

Results



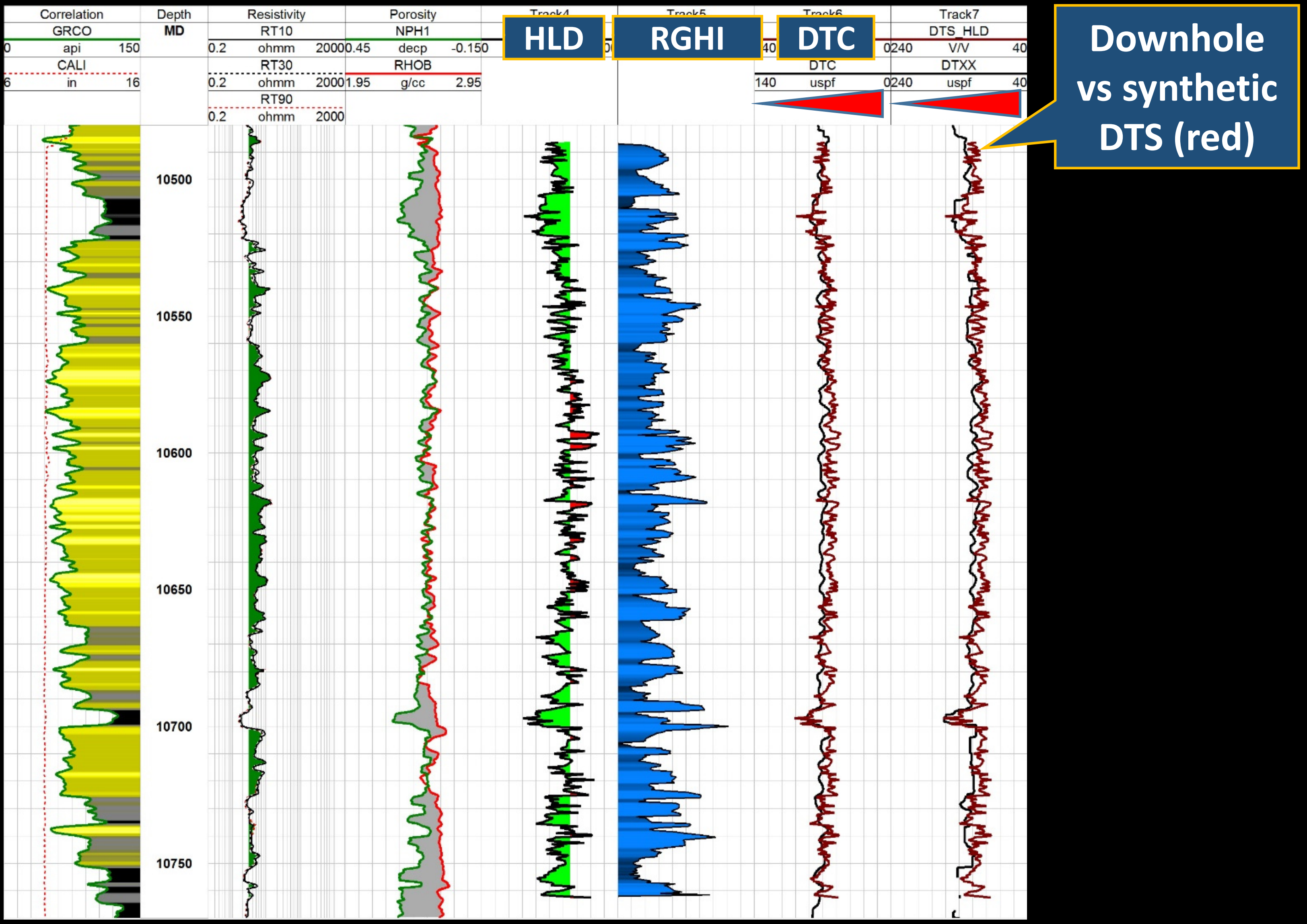
Heterogeneity – higher values flag more heterogeneous zones

Results



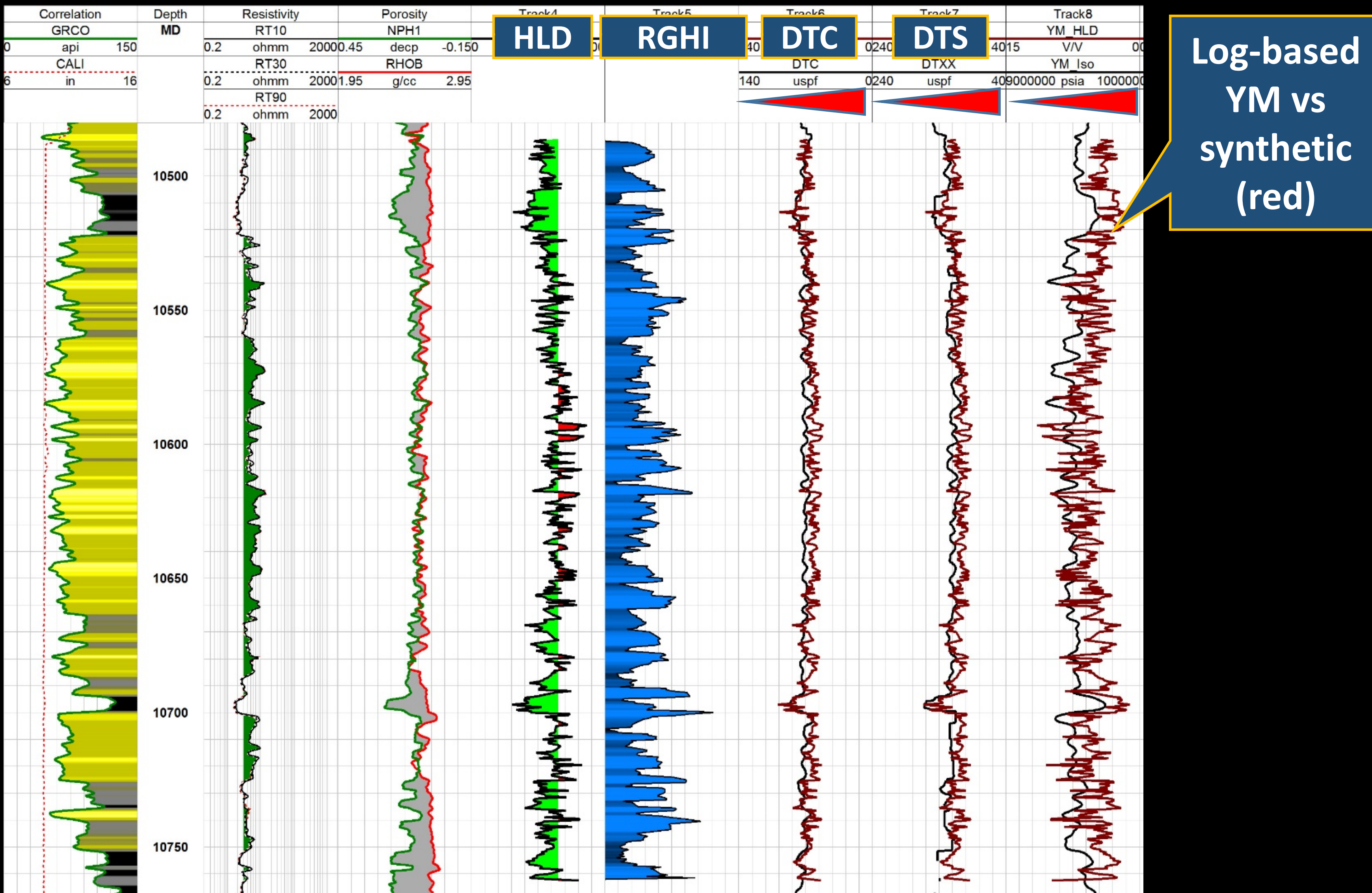
Downhole vs synthetic DTC (red)

Results

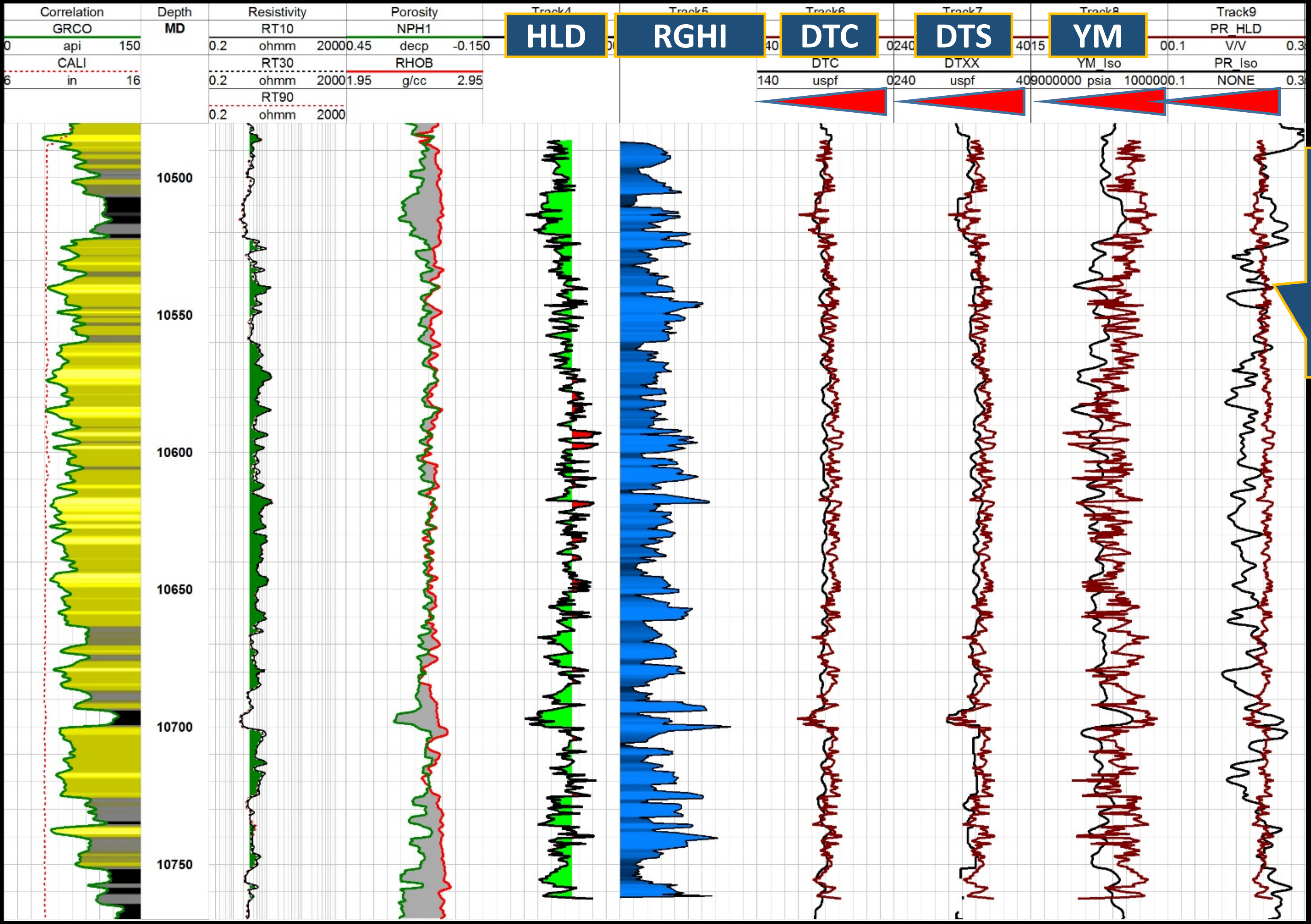


Correlation
GRCO
0 api 150
CALI
6 in 16
Depth
MD
Resistivity
RT10
0.2 ohmm 2000
RT30
0.2 ohmm 2000
RT90
0.2 ohmm 2000
Porosity
NPH1
0.45 decp -0.15
RHOB
1.95 g/cc 2.95
HLD
RGHI
DTC
DTC
140 uspf 40
Track7
DTS_HLD
240 V/V 40
DTXX
240 uspf 40
10500
10550
10600
10650
10700
10750
Downhole vs synthetic DTS (red)

Results


Correlation
GRCO
0 api 150
CALI
6 in 16
Depth
MD
10500
10550
10600
10650
10700
10750
Resistivity
RT10
0.2 ohmm 2000
RT30
0.2 ohmm 2000
RT90
0.2 ohmm 2000
Porosity
NPH1
0.45 decp -0.15
RHOB
1.95 g/cc 2.95
HLD
RGHI
DTC
DTC
140 uspf 40
DTS
DTXX
240 uspf 40
Track8
YM_HLD
V/V
YM_Iso
9000000 psia 1000000
Log-based YM vs synthetic (red)

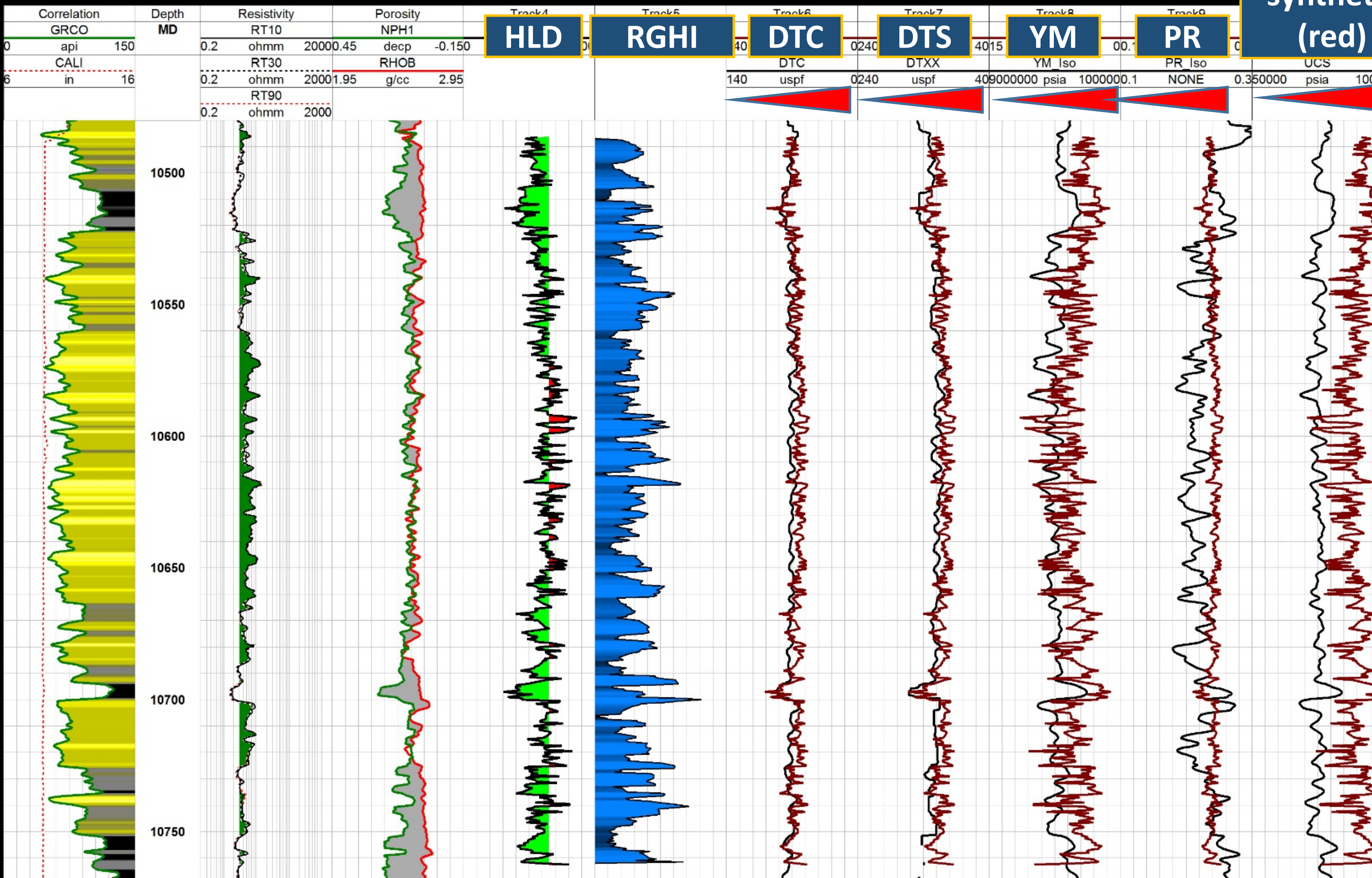
Results



Log-based PR vs synthetic (red)

Results

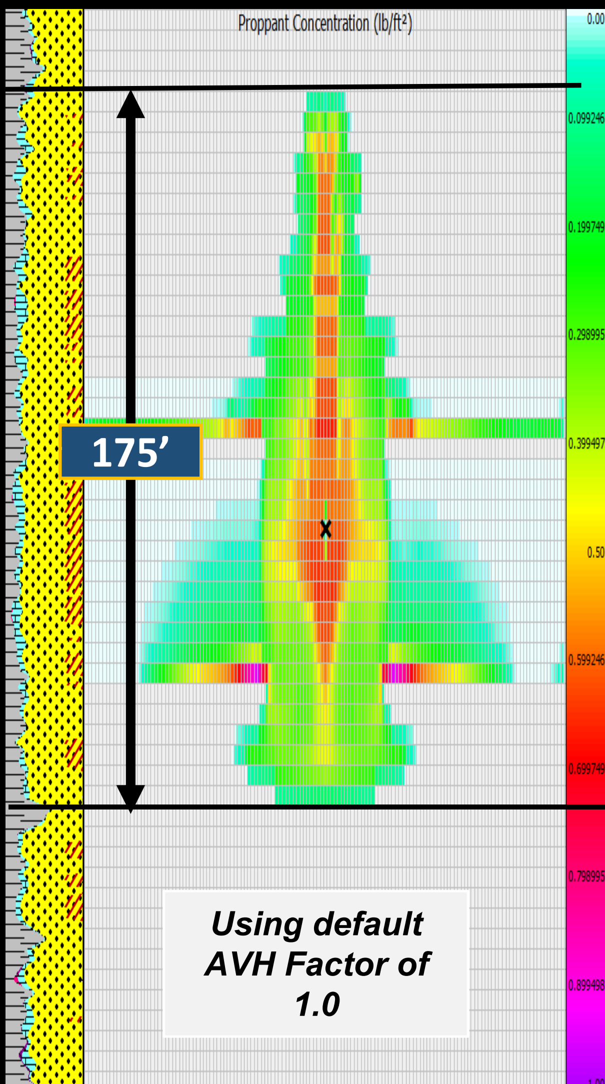
Log-based UCS vs synthetic (red)

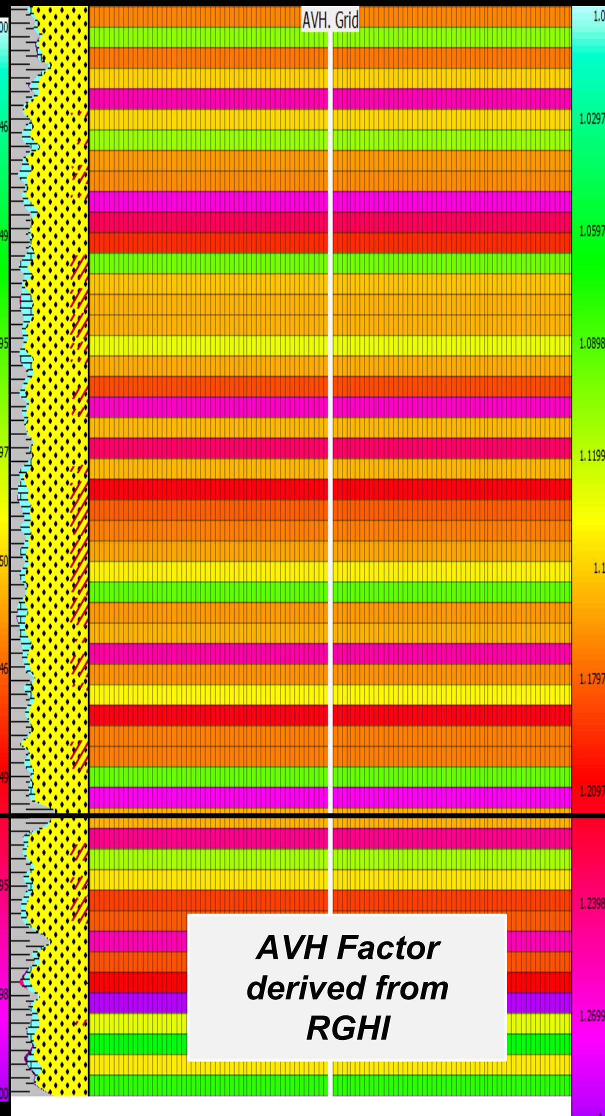


GOHFER® AVH Factor: Vertical to Horizontal Anisotropy

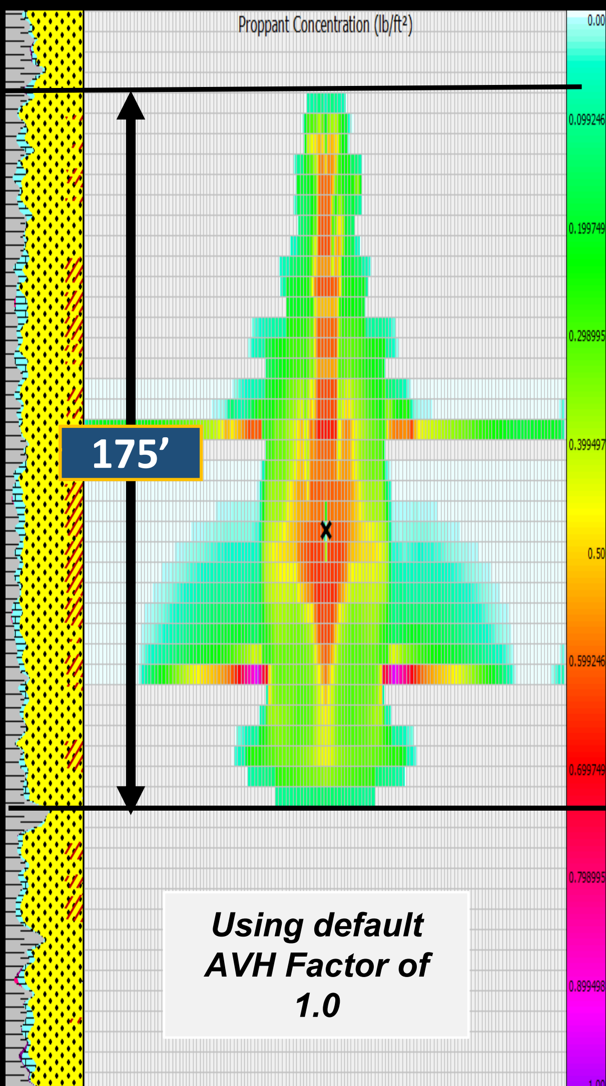
- **The vertical to horizontal (geomechanical) anisotropy (A_{VH}) factor models the impact of laminations and rock mechanical fabric on fracture extension pressure. In a highly laminated system it takes more energy to break vertically across layers than to extend laterally within a rock layer. An A_{VH} factor of 1.2 implies that it will take 20% more energy to extend the fracture vertically than horizontally.**

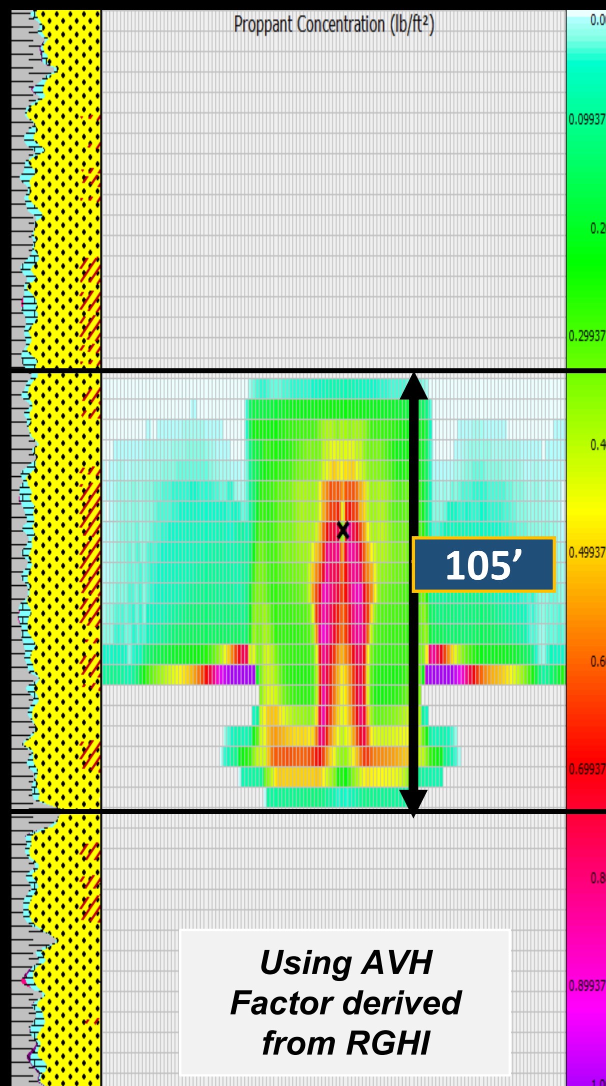
GOHFER Proppant Concentration Profile

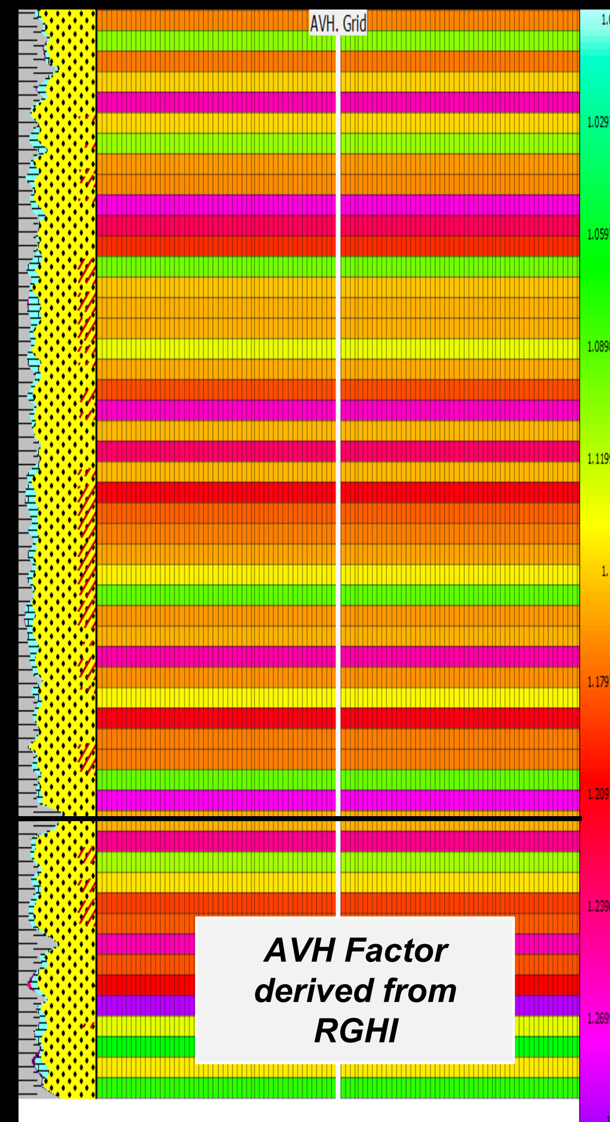




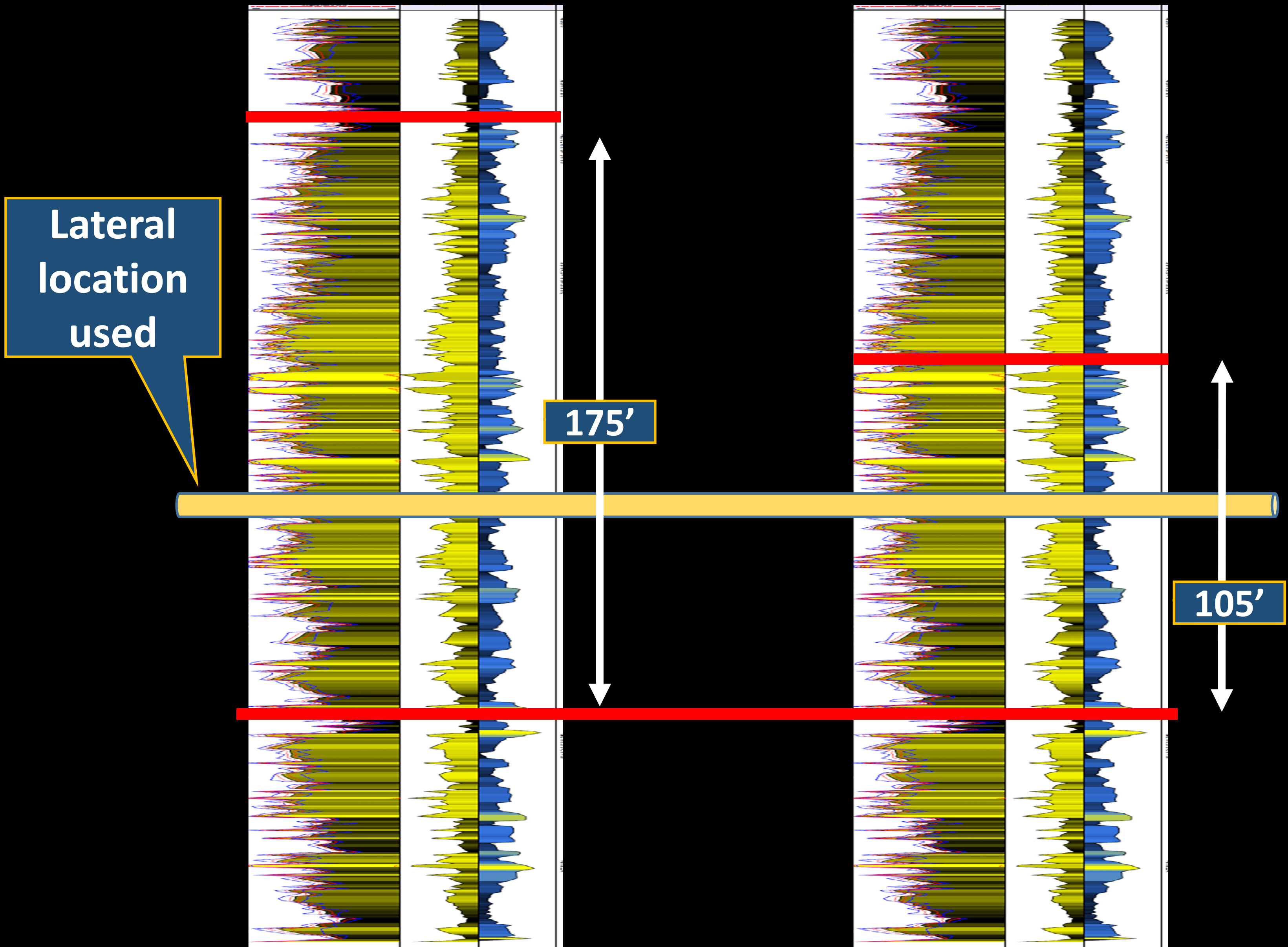
GOHFER® Proppant Concentration Profile





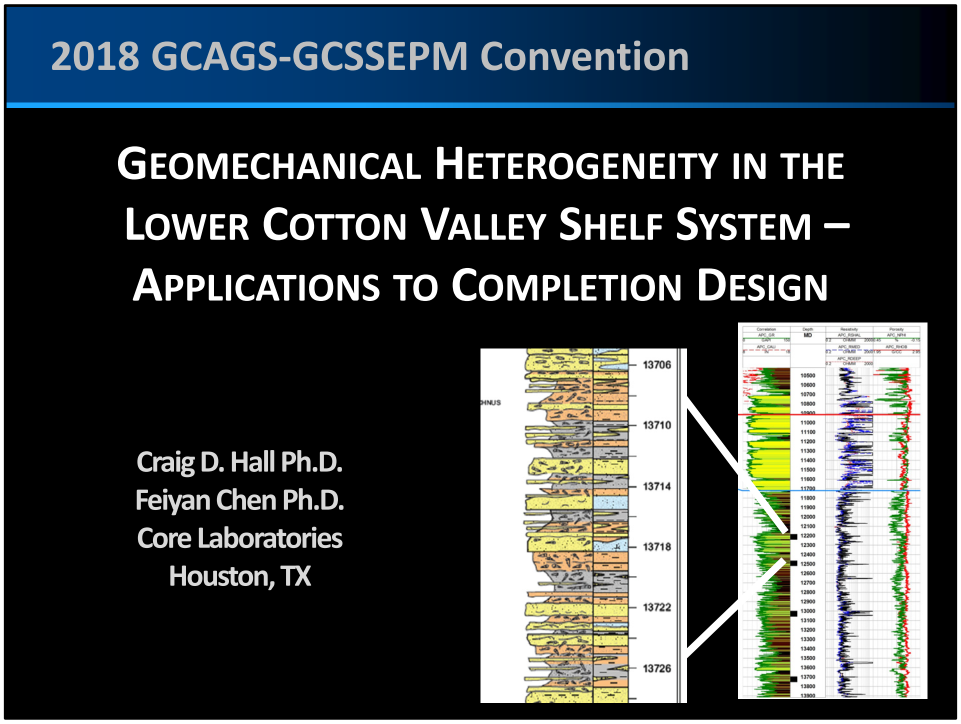


Results



Summary and Conclusions

- High-resolution rock mechanical properties were measured and analyzed across a Lower Cotton Valley, fine-grained sandstone reservoir and used to model frac height growth in GOHFER® software.
- The data document high-frequency geomechanical variations vertically within the reservoir interval.
- The results indicate a decrease in frac height growth from 175 to 105 feet.
- This modeling can be used to test multiple frac design scenarios and landing zone placements to increase the stimulated reservoir volume.



Thin bedded, unconventional reservoirs present us with challenges (mostly specific to unconventionals) that the industry has had to overcome in order to commercially extract hydrocarbons from them. Unconventional reservoirs seldom present us with 30- to 100-foot-thick, homogeneous sandstone and carbonate systems that can be characterized, modeled, and hydraulically stimulated based on data from a few sidewall cores and standard logging suites.

Outline

- Introduction
  - Key Question
  - Methods
  - Reservoir Geomechanical Heterogeniety Index concept
- Lower Cotton Valley Geology
- Results
- Summary and Conclusions

1

Talk structure

Outline

I would like to thank my employer - Core Laboratories, and Range Resources for allowing me to present this work to you today.

2

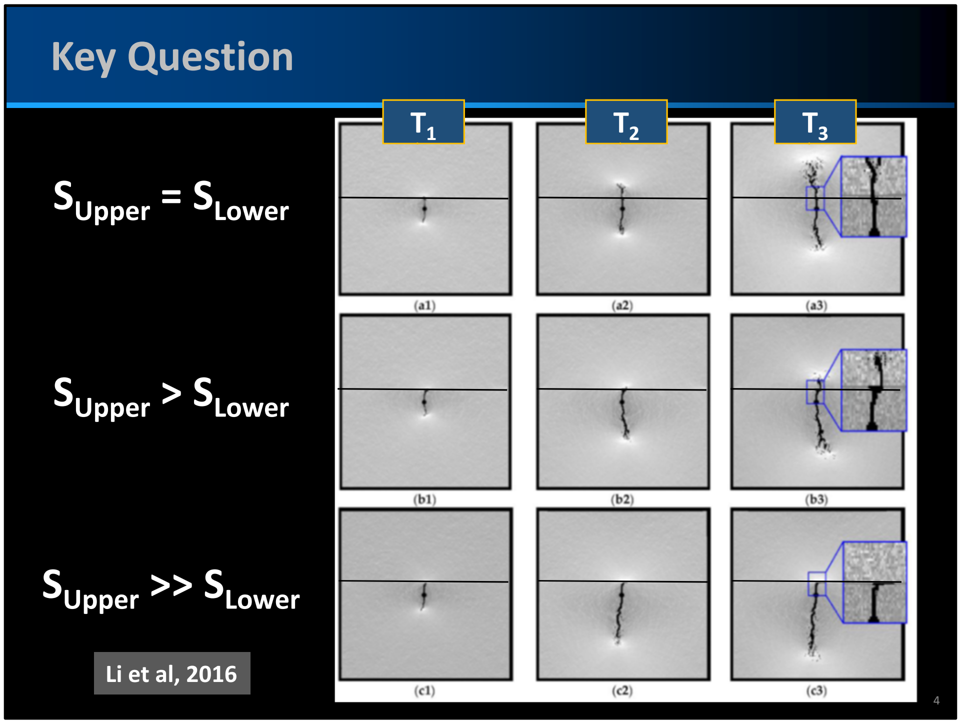
Talk structure

Key Question

- **What impact do vertical changes in rock mechanical properties (the mechanical stratigraphy) have on frac height growth?**

3

The key question we're asking here bears on efficiently creating the maximum, commercial, stimulated reservoir volume.



Mathematical modeling done by Li etal (2016) suggest that increasing contrast in bed strength across an interface can impede or attenuate upward fracture propagation.

Key Question

- Some thinly bedded reservoirs exhibit significant bed-scale changes in rock mechanical properties.
- Downhole sonic tools have limited ability to resolve bed-scale changes in rock mechanical properties.
- How can we economically and accurately determine the sub-sonic log-scale mechanical stratigraphy of these formations and account for them in a frac design simulator?

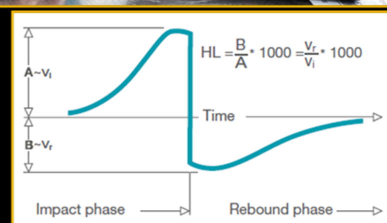
5

Fine-scale changes in rock mechanical properties can affect frac height growth. Frac design simulators rely on inputs from downhole sonic logs and benchtop rock mechanics data. However, downhole sonic logs may not be able to resolve mechanical stratigraphy we sometimes see in unconventional reservoirs that could be measured in inches.

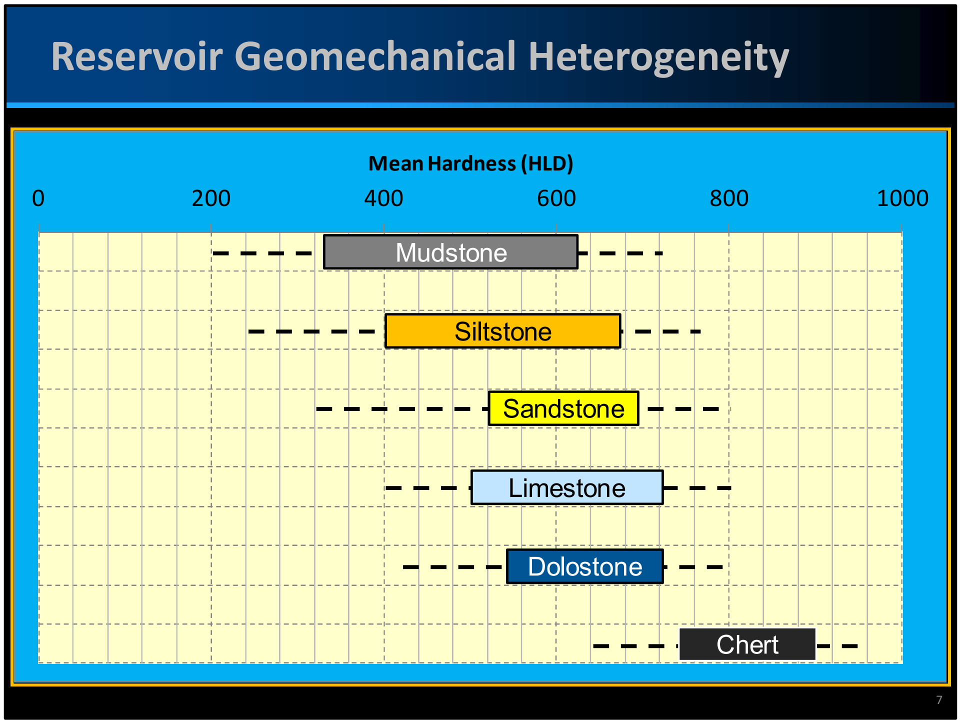
Methods

- **Procedure based on that developed by Dietmar Leeb (1978) essentially determining elasticity.**
- **Fast, non-destructive brittleness profile based on ratio of impact to rebound velocity of a magnetic “hammer”.**
- **Half-foot spacing.**
- **Average of ten (10) measurements at each depth.**
- **Hardness reported as H_{LD} for Leeb Hardness – Impact Device type D.**

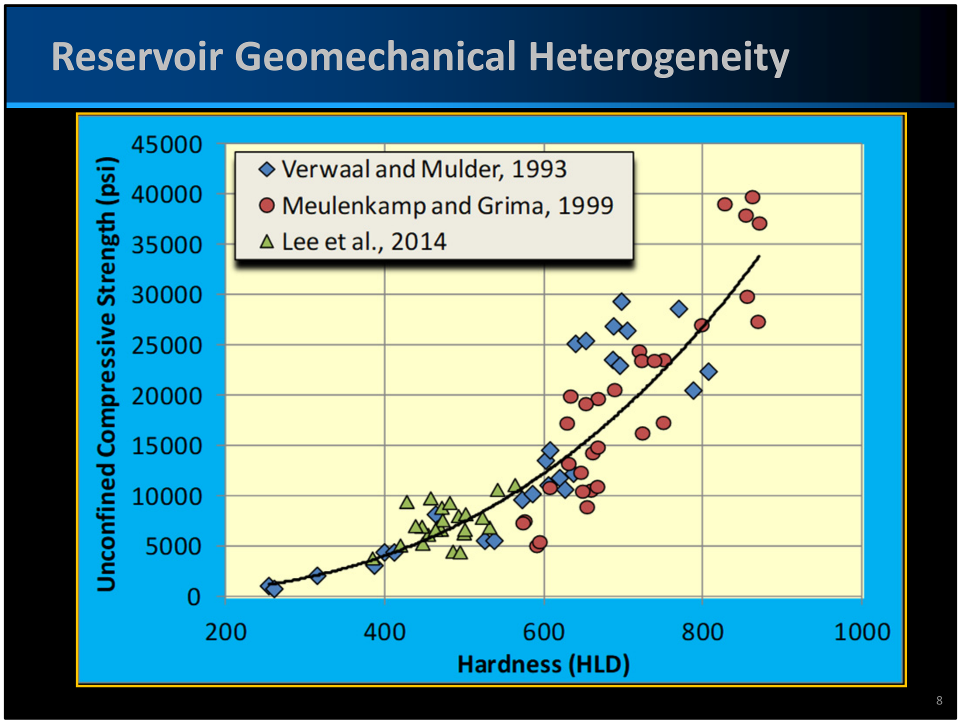
Equotip 550 Leeb



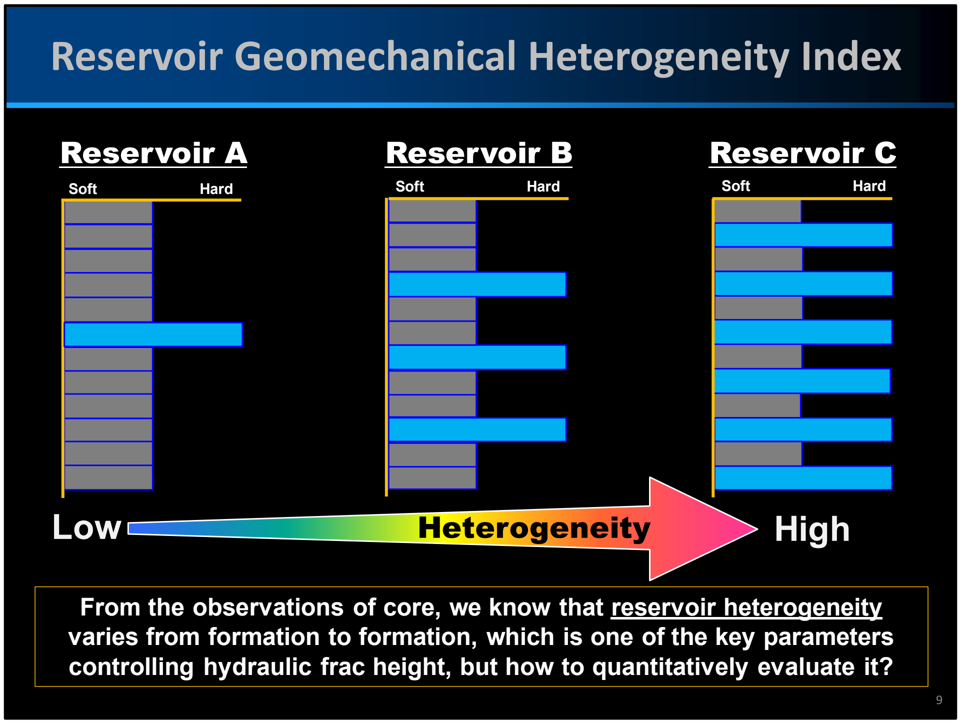
For several decades there have been several papers published on using hardness testing equipment to measure formation rigidity on conventional core, and develop a mechanical profile of a reservoir. I think it’s time we utilized this technology. I wanted to try this approach on the tight sands of the Lower Cotton Valley and model the impact (no pun intended) on frac height growth with and without the high resolution profile generated by this approach.



Based on hardness testing of various formations and lithologies in our various studies we've found similar ranges for most rock types. Within shales and detrital-quartz-rich lithologies hardness is a function of initial composition and burial history. Chert is the standout. Chert derived from biogenic quartz appears to be very effective at "hardening" a formation.



Published data on the relationship between hardness and unconfined compressive strength. We've found a good correlation between UCS determined from multi-stress triaxial testing and hardness measured on the same sample.



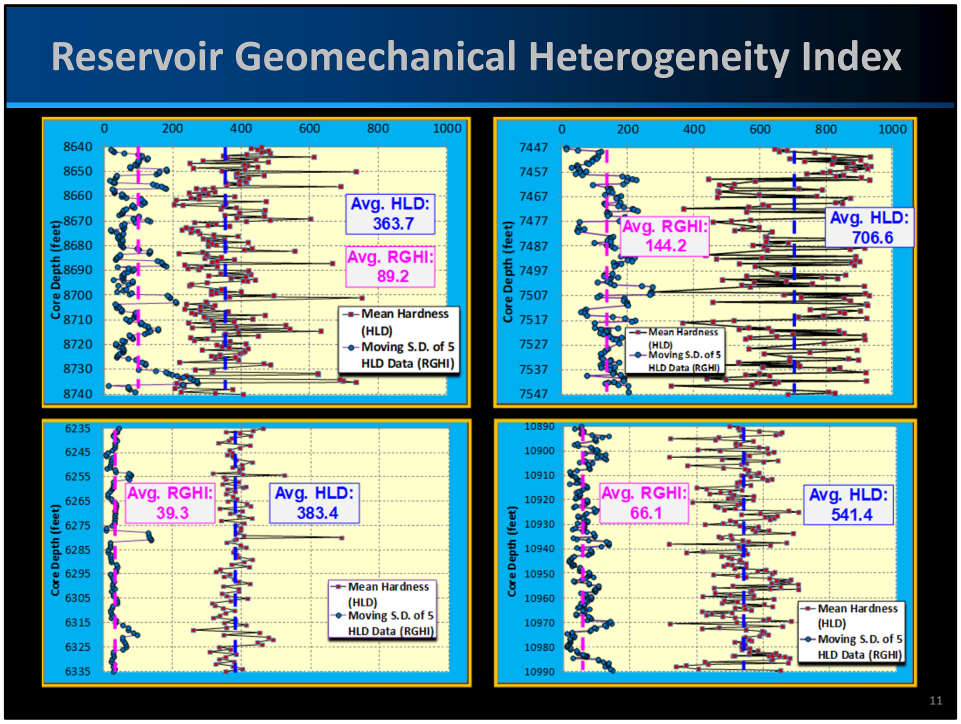
Vertical, geomechanical heterogeneity, or mechanical stratigraphy, is a function of interbedded lithologies of different geomechanical properties commonly related to the parameters of Young's Modulus and Poisson's Ratio. The frequency and magnitude of these vertical changes in mechanical properties is expressed as the Reservoir Geomechanical Heterogeneity Index.

Reservoir Geomechanical Heterogeneity Index

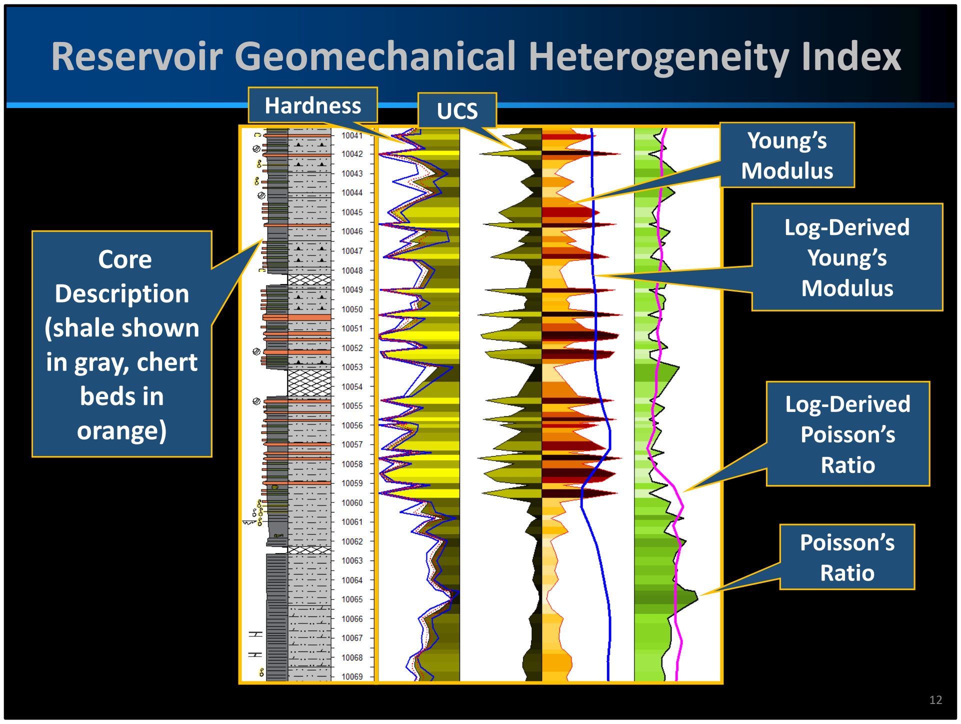
- **The mean value of 10 measurements at each depth is calculated.**
- **The Reservoir Geomechanical Heterogeneity Index (RGHI) is the moving Standard Deviation across 2 vertical feet of the mean values.**
- **It is essentially a portrayal of the vertical frequency and magnitude of the changes in geomechanical properties of the formation.**

10

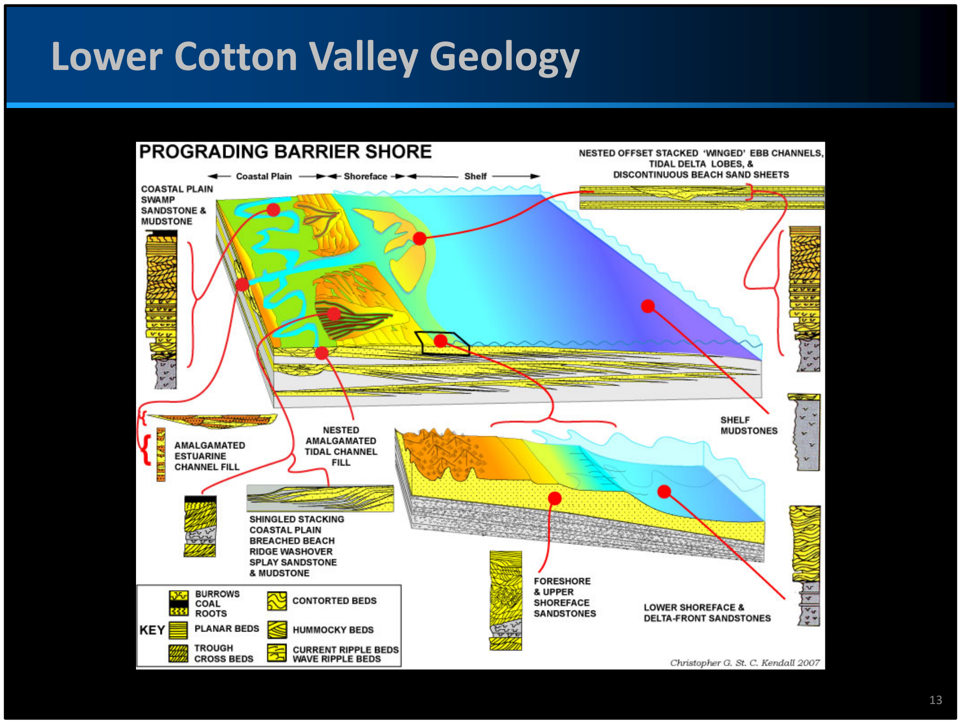
Calculation of the RGHI is a means to create a numerical proxy for the frequency and magnitude of the changes in geomechanical properties that can then be loaded into frac design simulators.



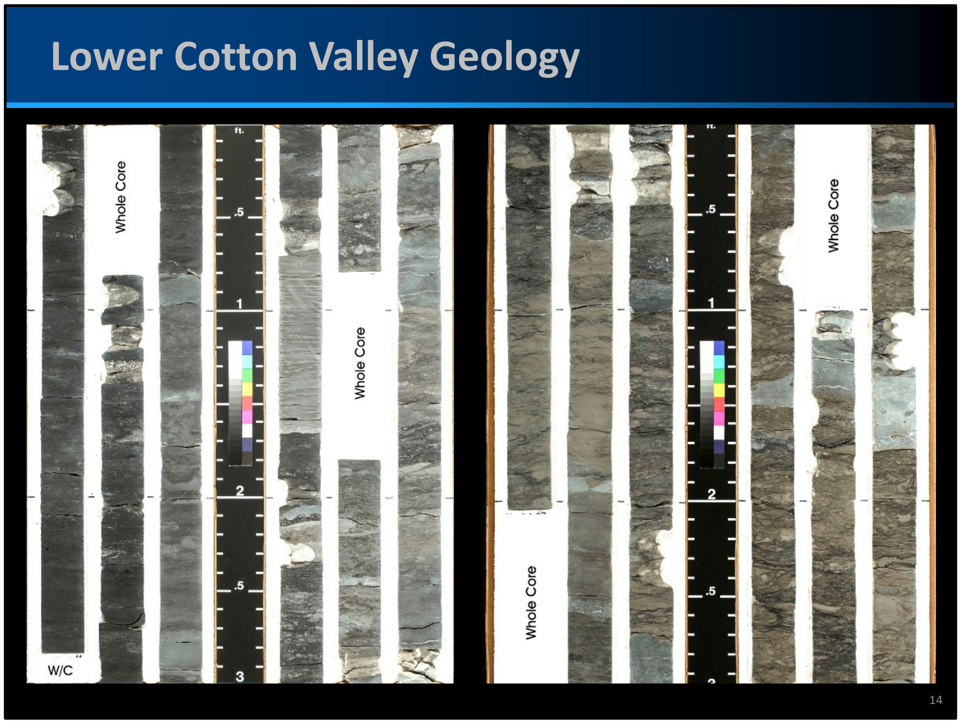
Results from various formations. Note in the two examples on the left that even though the two formations have similar average hardness, their geomechanical heterogeneity is very different. The Oklahoma Woodford is in the upper right. The average hardness is much higher than in the formation in the upper left, and it is the more heterogeneous by virtue of the thinly interbedded cherts and shales.



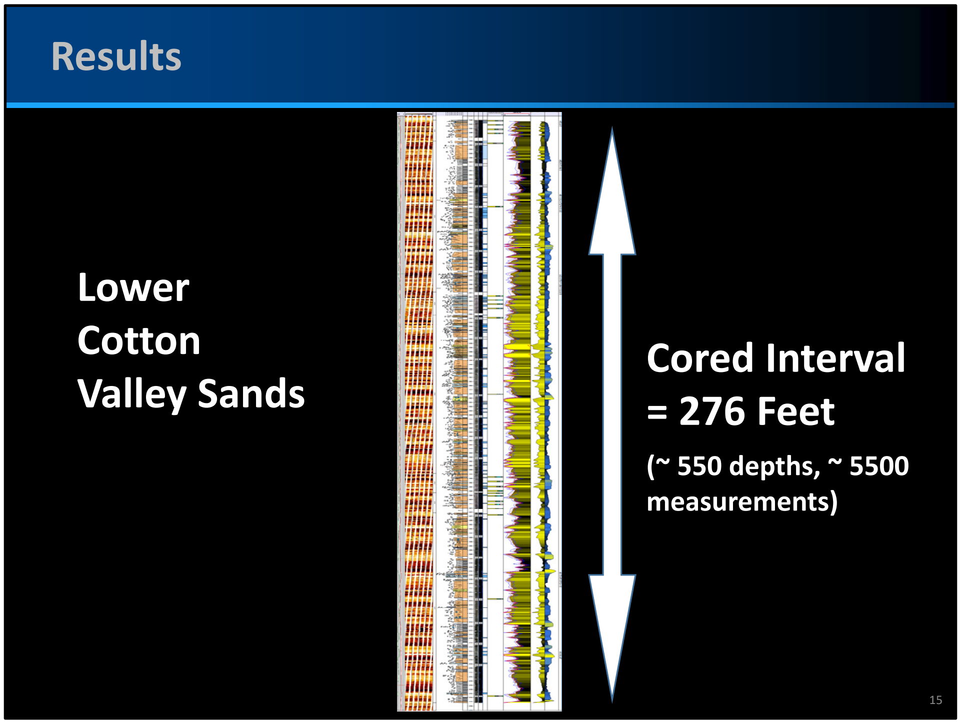
An example from the Woodford illustrating the very serrate pattern of the hardness curve due to the interbedded, dense cherts shown in orange in the core description. Using an algorithm developed by measuring the hardness of the samples used for rock mechanics testing we have calculated the UCS, Young's Modulus and Poisson's Ratio curves, and have displayed them with the downhole curves.



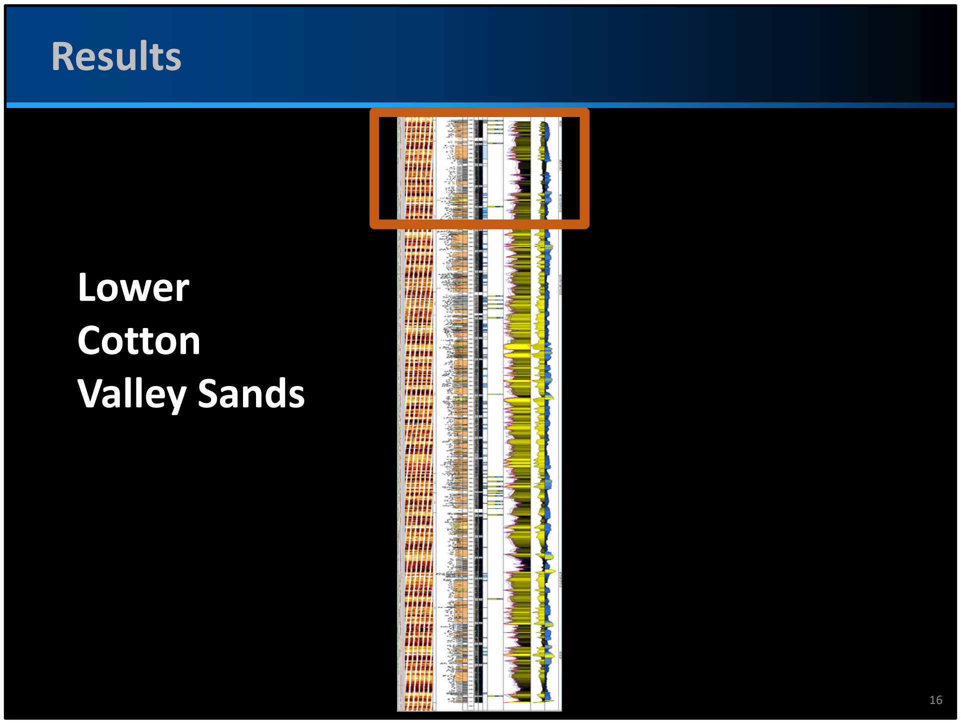
The Lower Cotton Valley reservoirs were deposited as extensive sheets of locally argillaceous, very fine-grained sandstone with thinly interbedded silty shales. Abundant pelecypod shell debris provided calcite cement that frequently lithifies specific zones and impacts the mechanical properties at a bed scale.



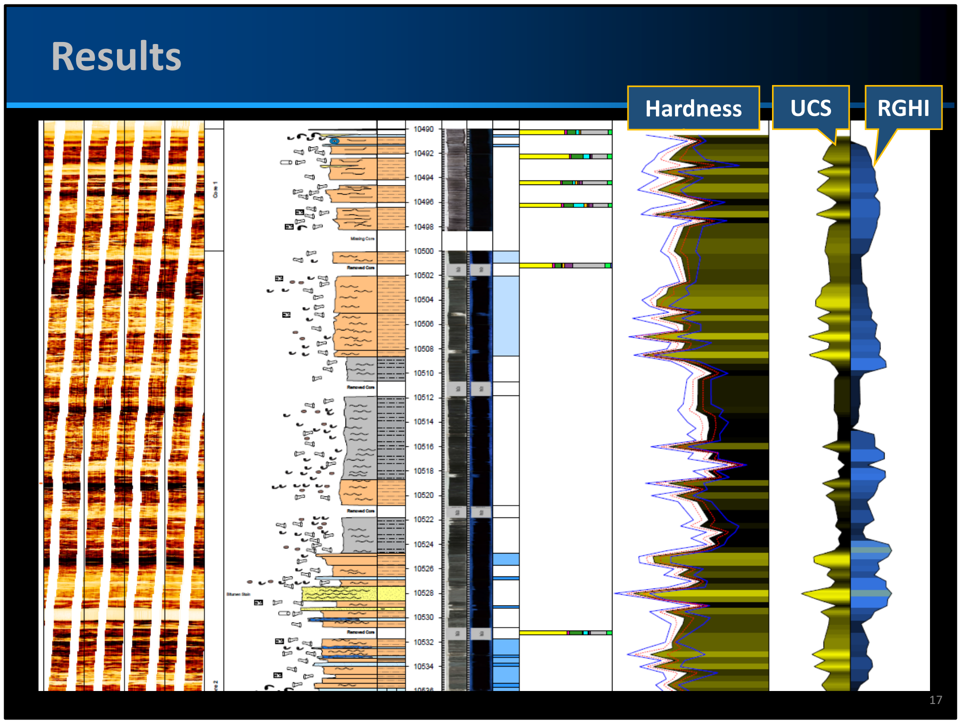
Core photos illustrating the interbedded architecture of the Lower Cotton Valley lower shoreface systems. Top is in the upper left corner. The light gray beds are mostly calcite-cemented, very fine-grained sandstone. The darker rock on the far left is silty calcareous shale.



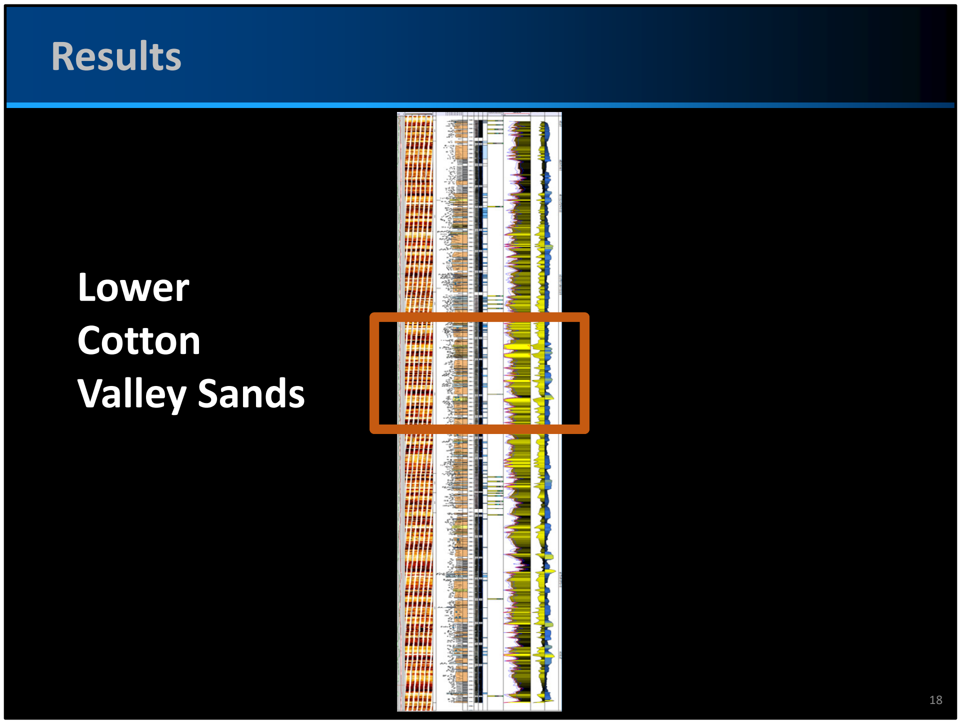
Bird's-eye view of the cored interval. We're going to zoom in on three key zones and examine the litho and mechanical stratigraphy.



First – this upper zone.

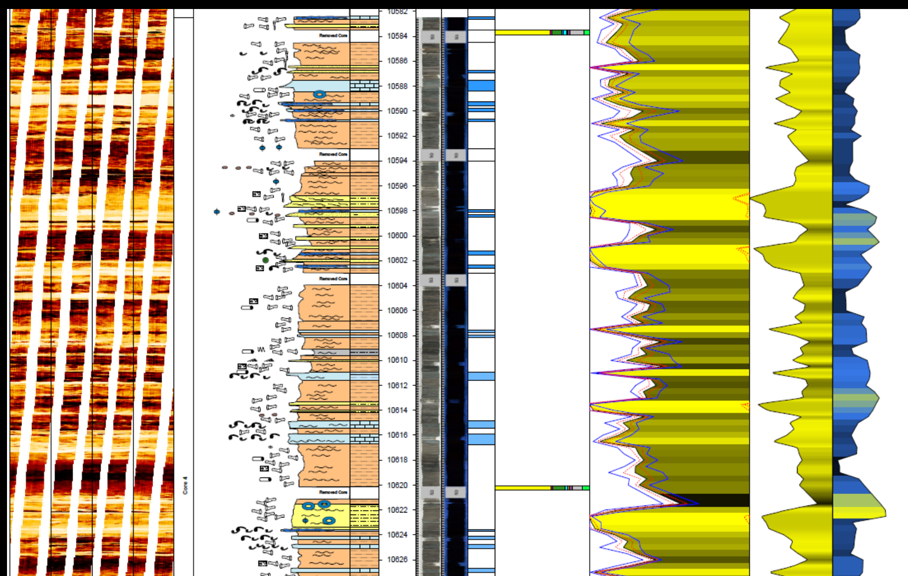


Greater hardness colored in yellow, lower hardness in black. Calculated UCS and RGHI curves shown. RGHI curve increases to the right indicating greater heterogeneity. Note the relationship between the shale content and the hardness.



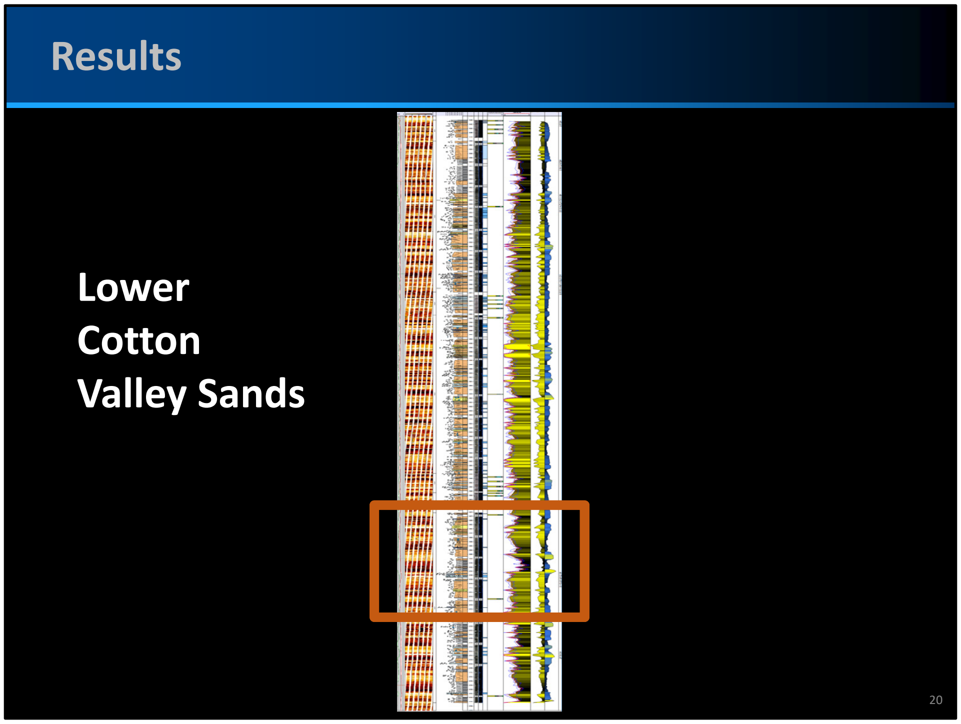
Now the middle section where hardness is higher overall.

Results



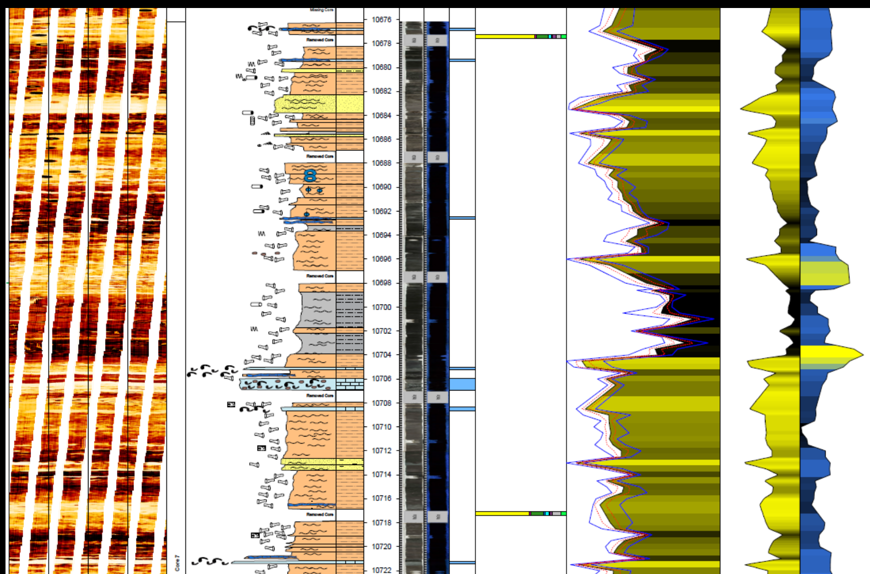
19

A very silty/sandy section with patchy limestones (blue lithologies). Average hardness is higher than in the upper zone, and maximum hardness is also very high.



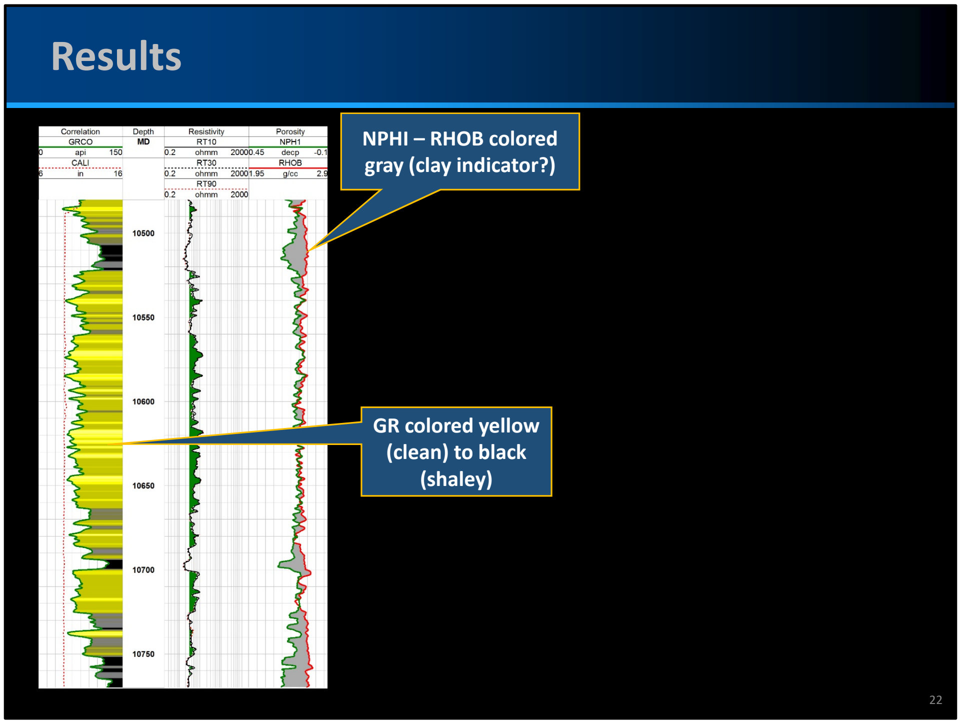
And this lower zone.

Results

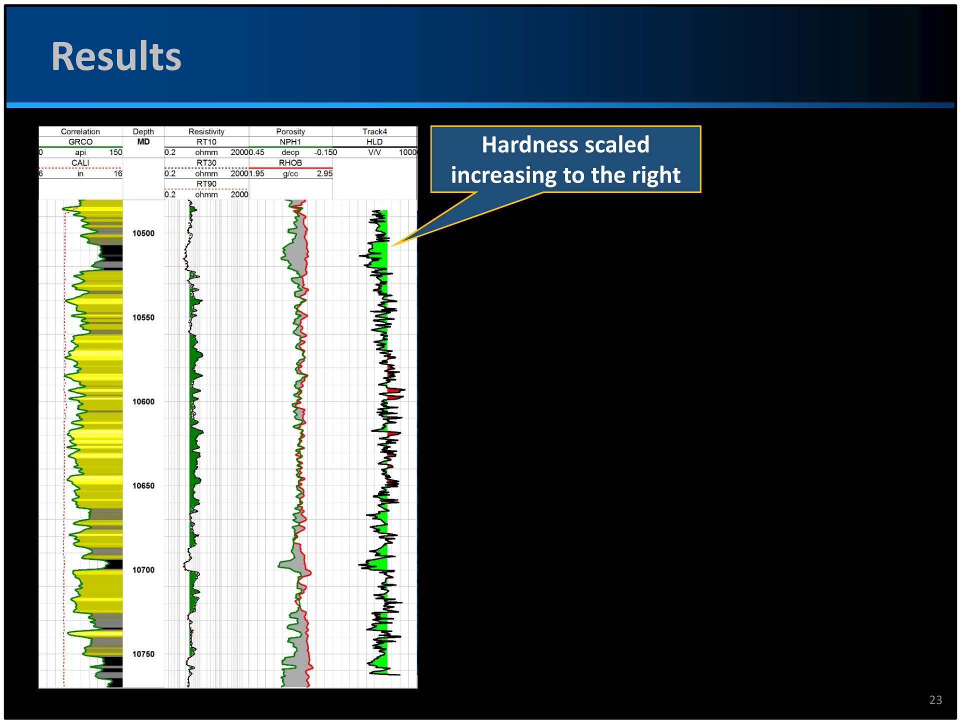


21

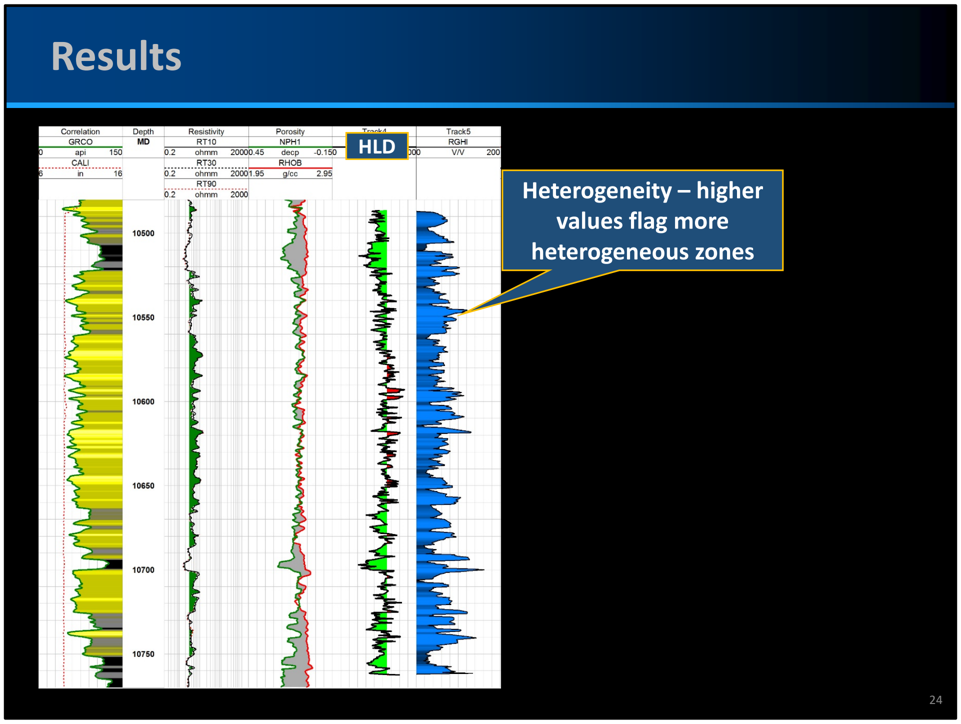
Note that we have another softer zone corresponding to a shaley interval, and the abrupt mechanical contact at its base. Immediately below the shale is a shell-rich limestone.



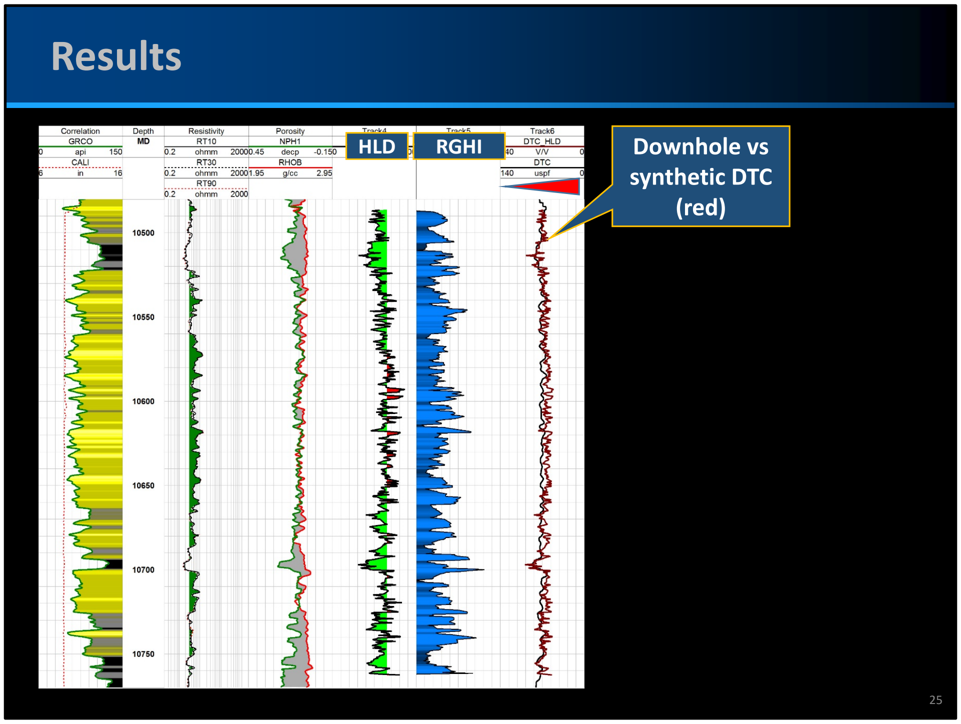
Now we're going to look at the differences between log- and core-derived mechanical properties. Gamma Ray curve is colored yellow for "cleaner" zones, and black for more argillaceous zones. The space between the RHOB and NPHI curves is colored gray as a type of clay "indicator".



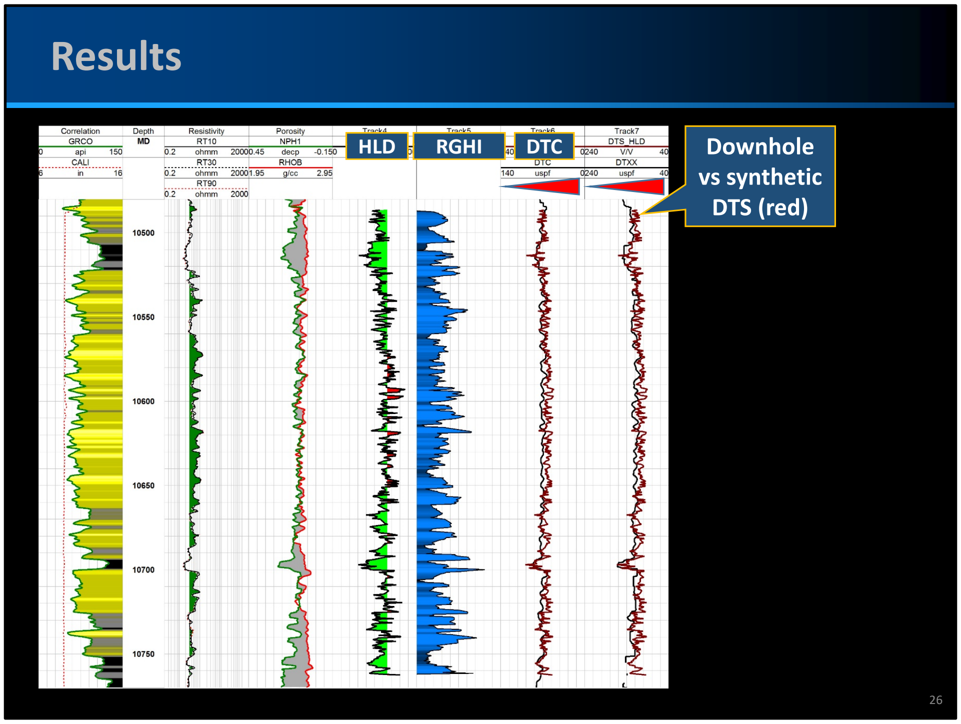
Hardness data plotted as a curve. Core data depths have been corrected to log depths.



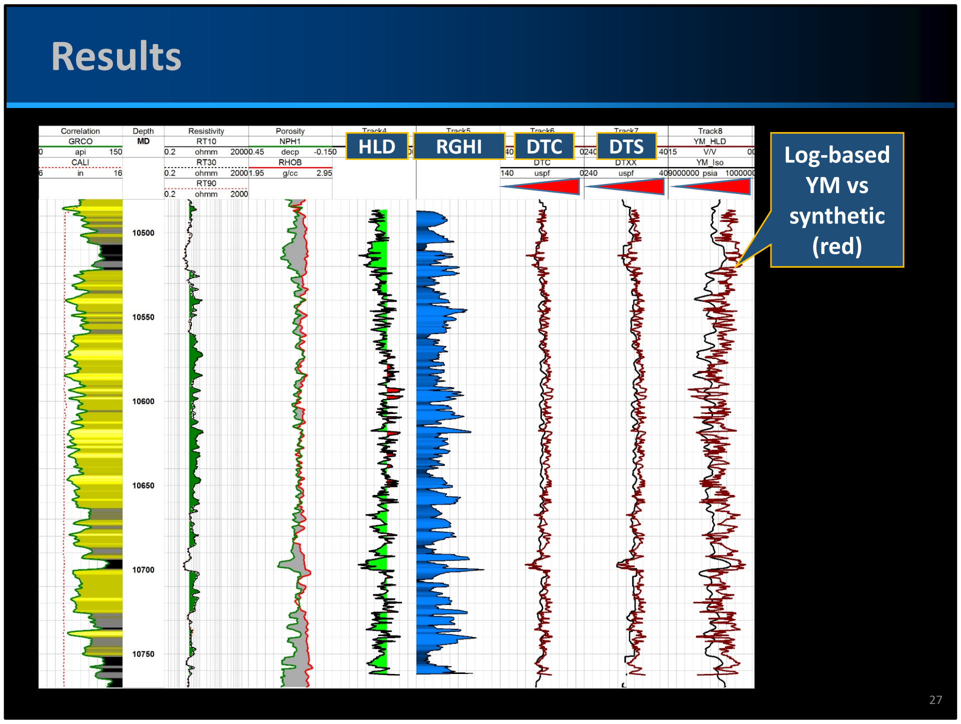
RGHI curve added. Note the middle zone characterized by more rapid changes in the heterogeneity compared to the more consistent upper and lower zone.



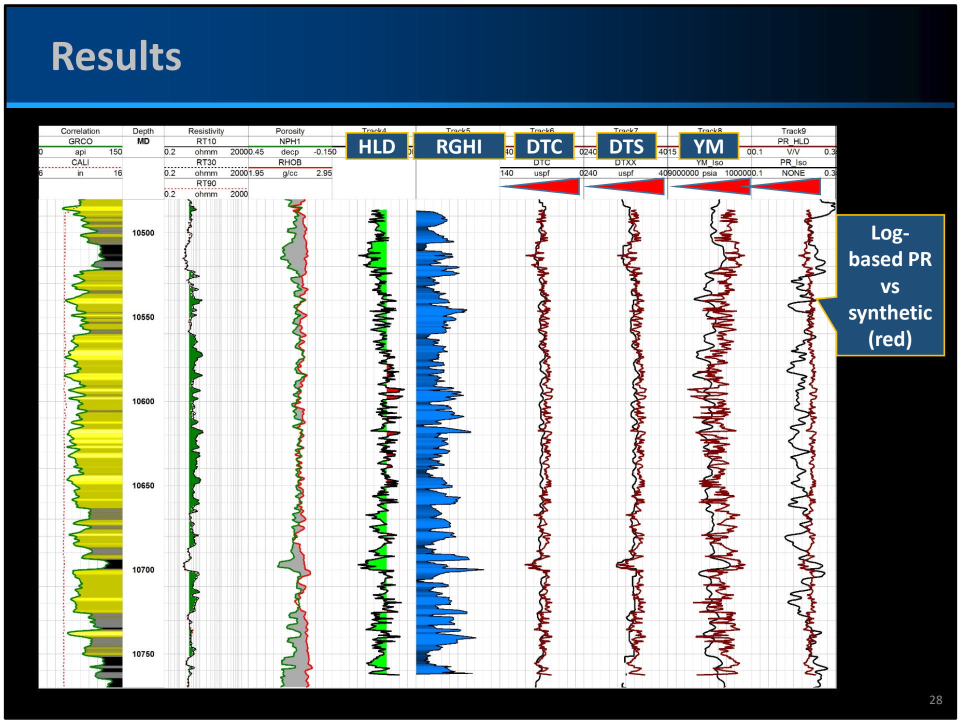
The downhole DTC curve with the higher resolution synthetic curve calculated from the hardness data. Red arrow indicates direction of increase. Note the near continuous overlay, and the higher frequency variations in the curve when compared to the downhole log.



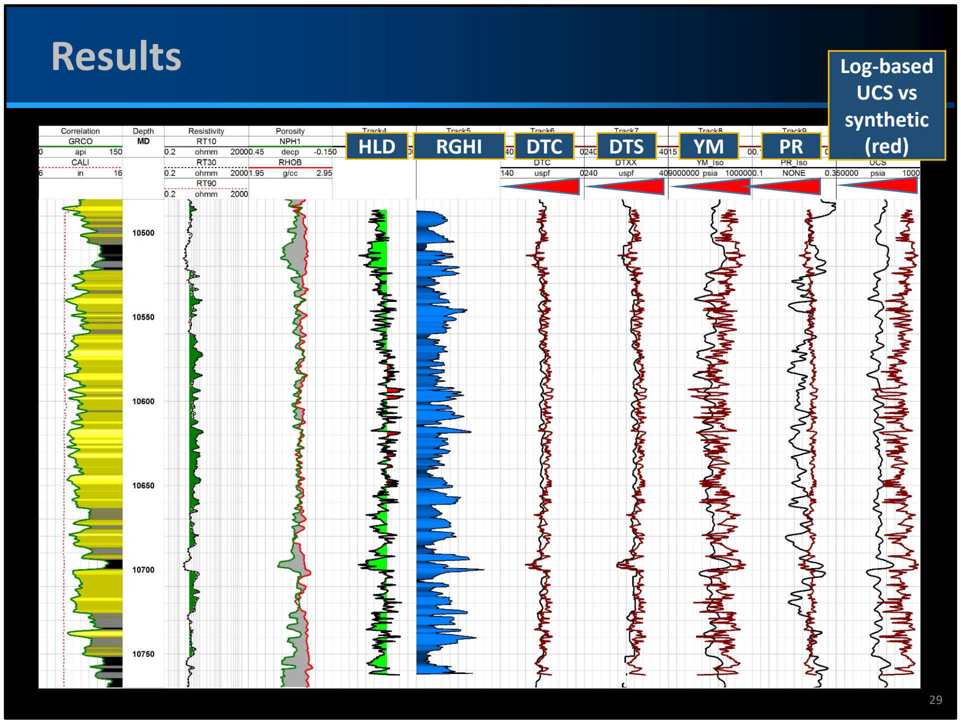
The downhole DTS curve with the higher resolution synthetic curve calculated from the hardness data. Again, we see near continuous overlay, and higher frequency variations in the curve when compared to the downhole log.



In the case of the Young's Modulus curves there is clearly more activity in the synthetic curve compared to the sonic log-derived curve. There are also several zones where the hardness-derived curve is lower than the sonic log-derived curve.



The sonic log-derived Poisson’s Ratio generally higher and exhibits greater amplitude compared to the hardness-derived curve.



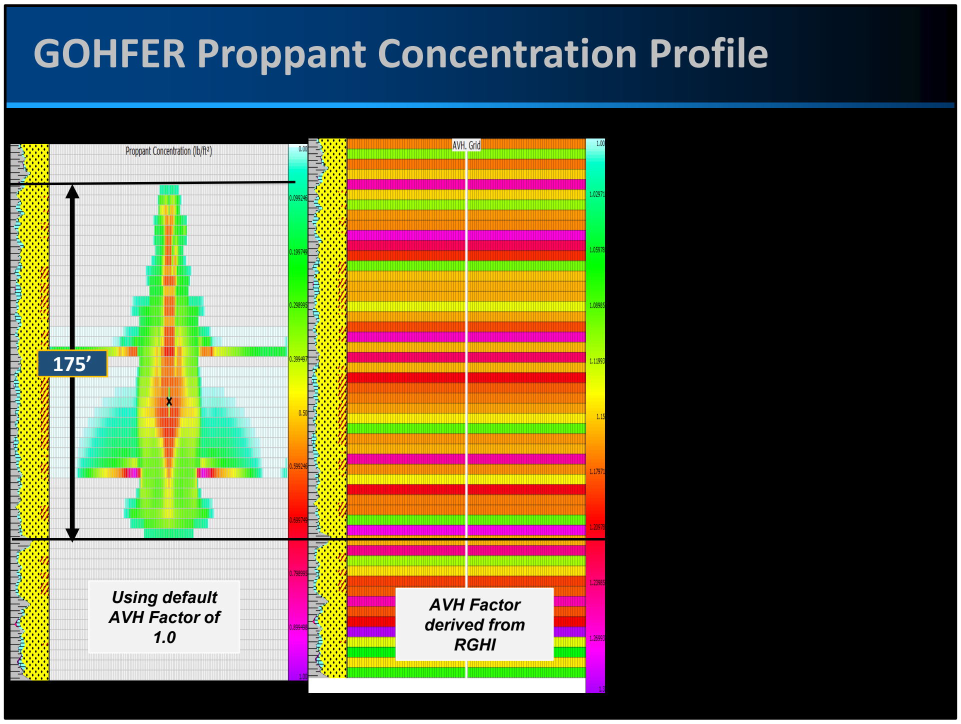
The hardness-derived UCS curve displays lower values and higher frequency changes compared to the sonic log-derived curve.

GOHFER® AVH Factor: Vertical to Horizontal Anisotropy

- **The vertical to horizontal (geomechanical) anisotropy (A_{VH}) factor models the impact of laminations and rock mechanical fabric on fracture extension pressure. In a highly laminated system it takes more energy to break vertically across layers than to extend laterally within a rock layer. An A_{VH} factor of 1.2 implies that it will take 20% more energy to extend the fracture vertically than horizontally.**

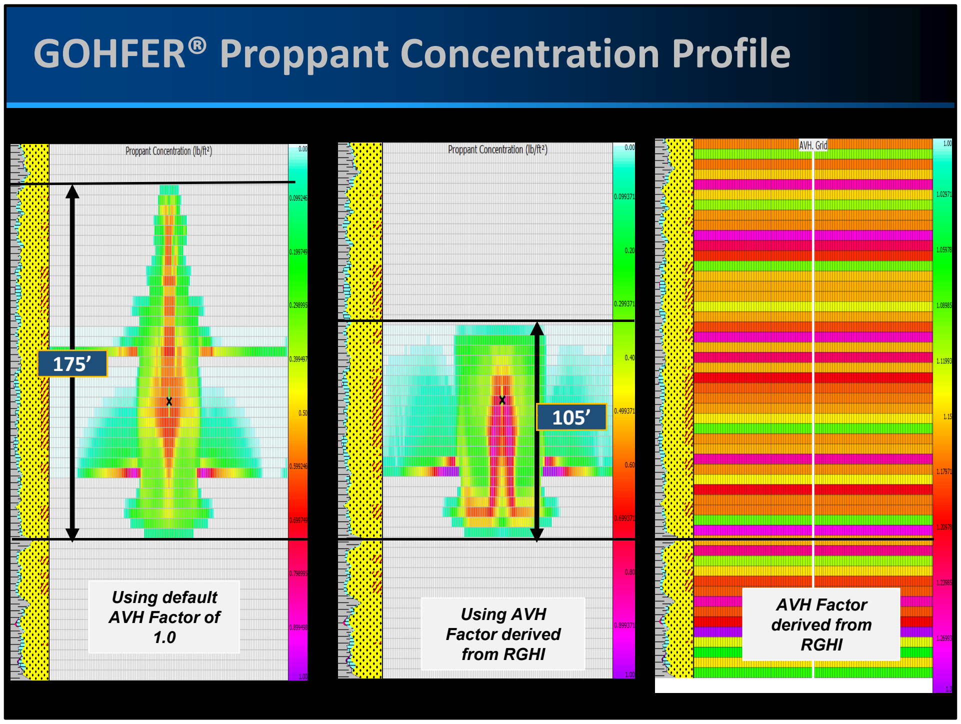
30

The AVH factor is the RGHI expressed in GOHFER. It is used as a means to instruct the simulator to account for the mechanical stratigraphy of the formation for the purposes of modeling frac height growth.

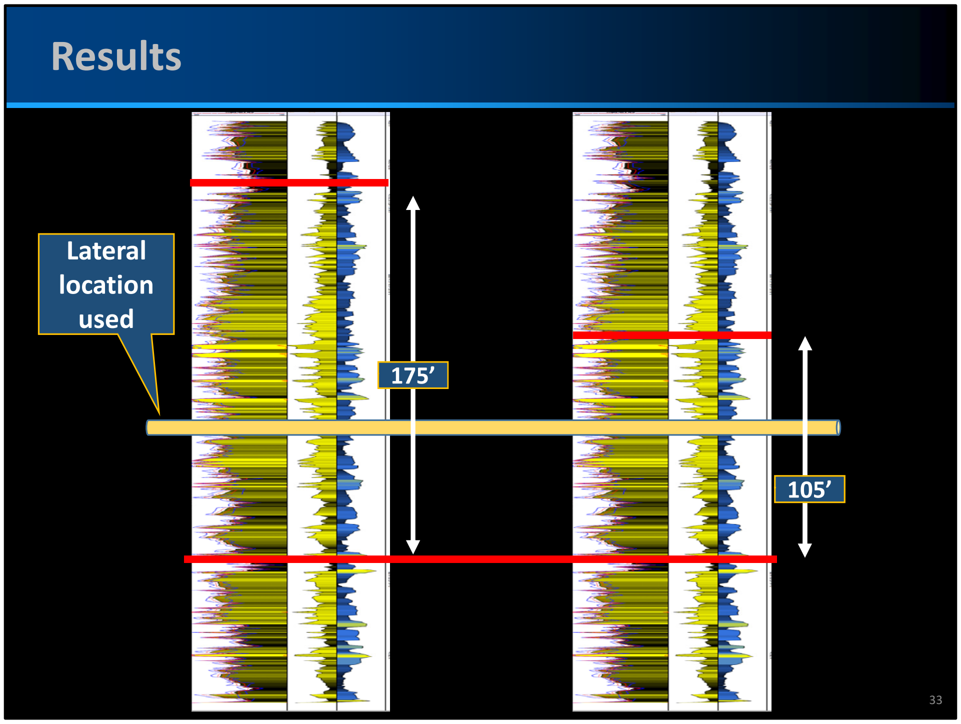


Well bore shown by the black "X". Without the AVH factor the predicted propped fracture height is 175 feet. The grid on the right is the GOHFER display of the mechanical stratigraphy. Hotter colors indicate greater heterogeneity.

The treatment design is hybrid gel treatment (linear gel and X-linked gel) 1,794 bbl fluid and 73,500 lb proppant (100 mesh + 40/70 sand).



With the AVH factor the predicted propped fracture height is 105 feet.



Looking at the fracture models against the geology. The proposed horizontal well bore is shown and the GOHFER-modeled frac ranges are in red. Note the simulator predicts near complete coverage of the sandstone interval, and the upward growth being terminated at the softer, shalier zone highlighted previously. In contrast, when the mechanical stratigraphy is input the simulator indicates that the harder, cemented, sandstones may effectively block upward frac growth, removing 70 feet from the stimulated reservoir volume. So with this we can rerun the simulator to test the effects of changes in pump rates, viscosities, and proppants (for example) on frac height growth.

Summary and Conclusions

- High-resolution rock mechanical properties were measured and analyzed across a Lower Cotton Valley, fine-grained sandstone reservoir and used to model frac height growth in GOHFER® software.
- The data document high-frequency geomechanical variations vertically within the reservoir interval.
- The results indicate a decrease in frac height growth from 175 to 105 feet.
- This modeling can be used to test multiple frac design scenarios and landing zone placements to increase the stimulated reservoir volume.

34

Conclusions