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A Chemostratigraphic and Geomechanical approach for enhanced reservoir characterization and optimization from the Spirit River Group of the Western Canada Sedimentary Basin

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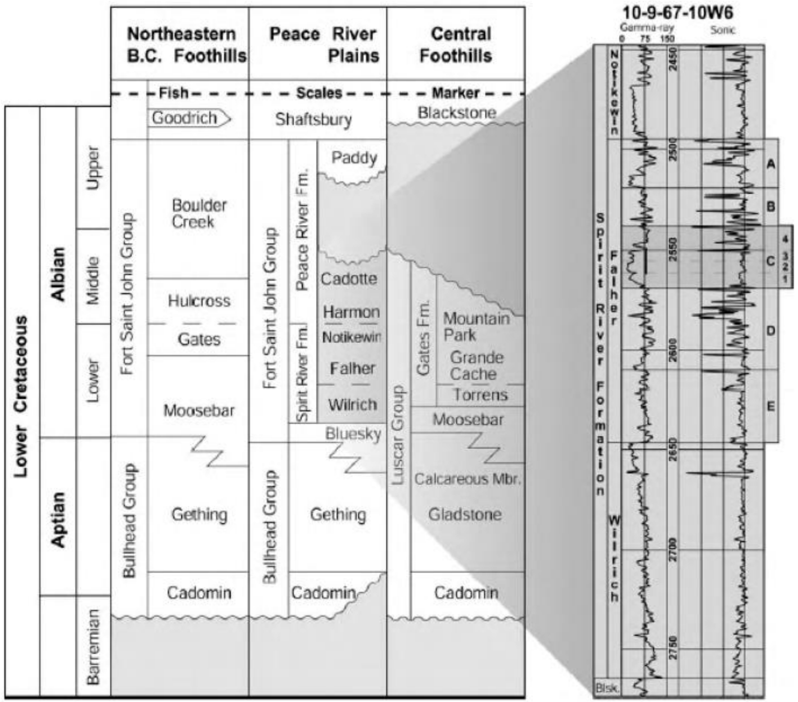
Presentation Outline

- Regional Setting
- Geology and Production History
- Chemostratigraphic Analysis
- Rock Mechanics
- Conclusions

Regional Setting

- The Spirit River Formation is part of the Western Canadian Sedimentary Basin (WCSB)
- Lower Cretaceous in age, the succession consists of interbedded channel argillaceous sandstones, siltstones, shales and coal seams.
- Named after the Spirit River, it was first described in Imperial Oil Spirit River No. 1 well by Badgley in 1952

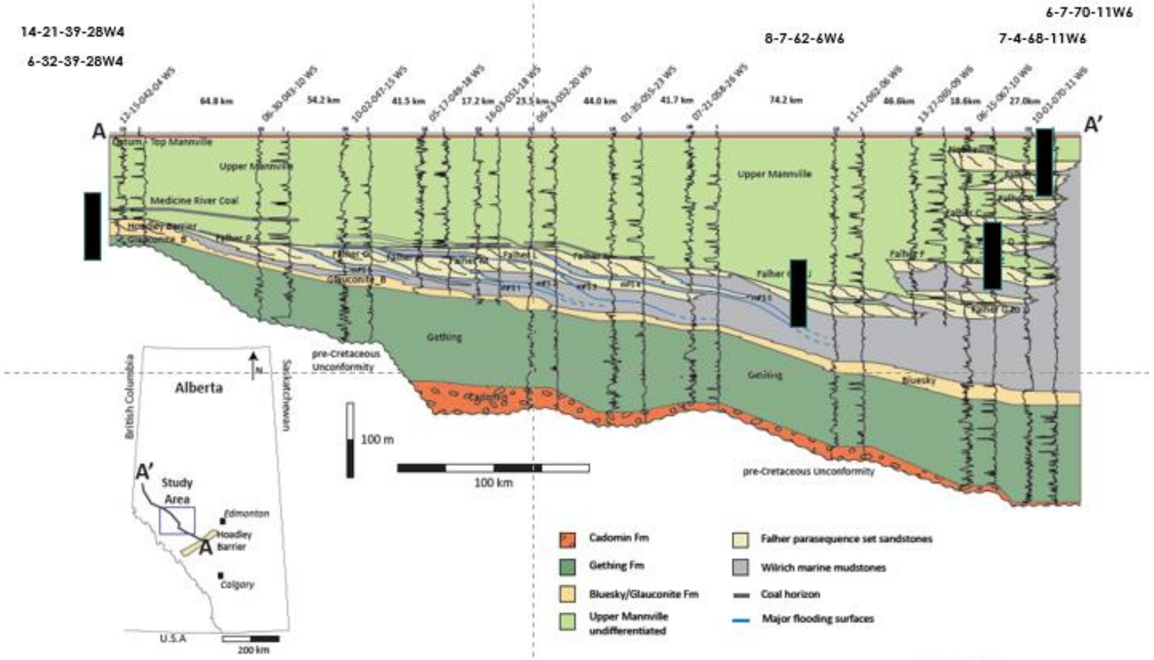
Stratigraphy



Spirit River Members

- **Notikewin** Member
  - Fine to medium grained argillaceous sandstone, dark shale, ironstone
  - Max thickness 28m
- **Falher** Member
  - Greywacke, shale, siltstone, coal
  - Max thickness 215m
- **Wilrich** Member
  - Dark shales, with thin interbedded sandstone and siltstone stringers
  - Max thickness 154m

Geological Environment



Newitt, 2017
University of Calgary
Tight Oil Consortium

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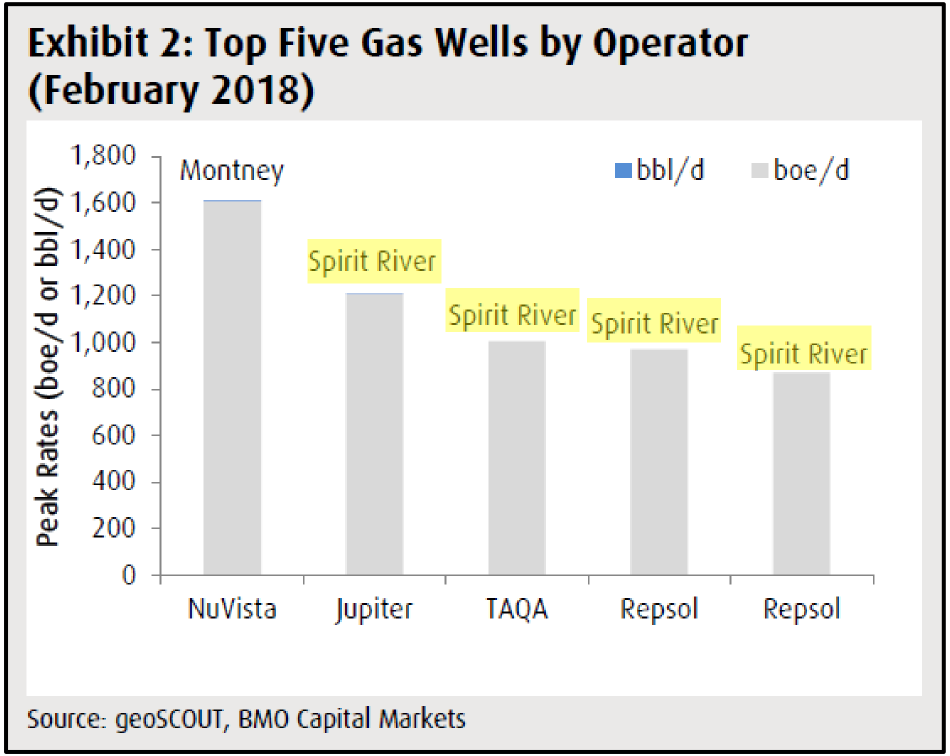
Production History



From the BMO 'Top Wells – Alberta, February 2018' report dated April 3rd 2018:

- Nineteen of the top 20 oil/condensate wells over the past 12 months in Alberta were producing from the Montney formation, with 18 operated by Seven Generations. The Deep Basin Spirit River Group accounted for 15 of the top 20 producing gas wells in Alberta over the last 12 months.
- For the last 12 months, Seven Generations holds the top performing oil/condensate well in Alberta, producing from the Montney formation at Kakwa, and cumulatively recovering 404mbbl of condensate. On the gas side, Jupiter holds the top gas well, producing from the Spirit River at Smoky, which has cumulatively recovered ~3.5bcf of gas since June 2017 and had a peak rate of ~3.1mboe/d.

Production History

Exhibit 8: Last 12 Months Top Gas Wells by Operator (Calendar Day Rate)

Unique Well ID	Current Operator Name	Formation	Spud Date	On Prod	Field Name	Pool Name	TVD (m)	Peak Mthly boe/d	Cum. Oil & Cond. (bbl)	Cum. Gas (mcf)	% oil
100/16-11-059-02W6/00	Jupiter Rsrcs Inc	Kfalher	10/13/2016	2017/06	SMOKY	FALH UND	3,298	3,092	4	3,524,643	0%
100/03-06-045-09W5/00	Bellatrix Expl Ltd	Kfalher	2/16/2017	2017/03	WILLESDEN GREEN	COMMINGLED MFP9537	2,329	2,015	276	3,361,759	0%
100/03-29-062-04W6/00	Seven Generations Enrg Lt	TRmontney	1/12/2017	2017/05	KAKWA	MONT UND	3,358	3,473	670	3,136,030	0%
102/01-14-059-02W6/00	Jupiter Rsrcs Inc	Kfalher	8/28/2016	2017/06	RESTHAVEN	COMMINGLED MFP9525	3,284	2,496	6	3,105,597	0%
102/09-16-065-08W6/00	Cdn Nat Rsrcs Ltd	Kfalher	12/4/2016	2017/03	WAPITI	COMMINGLED MFP9529	2,870	2,900	633	2,937,041	0%
100/16-16-065-08W6/00	Cdn Nat Rsrcs Ltd	Kfalher	1/20/2017	2017/03	WAPITI	COMMINGLED MFP9529	2,863	2,859	1,608	2,880,723	0%
100/10-02-062-05W6/02	Jupiter Rsrcs Inc	Kfalher	7/15/2016	2017/03	KAKWA	COMMINGLED POOL 005	2,789	2,175	396	2,858,795	0%
100/04-06-045-09W5/00	Bellatrix Expl Ltd	Kfalher	1/30/2017	2017/03	WILLESDEN GREEN	COMMINGLED MFP9537	2,339	1,873	500	2,807,823	0%
100/11-21-043-14W5/02	Peyto Expl&Dvlp Corp	Knotikwn	2/7/2017	2017/05	STOLBERG	FALH UND	3,207	3,391	1,266	2,759,970	0%
103/13-20-063-04W6/00	Seven Generations Enrg Lt	TRmontney	10/20/2016	2017/04	KAKWA	MONTNEY K2K	3,182	2,841	194,319	2,542,422	31%
102/08-09-076-13W6/00	Advantage O&G Ltd	TRmontney	9/7/2015	2017/03	POUCE COUPE SOUTH	MONT UND	2,670	1,658	0	2,455,487	0%
100/04-29-043-14W5/00	Peyto Expl&Dvlp Corp	Knotikwn	6/16/2017	2017/07	STOLBERG	TD UND	3,162	2,945	70	2,436,016	0%
100/04-13-058-02W6/00	Tourmaline Oil Corp	Kwilrich	1/7/2017	2017/03	SMOKY	SPRT R UND	3,372	2,363	0	2,434,017	0%
100/16-02-062-05W6/00	Jupiter Rsrcs Inc	Kfalher	11/16/2016	2017/03	KAKWA	COMMINGLED POOL 005	2,788	1,677	232	2,424,572	0%
103/13-29-061-05W6/02	Jupiter Rsrcs Inc	Kfalher	10/17/2016	2017/07	KAKWA	COMMINGLED POOL 005	3,006	1,863	20	2,319,188	0%
100/03-13-058-02W6/00	Tourmaline Oil Corp	Kwilrich	1/9/2017	2017/03	SMOKY	SPRT R UND	3,365	2,285	5	2,265,671	0%
100/12-33-068-08W6/02	NuVista Enrg Ltd	TRmontney	7/9/2016	2017/03	ELMWORTH	MONT UND	2,811	2,438	16	2,178,441	0%
100/15-19-063-04W6/00	Seven Generations Enrg Lt	TRmontney	11/6/2016	2017/05	KAKWA	MONT UND	3,193	3,719	161,852	2,167,946	31%
102/16-11-045-07W5/00	Bellatrix Expl Ltd	Kmannvl_U	2/15/2017	2017/04	PEMBINA	U MANN UND	2,068	1,546	4,274	2,092,163	1%
100/02-11-053-24W5/00	Tourmaline Oil Corp	Knotikwn	3/6/2017	2017/08	DALEHURST	COMMINGLED POOL 001	3,339	3,674	320	2,079,538	0%

Source: geoSCOUT, BMO Capital Markets.

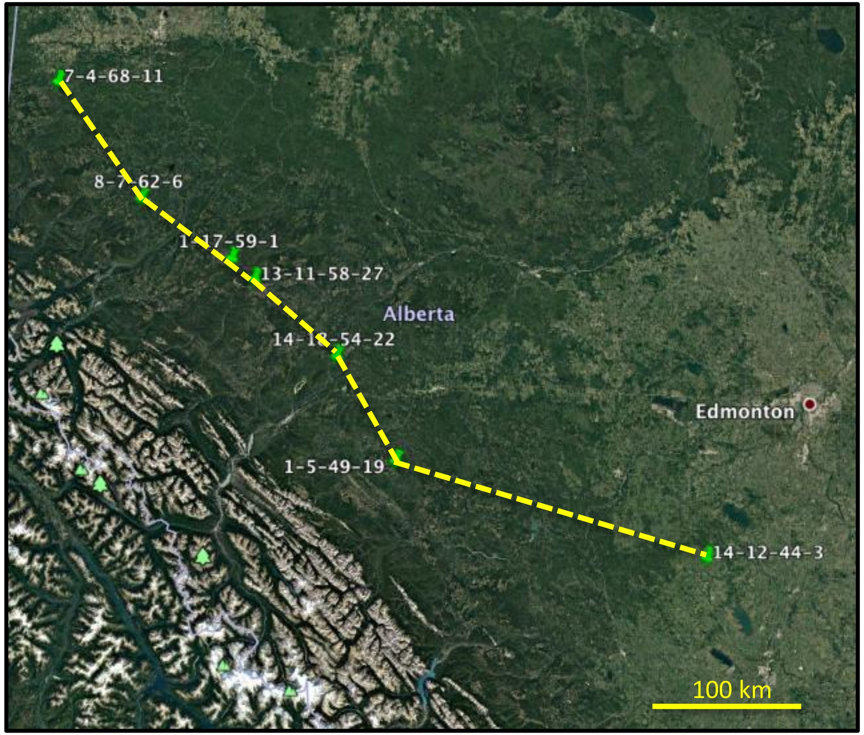
What is Chemostratigraphy ?

The characterization and correlation of sedimentary sequences based on changes in inorganic geochemical data.

It is often regarded as new technique, but versions of chemostratigraphy such as gamma, spectral gamma and wireline geochemical logs have been widely used in the oil industry for many years.

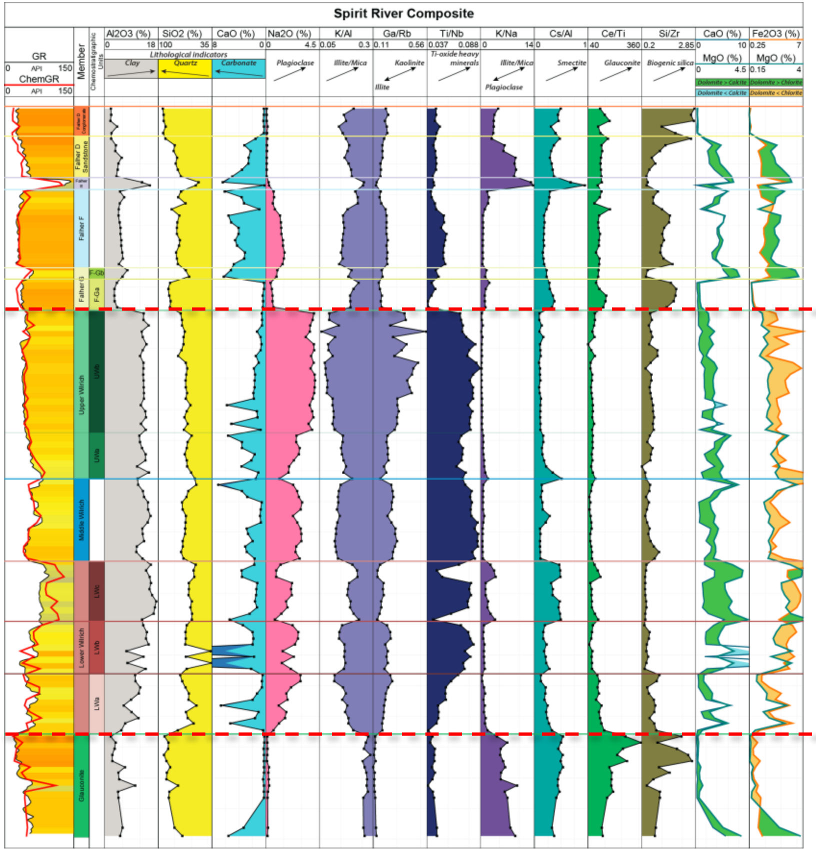
This application is utilising the chemistry to understand temporal and lateral variations in mineralogy, to determine regionally extensive changes, such as provenance or paleoclimate that can be used to correlate wells many miles apart, as well as identify variations in reservoir quality.

Study Interval and Samples



- Composite section constructed from cored sections of 5 wells penetrating the Spirit River and Glauconite (2 additional wells penetrating Notikewin and younger Falhers to be added)
- 116 ICP samples: 50 element geochemical dataset/sample
- 20 XRD samples used to calibrate mineral model

Composite Chemostratigraphic section

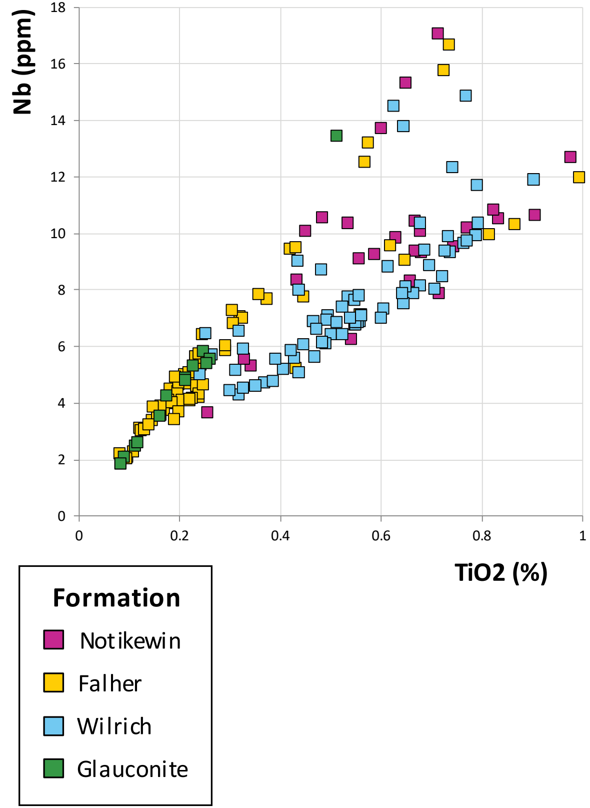


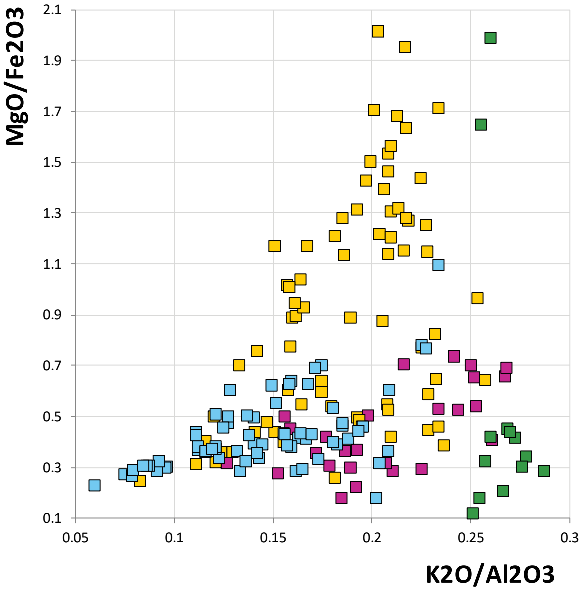
Falher: lower Al_2O_3 in the sandstones relative to the Wilrich, indicating ‘cleaner’, less lithic sands.
Low Ti/Nb values indicating a different provenance of the sediment, relative to the Wilrich.

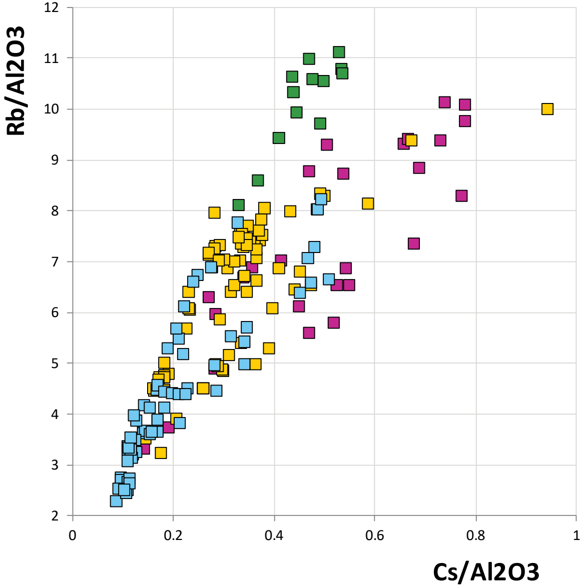
Wilrich: higher Al_2O_3 and Na_2O values in the Wilrich sands relative to the Falher; greater lithic content (feldspathic) – another indicator of a differing provenance between the Wilrich and Falher.

Glauconite: lower Fe_2O_3 and MgO values than the Wilrich. Higher Ce and Cs linked to glauconite and marine clays

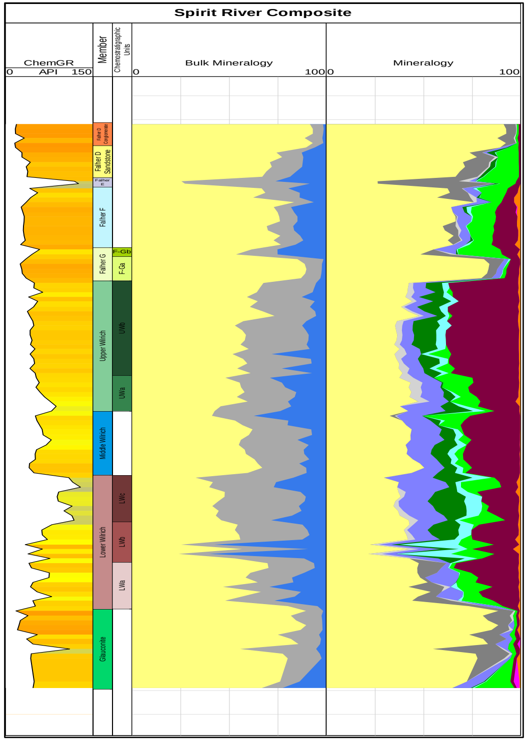
Graphical Differentiation







Spirit River Mineralogy



Mineralogy

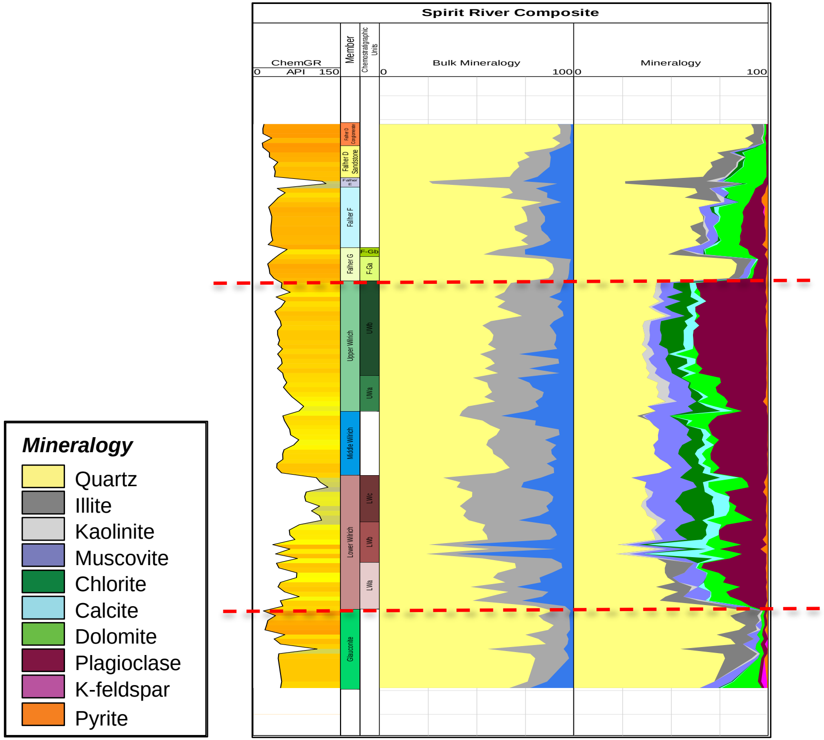
- Quartz
- Illite
- Kaolinite
- Muscovite
- Chlorite
- Calcite
- Dolomite
- Plagioclase
- K-feldspar
- Pyrite

Mineralogy

Calculated from elemental data with mineral model calibrated using a subset of XRD data (available from the AER).

Well	Member	Plagioclase	Dolomite	Kaolinite	Chlorite
100/8-7-62-06W6	Fahler F	6.3	15.0	0.0	2.7
100/8-7-62-06W6	Fahler F	12.2	18.6	0.0	2.4
100/8-7-62-06W6	Fahler F	12.8	18.2	0.7	1.8
100/8-7-62-06W6	Upper Wilrich B	40.9	0.0	0.8	10.9
100/8-7-62-06W6	Upper Wilrich B	41.6	0.0	1.5	7.8
100/8-7-62-06W6	Upper Wilrich B	44.0	0.0	1.0	14.2
100/8-7-62-06W6	Upper Wilrich A	39.7	0.0	0.9	12.9
100/8-7-62-06W6	Lower Wilrich C	25.4	0.0	2.7	17.8
100/8-7-62-06W6	Lower Wilrich B	30.2	0.0	1.3	11.0
100/8-7-62-06W6	Lower Wilrich B	14.0	16.4	0.0	4.1

Spirit River Mineralogy



Falher

Coarse grained, conventional reservoir. Less clay than the Wilrich

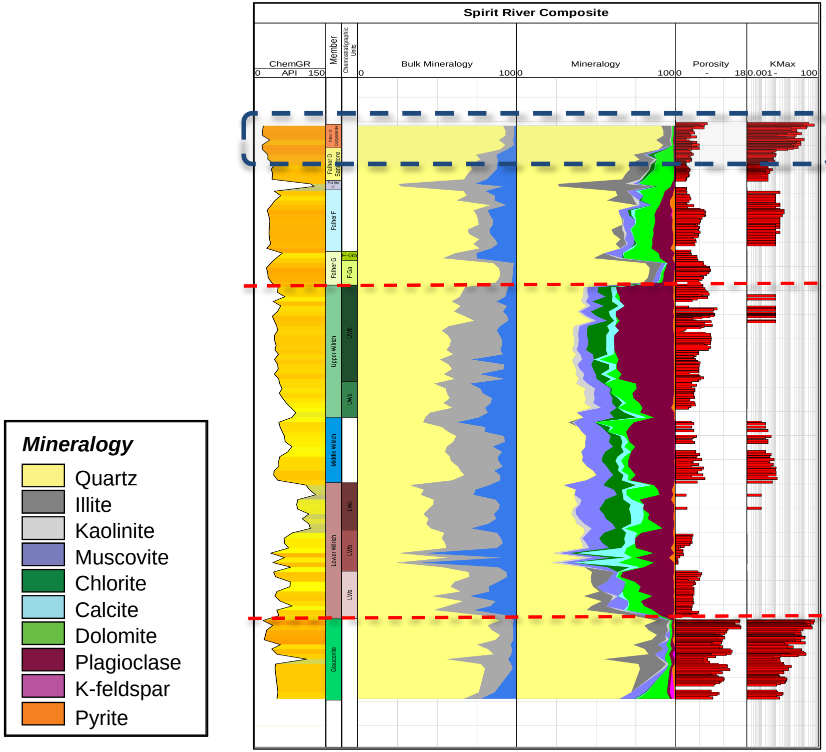
Wilrich

Considered a 'tight' unconventional reservoir. Thin sections reveal that the low porosity and permeability of the sandstones are due to a high degree of mechanical compaction and precipitation of cements and clays

Glauconite

This is a Hoadley Barrier Glauconite, where reservoir quality is excellent (high porosities/permeabilities!)

Mineralogy and Reservoir Quality



Falher

Highest permeability (KMax) associated with chert-pebble conglomerate facies commonly associated with foreshore-upper shoreface environments

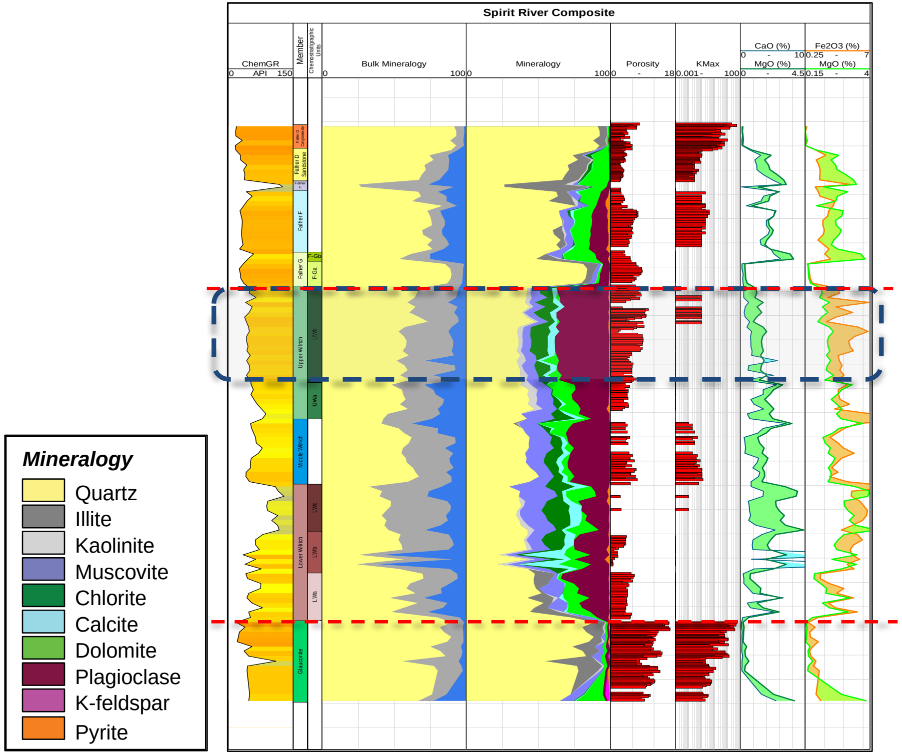
Wilrich

Locally enhanced permeability is related to early ferroan dolomite cement and even though it is pore filling, it reduces the effects of plastic deformation of ductile grains. *Chlorite* can also be a key component occurring early grain coating cements preventing quartz overgrowths preserving porosity and permeability

Glauconite

Highest porosity & permeability (KMax) associated with well sorted marine sands

Variation in Key Oxides



Falher

Coarse grained, conventional reservoir. Less clay than the Wilrich (more illitic, less chloritic)

Wilrich

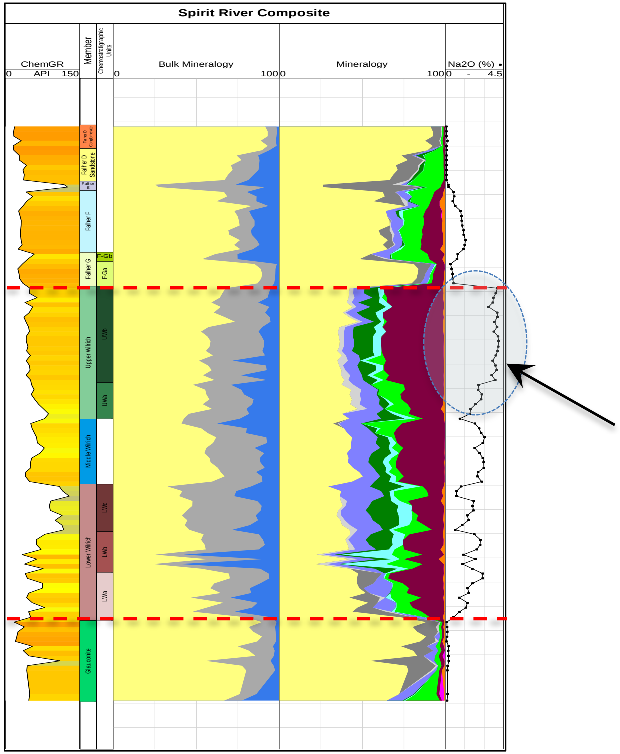
By examining the relationship between Ca, Mg and Fe it is possible to determine the dolomite and chlorite locations

Chlorite in the upper Wilrich is grain-rimming, preventing quartz overgrowths and retaining pore throats

Glauconite

Low clay contents overall, minor dolomite toward base

Variation in Sodium Oxide (Na20)



Mineralogy

- Quartz
- Illite
- Kaolinite
- Muscovite
- Chlorite
- Calcite
- Dolomite
- Plagioclase
- K-feldspar
- Pyrite

The **Wilrich** sandstones are more lithic than those of the Falher and Glauconite.

Significantly elevated Na values are attributed to plagioclase abundance which appears to be a defining feature of the **Wilrich** member

Discussion of Results

- The elemental data demonstrates clear geochemical differences between the Notikewin, Falher, Wilrich and Glauconite that reflect variations in;
  - Clay mineralogy
  - Carbonate (dolomite content)
  - Lithic content
  - Provenance
- The elemental data can also identify optimum reservoir characteristics that would be difficult to visually identify using cuttings

What is Rock Mechanics ?

The theoretical and applied science of the mechanical behaviour of rocks. It is that branch of mechanics concerned with the response of rock to the force fields of it’s physical environment

- Best known mechanical, or elastic, parameters:
  - Shear Modulus (μ), Bulk modulus (K), Young’s Modulus (E) and Poisson’s Ratio (σ)
- Elastic parameters can be measured in the lab or from wireline logs
- Shear (V_s) and Compressional (V_p) velocities are a function of bulk modulus, shear modulus and density
- If mineralogy is known it is possible to predict sonic velocities, Young’s modulus and Poisson’s Ratio based on theoretical bulk moduli and shear moduli for any mineral composition

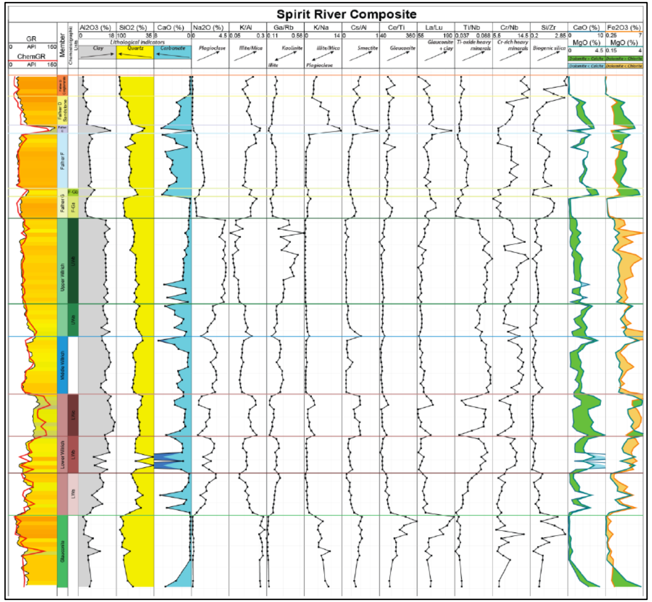
Applications to the Petroleum Industry

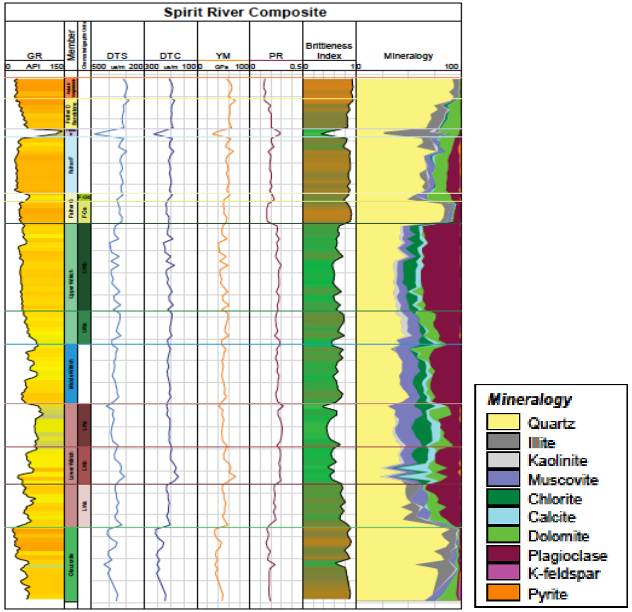
Rock mechanics are used by five distinct disciplines

- Hydraulic Frac' Design Engineers, who need to know rock strength and pressure environments to optimise frac placement
- Geologists and Engineers interested in in-situ stress regimes in naturally fractured reservoirs
- Drilling engineers who wish to prevent accidentally fracturing a reservoir with too high a mud weight, or who wish to predict overpressured formations to reduce the risk of a blowout
- Production or Completion engineers who want to determine if sanding or fines migration might be possible
- Geophysicists interested in using wireline logs to improve seismograms and seismic models, and interpretation of seismic attributes, seismic inversion, and processed seismic sections

Elemental data → Rock Mechanical Properties

Chemostrat has developed a new workflow that produces rock mechanical (or elastic) properties from elemental data acquired from core and rock cuttings





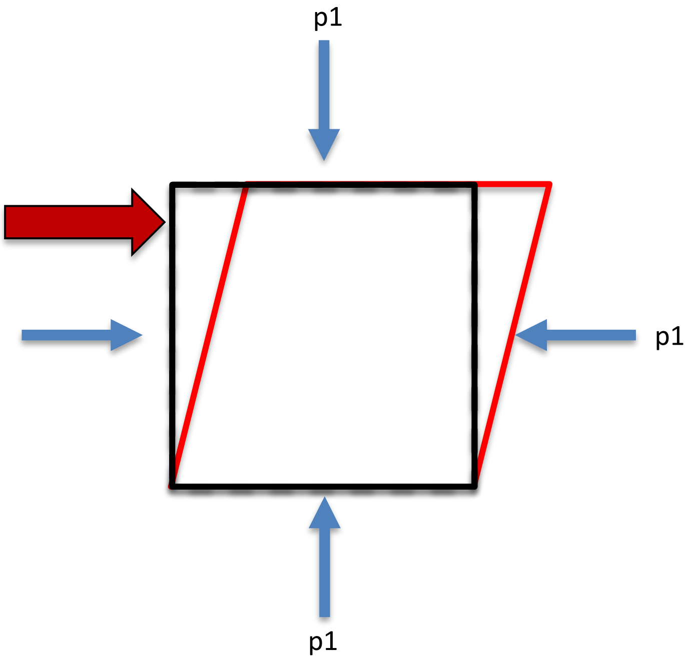
Velocity and Rock Strength

- Velocity = $\frac{10^6}{Dt}$
- $Velocity \propto \frac{Strength}{\rho}$ & $Dt \propto \frac{\rho}{Strength}$
- Strength is defined by Shear Modulus (μ) and Bulk Modulus (K)
- Young's Modulus (E) and Poisson's Ratio (σ) are two other critical rock properties

Shear Modulus (μ)

Shear Modulus defines the amount of shearing a material can withstand

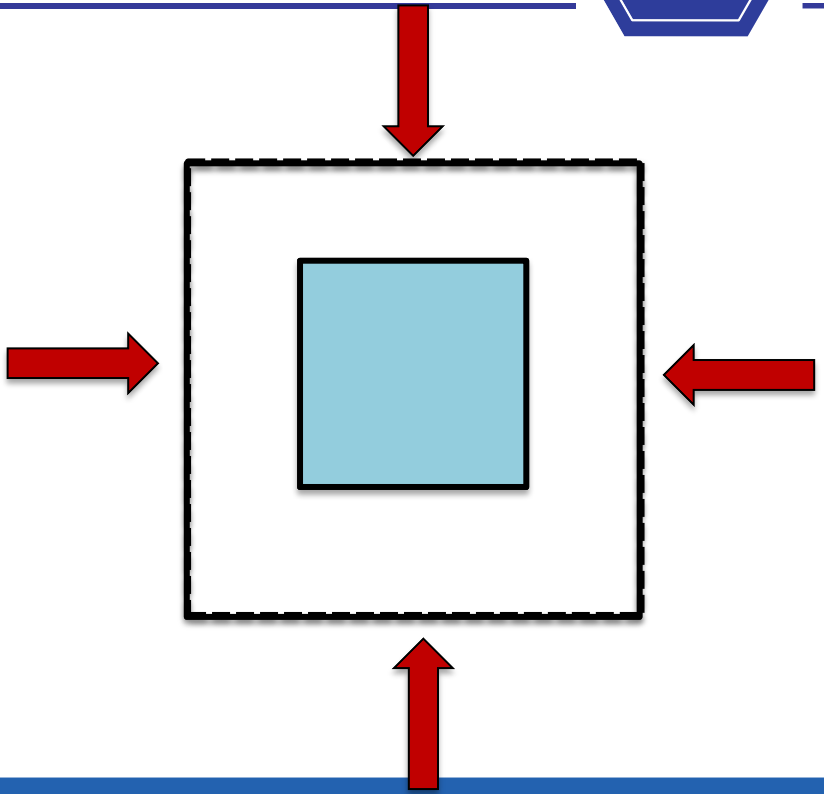
$$\mu = \rho v_s^2 = \frac{\rho}{D t_s^2}$$



Bulk Modulus (K)

Bulk Modulus defines the amount of <u>compression</u> a material can withstand

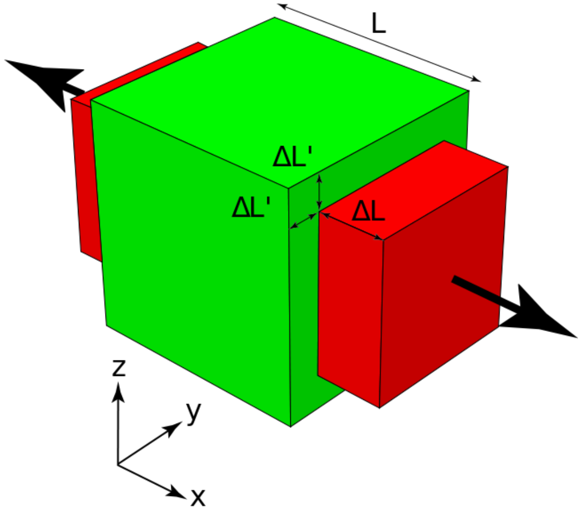
$$K = \rho\left(v_c^2 - \frac{4}{3}v_s^2\right) = \rho\left(\frac{1}{Dt_c^2} - \frac{4}{3}\left(\frac{1}{Dt_s^2}\right)\right)$$



Poisson's Ratio (σ)

Poisson's Ratio is the ratio of strain in a perpendicular direction to the strain in the direction of extension force

$$\sigma = \frac{1}{2} * \frac{\left(\frac{V_c^2}{V_s^2}\right) - 2}{\left(\frac{V_c^2}{V_s^2}\right) - 1} = \frac{1}{2} * \left(\frac{Dt_s^2 - 2Dt_c^2}{Dt_s^2 - Dt_c^2}\right)$$



Most materials have a Poisson's Ratio value between 0 and 0.5

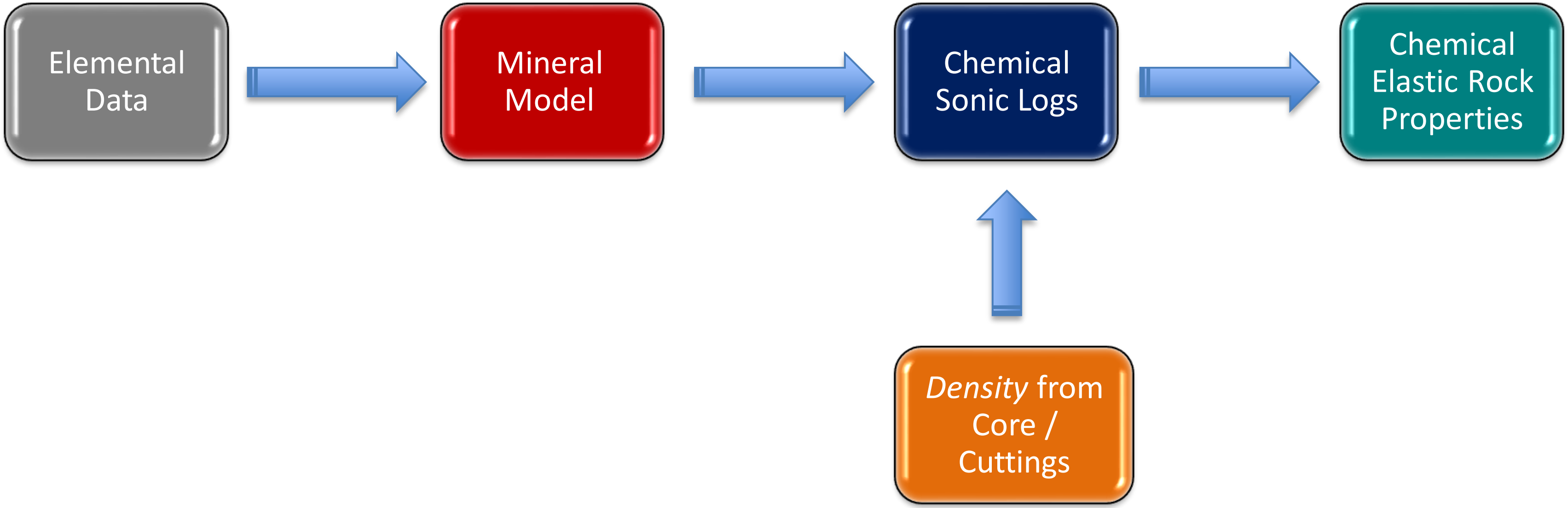
Young's Modulus (E)

Young's Modulus is the ratio of stress to strain and can be related to stiffness

$$E = 2\mu(1+\sigma) = 2\left(\frac{\rho}{Dt_s^2}\right)\left[1+\frac{1}{2}\left(\frac{Dt_s^2-2Dt_c^2}{Dt_s^2-Dt_c^2}\right)\right]$$

Stiffer or more rigid materials will have a higher Young's Modulus value compared to softer materials

Workflow


Elemental Data
Mineral Model
Chemical Sonic Logs
Chemical Elastic Rock Properties
Density from Core / Cuttings

Brittleness

Two types

- Mineral brittleness

Jarvie (2007) : $$\mathrm{BI} = \frac{Qtz}{Qtz+Cal+Cly}$$

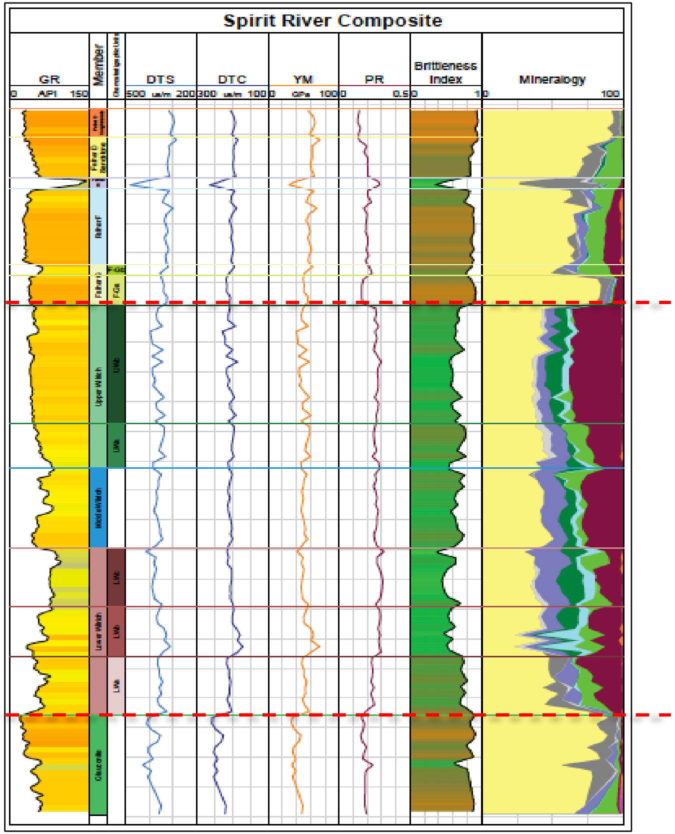
Wang (2009) : $$\mathrm{BI} = \frac{Qtz+Dol}{Qtz+Dol+Cal+Cly+TOC}$$

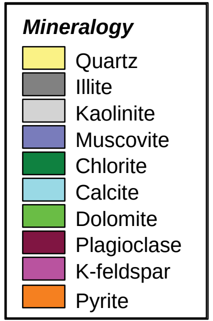
- Dynamic (Seismic) brittleness

Seismic Average : $$\mathrm{BI} = \frac{\sigma_{norm}+E_{norm}}{2}$$

Rickman et al (2008): $$\mathrm{BI} = \left\{\left(\frac{E-1}{8-1}\right) + \left(\frac{\sigma-0.4}{0.15-0.4}\right)\right\}*0.5$$

Results





The derived elastic parameters show subtle variations between the Glauconitic, Falher and Wilrich members

The more clay rich Wilrich is defined by higher shear (DTS) and compressional (DTC) slowness and Poisson's ratio, and as a consequence is less 'brittle' than the more silica rich Falher and Glauconitic members

High Quartz content ……

Conclusions

- The elemental data can confidently distinguish the Wilrich, Falher and Glauconitic units, which have very different geochemical signatures and Geomechanical properties
- Elemental data be used for multiple applications
  - Stratigraphic correlation
  - Mineralogy
  - Rock Mechanics
  - Geosteering
  - Completion optimization

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Thank You !

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