

Application of X-Ray Fluorescence (XRF) Analyses to the Characterization of Tight Reservoirs

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ABSTRACT

Portable X-Ray Fluorescence (XRF) instruments allow a large amount of data to be obtained in a short amount of time, with minimal sample preparation and at low cost. Rock powders, cuttings, slabs or core faces can be analysed directly using this technique. XRF analyses provide highly precise, and if calibrated properly, accurate data on the bulk chemistry of a sample. Elemental data obtained from the XRF analyses can be useful in determination of a chemical stratigraphy. However, geoscientists and engineers are more familiar with and more frequently work with mineralogy and reservoir properties rather than elemental composition.

We have developed normative mineral and reservoir property algorithms to convert the elemental data into these more familiar forms. Mineral abundances determined from the XRF analyses correlate well with those obtained by X-Ray Diffraction, thin section point counting and SEM analyses; however, the XRF determinations are far less costly.

The mineralogy and elemental data are also used to determine reservoir properties through a set of semi-empirical equations. Once data are obtained and calibrated mineralogy is determined using normative mineral algorithms. A "specific mineral interaction" model is then used to determine reservoir properties.

Porosity and mechanical properties such as Poisson's ratio and Young's modulus determined from mineral volumes obtained using the XRF data compare favorably with values obtained from wireline logs and lab analyses in vertical wells. These properties are particularly useful when applied to cuttings analysed during the drilling of lateral wells, where sophisticated log analysis is impractical or too expensive, for geosteering purposes and/or in real time or post well completion planning.

KEY WORDS

X-Ray Fluorescence, Major Element Chemistry, Trace Element Chemistry, Mineralogy, Reservoir Properties, Chemical Stratigraphy, Poisson's Ratio, Young's Modulus.

INTRODUCTION

Portable X-Ray Fluorescence (XRF) instruments allow a large amount of data to be obtained in a short amount of time, with minimal sample preparation and at relatively low cost. Rock powders, cuttings, slabs or core faces can be analysed directly using this technique. Our experience is that portable XRF instruments provide highly precise, but often inaccurate bulk elemental chemical data and that these instruments must be calibrated properly in order to obtain accurate data (also see Rowe and others, 2012). Elemental data obtained from the XRF analyses can be useful for some purposes, for instance in determination of a chemical stratigraphy and correlation of units (Chatellier, 2011; Smith and Malicse, 2011, Rowe and others,

2012; Weedmark and others, 2012; Griffiths and others, 2015). However, geoscientists and engineers are more familiar with and more frequently work with mineralogy and reservoir properties rather than elemental composition. XRF Solutions provide data in these forms (Weedmark and others, 2012; Spencer and Weedmark, 2015).

XRF Solutions have developed proprietary normative mineral algorithms in order to convert the elemental chemical data to mineralogy. Mineral abundances determined from the XRF analyses correlate well with those obtained by X-Ray Diffraction (XRD), thin section point counting and SEM analyses. Reservoir properties are determined from algorithms developed from mineralogy and fabric analyses. Laboratory and petrophysical log data are used to calibrate the algorithms. Once XRF data from core or cuttings are calibrated to lab and petrophysical log data from vertical wells reservoir properties can then be derived from XRF analyses of cuttings obtained from horizontal wells.

Below we discuss results from the Devonian Horn River Group shale gas of northeastern British Columbia, Canada. Although estimates vary the Horn River Group appears to contain several hundred TCF of natural gas.

STATEMENT OF THEORY AND DEFINITIONS

Cross, Iddings, Pirsson and Washington developed the CIPW Norm in the early 1900s based on typical minerals that precipitate from an anhydrous melt at low pressure. It simplifies the typical chemistry and mineralogy of igneous rocks. The CIPW Norm is not appropriate for determination of the mineralogy of sedimentary rocks. Our experience is that normative mineral algorithms for sedimentary rocks such as MINLITH (Rosen and Abbyasov, 2003) or SEDMIN (Kackstaetter, 2014) are generally unsuccessful in determining mineralogy because mineral compositions are underconstrained. Our normative mineral algorithms follow an approach that is similar to that of (Medrano and Piper, 1992) in that they employ both major and trace element composition. The addition of trace element distribution factors allow much better constraints to be placed on the mineralogy. XRF Solutions rely on the distribution of both major elements and trace elements in various minerals for our mineralogy determinations and optimize mass balance equations for each element.

XRF Solutions employ a semi-empirical specific mineral interaction model to determine reservoir properties such as porosity and the mechanical properties Young's Modulus and

Poisson's Ratio. Equations are set up in a similar manner to those used by Harvie, Moller and Weare (1984) and Spencer, Moller and Weare (1990) to parameterize the specific ion interaction model developed by Pitzer (1973) for complex electrolyte solutions. The fundamental equation is:

$$RP = \alpha_{(RP)} + \sum_i \beta_i^0 DV_i + \sum_i \sum_j \beta_{i,j}^1 DV_i DV_j + \sum_i \gamma_i CV_i + \sum_i \theta_i RV_i$$

Where RP is a reservoir property such as porosity, Young's Modulus or Poisson's Ratio; alpha is a function of the reservoir property; DV is the detrital volume of a mineral in the rock, CV is the cement volume of a mineral in the rock and RV is the recrystallized volume of a mineral in the rock; the beta, gamma and theta terms are fabric dependent phenomenologic coefficients. Phenomenologic coefficients are fit to empirical data and vary as a function temperature, pressure (burial depth) and rock composition. The equation is solved for all minerals i and j in the rock.

DATA AND OBSERVATIONS

Portable XRF instruments are quite versatile and can be used to directly analyse rock powders, cuttings, slabs or core faces. XRF Solutions use different instrumental set ups in order to optimize data collection from different materials. More than twenty standards are used for calibration of our instruments including six certified standards obtained from the United States Geological Survey (USGS) and three certified standards from the United States National Institute of Standards and Technology (NIST). These are supplemented by pure mineral standards and mixtures of these minerals. Calibration is different for each of these set ups as illustrated in Figure 1. We determine calibration curves for the major elements Mg, Al, Si, K, Ca, S and Fe plus 20 trace elements for each of the set ups. Calibration differs for each set up and from one instrument to another. Portable XRF instruments if properly set up can provide highly precise and accurate bulk chemical analyses of rocks.

Elemental data are obtained directly from the calibrated XRF instruments. An example of the major element data obtained from cuttings at 5 metre intervals for a 2800 metre vertical well (>500 analyses) from the Horn River Basin is displayed in Figure 1. Several stratigraphic units are recognized starting with the Devonian Keg River Formation (top labeled Dev KR in Figure 1) at the base, passing into the Horn River Group (Horn River in Figure 1), overlying Fort Simpson Formation (top labeled Dev Ft S in Figure 1) and several thin Devonian units (see Weedmark, 2014 for additional stratigraphic units) below

the Exshaw-Bakken Formation (Exshaw in Figure 1). These are overlain by sediments of the Missipian Banff Formation and Rundle Groups (Miss B and RG on Figure 1). Cretaceous sediments of the Buckingham Formation are present in the upper portion of the well.

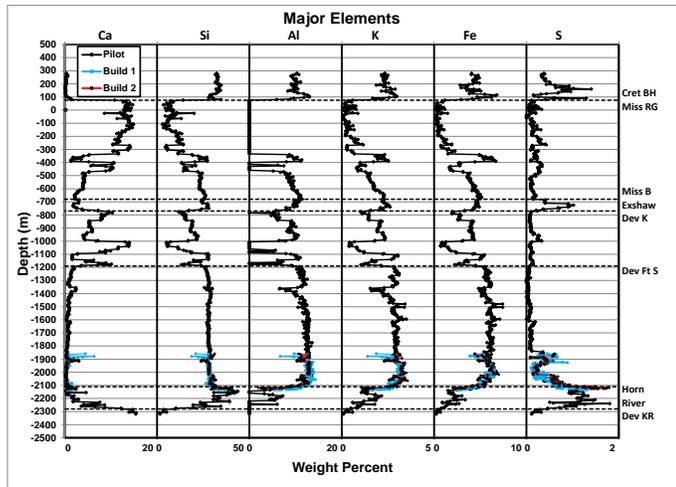


Fig 1. XRF Major Element Profiles. Major element profiles obtained from XRF analyses of cuttings collected at 5 metre intervals from a 2800 metre vertical well (>500 analyses) in the Horn River Basin. Data for the build section of two horizontal wells are also shown from 1850 to 2150 metres in blue and red.

Major element data can be useful in semi-quantitative assessment of units and determination of a chemical stratigraphy. For instance, Ca in this well is largely in carbonate minerals and the high Ca intervals are carbonates. Likewise, most of the S is in pyrite or other metal sulphides. The siliciclastic intervals are more difficult to assess lithologically. The Si is in quartz, clay minerals and other silicate minerals; Al, along with K and Fe are largely in clay minerals. Similarities in the Si, Al, K and Fe profiles indicate somewhat similar siliciclastic mineral compositions, but with different distributions. These data were obtained in 2010 and 2011 using a portable benchtop unit that was not capable of detecting Mg and had a relatively high detection limit for Al. Advances in portable XRF instruments over the last several years allow for the detection of Mg and these elements have lower detection limits for Al.

Mineralogy data obtained by XRD were used to determine the mineralogy of the cuttings from the siliciclastic sediments. We used data obtained from electron microprobe (EM) and SEM analyses to determine the elemental composition of minerals. The mineralogy, especially the clay assemblage, is quite different in the siliciclastic intervals. The most abundant mineral

in the Horn River Group is quartz, illite is the dominant clay mineral with minor amounts of chlorite and K and Ba feldspars, and some dolomite-rich beds. The clay mineral content of the overlying Fort Simpson Formation is much higher and contains illite and chlorite with minor kaolinite and smectite. The Cretaceous Buckingham Formation contains abundant illite, kaolinite and smectitic clay. We used data obtained from electron microprobe (EM) and SEM analyses to determine the elemental composition of minerals and determine trace element distributions in them.

RESULTS

Trace element profiles such as those in Figure 2 are also useful in chemical stratigraphic correlation. However, they also hold a wealth of information on the nature of the sediments. Profiles for Th and U, along with K, can be compared to spectral gamma well logs to position cores or cuttings. Synthetic gamma curves can also be determined from these elements and compared to total gamma well logs. Although carbon is too light an element to detect using portable XRF techniques, trace elements such as V, U and Mo along with several metals are related to organic matter and can be used as proxies for total organic carbon (Tribovillard and others, 2006; Smith and Malicse, 2011). The elements Mn and S can also be used as indicators of redox conditions.

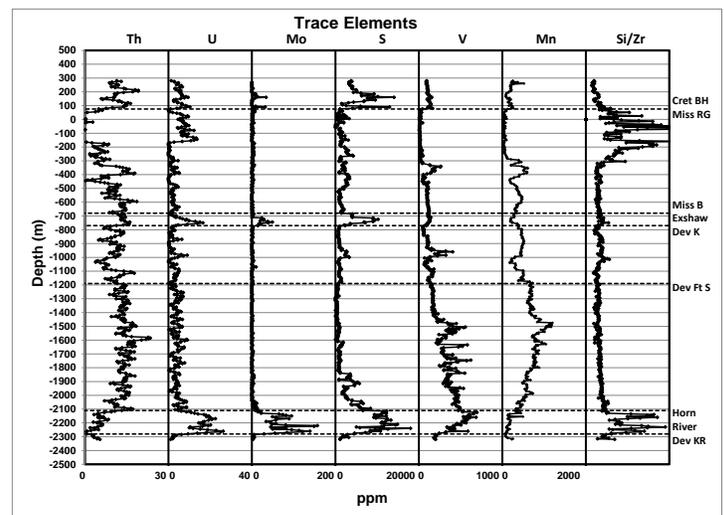


Fig. 2. XRF Trace Element Profiles. Selected trace element profiles obtained from XRF analyses of cuttings collected at 5 metre intervals from a 2800 metre vertical well (>500 analyses) in the Horn River Basin. See text for details.

XRF Solutions convert the elemental data obtained using the portable XRF instruments to mineralogy using our normative mineral calculations. Mineral percentages determined by XRF

Solutions normative procedure are compared to those obtained by XRD in Figure 3. We found a precision of about 5% for the XRD data based on replicate analyses of the same samples. Data are given for the most abundant minerals quartz, illite and chlorite in the Horn River Group (squares). The Duvernay Formation shale of Alberta, Canada, is part of the same system as the Horn River Group (Weedmark and Spencer, 2015; Spencer and Weedmark, 2015). The Alberta Geological Survey estimates the Duvernay Formation to contain more than 400 TCF of natural gas as well as significant NGLs and oil. The mineralogy is somewhat different and the most abundant minerals quartz, calcite, K-spar, illite and kaolinite along with pyrite percentages determined by XRF Solutions normative procedure are compared to those obtained by XRD (diamonds in Figure 3). Data from two other stratigraphic intervals with somewhat different mineralogy are also included in Figure 3. Unit 1 (circles) contains abundant quartz, kaolinite and ankerite; unit 2 (triangles) contains abundant dolomite and quartz. The vast majority of the data on Figure 3 fall within the 5% envelope expected from the precision of the XRD analyses. This demonstrates that our XRF normative mineral algorithms give comparable results to those obtained from XRD analyses. The XRF analyses are much more rapid and much less costly.

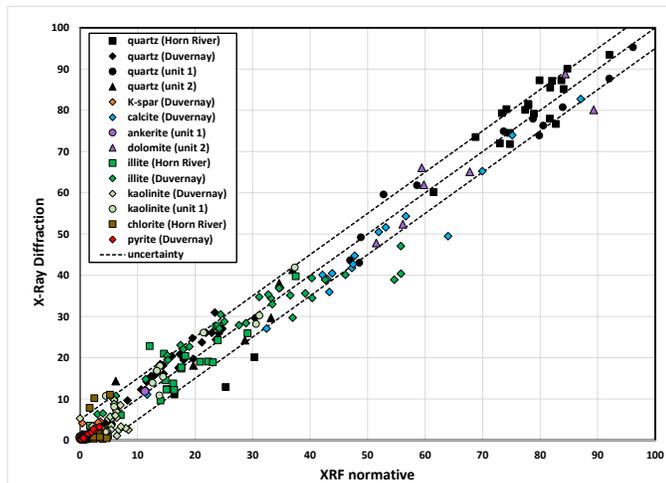


Fig. 3. Mineralogy Comparison. Mineralogy determined from XRF bulk chemical analyses using XRF Solutions normative mineral algorithm are compared to data obtained by XRD. Most points fall within a 5% envelope. See text for details.

DISCUSSION

XRF analysis can be conducted over an entire vertical well in order to determine a chemical stratigraphy and locate potential areas of interest for both industry and academic applications.

Elemental abundances provide a wealth of data that can be used to distinguish various chemical stratigraphic units. Each formation can be distinguished with relative ease using basic elemental abundance suites. Siliciclastic units can be distinguished from carbonate units through the Si and Ca profiles such as those on Figure 1. Carbonate units such as the Missippian Banff Formation and Rundle Group that “clean” upward can also be divided on the basis of these profiles. Division of siliciclastic units such as the Horn River Group and Fort Simpson Formation are readily apparent from the Si, Al, K and Fe profiles among others (see Weedmark, 2014 for a more detailed stratigraphic breakdown).

Chemical stratigraphy can be quite useful for many applications. For instance, two horizontal wells were drilled from the same pad as the verticle well in Figure 1. Data from the build section of each are also dispalyed in Figure 1 in the depth interval from about 1850 to 2150 metres. These data clearly show where the two wells landed near the top of the Horn River Group.

The major rock forming elements acquired through XRF methods are excellent for identifying rock formations and sub-units in the subsurface which can be correlated from well to well. XRF analysis also yields a large quantity of chemical information on trace elements. Trace elements related to TOC are used to locate zones with a high source rock potential, even though carbon itself is too light to detect using XRF. Areas of interest are located through XRF using relatively simple interpretations such as molecular percentages and TOC estimates to screen out samples for more expensive or time consuming lab analyses. The trace elements Ni, Mo, V, and U are associated with organics and can be detected by XRF. Concentrations of Ni and V preserved in sediments above 100 PPM, which is the case in the Horn River Group, are associated with kerogen from marine algae (Lewan & Maynard, 1982). U accumulates on or within organics while Mo is captured in associated sulphides under reducing conditions and both remain if the sediments do not get oxidized (Kowalski et al., 2009). Combinations of these specific trace elements are used to predict zones of higher and lower TOC. Redox-sensitive trace metals (U, V, and Mo), which are soluble under oxidizing conditions but precipitate (or adsorb) under anoxic conditions, are used to identify the redox state of sediments (Morford et al., 2005). The S content also correlates closely with these and appears to be contained either within the organics or as part of the sulphides formed under reduced conditions. In certain areas the S and Fe increase dramatically while the other TOC indicators drop. This indicates there is pyrite, which may not be entirely related to bacterial reduction of organics but also to other processes such as precipitation from hydrothermal fluids or alteration of minerals.

The trace metal Mn can also be used to help determine redox conditions during deposition. Mn will tend to be mobilized out of the sediments and into the overlying water mass under reducing conditions (Morford et al., 2005), thus resulting in low preservation in the rock record. Any significant accumulation

of Mn in the rock is a strong indication that these rocks were deposited under oxidizing conditions and organic carbon is unlikely to be preserved. In general, a strong inverse relationship between the amount of Mn present in the rock and both FeS₂ and TOC content is observed. Where organics are destroyed under oxidizing conditions, the U and Mo tend to be mobilized while the V is more resistant and can accumulate within the sediments. It is possible that V can be used as an indicator for primary original organic production, while Mo and U show areas where those organics are preserved.

There are several changes in TOC indicator levels through the well displayed in Figure 2. The intervals with high organic carbon accumulation based on elevated Mo, U, and S and low Mn include the Buckingham Formation, Exshaw Formation and the Horn River Group. The actual amount of Mo, U, and V present in the organics can vary significantly depending on the organic source and the water conditions during the time of deposition. This makes it difficult to directly compare source rocks from different formations to determine which has a higher TOC content. However for a single formation, intervals with higher TOC indicators are likely to have higher TOC values. The concentrations of trace elements are related to the original TOC content and that portion which was preserved. No relationship has been established between trace element chemistry and the maturity of the source rock. If the organic content has decreased due to maturation and hydrocarbon expulsion then the TOC indicators predict higher TOC than is actually present.

There is a general belief within academia and industry that silica cementation within the Horn River Group is dominantly the result of biogenic siliceous oozes formed on the seafloor during deposition (Ross & Bustin, 2008). The explanation for the presence of the high TOC is that this basin was restricted early and therefore turned anoxic in the presence of large amounts of organic matter. An alternative hypothesis is that hydrothermal activity is the source of silica cementation which better explains the presence of elevated TOC levels, hydrothermal mineral assemblages, discontinuous stratigraphic intervals, sulphide ore deposits and variable compaction associated with the Horn River Group. The mineralization is present in the form of pyrite, arsenopyrite, chalcopyrite, sphalerite and galena which are commonly associated with SEDEX deposits (Goodfellow and others, 1993; Goodfellow and Lydon, 2007; Jowitt, 2013). Authigenic barite, monazite and Ba-rich feldspars are also present. Data indicate that hydrothermal activity may be one of the dominant processes necessary for the creation of many black shale units and that there are likely different classes of black shale (Spencer and others, 2011; Spencer and Weedmark, 2015).

It is possible to separate detrital quartz content from quartz cement using the trace metal Zr. Zirconium is present in the resistant mineral zircon, which originates in igneous or metamorphic rocks. These zircon minerals have a tendency to accumulate in a consistent ratio with the detrital quartz; either because both minerals are chemically and physically resistant or

that small zircon inclusions are present in detrital quartz grains. The ratio at which these minerals accumulate can be different for rocks deposited from different source rocks; however, if the source remains the same then so will the ratio. The Si/zirconium ratio for the Horn River well is displayed in Figure 2.

This is clearly evident for rocks in the Fort Simpson Formation which have a consistent Si/Zr ratio. This ratio provides a baseline for quartz which is present in the rock as a detrital component. The quartz/Zr increases significantly in the Horn River Group and is also variable. If we assume the source for the Horn River Group siliciclastics is the same as for the Fort Simpson Formation, then there is more quartz in the rock than should be present from detrital input. This additional quartz is present in the form of cement based on SEM observations. The amount of quartz cement present in a sample is directly related to how high above the baseline the Si/Zr ratio is.

There are two basic end members of rock fabrics present in both the Fort Simpson Formation and the Horn River Group. One is a fully detrital fabric which contains high clay content and shows significant compaction. The second is a heavily quartz cemented fabric which has a relatively low clay content and is only slightly compacted. There is a relationship between the Si/Zr ratio and the amount of quartz cement present and the quartz cementation significantly affects the mechanical properties of the rock. Increases in the amount of quartz cement and decreases in the amount of clay in a rock cause it to become more brittle.

The mechanical properties appear to be fabric controlled and each mineral contributes to the make-up of a specific fabric. Understanding these relationships makes it possible to predict the mechanical properties of a rock using only the mineralogy and fabric. The mechanical properties of an unconventional shale reservoir are very important in oil and gas exploration. If a rock is too ductile or too strong it may not be possible to hydraulically fracture the rock. Quartz and feldspars are all relatively brittle (low Poisson's Ratio) with variable rock strengths (Young's Modulus). Calcite and dolomite have very high Poisson's Ratio and Young's Modulus. This causes these minerals to be relatively ductile but quite strong. Most clay types can generally be considered to have a low Poisson's Ratio and a low Young's Modulus; however, anisotropic minerals such as illite or mica can be ductile in one orientation and brittle in another. High concentrations of these clays can have a negative impact on hydraulic fracturing by making the rock too ductile or allowing fractures to close over time due to embedment.

A semi-empirical specific ion interaction algorithm for predicting Poisson's Ratio and Young's Modulus from XRF data has been developed for the Horn River Group and Fort Simpson Formation. It is based on the relationship of mineralogy and rock fabric tailored to these formations. The XRF determined Poisson's Ratio values for two wells are compared to those determined from wire line sonic and density logs in Figure 4. In this case the phenomenologic coefficients

for the algorithm were determined using data from well A (same well as in Figures 1 and 2). The algorithm was then tested on well B. The correlation for Poisson's Ratio is excellent. The algorithm has since been used on several additional wells with similar results.

Calculated Mechanical Properties – Horn River

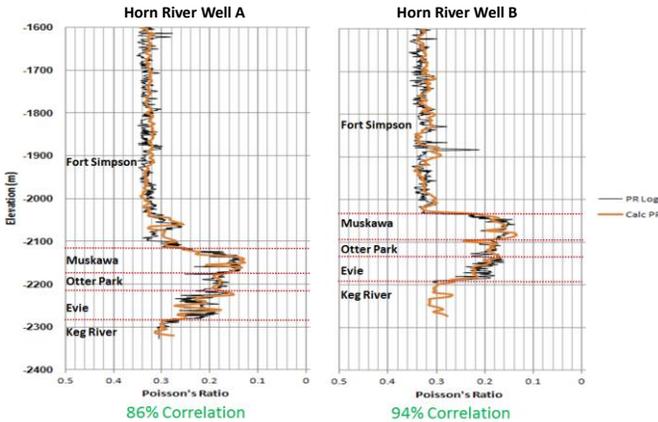


Fig. 4. Poisson's Ratio. Poisson's Ratio values calculated using the semi-empirical specific mineral interaction algorithm are displayed in orange and compared to values obtained from wireline sonic and density logs in black. Each subunit of the Horn River Group and Fort Simpson Formation is labelled and separated by a dashed red line.

The XRF determined Young's Modulus values for the same two wells are compared to those determined from wire line sonic and density logs in Figure 5. In this case the phenomenologic coefficients for the algorithm were determined using data from well A. The algorithm was then tested on well B. Comparison of the data sets again produce an excellent correlation. The algorithm has since been used on several additional wells with similar results.

There is more difficulty in accurately calculating Young's Modulus using only mineralogy because small amounts of a mineral present as cement can dramatically increase the strength of the rock depending on what mineral is present as cement and how the cement forms. Both Poisson's Ratio and Young's Modulus values are mineralogy, fabric, and stress dependent which is why the algorithm cannot be applied universally to other formations without adjustments.

The main goal of developing XRF techniques for calculating mineralogy, TOC, trace metal indicators and rock mechanics in vertical wells is to apply these same techniques in horizontal wells. Oil and gas operators are currently very limited in the amount of data they can collect in horizontal wells due to the cost, risk, and simple mechanics of trying to log these wells with conventional wireline tools. However, these production wells are exactly where the most information is required in order to effectively and affordably induce hydraulic fractures, which control both short and long term production.

Calculated Mechanical Properties – Horn River

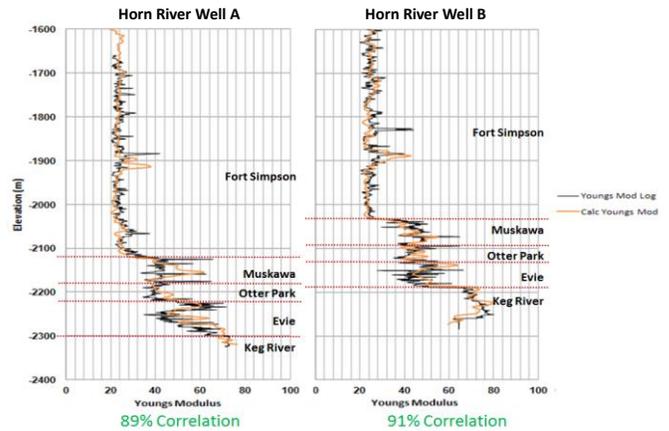


Fig. 5. Young's Modulus. Young's Modulus values calculated using the semi-empirical specific mineral interaction algorithm are displayed in orange and compared to values obtained from wireline sonic and density logs in black. Each subunit of the Horn River Group and Fort Simpson Formation is labelled and separated by a dashed red line.

Information from two horizontal wells drilled in opposite directions from the same pad as well A, the same well and build sections shown in Figures 1 and 2 are summarized in Figure 6. Both wells land near the top of the Horn River Group (compare data from prior to about 300 m). However, lateral 1 moves stratigraphically upward into the clay-rich (higher Al content), TOC-poor (low U and Mo) Fort Simpson Formation. Although the trajectory of lateral 1 is relatively flat the formations dip away from the pilot well toward the toe of the horizontal well. Trace element markers indicate the majority of the well bore is several 10's of metres above the targeted organic-rich Horn River Group. The relatively high Poisson's Ratio and low Young's Modulus in this zone are not favourable for completion.

In contrast, lateral 2, drilled in the opposite direction, stays within the target zone and is mostly within two thin stratigraphic intervals. The first interval, from about 325 to 950 metres has a relatively low clay content (low Al), and variable, but high quartz content with a high proportion of quartz cement. This interval has a high TOC as indicated by the Mo and U abundances. The relatively low Poisson's Ratio and high Young's Modulus in this interval are favourable for completion.

A carbonate bed is encountered at about 1000 metres in lateral 2. Major and trace element data indicate that this same carbonate bed is present at about 1475 metres. The well trajectory between these two points and the position of this marker in the pilot well can be used to determine the apparent dip of the beds in the two horizontal wells. The interval between the carbonate marker beds is quite consistent. It has a relatively low clay content (low Al), and an average quartz content similar

to the first interval. However, the quartz content of this interval is relatively constant and it contains a lower proportion of quartz cement. Therefore, it is easier to drill through than the first interval. This interval also has a high TOC content as indicated by the Mo and U abundances. The relatively low Poisson's Ratio and high Young's Modulus in this interval are favourable for completion. We feel that completions in this interval are likely more consistent than in the first interval.

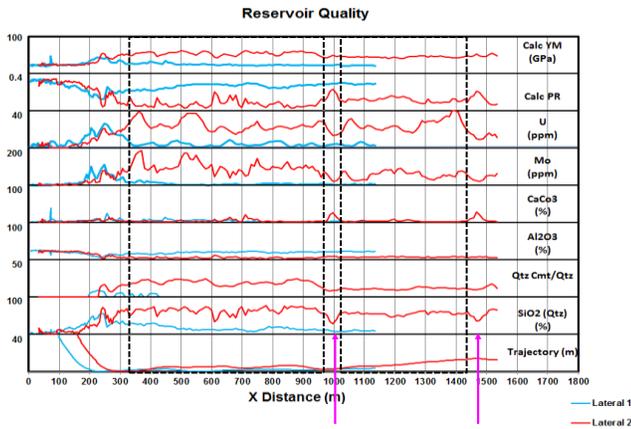


Fig. 6. Applications of XRF in Horizontal Wells. Combined chemical logs are displayed for two horizontal wells drilled from the same pad as the well shown in Figures 1 and 2 and well A in Figures 4 and 5. See text for details.

A second example of the application of XRF analyses in a horizontal well is shown in Figure 7. This example is from the Devonian Duvernay Formation in Alberta, Canada. Total organic carbon and mechanical properties were calibrated using XRF and laboratory analyses of core and petrophysical logs from nearby vertical wells using the same protocols as for the Horn River Group. Two intervals are outlined on Figure 7. The first interval covers about 350 metres. The interval has a higher clay (dominantly illite with lesser kaolinite) and TOC content, but lower carbonate (mostly calcite with minor dolomite) and quartz content than the majority of the well. Poisson's Ratio is slightly higher and Young's Modulus is significantly lower than the remainder of the well.

The second interval covers about 800 metres. The interval has a lower clay (dominantly illite with lesser kaolinite) and TOC content than the first. The carbonate (mostly calcite with minor dolomite) and quartz content are both higher than in the first interval. Poisson's Ratio is slightly lower and Young's Modulus is significantly higher than in the first interval. Overall these parameters are quite consistent through the interval.

Duvernay Case Study

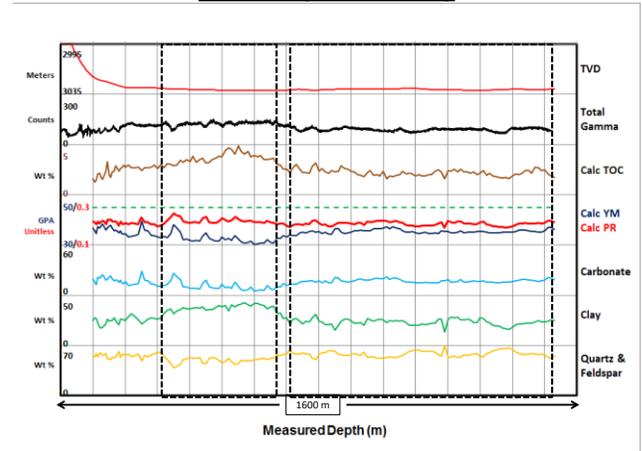


Fig. 7. Applications of XRF in Horizontal Wells. Combined chemical logs for a horizontal well drilled in the Duvernay Formation are displayed. There are significant differences in the reservoir quality along the well. See text for details.

Completions in the second interval are quite consistent in this well. This lithology is encountered in a large number of horizontal wells that we have analysed in the Duvernay Formation. Completions are generally successful and consistent. The first interval was also completed successfully; however, completions differ somewhat from the second interval. We have performed a large number of look back studies on horizontal well cuttings from the Duvernay Formation and identified several different lithologies with different mechanical properties. While several of these can be completed successfully, completions differ from one lithology to another. There are also some lithologies where a high proportion of completions have problems. Our clients use the data we provide to plan their completion strategies.

Production data are not available for many of the wells we have analysed and some of our clients do not provide production data or want it to remain confidential. We have performed look back studies of production from horizontal wells in the Duvernay and other formations. We find a strong correlation between the quality of the reservoir rock in the immediate vicinity of the well bore and production. As production records from some of the more recent wells we have analysed become available we continue to assess this aspect.

CONCLUSION

Portable X-Ray Fluorescence instruments allow a large amount of data to be obtained in a short amount of time with minimal sample preparation. The cost of these non-destructive analyses are quite low in comparison to conventional techniques. Portable X-Ray Fluorescence instruments are capable of analysing rock powders, cuttings, slabs or core faces directly. XRF analyses provide highly precise, and if calibrated properly, accurate data on the bulk chemistry of a sample. Elemental data

obtained from the XRF analyses can be useful in determination of a chemical stratigraphy.

Geoscientists and engineers are more familiar with and more frequently work with mineralogy and reservoir properties rather than elemental composition. XRF Solutions have developed normative mineral algorithms to convert bulk chemical data into mineralogy. Reservoir properties, porosity, Poisson's ratio and Young's modulus are determined from a semi-empirical specific mineral interaction model. Mineral abundances and reservoir properties determined from the XRF analyses correlate well with those obtained by more costly techniques.

Formation specific algorithms are developed from vertical wells. Once these are developed they can be applied to cuttings analysed during the drilling of lateral wells. The information obtained is particularly valuable for geosteering purposes and/or in real time or post well completion planning. Data obtained using portable X-Ray Fluorescence instruments provide a cost-effective means for optimization of both completions and production from horizontal wells.

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