LITHOFACIES CHARACTERIZATION OF MIXED-AEOLIAN-FLUVIAL DEPOSITS: EXAMPLE FROM THE PERMO-TRIASSIC OF THE CHESHIRE BASIN, NE UNITED KINGDOM

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Abstract

In order to improve prediction of accurate facies definitions (which has implications for fluid flow properties) in Triassic red-bed mixed fluvial and aeolian deposits, a study has been undertaken to assess the variability in lithofacies at outcrop scale from Burton Point and Helsby Forest Farm in the Cheshire Basin, England. Outcrop studies using the concept of Discrete Genetic Intervals from the fluvial Chester Pebble Beds at Burton Point demonstrated that the fluvial facies consists of amalgamated channel bars deposited within braided stream system. Reservoir heterogeneity is expected to results from decrease in bed thickness and fining upwards within beds, to fining upwards within cross strata. The Kinnerton Formation exposed at Burton Point and Helsby Forest Farm show that the Aeolian facies could be divided into moderate to high angle planar crossed stratified aeolian dune slip-face deposits (A1), horizontal to near horizontal dune base and dry interdune sub-facies (A2, B1), wavy laminated horizontal to near horizontal wet interdune deposits (B2) and interdune hollow fill mudstones (B3). Based on the grain size and sorting, the lithofacies A1 is expected to have the best reservoir quality sandstones while the B3 lithofacies may prevent vertical flow of fluid especially at well-scale. This study suggests that detailed outcrop studies is essential for more accurate definition of the lithofacies type, which is particularly important in interpreting depositional environments as well as reservoir studies.

Keywords: Cheshire Basin, aeolian, characterization, Permo-Triassic, lithofacies

1. Introduction

Production histories for many mature fields containing aeolian sandstone reservoirs such as in the southern gas basin of the North Sea (e.g. Heward, 1991) and in the Permian to Jurassic aeolian sequences in the western USA (e.g. Linquist, 1988) show that treating aeolian deposits as simple and homogeneous reservoirs is an over simplification (North and Prosser, 1993). Poor recoveries have also been recorded in most fluvial facies (e.g. the Bartlesville Sandstone which has been a major oil producer in Oklahoma, USA for more than 90 years. This is due to complex reservoir architecture inherent in fluvial as well as aeolian deposits which is very difficult to properly characterise with conventional subsurface information alone (Ye, 1977).

In arid regions, it is common for fluvial and aeolian deposits to be intermixed, with the result that the overall succession has all the complexities of aeolian and fluvial processes, plus the complexities produced at the junction between the two, and by the reworking of one by the other (North and Prosser, 1993). This phenomenon is seen in almost all Triassic continental red beds. Triassic red beds form oil and gas reservoirs in different parts of the world. For example the Sherwood Sandstone Group in Wytch Farm oil field, Wessex basin UK, and in Essaoura basin, Morocco. This study offers a detailed description of selected well exposed ancient aeolian and fluvial deposits exposures from Cheshire basin UK with the intension of illustrating the usefulness of detailed outcrop characterisation of Permo- Triassic red beds. The objectives are to document reservoir heterogeneities at different architectural scales using the concept of Discrete Genetic Intervals and their subdivision into several different smaller scale elements and to assess their implication for reservoir studies.

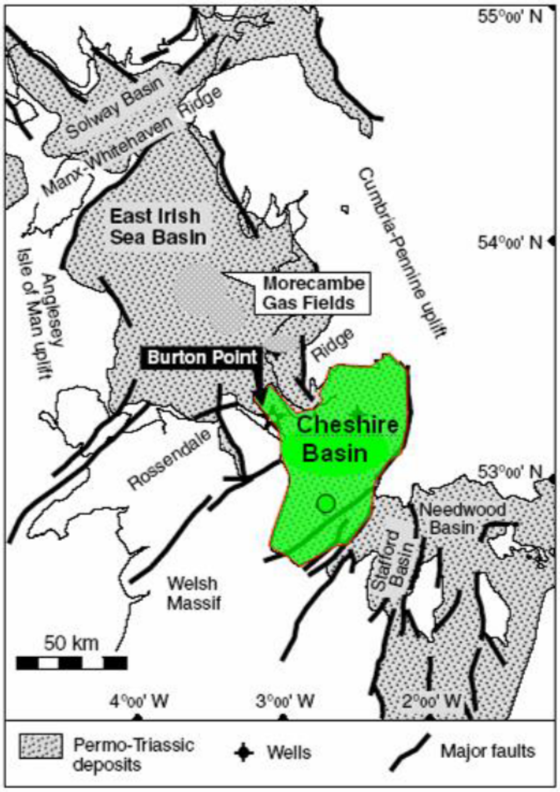

Figure 1. Location map of Cheshire Basin showing the position of Burton Point. From Stanistreet and Stollhofen, 2000.

2. Literature Review

The Cheshire basin, North East England is a faulted and folded half graben filled with Permo-Triassic deposits of largely continental origin (Chadwick, 1977). Most of the work on the area prior to the work of Thompson (1969; 1970) were focused more on the stratigraphy rather than sedimentology of the area. The influence of aeolian activity in the sandstones had been recognised by early workers. For example Wedd et al. (1923) referred to various parts of the Sherwood Group to be deposited in desert while by Taylor *et al*., (1963) suggested deposition by ephemeral sheet flood under predominantly arid conditions. Thompson (1969) described in detail and interpreted the Sherwood Sandstone Group outcrops around Frosham in the north-western part of Cheshire Basin as being the product of aeolian dune migration and ascribed them to the "Frosham Member" of the then Keuper Sandstone (later re-named the Helsby Formation). Further description and interpretation of lithofacies within the Keuper Sandstone led Thompson (1970) to identify low to moderate sinuosity fluvial deposits. The Triassic Stratigraphy of this area broadly follow the principle laid down by Warrington (1980) as shown in Figure 2.

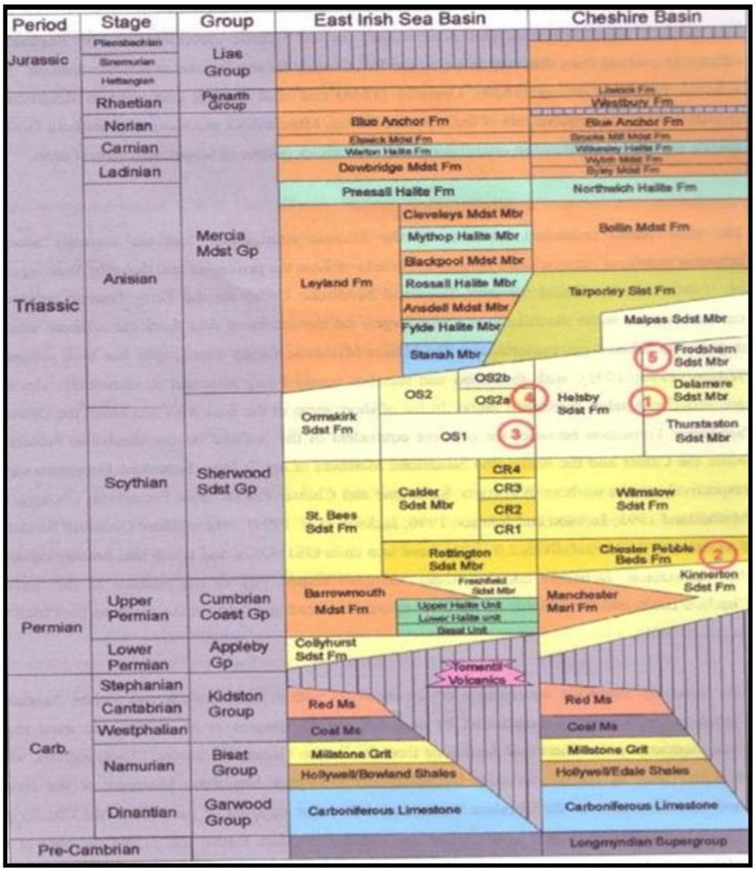

Table 1. Stratigraphy of NW England and the Irish Sea (after Warrington *et al.,* 1980)

3. Methodology

The research work involved field outcrop studies at two selected areas where both aeolian and fluvial facies are well exposed. The localities visited include Burton Point and Heldsby Forest Pack in Cheshire Basin, North West England. The work concentrated on the upper Permian Kinnerton Formation and lower Triassic Chester Formation. The concept of Discrete Genetic Intervals (DGI) developed by Kerr and Jiric (1990) which is of importance to reservoir geologist and engineers in the oil industries was employed in making a detailed investigation of the architectural elements of the studied aeolian and fluvial systems. In this approach, four hierarchy of architectural elements, each of which may influence fluid flow (e.g. Mial 1985, 1996; Mial and Tyler, 1991; Jordan and Pryo, 1992) are described. The hierarchies are:

1. Level 1: Multi-storey Discrete Genetic Intervals (MDGI) - This describes the stacking pattern of multiple DGIs. It is the largest rock volume of hierarchical reservoir architecture and shows vertical and lateral relationship between the stacked DGIs.

2. Level 2: Discrete Genetic Intervals (DGI) - This represents a brief episode of sedimentation that deposited a genetically related 3-D volume of sedimentary rock. The DGI is the fundamental sub surface mapping unit from an oil development point of view. For example the relation between meandering channels and the associated flood plain deposits.

3. Level 3: Facies within DGIs which are associated with the processes acting within the DGIs. This deal with variability within individual fills such as within meandering channel.

4. Level 4: Deals with variability of sub facies within the established facies

4. Results and Discussion

4.1 Results

4.1.1 Aeolian Systems

Two distinct Discrete Genetic Intervals are observed. They are Aeolian Dune (Facies A) and Interdune Deposits (Facies B) which are distinguished based on the nature of their cross bedding. Two sub-facies are recognized in the Facies A and are denoted by A1 & A2. The Facies B can be divided into three sub-facies B1, B2 and B3 based on their structure and position relative to Facies A.

4.1.1.1 Aeolian Dune Facies

4.1.1.1.1 Facies A1 - this sub-facies show moderate to high angle planar cross stratification (Fig. 2). The sandstones are medium to coarse grained and exhibit fine grain size differentiated laminae. The facies is interpreted as grain fall laminae deposited on slip face of aeolian dune form (Hunter, 1977; Kocurek, 1996; Spalletti *et al.,* 2010).

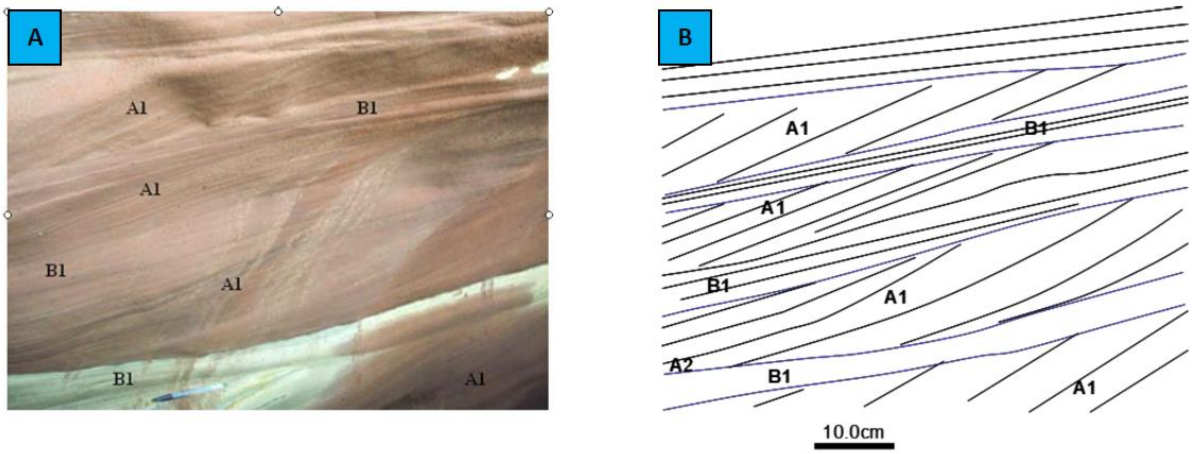

Figure 2. Outcrop Photo from Burton Point showing [A] interbedded aeolian dune face (A1), aeolian dune base (A2) and dry interdune (B1) deposits; [B] Interpreted sketch of [A] showing internal geometry.

4.1.1.1.2 Facies A2 – the sub-facies is characterized by horizontal to near horizontal laminae (Fig. 3). It consists of fine to coarse grained sandstones with more abundant thin dark argillaceous material. It commonly occur at the lower parts of Facies A1 (Fig. 3). This sub-facies is inferred to be deposited as aeolian dune toe deposits or dry Interdune deposits (Hunter, 1977; Kocurek, 1996; Nardi *et al.,* 2008).

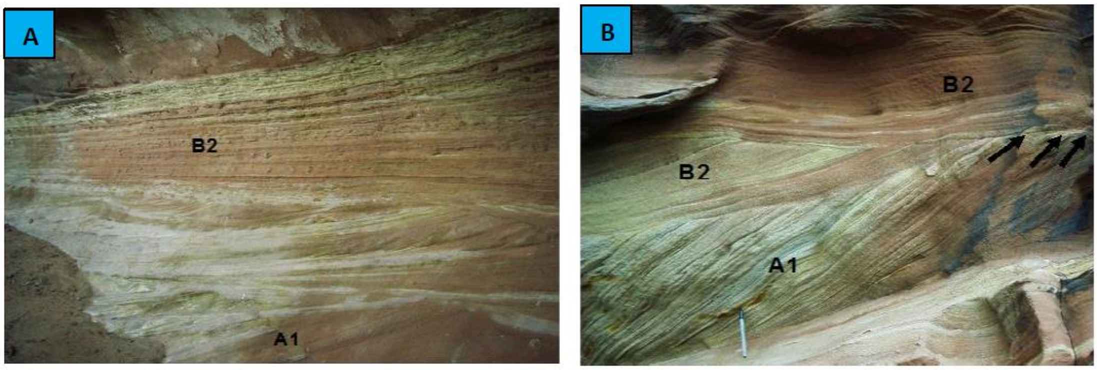

Figure 3. Outcrop photos Burton Point showing [A] Parallel wavy laminae of facies B2, intertonguing relationship between A2 and B2; [B] lateral interconnection of facies B2 and erosional truncation of facies A1 by B2 (arrows).

4.1.1.2 Interdune Facies

4.1.1.2.1 Facies B1 – this sub-facies comprises of fine to coarse sandstones having horizontal or near horizontal laminae with occasional concentration of coarse to very coarse grains. The sub-facies is interpreted as dry interdune deposit (Kocurek, 1996).

4.1.1.2.2 Facies B2- this sub-facies consists of fine grained sandstone with irregular to aligned concentration of coarse sands. They are characterised by parallel wavy laminae (Fig. 3A). They often exhibit centimetre scale lateral and vertical interfingring with the dune strata of facies A1 (Fig. 3A). Facies B2 may be interpreted as product of deposition within interdune areas where water table was periodically at sediment surface or wet (Kocurek, 1996).

4.1.1.2.3 Facies B3 – this sub-facies is composed of bright red mudstones with minor silt and fine sand fractions (Fig. 4). Horizontal bedding and desiccation cracks are the main structures. The facies are interpreted as representing deposition within confined Interdune hollows (Kocurek, 1996).

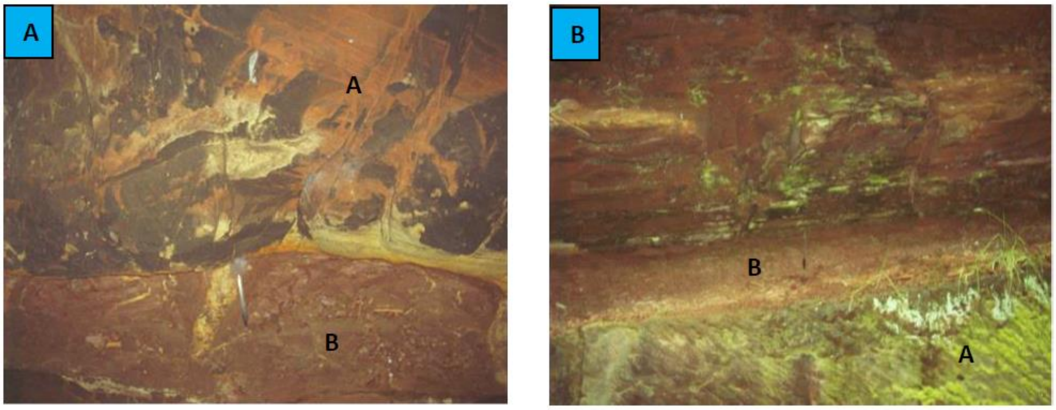

Figure 4. Outcrop photos from Heldsby Forest Farm showing [A] parallel laminated bright red coloured mudstone of B3; [B] a variety of B2 consisting of silty mudstone.

4.1.2 Fluvial Systems

Four levels of reservoir heterogeneity was observed on well exposed outcrop of fluvial deposit at Burton Point. Figure 5A shows a panoramic view of part of this deposit while Figure 5B is an interpreted sketch of the internal configuration.

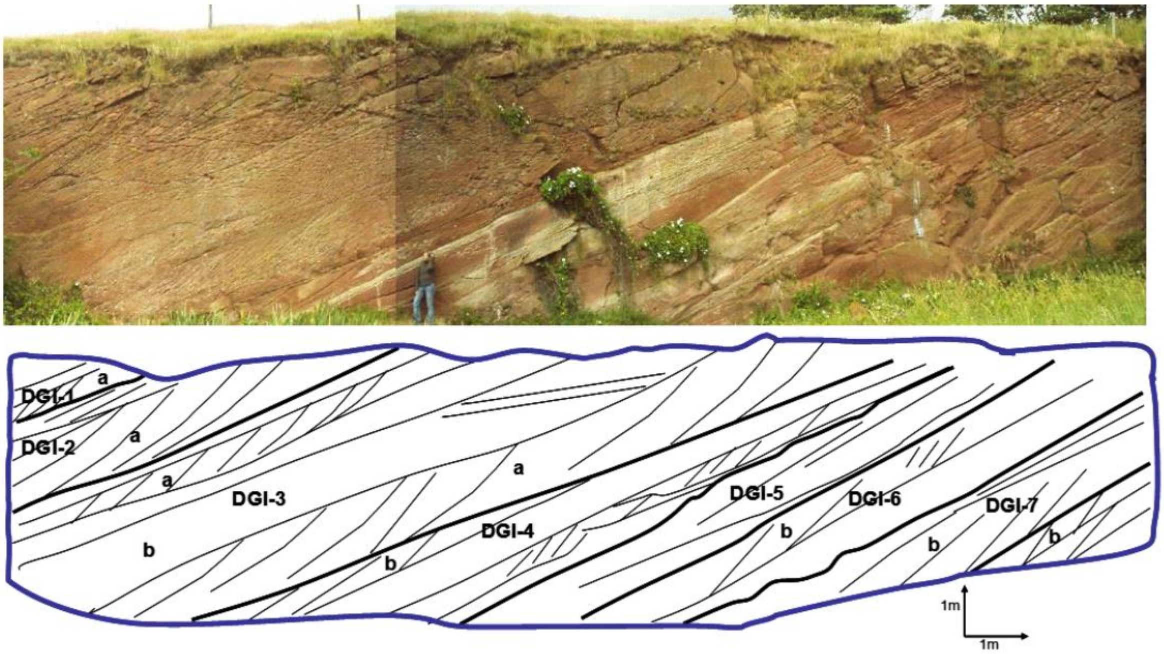

Figure 6. [A] Outcrop photo of part of a typical fluvial deposits. [B] Interpreted sketch of [A] showing the internal geometry of the deposit. DGI 1 to DGI 7 are discrete genetic interval characterised by basal lags and reduction in bed thickness within each. a & b are facies within the DGIs indicating trough cross bedding and planar cross bedding respectively.

1) Level 1: Multi-storey Discrete Genetic Intervals (MDGI) – seven DGIs are picked on the area covered by the picture. The DGIs are vertically superimposed, they are recognised by the presence of basal lags (fig.4.3)

and decrease in the thickness of bed size toward their tops. The DGIs are interpreted as channel bars and the stacking of sand bars is indicative of deposition within braided channel system. The occurrence of this deposit within an area dominated by aeolian sand systems is suggestive of deposition in perennial streams within stabilized aeolian system.

2) Level 2: Individual Discrete Genetic Intervals – A single DGI has the following features:

- Basal lag
- Grain size fines upwards
- Thickness of bed sets within DGI decrease upwards
- The lower parts of DGIs are characterised by trough cross beds with pebble lags along the cross beds
- DGI 3 has concentration of coarse and pebbly material from the central part down to the base.
- Beds become horizontal to near horizontal towards the top of the DGIs

3) Level 3: Facies within DGIs – Three different facies are observed within individual DGIs, they are:

1. Facies **a** – Medium to very coarse grains with pebbles. Characterised by trough cross bedding usually occurring towards the lower parts of DGIs
2. Facies **b** – Medium to coarse grains with pebble. Characterised by planar cross stratification with scattered pebbles towards the base.
3. Facies **c** – More or less parallel bedding towards the top of DGIs.

4) Level 4: Variability within cross beds – Centimetre scale fining upward of grains are observed on the cross beds.

4.2 Discussion

Processes operating in aeolian systems can be defined in terms of three end members: dry, wet and stabilizing systems (Kocurek and Havholm, 1993). In the dry aeolian system the water table has no effect on the substrate and no stabilizing factors occur so that deposition, bye pass and erosion along the substrate are controlled by the aerodynamic conditions only (Kocurek and Havholm, 1993). Such system are characterized by set of dune strata interbedded with dry interdune strata of limited thickness (Mountny, 2000). Facies A1 and B1 of this work clearly demonstrate this characteristics (Fig. 2 & 3). Hunter (1977) explained the processes operating on the slip-face of an aeolian dune as illustrated in Figure 7.

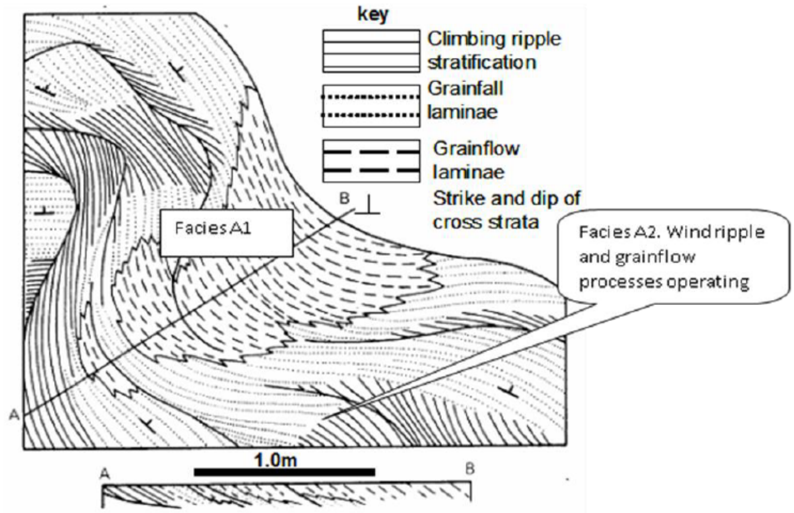

Figure 7. Model for processes operating from top to the base of an aeolian dune slipface depositing grainfall and grainflow strata. Note the absence of grainflow towards the base. (Modified from Hunter, 1977).

Wet aeolian systems are those where the water table or its capillary fringe intersect the accumulation surface so that both the aerodynamic configuration and the moisture content of the substrate determines whether the accumulation surface is depositional, bye pass or erosional (Kocurek and Havholm, 1993). These systems exhibit a variety of sedimentary structures ranging from sub aqueous current and wave ripples, wavy laminae and contorted bedding (wet surface condition) through adhesion structures, bioturbation structures and desiccation cracks (damp surface condition), to wind ripple laminae associated with dry surface conditions (Mountny, 2000). The diagram below is a summary model of Facies B2 and how they are related to Facies A1 and Facies A2 based on the studied interval.

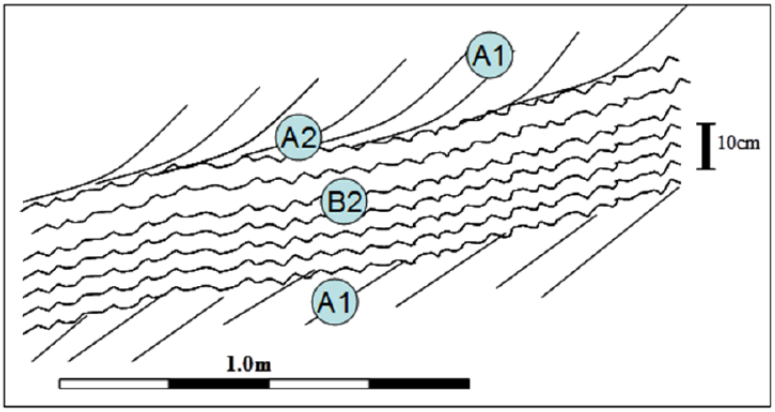

Figure 8. Model of wet interdune – dune relationship as observed in the study interval. A1 = dune slip-face facies, A2 = dune base facies and B2 = wet interdune facies.

Stabilised aeolian systems are those in which surface factors periodically stabilise the substrate and restrict aeolian transport while the system remain active overall (Kocurek and Havholm, 1993). Stabilizing agents include an elevated water table, development of desert crust, cements, soils, regs (serir), vegetation and mud drapes (Mountny, 2000). A spectrum from subaqueos environments to sabkhas to wet aeolian interdune to dry aeolian interdune systems can occur within stabilizing systems depending on sediment supply and time or space (Kocurek and Havholm, 1993). The fluvial facies described from the outcrop show characteristic similar to braided river deposits (e.g. Boggs, 2005) with individual DGIs representing channel bars and associated channel floor deposits. They commonly occur as ephemeral streams. Areas surrounding the aeolian dune field are commonly characterized by the presence of mixed aeolian and fluvial facies to form sand-sheet complex (e.g. Boggs, 2005. The proposed depositional model that can be used to explain the vertical and lateral relationship of the identified facies is shown in Figure 9, below.

4.2.1 Implications

The gain size (medium to coarse) as well as good sorting displayed by the aeolian dune facies (A1) makes it a more favourable reservoir interval than the dune toe facies (A2). This is due to the presence of dark argillaceous laminae which serves to reduce permeability in the facies A2. This implies that the reservoir performance is expected to reduce at the lower parts of aeolian dune sandstones where facies A2 are developed. Within the interdune units the dry interdune (B1) and wet interdune (B2) are expected to constitute the reservoir units. Their interfingring with the aeolian dune facies may increase connectivity of the sandstones but the presence of confine interdune hollow mudstone (B3) is anticipated to compartmentalize the reservoir when individual well-scale heterogeneity is considered.

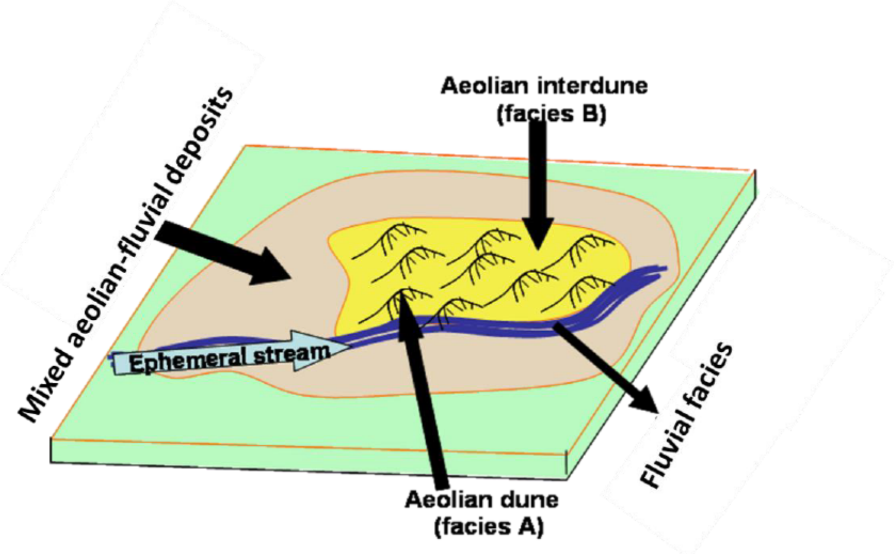

Figure 9. Aerial distribution and stratigraphic relationship between the identified lithofacies.

The fluvial facies are expected to serve as good reservoir units due to the amalgamated nature of the Discrete Genetic Interval (DGI) and the absence of floodplain mudstone intervals, but the poorer sorting may reduce the reservoir performance. Within each DGI, the porosity and permeability is expected to reduce upwards as a result of the fining-up grain size. Amalgamation of the DGIs invokes good reservoir thickness and vertical connectivity at well and even inter-well scale. Horizontal connectivity is also expected to be good due to lack of mudstone intervals within this facies.

The results of this study give insight into reservoir heterogeneity on outcrop scale using the concept of Discrete Genetic Intervals which from the oil development point of view is the fundamental subsurface mapping unit. This allows prediction of reservoir heterogeneity at individual well-scale to inter-well-scale. It provides information at even laminae scale which are often not accessible in well data. These could lead to successful prediction of large scale architectural reservoir heterogeneity and the smallest scale variability in an area dominated by mixed-fluvial and aeolian facies with implications at exploration through development to production stages.

4. Conclusion

This study demonstrates that it is possible to distinguish between aeolian and fluvial facies from the Permo-Triassic red beds exposed on Burton Point and Helsby Forest Farm in Cheshire basin, NE England. Four hierarchical levels of reservoir architecture was recognized based on the outcrop study of the fluvial facies. They are as follows in order of descending rock volume: multi-storey discrete genetic intervals which consists of amalgamated channel bars within braided stream system; discrete genetic intervals which are made-up of the channel bars within which there is upwards decrease in thickness of bed sets; bed sets within the channel bars where fining upwards of grain size occurs; and cross stratification within the bed sets where fining upwards of the grain size occur.

Lithofacies analysis of the aeolian facies provided insight into reservoir heterogeneity within the aeolian deposits. Four facies are recognised including aeolian dune and interdune facies. The aeolian facies can be divided into aeolian dune slip-face sub-facies and dune base sub-facies while the interdune facies are divided into dry and wet interdune as well as hollow fill sub-facies. The variability within these facies corresponds to the position of the facies within the aeolian system. The aeolian dune facies are related to dry aeolian systems while the damp and wet interdune facies are related to the wet aeolian system and the fluvial facies are related to stabilized aeolian system.

The aeolian dune facies are expected to be the best reservoir intervals followed by the interdune sandstones while the interdune hollow fills are expected to compartmentalize the reservoirs of the aeolian intervals. The amalgamated channel bar deposits of probable braided river origin are expected to serve as the reservoirs in the fluvial facies. Both lateral and vertical connectivity are envisaged in this facies due to lack of flood plain mudstone intervals. Accurate identification of the lithofacies as well as sub-facies using outcrop data is important for better prediction of reservoir heterogeneities in mixed aeolian and fluvial facies that commonly occur in desert environment.

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