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Chemostratigraphy of the Silurian Qusaiba Member, Eastern Saudi Arabia

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ABSTRACT

Given the unavailability of high resolution biostratigraphic data and difficulties in using lithostratigraphy for stratigraphic correlation, it was decided to employ chemostratigraphy to propose a scheme for the Silurian Qusaiba Member encountered in five wells in Eastern Saudi Arabia.

Chemostratigraphy may be defined as a reservoir correlation technique involving the utilization of inorganic geochemical data. Although Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma – Mass Spectrometry (ICP-MS) were used to acquire data for 50 elements, the scheme is based on changes in the following 'key' element ratios: Zr/Th, Cr/Ti, Th/Nb, Zr/P, Y/Yb, Zr/Yb and Y/P. Variations in these parameters are largely dependent on changes in source/provenance, reflecting increases or decreases in the abundances of particular detrital heavy minerals. The scheme comprises a hierarchical order of four zones, seven subzones and four divisions. The zones are labelled C1, C2, C3 and C4 is ascending stratigraphic order, with two, three and two subzones identified in C2, C3 and C4 respectively. In addition to this, chemostratigraphic divisions are noted in two of the subzones.

The chemostratigraphic scheme is considered robust as chemozones (general term used to describe any zone, subzone or division) are clearly defined in each well using geochemical profiles and binary diagrams plotted for key element ratios. Furthermore, high levels of statistical confidence are associated with the chemozones and most are correlative between three or more wells. The nonexistence of chemozones in particular wells is mainly explained by the sampling strategy employed. For example, the absence of subzone C3-2 (occurring towards the center of zone C3) in wells 4 and 5 is most likely to be explained by the uppermost part of the Qusaiba Member not being sampled. In other instances, particular chemozones may be missing as a result of erosion/non-deposition on a local scale.

One positive aspect of the study is that it was possible to identify the mid-Qusaiba reservoir sandstones which occur within chemozone C3-3 (at the top of zone C3) in each well. Consequently, chemostratigraphy may be utilized to recognize these sandstones in future wells, particularly in subhorizonal ones where their identification may be more difficult using wireline log signatures alone.

1. Introduction and geological setting

The following chemostratigraphy study was undertaken on the Silurian Qusaiba Member encountered in five wells located in Eastern Saudi Arabia. The objective of the study was to produce a chemostratigraphic scheme for these wells, concentrating mostly on the middle part of the Qusaiba Member where 'unconventional' reservoirs have been discovered, mainly in the form of argillaceous sandstones and siltstones.

Chemostratigraphy is defined as a reservoir correlation tool involving the application of inorganic geochemical data. The technique has been used since the 1970's but, prior to 1998, it was often used to relate observed changes in geochemistry to known geological events and/or chrono, litho and biostratigraphic boundaries (e.g. Kaminski and Malgren, 1989; Nandy et al., 1995). However, in more recent times the technique has increased in popularity and has been utilised to tackle a range of geological problems (Ramkumar, 2015). To name but a few, these include studies by Craigie (2015a and 2015b), Ratcliffe et al. (2010) Pearce et al. (1999), Hurst and Morton (2001), Pearce et al. (2005), Tavakoli (2015), Morath et al. (2015), McManus et al. (1998),

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Prakash Babu et al. (2002), Reitz et al. (2004), Sanchez-Vidal et al. (2005) and Wright et al. (2010). Although the following study is restricted to five wells, it is hoped that the chemostratigraphic scheme outlined in the present paper could be used to characterize/correlate the Qusaiba Member in other nearby wells in the future.

Fig. 1 shows the location of the study wells, while a stratigraphic column is presented in Fig. 2. Following the deposition of the glaciogenic Sarah Formation, a major marine transgression occurred as early as latest Ordovician in the Middle East (Armstrong et al., 2005). This continued and became more widespread over the Arabian plate during the Early Silurian, resulting in the deposition of the Qalibah Formation, which may be subdivided into the Qusaiba and Sharawra Members. According to Cantrell et al. (2014), the Qalibah Formation is defined as a second order sequence of sediments deposited in shoreface environments dominated by a highstand systems tract of progradational prodelta siltstones and sandstones. The initial flooding in early Silurian times led to the deposition of black organic rich shales of source rock quality at the base of the Qusaiba Member. These are informally known as the "Qusaiba hot shale" (Jones and Stump, 1999; Luning et al., 2000). The overlying part of this member comprises a series of third order cycles consisting mainly of prodelta muds and storm deposits (Miller and Melvin, 2005; Cantrell et al., 2014). The Mid Qusaiba Sequence Boundary (MQSB) is found immediately above argillaceous sandstones and siltstones, occurring towards the center of the Qusaiba Member, and is thought to represent a highstand systems tract. This was followed by an increase and then a decrease in sea level recorded by a transgressive and a highstand systems tract, the latter being identified at the top of the Qusaiba Member. A marine regression resulted in the deposition of silts and sands in prograding deltaic environments recognised in the overlying Sharawra Member in the southern part of the Arabian plate. The time equivalent strata in northern Saudi Arabia comprise shales and siltstones (Cantrell et al., 2014). The top of the Qalibah Formation is marked by the pre-Tawil unconformity, the formation of which was caused by a period of erosion associated with marine regression during the mid-late Silurian. This was followed by an increase in sea level and the deposition of marine to terrestrial braided stream sandstones and shales assigned to the Tawil Formation (Cantrell et al., 2014).

Although the basal part of the Qusaiba Member was sampled in well 5, this does not hold true for the other wells where the basal 200–400 ft of this interval was unsampled. Similarly, the uppermost 100–150 ft part of the Qusaiba Member was not included in the study, the only exception being well 2 where sampling extended to the uppermost part of this section.

A biostratigraphic scheme was produced for the Qusaiba Member encountered in these wells but is of low resolution, mainly owing to the fact that composite cuttings samples were taken over 30 ft intervals. For this reason, the results of this study are not discussed in the present paper. Although it is possible to utilise variations in wireline log response to identify the top and base boundaries of this formation, further differentiation was not possible using wireline logs/lithostratigraphy alone. Chemostratigraphy was found to be one of the few techniques that could be employed to provide a high resolution scheme for the Qusaiba Formation.

2. Materials and methods

A total of 113 core and 163 cuttings samples were analysed, with cuttings and core samples taken roughly every 10 ft and 3 ft respectively. All depths mentioned in the present report are quoted as log Depths (LD) in feet.

The cuttings samples were initially 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), with the latter most likely to have been caved. A magnet was then placed over the surface of each sample to eliminate any magnetic metallic fragments. The samples were later examined under a microscope and 'picked'. This 'picking' process involved the selection of fragments

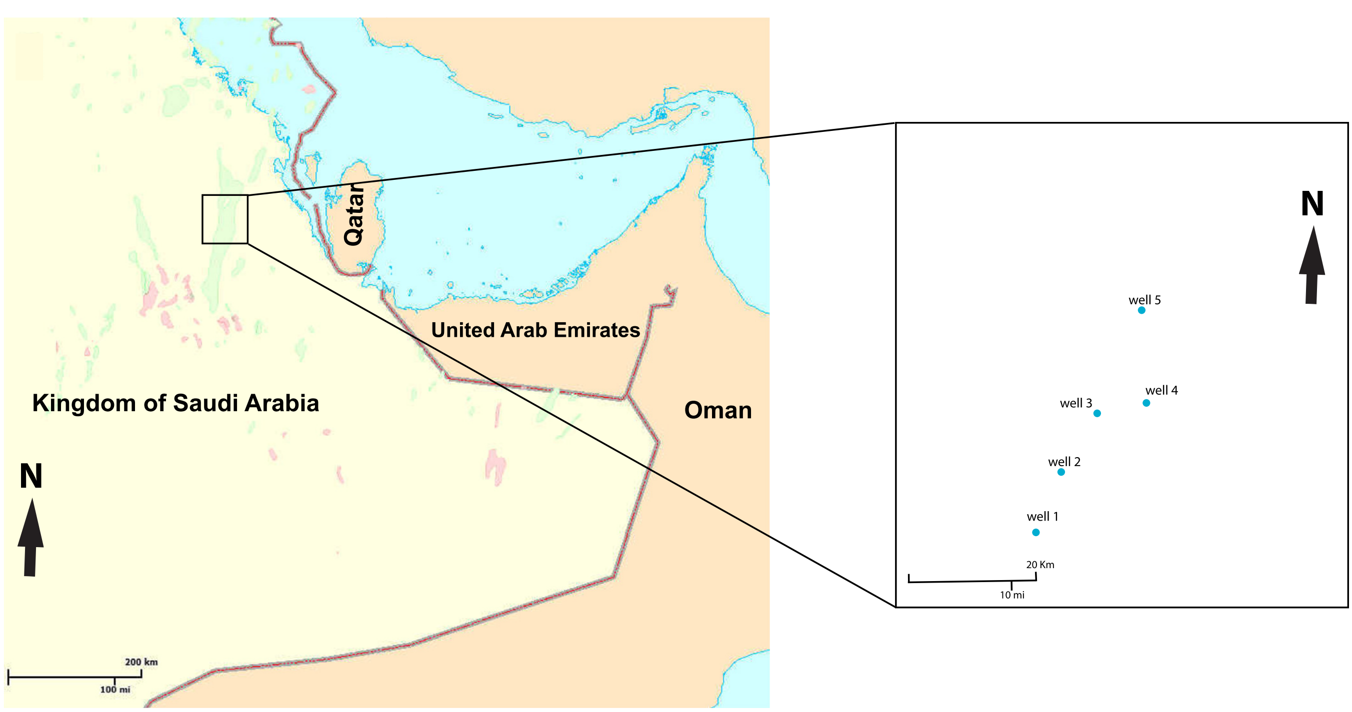

Fig. 1. Well location map.