Using Elemental Data for Accurate Wellbore Placement and Geosteering in Unconventional Reservoirs*

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Search and Discovery Article #80470 (2015)**
Posted August 31, 2015

*Adapted from oral presentation given at AAPG Annual Convention & Exhibition, Denver, Colorado, May 31-June 3, 2015

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Abstract

As the pursuit of oil and gas in unconventional reservoirs grows, it is increasingly evident that horizontal wellbore placement, or targeting, plays a first-order role in the production capability of a well. Indeed, the percentage of a wellbore “in target” is a common metric used when evaluating the causes for good or poor production from any particular well. The most common process used for geosteering a horizontal wellbore into a chosen target is the correlation of logging-while-drilling (LWD) total gamma ray (GR) to a vertical pilot-hole GR log. However limitations inherent to this procedure can reduce the ability to effectively use LWD GR data. These limitations can include short GR counting intervals vs rate of penetration (ROP), GR detector sizes, and data transmission. Geologic factors such as low GR contrast from bed to bed, and repetitive GR trends, especially in areas where faulting with significant throw (defined as ≥ to thickness of the target) can further complicate the correlation of LWD GR data back to the pilot hole. In the effort to more accurately geosteer wells we have employed the use of elemental data derived from energy-dispersive X-ray fluorescence (ED-XRF). Elemental data is acquired on vertical pilot holes at the heal and, where possible, near the toe of proposed laterals, at one foot intervals on core and five foot intervals on cuttings. This data is used to build a chemostratigraphic profile and zonation of the section. Chemostratigraphic zones are defined as having multiple elements (where possible) which illustrate distinct changes in chemical profiles from one zone to another. These zones must be correlative over reasonable distances (at a minimum the length of the horizontal wellbore) and must be readily identifiable in cuttings. Using these criteria chemostratigraphic zonations have been constructed in the Marcellus Shale, Lower Huron Shale, and Newman (Big Lime) Limestone. Well site ED-XRF data was used in conjunction with LWD GR to geosteer a

~25′ thick porosity zone which resides at the base of a ~400′ thick non-porous/non reservoir carbonate section of the Newman Limestone and immediately underlain by the siltstones and shales of the Borden Shale. Well site XRF data was successfully used to identify cave-ins that were mistakenly identified as the Borden Shale, determine the position of the wellbore in zones of non-descript GR signature, and determine the lateral extent of the reservoir interval.

EQT

Where
energy
meets
innovation.

USING ELEMENTAL DATA FOR WELLBORE PLACEMENT AND GEOSTEERING IN UNCONVENTIONAL RESERVOIRS

RANDY BLOOD

6/3/2015

ACKNOWLEDGMENTS

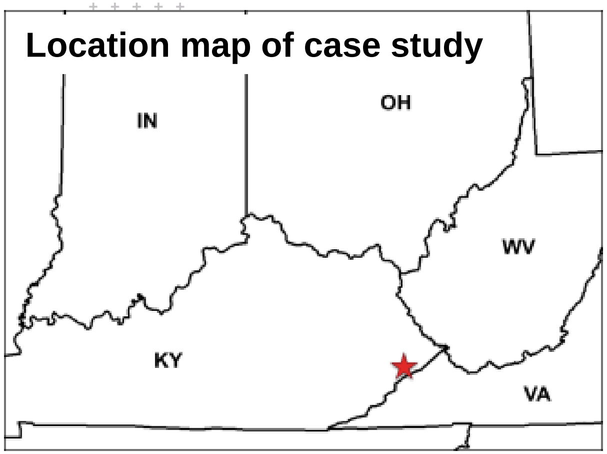
- Pukar Mainali
- Jennifer Kharrazi
- Mike Dix
- Milly Wright
- Katie Heckman
- Dave Riestenberg
- Ashley Douds
- Joe Morris
- EQT Production

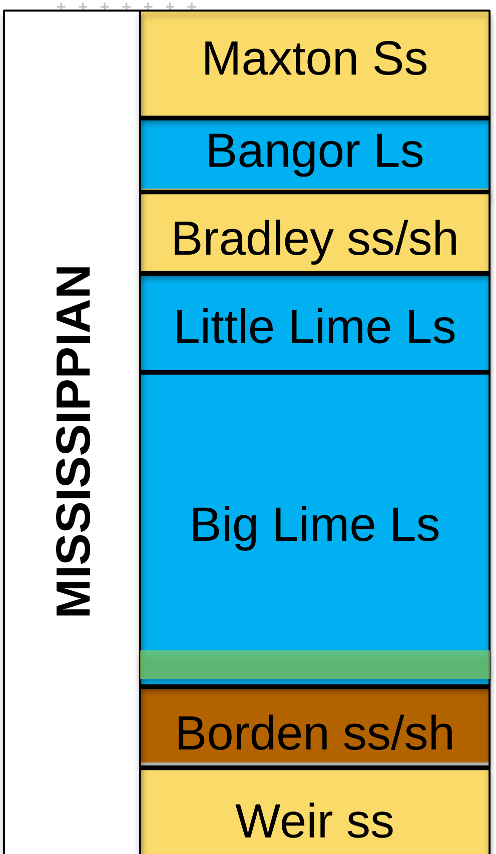
WHY USE ELEMENTAL DATA TO GEOSTEER?

- 2011 Halliburton study of Geosteering with gamma ray (GR) in the Haynesville Shale suggested that over 50% of wells were not where they were correlated to be over 50% of the time

- How do we trust GR to geosteer:
  - formations that lack GR character
  - variable GR character along same horizon
  - in faulted areas
  - repetitive GR character
  - encounter any or all of the above

THE BIG LIME





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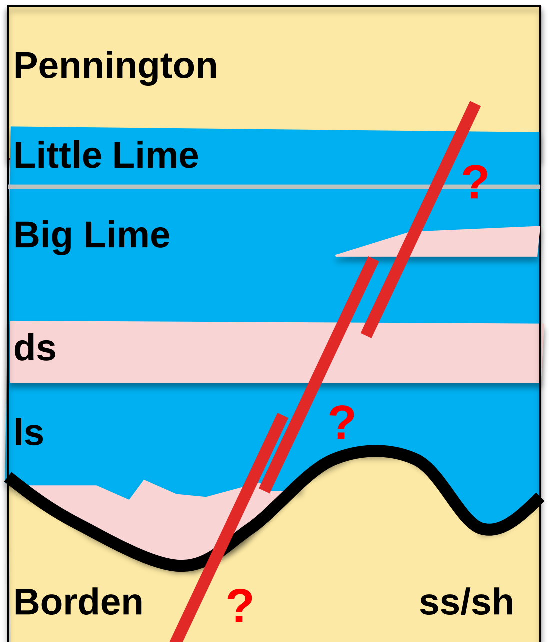


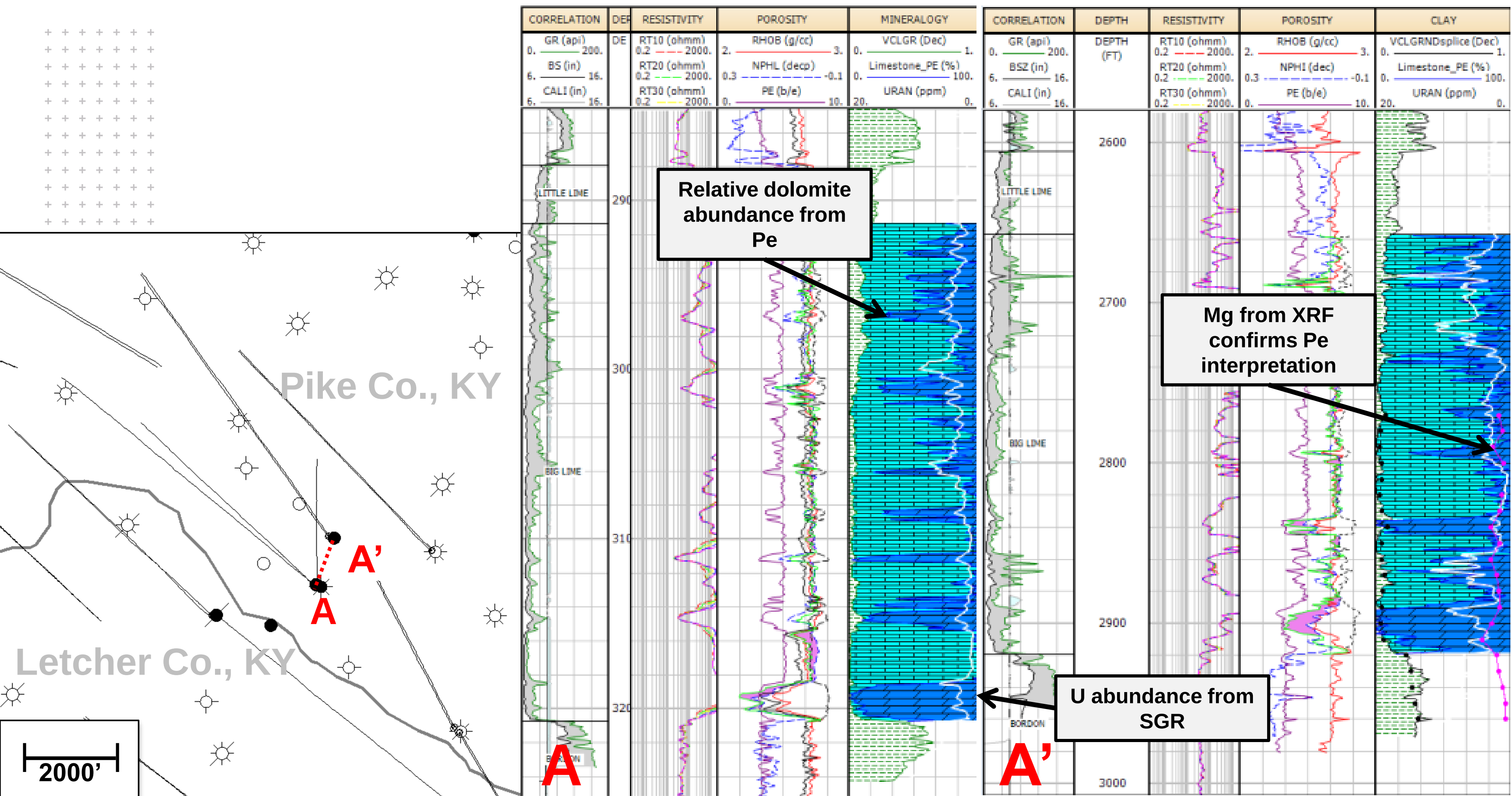
Target is a 20'-30' zone of dolomitic porosity at the base of the Big Lime section

Big Lime exposed at Pound Gap, KY/VA border

WHY NOT USE GR?

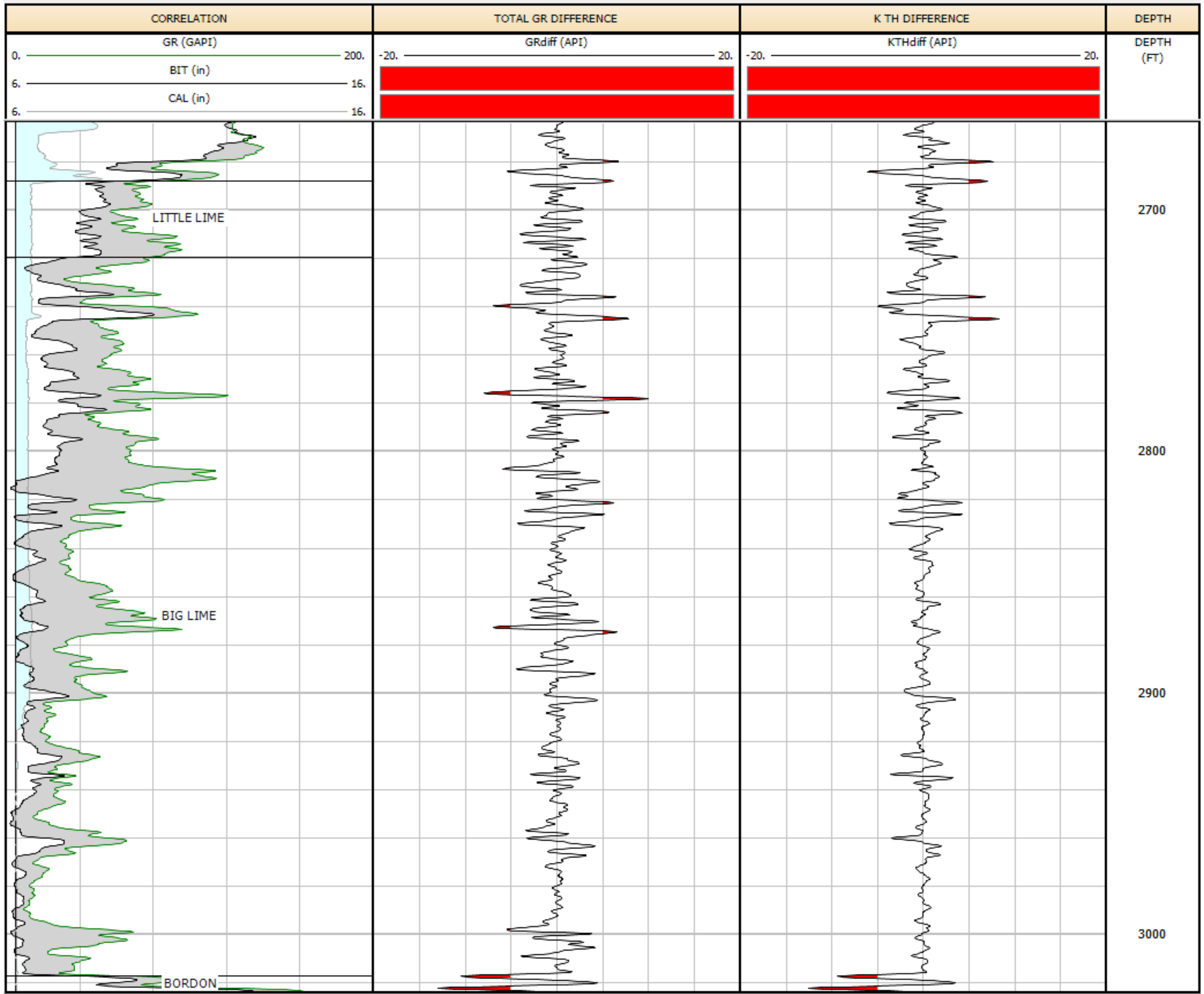
- **Strong correlation exists between U occurrence and the location of dolomite across most of the Big Lime. However the abundance of U is not linear with dolomite abundance.**
  - **U signature not consistent across reservoir.**

- **Especially apparent in lower Big Lime where clastic influx is minimal.**



WHY NOT USE SGR?

- **Most azimuthal tools require 5-10 API difference to detect bed boundaries which is rarely achieved in the carbonate section, especially once the U is stripped from the signature**



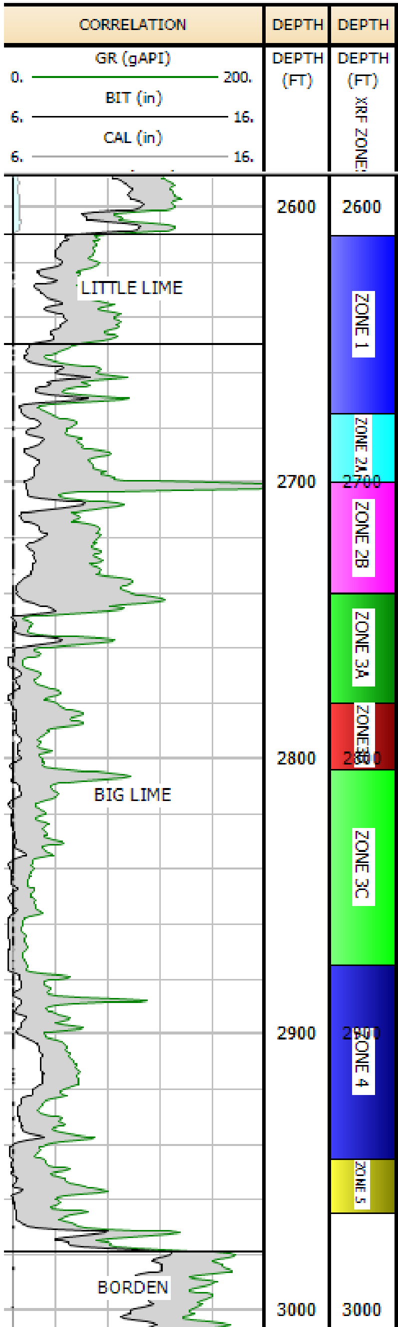
DEFINITIONS

- **Chemostratigraphy – the grouping of rocks of similar major and/or trace elemental composition into "zones" or "units".**

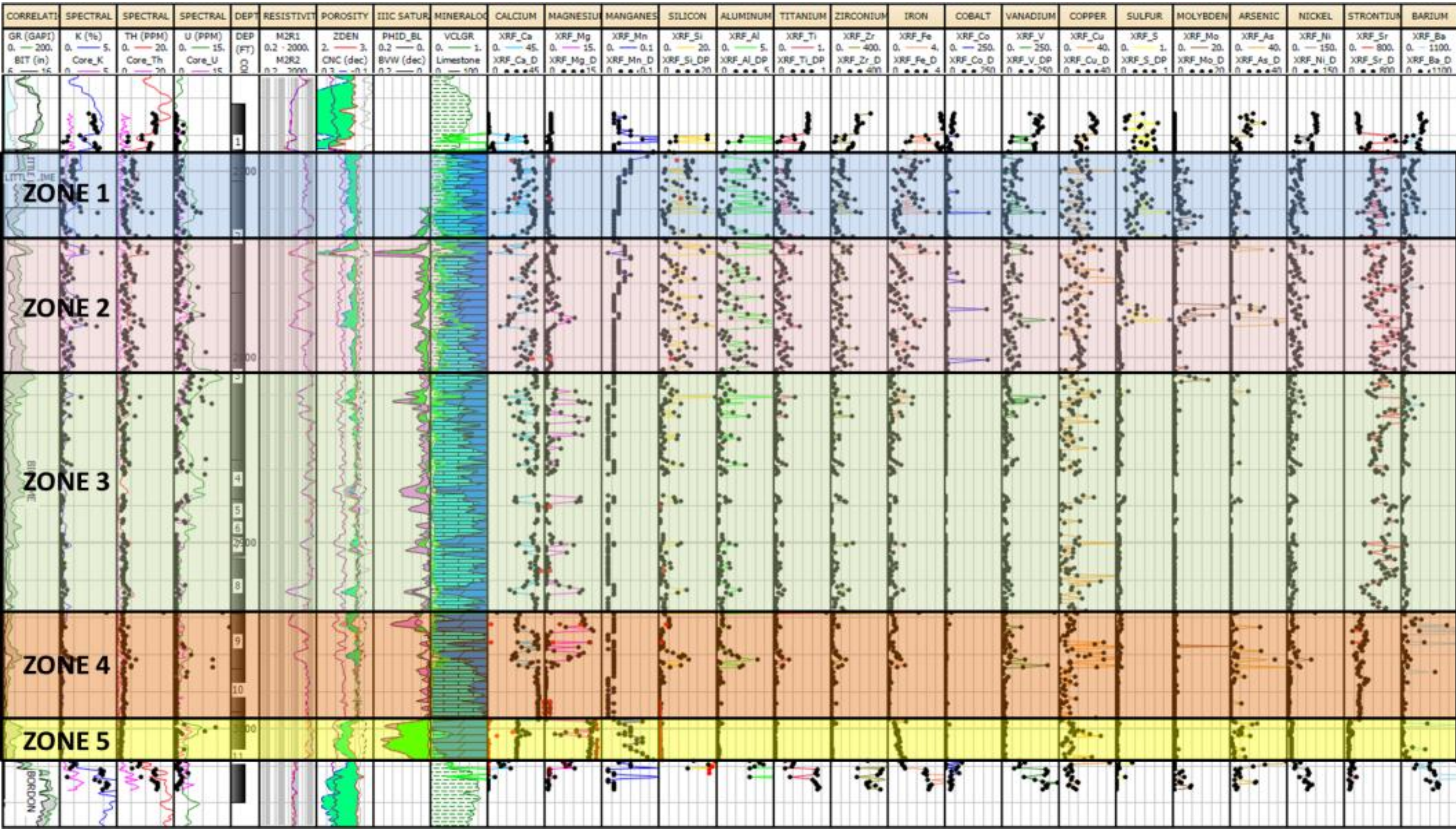
- **Chemosteering – correlating the elemental composition of samples from an unknown origin in a horizontal wellbore with the chemostratigraphy in a vertical pilot hole to determine the stratigraphic position of the wellbore .**
  - Pre-drill, a chemostratigraphy is developed on a vertical pilot hole encompassing the rocks to be encountered while landing and drilling the lateral.
    - Samples are retrieved while drilling the horizontal wellbore (try for 5' samples in curve and 10' samples in lateral), analyzed on location (usually by ED-XRF) and compared back to the pilot hole data to determine what chemostratigraphic zone the cuttings came from.

CRITERIA FOR ZONE DEFINITION

- **Distinct changes in chemical profiles from one zone to another**
- **Where possible rely on more than one indicator (element/ratio/enrichment) per zone**
- **Zones need to be readily identifiable in cuttings (horizontal data set will be generated on cuttings)**
- **Zones need to be correlative across reasonable distances (at a minimum the length of the wellbore)**



EXAMPLE ZONATION IN THE BIG LIME



DESCRIPTIONS OF ZONES

- **Zone 1: background levels of Mg, high detrital content (Al, Si, Ti, Zr, Fe) with enriched S**

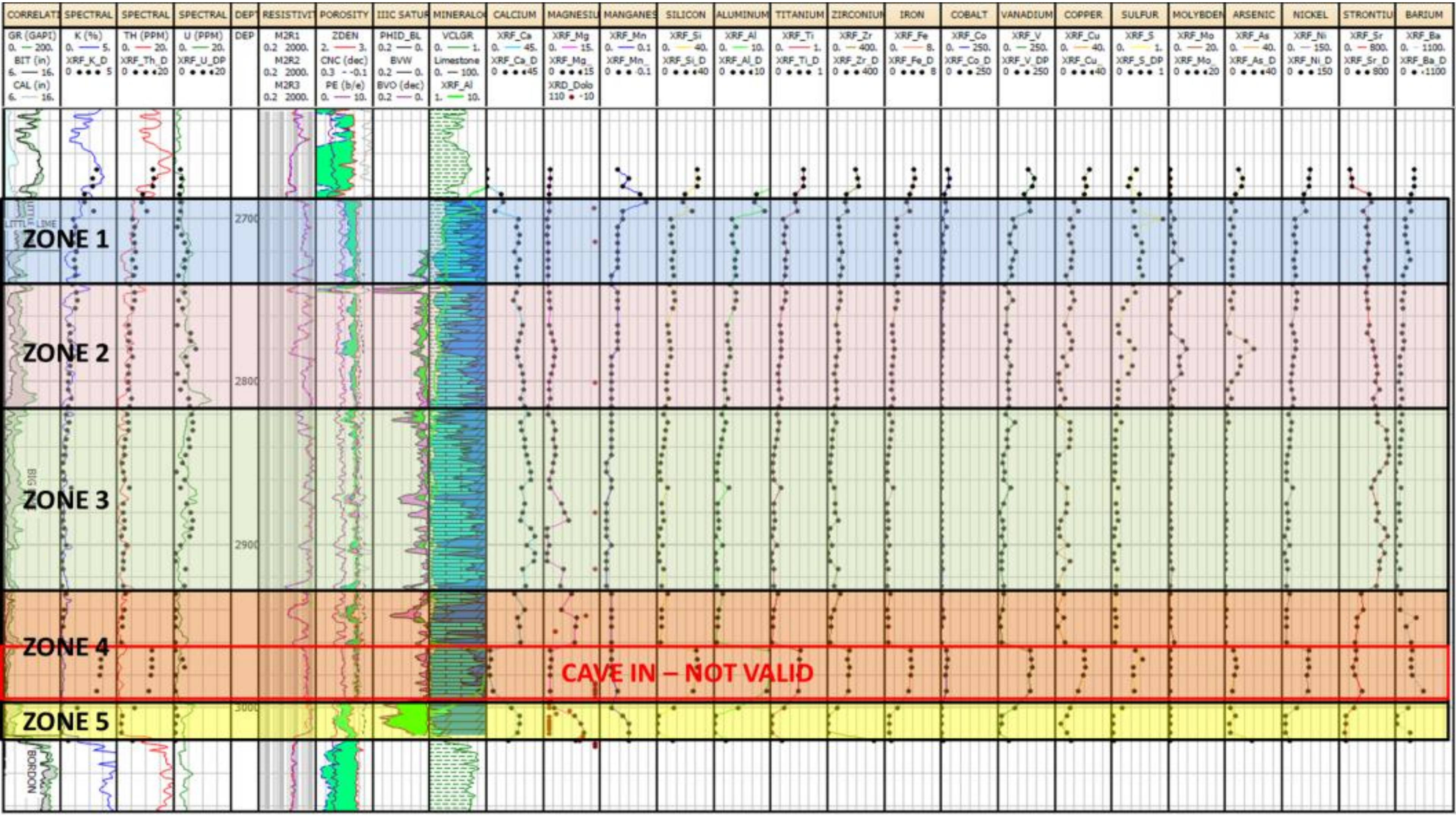
- **Zone 2: Decreased S, slight increase in Mg, elevated detrital indicators that decrease down through the section**

- **Zone 3: Ca dominated with discreet intervals of enriched Mg, near background levels of detrital indicators, with elevated Sr relative to overlying and underlying strata**

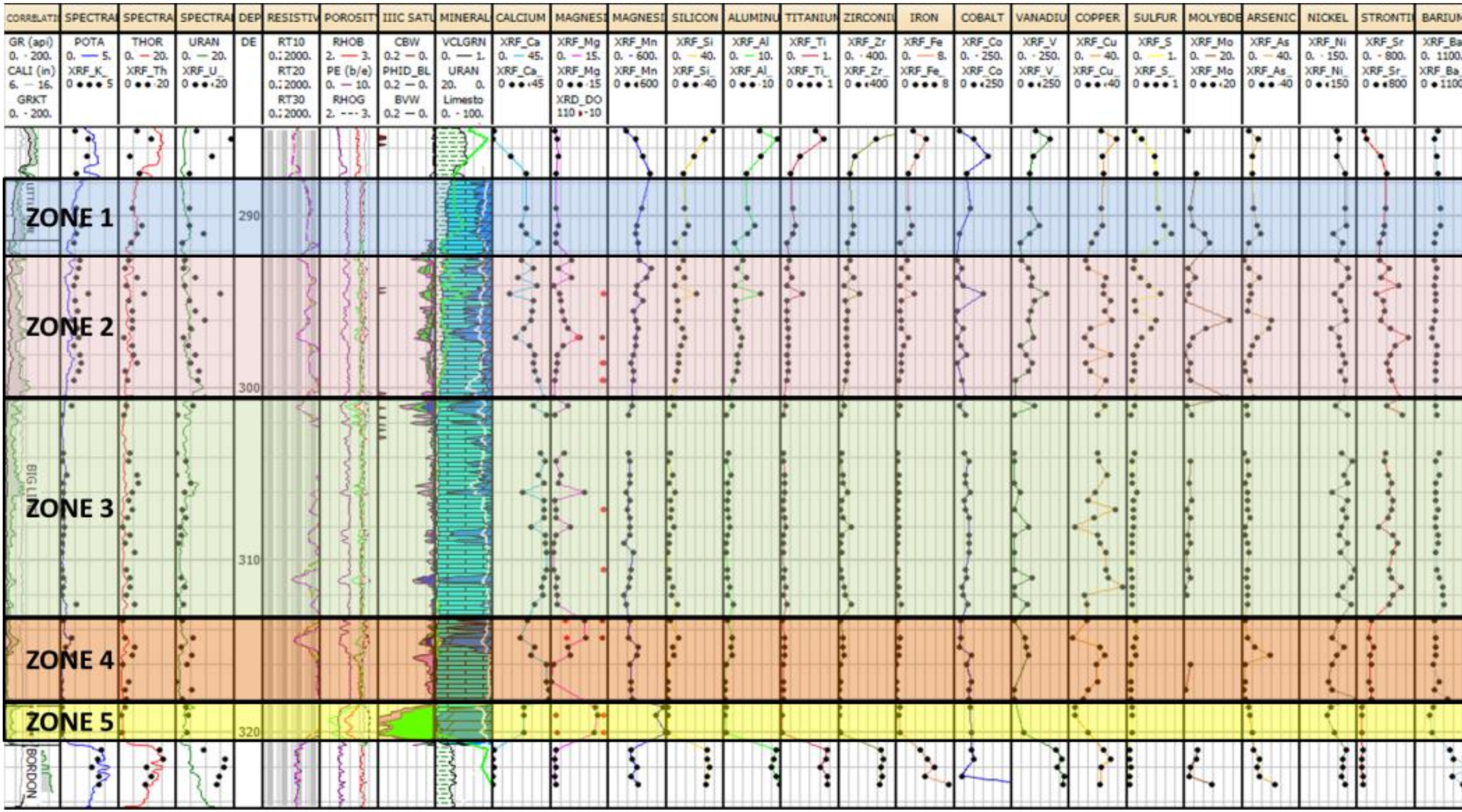
- **Zone 4: Mg, Ca mix with marked decreased Sr and presence of Ba. May have zones of elevated Cu and As**

- **Zone 5: Reservoir. Mg-rich, with increased Fe, and Mn relative to overlying strata. U decoupled from K, Th signal**

ZONATION - CUTTINGS



ZONATION – OFFSET WELLS

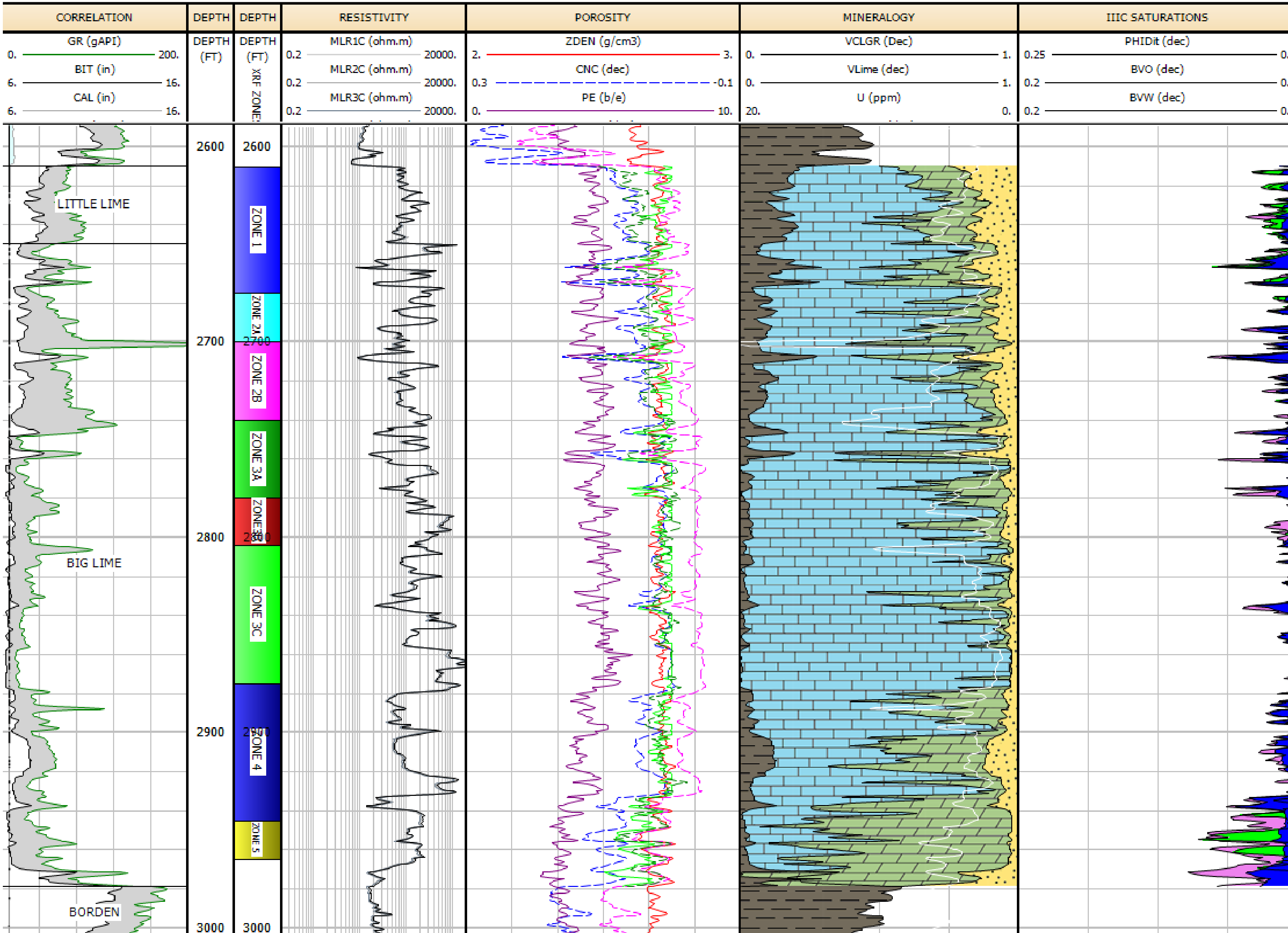


SUMMARY

- **PROS:**
  - Use of XRF data to geosteer was successful in three wells
  - Zones were readily identifiable while drilling
  - Data used to calculate mineral abundances along the wellbore to be used by the completions group
  - Data allowed us to discern location of the wellbore when ambiguous on GR
  - Easily identify cave-ins from overlying Pennington as opposed to the underlying Borden
  - Cuttings lag can be determined by comparing XRF tops to GR tops, or by generating an elemental GR from the XRF and matching the curve to the LWD GR curve

- **CONS:**
  - ROP's in excess of 60fph made it difficult to keep up with the bit without skipping samples (10' samples)
  - Gas moves at a different velocity than the cuttings so the mud loggers trip tests are irrelevant to getting the cuttings on depth (may be specific to foam systems, especially when oil is present)
  - Although we could project the lag along the wellbore, after reaching TD we can no longer collect cuttings that are correlated to a depth. The result is that the cuttings that are coming to surface while the rig circulates and cleans are not useful for chemosteering

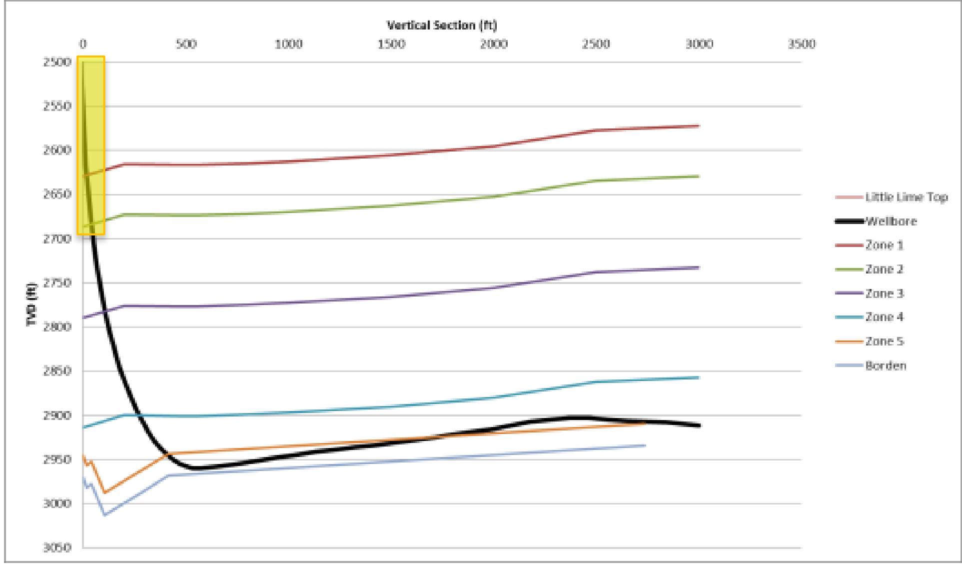
CHEMOSTRATIGRAPHIC ZONATIONS

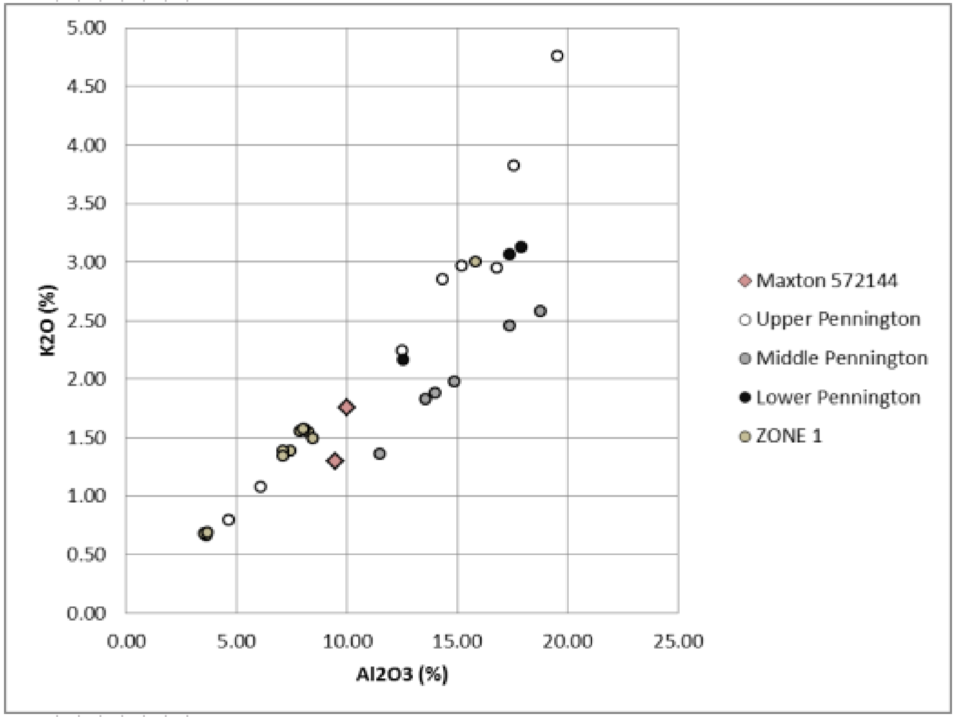


DRILLING THE CURVE

- **Pennington: elevated S, low carbonate, high clastics**

- **Zone 1: increased carbonate with elevated S**





- **Maxton sands (pink diamonds indicate Maxton samples when encountered in previous well)**

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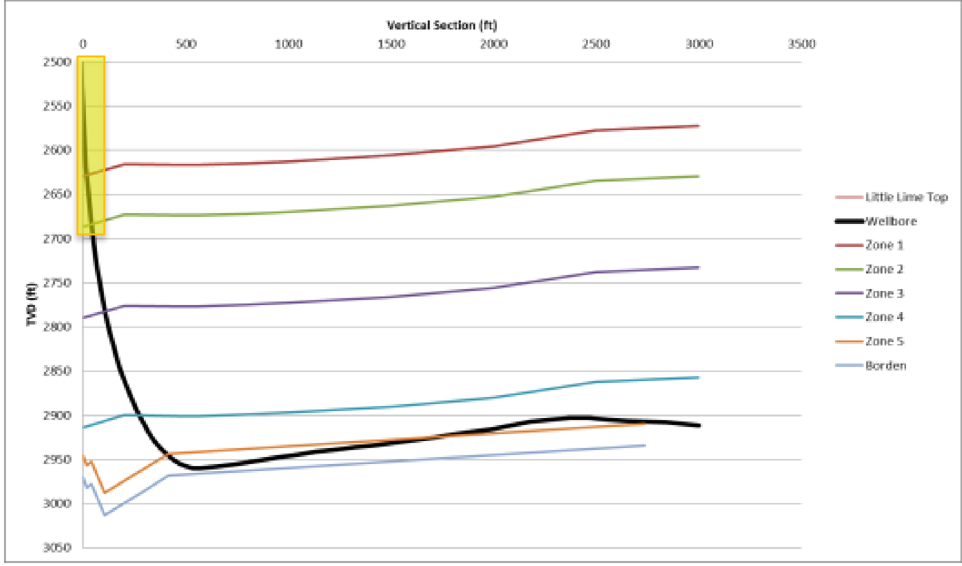

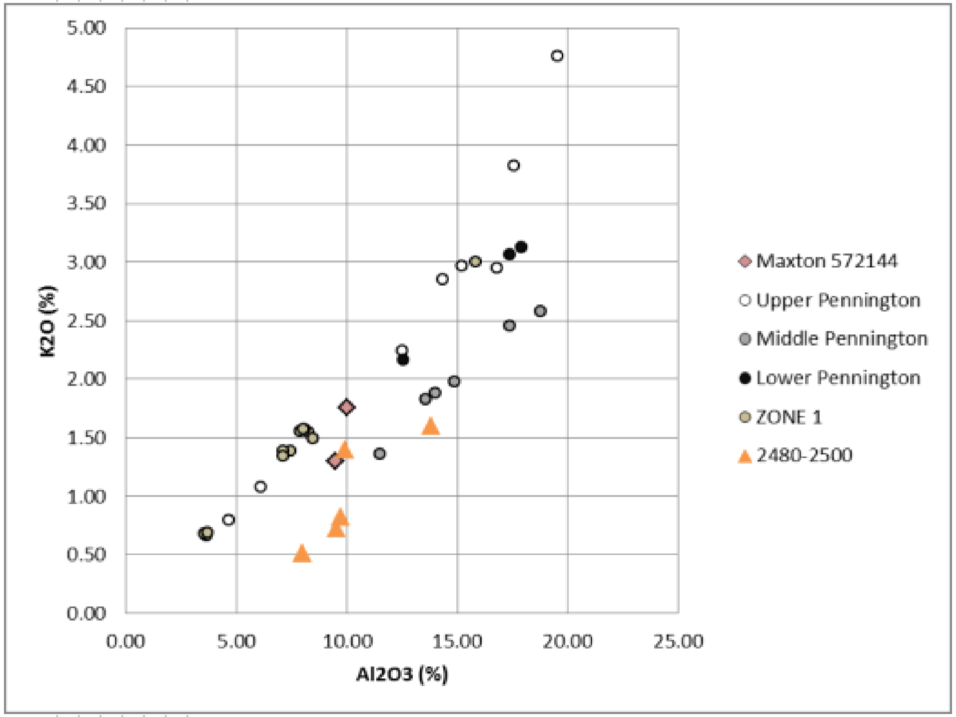

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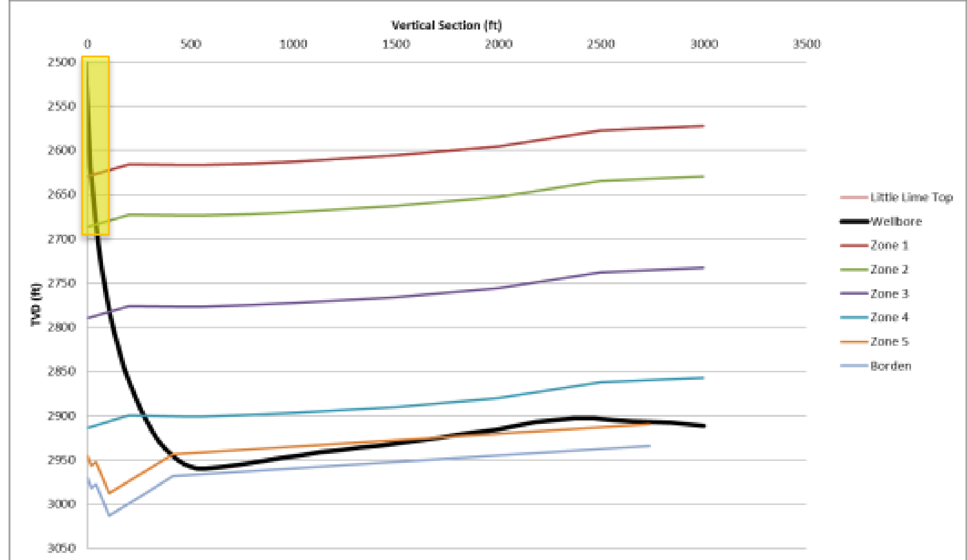

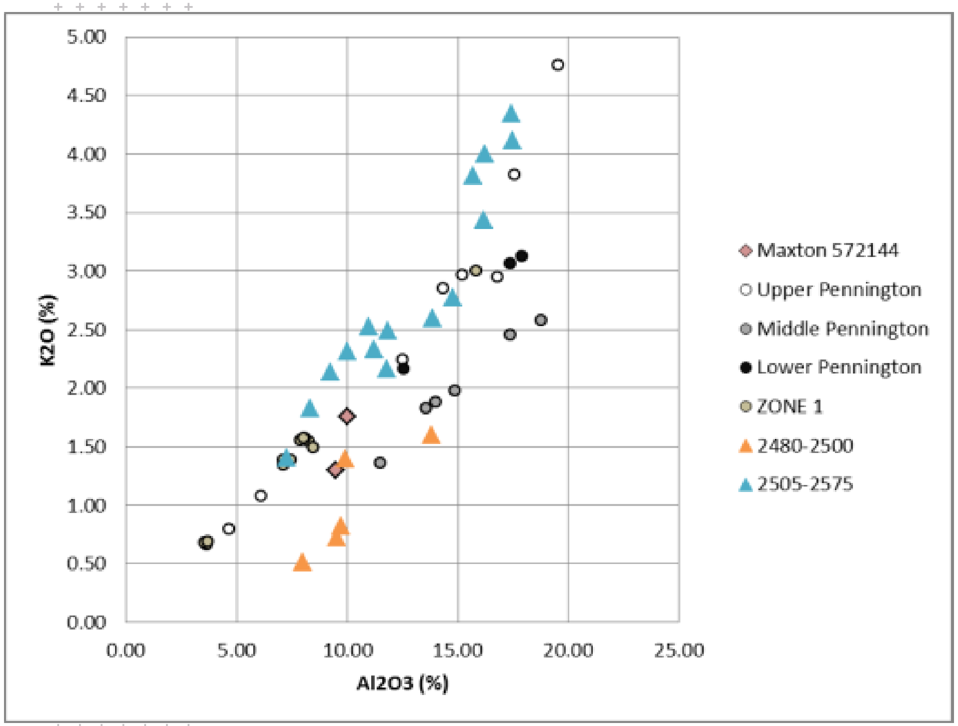

- **Maxton sands (pink diamonds indicate Maxton samples when encountered in previous well)**
- **Maxton sand**
- **Upper Pennington shale section**

DRILLING THE CURVE

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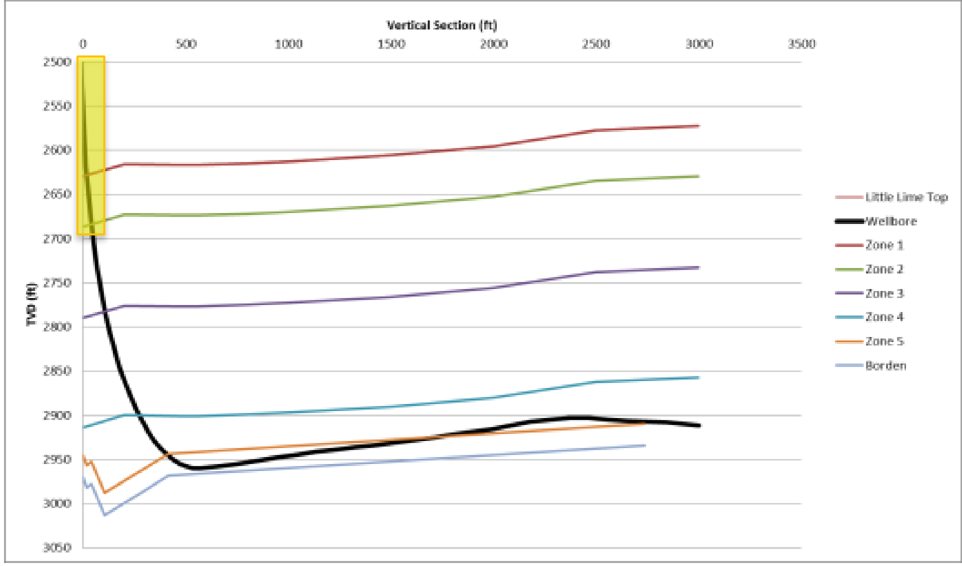

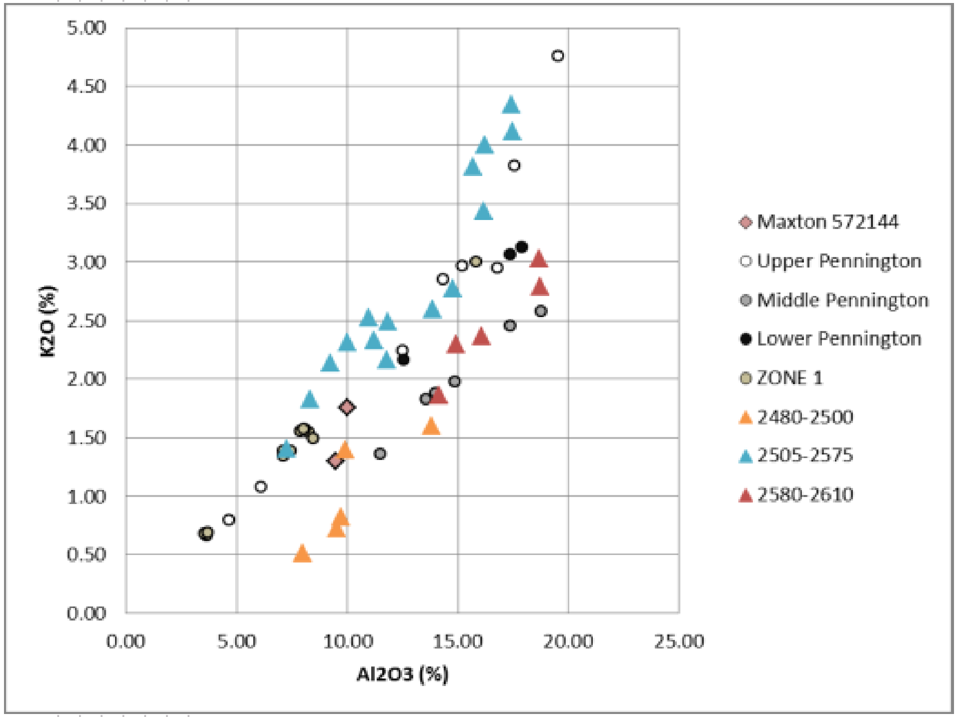

- **Maxton sands (pink diamonds indicate Maxton samples when encountered in previous well)**
- **Maxton sand**
- **Upper Pennington shale section**
- **Middle Upper Pennington shale section**

DRILLING THE CURVE

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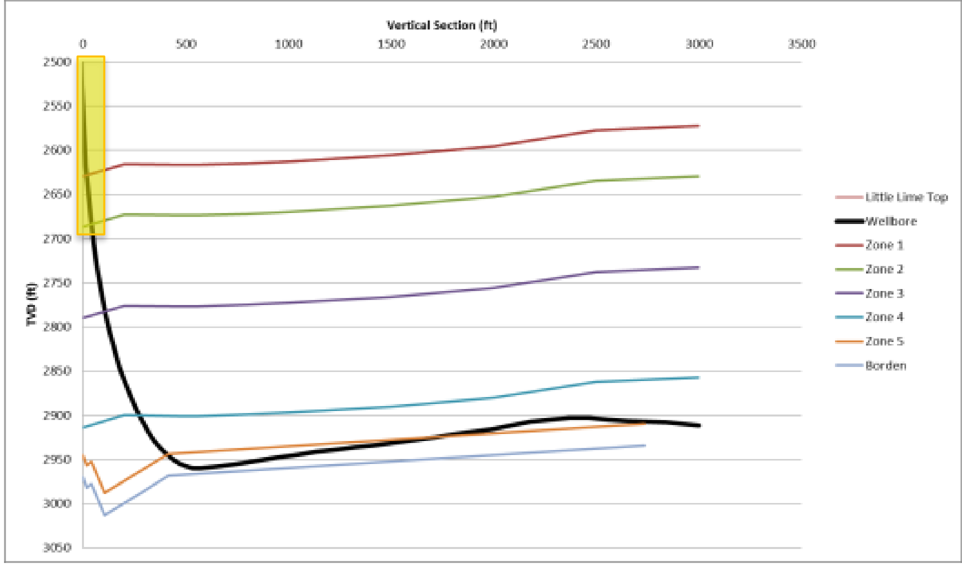

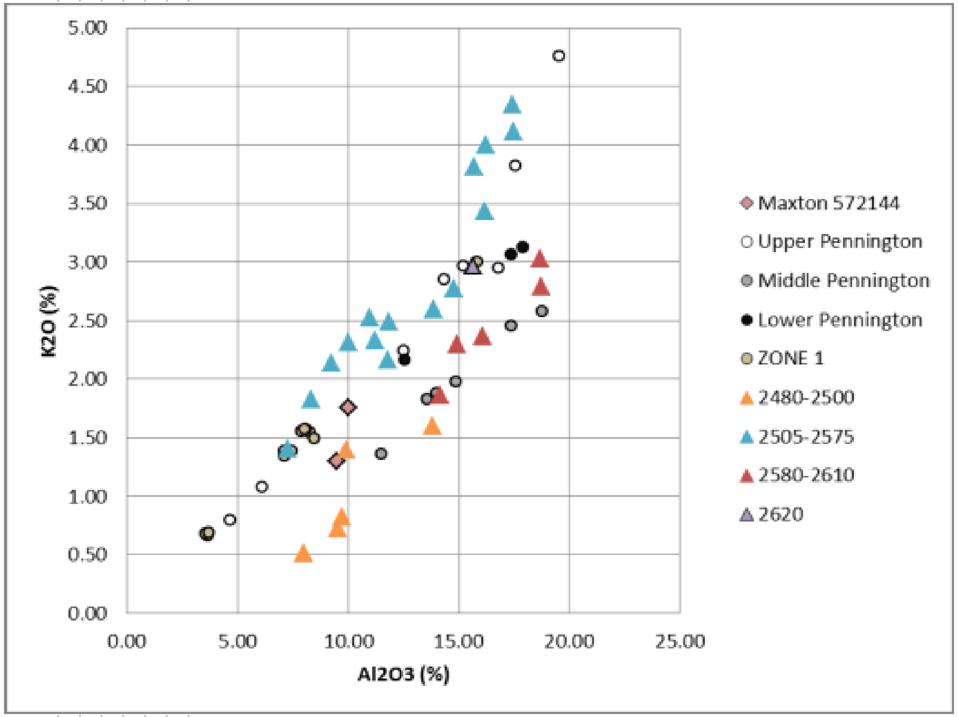

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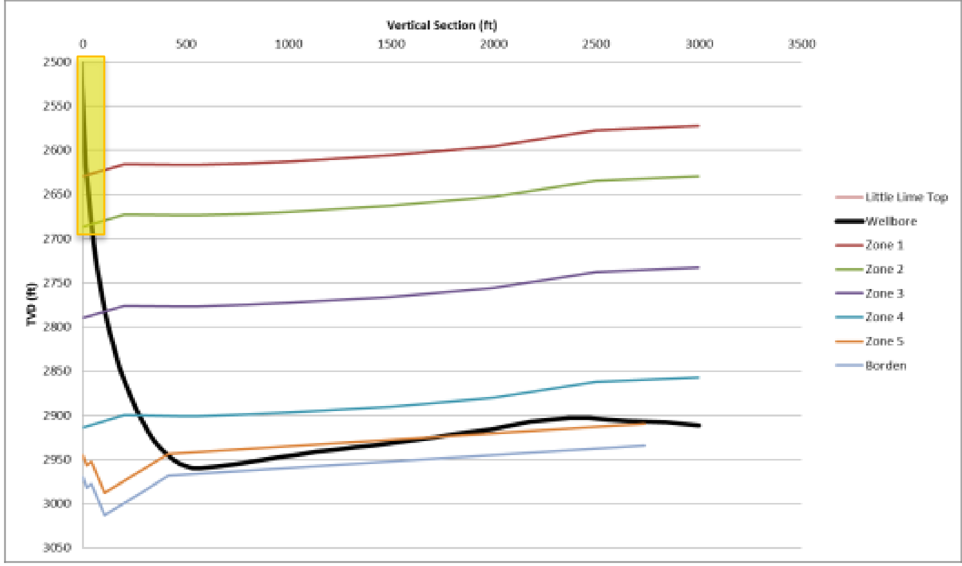
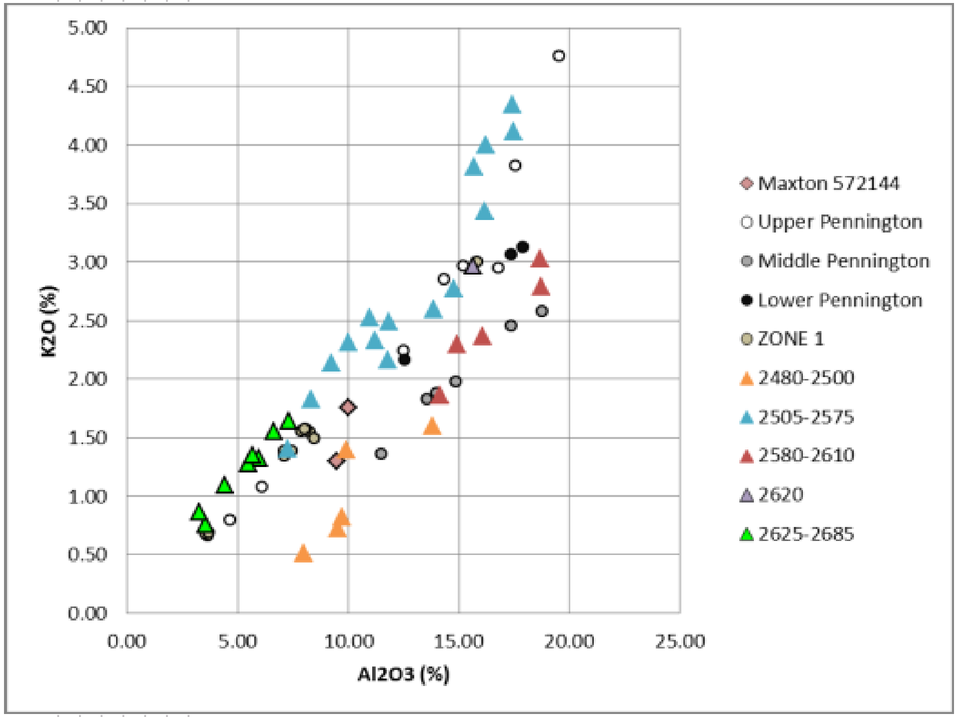
- **Upper Pennington shale section**
- **Middle Upper Pennington shale section**
- **Lower Upper Pennington shale section**

DRILLING THE CURVE

- Pennington: elevated S, low carbonate, high clastics
- Zone 1: increased carbonate with elevated S





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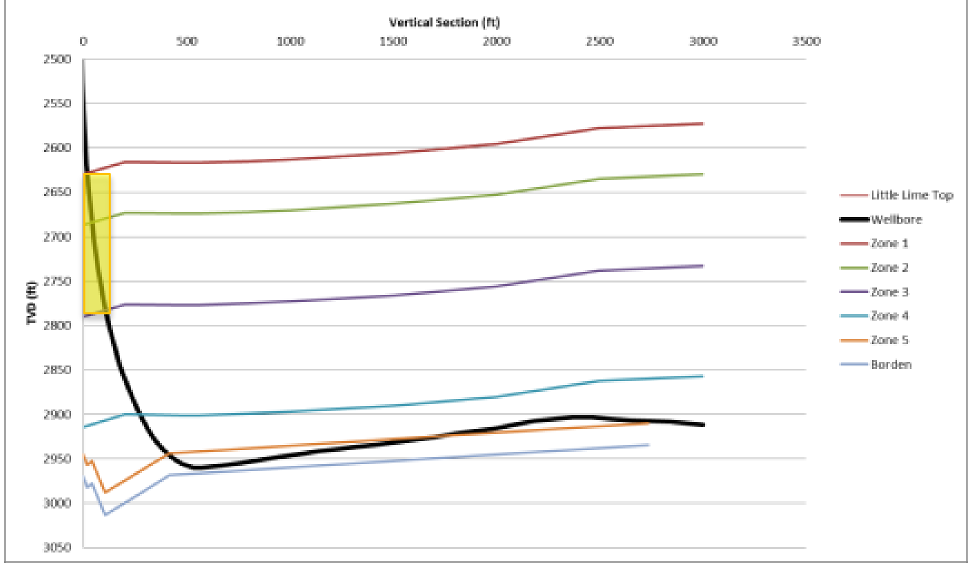
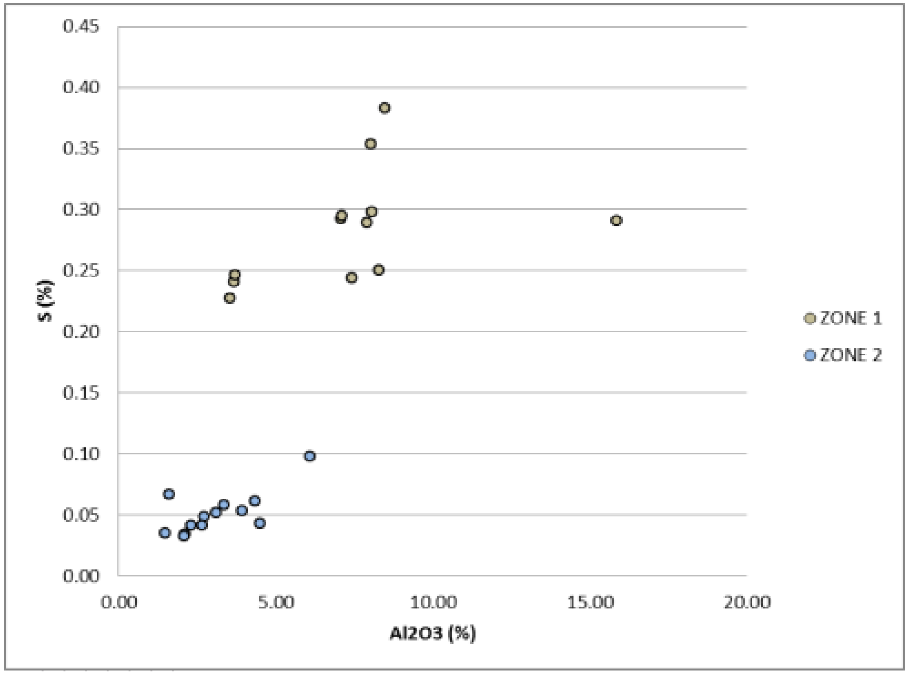
- Upper Pennington shale section
- Middle Upper Pennington shale section
- Lower Upper Pennington shale section
- Zone 1 chemistry

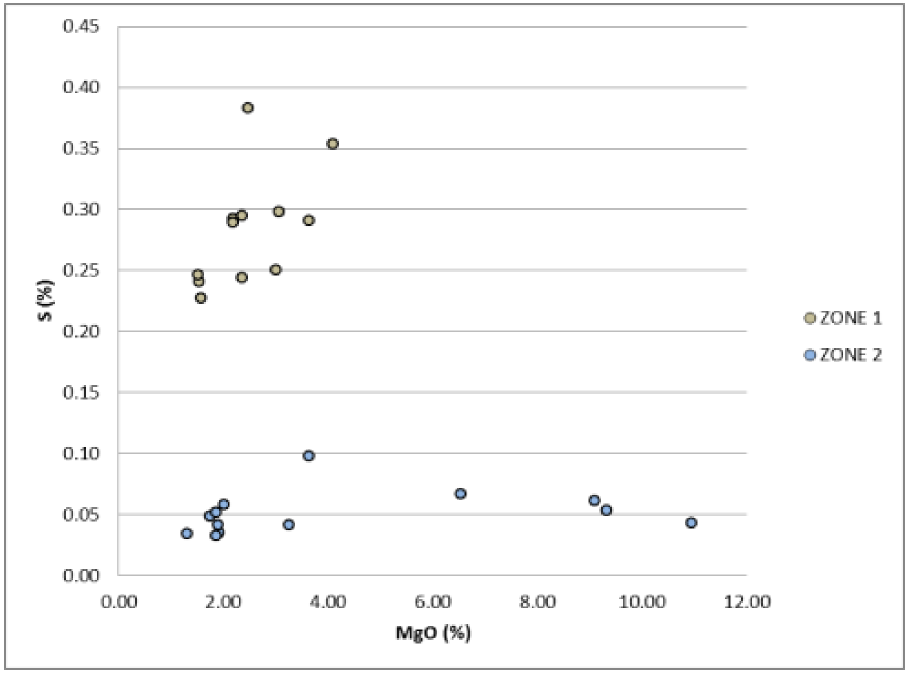
DRILLING THE CURVE

- Zone 1: increased carbonate with elevated S

- Zone 2: marked decrease in S, reduction in clastics



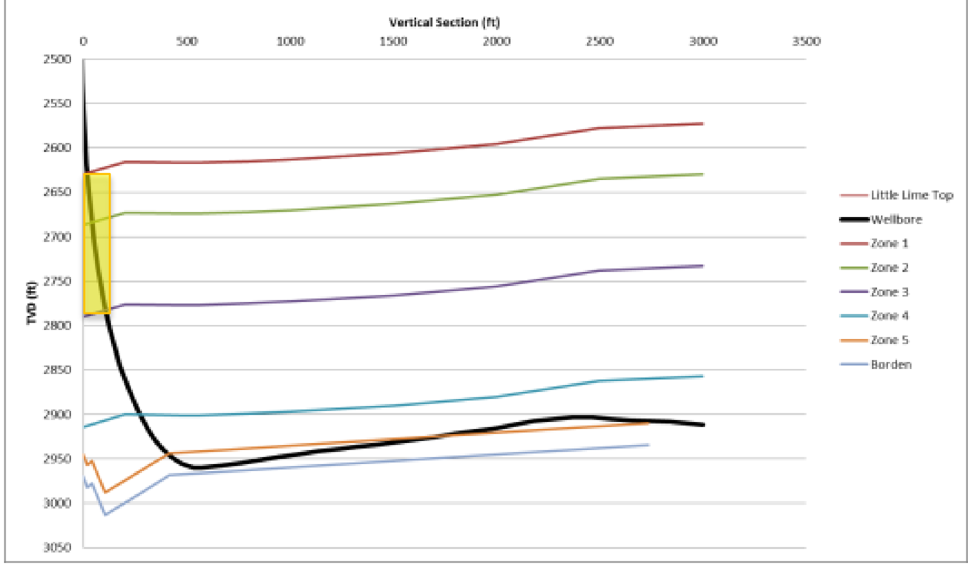


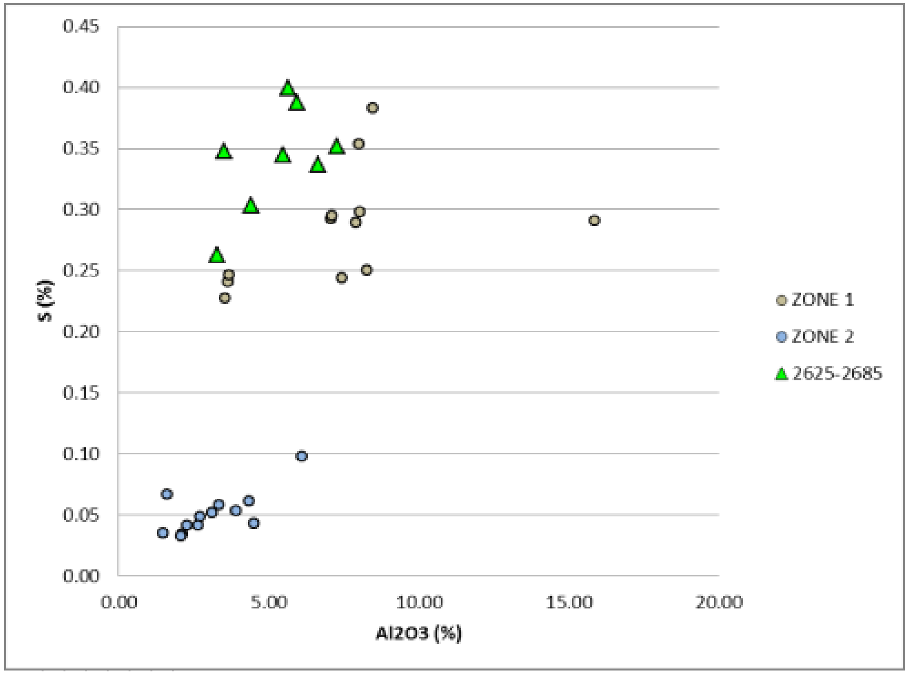


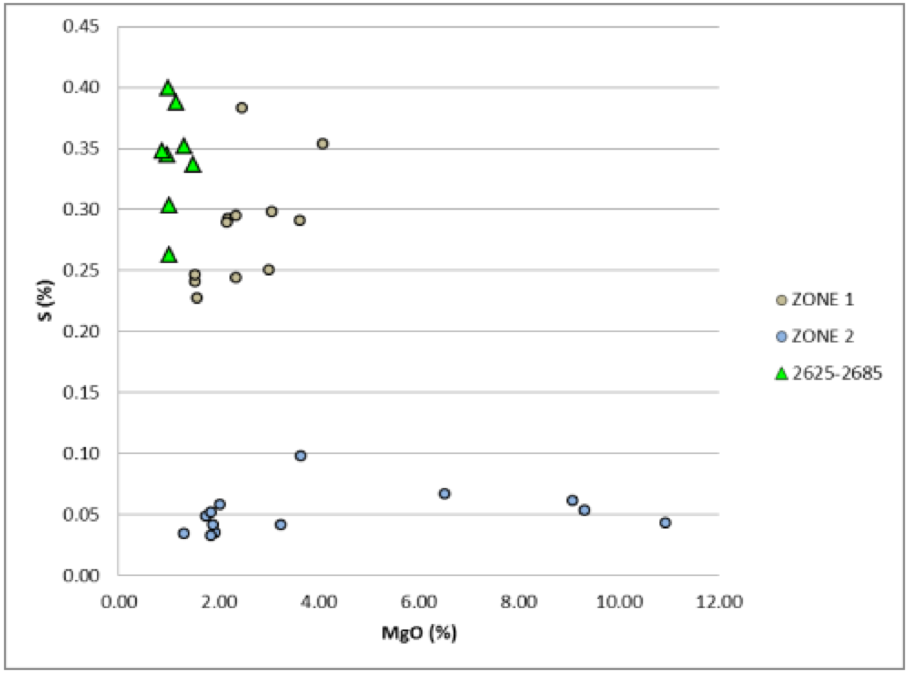
- Marked reduction in S denotes the boundary between Zone 1 and Zone 2

DRILLING THE CURVE

- **Zone 1: increased carbonate with elevated S**
- **Zone 2: marked decrease in S, reduction in clastics**







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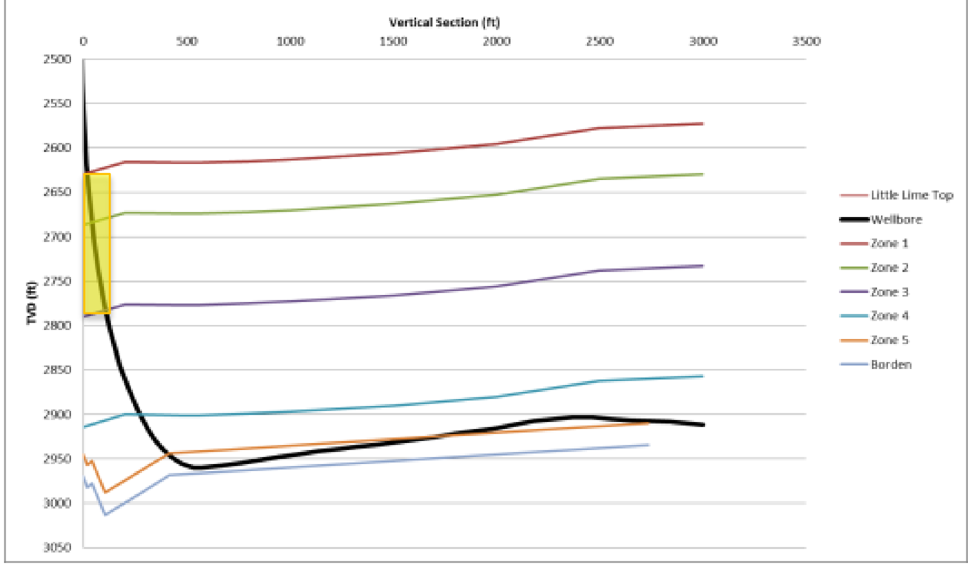
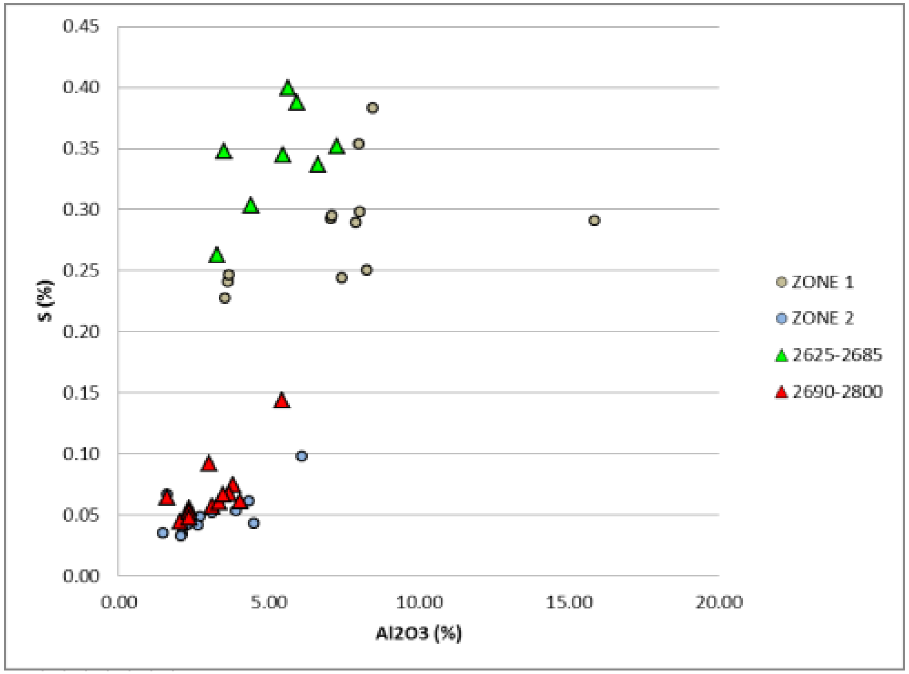
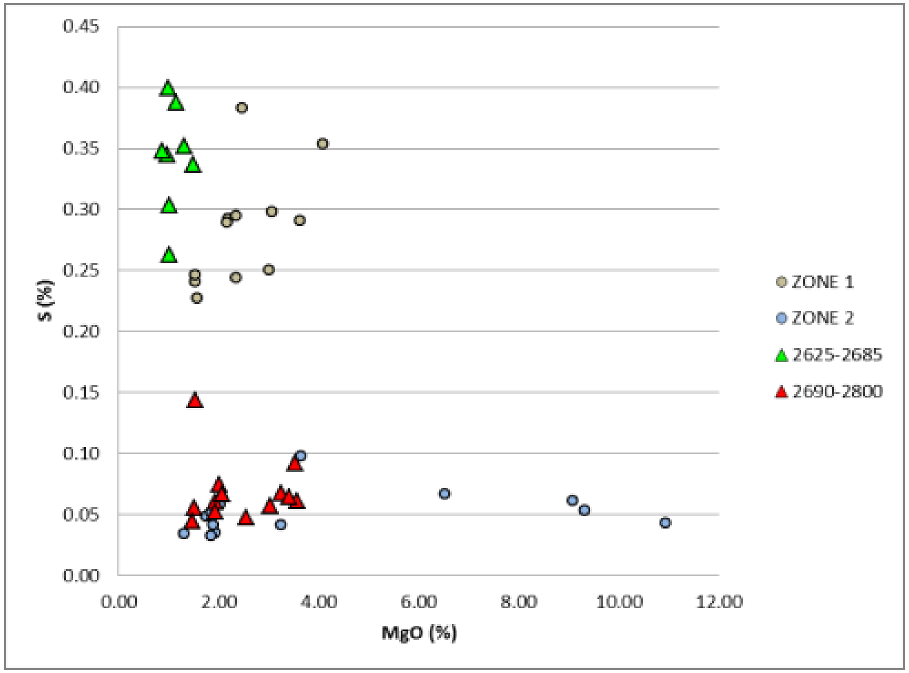


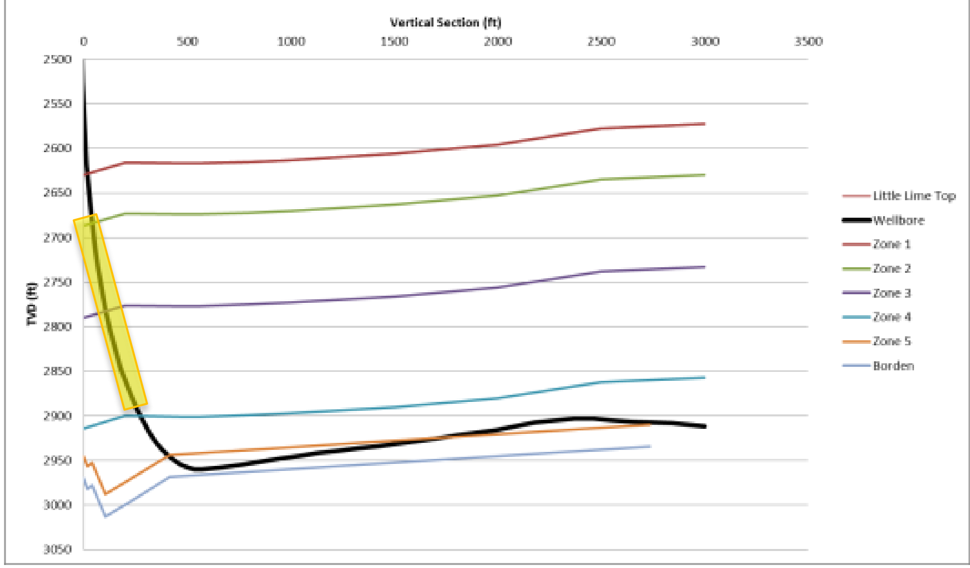


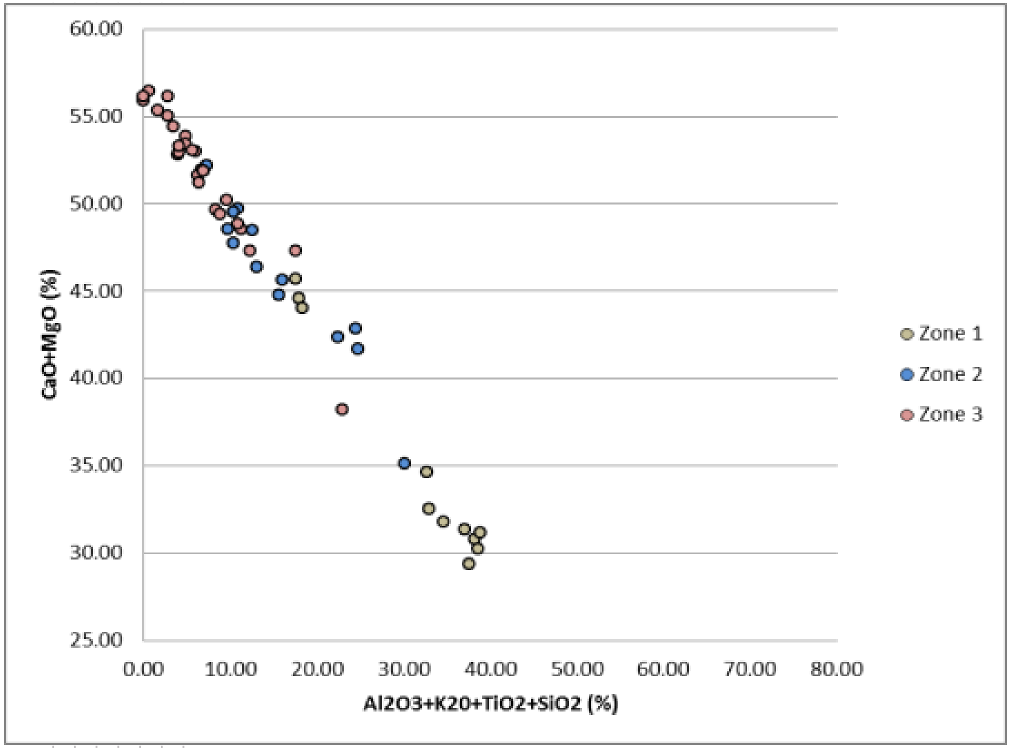


- **Marked reduction in S denotes the boundary between Zone 1 and Zone 2**

DRILLING THE CURVE

- **Zone 2: marked decrease in S, reduction in clastics**
- **Zone 3: further reduction in clastics high Sr**



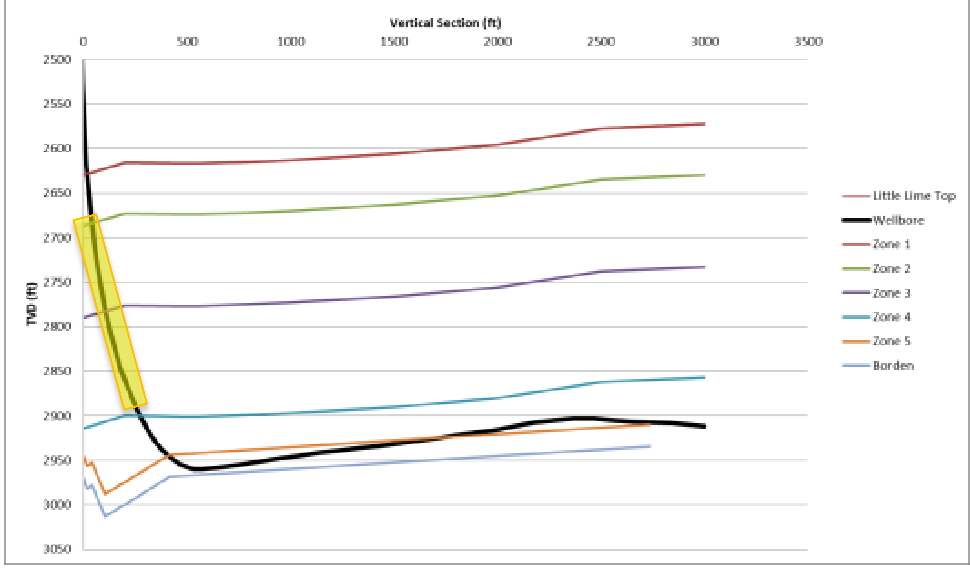


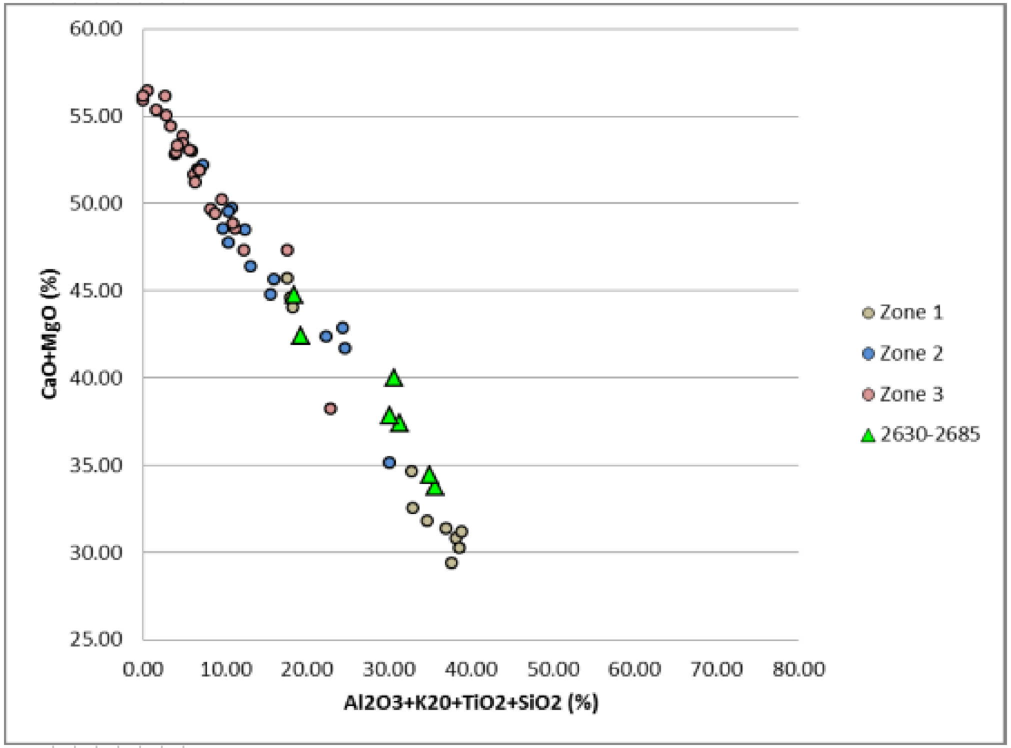
- **Reduction in clastic influx denotes Zones progressively deeper into the Big Lime**

DRILLING THE CURVE

- **Zone 2: marked decrease in S, reduction in clastics**

- **Zone 3: further reduction in clastics high Sr**





- **Reduction in clastic influx denotes Zones progressively deeper into the Big Lime**

- **Zone 1**

DRILLING THE CURVE

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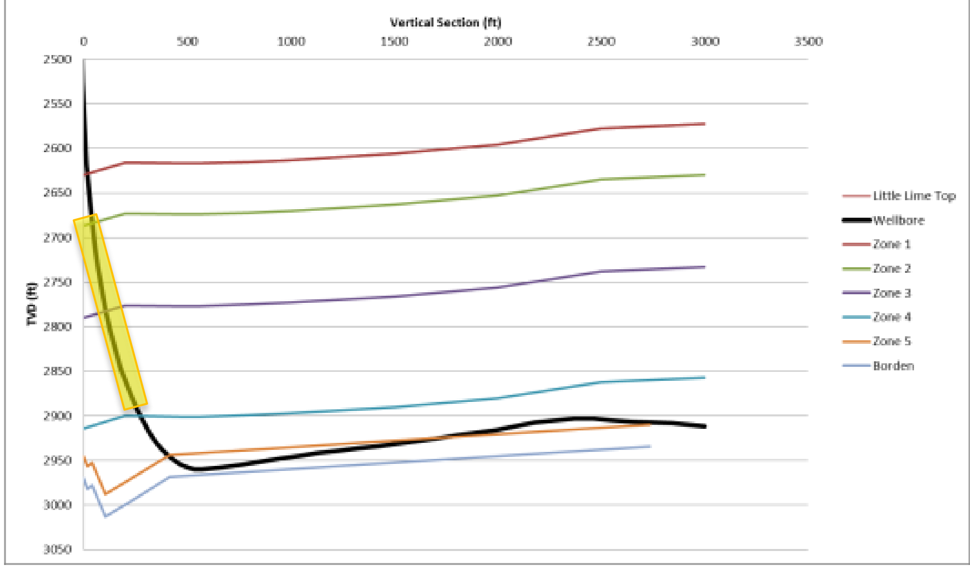

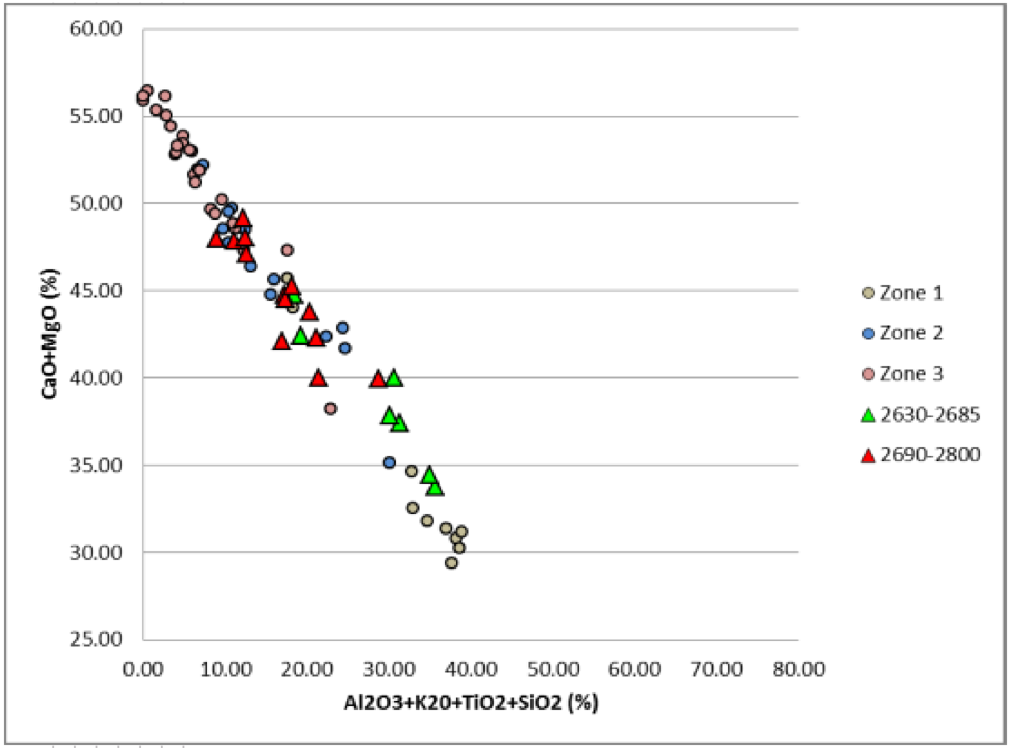

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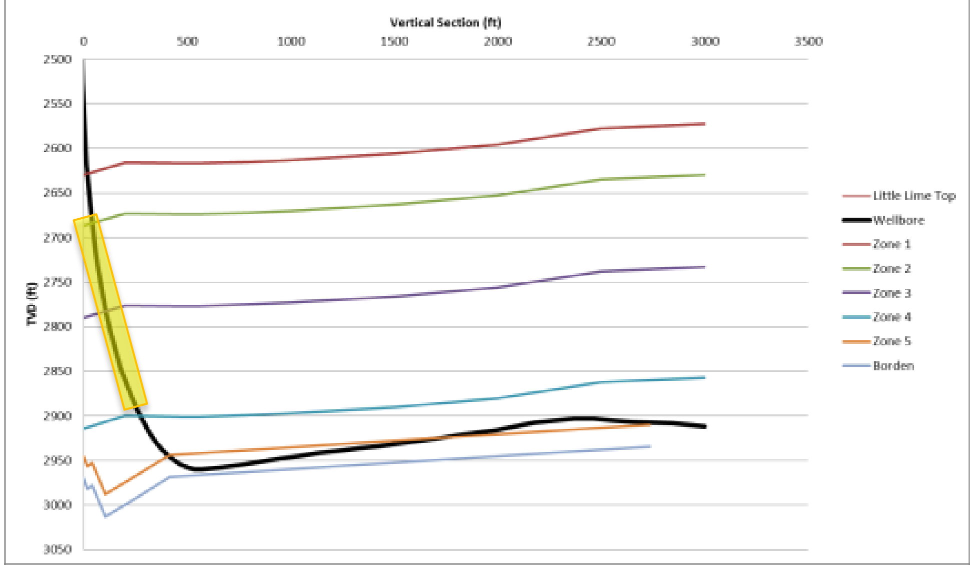

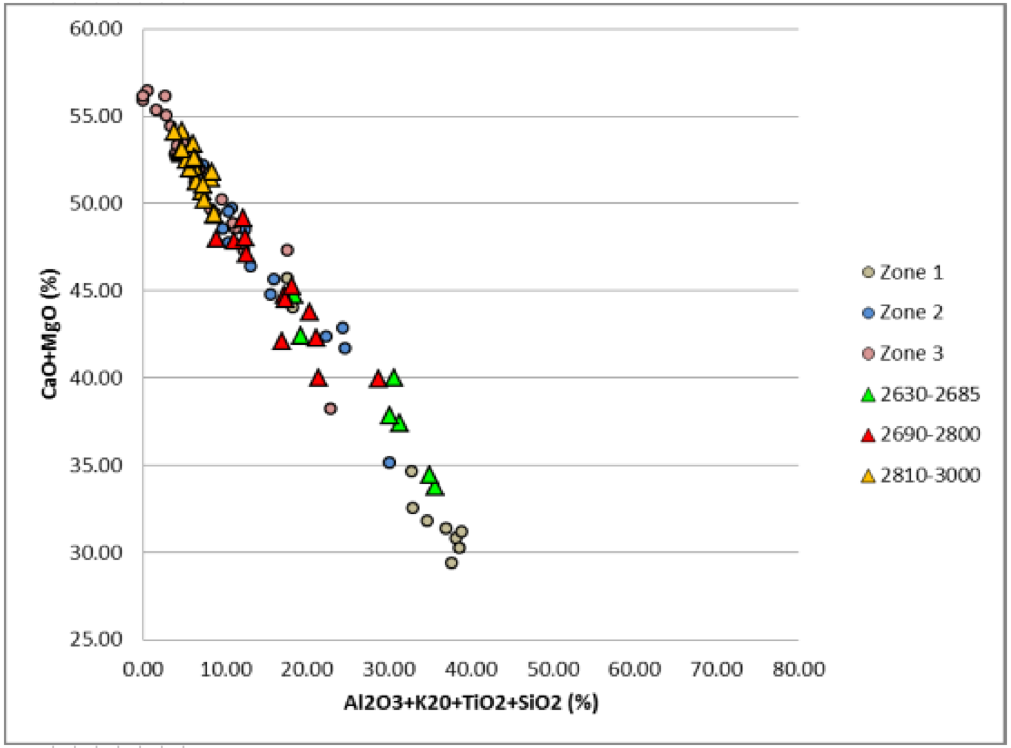

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- **Zone 1**
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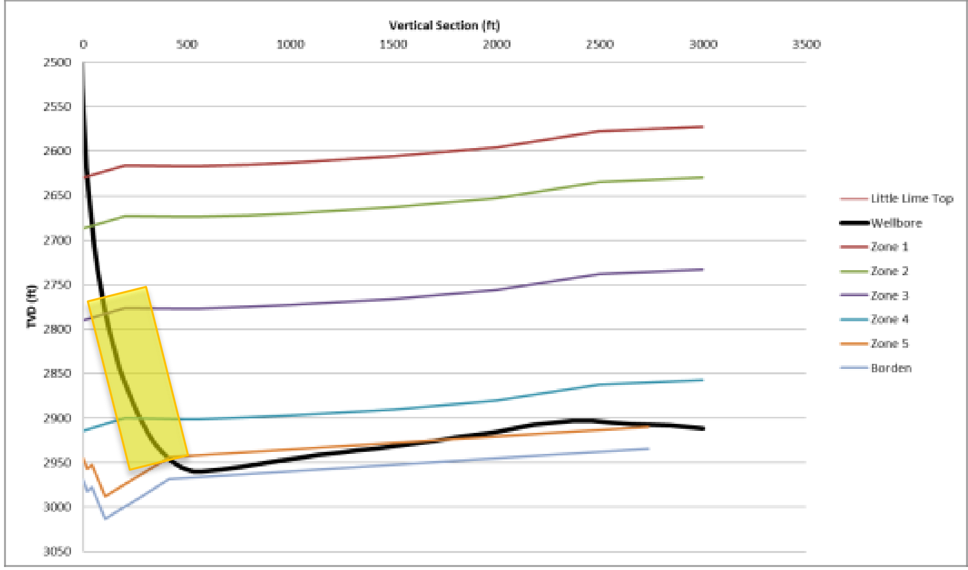
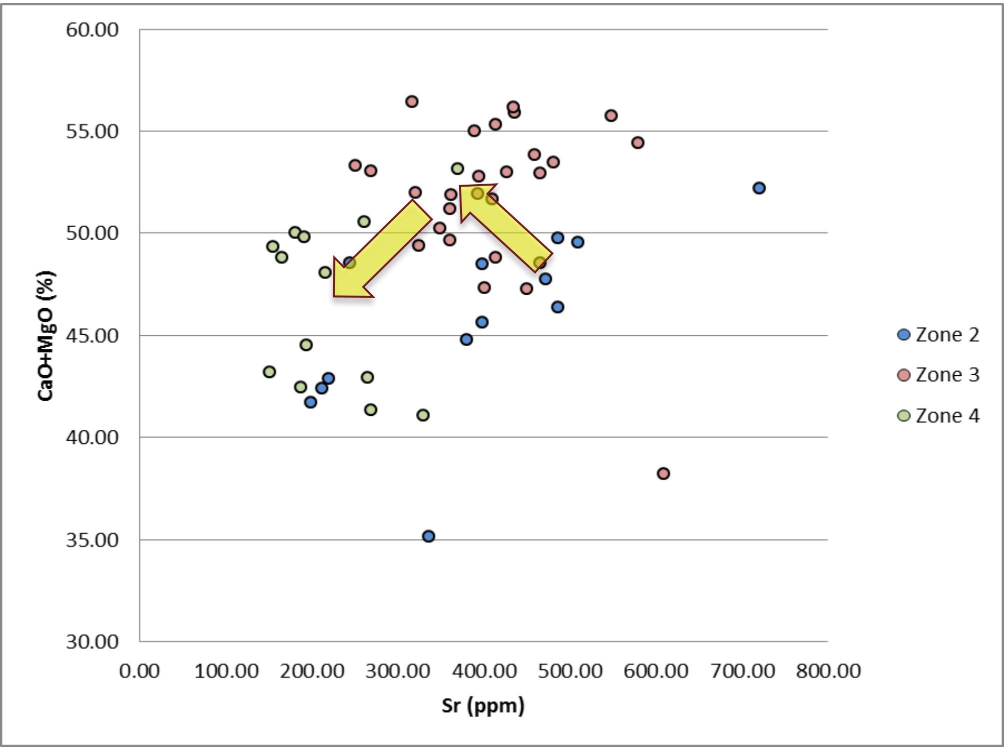
- **Zone 3**

DRILLING THE CURVE

- **Zone 3: further reduction in clastics high Sr**
- **Zone 4: marked reduction in Sr, variable occurrence of dolomite**

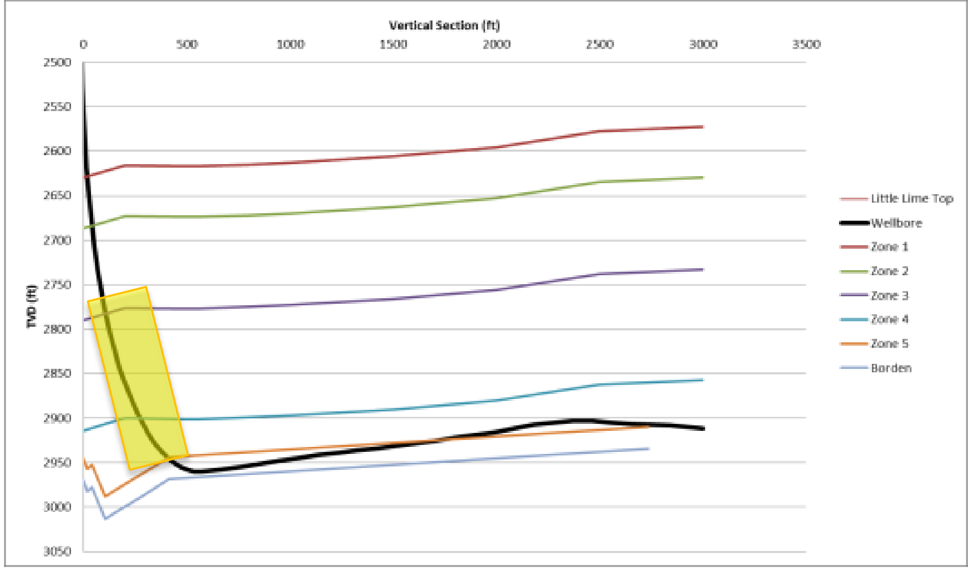


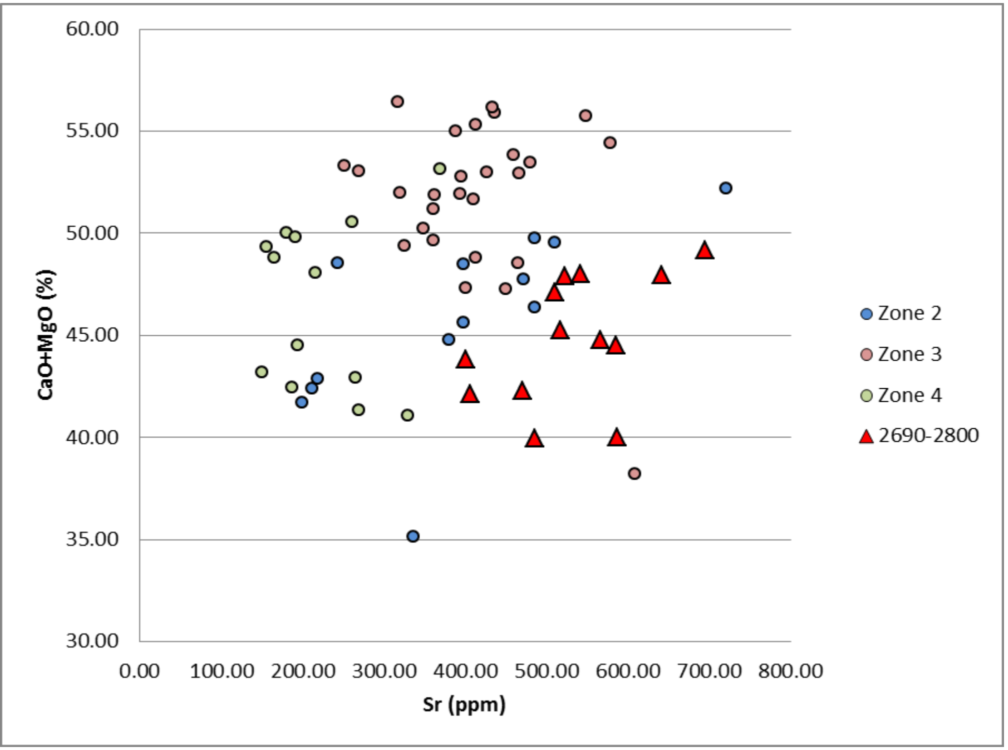


- **Stepwise drop in Sr levels denotes transition from Zone 2 to Zone 3 to Zone 4.**

DRILLING THE CURVE

- **Zone 3: further reduction in clastics high Sr**
- **Zone 4: marked reduction in Sr, variable occurrence of dolomite**





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DRILLING THE CURVE

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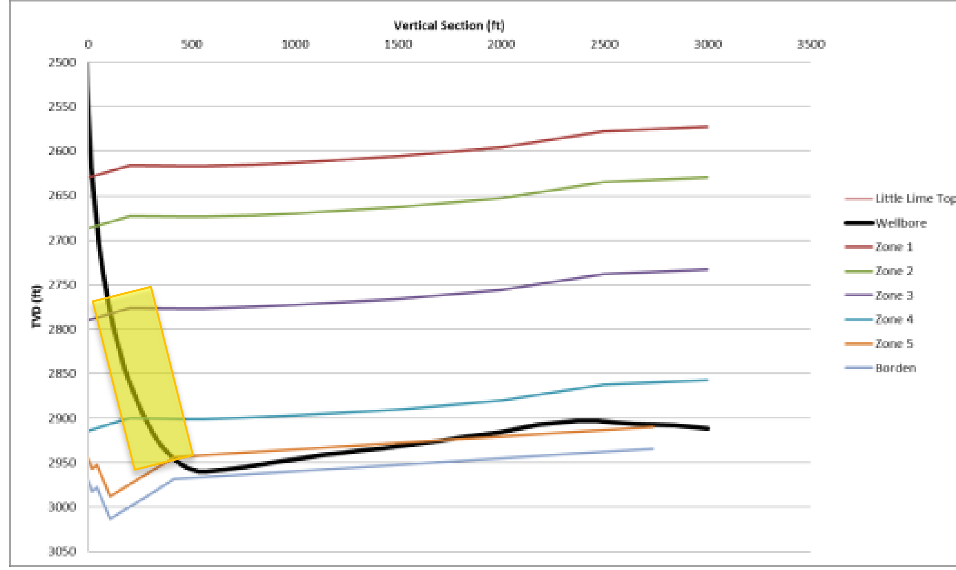

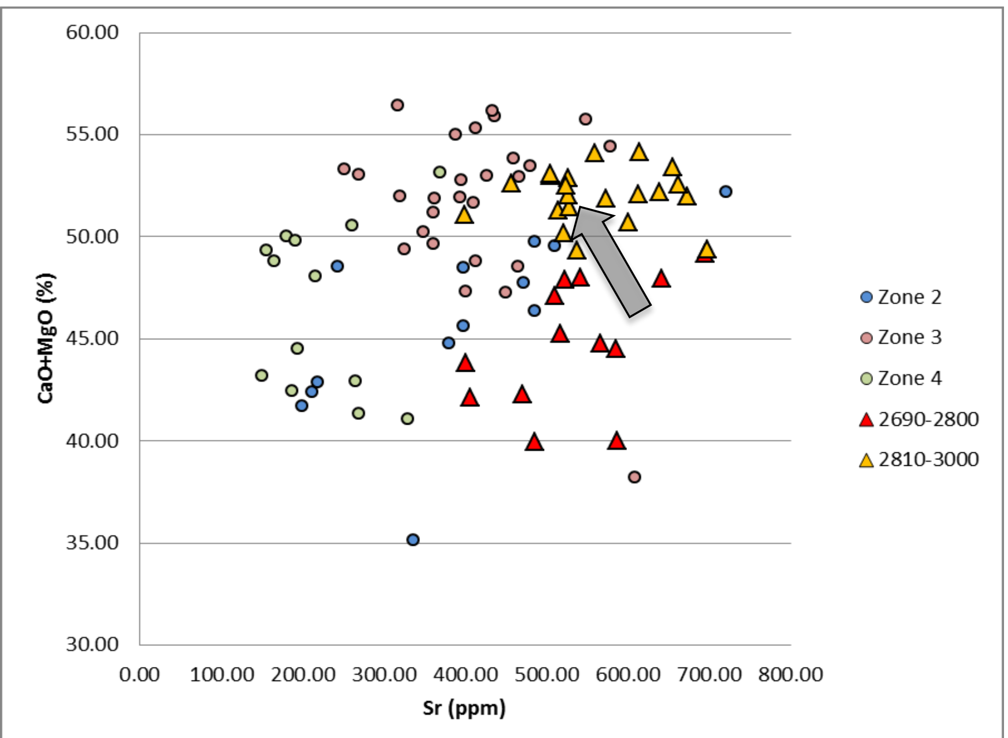

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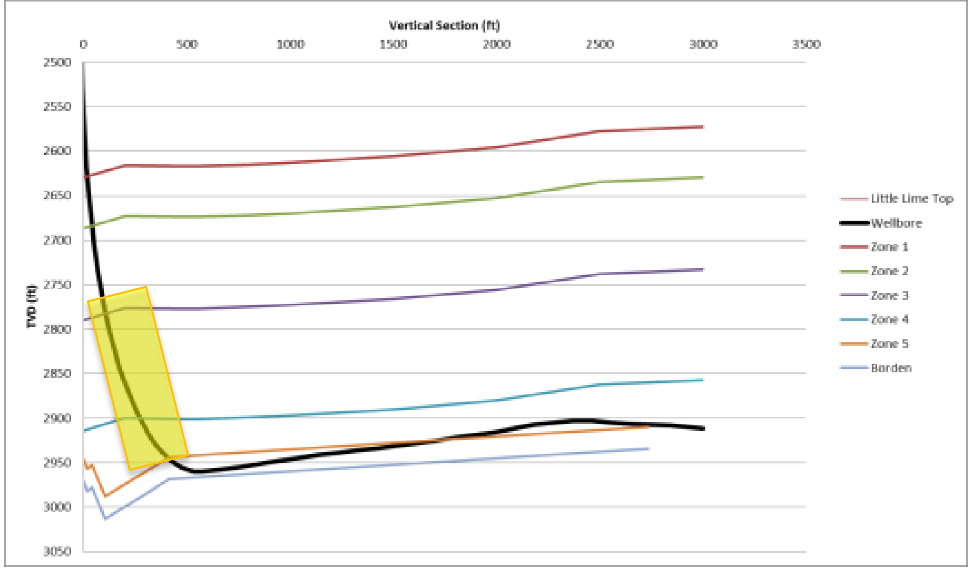

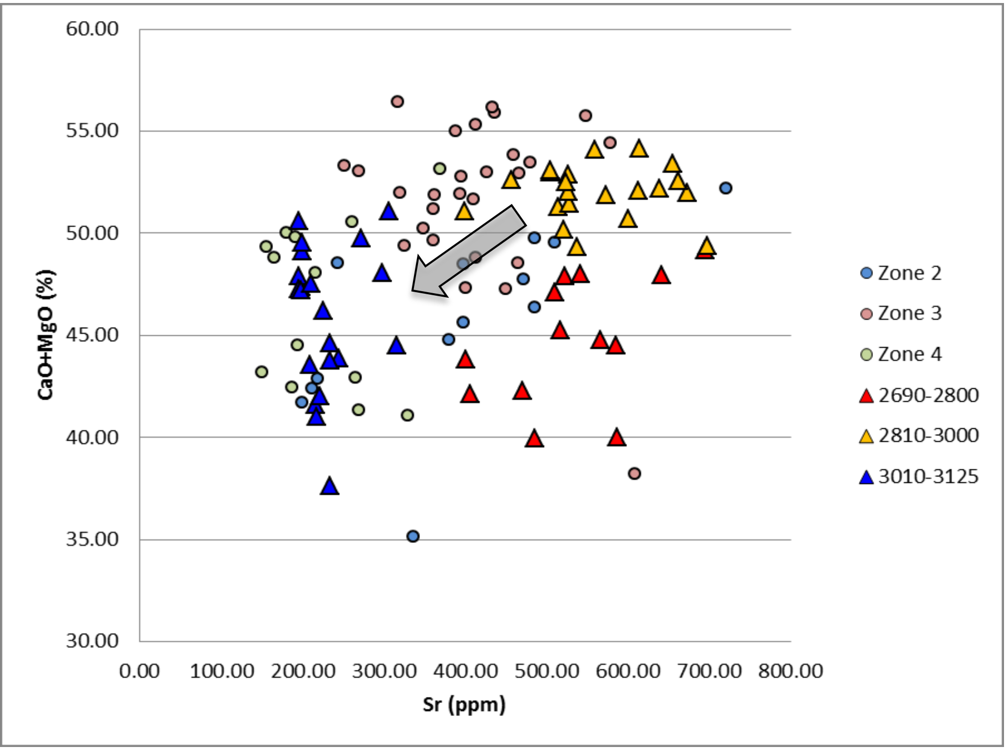

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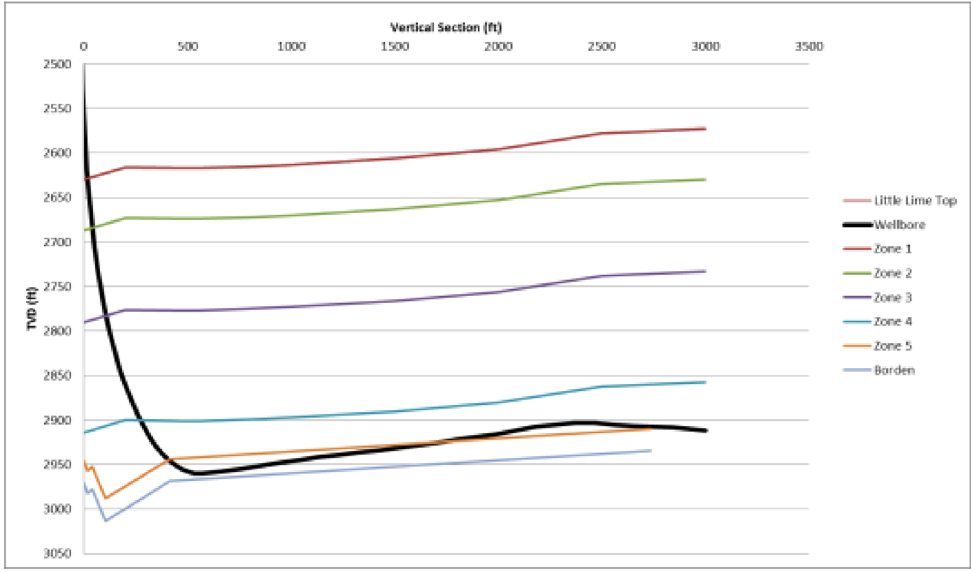
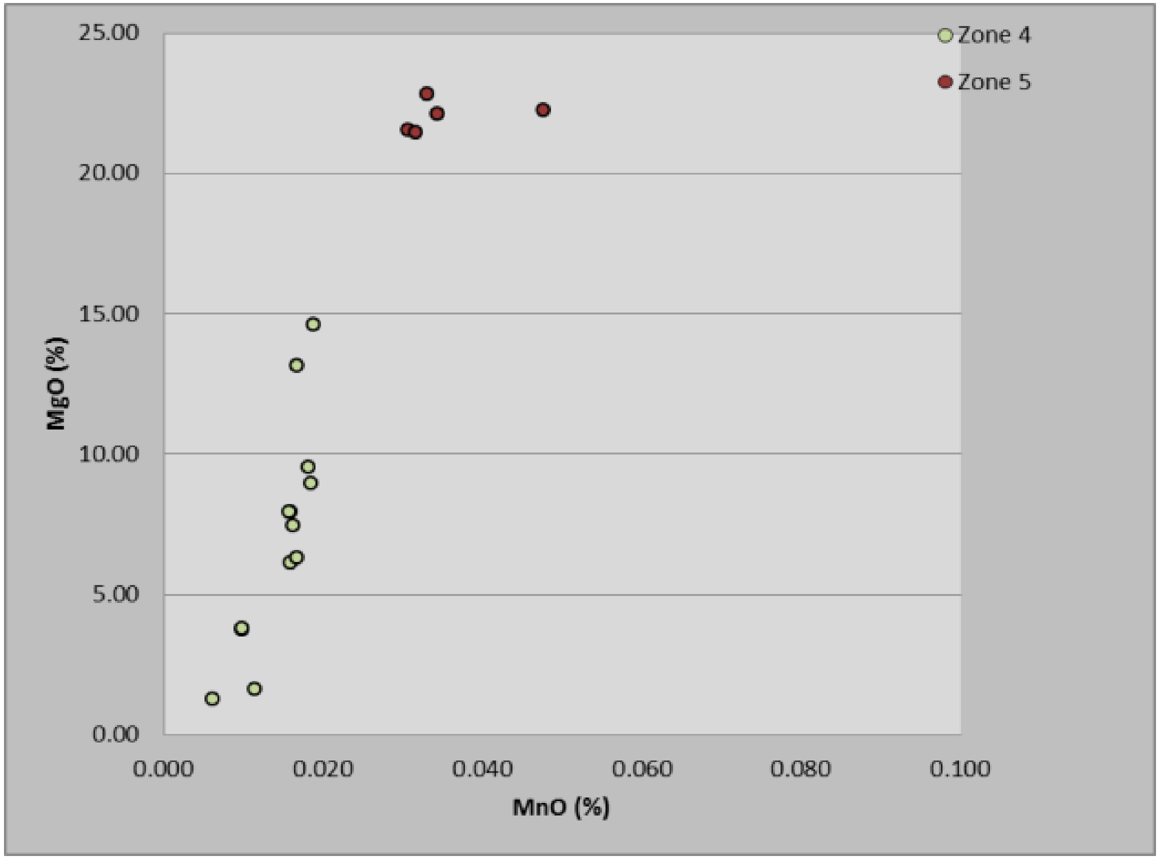
- **Zone 2**
- **Zone 3**
- **Zone 4**

LATERAL

- **Zone 4: marked reduction in Sr, variable occurrence of dolomite**
- **Zone 5: mainly dolomite with elevated Mn**

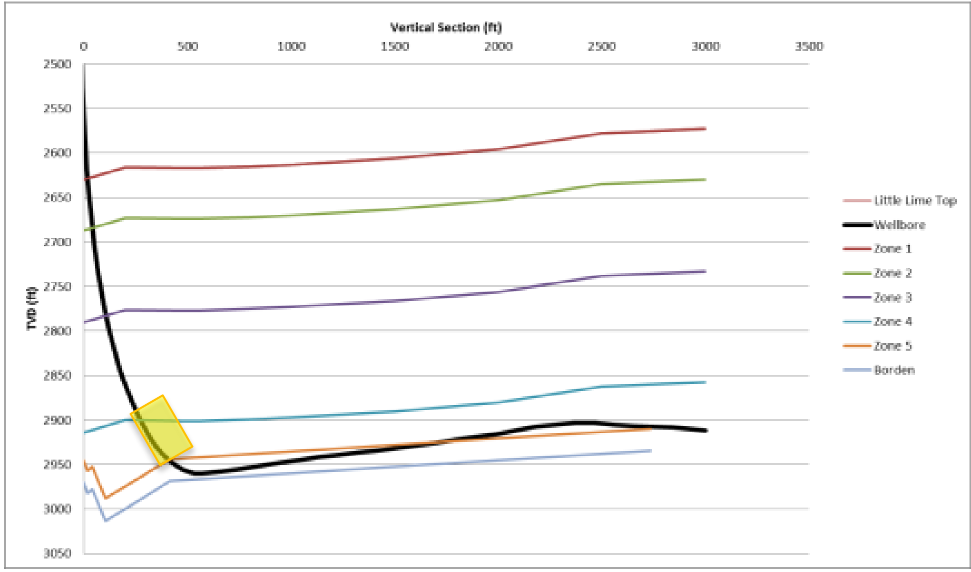


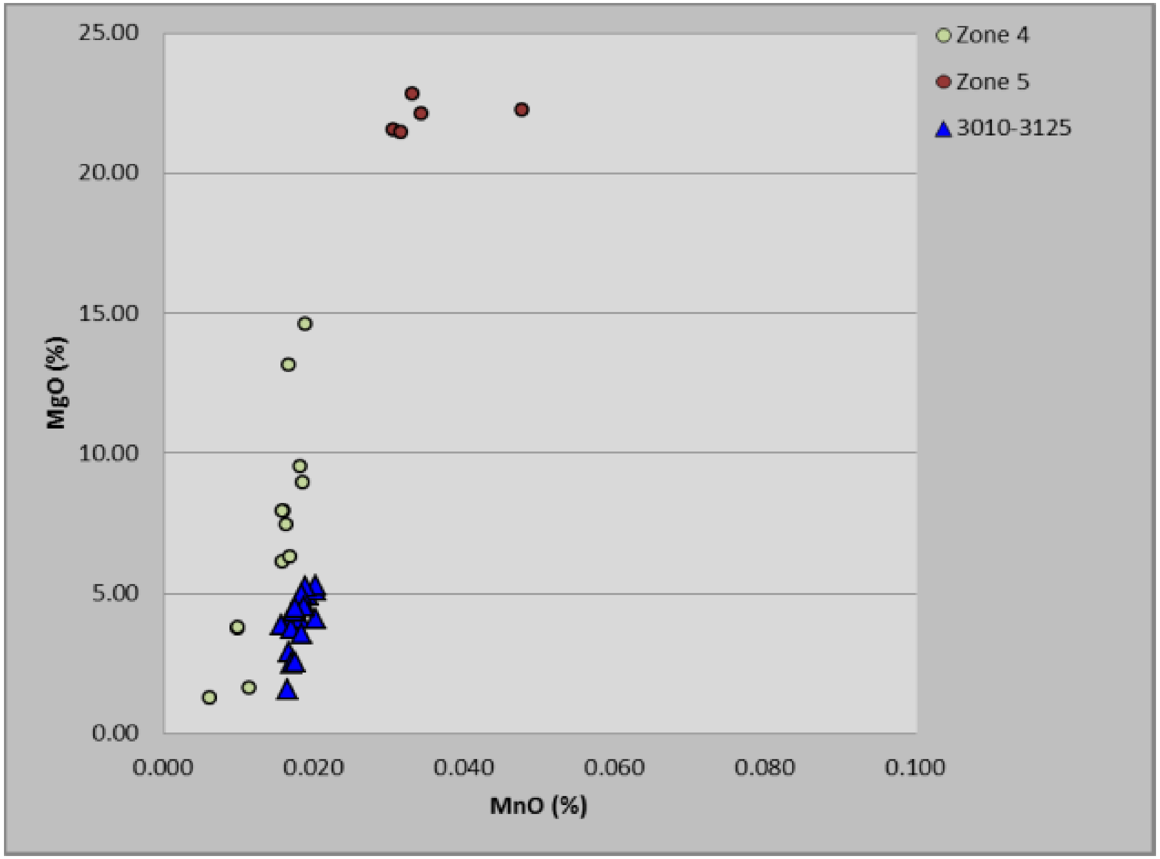


LATERAL

- **Zone 4: marked reduction in Sr, variable occurrence of dolomite**

- **Zone 5: mainly dolomite with elevated Mn**



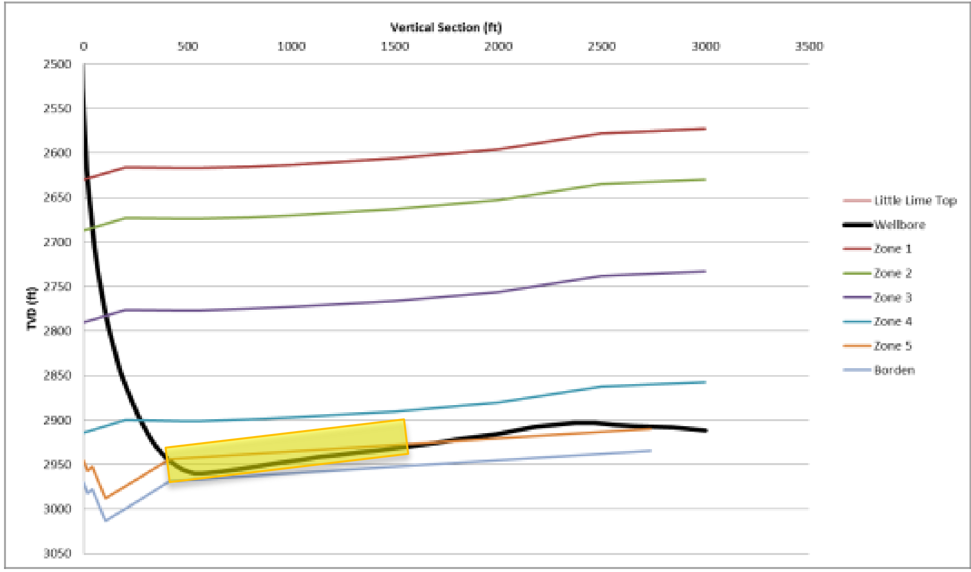


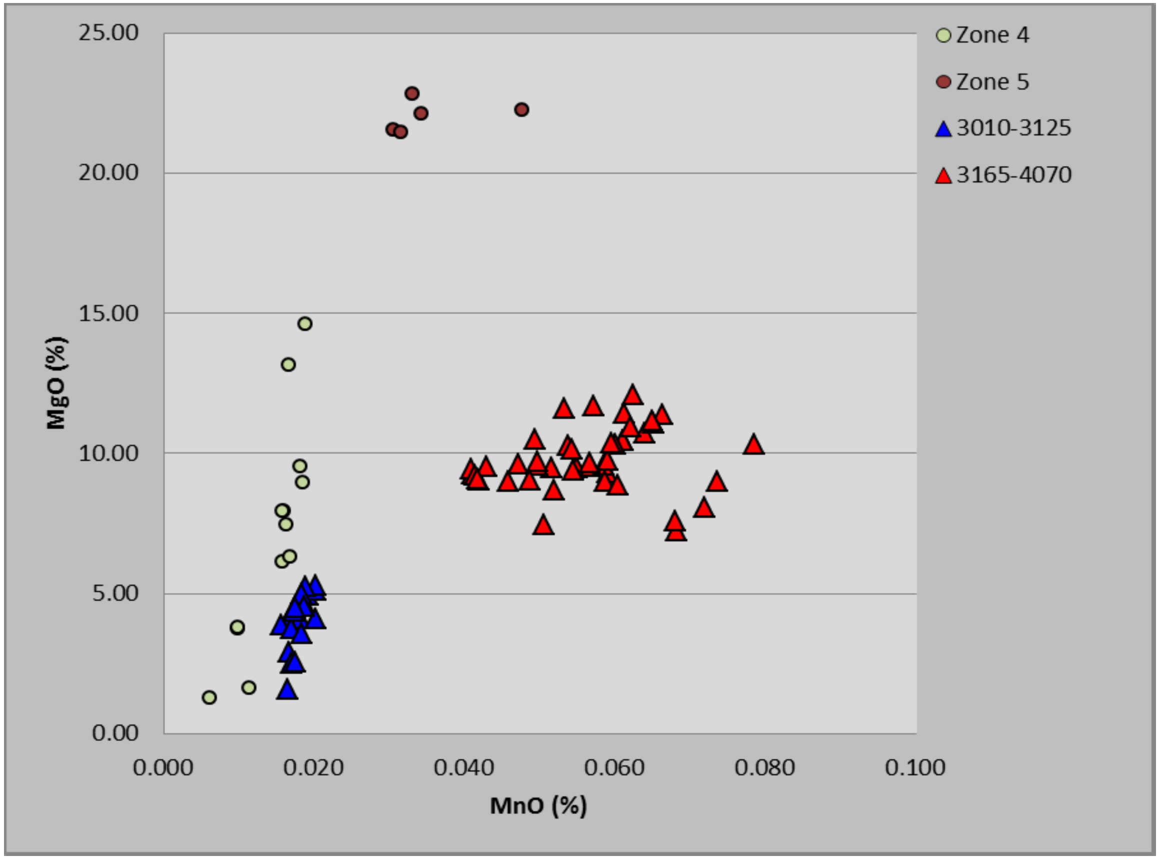
- **Zone 4 (landing)**

LATERAL

- **Zone 4: marked reduction in Sr, variable occurrence of dolomite**

- **Zone 5: mainly dolomite with elevated Mn**

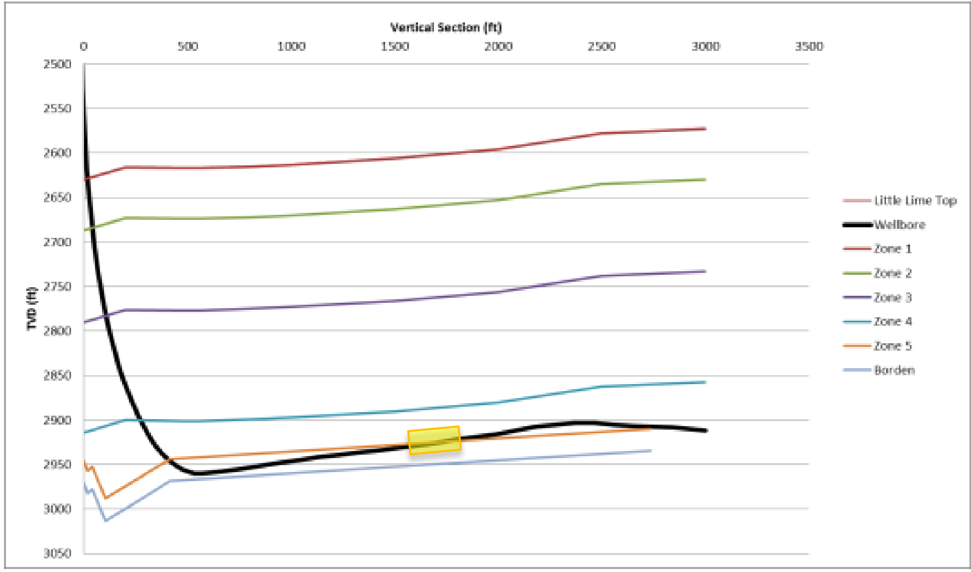


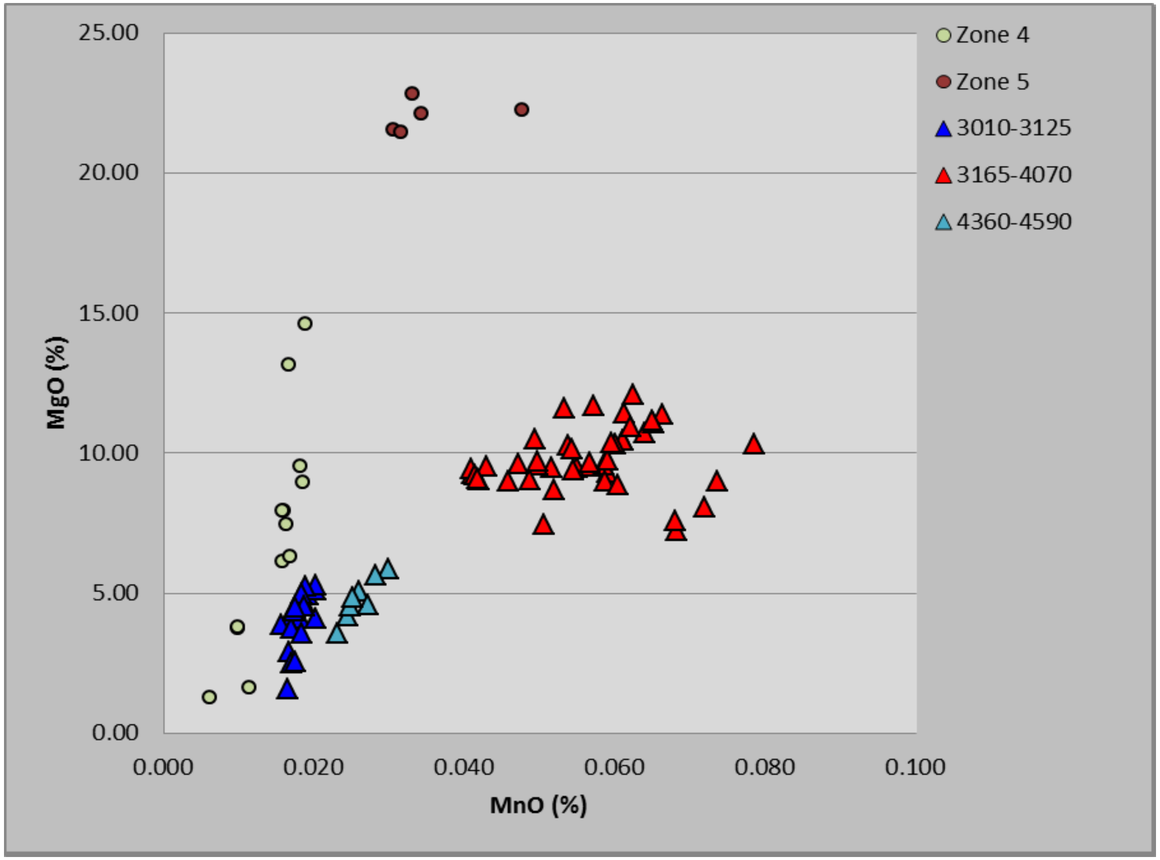


- **Zone 4 (landing)**
- **Zone 5 (do not see levels of Mg seen in pilot hole)**

LATERAL

- **Zone 4: marked reduction in Sr, variable occurrence of dolomite**
- **Zone 5: mainly dolomite with elevated Mn**



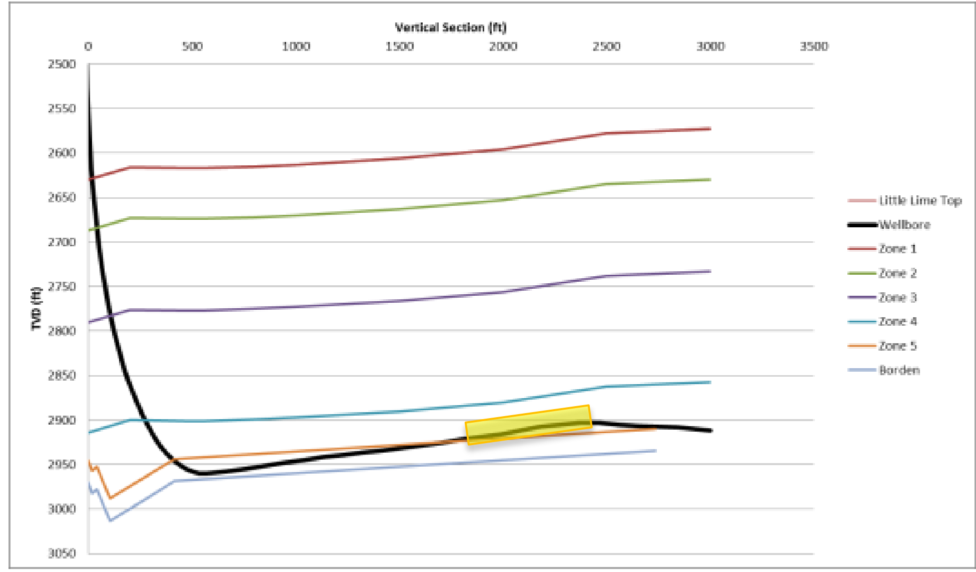


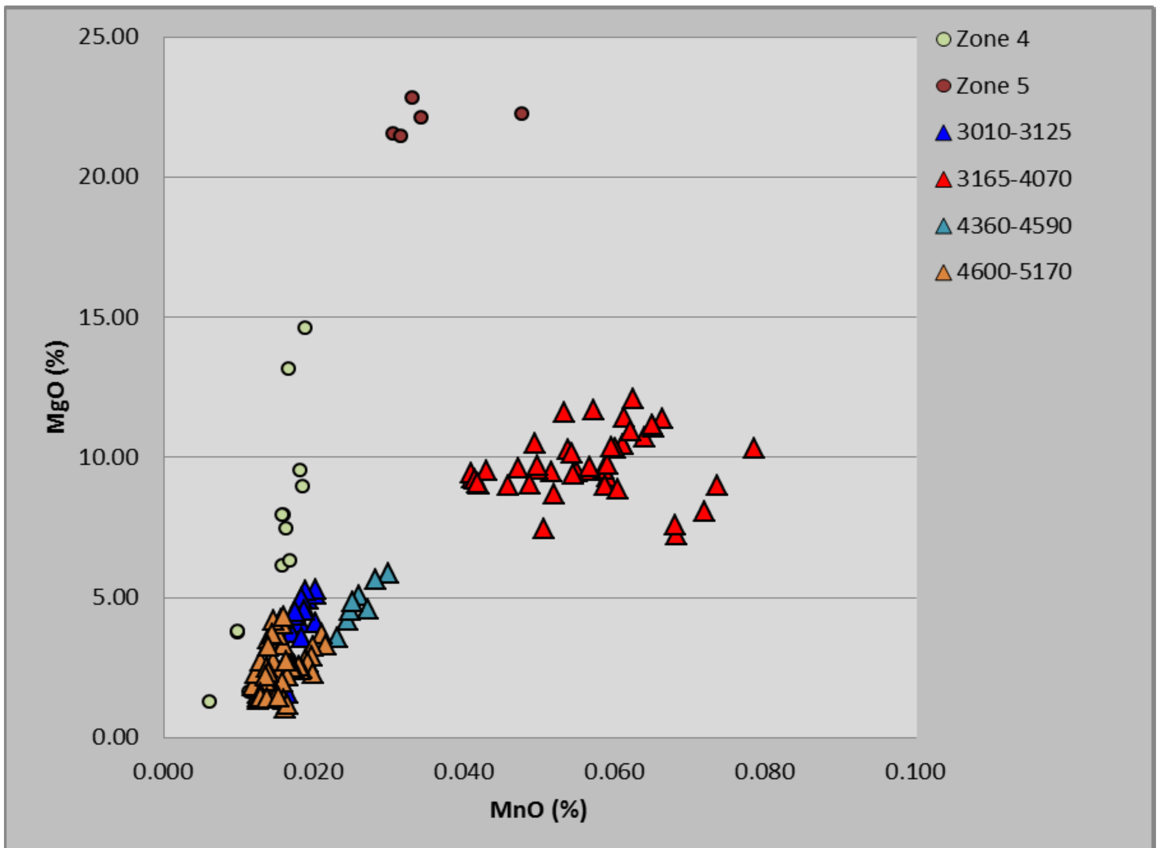
- **Zone 4 (landing)**
- **Zone 5 (do not see levels of Mg seen in pilot hole)**
- **Zone 4 chemistry slightly dolomitic**

LATERAL

- **Zone 4: marked reduction in Sr, variable occurrence of dolomite**

- **Zone 5: mainly dolomite with elevated Mn**





- **Zone 4 (landing)**
- **Zone 5 (do not see levels of Mg seen in pilot hole)**

- **Zone 4 chemistry slightly dolomitic**
- **Zone 4 chemistry limestone similar to what was seen while landing**

LATERAL

- **Zone 4: marked reduction in Sr, variable occurrence of dolomite**
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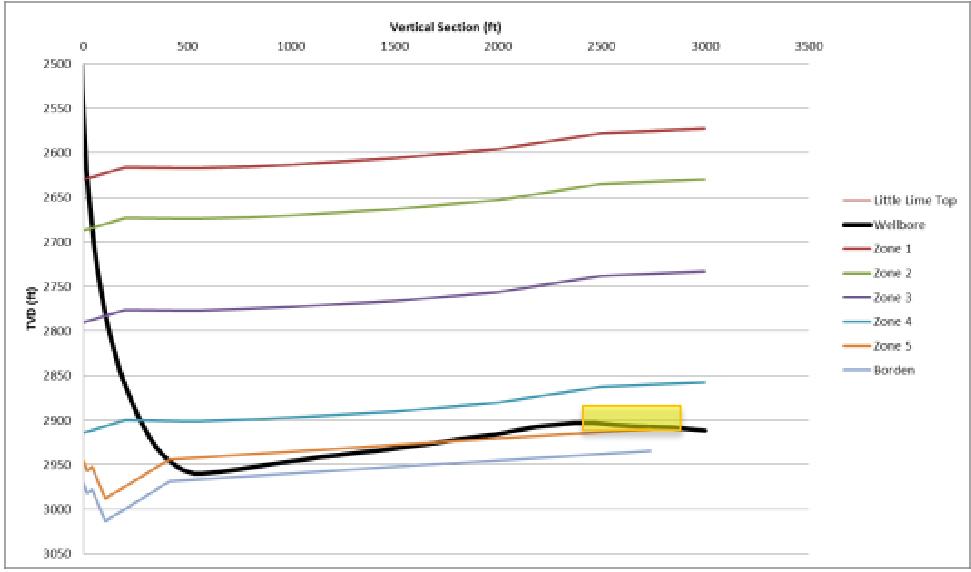
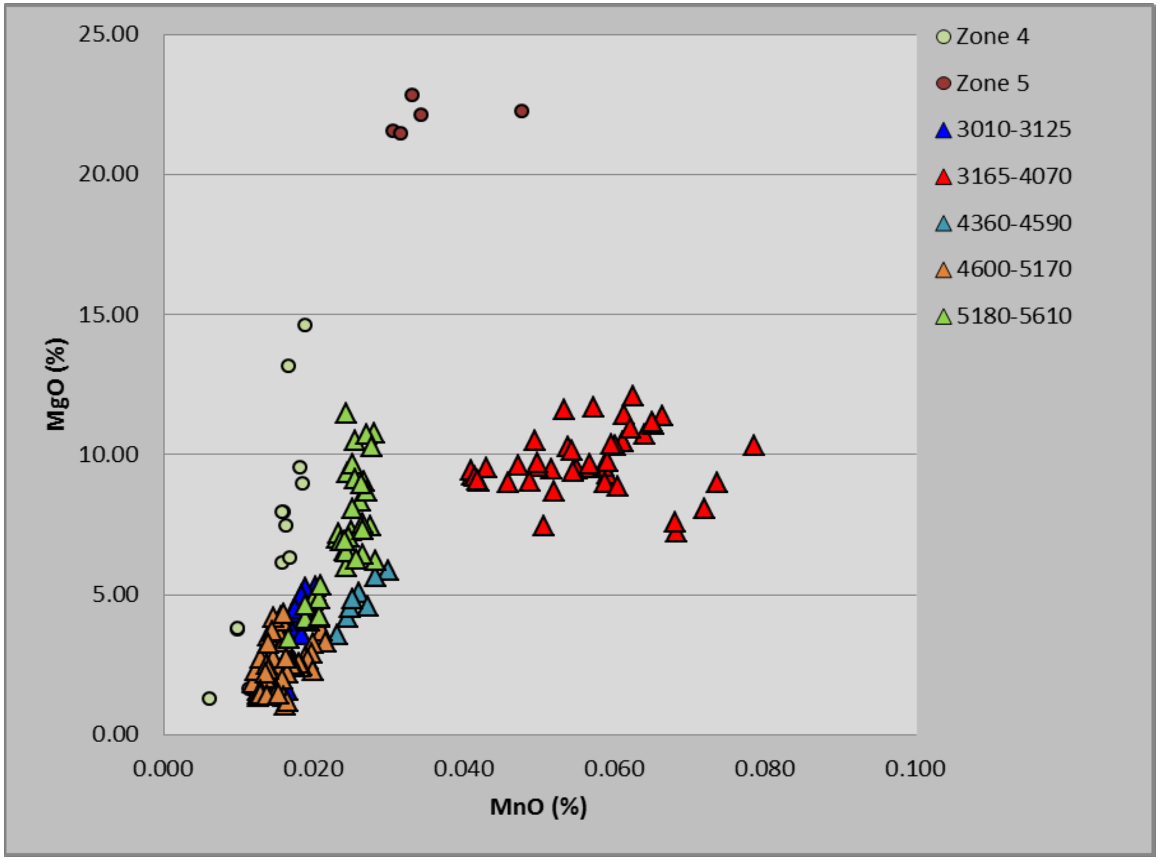


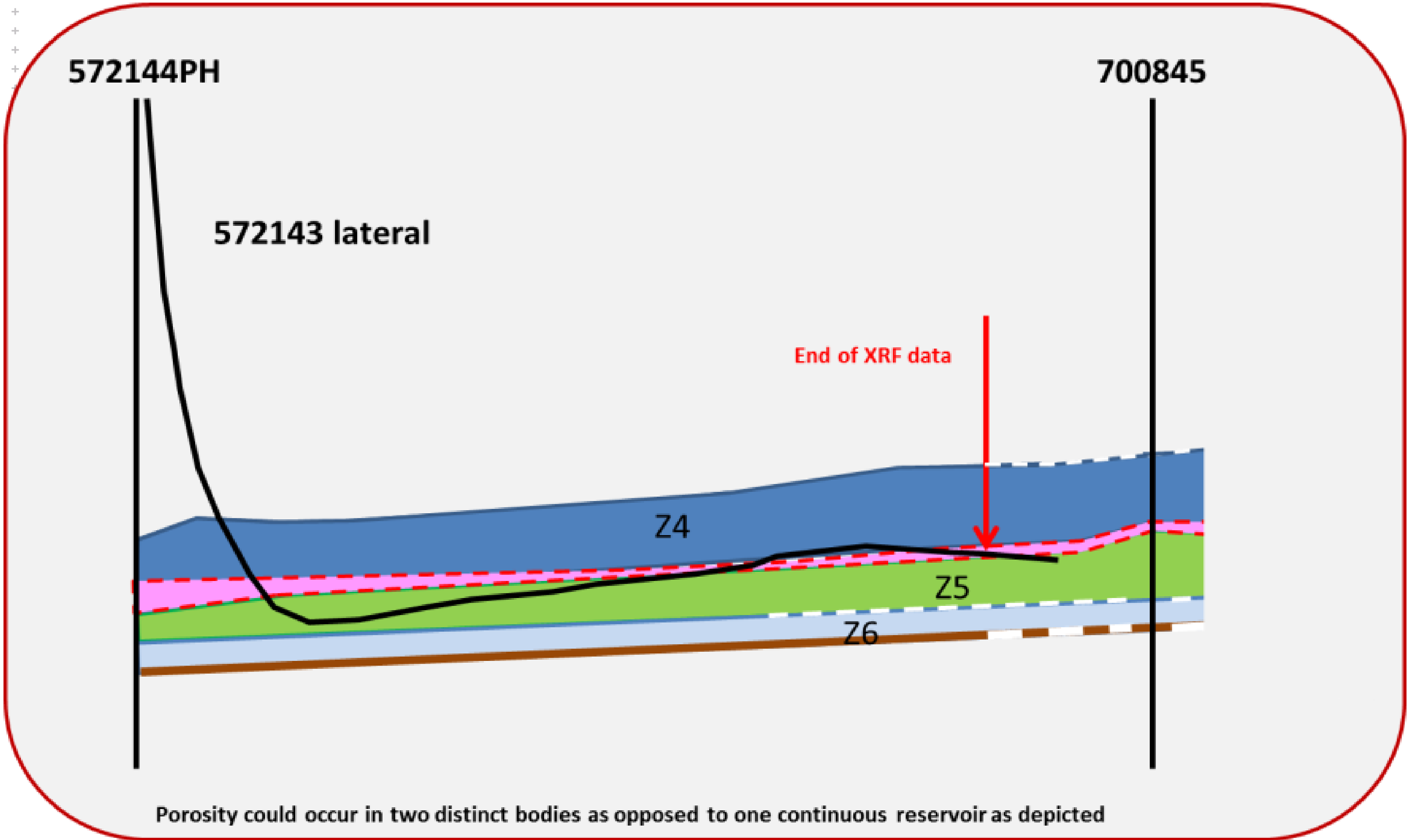


- **Zone 4 (landing)**
- **Zone 5 (do not see levels of Mg seen in pilot hole)**
- **Zone 4 chemistry slightly dolomitic**
- **Zone 4 chemistry limestone similar to what was seen while landing**
- **Data ends in Zone 4 chemistry with elevated limestone abundance**

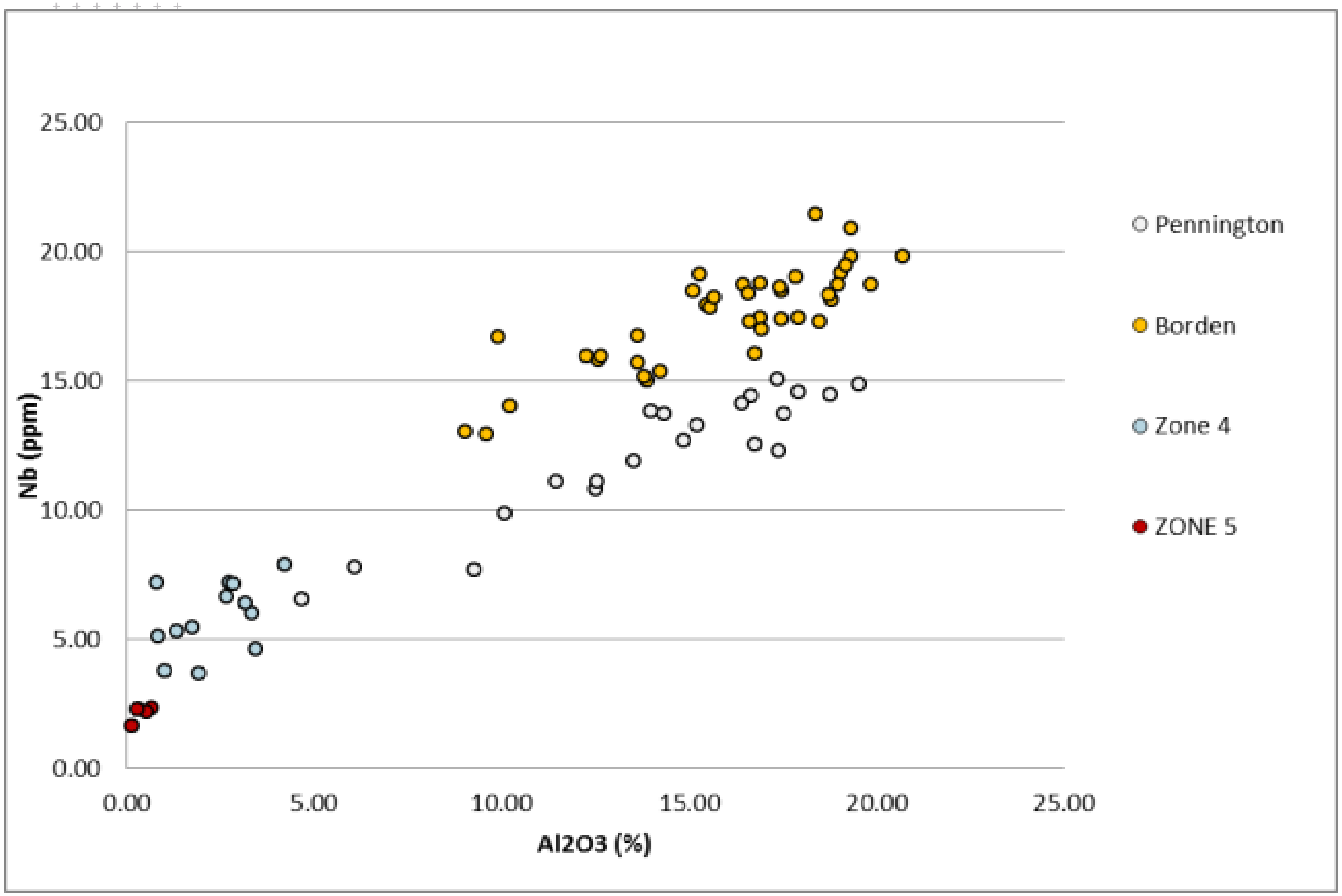
CARTOON MODEL OF RESERVOIR

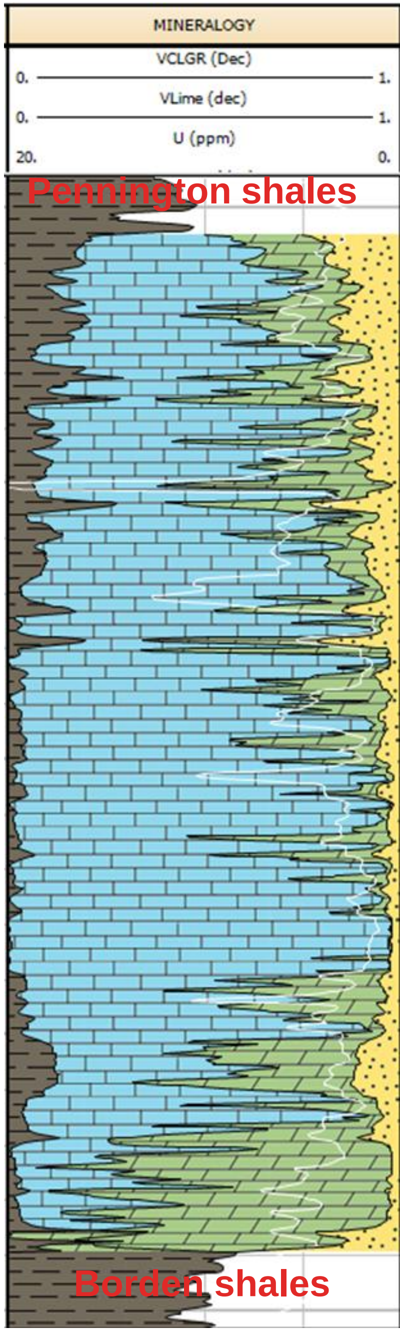
- **Model proposed to explain observations seen in the well**

- **Wellbore landed in Zone 5 although it was not as dolomitic as the pilot hole indicated**
- **Drilled out of the dolomite into limestone followed by dolomitic limestone**
- **Based on offset log data, structure, and wellbore trajectory, the wellbore likely passed back into Zone 5 dolomitic reservoir near TD.**



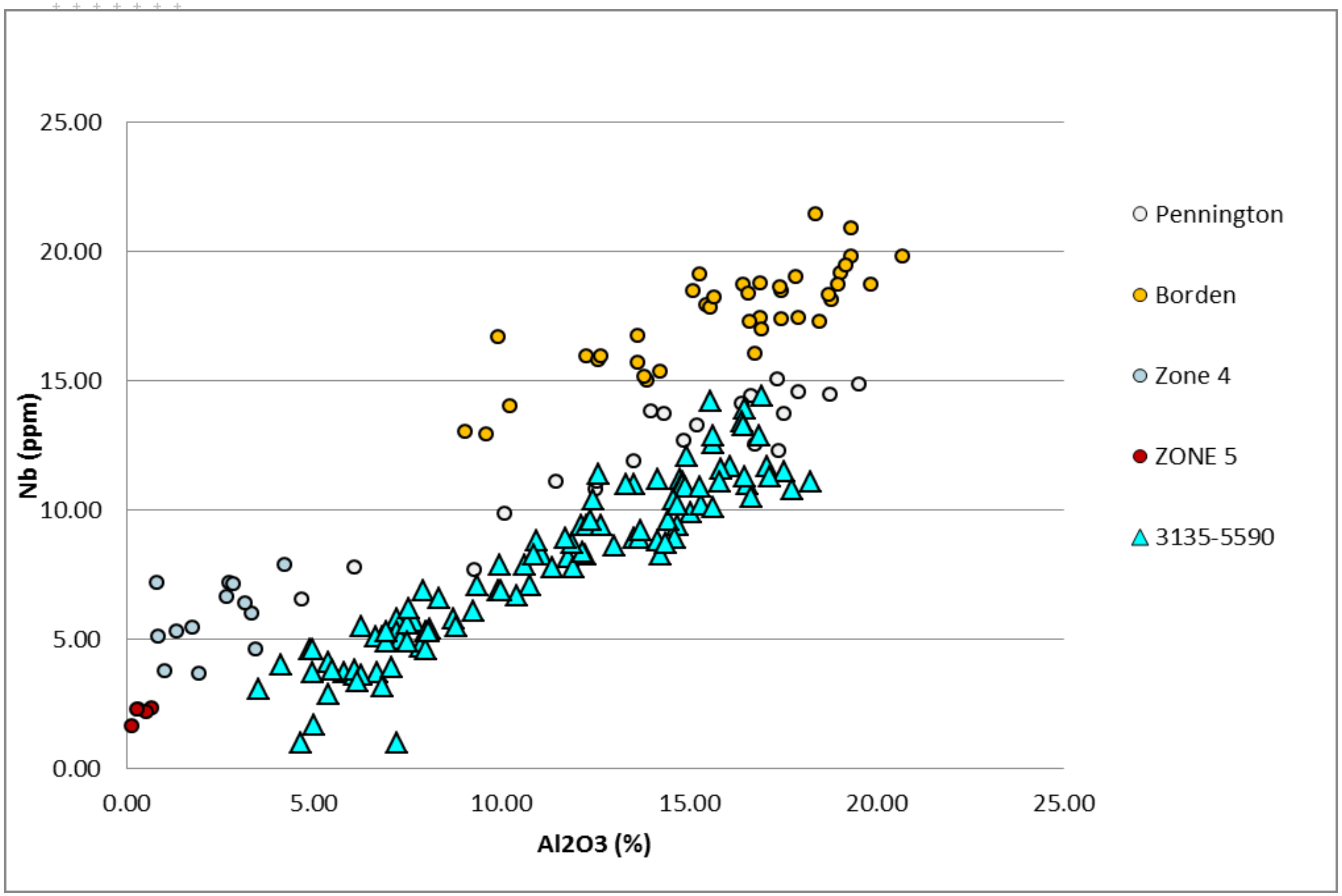
IDENTIFYING BORDEN VS CAVE-INS

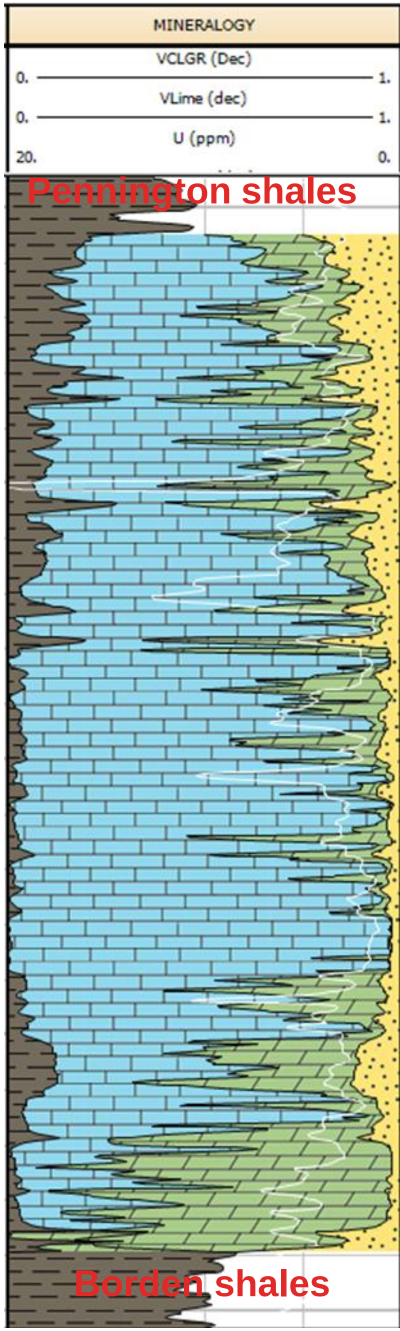




- White circles indicate Pennington trendline, yellow the Borden.
- On multiple cross plots all samples plot along the Pennington trend.

IDENTIFYING BORDEN VS CAVE-INS





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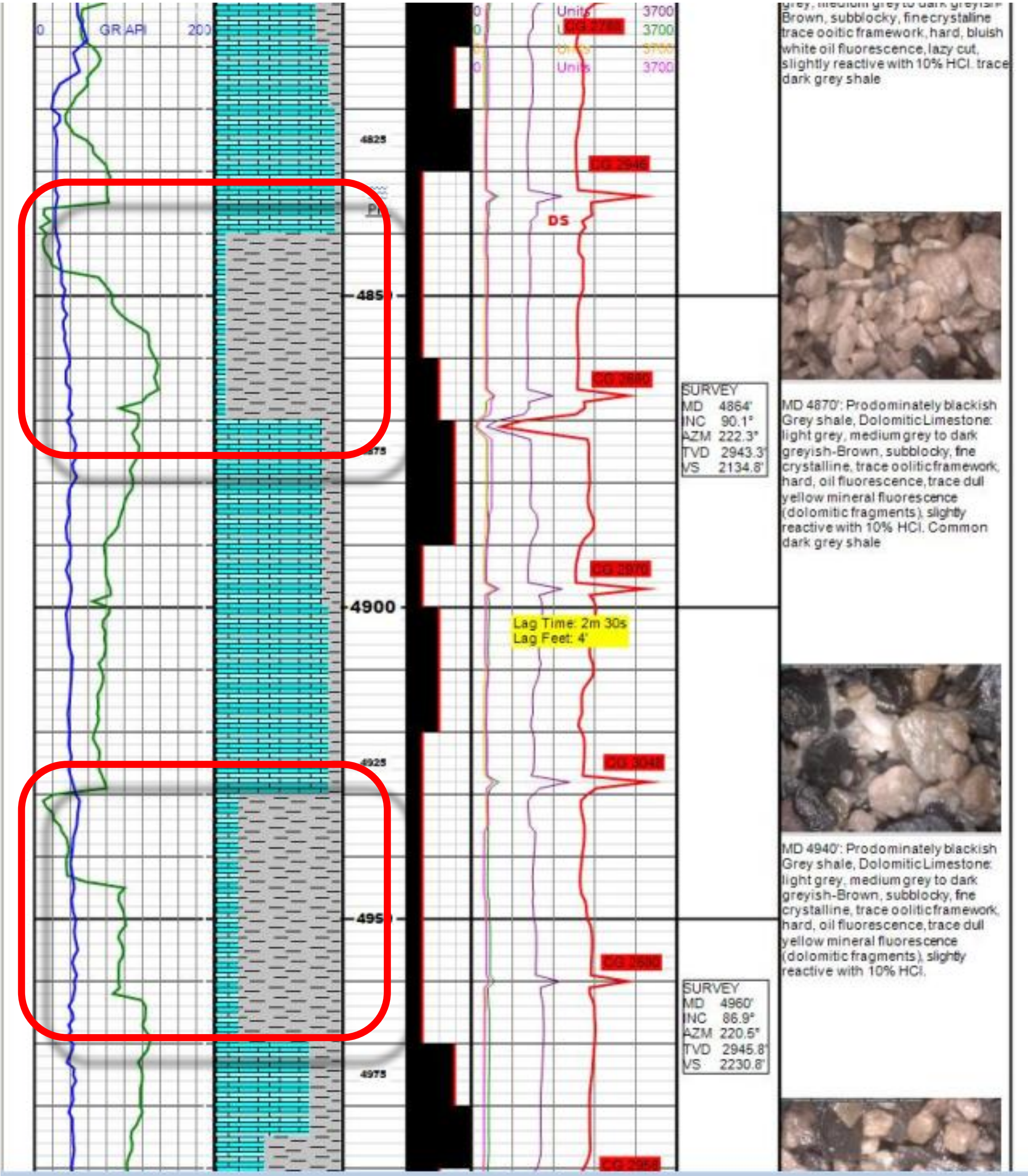
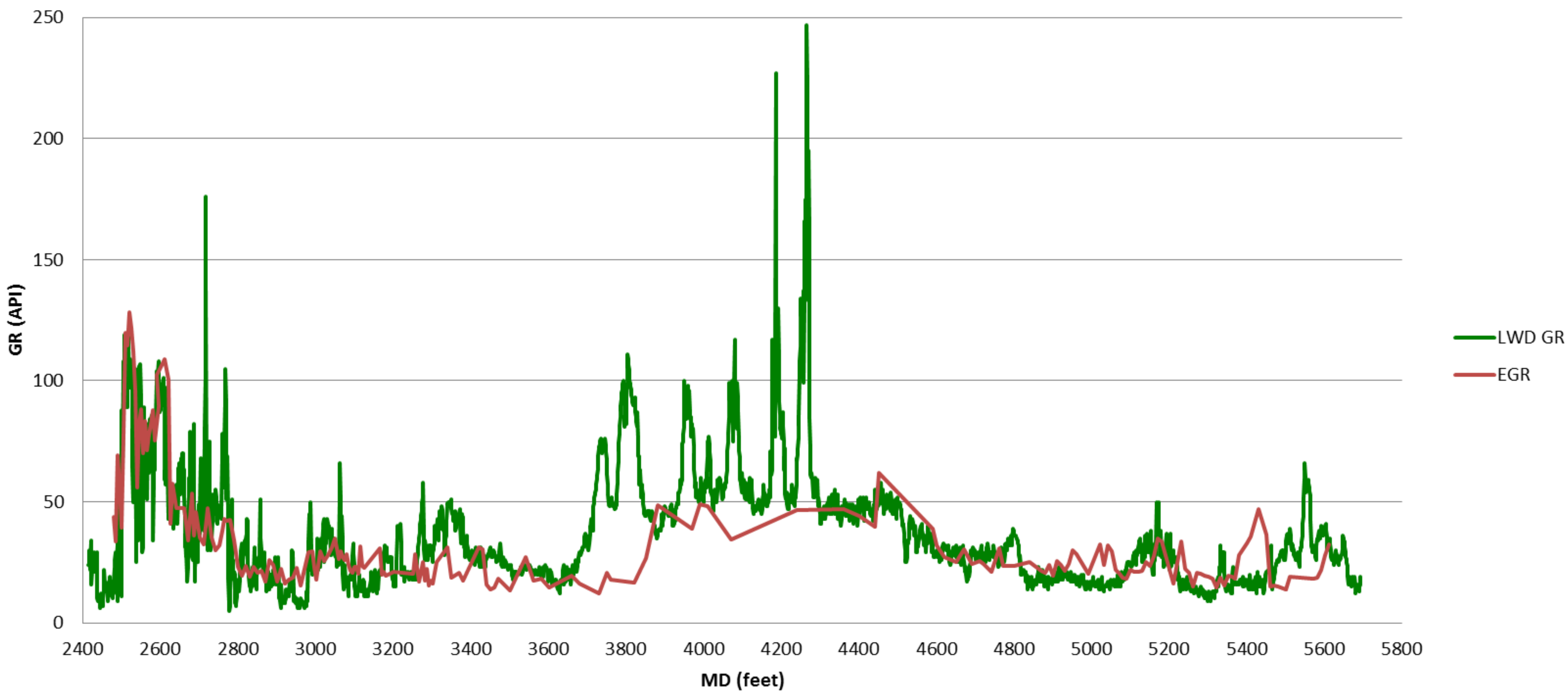
IDENTIFYING BORDEN VS CAVE-INS



- **Cave-ins seemed most prevalent at:**
  - **Low ROPs**
  - **Slides especially those preceded by high ROP**
- **It is thought that the reduction in ROP allows for more force on and/or more efficient cleaning of the hole**
- **The cave-ins are not overly rounded suggesting that they at best are falling to the heal of the wellbore before being carried to the surface**

LWD GR vs EGR

- **Measured K, Th, U from the XRF device allows us to build a synthetic GR curve from the elemental data**
- **This data could then be compared back to the LWD GR and peaks matched to help properly lag the samples**
- **Flat lines indicate zones of cave-in material where the calculated GR is invalid**



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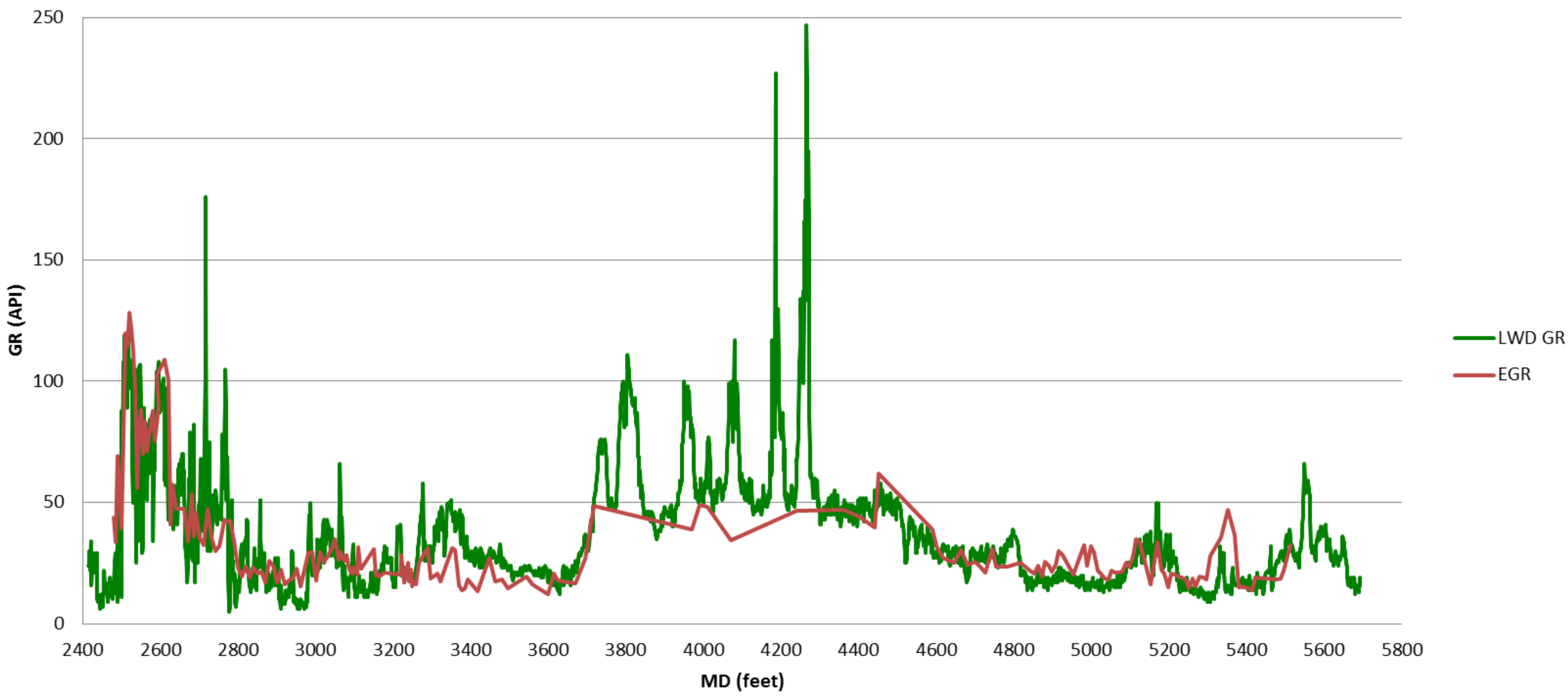
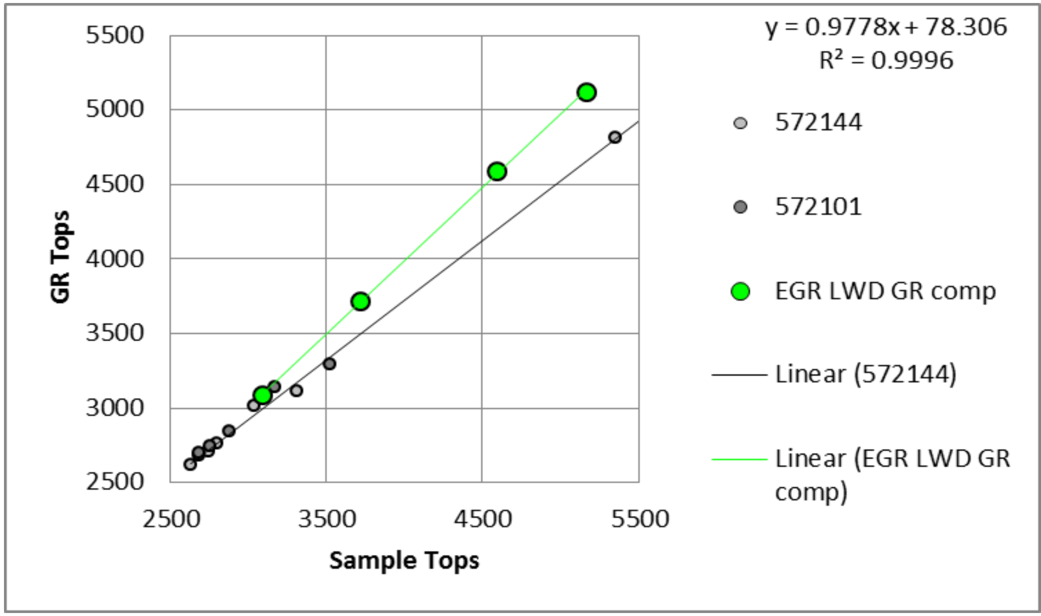


SAMPLE LAG

- **Mudlogger calculated a lag time every 100' along the well bore, which at TD was 3m 38s or 5 feet**
- **However, due to their differing densities the cuttings move at a different velocity than the gas, and move much less efficiently.**
- **A cuttings lag model was created by comparing the LWD GR to EGR curve.**
- **This well showed much less of a lag than did the previous Big Lime wells**
- **The equation of the trendline was then used to determine the lag along the lateral**
- **At TD of the well the sample lag was ~110'**
- **Further the samples at the toe were dominated by cave-ins bringing the last usable cuttings data to a lagged MD of 5513'**



DETERMINING ROCK MECHANICS AND INFERRING STRESS STATE FROM XRF DATA: EXAMPLE FROM THE BIG LIME

Where energy meets innovation.

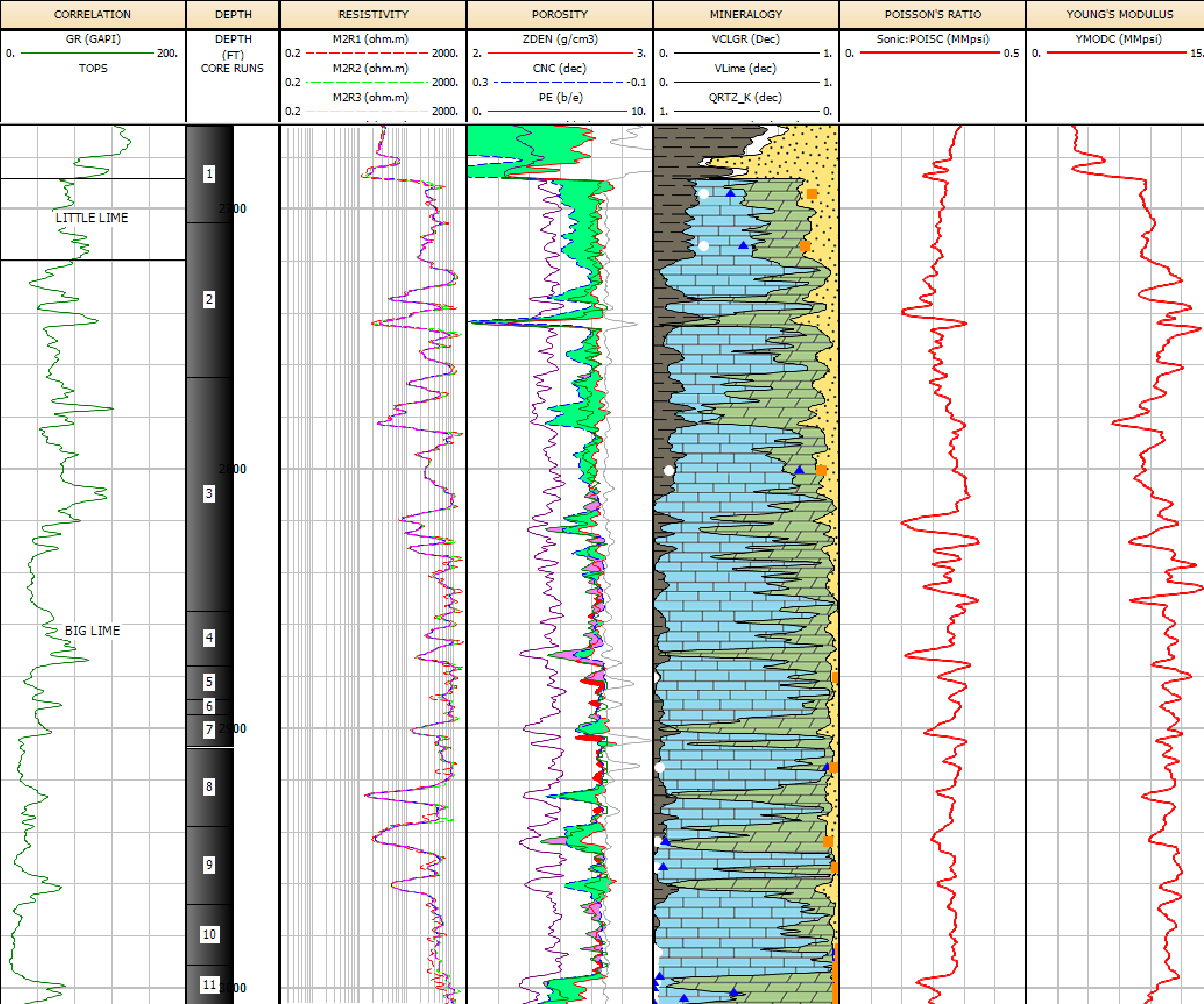
SUMMARY

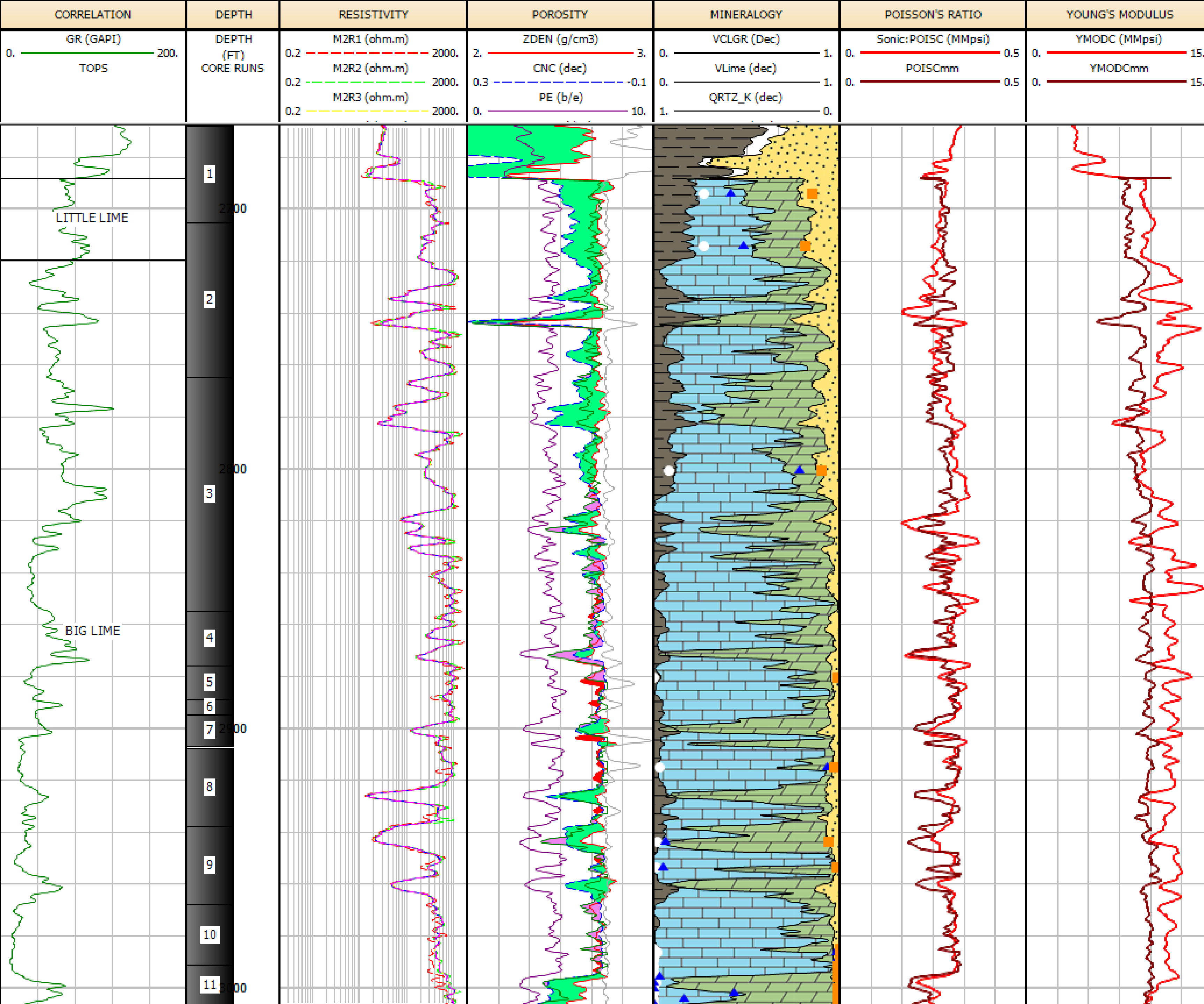
- In consolidated rocks at or below normal reservoir pressures the mechanical properties of rocks are largely controlled by mineral type and abundance.

- Construction of a multi-mineral model then can be used to predict the mechanical properties of the rock.

- With an understanding of mineral constituents and their stoichiometry, minerals can be predicted from elemental data derived from XRF.

- After the rock mechanical data is calculated it can be applied to the effective stress equation to determine minimum horizontal stress in both vertical and horizontal wellbores.


CORRELATION
DEPTH
RESISTIVITY
POROSITY
MINERALOGY
POISSON'S RATIO
YOUNG'S MODULUS
GR (GAPI)
0.
200.
TOPS
DEPTH
(FT)
CORE RUNS
M2R1 (ohm.m)
0.2
2000.
M2R2 (ohm.m)
0.2
2000.
M2R3 (ohm.m)
0.2
2000.
ZDEN (g/cm3)
2.
3.
CNC (dec)
0.3
-0.1
PE (b/e)
0.
10.
VCLGR (Dec)
0.
1.
VLime (dec)
0.
1.
QRTZ_K (dec)
1.
0.
Sonic:POISC (MMpsi)
0.
0.5
YMODC (MMpsi)
0.
15.
LITTLE LIME
BIG LIME
1
2
3
4
5
6
7
8
9
10
11


CORRELATION
DEPTH
RESISTIVITY
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MINERALOGY
POISSON'S RATIO
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GR (GAPI)
0.
200.
TOPS
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CORE RUNS
M2R1 (ohm.m)
0.2
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0.3
-0.1
PE (b/e)
0.
10.
VCLGR (Dec)
0.
1.
VLime (dec)
0.
1.
QRTZ_K (dec)
1.
0.
Sonic:POISC (MMpsi)
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0.5
POISCmm
0.
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YMODC (MMpsi)
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15.
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LITTLE LIME
BIG LIME
1
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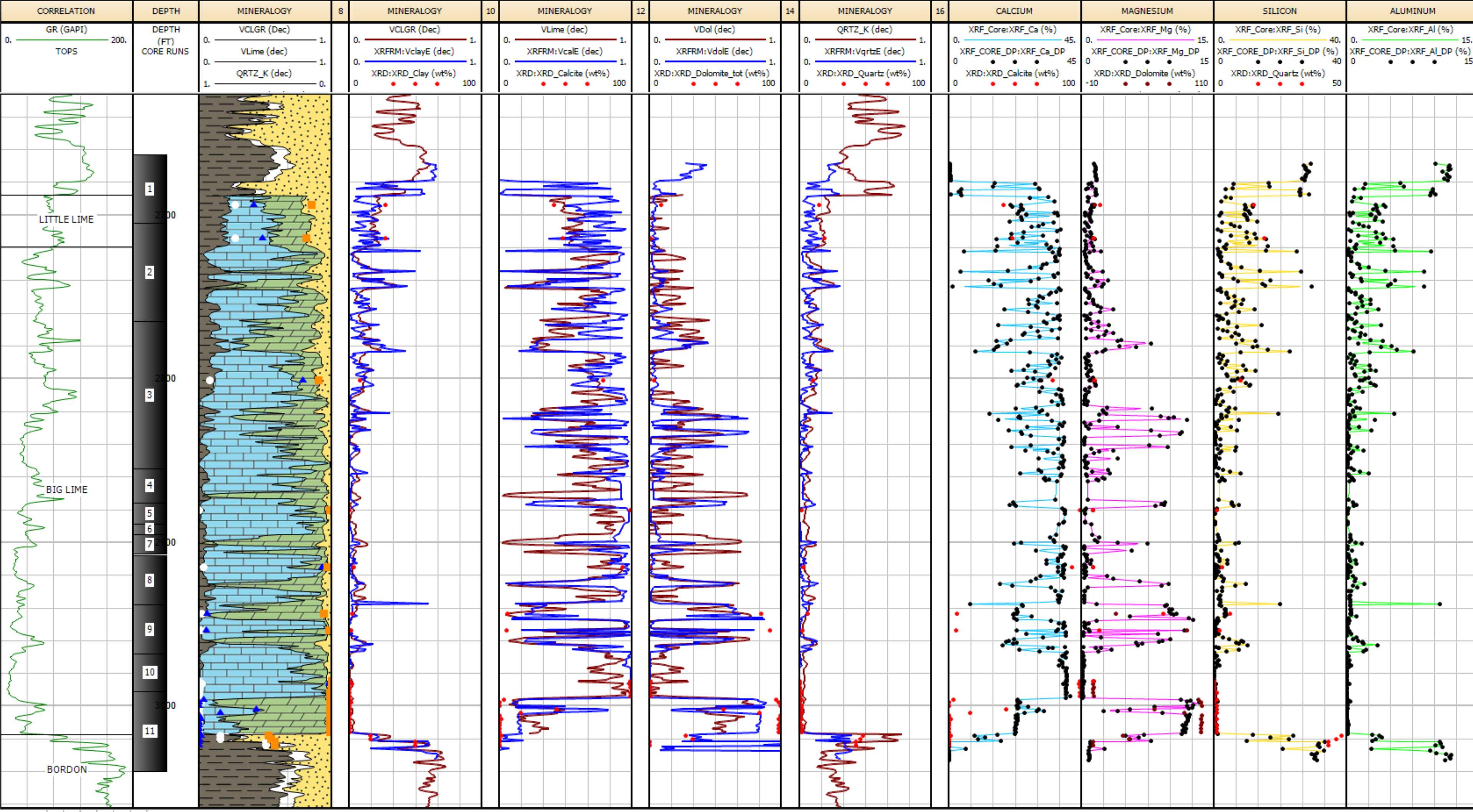
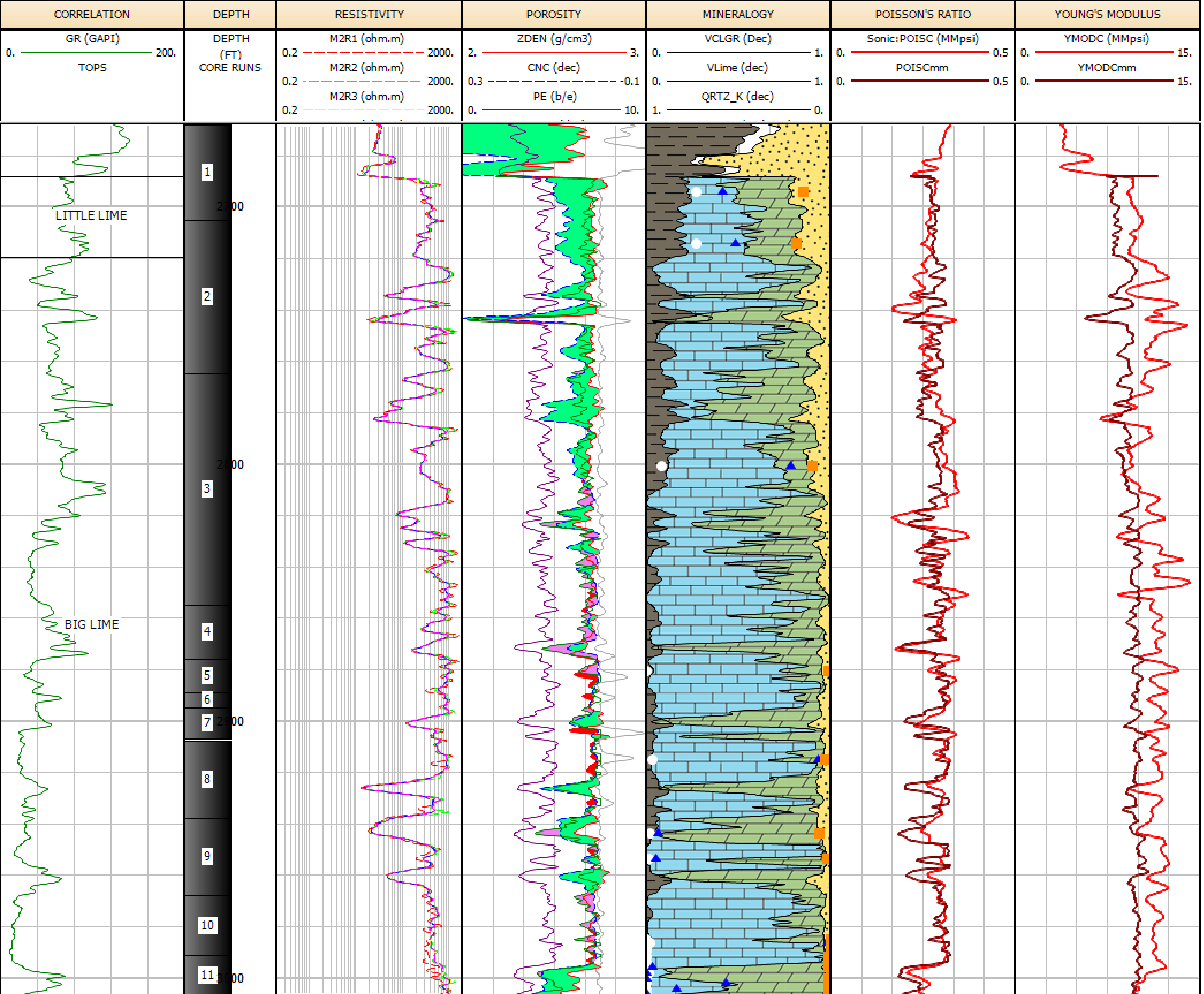
10
11



- **Good agreement is seen between log-derived mineralogy (brown curve) and XRF-derived mineralogy (blue curve)**



CORRELATION
DEPTH
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POROSITY
MINERALOGY
POISSON'S RATIO
YOUNG'S MODULUS
GR (GAPI)
0. 200.
TOPS
DEPTH
(FT)
CORE RUNS
M2R1 (ohm.m)
0.2 2000.
M2R2 (ohm.m)
0.2 2000.
M2R3 (ohm.m)
0.2 2000.
ZDEN (g/cm3)
2. 3.
CNC (dec)
0.3 -0.1
PE (b/e)
0. 10.
VCLGR (Dec)
0. 1.
VLime (dec)
0. 1.
QRTZ_K (dec)
1. 0.
Sonic:POISC (MMpsi)
0. 0.5
POISCmm
0. 0.5
YMODC (MMpsi)
0. 15.
YMODCmm
0. 15.
LITTLE LIME
BIG LIME
1
2
3
4
5
6
7
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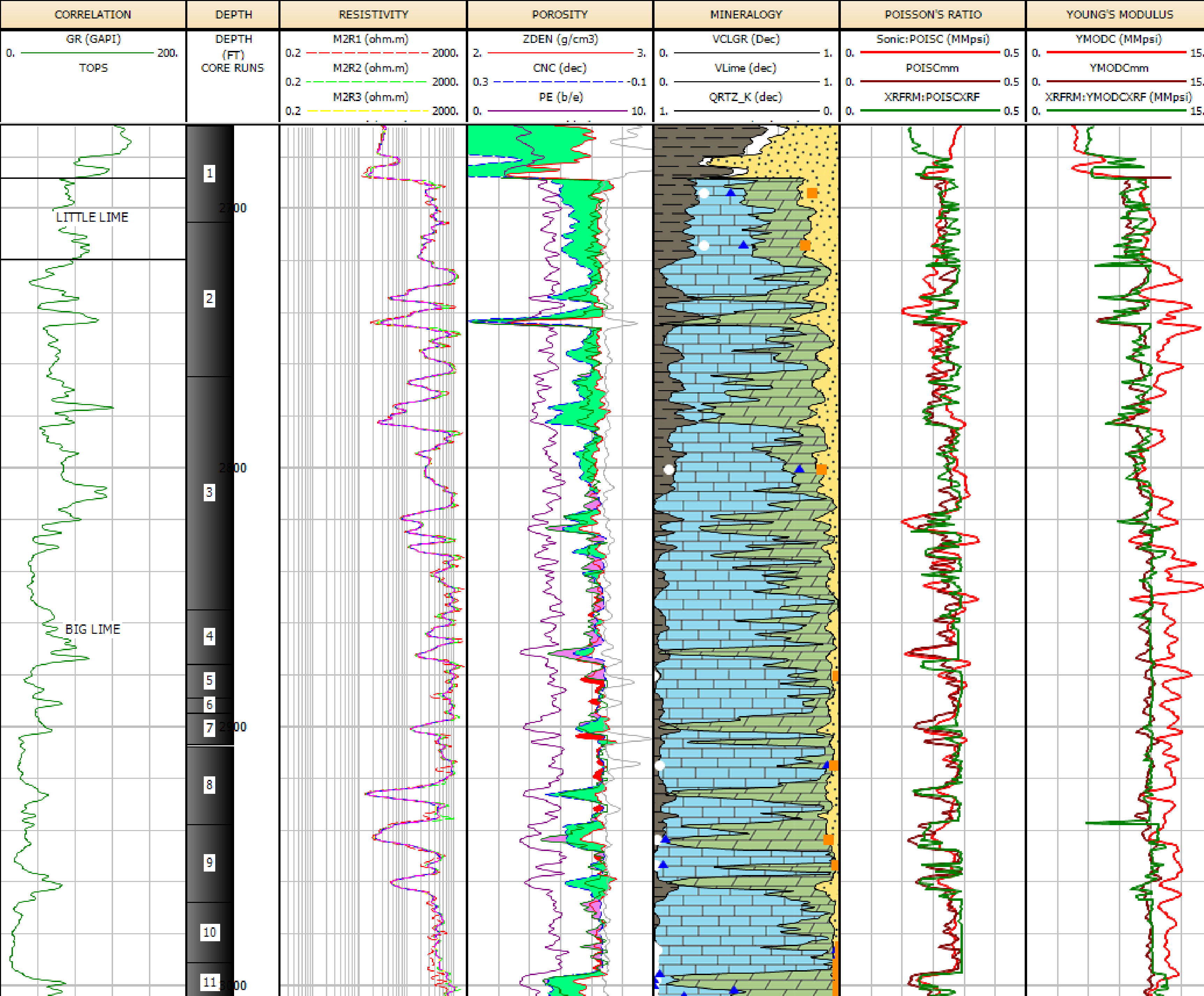
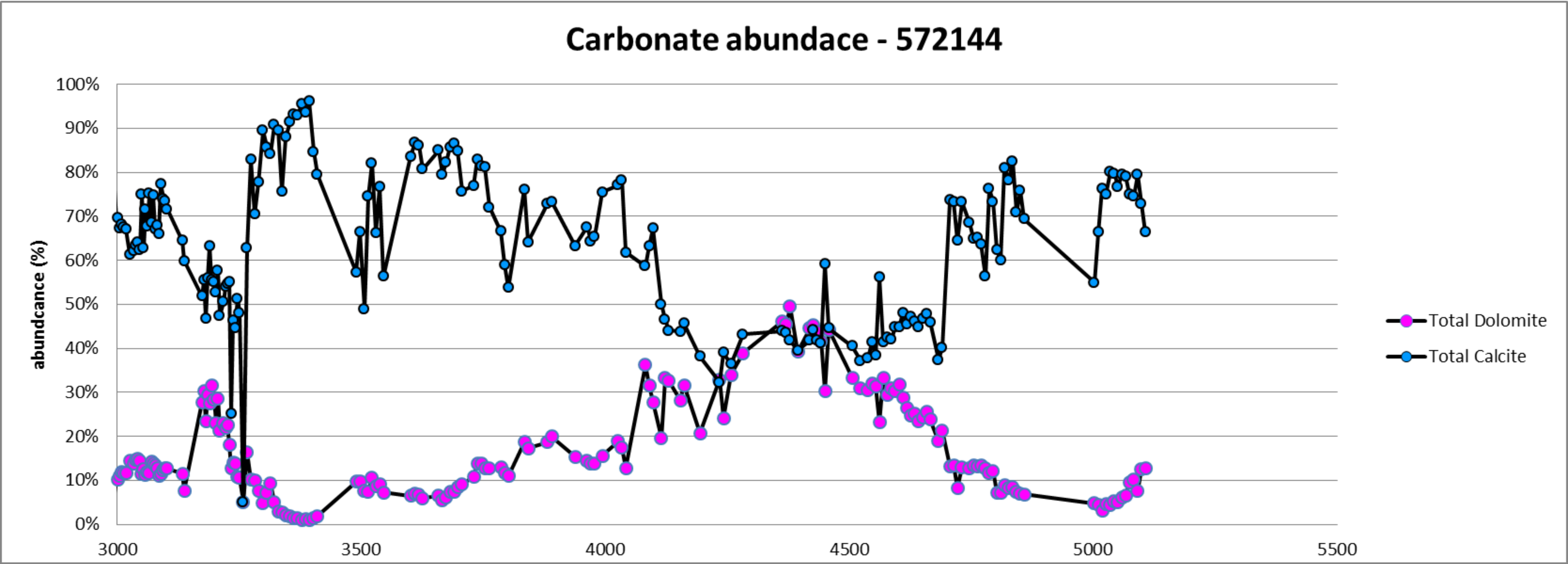
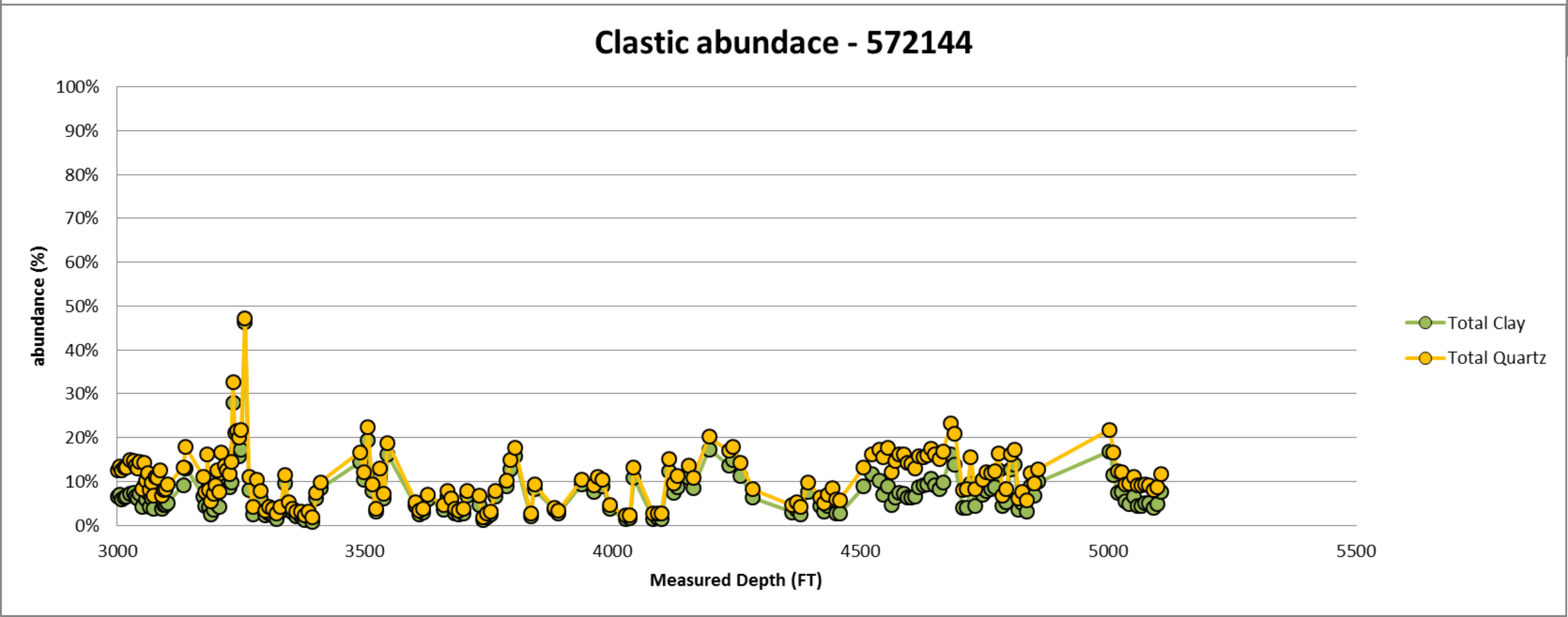
10
11

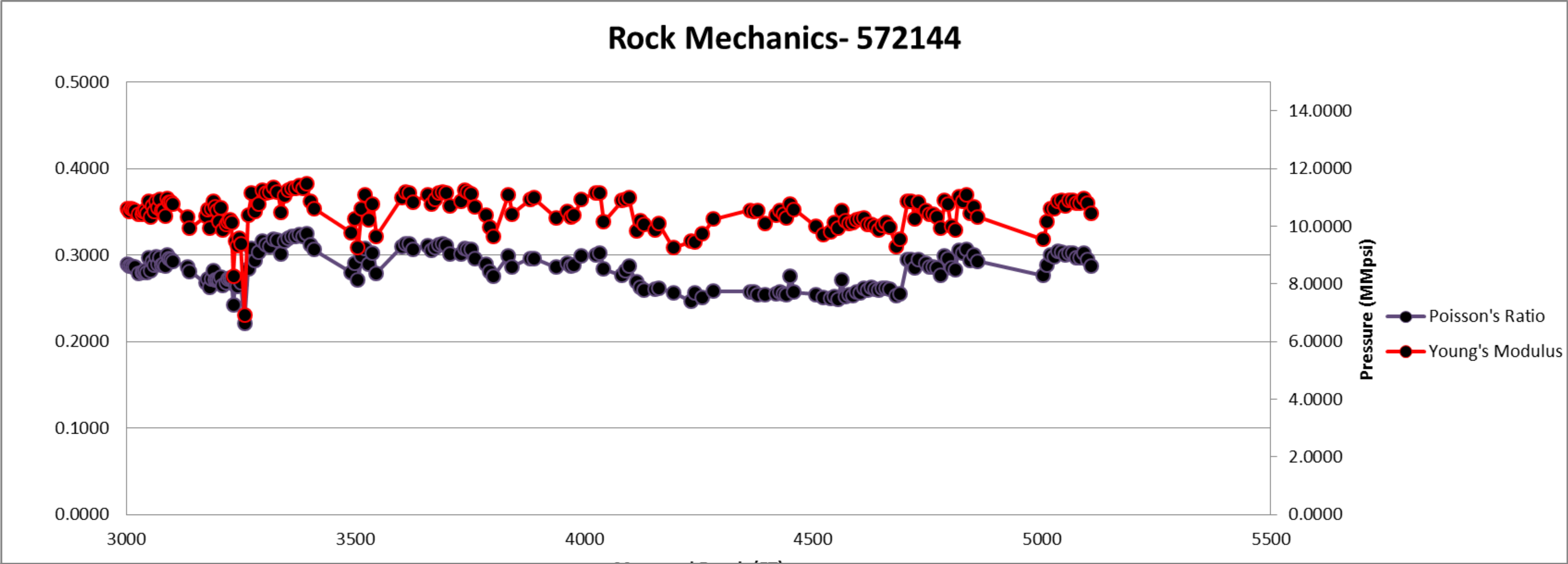

CORRELATION
DEPTH
RESISTIVITY
POROSITY
MINERALOGY
POISSON'S RATIO
YOUNG'S MODULUS
GR (GAPI)
0. 200.
TOPS
DEPTH (FT)
CORE RUNS
M2R1 (ohm.m)
0.2 2000.
M2R2 (ohm.m)
0.2 2000.
M2R3 (ohm.m)
0.2 2000.
ZDEN (g/cm3)
2. 3.
CNC (dec)
0.3 -0.1
PE (b/e)
0. 10.
VCLGR (Dec)
0. 1.
VLime (dec)
0. 1.
QRTZ_K (dec)
1. 0.
Sonic:POISC (MMpsi)
0. 0.5
POISCmm
0. 0.5
XRFRM:POISCXRF
0. 0.5
YMODC (MMpsi)
0. 15.
YMODCmm
0. 15.
XRFRM:YMODCXRF (MMpsi)
0. 15.
LITTLE LIME
BIG LIME
1
2
3
4
5
6
7
8
9
10
11

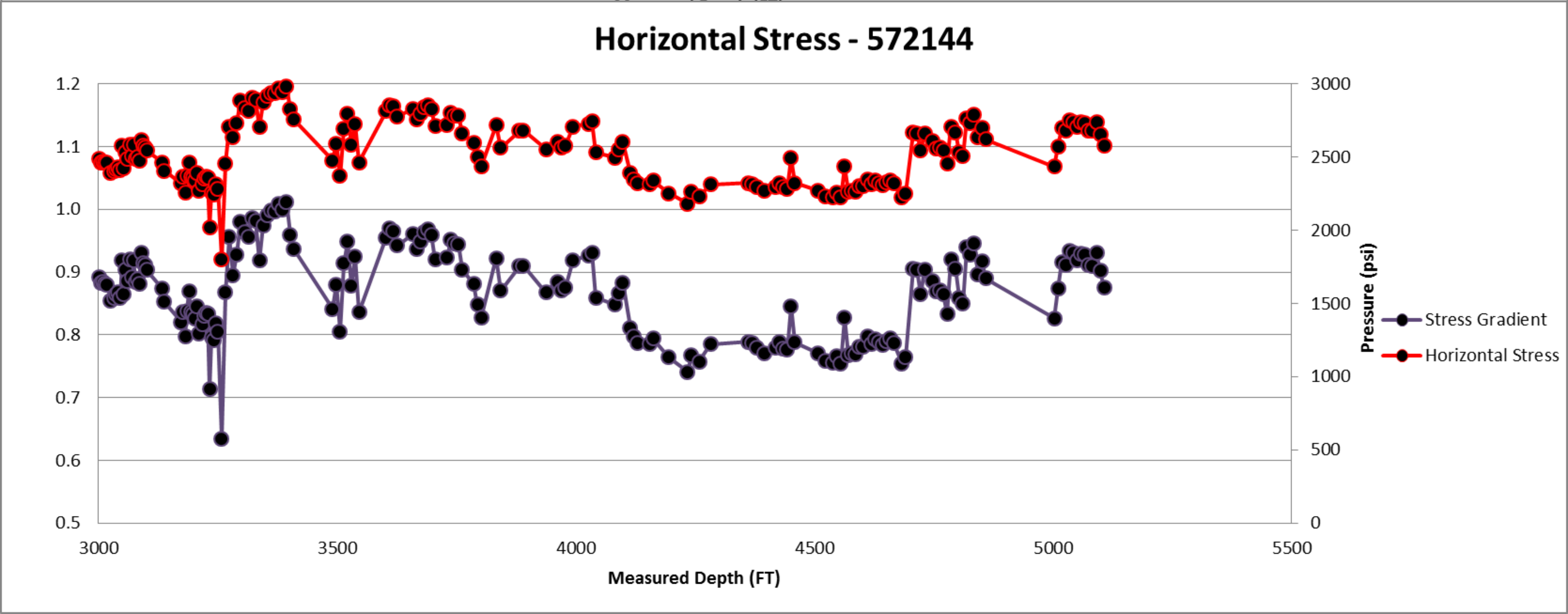


Carbonate abundace - 572144
abundcance (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
3000
3500
4000
4500
5000
5500
Total Dolomite
Total Calcite



Clastic abundace - 572144
abundance (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
3000
3500
4000
4500
5000
5500
Measured Depth (FT)
Total Clay
Total Quartz


Rock Mechanics- 572144
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
14.0000
12.0000
10.0000
8.0000
6.0000
4.0000
2.0000
0.0000
Pressure (MMpsi)
Poisson's Ratio
Young's Modulus
3000
3500
4000
4500
5000
5500


Horizontal Stress - 572144
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
3000
2500
2000
1500
1000
500
0
Pressure (psi)
Stress Gradient
Horizontal Stress
3000
3500
4000
4500
5000
5500
Measured Depth (FT)

CONCLUSIONS

- **Elemental data offers a useful means of geosteering in areas where steering with GR is ambiguous**
- **A robust zonation is easily identifiable in cuttings**
- **Proper lagging of samples can be achieved by building an elemental GR and comparing it back to LWD GR**
- **In combination with a geologic model the data can be used to make real time decisions that can save time and money.**
  - Identifying cave-ins from underlying shales
  - Identifying pinch out of reservoir facies

- **XRF data can be used to calculate normative mineral volumes which can in turn be used to calculate mechanical properties of the rock**

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