Unconventional Methods For Unconventional Plays:

Using Elemental Data To Understand Shale Resource Plays

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Part 1

Shales are an important hydrocarbon resource; yet understanding them as reservoirs remains problematic. Their fine-grained, organic-rich yet superficially homogenous character make the application of traditional reservoir characterisation methods impractical or impossible. Increasingly, in the North American shale plays, inorganic geochemical data are being used as a one-stop method for understanding shale reservoirs. For decades, elemental data have been used to help solve stratigraphic problems, i.e. definition of chemostratigraphic frameworks. However, the same dataset acquired for chemostratigraphic studies can be used to model shale mineralogy, model TOC levels, determine paleoredox conditions, identify zones of biogenic silica in shales and provide information about transgressive – regressive cycles.

The applications of elemental data to understanding shale plays fall into two natural groupings. The first is the traditional use of geochemical data to aid in understanding regional and reservoir-scale stratigraphy. This application is discussed in this issue of *PESA News Resources*. The second main use geochemical data is in modeling applications, such as those listed above, and this will be discussed in the next issue of *PESA News Resources*.

Introduction

In the past decade, shale resource plays have risen to the forefront of hydrocarbon exploration, as shown by the numerous 'shale conferences' in the past two years alone (Critical Assessment of Shale Resource Plays, Hedberg Research Conference Dec 2010, Austin, Texas, World Shale Gas Conference & Exhibition, Nov 2010, Dallas Forth Worth, Texas, Nov 2011, Houston, Texas, Global Unconventional Gas Conference, June 2010, Amsterdam, Shale Gas World Europe, Dec 2010, Warsaw, Poland, Shale Gas Insight 2011, Nov 2011 Philadelphia, Pennsylvanian, Shale Gas Asia 2011, Feb, New Delhi, India to name but a few). Although the majority of active producing shale plays are in North America, the success there has led to increased interest in shale formations around the world, including in Australia, where according to a June 2011 report commissioned by the US Energy Information Agency, Australia has 396 Tcf of technically recoverable shale gas resources. This is equivalent to about 20% of the combined equivalent resources of Canada, Mexico and the United States and it exceeds the estimated recoverable reserves of CSG in Australia.

Despite the activity and the large number of well completions, the fine grained, macro-scale homogeneity of many formations currently being exploited in North America negates some of the more traditional approaches to reservoir characterisation and stratigraphic correlation, which has resulted in the search for new methodologies that enable better stratigraphic understanding of shale reservoirs. Here, the application and potential of one approach is demonstrated, namely the application of inorganic whole rock geochemical data (or chemostratigraphy) to shale resource plays.

Inorganic whole rock geochemical data have been used to define stratigraphic correlations in the petroleum industry for over a decade now (Ratcliffe et al., 2010 and references cited therein). The technique of chemostratigraphy relies upon recognising changes in element concentrations through time and using those to model changes in geological features, such as paleoclimate (Pearce et al., 2005, Ratcliffe et al., 2010) and provenance (Ratcliffe et al., 2007,

Wright et al., 2010). Published accounts using this approach are largely on fluvial successions, where stratigraphic correlation using traditional techniques are often problematic (e.g. Pearce et al., 2005, Ratcliffe et al., 2006, Ratcliffe et al., 2010, Wright et al., 2010 and Hildred et al., 2011). Over the same decade, inorganic whole rock geochemical datasets have routinely been acquired from mudrocks, the data typically being used to help elucidate paleoredox conditions during oceanic anoxic events (e.g. Tribovillard et al., 2006, Turgen and Brumsack, 2006, Tribovillard et al., 2008, Negri et al., 2009, Jenkyns, 2010). Here, approaches of the chemostratigrapher and the oceanic anoxic event are combined and pragmatically applied to shale gas plays in North America.

While the applications presented here are largely tested on the Haynesville Formation and, to a lesser extent, the Eagle Ford and Muskwa formations, the approaches adopted herein would be equally applicable to any shale resource play.

Methodology and dataset

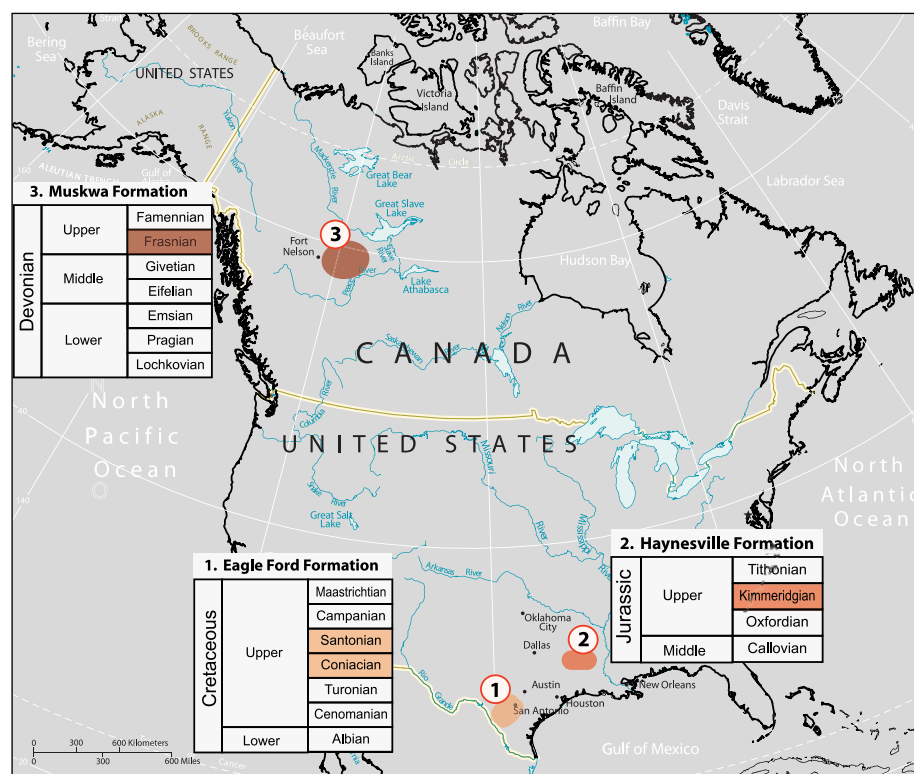The data for this article are largely from the Haynesville Formation, with less extensive datasets

Fig. 1. Geographic location and ages of the shale reservoir plays referred to in the text.

from the Muskwa Formation and the Eagle Ford Formation also being drawn upon (Figure 1). All of these formations are proven shale gas plays, with each being extensively drilled for exploration, appraisal and production.

The Haynesville Formation is late Jurassic (Kimmeridgian) in age. It is a locally calcareous and organic rich (TOC values are 2-6%) mudrock that occurs in northeast Texas and northwest Louisiana (Figure 1). It was deposited in an extensive intra shelf basin on the young, passive margin of the US Gulf Coast during a period of arid climatic conditions. Basement faulting and salt movement controlled the initial water depths, resulting in regions of the sea bottom having restricted communication with the open ocean and therefore recurrently experiencing anoxic bottom water conditions. The Eagle Ford Formation is a dark grey calcareous, locally organic-rich mudstone of Cenomanian – Turonian age (Figure 1). It sub-crops in south Texas forming a narrow strip that is 150 miles long. Over this distance, the Eagle Ford Shale Formation varies in thickness from approximately 75 ft to 300 ft. The Muskwa Formation is Frasnian (Devonian) in age and is located in northern Alberta, northeastern British Colombia and in the southern portion of the Northwest Territories, Canada (Figure 1).

All data for this article have been acquired using Inductively Coupled Plasma Optical Emission (ICP-OES) and Mass Spectrometry (ICP-MS), following a Li-metaborate fusion procedure (Jarvis and Jarvis, 1995). These preparation and analytical methods provide data for 10 major elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MgO, MnO, CaO, Na_2O, K_2O, P_2O_5), 25 trace elements (Ba, Be, Co, Cr, Cs, Cu, Ga, Hf, Mo, Nb, Ni, Pb, Rb, Sc, Sn, Sr, Ta, Tl, Th, U, V, W, Y, Zn, and Zr) and 14 rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Ho, Dy, Er, Tm, Yb, and Lu).

Stratigraphic applications of whole rock inorganic geochemical data in shales

Developing stratigraphic frameworks is the key to the exploration and exploitation of any formation in any hydrocarbon basin. In shale plays, the more traditional methods used to define stratigraphic correlations in the oil industry are somewhat limited. Commonly, the restricted basin nature of their accumulation can limit the use of biostratigraphy, and
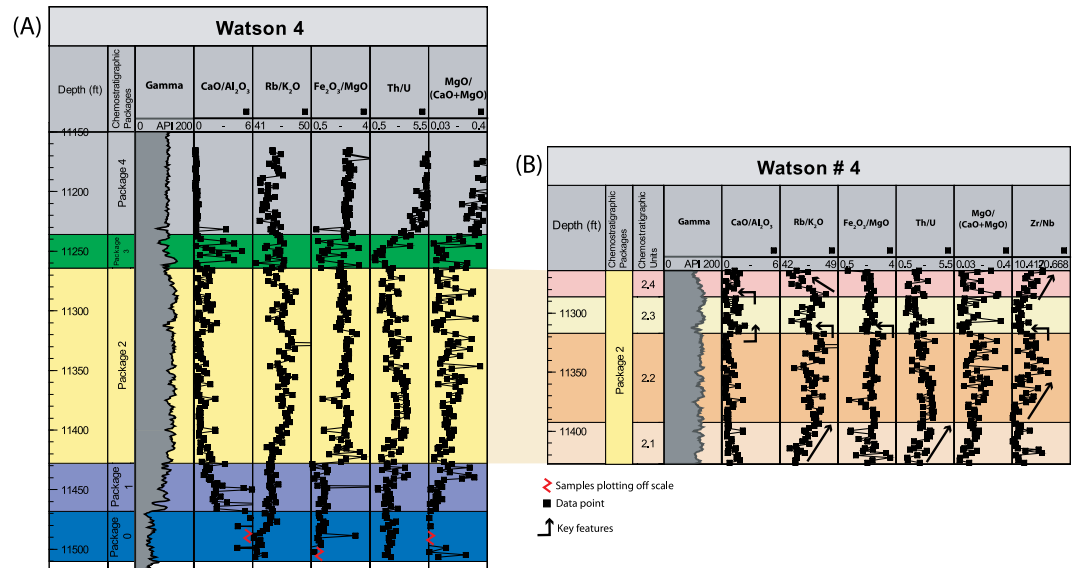

Fig. 2. Geochemical characterisation of the Haynesville Formation as penetrated in Well Watson-4. Logs for a series of key elemental ratios are plotted relative to depth in order to characterise broad scale "Chemostratigraphic Packages" (Plot A) and finer scale geochemical units Plot B). All samples analysed here are from conventional core and all data were acquired using ICP OES MS with a Li-metaborate fusion preparation.
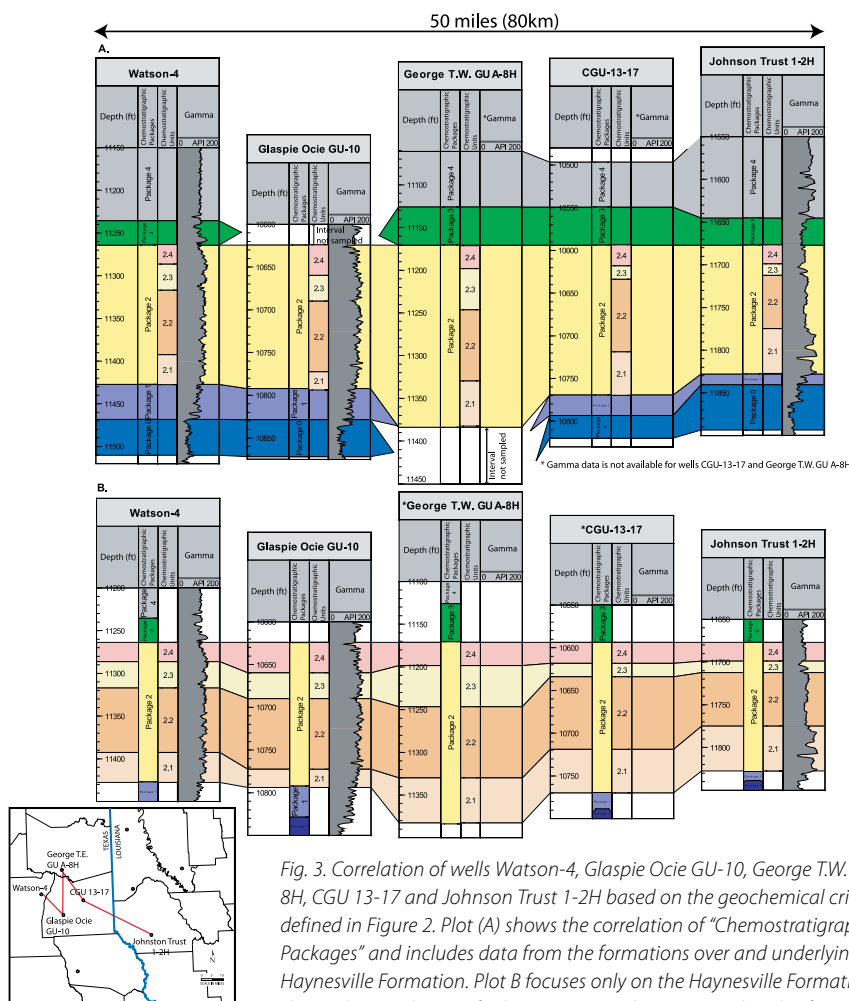
palynomorphs are often thermally degraded. Also, electric log correlations are hampered by the variable controls on U, K and Th. In typical fluvial and shallow oxic marine settings the K, Th, and U are all largely controlled by the amount of clay versus sand, enabling lithostratigraphic and sequence stratigraphic correlations to be made from the gamma logs. However, in the Haynesville Formation, U is associated with TOC and minerals derived from authigenic enrichment in anoxic conditions, whereas K and Th are associated with the amount of terrigenous-derived material. These associations are discussed in greater detail in Part 2 of this article. Therefore, using gamma logs for stratigraphic correlations in shale gas plays is enigmatic. Furthermore, the apparent macro-scale homogeneity of the mud-rocks precludes the recognition of sedimentary facies that can be used for stratigraphic correlations, particularly when only cuttings samples are available.

Chemostratigraphy has been used to characterise and correlate the Haynesville Formation, along with underlying and overlying portions of the Smackover and Bossier formations respectively. Figure 2 shows a chemostratigraphic package and unit level characterisation of the Haynesville Formation in a single well. On Figure 2a the study intervals are divided into a series of first order Chemostratigraphic Packages, 0-4, based on changing values of CaO/Al_2O_3, $Rb/K2O$, Fe_2O_3/MgO, Th/U and $MgO/(CaO+MgO)$:

- Package 4 (approximately equivalent to the Bossier Formation) is identified by higher Th/U and $MgO/(CaO+MgO)$ values than underlying packages.

- Package 3 (transitional between the Haynesville and Bossier formations) is identified by generally lower Fe_2O_3/MgO and Rb/K_2O values compared to Package 2 and lower Th/U values compared to Package 4.This interval also displays elevated CaO/Al_2O_3 values relative to Packages 2 and 4.

- Package 2 (equivalent to the Haynesville Formation) is characterised by higher Fe_2O_3/MgO values than underlying packages and lower Th/U and $MgO/(CaO+MgO)$ values than the overlying Package 4.

- Package 1 (transitional between the Haynesville and Smackover formations) is characterised by CaO/Al_2O_3 values that are intermediate between those of Packages 0 and 2, and lower Fe_2O_3/MgO values than overlying packages.

- Package 0 (equivalent to the Smackover Formation) is identified by high CaO/Al_2O_3 ratios.

It is possible to further subdivide the Haynesville Formation (Chemostratigraphic Package 2) into a series of higher resolution Chemostratigraphic Units; 2.1, 2.2, 2.3 and 2.4 (Figure 2b). These units are defined by more subtle geochemical variations in CaO/Al_2O_3, Rb/K_2O, Fe_2O_3/MgO, Th/U, $MgO/(CaO+MgO)$ and Zr/Nb ratios. The resultant Chemostratigraphic Package and Chemostratigraphic Unit correlations are displayed on Figures 3 and 3b for wells Watson-4, Glaspie Ocie GU-10, George T.W.

Fig. 3. Correlation of wells Watson-4, Glaspie Ocie GU-10, George T.W. GUA-8H, CGU 13-17 and Johnson Trust 1-2H based on the geochemical criteria defined in Figure 2. Plot (A) shows the correlation of "Chemostratigraphic Packages" and includes data from the formations over and underlying the Haynesville Formation. Plot B focuses only on the Haynesville Formation and shows the correlation of "Chemostratigraphic Units" within this formation. Inset map shows relative positions of well in correlation panels.

GUA-8H, CGU 13-17 and Johnson Trust 1-2H.

High resolution stratigraphic applications of whole rock inorganic geochemical data in shales

Although high resolution stratigraphic frameworks are always desirable, the need for them is exacerbated in shale plays by the increased use of horizontal drilling in their exploitation. Typically, the horizontal leg of a well will be several thousand feet in length, with the aim of remaining in a thin stratigraphic horizon over as much of that distance as possible. Figure 4 schematically shows how the well-bore pathway through the Eagle Ford Formation in a 'horizontal' sidetrack well can be related back to the pilot hole by analysis of cuttings samples. The ideal target zone for this lateral well through the Eagle Ford Formation is coincident with the geochemically defined Unit 2.3 (Schmidt et al., 2010). At the top of top Unit 2.3 (the top of the target zone) there is a very marked downhole increase in P_2O_5 values, together with an increase in TiO_2/Nb and decrease in Th/U values. From the top of this unit to its base, the P_2O_5 decreases and

the TiO_2/Nb increases, with the unit 2.3 / 2.2 boundary (base of target zone) being defined by a decrease in TiO_2/Nb values and an increase in P_2O_5 values (Figure 4). By analysing cutting samples from the horizontal offset to the vertical hole the point at which the well bore enters the target zone is clearly defined by the sharp increase in P2O5 values around 15,800' (MD).

Geochemistry and mineralogy

The key to fully utilising major and trace element changes in any ancient sequence is understanding the geological controls on each of the elements (Ratcliffe et al., 2007, Hildred et al., 2011, Wright et al., 2010). A simple, but effective way to achieve this is the consideration of the Eigen-vector (EV) scores calculated when PCA (principal component analysis) is carried out on a geochemical dataset (Pearce et al., 2005, Svendsen et al., 2007; Ellwood et al., 2008; Pe-Piper et al., 2008, Ratcliffe et al., 2010). One Figure 5, EV1 and EV2 scores, which together account for 73% of the variation within the entire Haynesville Formation dataset, are plotted. On cross-plots such as that displayed on Figure 5, the more closely elements plot to one

another, the more closely linked they are in the sediment. It is apparent from Figure 5 that the elements fall into three broad groups:

- Group 1 elements include CaO, MgO, MnO and Sr, a grouping of elements associated with carbonate minerals such as calcite and dolomite.

- Group 2 elements include Mo, U, Ni, V, Cu, Zn and Co. These are all elements associated with authigenic enrichment under anoxic conditions (Tribovillard et al., 2006).

- Group 3 elements contain almost all other elements and are associated with terrigenous minerals, including clay minerals (e.g. Al_2O_3, K_2O, Th), quartz (SiO_2), feldspars (Na_2O) and heavy minerals (e.g. Zr, Hf).

The significance of these element groupings will be discussed further in Part 2 of this article.

Conclusions

In this first look at the application of elemental data to helping develop shale resource plays, the 'traditional' use of elemental data for chemostratigraphy and its extension to high resolution definitions for placement of well-bores has been described. In the next part of the article, the more unconventional applications of mineral and TOC modelling, identification of biogenic silica, recognition of transgressive-regressive cycles and modelling of paleoredox conditions will be discussed.

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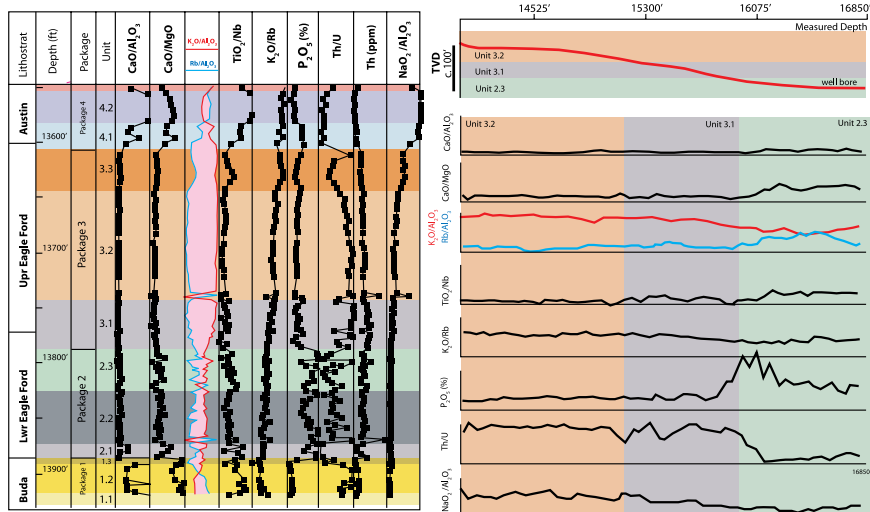
Fig. 4. Using geochemical data to determine the well-bore pathway of a horizontal well relative to the stratigraphy of the vertical pilot hole in the Eagle Ford Formation, Texas. Left hand panel displays the chemostratigraphic zonation of a vertical hole through the Eagle Ford Formation. Samples analysed in the vertical hole are a mixture of core and cuttings. The right hand panel displays the chemical variations in a "horizontal" sidetrack identified by analysis of cuttings samples. Diagram redrawn from Ratcliffe et al., (2011)

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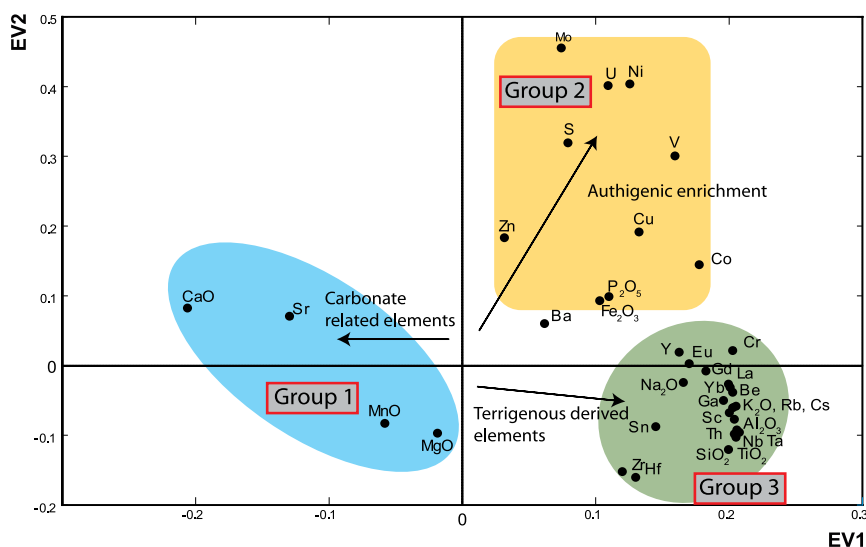
Fig. 5. Eigen vector 1 (EV1) vs. Eigen vector 1 (EV2) calculated from data in the Haynesville Formation from well George T.W GUA-8H. Elements fall into three broad groupings reflecting their mineralogical associations in the formation.