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Applications of chemostratigraphy in Cretaceous sediments encountered in the North Central Rub' al-Khali Basin, Saudi Arabia

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ABSTRACT

The following study was undertaken on inorganic geochemical data acquired for 832 core and cuttings samples taken from Cretaceous sediments encountered in 11 wells in the North Central Rub' al-Khali Basin, Saudi Arabia. The study sections extend from Khafji Member at the base of the Wasia Formation to the basal part of the Aruma Formation. The principal objective of the study was to produce a chemostratigraphic scheme for these wells, though a comparison was also made with a previous lithostratigraphic scheme.

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 scheme is based on changes in the following 'key' elements and ratios: Ca, Al, Zr, P/Y, Zr/P, Zr/Y, Zr/Nb, Mo and Zr. The scheme comprises a hierarchical order of five zones, 18 subzones and four divisions, with the zones labelled C1, C2, C3, C4 and C5 in ascending stratigraphic order. The definition of these zones are mainly based on changes in Ca and Al reflecting variations in bulk lithology as a response to changes in base level. Zone C1 is dominated by elevated Al and low Ca concentrations and represents calcareous mudrocks deposited in a lagoonal–prodelta environment. An increase in base level led to the formation of highly calcareous rudistic limestones deposited in a shallow marine environment, with a further increase in base level resulting in the deposition of calcareous mudrocks with high Al values in zone C3. Zone C4 comprises rudistic limestones (with elevated Ca and low Al) deposited in shallow marine conditions, while C5 is dominated by calcareous mudrocks and argillaceous limestones deposited in a prodeltaic paleoenvironment. Although the definition of zones mainly relates to changes in base level/bulk lithology, more subtle changes in provenance are modelled using the P/Y, Zr/P, Zr/Y and Zr/Nb ratios which are used to define most subzones and divisions. Variations in this ratio are almost entirely dependent on changes in source/provenance.

Although all of the zones and most of the subzones are correlative between the study wells it is noted that different criteria are used to define the zone C2 and C4 subzones in the eastern and western wells of the study area. This suggests that separate sediment sources were responsible for the delivery of clastic material to these carbonate 'reefs' during the deposition of these subzones.

One important conclusion from this study is that there are close links between the chemostratigraphic and lithostratigraphic correlations but the former offers a much higher level of resolution.

1. Introduction and geological setting

The principal goal of the study was to employ geochemical data acquired from core and cuttings samples to produce a chemostratigraphic scheme for Cretaceous sediments encountered in 11 wells located in the North Central Rub' al-Khali Basin, Saudi Arabia, close to the boundary between Saudi Arabia and the United Arab Emirates. Although the focus of this study was chemostratigraphy, sedimentological data were integrated in this study and a detailed comparison between the chemostratigraphic correlation and an existing scheme based on lithostratigraphy is discussed. The location of the study wells are illustrated in Fig. 1.

Chemostratigraphy is a reservoir correlation technique involving the application of inorganic geochemical data and it has been applied to sediments of almost any age, any lithology and accumulating in a range of depositional environments (Pearce et al., 1999, 2005; Racey et al., 1995; Ratcliffe et al., 2010; Craigie, 2015). The technique is particularly useful in correlating the aforementioned Cretaceous formation where it is often

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difficult to place lithostratigraphic markers owing to the somewhat "continuous" character of the gamma ray and other logs.

Fig. 2 shows a generalized stratigraphic column for the study interval which extends from the Albian Khafji Member to the top of the Campanian Ruwaydha Member in each well. The Khafji and Safaniya Members mainly comprise calcareous mudrocks thought to be deposited in lagoonal–prodelta paleoenvironments during a period of relatively low base level; however, an increase in base level resulted in the deposition of shallow marine carbonates (mainly rudistic limestones), in the Maddud, Wara, Ahmadi and Rumaila Members. This increase in base level culminated in the deposition of calcareous mudrocks deposited in a slightly deeper marine environment in the uppermost part of the Rumaila Member. This was followed by a period of tectonic instability resulting in a decrease in base level and the deposition of shallow marine rudistic carbonates in the Mishrif Member. The pre-Aruma Unconformity (PAU) marks the upper boundary of the Wasia Formation and represents a major depositional hiatus spanning the Turonian to Upper Campanian (Cantrell et al., 2014). This was followed by an increase in base level resulting in the deposition of pro-deltaic mudrocks, calcareous mudrocks, argillaceous limestones and subordinate sandstones in the basal part of the Aruma Formation, represented by the Tuwail and Ruwaydha Members. The was succeeded by a further increase in base level and the deposition of carbonates and deep marine sediments but the present study intervals only extend to the basal part of the Aruma Formation which is dominated by pro deltaic mudrocks, calcareous mudrocks and argillaceous limestones. For more detailed information on the sedimentology and geological setting of Cretaceous sediments in Saudi Arabia, the reader is referred to the works of Sharland et al. (2001) and Cantrell et al. (2014) and references therein.

2. Materials and methods

A total of 832 core and cuttings samples were analyzed in the present study. 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 μm) and the largest fragments (>3 mm). The latter were most likely to have been caved. 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. Approximately 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. A detailed description of all core and cuttings samples were made prior to analysis.

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 c. 50 elements, including all of the major elements and a large number of trace and rare earth elements (REEs). The powdered samples were liquefied using the alkali fusion preparation technique. This involved mixing the samples with a lithium metaborate flux and then heatring this to create a 'melt'. The melt was then dissolved in hydrofluoric acid, prior to being introduced into the ICP machines as an aerosol via a nebuliser. The ICP–OES technique measured abundances of major (e.g. K, Na, Si, Al), and high concentration trace elements (e.g. Zr, Sr, Ba), while ICP–MS was employed to acquire data from the low abundance trace elements (e.g. Rb, Cs, Ta) and REE (e.g. 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. Data for all major elements are provide 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. The assessment of data quality was based on the analysis of standard reference materials during the analysis of the core and cuttings samples in order to check on analytical precision (i.e. repeatability) and accuracy (i.e. closeness of results to 'known' values of each element). The data was considered to be of high quality in terms of both accuracy and precision.

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, Tl, U, V, W, Y, Zn and Zr, and REE. 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

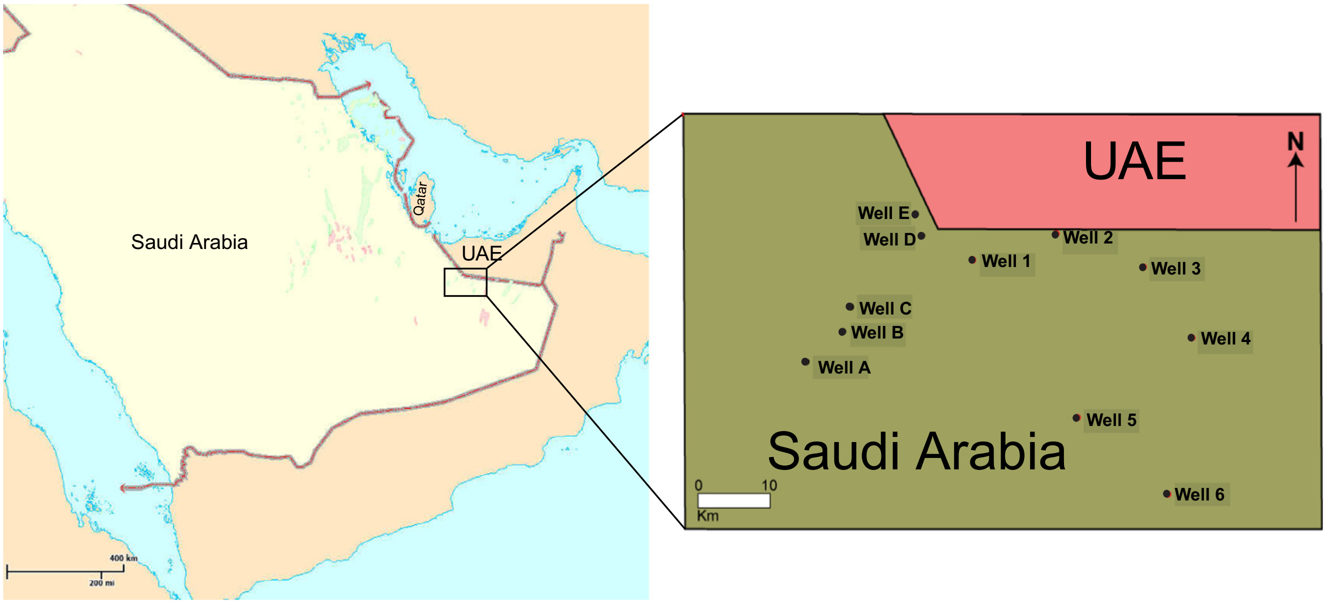

Fig. 1. Well location map.