Applications of chemostratigraphy in Middle Jurassic unconventional reservoirs in eastern Saudi Arabia

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ABSTRACT

The following study was undertaken on inorganic geochemical data acquired for 1,032 core and cuttings samples taken from Middle Jurassic and Upper Jurassic sediments encountered in five wells in eastern Saudi Arabia. The study sections extend from the upper part of the Middle Jurassic Dhruma Formation to the base of the Upper Jurassic Arab Formation, though the principal focus was on the intervening Hanifa and Tuwaiq Mountain formations where potential unconventional hydrocarbon reservoirs have been encountered. The principal objective of the study was to produce a chemostratigraphic framework for these wells. A secondary aim was to utilize the geochemical data to recognize organic-rich zones and seals. The study sections mainly comprise limestones, argillaceous limestones and calcareous mudrocks, with the latter lithologies being more abundant in the Tuwaiq Mountain and Hanifa formations.

Although ICP-OES (Inductively Coupled Plasma–Optical Emission Spectrometry) and ICP-MS (Inductively Coupled Plasma–Mass Spectrometry) were used to acquire data for 50 elements, the chemostratigraphic framework is based on changes in the following ‘key’ elements and ratios: Nb/Cr, Zr/Nb, Zr/Cr, Cr/Th, Cr/Ta, La/Lu, Zr/Yb, Nb/Ti and Ti/U. Variations in these parameters are dependent on changes in source/provenance, reflecting increases or decreases in the abundances of particular detrital heavy minerals. The framework comprises a hierarchical order of 5 zones, 10 subzones and 8 divisions. The zones are labeled C0, C1, C2, C3 and C4 in ascending stratigraphic order, with C2, C3 and C4 being divided into subzones. Further divisions are also recognized in some subzones. Zones C1, C2, C3 and C4 are correlative between all five wells, with the absence of C0 in three of the wells, probably explained by the existence of this zone below the present sampling intervals of these wells. Unlike most zones, some of the subzones/divisions are not identified in all wells. This is mostly explained by local variations in provenance being responsible for the presence of some subzones/divisions in certain wells but not others. In other instances the absence of particular subzones and divisions may have resulted from localized erosion/non-deposition. Lithostratigraphic boundaries are relatively easy to place in wells 1, 2 and 3 where there are similar changes in e-log response in all three study sections. However, this does not hold true for wells 4 and 5 where e-log trends are more or less obvious. In these wells it has been necessary to utilize chemostratigraphy in combination with much more subtle increases/decreases in e-log trends to identify these boundaries. In addition to enabling the placement of lithostratigraphic boundaries in wells 4 and 5, it is possible to use chemostratigraphy to produce a correlation scheme of much higher resolution than was possible by employing lithostratigraphy. For example, the Dhruma Formation was previously defined as a single lithostratigraphic unit but a fourfold chemostratigraphic zonation of this formation is now proposed for wells 1 and 2 (i.e. zones C0, C1, subzone C2-1, division C2-2a which occur in ascending order).

By comparing profiles plotted for U, Mo and TOC it is possible to identify units in which there is a relatively high proportion of organic matter. Sediments producing high values of these parameters may be considered potential unconventional reservoirs, with the most organic-rich zones present in wells 1 and 2. Potential seals have been identified above the ‘reservoir’ sections of these two wells. These produce elevated values of Al and K, inferring an abundance of clay minerals which may prevent or reduce the propagation of induced fractures during future ‘fracking’ operations conducted in the vicinity of these wells.
INTRODUCTION

The principal objective of the study was to use geochemical data acquired from core and cuttings samples to produce a chemostratigraphic framework for Middle–Late Jurassic sediment encountered in five wells located in eastern Saudi Arabia. A secondary objective was to utilize this data to recognize potential unconventional hydrocarbon reservoirs and seals/cap rocks in each well.

The location of the study wells are illustrated in Figure 1, showing that wells 1 and 2 are separated by around 1 km while Well 3 was drilled approximately 70 km to the west of these. Wells 4 and 5 are located in the southern part of the study area. The study sections extend from the uppermost part of the Middle Jurassic Dhruma Formation to the base of the Upper Jurassic Arab Formation, though the principal focus was on the Tuwaiq Mountain and Hanifa formations where organic-rich reservoirs have been identified (Figure 2).

GEOLOGICAL SETTING

A major depositional hiatus spanning around 20 million years existed between the deposition of the Upper Triassic Minjur Formation (not shown in Figure 2) and the overlying Toarcian Marrat Formation. According to Cantrell et al. (2014), this unconformity coincides with a period of contractional fold growth. The Arabian platform experienced a gradual increase in the rate of subsidence during the Jurassic. This resulted in high accommodation potential and high sedimentation rates. However, this subsidence was interrupted by significant periods of non-deposition which gradually decreased in intensity with time (Al-Husseini, 1997; Le Nindre et al., 2003; Cantrell et al., 2014). The Marrat Formation is dominated by the deposition of carbonates but this was followed by an episode of non-deposition in the Aalenian.

A marine transgression resulted in the deposition of carbonates in the Dhruma Formation, which extends from the Upper part of the Aalenian to the uppermost Bathonian. A major hiatus separates the Dhruma Formation from the overlying Tuwaiq Mountain Formation. This was followed by a major
increase in sea level during the deposition of carbonates and mudrocks of the Tuwaïq Mountain Formation. According to Cantrell et al. (2014), “the high subsidence rate at that time led to the development of unfilled intrashelf basins in which important source rocks accumulated, i.e. the organic-rich facies of the Tuwaïq Mountain.”

A significant fall in sea level occurred at the end of the Callovian. This led to emergence and non-deposition during the Early Oxfordian (Dromart et al., 2003; Tremolada et al., 2006; Cantrell et al., 2014). A marine transgression in the Oxfordian resulted in the deposition of shallow-marine carbonates and mudrocks assigned to the Hanifa Formation. The carbonates were deposited on the edge of intrashelf basins, with coeval mudrocks (with hydrocarbon source-rock potential) deposited in deeper marine environments within the basins (Hughes et al., 2008; Cantrell et al., 2014). Gradual infilling of these previously established intrashelf basins by deep- to shallow-marine carbonates resulted in the Jubaila Formation. This was succeeded by shallow-marine carbonates of the Arab Formation and then by the predominantly evaporite succession of the Hith Formation (Hughes and Naji, 2009; Cantrell et al., 2014).

Figure 2 illustrates a generalized stratigraphic column showing the formations and principal increases and decreases in sea level with time. The maximum flooding surfaces, labeled J10, J20, J30, J40 and J50 in ascending stratigraphic order, are also included in this diagram (Sharland et al., 2001). Although the study sections extend from the Dhruma to the Arab formations, the main focus in each well was the Tuwaïq Mountain and Hanifa formations. Figure 3 shows generalized depositional environments recorded during the deposition of these formations. This map also illustrates that the study area was located within an intrashelf basin where relatively deep-water paleoenvironments persisted. Although the sediments of these formations are mainly mudrocks and calcareous mudrocks with subordinate argillaceous limestones, they also comprise a significant proportion of detrital material which was mainly derived from continental sediments to the west.

The lithostratigraphic boundaries of each well are shown in Figure 4. E-log data are included for these wells, though it should be noted that not all of the e-log data are available for each well. For example, spectral gamma logs are only included in Well 1, while the sonic log was not provided for Well 5. Placement of the formation boundaries was based on lithostratigraphic criteria. The lithostratigraphic boundaries are most clearly defined in wells 1, 2 and 3 and are much more difficult to place in wells 4 and 5. For this reason, the following discussion principally relates to wells 1, 2 and 3.

The Dhruma Formation is dominated by limestones with occasional argillaceous limestones and calcareous mudrocks. The top of the Dhruma Formation is tentatively placed to coincide with a very subtle increase in gamma. The overlying Tuwaïq Mountain Formation comprises limestones, argillaceous limestones and calcareous mudrocks and is characterized by an overall upward increase
in gamma from the lowermost to the middle part, caused by an increase in U-bearing organic matter and a decrease in carbonate content (see U spectral data plotted for Well 1 in Figure 4). The sediments occurring towards the middle part of the Tuwaiq Mountain Formation generally comprise calcareous mudrocks with elevated TOC values (typically > 4%) in wells 1, 2, and 3. The sediments are interpreted to have been deposited towards the center of an intrashelf basin under relatively deep-marine anoxic conditions. The uppermost part of this formation is characterized by an upward decrease in gamma reflecting the deposition of carbonate sediments with higher proportions of calcite and lower levels of organic matter.

The basal part of the Hanifa Formation is characterized by elevated gamma-ray values. In Well 1, these are shown by the spectral gamma logs to be mainly dependent on high concentrations of U which, as with the Tuwaiq Mountain Formation, is concentrated in organic matter. The relatively low density and slow sonic log values are also indicative of a higher proportion of organic matter in these sediments. However, this is followed by a decrease in gamma towards the middle of the Hanifa Formation which reflects increases and decreases in carbonate content and organic matter respectively. The uppermost part of the Hanifa Formation is dominated by calcareous mudrocks with low proportions of organic matter. This is demonstrated by the fact that K (associated mainly with illite) and Th (associated with Th-bearing heavy minerals) concentrations are high in these sediments, yet values of U are low. This is discussed in more detail in later part of this paper. It is probable that these sediments were deposited in shallow-marine environments, in slightly deeper water compared to the limestones of the Dhruma and uppermost Jubaila formations, but shallower than the water depths that persisted during the deposition of the organic-rich mudrocks found towards the middle of the Tuwaiq Mountain Formation and in the lowermost Hanifa Formation. The basal part of the Jubaila Formation is very similar in character to the uppermost part of the Hanifa Formation but...
is marked by a gradual decrease in gamma and increase in the proportion of carbonate with the uppermost part of this interval dominated by limestones deposited in shallow-marine environments. The base of the Arab Formation was only sampled in Well 5.

Figure 4 shows that variations in e-log trends, and in the gamma log in particular, are very similar in wells 1, 2 and 3 where it is possible to recognize the principal lithostratigraphic zones with the highest degree of accuracy. However, it is much more difficult to place these boundaries in wells 4 and 5, where their definition is based on more subtle increases and decreases in e-logs and calibration with chemostratigraphic data (this is discussed in a later section of this paper). This is a function of the fact that these wells are located to the south of the study area where the deposition of limestones and subordinate calcareous mudrocks under shallow-water conditions predominated. The deeper marine conditions, which deposited the organic-rich sediments in the Tuwaiq Mountain and basal Hanifa formations and the clay-rich sediments in the upper Hanifa and lowermost Jubaila formations in the vicinity of wells 1, 2 and 3, did not exist around wells 4 and 5. Consequently, changes in clay content and organic matter were more subtle in the latter two wells, resulting in more consistent e-log trends. The lithostratigraphic boundaries of wells 4 and 5 were placed with a very low level of confidence.

Owing to the absence of high-resolution biostratigraphic data, it is not possible to place flooding surfaces or sequence boundaries in these wells with any degree of accuracy and the sequence stratigraphy of these wells is not discussed in any detail in the present paper. However, for further information on the sedimentology and sequence stratigraphy of these Middle Jurassic sediments on a regional scale, the reader is referred to Sharland et al. (2001), Hughes et al. (2008) and Cantrell et al. (2014).

**MATERIALS AND METHODS**

Chemostratigraphy is a reservoir correlation technique involving the application of inorganic geochemical data and has been applied to sediments of almost any age, any lithology and accumulating in a range of depositional environments (Racey et al., 1995; Pearce et al., 1999, 2005; Ratcliffe et al., 2010). The technique is particularly useful in correlating the Middle and Upper Jurassic sediments where it is often difficult to place lithostratigraphic markers owing to the somewhat ‘continuous’ character of the gamma-ray, density, neutron and sonic logs. This is especially true where core material is unavailable. Although the principal applications of the technique generally results in a correlation framework, Wright et al. (2010) showed that it was possible to use inorganic geochemical data to determine the degree of anoxia and model TOC (Total Organic Carbon) in shale resource plays in North America including the Haynesville, Eagle Ford and Muskwa formations. Inorganic geochemical data has been utilized for this purpose in unconventional plays throughout the globe, though very little information has been published.

Where TOC data is available, this is compared with geochemical data but TOC analysis was not performed on some study sections. However, it is possible to use the SCHMOKER equation to provide a very crude estimate of TOC. This was used by Schmoker and Hester (1983) to calculate TOC of the Upper and Lower members of the Mississippian and Devonian black shale of the Bakken Formation and is calculated as follows:

\[
TOC \text{(wt\%) = (154.497/p) - 57.261, where 'p' is the density (gm/cm}^3)\).
\]

A total of 1,032 core and cuttings samples were analyzed in the present study. In general, cuttings samples were taken every 10 ft, while core material was selected at 1–3 ft intervals. The cuttings samples were first washed in liquid detergent to remove drilling additives and then dried in an oven. The samples were then sieved to remove the finest dust fragments (< 10 microns) and the largest fragments (> 3 mm). The latter were most likely to have been caved from sediments occurring above the depths from which the cuttings were taken. A magnet was then placed over the surface of each sample to remove any magnetic metallic fragments. The samples were later examined under a microscope and ‘picked’. This ‘picking’ process involved the selection of fragments that were considered to be representative of a given lithology at a given depth. A detailed examination of e-log signatures and mud log descriptions was used to determine the dominant lithology in any given sample and only fragments of such a lithology were ‘picked’ in each sample. Approximately
Figure 4: Study intervals of each well, including lithostratigraphic boundaries. Note that not all of the wireline logs were run or are available for all of the wells. For example, spectral gamma data are only available in Well 1, while the sonic log was not run in Well 5. All depths are log depths in feet.
60–80 fragments were selected in each sample. This material was then ground to a fine powder using an agate grinder. Core samples were also ground in this way. Detailed descriptions of all core and cuttings samples were made prior to analysis.

In order to determine whether the cuttings had been selected from the correct depths a synthetic gamma ray was constructed using values of U, Th and K. This was then compared directly with the gamma ray of each well. Given that a close match between the values of synthetic and log derived gamma were observed, the cuttings were deemed to have been ‘picked’ correctly, with data generated from these samples considered to be ‘representative’.

The ICP-OES (Inductively Coupled Plasma–Optical Emission Spectrometry) and ICP-MS (Inductively Coupled Plasma-Mass Emission Spectrometry) techniques were used to acquire data for ca. 50 elements, including all of the major elements and a large number of trace and rare earth elements. The powdered samples were liquefied using the alkali fusion preparation technique. This involved heating the samples with a lithium metaborate flux and then dissolving this mixture in hydrofluoric acid, prior to injection into the ICP machines. The ICP-OES technique measured abundances of major elements (e.g. K, Na, Si, Al), high concentration trace elements (e.g. Zr, Sr, Ba) and the LREE’s La Ce and Nd, while ICP-MS was employed to acquire data from the low-abundance trace elements (e.g. Rb, Cs, Ta) and rare earth elements (e.g. La, Lu, Yb). The ICP-OES and ICP-MS techniques were used in preference to other analytical techniques as they are considered to provide the best quality data for the largest number of elements. Detection limits for most elements analyzed by ICP are in the order of 1 ppb (parts per billion). Data for all major elements are provided as wt% oxide values but, for brevity, the symbols, rather than the full oxide symbols are quoted in the present study. For example Mn is quoted instead of MnO.

Geochemical analysis of all samples was undertaken using ICP-OES and ICP-MS, with data being acquired for the major elements Al, Si, Ti, Fe, Mn, Mg, Ca, Na, K and P, the trace elements Ba, Be, Co, Cr, Cs, Cu, Ga, Hf, Mo, Nb, Ni, Pb, Rb, Sc, Sn, Sr, Ta, Th, Ti, U, V, W, Y, Zn and Zr, and the rare earth elements (REEs). All major elemental data are quoted as % oxide values, while trace and rare earth element concentrations are in ppm (parts per million). The REEs comprise the elements La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu, and decrease in ionic radii from La to Lu. They are normally subdivided into three main groups: light rare earth elements (LREEs) – La to Nd; middle rare earth elements (MREEs) – Sm to Tb; and heavy rare earth elements (HREEs) – Dy to Lu. In addition to this data for S, Br and Cl were acquired using the XRF (X-Ray Fluorescence) technique.

GEOCHEMISTRY AND MINERALOGY

The mineralogical affinities of elements are first established by comparing the geochemical data with available mineralogical data. However, it is also possible to establish element: mineral links using graphical and statistical techniques.

Comparison with Mineralogical (XRD) Data

Figure 5 illustrates data derived by ICP and XRD (X-Ray Diffraction) analysis for equivalent samples from the five study wells. This diagram shows a very close comparison between the trends plotted for kaolinite, Al and Ga, inferring that both are predominantly concentrated in kaolinite. The element K shows a reasonably close link with illite-mica and illite-smectite but a negative association with alkali feldspar. This infers that, though some K may be associated with alkali feldspar, most is concentrated in illite and/or mica. The links between Si, Na and Ca with quartz, plagioclase feldspar and calcite are also clearly demonstrated in Figure 5.

Statistical Techniques (Principal Component Analysis)

Although it is possible to use XRD data to establish the mineralogical affinities of elements associated with minerals occurring in abundances greater than 1% (e.g. calcite, quartz, feldspars), this is rarely possible with respect to accessory minerals. For this reason, it is necessary to use Principal Component
Figure 5: Comparison between whole rock XRD and geochemical data in Well 1. This was used to aid the establishment of certain element:mineral links. All depths are log depths in feet.
Analysis (PCA) to determine such links. This is a statistical technique used to identify important element associations, as elements occurring together in the same area of the eigenvector plots have similar distributions and are likely to have similar mineralogical affinities. The principal component scores for the original vectors (eigenvectors) indicate the association of certain elements and the relationship between some elements and mineralogy. The principal element associations predicted by the interpretation of PCA results are discussed in the following paragraphs.

Eigenvectors 1 and 2 represent 42.2% and 10.23% respectively of the variation in the geochemical dataset. When these parameters are plotted in a binary diagram the following associations are revealed in Figure 6a:

**Group 1:** includes Ca. This element is mainly concentrated in carbonate minerals.

**Group 2:** includes Co, LREE, MREE, HREE, Fe, Be, Si, Cs, Ti, Rb, K, Ta, Nb, Th, Al, Ga, Hf, Sc and Zr. These elements are considered to occur in a variety of non-carbonate minerals as they plot furthest from Ca on the EV1 versus EV2 crossplot.

**Group 3:** includes Mo, U, Ni and V. These elements are mainly found in abundance where anoxic conditions persisted. A more detailed discussion on the mineralogical affinities of these elements is included in a later section of the present paper.

**Group 4:** includes Y and Cr. These elements are mainly concentrated in heavy minerals.

**Group 5:** includes Ba. This element is normally concentrated in drilling additives in core and cuttings samples.

Eigenvectors 2 and 3 represent 10.23% and 6.7% respectively of the statistical variation. When these parameters are plotted in a crossplot (Figure 6b) they reveal the following associations:

**Group 1:** includes Ca and Mn. Based on the results of XRD, it is thought that Ca is concentrated, almost exclusively, in calcite. The fact that Mn plots close to calcite may infer that this element has similar mineralogical affinities.

**Group 2:** includes Rb and K. Based on the XRD data, it is probable that K is mainly concentrated in illite and/or mica. The close association illustrated between K and Rb suggests that Rb may also be linked to these minerals.

**Group 3:** includes Mo, U, Ni and V. These elements are mainly found in abundance where anoxic conditions persisted.

**Group 4:** includes Y, P and Cr. These elements are mainly concentrated in heavy minerals, though it is possible that some P is associated with biogenic phosphate.

**Group 5:** includes Nb and Ta. These elements are thought to be concentrated in a variety of Nb- and Ta-bearing heavy minerals including rutile, anatase, titanite, titanomagnetite and ilmenite.

**Group 6:** included Al, Sc and Ga. Given that Al and Ga are mainly associated with clay minerals, particularly kaolinite (as shown by the aforementioned XRD data), it is entirely probable that Sc and Cs are also linked to clays.

**Group 7:** includes Zr and Hf. These elements are almost exclusively concentrated in zircon.

**Group 8:** includes Ba and S. The element Ba is normally linked to drilling additives and it is probable that at least some S is associated with such additives.
Although PCA has been used to establish element:mineral links in a number of studies, the drawback to using this technique is that the presence of one or two samples yielding anomalously low or high values of particular elements may result in the identification of groupings of elements in eigenvector crossplots that do not reflect the “true” mineralogical affinities of the majority of samples. Such “statistical artifacts” may result in erroneous interpretations, so it is advisable to support interpretations of statistical data by utilizing binary diagrams (Figures 7 to 9). For example, the strong positive relationship shown in the Al versus Ga crossplot (Figure 7a) infers that these elements are...
concentrated in clay minerals, providing further support of the interpretations based on XRD and eigenvector analysis. The fact that K shows a close relationship with this element (Figure 7b), suggest that this element is also associated with these minerals. The positive trends shown in the K versus Rb (Figure 7c) and Ga versus Cs crossplots (Figure 7d) infer that Rb and Cs have similar mineralogical affinities.

Figures 8a and 8b illustrate strong positive trends between Ta and Ti and Nb and Ti respectively. These elements are lined with a variety of heavy minerals, including rutile, anatase, titanomagnetite and ilmenite. Positive trends are revealed in the Nb versus Cr (Figure 8c) and Zr versus Y (Figure 8d) crossplots, inferring a heavy mineral association for these elements. However, the fact that these trends are less well developed may be taken as evidence that these elements are linked to different specific heavy minerals. For example, Zr is concentrated in zircon, while Y is more likely to be associated with apatites and monazites. The binary diagrams plotted for Mo versus Ni (Figure 9a), Mo versus U (Figure 9b), Ni versus U (Figure 9c) and V versus Ni (Figure 9d) show positive trends between these elements, the inference being that they are associated with sediments deposited under anoxic environments.

Further discussion on the mineralogical affinities of elements associated with heavy minerals and anoxia/organic matter is provided in the following paragraphs.
KEY ELEMENTS AND RATIOS USED FOR CHEMOSTRATIGRAPHIC PURPOSES

Although data were provided for 50 elements, most chemostratigraphic correlation schemes are generally based on variations in 4–12 ‘key’ or ‘index’ elements. In the present study, the framework is largely based on variations in the ‘stable’ elements (e.g. Cr, Th, Nb, Ti, Zr, Hf, Ta, Y and HREE) associated with heavy minerals as these are largely unaffected by post depositional weathering and/or diagenesis. Although the association of these elements with heavy minerals has been proven in the present study using statistical and graphical techniques, it is often very difficult to establish precise mineralogical affinities. The exceptions to this are Zr and Hf which are almost exclusively concentrated in detrital zircon. However, the elements Ti, Ta and Nb may be associated with a variety of heavy minerals, including rutile, anatase, titanite and opaque heavy minerals (e.g. ilmenite, magnetite, titanomagnetite). High concentrations of Cr occur in chrome spinel but this element may also be found in opaque heavy minerals. The element Th is generally most abundant in monazite but, given the low abundance of this mineral in most sedimentary rocks, it is most likely to be concentrated in zircons, apatites and opaque heavy minerals. Apatites and monazites typically form likely hosts for Y but, as with Th and HREE, it is probable that this element may be associated with a range of heavy minerals. A more detailed account of the mineralogical affinities of element associated with heavy minerals is provided by Mange and Morton (2007).
The following ‘key’ elemental ratios were used to place chemostratigraphic boundaries:

**Zr/Yb**: zircon *versus* Yb-bearing heavy minerals

**Zr/Nb**: zircon *versus* Nb-bearing heavy minerals (i.e. rutile, anatase, sphene, titanomagnetite, magnetite, ilmenite)

**Ti/U**: Ti-bearing heavy minerals (i.e. rutile, anatase, sphene, titanomagnetite, magnetite, ilmenite) *versus* U-bearing organic matter and heavy minerals

**Cr/Th**: Cr-bearing heavy minerals (e.g. chrome spinel) *versus* Th-bearing heavy minerals

**Cr/Ta**: Cr-bearing heavy minerals (e.g. chrome spinel) *versus* Ta-bearing heavy minerals

**Zr/Cr**: zircon *versus* Cr-bearing heavy minerals (e.g. chrome spinel)

**Nb/Cr**: Nb-bearing heavy minerals (i.e. rutile, anatase, sphene, titanomagnetite, magnetite, ilmenite) *versus* Cr-bearing heavy minerals (e.g. chrome spinel)

**La/Lu**: La-bearing heavy minerals *versus* Lu-bearing heavy minerals.

Figure 9: Binary diagrams used to aid the establishment on element:mineral links with regard to elements concentrated in organic matter and/or associated with anoxic paleoenvironments.
Variations in these ratios are almost exclusively associated with changes in heavy mineral distributions and so provenance. The only possible exceptions to this are Ti/U and La/Lu. Although Ti is generally associated with heavy minerals, U may have mixed mineralogical affinities being concentrated in a range of heavy minerals and organic matter. In the Tuwaiq Mountain Formation (chemostratigraphic zone C3) in the present study wells, it is mainly influenced by the presence of organic matter and the persistence of anoxic paleoenvironments (see below for more detailed discussion). Variation in Ti/U is only used to define the C2-2a:C2-2b division boundary occurring in the Dhruma Formation which is largely devoid of organic matter - the assumption being that U is associated with heavy mineral, rather than organic matter over this section. With respect to the La/Lu ratio, Lu is a HREE mainly concentrated in heavy minerals, though La may be concentrated in clay minerals, feldspars and/or heavy minerals. For this reason, it is unclear whether the La/Lu ratio is influenced by changes in heavy provenance, depositional environment, weathering and/or diagenesis.

**ELEMENTS USED TO DEFINE CHANGES IN DEPOSITIONAL CONDITIONS AND THE ABUNDANCE OF ORGANIC MATTER**

Concentrations of Mo, Ni, Co, Zn, Cu, V and Mn are heavily influenced by variations in redox. Although levels of Mo, Ni, Cu, Co and Zn generally increase with anoxia, Mo generally shows the closest links with anoxia. The association between high values of this element and anoxia has been noted by several workers including Crusius et al. (1996), Craigie (1998), Lyons et al. (2003), Tribovillard et al. (2006), Scott and Lyons (2012) and Chappaz et al. (2014). There is general agreement that Mo\(^{VI}\)S\(_4\)\(^{2-}\) is progressively transformed to Mo\(^{VII}\)S\(_4\)\(^{2-}\) in the presence of dissolved sulphide but the steps after Mo\(^{VII}\)S\(_4\)\(^{2-}\) formation and the precise mechanism of Mo incorporation into the sediments is a matter of debate. In a recent study of ancient and modern sediments, Chappaz et al. (2014) concluded that, although some Mo is concentrated in pyrite, forming under anoxic conditions, this is not the main host of this element in such environments. In fact, there are four potential mechanisms for Mo incorporation mentioned in this paper. The first involves Fe-Mo-S precipitation and would lead to the formation of the compound Fe\(_2\)Mo\(_3\)S\(_{14}\) in the water column. The second pathway involved Mo\(^V\) reduction with an intermediate Mo\(^V\) species forming at the sediment water interface. A third possibility may be that Mo fixation and possible reduction is caused by organic matter. Finally, there is a possibility that this element could be incorporated into polysulphides. Clearly, further research is warranted in the specific mechanisms of Mo uptake in sediments deposited in anoxic environment. In spite of this, the link between the abundance of this element and anoxia is well established and this element is considered to be the principal indicator of such conditions in the present study.

The elements Cd, Cu, Ni and Zn are chalcophile elements associated with sulfi de deposits in the Earth’s crust. High abundances of these elements have been noted in anoxic sediments (Calvert and Pedersen, 1993; Craigie, 1998; Tribovillard et al., 2006; Wright et al., 2010). These elements are most likely to be precipitated in dissolved sulphide in the presence of anoxic waters (Calvert and Pedersen, 1993). However, Calvert and Pedersen (1993) noted that not all anoxic basins show signifi cant enrichments for all of these elements. The abundance of these elements in sedimentary rocks ultimately depends on both the development of anoxia and the supply from hinterland areas. Where the supply is low, concentrations of these elements will be reduced, even where anoxic conditions persisted. In the present study, Cu and Cd values are generally low and show no signifi cant increases with anoxia so it is possible that the original supply of these elements to the basin, either in solid or dissolved states, was low. For this reason, both have not been utilized for chemostratigraphic purposes.

As with the aforementioned elements, an association between V and the development of anoxia has been recognized in a number of basins (Calvert and Pedersen, 1993; Craigie, 1997; Wright et al., 2010). According to Wanty and Goldhaber (1992) and Calvert and Pederson (1993), elevated levels of dissolved sulphide result in a reduction of V(IV) to V (III), which precipitates as V\(_2\)O\(_5\) or V(OH)\(_3\). However, it is also possible that some V is removed from the water column by absorption of its reduced species VO\(_2^+\) or VO(OH)\(_2^-\). An association of V with organic matter, possibly as a result of complexation of VO\(_2^+\) by dissolved organic matter is also possible (Emerson and Huested, 1991; Calvert and Pedersen, 1993).
The distributions of U are largely controlled by the abundance of organic matter and the presence of anoxic environments. Uranium has IV and VI states but the latter is much more easily ‘mobilized’ and is found in groundwaters under standard aqueous conditions. The U(IV) species is much more “stable”, though it can be mobilized in the form of phosphate complexes (Langmuir, 1978). Indeed, high values of U in the VI state, and small amounts of U(IV), have been found in organic matter in soil samples forming under oxic conditions (Regenspurg et al., 2010). During anoxia U(VI) in known to convert to U(IV) which often precipitates as uraninite (UO₂) (Abdelouas et al., 2000). In this reduced U(IV) state it is also known to substitute for Ca in biogenic phosphate (Craigie, 1998). In the present study, U is used to identify organic-rich sediments and intervals that were deposited under anoxic conditions.

The element Mn is known to occur close to oxic-anoxic boundaries. Under anoxic conditions, this element is ‘leached’ from sediments. However, enhanced precipitation of Mn (oxyhydr)oxides is typically associated with the mixing of reducing anoxic waters close to the oxic-anoxic boundary. Further information of this mechanism of Mn precipitation is provided by the works of Calvert and Pedersen (1993) and Wirth et al. (2013).

CHEMOSTRATIGRAPHIC CHARACTERIZATION

As with most chemostratigraphic correlations, the present framework scheme comprise a hierarchical order of zones, subzones and divisions based on changes in key elemental ratios. Each zone, subzone and division is defined using specific values of one or more key element ratios. For example, zone C1 is characterized by Nb/Cr ratios exceeding 0.15 and Zr/Nb values of less than 6.2. Variations in the key elements and ratios are considered to represent changes in source/provenance. These changes may be subtle but produce significant changes in the proportion of particular heavy minerals and, hence, variations in key element ratios. Details of the scheme are illustrated in Figures 10 to 14 and discussed in detail in the following paragraphs.

Chem stratigraphic Zones

Figure 10 shows the characterization/correlation of chemostratigraphic zones in wells 1 and 2, while the differentiation of these are also demonstrated using the binary diagrams plotted in Figure 11. The chemostratigraphic zones are labeled C0, C1, C2, C3 and C4 in ascending stratigraphic order, with C0 yielding lower Nb/Cr than in C1, C2 and C3, while C1 produces lower Zr/Nb than in C2. Zone C2 is characterized by higher Nb/Cr and Zr/Cr, but lower Cr/Th and Cr/Ta, than in C3. The C3:C4 boundary is defined by sharp upward decreases in Cr/Th and Cr/Ta, with both ratios being higher in C4. It is also noteworthy that Zr/Cr values are higher in zone C4 than in C3. The principal geochemical characteristics of each zone are summarized in Table 1. Figure 11a illustrates that, while a minority of zone C0 samples plot with high Nb/Cr ratios in the C1 ‘field’ most produce low values of this ratio, while all of the samples assigned to zone C1 plot in the correct ‘field’. Definition of the C0:C1 boundary in Well 1 is based on a lower number of samples but all of the zone C0 and C1 samples plot in the correct field (Figure 11b). Figures 11c and 11d are Cr versus Zr/Nb crossplots used to distinguish zones C1 and C2 in wells 2 and 1 respectively. Although there is some ‘overlap’ most C1 samples yield distinctly lower Zr/Nb ratios than in C2. The Cr/Th versus Cr/Ta binary diagrams (Figures 11e and 11f) illustrate that zone C3 generally yields higher values of both ratios than in zones C2 and C4 in wells 1 and 2.

| Zone | Characteristics |
|------|-----------------|
| C4   | lower Cr/Th (< 20.7) than in C3 lower Cr/Ta (< 103) than in C3 higher Zr/Cr (> 1.0) than in C3 |
| C3   | higher Cr/Th (> 20.7) than in C2 and C4 higher Cr/Ta (> 103) than in C2 and C4 lower Zr/Cr (> 1.0) than in C2 and C4 lower Nb/Cr (< 0.15) than in C2 |
| C2   | higher Nb/Cr (> 0.15) than in C0 & C3 higher Zr/Nb (> 6.2) than in C1 lower Cr/Th (< 20.7) than in C3 lower Cr/Ta (< 103) than in C3 higher Zr/Cr (> 1.0) than in C3 |
| C1   | higher Nb/Cr (> 0.15) than in C0 lower Zr/Nb (< 6.2) than in C2 |
| C0   | lower Nb/Cr (< 0.15) than in C1, C2 and C3 |
Figure 10: Correlation of chemostratigraphic zones in wells 1 and 2 based on variations in \( \text{Zr/Nb} \), \( \text{Nb/Cr} \), \( \text{Cr/Th} \), \( \text{Cr/Ta} \) and \( \text{Zr/Cr} \). The \( \text{Si/Al} \), \( \text{Al} \) and \( \text{Ca} \) profiles have not been used for chemostratigraphic purposes but are employed to assess data quality (see text for details). Arrows indicate significant ‘trends’ in data used to define boundaries. The areas colored in white represent sample ‘gaps’ between zones. All depths are log depths in feet.
Chemostratigraphic Subzones

Figure 12 shows the definition of chemostratigraphic zones, subzones and divisions in wells 1 and 2, while Figure 13 illustrates the chemostratigraphic zonation with respect to Well 5. Chemostratigraphic subzones are recognized in zones C2, C3 and C4. A broad twofold subdivision is proposed for zone C2, with subzone C2-1 occurring at the base and producing lower Cr/Ta ratios than in the overlying subzone C2-2. In wells 1 and 2 the zone C3 subzones are labeled C3-1, C3-2 and C3-3 in ascending stratigraphic order, with C3-2 defined by the highest Zr/Yb values. In Well 5 only two subzones are recognized in zone C3 and, as they are defined using different geochemical criteria to those in 1 and 2,
Figure 12: Correlation of chemostratigraphic zones, subzones and divisions in wells 1 and 2 based on variations in Zr/Nb, Cr/Th, Cr/Ta, Zr/Cr, La/Lu, Zr/Yb and Ti/U. Arrows indicate significant ‘trends’ in the data used to define boundaries. The areas colored in white represent sample ‘gaps’ between zones, subzones and divisions. All depths are log depths in feet.
Middle Jurassic chemostratigraphy, Saudi Arabia

| Depth (ft) | Gamma API | Si/Al | Al % | Ca % | Zr/Nb | Nb/Cr | Cr/Th | Cr/Ta | Zr/Cr | Zr/Cr | La/Lu | Zr/Yb | Ti/U | Chemo |
|-----------|------------|-------|------|------|-------|-------|-------|-------|-------|-------|-------|-------|------|-------|
| 0         | 80         | 8     | 7    | 35   | 12    | 0.4   | 0     | 300   | 0     | 3     | 0     | 320   | 0    | 120  |
| 50        | 80         | 8     | 7    | 35   | 12    | 0.4   | 0     | 300   | 0     | 3     | 0     | 320   | 0    | 120  |

Figure 13: Chemostratigraphic zonation proposed for Well 5. Note that the zone C3 subzones are defined using a different criteria in this well to those encountered in wells 1 and 2 (see text for further discussion). Arrows indicate significant ‘trends’ in the data used to define boundaries. All depths are log depths in feet.
they are labeled differently (Figure 13). Subzone C3-A occurs at the base of C3 in this well and yields lower La/Lu ratios than in the overlying subzone C3-B. Of the zone C4 subzones, C4-0 and C4-2 are identified at the base and top respectively and produce lower Zr/Yb ratios than in the intervening subzone C4-1. Although the subzone C4-1:C4-2 boundary coincides with an upward decrease in Zr/Yb in all wells, the specific values of this ratio used to define C4-1 and C4-2 are much higher in wells 1 and 2 than in 4 and 5. These inconsistencies in the definition of the zone C3 and C4 subzones may be explained by minor variations in source/provenance or depositional environment between these wells. The criteria used to define subzones are summarized in Table 2.

**Chem stratigraphic Divisions**

Chem stratigraphic divisions have only been recognized in subzones C2-2, C3-2, C4-1 and C4-2 (Figure 12). Of the two C2-2 divisions, C2-2a occurs at the base and produces lower Ti/U ratios than in the overlying division C2-2b. The subzone C3-2 divisions are labeled C3-2a and C3-2b in ascending order, with the latter producing lower values of Zr/Cr. Division C4-1a is identified at the base of subzone C4-1 and yields higher Nb/Cr ratios than in the overlying division C4-1b. Division C4-2a occurs at the base of subzone C4-2 and is characterized by lower Zr/Cr ratios than in the overlying division C4-2b. Details of the principal geochemical parameters used to recognize each chem stratigraphic division are summarized in Table 3.

| Subzone | Characteristics |
|---------|-----------------|
| C4-2    | lower Zr/Yb (< 80 in Well 1 and Well 2, < 56.9 in 4 and 5) than in C4-0 and C4-2 |
| C4-1    | higher Zr/Yb (> 80 in Well 1 and Well 2, > 56.9 in 4 and 5) than in C4-0 and C4-2 |
| C4-0    | lower Zr/Yb (< 56.9) than in C4-1 |
| C3-B    | lower La/Lu (< 132) than C3-A |
| C3-3    | lower Zr/Yb (< 35) than C3-2 |
| C3-2    | higher Zr/Yb (> 35) than C3-1 and C3-3 |
| C3-1    | lower Zr/Yb (< 35) than C3-2 |
| C2-2    | higher Cr/Ta (> 103) than in C2-1 |
| C2-1    | lower Cr/Ta (< 103) than in C2-2 |

| Divisions | Characteristics |
|-----------|-----------------|
| C4-2b     | higher Zr/Cr (> 1.7) than in C4-2a |
| C4-2a     | lower Zr/Cr (< 1.7) than in C4-2b |
| C4-1b     | generally lower Nb/Cr (< 0.29) than in C4-1a |
| C4-1a     | generally higher Nb/Cr (> 0.29) than in C4-1b |
| C3-2b     | lower Zr/Cr (< 0.72) than in C3-2a |
| C3-2a     | higher Zr/Cr (> 0.72) than in C3-2b |
| C3-2b     | higher Ti/U (> 0.1) than in C2-2a |
| C2-2b     | lower Ti/U (< 0.1) than in C2-2b |

**CHEMOSTRATIGRAPHIC CORRELATION**

The identification of chem stratigraphic zones, subzones and divisions are shown in Figures 12 and 13, while Figure 14 illustrates the correlation of these between the five study wells. Although statistical analysis has not been performed on the current dataset, chem stratigraphic zones are normally identified with a high level of confidence and are correlative subregionally, while subzones may be recognized on field or subregional scales. By contrast, a relatively low level of confidence is associated with the placement of division boundaries which are normally only recognized on a field-scale in closely-spaced wells. In the present study, all of the chem stratigraphic zones are correlative between the study wells except for C0 which is thought to exist below the study intervals of 3, 4 and 5. Although subzones C4-1 and C4-2 are correlative between all five wells, this does not hold true for the other subzones. For example, the zone C2 subzones are identified in wells 1, 2 and 5, but C2-1 and C2-2 are considered to be absent in wells 3 and 4 respectively. The absence of these subzones in these two wells is likely to be explained by erosion/non-deposition on a local scale. With regard to the C3 subzones, these are labeled C3-1, C3-2 and C3-3 in ascending stratigraphic order in wells 1 and 2, but it is not possible to further subdivide this zone in wells 3 and 4. Furthermore, a completely different subdivision of C3 is proposed for Well 5 (i.e. labeled C3-A and C3-B), where variations in La/Lu (as
opposed to Zr/Yb in wells 1 and 2) are used to define two subzones. It is probable that local variations in source/provenance were responsible for the differences in the way C3 subzones are defined in Well 5 compared to wells 1 and 2. The fact that no further subdivision of C3 is possible in wells 3 and 4 may suggest that there were no significant changes in provenance during the deposition of this zone in the vicinity of these wells. Another inconsistency shown in Figure 14 is that subzone C4-0 is only identified in Well 4. The fact that some subzones are absent in particular wells is not surprising, given the large distances (> 60 km) between them, with the exception of wells 1 and 2. It is probable that localized variations in source/provenance were responsible for the deposition of subzone C4-0 in the immediate vicinity of Well 4. The fact that subzones C4-0 and C4-1 are thickest in Well 4 implies that there was more accommodation space created by structural movement, though no definitive evidence of this is presented. There is a very strong correlation of zones, subzones and divisions between wells 1 and 2 but this is best explained by the fact that these wells are located only about 1 km apart. The absence of subzone C2-1 in Well 3 and C2-2 in Well 4 are most likely to be a result of erosion/non-deposition on a local scale.

As with many studies, less confidence is associated with the definition of chemostratigraphic divisions which are generally only correlative between closely spaced wells. For example the subzone C2-2, C3-2 and C4-1 divisions are only identified in wells 1 and 2, while divisions C4-2a and C4-2b are only present in Well 5. These divisions/subzones/zones are considered to reflect changes of source/provenance on a local scale, explaining the fact that they do not correlate across the entire study area.

CHEMOSTRATIGRAPHY VERSUS LITHOSTRATIGRAPHY

In addition to showing the definition of chemostratigraphic boundaries in each well, Figure 14 illustrates the comparison between the lithostratigraphic and chemostratigraphic correlations. The lithostratigraphic boundaries were provided by Saudi Aramco and were considered to be very well defined in wells 1 and 2 where there is good core coverage and considerable variation in e-log response reflecting changes in base level. These boundaries were much more difficult to place in the other wells, particularly 4 and 5, where core coverage was more limited and the study intervals are dominated by carbonates with ‘flat’ gamma-ray responses. For this reason, the definition of lithostratigraphic boundaries in these wells is based on a close comparison between the chemostratigraphic zonation and e-log response. The top boundary of the Dhruma Formation is defined close to the center of zone C2-2 in wells 1, 2 and 3 (roughly equivalent to C2-2a:C2-2b boundary in wells 1 and 2). This boundary is placed midway between the top of C2-1 and C3 in Well 4 where subzone C2-2 is thought to be missing. Characterization of this boundary is more difficult in Well 5 but it coincides with a slight upward decrease in the gamma-ray log occurring close to the center of C2-2. The overlying Tuwaiq Mountain Formation roughly extends from the middle of subzone C2-2 to the C3-2:C3-3 boundary in wells 1 and 2. The top of this boundary is also located immediately below a flooding surface at the base of the Hanifa Formation, which has been defined using geochemical data (see following paragraphs for further information). The Hanifa Formation encompasses subzones C4-0 (Well 4 only) and the basal part of C4-1, while the Jubaila Formation occurs at the top of the study sections within the upper part of C4-1 and C4-2.

Clearly, chemostratigraphy has been used to aid the placement/refinement of lithostratigraphic boundaries, particularly in wells 4 and 5. For example, the Tuwaiq Mountain Formation: Hanifa Formation boundary occurs towards the top of zone C3 and is defined by a sharp increase in gamma immediately above the Tuwaiq Mountain Formation, at the base of the Hanifa Formation, in wells 1, 2 and 3. A much more subtle increase in gamma is noted near the top of C3 in wells 4 and 5 where the same lithostratigraphic boundary is placed (Figure 14). The other lithostratigraphic boundaries of these two wells are placed with very little confidence but an attempt has been made to define them within the same chemostratigraphic zones/subzones that they occur within wells 1, 2 and 3 and by recognizing with very subtle changes in e-log response.

Although this exercise may have some merits, the placement of all lithostratigraphic boundaries in wells 4 and 5 is tentative. However, the principal application of the technique was to produce a zonation of higher resolution than was possible by utilizing lithostratigraphy in isolation. Figure 14 clearly demonstrates that it is possible to use chemostratigraphy for this purpose. For example
Figure 14: Correlation of chemozones in study wells and identification of potential unconventional reservoirs and seals/cap rocks. Details of how potential unconventional reservoirs and seals/cap rocks have been identified using geochemical data are illustrated in Figures 15–19 and in the text. All depths are log depths in feet.
the Tuwaiq Mountain Formation is subdivided into chemozones C2-2b, C3-1, C3-2a and C3-2b in wells 1 and 2, while the Hanifa Formation comprises C3-3 and most of C4-1a. The overlying Jubaila Formation comprises subzones C4-1 (and associated divisions) and C4-2. Such high levels of stratigraphic resolution were not possible prior to chemostratigraphic analysis.

**IDENTIFICATION OF ORGANIC-RICH RESERVOIR-PRONE ZONES AND SEALS**

Although the principal focus of the study was to produce a chemostratigraphic correlation scheme, the geochemical data were also used to model the abundance of organic matter and to recognize potential unconventional reservoirs and seals/cap rocks. Figure 15 illustrates profiles plotted for wireline logs, SCHMOKER (formula based on values of density log and provides a very crude indication of TOC) and various key elements used to provide an indication of reservoir and/or seal potential in Well 1. The element U is generally associated with organic matter but is also partly influenced by redox conditions and often occurs in the highest concentrations in anoxic paleoenvironments where the proportion of preserved organic matter is highest. The elements Mo, Ni, V and Zn are generally associated with anoxic environments, though Mo is considered to provide the most accurate indication of anoxia in the present wells. A profile is also plotted for Mn as this is a good paleoenvironmental indicator, with the highest levels of this element being associated with suboxic conditions. Of the other elements included in this figure, Al and K are mainly linked with clay minerals and high values of these elements may be used to identify potential unconventional seals/cap rocks containing high levels of clay minerals which may reduce/prevent the propagation of man-induced fractures during the fracking process. The Si/Al ratio provides a crude indication of the proportion of detrital quartz versus Al-bearing clay minerals.

Figure 15 illustrates that the highest values of TOC (> 3%) in Well 1 are colored in orange, and infers that this unit is of greatest interest in terms of its hydrocarbon bearing/reservoir potential. Within this unit there is some variability, with the beds labeled 1, 2 and 3 considered to be of greatest geological and stratigraphic significance. Bed 1 yields elevated values of U, Mo, Ni, V, Zn and TOC, suggesting that sediments assigned to this interval contain a high proportion of organic matter that was preserved under anoxic conditions. Although bed 2 produces the highest TOC values in this well, concentrations of Mo, Ni, V and Zn are generally low and levels of U are only moderate. This suggests that the supply of organic matter (e.g. from a nearby fluvial source) was high but these sediments may have accumulated under anoxic-suboxic, rather than completely anoxic conditions. Bed 3 yields high U, Mo, Zn, V and Ni but relatively low TOC compared with beds 1 and 2. It is probably that bed 3 accumulated under anoxic conditions but the supply of organic matter was relatively low, explaining the low TOC values. The units colored blue in this diagram have limited hydrocarbon bearing/reservoir potential as they are characterized by low levels of Mo, U, Ni, V, Zn and TOC. The fact that samples in these intervals yield high levels of Ca, infer that they are “pure” carbonates and probably accumulated under shallow-water conditions. By contrast, the zone highlighted in brown in Figure 15 produces relatively low concentrations of Ca but elevated Al and K, indicating the presence of Al- and K-bearing clay minerals. This may represent a potential seal/cap rock. The fact that this zone also produces high values of Mn may infer deposition under suboxic conditions.

Well 2 is located very close to Well 1 and produces similar geochemical characteristics. As with Well 1, there is a principal zone of interest colored in orange in Figure 16, the only difference being that the upper half of this zone in Well 2 yields slightly lower values of TOC. The three ‘beds of interest’ are also noted in Well 2 and are highlighted in red in Figure 16. As with Well 1, bed 1 produces high TOC, SCHMOKER Mo, Ni, Zn and V, with reasonably high U, inferring accumulation of organic matter under anoxic conditions. Bed 2 also produces elevated levels of TOC and U, though Mo concentrations are slightly lower. As with bed 2 in Well 1, this may be taken as evidence that the overall quantity of organic matter is high but that this was preserved under anoxic-suboxic, rather than completely anoxic conditions. Bed 3 yields high concentrations of U, V, Ni, Zn and Mo but relatively low TOC. Another similarity between the two wells is that much of the study section comprises carbonate sediments with low TOC, Mo and U and, therefore, limited hydrocarbon bearing potential (blue colored units in Figures 15 and 16). It is also noted that a potential seal/cap rock is defined by elevated concentrations of Al, K and Mn (Figure 16).
Limited H/C generation potential
High Ca= high carbonate content
Low Al= low quantity of clay minerals
Low Mo, U, TOC= low levels of organic matter

Potential Seal/ Cap Rock
Low Ca= Low carbonate content
High Al= High quantity of clay minerals
Low Mo, U, TOC= low levels of organic matter
High Mn= suboxic paleoenvironment

Limited H/C generation potential
High Ca= high carbonate content
Low Al= low quantity of clay minerals
Low Mo, U, TOC= low levels of organic matter

bed 1. high U and Mo
bed 3. high U and Mo
bed 2. high TOC, moderate U and low Mo

Generally high TOC values = potential unconventional reservoir.

Figure 15: Recognition of potential unconventional reservoirs and and seals/cap rocks in Well 1 using geochemical data. All depths are log depths in feet.
Limited H/C generation potential
High Ca = high carbonate content
Low Al = low quantity of clay minerals
Low Mo, U, TOC = low levels of organic matter

Potential Seal/ Cap Rock
Low Ca = Low carbonate content
High Al = High quantity of clay minerals
Low Mo, U, TOC = low levels of organic matter
High Mn = suboxic paleoenvirnoment

Generally high TOC values = potential reservoir

Limited H/C generation potential
bed 2: high TOC, moderate U and low Mo

bed 2: high TOC, moderate U and low Mo

Limited H/C generation potential
High Ca = high carbonate content
Low Al = low quantity of clay minerals
Low Mo, U, TOC = low levels of organic matter

Figure 16: Recognition of potential unconventional reservoirs and seals/cap rocks in Well 2 using geochemical data. All depths are log depths in feet.
Figure 17 shows the key profiles plotted for Well 3. Unlike the two aforementioned wells, it is much more difficult to assess the reservoir and seal potential of Well 3 owing to the absence of inorganic geochemical data over large sample gaps. In spite of this drawback, a ‘zone of interest’ is identified (colored in orange) based on elevated gamma readings. Based solely on the SCHMOKER curve and calibration with wells 1 and 2, the lowermost part of this section probably yields the highest values of TOC but, owing to the absence of TOC data and low number of analyzed samples (two cuttings only), the validity of this theory needs to be verified. Significantly, samples occurring towards the top of this section (colored in red) plot with high U, Mo, Ni, Zn and V concentrations, inferring accumulation of sediments under relatively anoxic conditions but the low values of SCHMOKER infers that TOC levels were low, probably caused by a relatively low supply of organic matter to this locality. These samples are assigned to bed 3 which, based on the geochemical data and calibration with the placement of chemostratigraphic boundaries, is considered to be correlative with the same bed in wells 1 and 2.

As with wells 1 and 2, the main zone of interest in Well 4 yields slightly higher gamma-ray readings and is colored in orange in Figure 18. It is noted that TOC and SCHMOKER values are low throughout this section, as are U and Mo. This infers that conditions were relatively oxic-suboxic and/or the supply of organic matter to this locality was low. Although beds 1 and 2 cannot be identified in this well, bed 3 is tentatively defined by slight increases in U and Mo. Given that TOC levels are below 3% throughout this well, the reservoir/hydrocarbon bearing potential is considered to be poor.
Figure 18: Recognition of potential unconventional reservoirs and seals/cap rocks in Well 4 using geochemical data. All depths are log depths in feet.
Furthermore, even if reservoir potential was high, values of Al and K are low immediately above this, suggesting that there may be no seal to the propagation of induced fractures. However, additional work on seal integrity is required in order to determine whether this theory is correct.

The key element profiles plotted for Well 5 are shown in Figure 19. In many ways this well is similar to that of Well 4 as low TOC, SCHMOKER, U and Mo values indicate that there is limited hydrocarbon bearing potential in this study section. The section highlighted in orange yields slightly higher gamma, U and TOC values and may contain some organic matter, though values of these are still relatively low, suggesting non-reservoir/limited hydrocarbon bearing potential. Furthermore, the low Mo values indicate deposition under oxic conditions. The interval colored red produces slightly higher U and Mo and is thought to represent bed 3. Given that this bed is identified in all 5 wells, it may represent a regionally correlative flooding surface.

Summary and Comparison of Reservoir Quality and Seals/Cap Rocks Between Wells

Based on values of TOC, SCHMOKER, U and Mo (and Ni, V, Zn to a lesser extent) the highest hydrocarbon bearing potential/most suitable unconventional reservoirs exist in wells 1 and 2, with the very limited hydrocarbon generation capacity in wells 4 and 5. Owing to the lack of available samples and TOC data, the reservoir potential of Well 3 cannot be assessed accurately, though high values of SCHMOKER and gamma have been recorded through parts of this study section. On this basis, it is probable that unconventional reservoirs exist in Well 3, though further testing would be required. Based on a detailed comparison with gamma-ray trends and the chemozones in which beds 1, 2 and 3 are placed there is a very high likelihood that these beds are correlative between wells 1 and 2. Bed 1 yields high levels of TOC, SCHMOKER and U in both wells, suggesting a high proportion of organic matter. Furthermore, the fact that this is accompanied by high Mo, Ni, Zn and V values in both wells infers that the organic matter was preserved under anoxic conditions. This bed may represent a flooding surface persisting over at least a field, and possibly a subregional, scale. Bed 2 produces high TOC in these two wells but generally lower Mo, Ni, V and Zn. It is probable that this bed contains a high proportion of organic matter derived from a local source (fluvial?) but the fact that this is not accompanied by such high Ni, Zn, Mo and V may infer that conditions were anoxic-suboxic. Of the three beds, only bed 3 is correlative between the five study wells, inferring that this represents a regionally correlative flooding surface. Although this bed was deposited under anoxic conditions (based on high U, Mo, V etc.), it also contains a low proportion of organic matter and, consequently, has limited hydrocarbon bearing potential.

In addition to using inorganic geochemical data to recognize potential reservoirs, it is also possible to use this data to identify likely unconventional seals/cap rocks. These are identified on the basis of elevated concentrations of Al and K but have only been recognized in wells 1 and 2. However, more work on the applications of inorganic geochemical data to predict of seal integrity is required before this may be considered a proven technique in this regard.

CONCLUSIONS

Based on the chemostratigraphic study of wells 1–5, the following conclusions have been noted:

(1) The “key” element ratios used to define chemostratigraphic boundaries include Nb/Cr, Zr/Nb, Zr/Cr, Cr/Th, Cr/Ta, La/Lu, Zr/Yb, and Ti/U. Variations in these parameters are largely dependent on changes in source/provenance.

(2) The scheme comprises a hierarchical order of 5 zones, 10 subzones and 8 divisions. The zones are defined as C0, C1, C2, C3 and C4 in ascending stratigraphic order, with C0 yielding lower Nb/Cr than C1, while C1 produces lower Zr/Nb than in C2. Zone C3 is characterized by the higher values of Cr/Th and Cr/Ta, but lower Zr/Cr, than in C2 and C4. It is also noteworthy that zone C3 yields lower Nb/Cr ratios than in C1 and C2.
Limited H/C generation potential  
High Ca= high carbonate content  
Low Al= low quantity of clay minerals  
Low Mo, U, TOC= low organic matter

Bed 3 slightly higher U

Zone of slightly higher GR and U values but levels of TOC, Schmoker and U are low, indicating that this section has poor reservoir potential.

Limited H/C generation potential  
High Ca= high carbonate content  
Low Al= low quantity of clay minerals  
Low Mo, U, TOC= low organic matter

Figure 19: Recognition of potential unconventional reservoirs and seals/cap rocks in Well 5 using geochemical data. All depths are log depths in feet.
(3) Chemostratigraphic subzones are identified in zones C2, C3 and C4. Of the two C2 subzones, C2-1 occurs at the base and produces lower Cr/Ta ratios than in the overlying subzone C2-2. In wells 1 and 2, the zone C3 subzones are labeled C3-1, C3-2 and C3-3 in ascending order, with C3-2 defined by the highest Zr/Yb values. In Well 5, a twofold subdivision is proposed using different geochemical criteria. In this well subzone C3-A is recognized at the base of C3 and is characterized by lower La/Lu ratios than in the overlying subzone C3-B. Of the three zone C4 subzones, C4-1 yields higher Zr/Yb ratios in the underlyng subzone C4-0 and the overlying C4-2.

(4) Chemostratigraphic divisions are only recognized in subzones C2-2, C3-2, C4-1 and C4-2 where twofold subdivisions are proposed of each based on variations in Ti/U, Zr/Cr, Nb/Cr and Zr/Cr respectively.

(5) All of the chemostratigraphic zones are correlative between the study wells except for C0 which is thought to exist below the present study intervals of wells 3, 4 and 5.

(6) Unlike the zones, some of the subzones are only correlative between closely spaced wells and some cannot be identified with any confidence in others. For example, the zone C2 subzones are identified in wells 1, 2 and 5 but C2-1 and C2-2 are considered to be absent in wells 4 and 3 respectively. The absence of these subzones in these two wells is likely to be explained by erosion/non-deposition on a local scale. With regard to the C3 subzones, these are labeled C3-1, C3-2 and C3-3 in ascending stratigraphic order in wells 1 and 2 but it is not possible to further subdivide this zone in wells 3 and 4. Furthermore, a completely different subdivision of C3 is proposed for Well 5 where variations in La/Lu are used to define two subzones. It is possible that local variations in source/provenance are responsible for the observed variations in the way that the zone C3 subzones are defined in these wells. Subzones C4-1 and C4-2 are correlative between all five study wells (except possibly C4-2 which is considered to occur above the present study interval of Well 3) but C4-0 is only identified in Well 4. The absence of this subzone in the other wells may be explained by erosion/non-deposition. Alternatively, it is possible that C4-0 only exists in the immediate vicinity of Well 4 where a local change of source/provenance resulted in the deposition of this subzone.

(7) Chemostratigraphy has been utilized to aid and refine the placement of lithostratigraphic tops. In addition to this it is possible to use the technique to produce a scheme of much higher resolution than was possible prior to chemostratigraphic analysis.

(8) In addition to using the geochemical data to propose a chemostratigraphic framework, the data have also been utilized to identify potential unconventional reservoirs and seals/cap rocks. By comparing profiles plotted for U, Mo, TOC and SCHMOKER it is possible to identify units in which there is a relatively high proportion of organic matter. These are potential unconventional reservoirs and the most suitable ones are found in wells 1 and 2. Based on SCHMOKER and gamma-ray values alone, it is possible that high quality reservoirs also exist in Well 3 but, owing to the lack of geochemical data available through the study interval of this well, this cannot be assessed properly in the present study.

(9) Potential seals have been identified above the “reservoir” sections of wells 1 and 2. These produce elevated values of Al and K, inferring an abundance of clay minerals. It is possible that the high proportion of clay minerals may prevent the propagation of man-induced fractures during future fracking operations in the vicinity of these wells.

(10) The study intervals of wells 4 and 5 generally produce low values of TOC, Mo and U, inferring that there are no suitable unconventional reservoirs in these sections. It is also notable that Al and K concentrations are reasonably low through these sections, inferring poor sealing capacity even if unconventional reservoirs were to be found.

(11) It is recommended that further research is undertaken on the applications of inorganic geochemical data to predict seal integrity.
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