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Geological Reservoir Modelling for Whicher Range Field Tight Gas Sand

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DECLARATION

”To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any other university”

Signature: Cesar Orsini

Date:

ABSTRACT

Tight gas sands are one type of gas accumulation generally referred to as 'unconventional gas reservoirs' by virtue of their significantly lower permeability and the attendant operational challenges for achieving viable production rates and recovery volumes. Large quantities of gas are understood to be trapped in Whicher Range Field tight gas reservoir. The Whicher Range Field, located in south-western WA close to the southern termination of the Dampier to Bunbury gas pipeline, is variably estimated to contain from 1 to 4 trillion cubic feet (TCF) of gas in place making it an important potential source of gas for local markets. There is a long history of endeavours in the Whicher Range field, extending back to 1968 and continuing through to the present day, with the challenge being to produce this gas at commercial rates. Success has so far eluded a series of operators of the field. It has been recognised that complex geological factors must be taken into account to define a successful well completion and design strategy. Lack of commercial production even after several reservoir stimulations has brought out questions related to drainage-area size and shape and about optimum strategies needed to develop the field.

A key driver for this research is the need for a better understanding of the depositional system and the reservoir properties including geometry, sand body distribution, connectivity and quality within the Sue Group in the Whicher Range area in order to better predict the lateral and vertical reservoir extension.

The aim of this project is to develop a geological reservoir model in the Southern Perth Basin, focused on the tight gas sands in the Permian section of the Whicher Range area, which will be beneficial for the reservoir development and production of the field and also can be used as an analogue for other tight gas sand (TGS) reservoirs worldwide.

The main challenge of this work is related to the volume and particularly the quality of data available to construct the model, which added a significant degree of uncertainty, however, this is compensated for through the application of empirical relationships, and comparison with modern analogues, which greatly assisted in generating an improved and more realistic geological model.

Core, well log data and depositional analogues were used to predict the depositional environments, and the application of sequence stratigraphic fundamentals helped to provide a chrono-stratigraphic framework and to better elucidate the reservoir facies, geometries and distribution. Furthermore, the 2D seismic interpretation, integrated with regional tectonic and basin evolution knowledge were key in defining the structural framework for the geological model. On the other hand, detailed well log data QC, conditioning and interpretation accompanied by the use of core data, empirical relationships and analogue data from an extensive TGS database were applied to develop the petrophysical analysis. Finally, the construction of the geological reservoir modelling was performed by applying object-based model methods and using parameters based on empirical equations and analogue data.

Based on this study a fluvial meandering system with non-marine influence has been defined for the Willespie Formation in the Whicher Range area. Six facies and facies associations were recognized, from which channel fill sediments (CH1) represent the facies with the best reservoir quality. The reservoir is composed of lithic-arkoses and arkoses in which the reservoir quality seems to be mainly controlled by clay type, morphology and distribution. Porosities in the field range between 2 and 15% and permeabilities are most likely to be below 0.1mD.

Four third-order stratigraphic sequences and 8 fourth order depositional sequences are recognized in the Permian section. The mean channel width for all wells is 175m and the estimated channel belt width mean is 1600m. From the generation of the geological model it was found that the interval above the SB_4 displays the highest degree of amalgamation of CH1 facies but also the best rock quality properties.

Furthermore, there is a good relationship between CH1 facies and the best porosities in the area and a fair relationship between facies, rock quality and rock permeability.

Given the results from this study, some recommendations for further studies and future well planning strategies are provided.

ACKNOWLEDGMENTS

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ENCLOSURES

Chapter 1- INTRODUCTION

A key driver for this research is the need for a better understanding of reservoir connectivity within the Sue Group in the Whicher Range area. Litho-stratigraphic correlations tend to over-estimate the lateral connectivity of reservoir sandstones. A sequence stratigraphic framework, based on modern concepts, uses key surfaces to subdivide successions into sequences and systems tracts of genetic stratigraphic units. This approach generates a more objective prediction of intervals with optimum reservoir connectivity (Galloway, 1989).

Additionally, this study aims to contribute in developing a better understanding of sequence stratigraphic applications in continental fluvial environments with no-marine influence, which is an area that, although previously investigated by different authors i.e. Shanley and Mc Cabe, 1994; Posamentier, 1992a remains as a controversial and poorly documented topic in stratigraphy research worldwide (Catuneanu, 2010). As part of this study, an investigation about how sequence stratigraphy concepts can be applied to these non-marine environments is included.

Future petroleum exploration and development in the southern Perth Basin can benefit from the application of high-resolution sequence stratigraphy to build sound geological reservoir models. This will increase the identification of stratigraphic traps, provide better understanding of likely compartmentalization of reservoirs and determine their potential economic significance.

The presence of anticlinal traps that involve Permian fluvial bodies in the Whicher Range section is recognized (Cadman et al, 1994). However, the fluvial body geometry, orientation and connectivity are currently unknown. Analysis of these factors, from the available cores and wireline logs (electrofacies), and by comparison with modern depositional analogues, is necessary to gain an understanding of the depositional style and position of fluvial sandstone bodies within the reservoir sequence. Such a geological reservoir model will be potentially beneficial for assessing reservoir development and likely production in the Whicher Range area.

The applicability of the model will depend on many factors including: (1) the application of geological and sequence stratigraphic concepts, (2) the integration of previous works on the area, (3) correlation of well logs, (4) interpretation of the environment of deposition based on electrofacies and core data, and (5) the relationship of this environment with the structural configuration of the basin.

Ideally, a full investigation will provide key steps to establish a coherent geological setting and help characterise this tight gas sand field. However, the volume and quality of data actually available to construct the geological reservoir model are limited, resulting in increased uncertainty than might otherwise be the case. The application of empirical relationships, and the comparison with modern analogues, greatly assists in generating an improved and more realistic model.

Aims and Objectives

The purpose of this research is to study various geological parameters of the Sue Group in the Whicher Range area to help characterise the tight gas sand reservoir. This study is based on a review of all the existing geological and geophysical data, together with new interpretation of well drilling reports, wire line and other well data, specifically for the Whicher Range area and from some nearby wells. A primary aim is to develop a 3D geological model of the reservoir. The ultimate objectives are that this model will provide a better understanding of the productivity potential of this field and help guide future field development plans and exploration within this area, and other areas with analogous depositional histories.

Primary Objectives of the study of the Sue Group reservoir

The primary objectives of the study are:

- To construct an internally consistent framework for the non-marine sediments of the Sue Group based on modern sequence stratigraphic concepts.
- To develop a log motif (electrofacies) scheme for the Sue group in the Whicher Range area.
- To establish the relationship between petrophysical properties and lithologies for the sediments comprising the Sue Group.
- To interpret the main geological features and structural events from seismic data and to correlate with well logs.
- To define and map the areal and vertical distribution of reservoir lithofacies.
- To build a 3D geological model of the Whicher Range Field to better predict the production potential of this field.

Layout of the thesis

To address the objectives of the thesis, this document is constructed in seven chapters, each one representing a different stage in the construction of a 3D geological model. The first chapter introduces the importance of the study, outlining the data available, definitions and the regional geology.

In Chapter 2, a sedimentological model based on core and log facies is constructed and the depositional environment controlling geobody architecture is interpreted. Results from this phase provide key information about the reservoir geometry and facies distribution.

Chapter 3 combines regional information including depositional environments and tectonics to construct a sequence stratigraphy framework for the Permian section.

This framework provides a time constraint which helps to better correlate and predict the vertical and lateral geobody distribution.

In Chapter 4, the structural framework is generated with the aim of setting up a structural model to honor the structural variables controlling deposition during the Permian.

In Chapter 5, a petrophysical analysis is performed with the objective of defining the reservoir properties of the Willespie Formation in the Whicher Range Field, which is necessary to populate the geological reservoir properties. Also, the results from the reservoir quality analysis published in the APPEA Extended Conference Abstract is shown in this chapter.

Chapter 6 is developed in two main sections: channel width and channel belt width estimation from thickness using regression presented by different authors, which is done to define the magnitude of the main reservoir facies to be used for the modelling phase and finally, the construction of the 3D geological reservoir model, in which results from all the previous chapters are applied and a comparison between 12 different object modelling realizations is presented.

Four enclosures to the thesis are appended, including: Enclosure 1 corresponding to a core description for WR4 matched with facies and electrofacies, enclosure 2, which displays the facies proportion statistics, and enclosure 3 that contains the results from the channel width and channel belt width estimation using equations from different authors. Finally, the fourth enclosure is a conference paper published during the course of the study:

Orsini, C.D, Rezaee, R., Wilson, M.E. "Factors controlling tight gas sand quality in the Whicher Range gas field, southern Perth Basin, Western Australia." *APPEA Conference.* Perth: APPEA, 2011.

An additional publication comprising Chapter 2 in Geological Survey of Western Australia special publication:

Orsini, C., Rezaee, R. *Depositional Systems, Sequence Stratigraphy Frameworks and Geological Modelling of fluvial Bodies.* Vol. 112, chap. 2 in *Whicher Range Tight Gas Sands Study*, by Western Australia energy research alliance (wa:era), 1-56. Perth: Geological Survey of western Australia, 2012.

is not given in the appendices since this is considered an early working version of chapters 1, 2, 3 and 4.

Data available to the study

Data was primarily supplied by Curtin University of Technology, Department of Petroleum Engineering, with input from the Department of Mines and Petroleum (WAPIMS) and Whicher Range Energy.

Wireline log suites were available for six wells; Whicher Range 1, Whicher Range 2, Whicher Range 3, Whicher Range 4, Whicher Range 5 and Sue 1. Core photography and reports were available from four wells in several intervals; Whicher Range 1 (core # 21, 22, 23, 24, 25 & 26), Whicher Range 2 (core # 1,2,3 & 4) and Whicher Range 3 (core # 1, 2,3,4,5,& 6) and Whicher Range 4 (core # 1,2 & 3). Also, 2D seismic data was provided by Whicher Range Energy.

The Study Area

The Whicher Range Field is located onshore Western Australia approximately 25 km south of Busselton and approximately 215 km south of Perth in the Bunbury Trough (Figure 1). The Whicher Range wells were drilled within an extensively faulted anticline. According to Amity Oil (2004), the areal closure mapped at the top of the Sue Group, after reprocessing seismic data, is about 110 km^2 (Figure 1). Five vertical wells have been drilled in the Whicher Range field. The first well, Whicher Range 1, was drilled in 1968 by Union Oil. Whicher Range 2 was drilled in 1980 by Mesa Australia Limited. Whicher Range 3 was drilled in 1981 by BP Petroleum

Development Australia Pty Ltd. Whicher Range 4 was drilled in 1997 and Whicher Range 5 was drilled in 2003 both by Amity Oil.

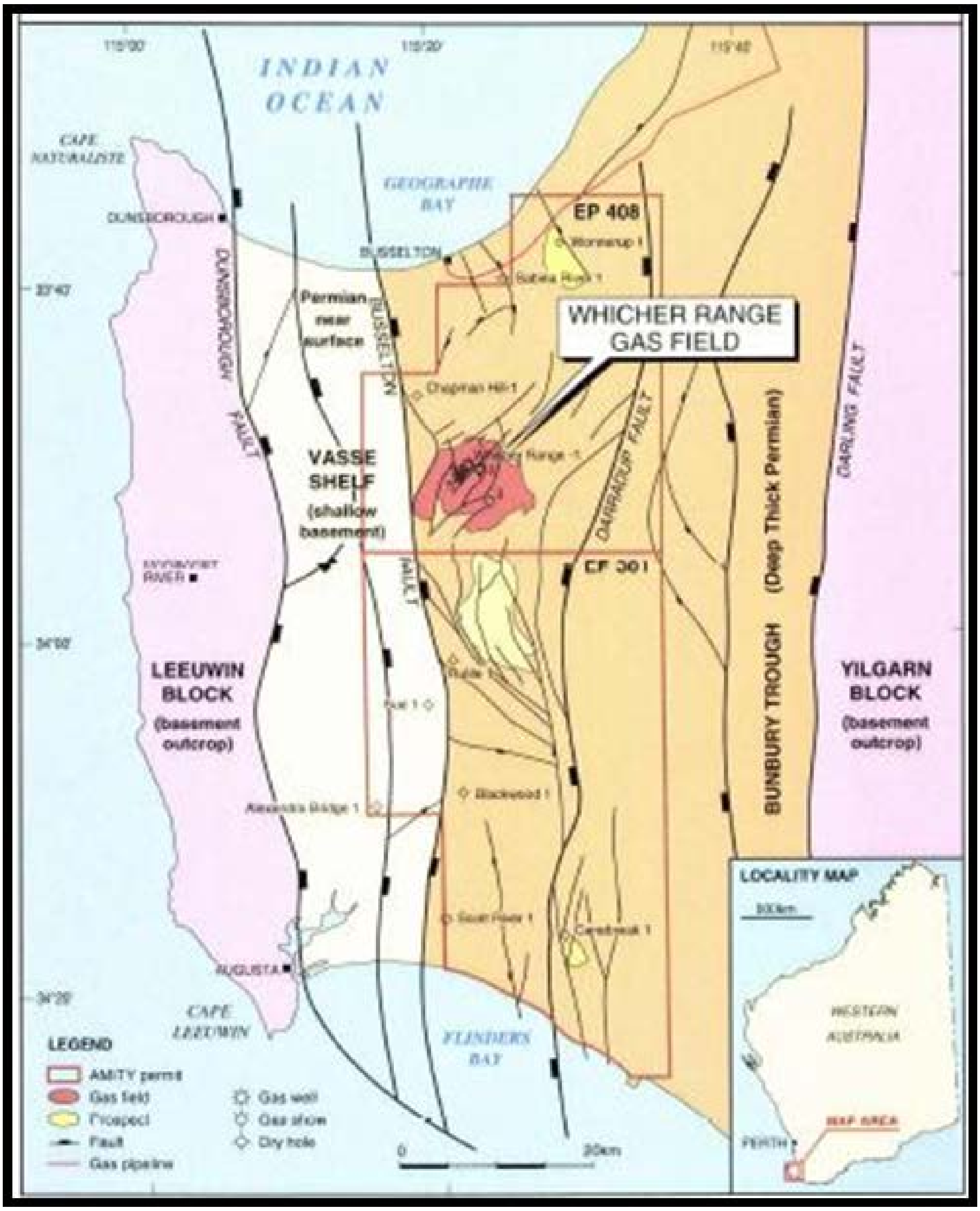


Figure 1. Location of Whicher Range Field in Southern Perth Basin, WA (From Well Completion Report Whicher Range 5. Amity Oil Limited, 2004.

Tight Gas Sands Definition

'Tight gas' is a concept or term normally applied to low-permeability reservoirs that produce natural gas, primarily from sandstone. However, vast quantities of gas have been produced from low permeability carbonates, shales and coal beds. These are generally referred to, collectively, as ‘unconventional gas’ sources.

The oil industry definition for a tight reservoir, according to Law and Curtis (2002), is a rock with permeability of 0.1 millidarcy or less. In some countries, tight gas is defined by flow rate and not by permeability. One of the most popular definitions of tight gas is from Holditch (2006) and Nehring (2008), “a reservoir that cannot be produced at economic flow rates or recover economic volumes of natural gas unless the well is stimulated by a large hydraulic fracture treatment or produced by use of horizontal wellbores or multilateral wellbores”.

The Whicher Range field bears all the attributes mentioned in these definitions.

Perth Basin regional framework

The Perth Basin is defined as an onshore and offshore sedimentary basin located in Western Australia. Freeman and Donaldson (2006) refer to it as a deep linear north–south rift trough with a series of sub-basins, shelfs, troughs, and ridges filled with a sedimentary sequence deposited from the Early Permian to late Cretaceous (Figure 2). The boundaries of the Perth Basin are the margin of the Southern Carnarvon Basin in the north, the South Coast in the south, the Darling Fault in the east and the Indian Ocean continental shelf in the west (Mory and Iasky, 1996). The Perth Basin has been subdivided into northern, central, and southern basins. The focus of this research, the Whicher Range gas field is located within the southern Perth Basin (Figure 2).

Shallow basement (Harvey Ridge) separates the Dandaragan Trough from the Bunbury Trough (Cadman, et al., 1994). The Bunbury Trough is a relatively deep graben, bounded in the east by the Darling Fault and the Yilgarn Craton; and in the west by the Dunsborough Fault and the Leeuwin Complex (Playford *et al.,* 1976; Crostella and Backhouse, 2000), as shown in Figure 2.

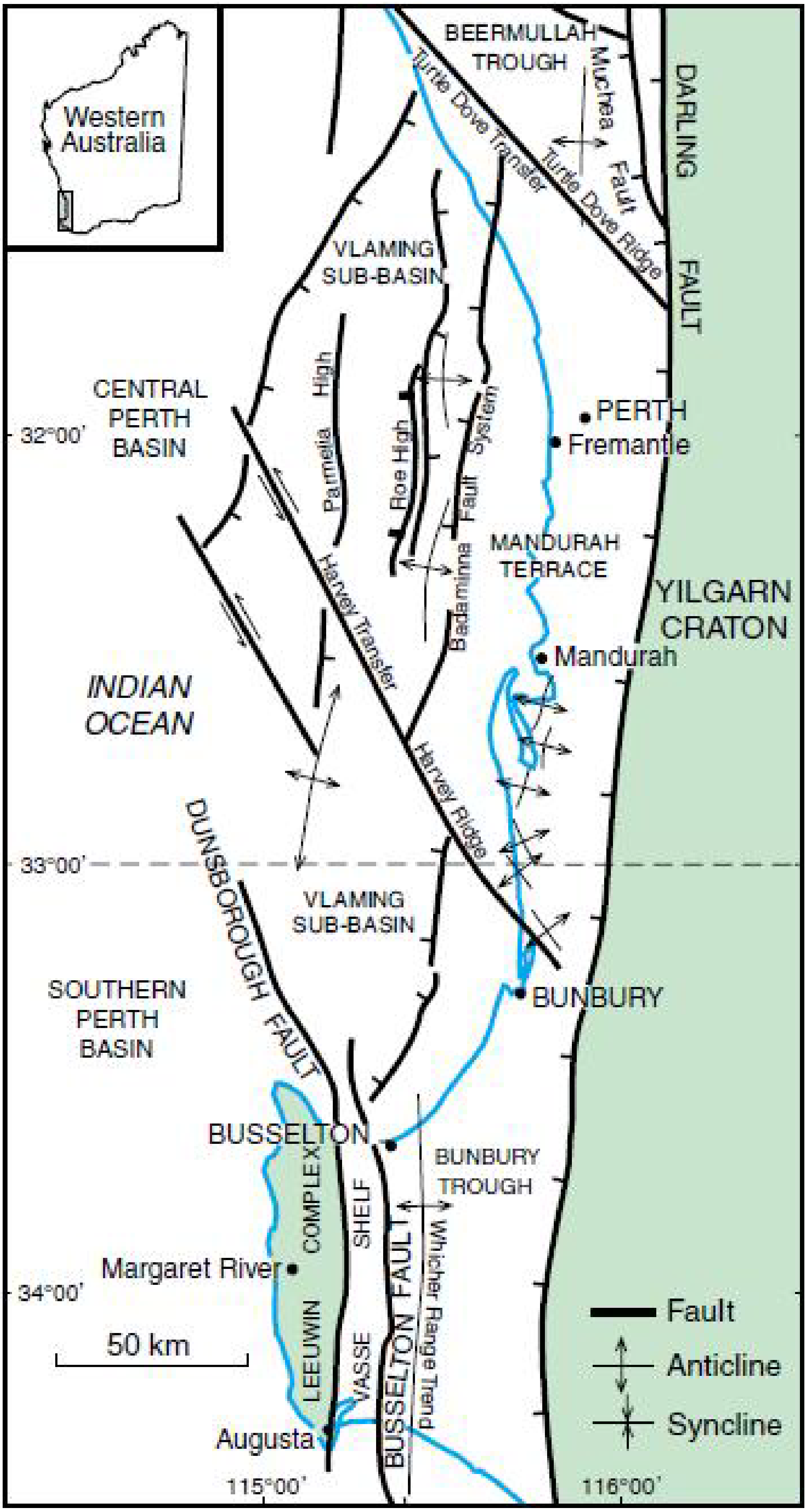


Figure 2. Basin subdivisions and tectonic lineaments of the central and southern Perth Basin (Modified by Freeman and Donaldson 2006 from Crostella and Backhouse, 2000).

The structural style of the Perth Basin was developed through oblique rifting in a transtensional tectonic regime (Marshall *et al.,* 1989). The main rifting phases occurred in the Permian and Jurassic to earliest Cretaceous, the youngest event corresponding to the final rifting and breakup of Gondwana lithosphere between Australia from Greater India (*Marshall et al,* 1989; Mory and Iasky, 1996; Song and Cawood, 1999). Figure 3 displays the different tectonic rift stages impacting the Perth Basin.

The structure of the southern part of the basin is characterized by compressional anticlines with planar normal faults. The compressional structures (anticlines) may have been generated as a consequence of a “limited” tectonic stress relief existing in the relatively narrow trough occurring between the two basement highs: Leeuwin Complex and the Yilgarn Craton (Crostella and Backhouse, 2000) or most likely due to regional inversion of the Perth Basin associated with the Neocomian break-up (Song and Cawood, 2000).

According to Baillie *et al.,* (1994) and Crostella and Backhouse (2000), the depositional settings in the southern Perth Basin in the Permian and into the Early Triassic were fluvial to lacustrine. The Permian ‘Sue Coal Measures’ were originally defined by Playford *et al.,* (1976) and later defined as the ‘Sue Group’ by Le Blanc Smith and Kristensen, 1998. The group is characterized by interbedded sandstone, siltstone and coal deposited in the Bunbury Trough. This group is subdivided into the Woodynook Sandstone, Rosabrook Coal Measures, Ashbrook Sandstone, Redgate Coal Measures and Willespie Formation (Le Blanc Smith and Kristensen, 1998). Description of the Sue group is summarised in Table 1.

In the Early Triassic, the continental sedimentation in the Bunbury Trough (Sabina Sandstone) propagated northwards, and by Middle Triassic times, fluvial sedimentation dominated throughout the majority of the basin (Lesueur Sandstone).

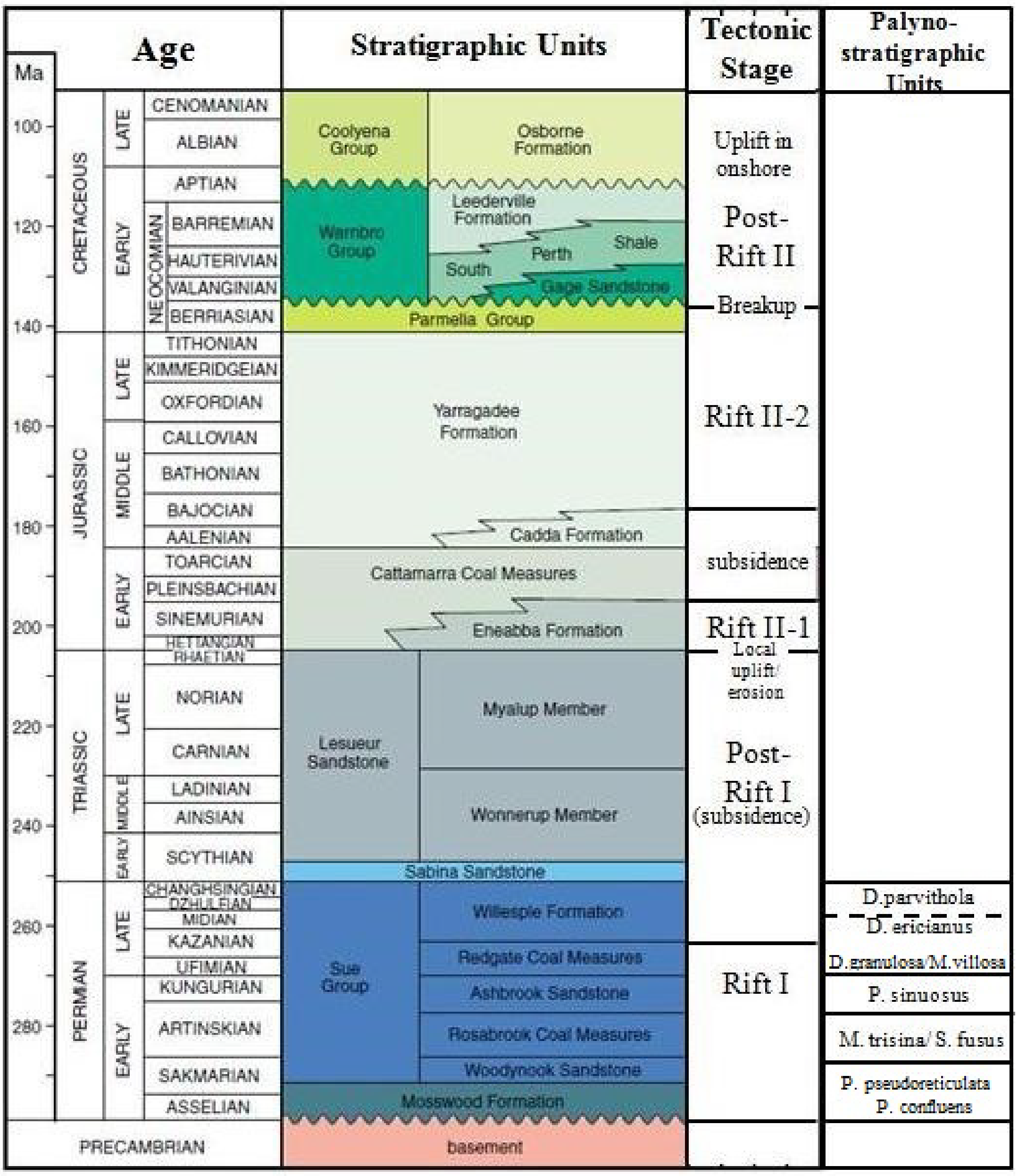


Figure 3. Stratigraphy, tectonic phases and Permian palynology of the central and southern Perth Basin (Modified from Crostella and Backhouse, 2000).

Table 1. Permian formation descriptions in the southern Perth Basin (after Crostella and Backhouse, 2000)

FORMATION	DESCRIPTION
Willespie Formation	Le Blanc Smith and Kristensen (1998) describe the Willespie Formation as a thick unit composed of poorly sorted feldspathic sandstone, with subordinate conglomerate, siltstone, shale, and sporadic thin, lenticular sub-bituminous coal that lies conformably above the Redgate Coal Measures. In Sue 1 a complete type section of 1060 m thickness is present (1216–2276) m. The Willespie Formation is distinguished by numerous upward-fining sandstone cycles and lenticular coal seams are common, with thicknesses generally less than 0.5 m (Le Blanc Smith and Kristensen, 1998). Sandstone porosity is fair to good, with local tight streaks. An alluvial to upper deltaic environment of deposition within a lacustrine setting is inferred. The Willespie Formation in the Vasse River Coalfield is unconformably overlain by the Cretaceous Warnbro Group, but in Sue 1 and elsewhere it is overlain by the Triassic Sabina Sandstone, with an apparently conformable contact, the unit ranges from the *D. ericianus*to to the *Dulhuntyispora parvithola* Zone, and Backhouse (1993) recognized the appearance of *Camptotriletes warchianus* and *Microbaculispora* sp. as a potentially useful biohorizon, but did not erect zones based on these species.
Redgate Coal Measures	Characterized by coaly, poorly-sorted felspathic sandstone overlying the Ashbrook Sandstone. The type section in Sue 1 is 146 m thick (2276–2422m). The coal seams are of limited extent, both vertically and horizontally (Crostella and Backhouse, 2000). The sandstone beds fine upwards and are similar to those of the underlying Ashbrook Sandstone, although with more frequent and thicker argillaceous beds. Le Blanc Smith and Kristensen (1998) interpreted that the deposition was in an alluvial environment that ranged from braided streams to swamp and lacustrine deltas. The Redgate Coal Measures passes conformably upwards into the Willespie Formation. In Sue 1, the unit appears to range palynostratigraphically from the *Microbaculispora villosa* Zone into the lower part of the *Didecitriletes ericianus* Zone, an interval currently dated as Ufimian to Kazanian.
Ashbrook Sandstone	Consists of poorly sorted feldspathic sandstone unit,

	without major coal seams, that overlies the Rosabrook Coal Measures. In the type section in Sue 1, it is 262 m thick (2422–2684 m). A lacustrine–deltaic environment of deposition is envisaged for the Ashbrook Sandstone. The Ashbrook Sandstone is conformably overlain by the Redgate Coal Measures. Palynostratigraphically, the unit is characterized by the *Praecolpatites sinuous* Zone, which is now considered to be approximately Kungurian in age (Mory and Backhouse, 1997)
Rosabrook Coal Measures	Poorly sorted feldspathic sandstones interbedded with siltstones and carbonaceous shale grading upwards to coal represent this formation. The unit in Sue1 is 198 m thick (2684–2882 m). The seams of black and bituminous coal range from 0.1 to 4.5 m in thickness on the Vasse Shelf and have similar thickness in Sue#1. According to Le Blanc Smith and Kristensen (1998) the Rosabrook Coal Measures is interpreted to have been deposited in a fluvial-plain setting in which deltas prograded into a lacustrine environment. The contact between the Rosabrook Coal Measures and the Woodynook Sandstone is transitional, and the two units are lithologically similar. They are distinguished from each other by the presence of significant coal seams in the Rosabrook Coal Measures. The Rosabrook Coal Measures are conformably overlain by the Ashbrook Formation.
Woodynook Sandstone	Characterized mainly by poorly sorted fluvial sandstone. The type section in Sue 1 is 121 m thick (2882–3003 m). According to Le Blanc Smith and Kristensen (1998) the transitional upper contact with the Rosabrook Coal Measures is conformable, and is placed immediately beneath the stratigraphically lowest coal seam of that unit. In the type section, the top of the unit falls within the *Pseudoreticulatispora pseudoreticulata* Zone, but the base of the unit may be within the *P. confluens* Zone, although the evidence is uncertain. The unit is Sakmarian (Early Permian) in age. No reliable palynological samples are available from this interval in Sue 1 (Backhouse, 1993).

Mosswood Formation	Consists of dark grey-brown to black argillaceous mudrocks, with minor siltstones and fine-grained sandstones. In Sue 1, a few granules and a small pebble of pink granite are present, embedded as erratics within an argillaceous matrix (Williams and Nicholls, 1966).The depositional environment is considered to be fluvio-lacustrine, with the minor erratics indicating the presence of melting icebergs that dropped icerafted morainic deposits onto the basin floor. The upper contact with the Sue Group is conformable and gradational, corresponding to a decrease in fine clastic material. The thickness in Sue 1 is 51 m (3003–3054m) The Mosswood Formation in Sue 1 contains palynomorphs of the *Pseudoreticulatispora confluens* Zone and Stage 2 (Backhouse, 1993) that indicate an Asselian to early Sakmarian age.

Chapter 2 - DEPOSITIONAL SYSTEMS AND RESERVOIR QUALITY OF THE WHICHER RANGE FIELD

Introduction

One of the main prerequisites to producing a robust geological model is to define the depositional environment controlling the reservoir geometry. This is mostly done by interpreting key sedimentary features from core, wireline logs and seismic data that allow elucidation of the depositional setting and integration of the results with regional information including that compiled from previous studies.

Key sedimentary deposits that are organised into "facies" occur in predictable patterns, in terms of their lateral and vertical distribution, and can be linked to sedimentary processes and depositional environments. Furthermore, these *facies* can have different reservoir properties and hence a major influence on reservoir geometry.

The term *facies* has been used for many years and therefore has a well understood definition described by many authors (i.e. Walker; 1992). Herein *facies* is referred to as a deposit with a particular combination of lithological, structural and textural attributes that facilitate the classification and characterization of a rock through comparison with other rock bodies.

Ideally, facies descriptions are performed by direct observation of key depositional features over the entire reservoir rock. However, costs related to acquisition do not always allow core data to be taken through the entire reservoir section. By introducing electrofacies representing well log scale sedimentary units it is possible to infer likely lithological facies in areas where only log data is available.

Electrofacies is defined as "the set of log responses which characterizes a bed and permits it to be distinguished from the others" (Serra, 1984). In this work, sediment or facies interpreted to correspond to geological features have been evaluated from conventional logs through the definition of an electrofacies scheme.

Similar log motifs or patterns of well log response may be produced for fundamentally different depositional environments. Likewise, the same depositional system could show different well-log signatures as a result of varying factors including sediment supply, depositional energy, accommodation space and tectonic controls. Because of the similarities in some log motifs, for different depositional environments, full integration of a range of data sets is essential to generate the most likely depositional facies model (i.e. the need to combine studies of log motifs with those on cores and biostratigraphic and seismic data).

The identification of specific depositional elements such as channel fills, splays, etc, based on the use of facies and electrofacies, is helpful in understanding their morphology and distribution within an area. This, together with the knowledge of the relationship with the tectonic setting has a direct impact in the interpretation of the paleodepositional environment.

Based on regional studies of the Southern Perth Basin, the stratigraphic and tectonic setting of the Whicher Range Field has been characterised by almost uninterrupted sedimentation during the Late Permian to Early Triassic, with a possible short break at the top of the Willespie Formation. According to Iasky (1993) the South Perth Basin sedimentation is most likely fault controlled, as inferred by the eastward thickening of the Permian towards the Darling Fault seen through the seismic data.

A fluvial meandering sedimentary environment has been inferred for the Willespie Formation, based on the direct application of core data and electrofacies schemes. This interpretation is in agreement with the fluvial- lacustrine depositional setting pointed out by previous authors (Crostella and Backhouse, 2000).

Rock quality constitutes another important parameter necessary to produce a robust reservoir model. This describes the effect that post depositional events (diagenesis) have either in the improvement or detriment of rock properties such as porosity and permeability.

There are limited studies describing the rock heterogeneity, internal structure and reservoir quality of the Willespie Formation, and as a consequence, the main factors controlling these parameters, along with lateral reservoir connectivity and fluid flow mechanism, remain unknown.

Available data from 5 Whicher Range wells, including wireline logs, core data, well reports and petrographic data, were studied to define the syn-depositional and post-depositional events affecting the reservoir rock quality.

Depositional Systems

Sedimentary facies

In order to generate an approach for well log correlation and to develop an electrofacies scheme for the Whicher Range field, the first step was to define the facies present in core data. In Whicher Range 4, facies were interpreted using mainly the core descriptions performed by Martin (Whicher Range 4 well completion report, 2004) but review and completed as part of this study using both the physical core, stored in the Whicher Range Energy office and the photos taken by CoreLab Australia.

Six facies were identified from core in the Willespie Formation. These facies are embedded in three main lithology groups (Sandstone, Heterolithic and Mud) as can be seen on Enclosure 1 and Figure 4.

The first lithology group is *sandstone* and is represented by the following facies:

Coarse Sandstones (S_C): Characterized by brownish to light grey coloured coarse-grained sandstones to conglomerates, medium to poorly sorted. The most common sedimentary structures are cross stratification and rip-up clasts. No bioturbation was observed in this facies.

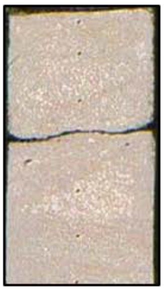
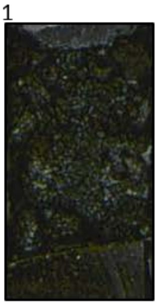
1 	2 		**SC** 1) Coarse grained to conglomeratic poorly sorted sand 2) Medium to coarse grained cross bedded sandstone
3 	4 		**SM** 1) Massive sandstone medium grained faintly cross bedded 2) Massive sandstone medium grained
5 	6 		**SL** 1) Laminated sandstone rooted 2) Laminated sandstone
7 	8 		**HL** 1) Heterolithic laminated sandstone and siltstone / wavy lamination 2) Heterolithic laminated sandstone and siltstone planar lamination
9 	10 	11 	**M** 1) Mudstone – Carbonaceous siltstone with fine laminations of very fine grained sandstone 2) Mudstone- Massive mudstone **C** 1) Coal

Figure 4. Facies in the Willespie Formation from core of Well Whicher Range 4.

Massive Sandstones (S_M): light grey to light brown, moderate to well-sorted sandstones with grain sizes varying from coarse to fine. Some rip-up clasts are present as are faint cross- or planar-lamination. No bioturbation was observed in this facies.

Laminated Sandstones (S_L): Light grey to grey sandstones, well- to very well-sorted with fine to very fine grain sizes. The main sedimentary structures observed are planar-, flaser- and wavy-lamination, rip-up clasts and clay drapes. A low grade of bioturbation or burrowing is observed.

The second lithology group is *Heterolithics* represented by the facies below:

Heterolithic laminated sandstones and siltstones (HL): Light grey to grey coloured, well to very well sorted, laminated, very fine to fine grained sandstones inter-bedded with siltstones that are in some cases carbonaceous. The sedimentary structures present are low angle, planar, current ripples and wavy lamination, mud drapes and soft sediment deformation features. Bioturbation is common in this facies.

The third lithology group is Mud and is represented by:

Mudstone (M): Characterized by massive dark to grey mudstone or carbonaceous siltstone with scarce lenses or laminations of very fine grained sandstone. Lithologies are well sorted, sometimes containing coaly material. Sedimentary structures present in this facies are planar laminations. Bioturbation is rare.

Coal (C): Characterized by dark black coal and carbonaceous mudstone. Some are friable.

Facies associations (FA) and electrofacies

Facies identified in core were related to the depositional environment and matched with electrical well log responses (electrofacies). The interpreted electrofacies were then extrapolated to the entire Willespie Formation of the Whicher Range field. This step is important to better characterize the spatial distribution of each electrofacies throughout the field and therefore to most accurately generate the 3D facies model. Electrofacies interpretation in this study is mainly based on the use of the gamma ray log motif, and for the coals, sonic log response (DT). An attempt to use density and neutron responses was performed but was discarded due to the poor quality of these logs caused by poor hole conditions.

1. Channels/Point Bar facies association (CH1 FA)

This facies association is mainly composed of sandstone facies SC, SM and SL.

Description

This consist of sharp based, blocky to fining upward sandstone units, which from base to top, comprise coarse to conglomeratic, poorly sorted sandstones which progressively grade upwards from massive to laminated medium grained sandstone.

The Channel 1 (CH1) facies association comprises mostly massive sandstone grading to cross-bedded and parallel laminated toward the top. The GR signature is blocky to bell shaped and commonly displays a gradual fining upward trend from low to medium GR (40 to 70 API) from base to top.

This facies may be isolated or stacked, forming multi-storey channel complexes. The average thickness of this facies association is about 9 m (with a minimum of 3 m and maximum of about 24m).

When observed in image logs, CH1 FA are represented from base to top by a sharp conductivity contrast (possibly related to coarse erosive bases) followed by planar lamination and/or thick massive sandstone grading upward to a parallel cross stratification and parallel laminated sandstones, as represented in Figure 5.

The grains are dominantly quartz with subdominant components of plagioclase and orthoclase feldspars, garnet and micas. This facies association is reported to include diagenetic quartz overgrowths and calcareous cement (Lindsey, 1982).

Interpretation

The fining upward successions defining the CH1 FA are interpreted as point bar channel deposits.

The blocky to mostly bell shaped pattern identified on the GR log generally implies a progressive reduction in energy level in the clastic systems and a continuous sediment supply and/or sedimentation rate. Additionally, the blocky serrated log motif indicates intermittent changes in energy level.

Poorly sorted coarse to conglomeratic lag deposits and rip-up clasts at the bottom of these sand bodies suggest a depositional setting controlled by a high-energy environment, possibly associated with flooding periods.

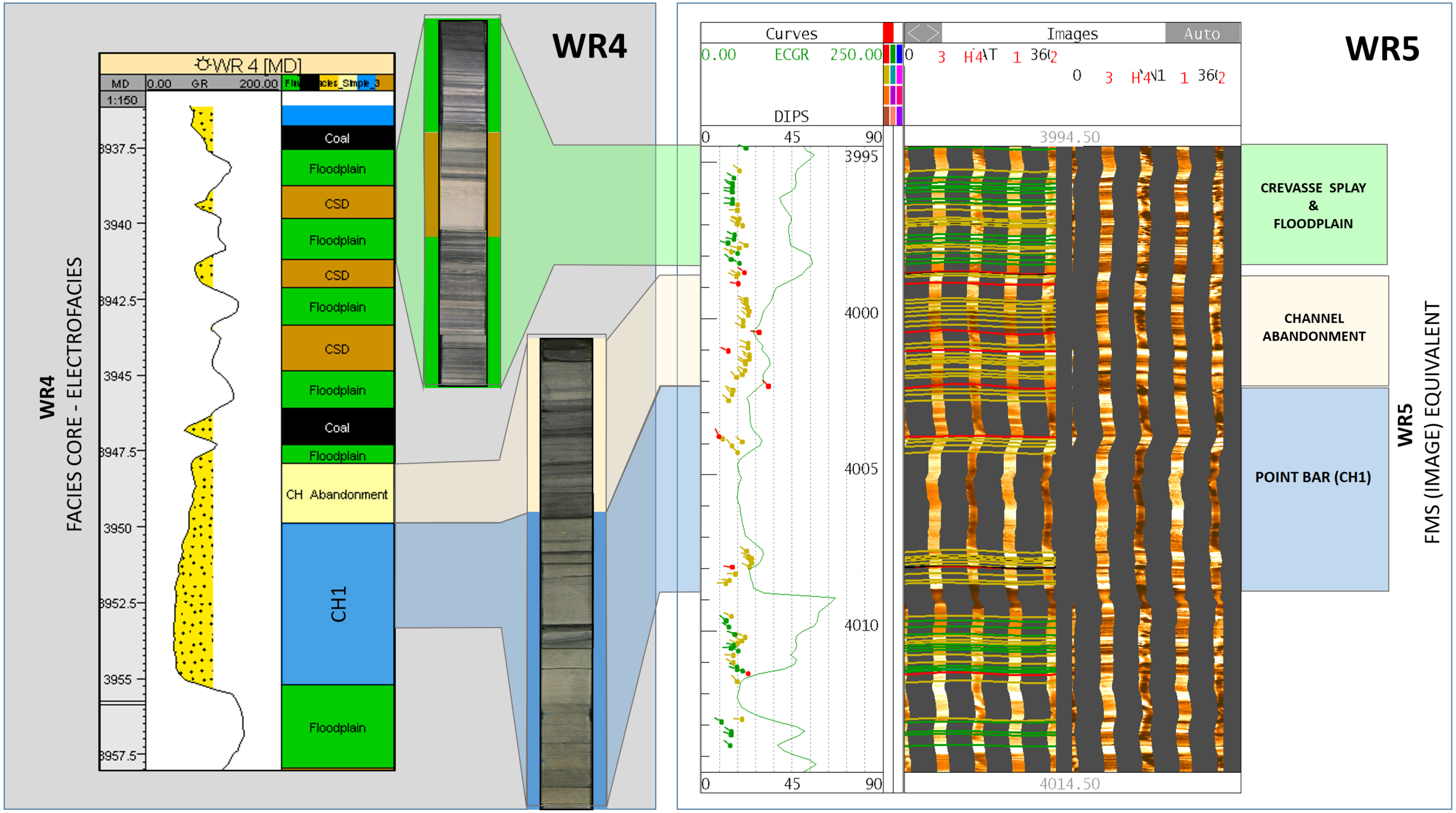


Figure 5. Log motifs (Electrofacies) of Facies Associations defined for Willespie Formation in Whicher Range Field and their equivalent image log response seen in the FMS acquired in Whicher Range 5 well

Sharp channel bases when followed by massive sandstone, represent erosive surface generated by rapid high-energy sediment transport and deposition. Cross-bedded facies overlying massive facies (with homogeneous grain size), identified from core and image logs (WR5) are most likely to represent a lateral migration of the channel or migration of dunes within the channel.

The upward decrease in grain size from medium to fine grain and the variation in key sedimentary structures from graded bedding to planar laminations towards the unit top may be interpreted as a drop in the energy conditions in the system.

To sum up, channel electrofacies are identified in the five wells drilled on the Whicher Range field into the Willespie Formation and are interpreted as channel fills produced by channelized bed load traction deposits occurring within a fluvial system.

A facies association log displaying the distribution of channels facies CH1 is shown in Figure 6.

2.Channel Abandonment facies association (FA CHAB)

Description

This facies association is represented mainly by laminated sandstone facies and some heterolithic facies (SL, HL) but organic material is also common. This facies typically displays fine-grained lithofacies and is mainly recognized by its characteristic fining-upward trend, displayed in both core and in gamma ray log (Figure 5 and Enclosure 1). From image logs, some sheet-like sands and convolute structures are also recognized in this facies. The CHAB facies association is represented by medium gamma ray values from 60 to 90 API, as displayed in Figure 5. The average thickness is circa 2.5m.

Interpretation

Fine-grained texture in channel abandonments is a consequence of the total or partial isolation of an old stream from the main channel flow after the neck/chute cut-off. The fining upward trend characterizing this facies may be interpreted as a slow or temporal discharge diversion from the main turbulent currents entering from the main channel flow.

Occasionally, coal, clay or other organic-rich material may cap this facies. This facies is vertically and laterally associated with CH1 facies associations at its base and crevasse splays/floodplain facies at its top.

For the purpose of this study, the crevasse splays are subdivided into two main categories based on their internal structure and most likely lateral distribution pattern: a) crevasse splay proximal (CH2/CSP) and b) crevasse splay distal (FA CS).

3.Crevasse Splay facies association (CH2/CSP FA)

Description

This facies association is represented by sandstone lithofacies SM and SL with some Heterolithic lithofacies, showing a sharp-based fining-upward log motif which, when observed on image logs (FMS), seems to present some faint cross lamination. It frequently overlies the crevasse splay (FA CS) facies but occasionally overlies floodplain facies, generally incised through the entire floodplain (FA FP). Occasionally, this facies may be capped by a soil and/or carbonaceous shale. The average thickness of this facies is 2.9 metres.

Interpretation

The CH2/CSP facies association is interpreted as crevasse channel deposits that are formed by the cut of a small channel into a previous generated crevasse splay. This crevasse channel can progressively feed areas further from the channel belt and create new channels.

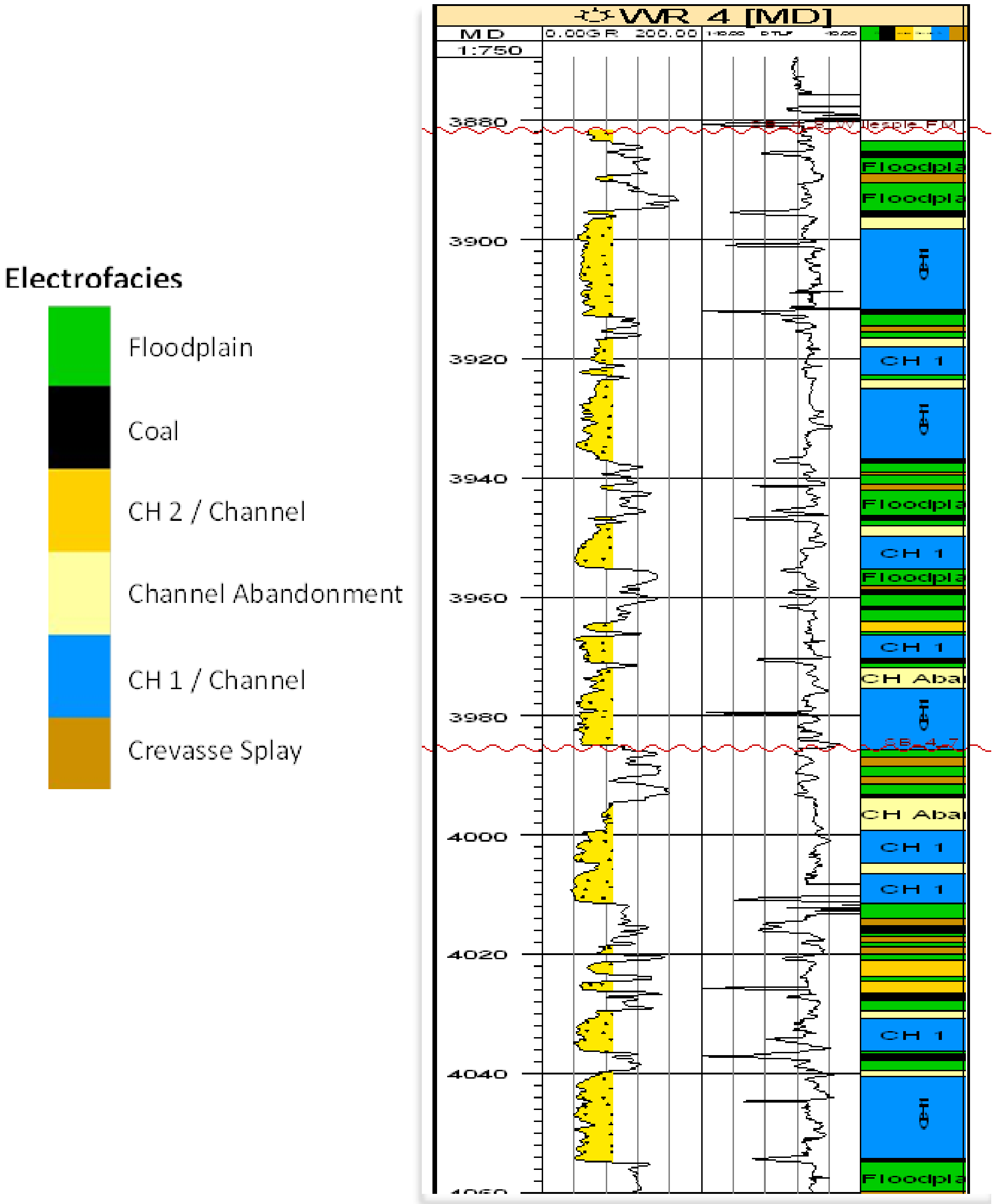


Figure 6. Electrofacies Interpretation base on the core facies identified in well # 4 over a section of the Willespie Formation, Whicher Range Field.

4.Crevasse Splay facies association (FA CS)

Description

This facies association is represented by sandstone lithofacies SM or SL and the Heterolithic lithofacies HL. Overall, this facies association is characterized by interbedded very fine-grained sandstone and siltstone, parallel laminated and thin ripple-laminated sandstones. The CS FA is occasionally rooted throughout. It is represented in well logs with generally coarsening-upward spiky log motifs. The average thickness recorded for this facies is 1.4 metres.

Interpretation

Individual crevasse splays are deposited from abrupt inundation of and deposition of sediment onto a floodplain. The upward coarsening pattern, and in some cases spiky log motif, of a single unit is characteristic of the moderate flow during deposition and suggests progressive and/or episodic periods of higher-energy deposition within a general low energy environment.

A succession of individual crevasse splays may show upward thickening within the overall package, indicating progradation of the splay system onto the floodplain. Distal crevasse splay deposits are often represented as thin bands of sandstone inter-fingered with proximal floodplain fines and display heterolithics, laminations, and soft sediment deformation (Enclosure 1 and Figure 7).

Splays are common features related to many rivers. The primary cause of the start and development of new channels is crevassing and crevasse splay evolution. Smith et al. (1989) suggest that depending on the characteristic morphology of the sand bodies there are three related stages of crevasse splays as shown in Figure 8.

5.Floodplain facies association (FA FP)

Description

This facies is characterized by interbedded mudstone and siltstone and very fine and thin sandstone laminations represented by lithofacies (M).

Floodplain/overbank deposits are generally sheet-like units with planar stratification. They are erosionally overlain by channel deposits and are occasionally interbedded with crevasse splay facies. The main sedimentary structures present in this facies are thin planar bedding, load casts and soft sediment deformation structures.

Floodplain electrofacies are characterized by high GR values of 100 to 150 API for the mudstone and siltstone facies but also medium GR values (70 API) for fine-grained sandstones. Commonly, the log signature is serrated with a slightly fining upward trend. The thickness of floodplain deposits in the Willespie Formation within the Whicher Range area ranges from a few centimetres up to 10 m.

Interpretation

This facies is interpreted to be deposited in areas distal and proximal to channels and includes levees built as ridges on either side of a major channel during rising flow. Floodplain sediments are carried from the main and tributary channels via smaller channels of crevasse splays, sheet flows, and the large-scale vortices at channel margins.

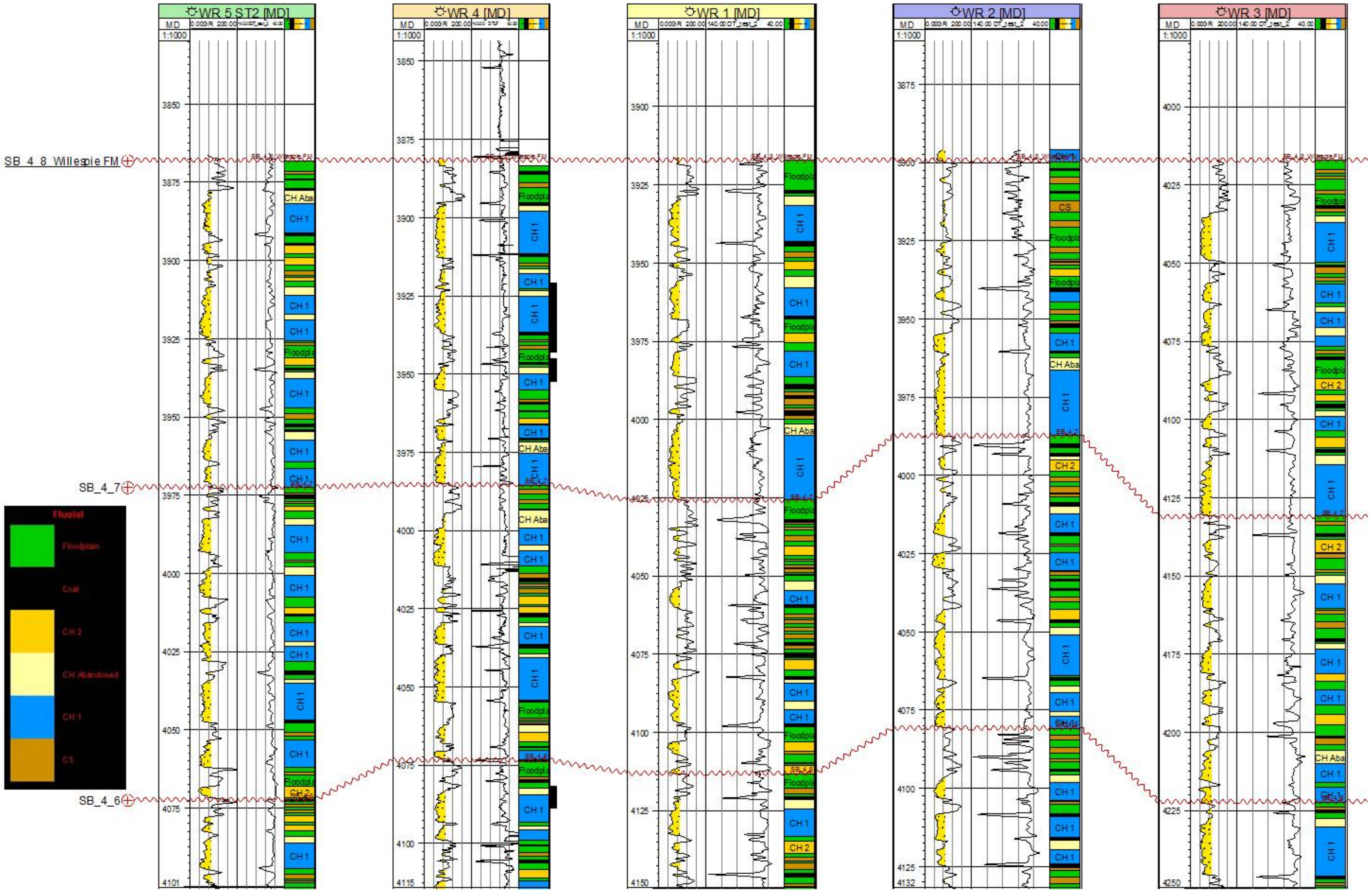


Figure 7. Cross section showing electrofacies interpretation in the Willespie Formation.

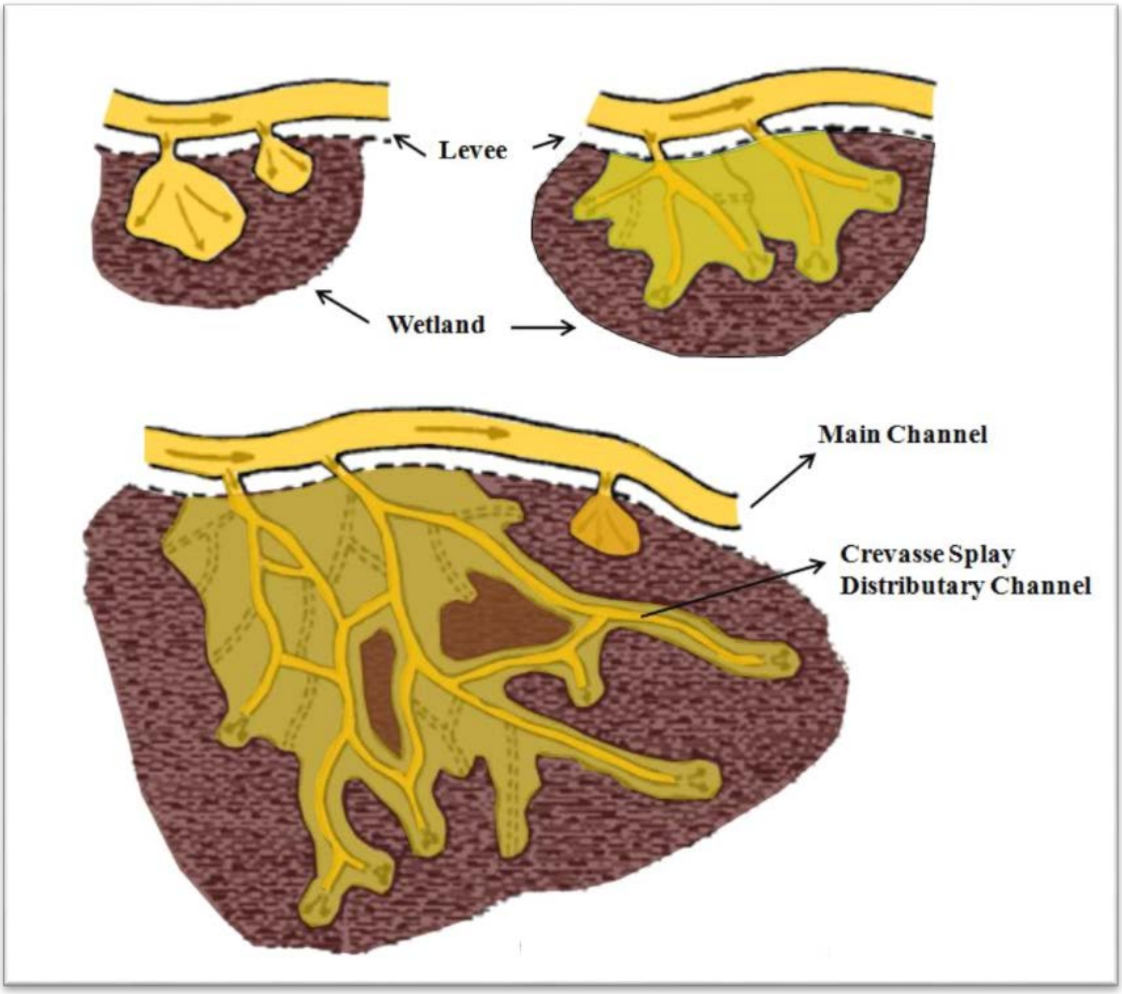


Figure 8. Stages of Crevasse Splay (After Smith et al., 1989)

When displaying fining upward trends, floodplains are most likely to have growth during settling of fine-grained sediments in very low energy environments, indicating temporarily decelerating flows, whereas, when found within coarsening upwards facies, may reflect deposition during periods of energy fluctuation.

Grain sizes and internal structures within floodplain deposits depend on local flow conditions and sediment availability. Figure 5 and Enclosure 1 show example of this facies.

6.Coal and organic mudstone deposits facies association (FA C)

Description

This facies is represented by lithofacies C.

A key feature of the coal electrofacies is its high sonic transit time (DT) response, generally greater than 100 µs/ft, with a variable GR response depending on its silt and clay content, but mostly low gamma ray readings. This facies can be also recognized by its characteristic low density and high resistivity log response.

The coal seams in the Willespie Formation are commonly thin, ranging from a few centimetres to about 2 metres (0.8 m on average) and therefore are represented by a spiky log signature. They appear to be transitional with many of the coals capping the fine-grained siltstone and carbonaceous mudstone fining-up sequences.

Interpretation

Fine grained carbonaceous mudstones rich in coal seams are interpreted as vegetated areas. The coals are well defined stratigraphic surfaces used for local well log correlation, as will be discussed later in more detail.

Electrofacies and facies associations distribution

The generation of a log facies for the entire studied section is a prerequisite for undertaking high-resolution stratigraphic analysis and for the prediction of reservoir architecture. An example of this electrofacies interpretation is displayed in Figure 7.

Depositional patterns within this fluvial depositional system formed a complex arrangement of sand/shale facies. Sandy and Heterolithic lithofacies, mainly represented by FA CH1 (36%), CH2 (8%), CHAB (9%) and CS (11%), comprise 64 percent of the total thickness drilled by the five WR wells (as shown in Figure 9a). However, only 53 percent of them corresponding to CH1, CHAB and CH2/CS CH facies associations are most likely to represent the reservoir within the Whicher Range field. The remaining facies, comprising mudstones and coals, mainly represented by FP (32%) and Coal (4%), are most likely to correspond to intra-formational seals and the source rock of this reservoir.

Based on the comparison of the facies proportions from the five drilled wells (Figure 9b-f). There is an apparent difference in percentage of the main reservoir facies CH1 between Whicher Range 3 and Whicher Range 5 vs. the other three wells (Whicher Range 1, Whicher Range 2 and Whicher Range 4). At the same time, these two similar wells (Whicher Range 3 and Whicher Range 5) also display a slightly lower percentage of non-reservoir (intra-formational seal) facies.

The sand/ shale ratio over the entire drilled section of the Willespie Formation in each of the five WR wells was calculated from the grouping of facies, and gave values ranging from circa one in Whicher Range 1, Whicher Range 2, Whicher Range 4 to ~1.5 in Whicher Range 3 and Whicher Range 5 wells, as displayed in Figure 10 .

However, observation of sand/shale distribution from electrofacies and gamma ray logs shows an increase in sand content upward, which is most likely to be related to lateral/vertical facies variations caused by sediment distribution within the basin.

An estimation of facies defined over the five Whicher Range wells displays the dominant proportion of the CH1 facies within the sections penetrated by the wells in the Whicher Range Field, as shown in Figure 9a.

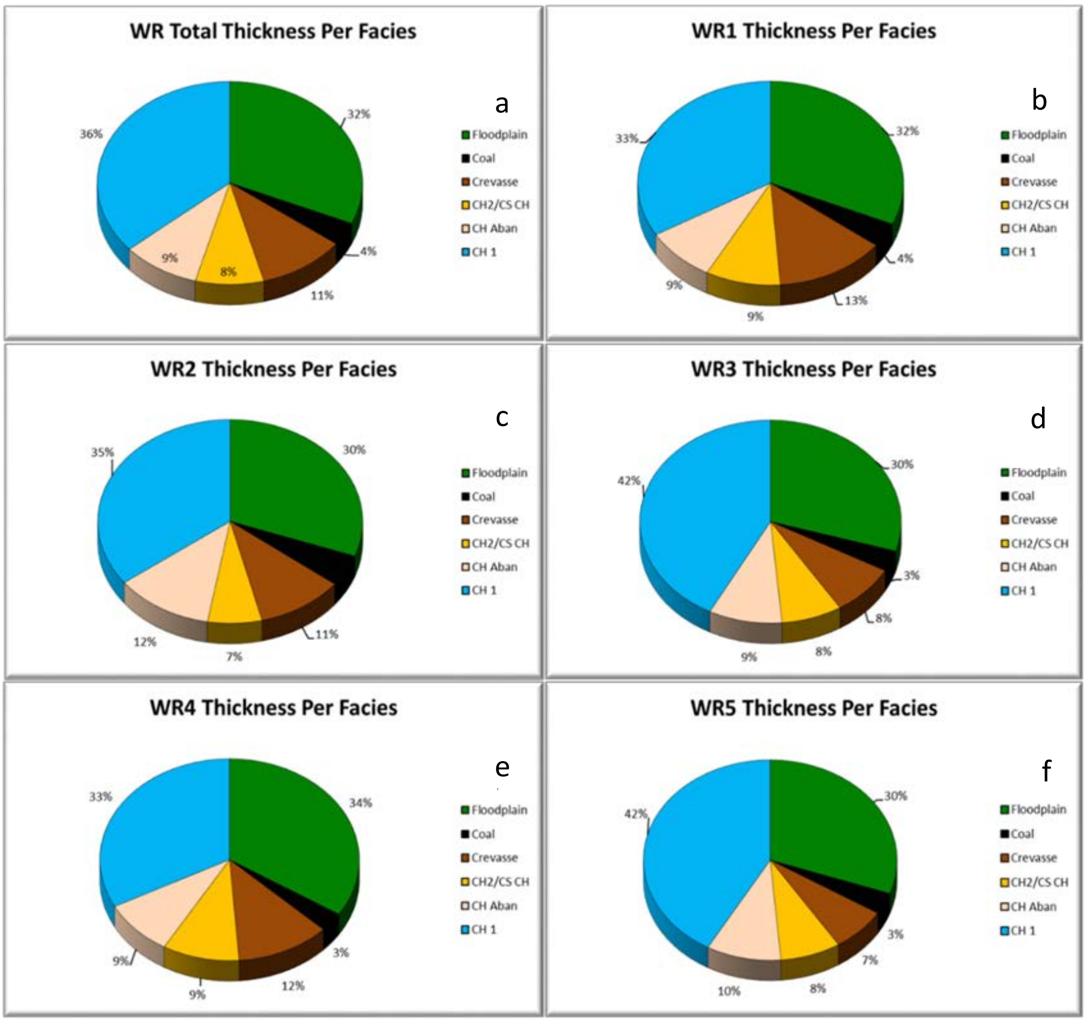


Figure 9. Pie Charts showing the facies associations thicknesses in general and each one of the Whicher Range wells.

However, it is important to note that the statistics displayed in the pie charts correspond to the facies estimates performed along the Willespie Formation interval drilled by each well. As shown above, the five drilled Whicher Range wells crossed different thicknesses and stratigraphic intervals and therefore care should be taken when applying these statistics to perform comparisons of shale/sand ratios and possible changes in facies related to variation in facies proportions. A better approach is to performed statistical analysis between chrono-stratigraphic intervals, as shown later in this document.

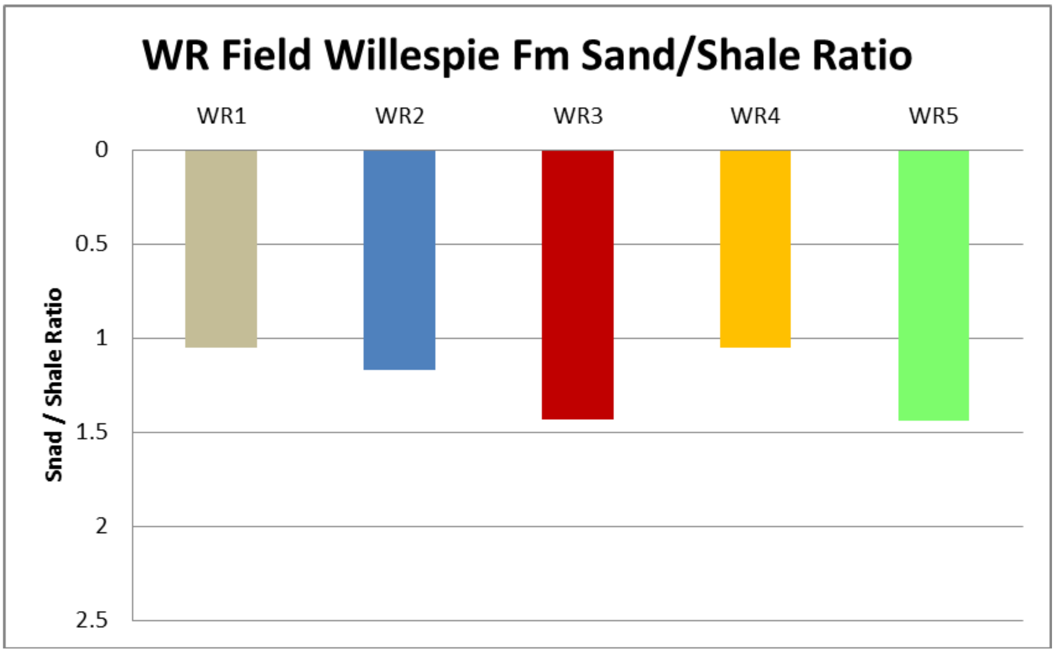


Figure 10. Sand/ Shale ratio by well in Whicher Range field

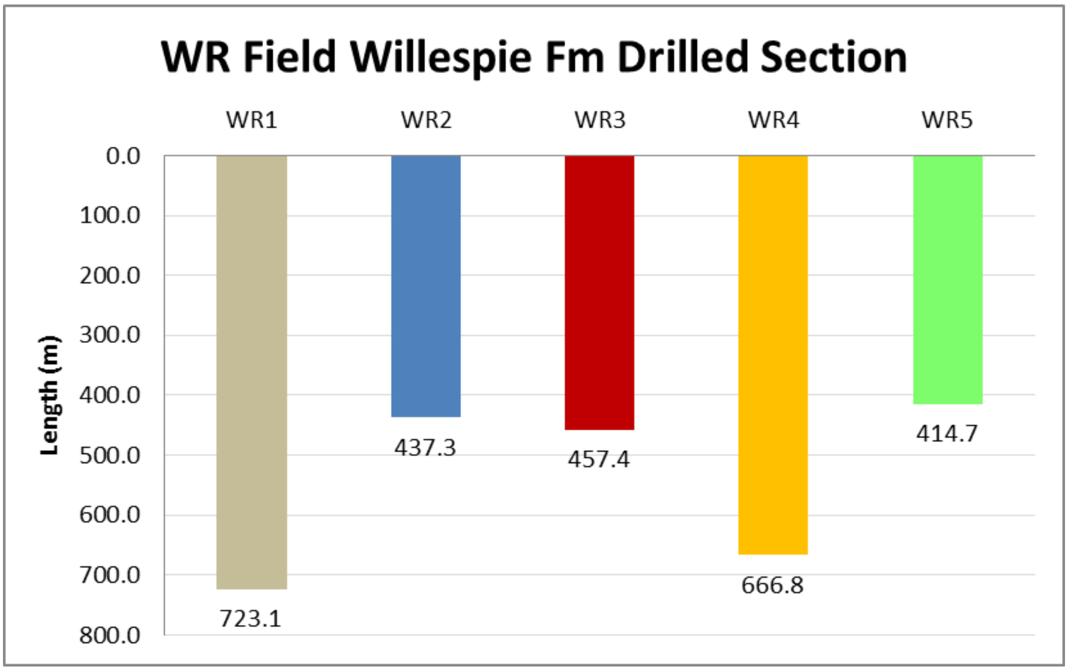


Figure 11. Length of the drilled section of the Willespie Formation for each of the Whicher Range vertical wells.

Reservoir Quality

Reservoir quality was interpreted based on previous thin section analysis performed for Whicher Range wells. Available data from 5 wells, including wireline logs, core data, well reports and petrographic data, were studied to define the syn-depositional and post-depositional events affecting the rock quality.

Factors controlling Reservoir Quality

Depositional Environment and facies in Willespie Formation

Changes in and within depositional environments have been proved to be a control in reservoir properties (Weber, 1980). This occurs because rock geometries and sediment characteristics are linked to environmental variations which describe a particular depositional setting. The influence of depositional conditions in rock quality may be recognized by classifying the reservoir unit in terms of depositional facies. A fluvial environment with no marine influence was defined for the Permian Willespie Formation, by integrating core, palynological and well log data. Depositional facies interpreted from core and wire-line logs were compared to porosity and permeability from core data to determine the relation between rock quality and the depositional environment. From this analysis, it was interpreted that, despite local exceptions, low reservoir quality is mostly related to floodplain, crevasse splay and channel abandonment whereas better qualities are associated with CH1 (point bars) and crevasse channel facies (Figure 12). Minor exceptions may be related to shifts in facies boundaries. Overall, the lower reservoir quality, intervals seem to be related to the more argillaceous facies and thus reservoir quality seems to be controlled by depositional environment conditions.

Rock composition and sediment characteristics

Rock classification of the Willespie formation in the Whicher Range area is based on thin section analysis (Poynton & Hollams, 1980). Using Folk's (1974) classification, rocks in Whicher Range 1 and Whicher Range 2 are classified mostly as lithic arkoses and arkoses with rare feldspathic litharenites (Figure 13). The components of these sandstones are dominant quartz, abundant feldspar, and minor rock fragments.

The rock fragments are polycrystalline quartz and metamorphic and igneous rock fragments. In some samples, lesser amounts of garnets and micas such as biotite and muscovite are present. Also, detrital and authigenic clays such as kaolinite, illite/smectite chlorite and minor amounts of illite are present together with calcite cement and quartz in less amounts. Some quartz and feldspar overgrowth are found as well (Figure 13).

Some feldspar grains are dissolved and others were partially or totally altered to kaolinite clay booklets. Still others are shattered and often occur along a microlineament, a behavior also exhibited by rock fragments. Whicher Range 2, displays local variation in feldspar amount. The upper core intervals display fewer feldspathic components and contain more authigenic clays than the lower cored sections. However, there is no evidence of reservoir quality variation between these intervals suggesting that gross rock composition does not have a distinct effect on reservoir quality. Variations in lithology (particularly in the clays) are probably very important in interpreting the diagenetic history of these sandstones.

According to Poynton & Hollams (1980) and Irwin (1998), Whicher Range sandstones are fine grained to coarse grained, poorly to moderate sorted sandstones and the grains are angular to subrounded with mostly long grain-to-grain contacts indicating moderate to heavy compaction. These authors also mentioned that the entire interval appears to be highly stressed and the sandstone flow units are approaching a "ductile state".

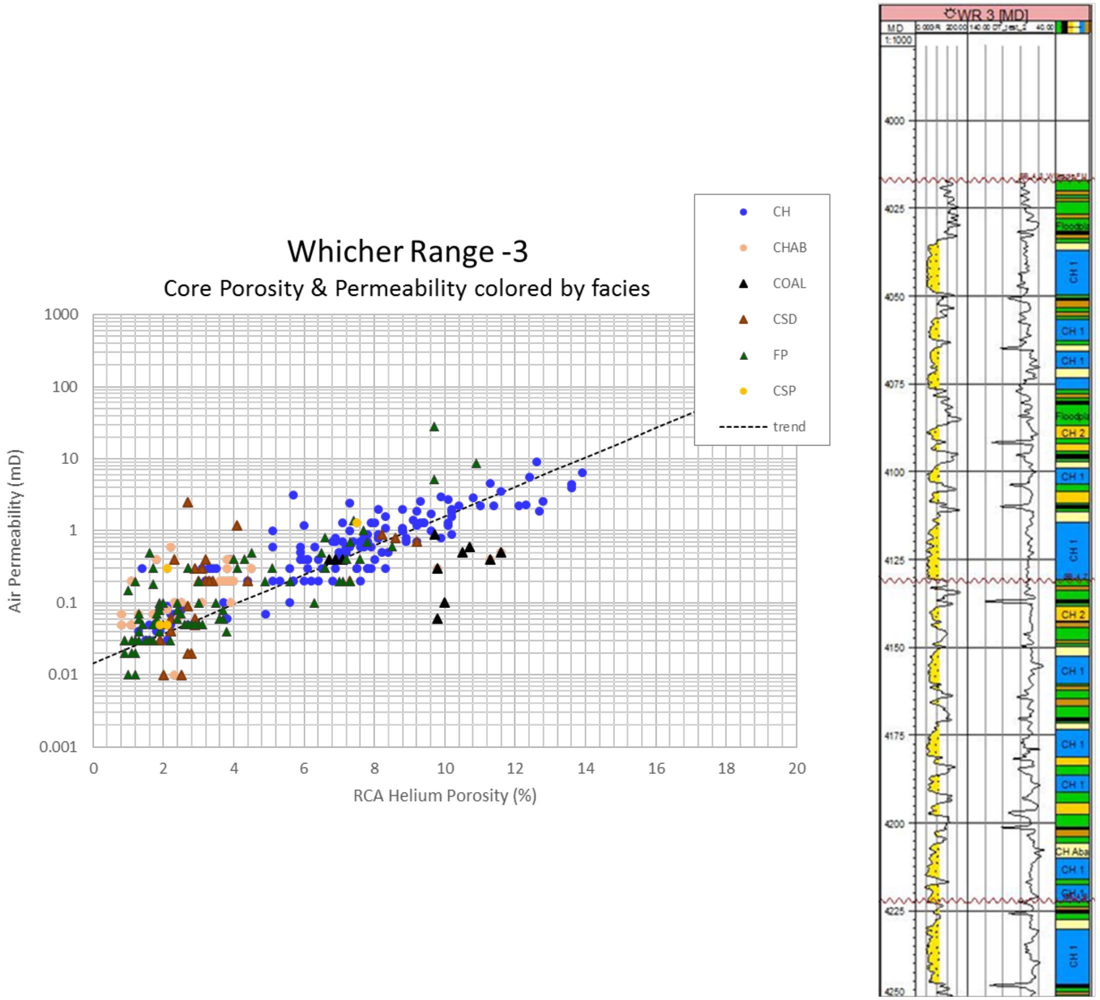


Figure 12. Rock quality vs electrofacies In Whicher Range field

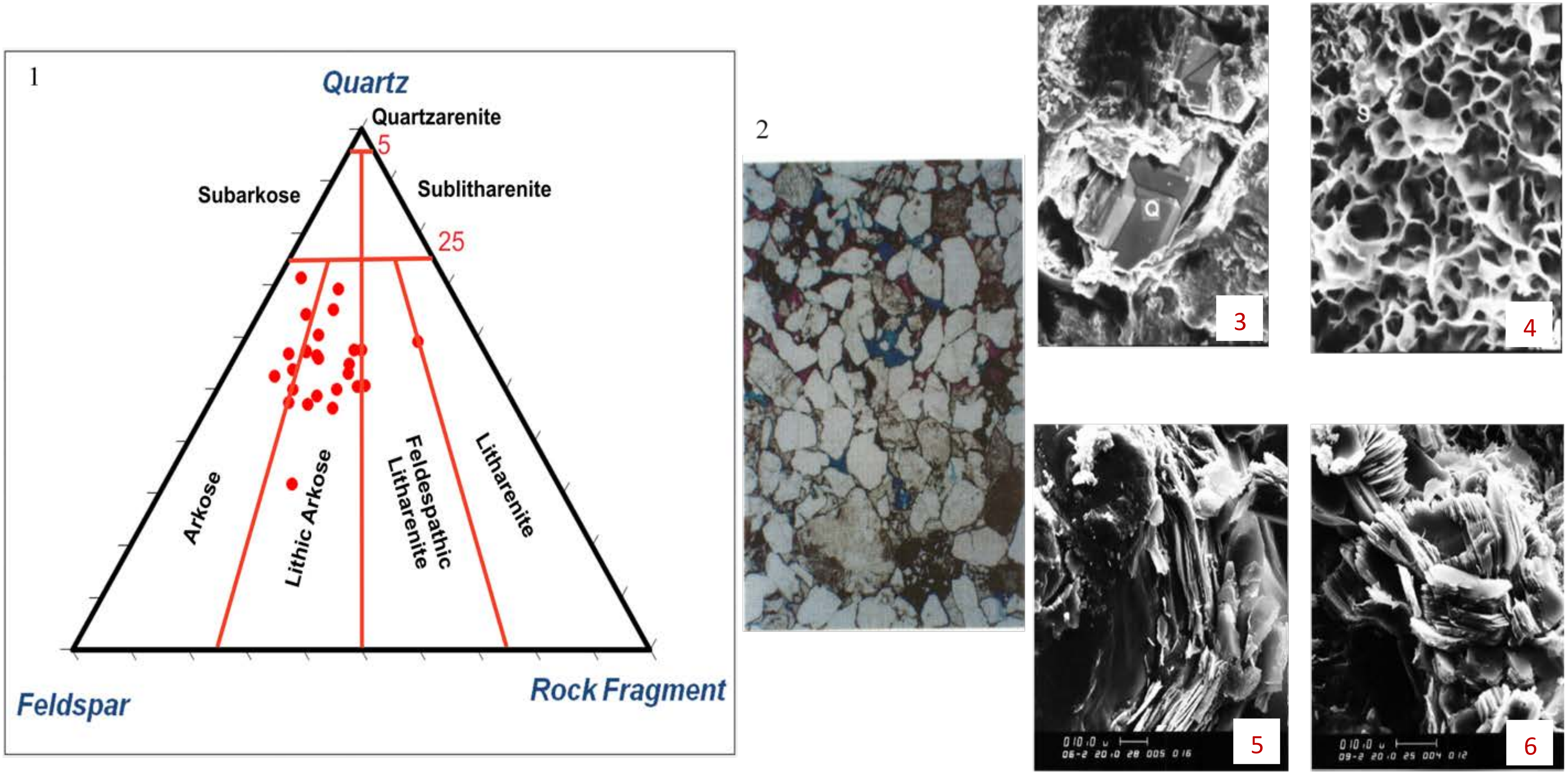


Figure 13. 1) Rock Classification using Folk (1974) for WR1&2 well; 2) Thin section showing Lithic Arkose from Whicher Range; and SEM photos showing 3) Quartz overgrowths, 4) Smectite pore lining, 5) detrital mica curved around framework grain 6) Kaolinite and illite infilling pore space. (from Lynsley, P., 1982 ; Poyton, D.J, 1982 and Fanning et al 1982)

Cross-plots of grain size versus rock quality for Sue Coal Measure sandstones show a good interrelation between grain size and permeability. Permeability displays better relation above 0.1mD (Figure 14). However, the amount of data available is not enough to give a definitive conclusion about this relationship. Based on comparison between grain size, facies and cement data from Whicher Range 2 it can be observed that grain size varies in agreement with facies.

Calcite cements are more likely to be associated with larger grain sizes mostly found in channel deposits. Thin section data suggest that mica is possibly contributing to porosity reduction. It is evident that when the percentage of mica rises in the samples the values of porosity decrease. According to Pittman and Larese (1991) - "grain susceptible to ductile deformation typically contain large amounts of clays and/or micas…the ratio of the weight percent of clays and micas to that of brittle grains is a good indicator of ductility". Some of the crevasse splay facies are highly ductile, it is assumed by the presence of abundant mica and structural clay as is shown in the SEM and thin section data from Whicher Range 2 and 3 (Linsley, 1982 and Fanning et al. 1982).

Clay effects in reservoir quality

According to clay analysis from well Whicher Range 1 and Whicher Range 2 structural and dispersed clay are similarly abundant. Structural clays together with other ductile grains contribute to porosity reduction by compaction whereas dispersed clay may clog pore throats and therefore diminish permeability. Core data analysis indicates diversity in clay content between the analyzed wells. Overall, smectite, chlorite and smectite/illite seem to be the dominant clays in Whicher Range 2 and Whicher Range 3 whereas kaolinite is more common in Whicher Range 1 and Whicher Range 4.

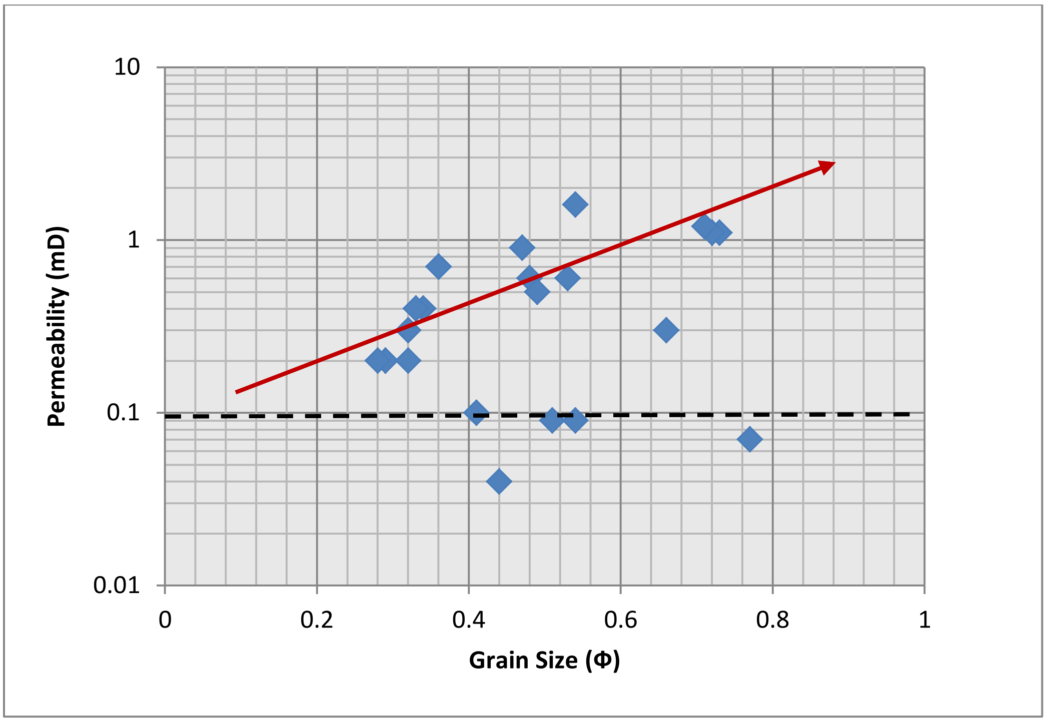


Figure 14. Grain size vs permeability showing a good relationship above 0.1mD.

Chlorites, smectites and smectite/illites present as grain coatings are found to have a strong effect in permeability reduction (Neasham,1977) due to the large surface-area to volume ratios and the intricate micropore-creating morphologies (Wilson, 1994) characteristic of these types of clays. Similar to tight gas sandstones in Mesaverde Group (Wilson, 1982), rock quality in Whicher Range sandstone units seems to be strongly controlled by type, morphology, abundance and distribution of clays.

Core analysis results together with SEM/XRD data show the strong effect of clay (content, morphology and distribution) in rock properties (porosity and permeability). A distinct example is represented in Figure 15. This shows how lower porosities seem to be related to illite content whereas higher porosities are linked to smectite and kaolinite clay content.

Authigenic clays such as chlorite, kaolinite and smectite are associated with the chemically unstable grain types (feldspar, siltstone and shale) present in arkoses and lithic arkoses. Although clay cementation seems to constitute the main control in reservoir quality, other controls also affect rock quality in minor proportions. These comprise deformation of ductile fragment, calcite and quartz cementation, compaction and grain rearrangement. The last two are more likely to be associated with early diagenetic stages.

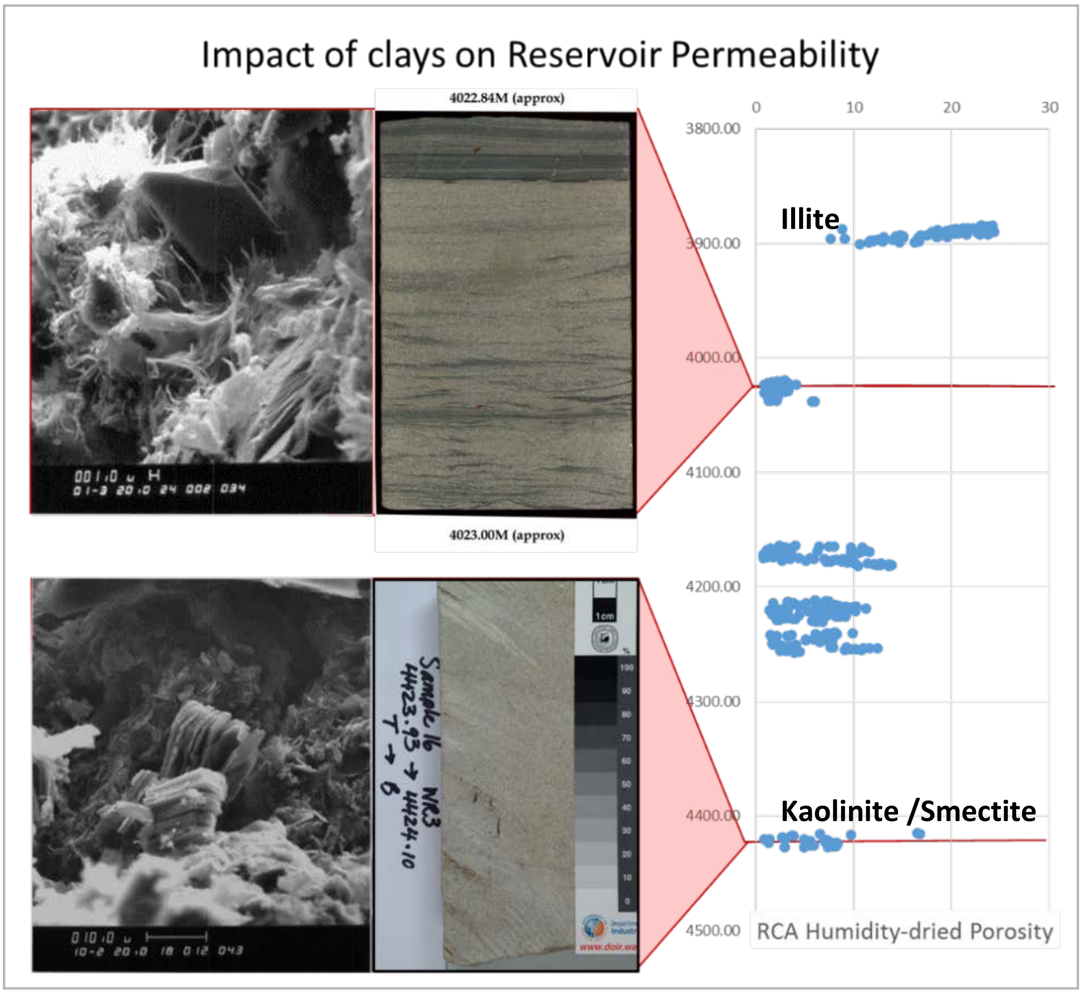


Figure 15. Effect of clay type in controlling rock properties. Higher porosities are found to be associated with kaolinite-smectite clays (e.g. at circa 4420m) whereas illite clays play an important role in reducing rock porosity (e.g. at circa 4020m).

Discussion

A robust geological reservoir model, to be of use in forecasting reservoir production in the Whicher Range field, needs to have an accurate definition of the reservoir architecture/ dimension, connectivity and capture heterogeneities in the reservoir bodies. The majority of these characteristics are tightly linked to depositional and post-depositional processes, which are controlled by both the tectonic setting of the basin and the sedimentary environment of deposition.

Most regional tectonic research studying Western Australia's evolution (Crostella, 2000; Song & Cawood, 2000; Baillie et al, 1994) points out, that Permian to early Triassic age sedimentation in the southern Perth basin has occurred within a continental environment, as evidenced in the geodynamic framework tectonic maps displayed in Figure 16.

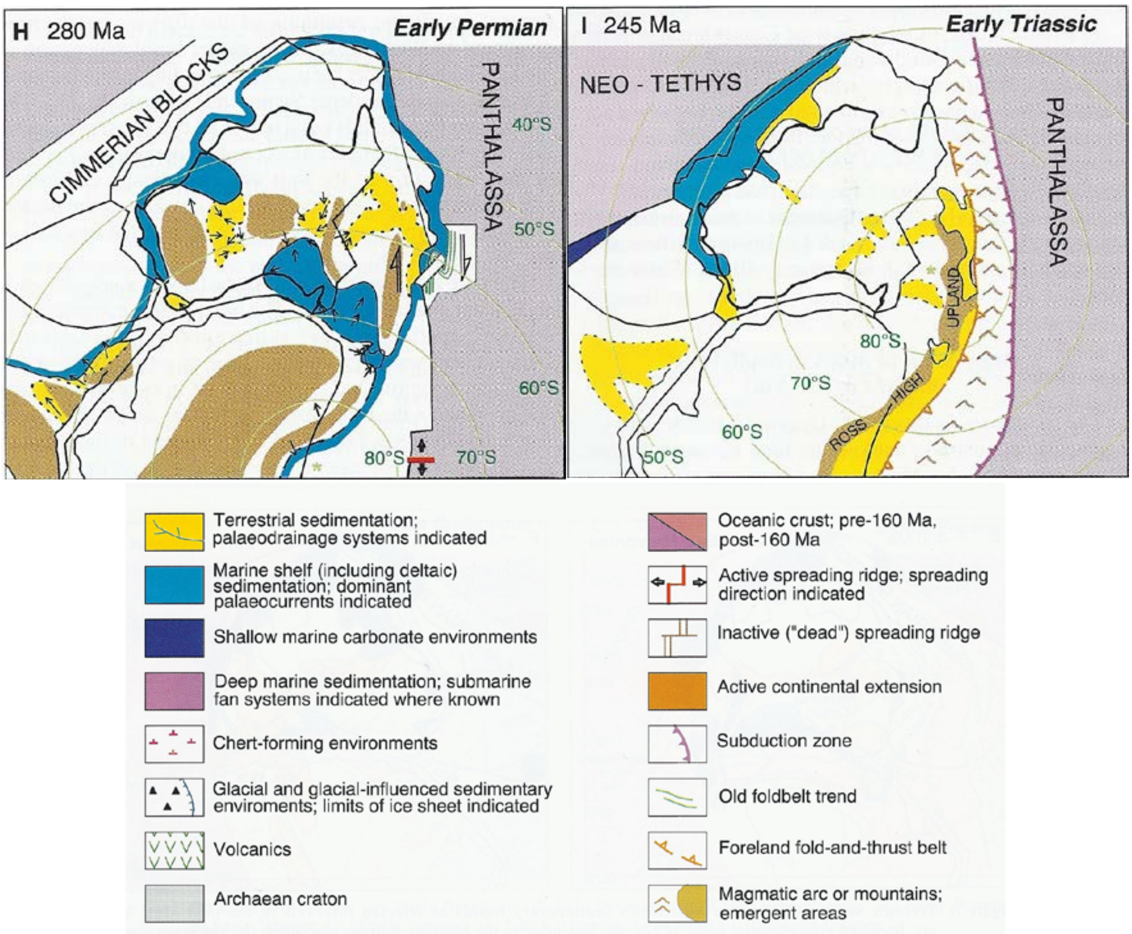


Figure 16. Tectonic framework of Western Australia sedimentary basins from Early Permian to Early Triassic (modified from Baillie *et al*, 1994)

Similar studies also suggest that deposition in the area may have been influenced by the active extensional tectonism occurring during the different stages of the rift development. This is inferred from the syn-sedimentary thickening of strata towards the Darling Fault observed from seismic data (Iasky, 1993).

According to Leeder & Gawthorpe (1987), within extensional structural settings the tectonically modified slopes resulting from uplifting and downtilting processes occurring in half-graben/tilt-block systems are most likely to influence the facies architecture during sedimentary deposition. In contrast, the "asymmetrical vectors" developed across the graben, would most likely be controlling the facies distribution.

Based on the previously described tectonic background, and the facies, electrofacies and facies associations study carried out in this project and presented within this chapter, the Whicher Range depositional environment is interpreted as an axial fluvial sinuous meandering system within a rift basin.

Available paleocurrents data indicates that this fluvial system is flowing northward along the Bunbury Trough with channels possibly migrating toward the Darling Fault, a major structural feature controlling the direction of the axis of maximum subsidence. An example of the structural setting and its relation with the depositional architecture for the Whicher Range area is shown in Figure 17 and Figure 18.

Key depositional features interpreted in the Willespie Formation sandstone suggest that sediment was deposited in an environment characterized by cycles of high to medium energy flow, possibly related to seasonal periods or tectonic activity. The textural characteristics of the bedding and the organic plant debris content in the mudstone interbeds, and the fossil content of the Willespie Formation support the aforementioned environmental interpretation.

The interpreted meandering systems deposited in the South Perth Basin, around the Whicher Range area, are characterized by stacked fining upward parasequences well-represented in both the electrofacies and the core facies defined in this study. The observed decreasing upward pattern in grain size distribution may be an indication of a progressive lateral shifting from sandy channel fill sediments (FA CH) to heterolithic channel abandonment and crevasse channels (FA CHAB and FA CH2/CS) and finally to more argillaceous floodplain deposits (FA CS, FA FL & FA C).

The successful calibration of electrofacies against core facies and facies associations performed along and between wells, allowed improved understanding of the magnitude and distribution of facies and enhanced prediction of the sedimentary environment of deposition in the Whicher Range field. However, a key step in the interpretation remains to translate the recognized facies into a 3D geological model that replicates the reservoir and therefore provides a better prediction of the reservoir properties distribution and connectivity. Knowledge of the ratio of channel fill to floodplain deposits within a given interval will be a key input parameter to be included within the 3D reservoir model. This parameter constitutes a good indicator of the degree of connectivity between individual channel-fill reservoirs.

According to the results from the sand / shale ratio calculation performed in all the wells drilled within Whicher Range field, Whicher Range 5 and Whicher Range 3 wells appear to have the highest sand content in comparison with Whicher Range 2, Whicher Range 1 and Whicher Range 4 which display lower proportions of sand. However, it is important to be aware that comparing sand / shale ratios calculated from non-equivalent chrono-stratigraphic intervals may end in misleading interpretations. For this reason, comparative sand/shale ratios performed by chrono-stratigraphic sequences will be presented later in this document.

Analysis of the sand/shale ratios estimated for all Whicher Range wells, along their entire drilled sections, indicates a progressive reduction in fine-grained facies (heterolithics and mudstones) upward which may be interpreted to be related to a rising on the dip slope caused by a tectonic movement in the hanging wall. According to Leeder and Gawthorpe (1987), this would lead to the progressive reduction of fine-grained floodplain deposits.

Medium to high sandstone to mudstone (sand/shale) ratio estimated in the five Whicher Range wells is a key diagnostic element in interpreting moderate sinuosity fluvial environments. The sedimentological evidence indicates that the area was crossed by sinuous fluvial channels that, according to the dipmeter interpretation from Whicher Range 3 to Whicher Range 5 wells, are oriented in a NW-SE direction.

In reference to the reservoir quality, the most important factors controlling the rock quality of the Whicher Range tight sandstones are clay type, distribution and morphology. The abundance of clay coatings and dispersed clays, which significantly reduces permeability, is linked to environmental factors.

Extensive compaction due to ductile grain deformation as well as clay and calcite cements are the main post-depositional factors affecting the reservoir quality of the medium to coarse-grained, poorly-sorted lithic-arkose sandstones of the Willespie Formation. Also, a combination of syn-depositional parameters, controlling composition and texture of the sandstone, and post-depositional diagenetic events have had a critical control on the distinctive low porosity and permeability of this tight gas sand reservoir.

Figure 17. Satellite Image displaying the rift basin of Lake Baikal, Russia, a modern structural and depositional analogue for the Whicher Range Field.

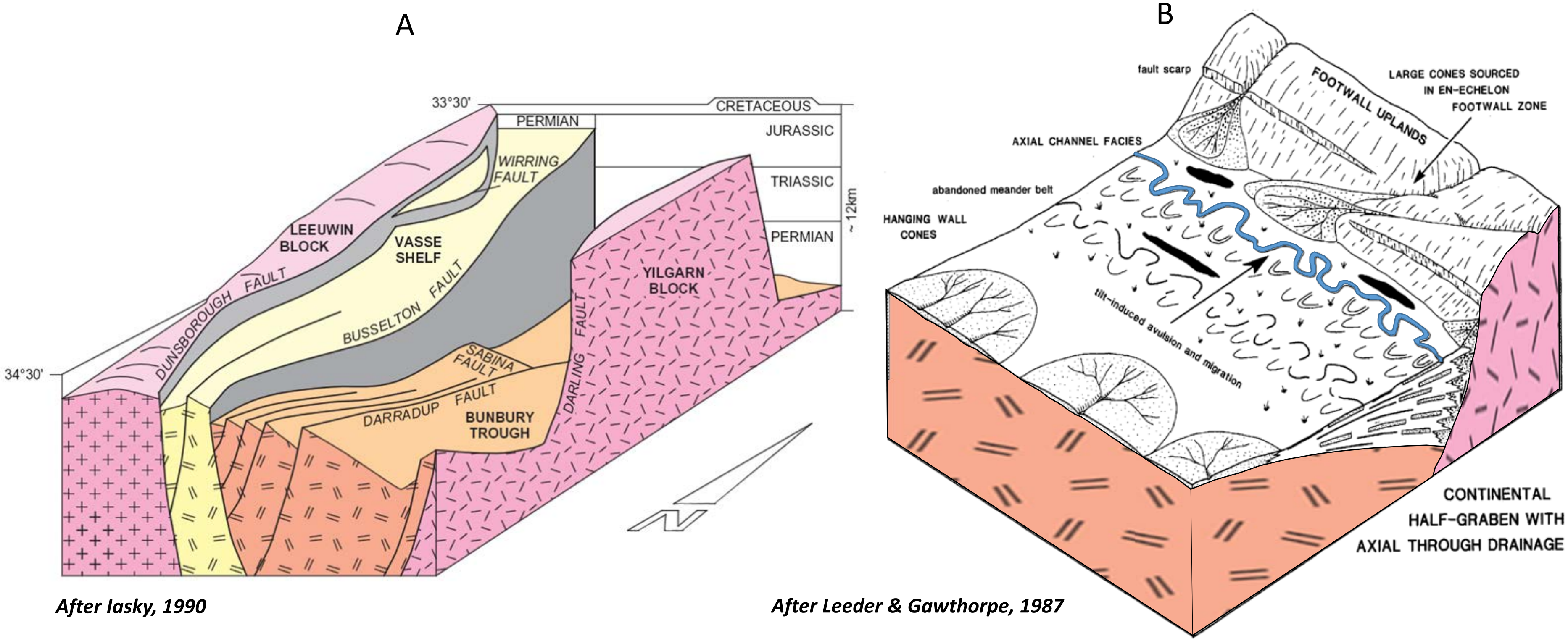


Figure 18. A) Block model of the Southern Perth Basin, showing the Bunbury Trough as the main subsidence axis of the Whicher Range Field (After Le Blanc & Christensen, 1998). B) Block diagram for a facies model of a continental basin with axial through drainage (After Leeder & Gawthorpe, 1987) .

Chapter 3 - PERMIAN SEQUENCE STRATIGRAPHY

Introduction

Sequence stratigraphy is defined as 'the analysis of cyclic sedimentation patterns that are present in stratigraphic successions, as they develop in response to variations in sediment supply and space available for sediment to accumulate' (Posamentier and Allen, 1999). The sequence stratigraphy concepts have been developed by many workers such as Posamentier and Vail (1988), Galloway (1989), Van Wagoner *et al*. (1990), Posamentier and Allen (1999) and Embry 2001a.

An understanding of sequence stratigraphy as applied to non-marine systems is important to this study because predictable facies association are developed within depositional sequences. A depositional sequence is a stratigraphic unit composed of a relatively conformable succession of genetically related strata, constrained at the top and base by unconformities or their correlative conformities (Shanley & McCabe, 1994).

For non-marine settings, such as in the case of the Sue Group, the factors controlling the architecture of fluvial systems are charge and nature of sediment supply and the alteration of accommodation space. The 'accommodation space' term defines the space available for sediments to be deposited. In alluvial to fluvial environments it is represented by the space between the ground surface and the tilting of the hypothetical surface known as the dynamic equilibrium fluvial profile (Posamentier and Allen, 1999). The dynamic equilibrium profile "is achieved where the river is able to transport the sediment load without aggradation or degradation of the channels" (Leopold and Bull, 1979), and in part, is a function of the elevation of the base level.

The alluvial gradient is primarily controlled by back-tilting of this profile generating accommodation space in the alluvial plain (positive alluvial accommodation), whereas front-tilting produces common incision and erosion (negative alluvial accommodation, Figure 19) (Posamentier and Allen, 1999). The accommodation is determined by tectonic uplift and subsidence, inclination of the fluvial equilibrium profile and climate (energy flux) .

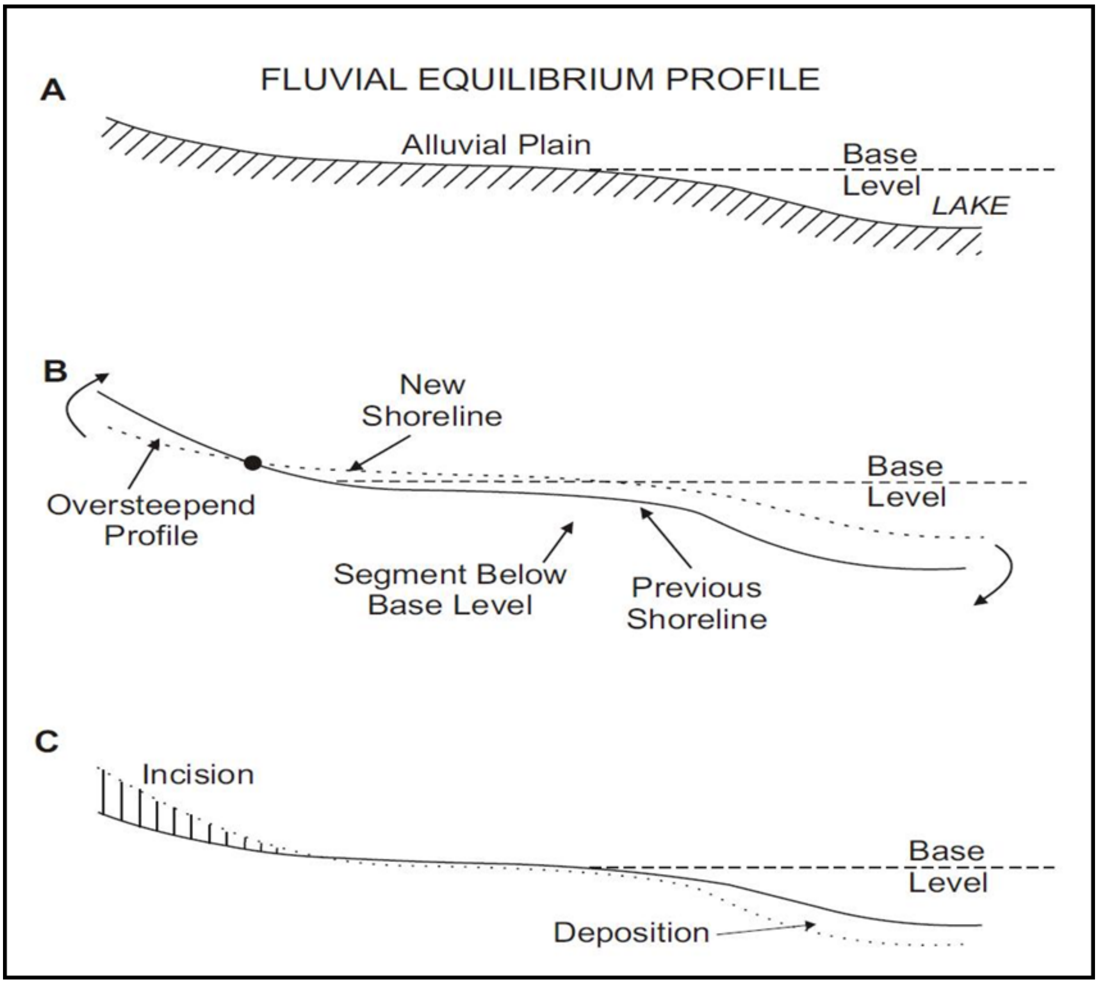


Figure 19. Fluvial Equilibrium Profile (after Posamentier and Allen, 1999).

The conventional sequence stratigraphic divisions of low-stand, transgressive and high-stand system tracts in fluvial settings with marine or non-marine influence have been used by many authors (i.e. Shanley and McCabe 1994; Posamentier and Allen, 1999).

Systems tracts are interpreted from stratal stacking patterns and are distinct stratigraphic units deposited during specific phases of relative base-level change.

The Highstand Systems Tract (HST) is characterized by a sedimentary succession deposited when the sediment supply is equal to or greater than the rate of accommodation creation. Consequently, depositional trends and stacking patterns are dominated by a combination of aggradation (early stage) and progradation (late stage), as mentioned by Catuneanu (2006).

The Transgressive Systems Tract (TST) is characterized by a sedimentary succession deposited when the rate of accommodation creation is more than the rate of sediment supply. This can be recognized by its typical retrogradational stacking patterns resulting in general fining upward profiles (Catuneanu, 2006).

The Lowstand Systems Tract (LST) is the sedimentary succession deposited during the early stage of base-level rise. As a consequence, depositional patterns are dominated by low rate aggradation and progradation across the entire sedimentary basin which are represented by a coarsening upward profile in non-marine strata (Catuneanu, 2006).

However, more recent studies have criticized the use of conventional sequence stratigraphy for fluvial settings with no marine influence. Blum (1990, 1994), Miall (1991) and more recently Catuneanu and Elango (2001) and Catuneanu (2006) studied fluvial systems under the influence of upstream controls independent of the base level (no marine influence). They pointed out that the use and classification of the previously mentioned systems tracts do not apply for no marine depositional settings. Instead, unconformity-bounded fluvial sequences may be subdivided into low- and high-accommodation systems tracts, based on the relative abundance of fluvial architectural elements.

Low Accommodation Systems Tracts (LAST) are conventionally formed on top of sub-aerial unconformities and indicate the restart of sediment accumulation within a no marine influenced continental depozone, in which the amount of available fluvial accommodation is restricted. Low accommodation states generate incisions and a progradational depositional style which is accompanied by aggradation, similar to that expected from a LST. The stratigraphic architecture is commonly represented by multi-storey channel fills and a general lack of floodplain deposits (Boyd *et al*., 1999; Catuneanu, 2006).

The High Accommodation Systems Tract (HAST) is attributed to high rates of creation of fluvial accommodation, which is represented by an aggradational depositional style. This is characterized by a low energy regime where fluvial stratigraphic architectures are deposited. Sediments are generally fine-grained with channel/ channel fill deposits isolated within floodplain facies. The depositional style is aggradational and fining upward, with less influence from the underlying topography or structure. It is similar in style to the Transgressive and Highstand Systems Tracts (Boyd *et al*.,1999; Catuneanu, 2006).

Although there exist particular differences between the standard and the recently developed system tracts terminology for non-marine environments, the concepts behind both of them share common points in respect of accommodation, rate of sediment supply and stacking patterns. However, the correlation between low-accommodation and low stand systems tracts, and also between high-accommodation and Transgressive to Highstand Systems Tracts is speculative.

The first step to construct a sequence stratigraphic framework, is to identify key surfaces (e.g. sequence boundaries, flooding surfaces and transgressive surfaces), depositional styles (aggradational, retrogradational and progradational) and stacking patterns.

A Sequence Boundary (SB) is a surface that originates as a consequence of an important downward shift of the fluvial equilibrium profile to a position below the current fluvial profile. This produces negative accommodation, to which alluvial systems respond by downcutting (Posamentier and Allen, 1999). Maximum Flooding Surface refers to the surface of deposition at the time the shoreline reaches a maximum landward position. Further upstream, the maximum flooding surface corresponds to the highest level of the water table relative to the land surface (Posamentier and Allen, 1999; Catuneanu., 2006). On the other hand, a Flooding Surface represents the boundary across which there is evidence of an abrupt increase in water depth (Miall, 1997). A Transgressive Surface indicates the beginning of an important and extended period of transgression (landward migration of the shoreline) within a succession.

The expected stacking patterns during different system tracts are illustrated in Figure 20. Low stand system tracts (LST) typically comprise amalgamated fluvial deposits, overlying a sequence boundary. They are topped by a surface of transgression and the overlying sediments represent low accommodation and are typically marked by coal or lacustrine sediments. The depositional style is aggradational and progradational across the entire sedimentary basin (Catuneanu, 2006).

The Transgressive Systems Tract (TST) is marked by an upward increase in lacustrine facies and channel isolation. Its depositional stack style is retrogradational and it is topped by the maximum flooding surface (MFS). The Highstand Systems Tract (HST) is marked by progradational stacking patterns associated with lacustrine delta infilling. Decreasing rate of accommodation could lead to the development of an aggradational style in the late HST which would be represented by an increment of amalgamated channel belt sandstones topped by the next sequence boundary.

Workflow of Sequence Stratigraphic Analysis

According to Posamentier and Allen (1999), the application of sequence stratigraphic principles can generate realistic, plausible, and predictive models for petroleum, or other natural resources exploration. The accuracy of sequence stratigraphic analysis in the construction of a geological model is always related to the quantity and quality of the available data.

The basic workflow used in sequence stratigraphic interpretation is divided into three stages: tectonic setting, depositional environment and sequence stratigraphic framework. This workflow does not pretend to establish an unbreakable rigid template to follow, but a guide that would need to be adjusted to each particular case (Catenuanu, 2006).

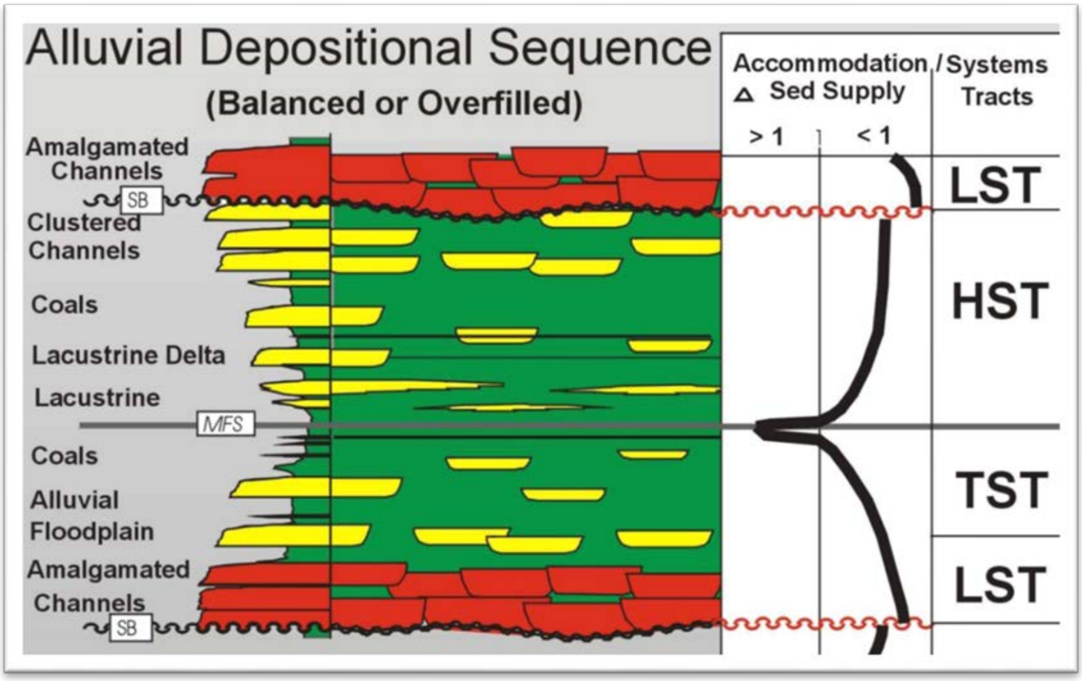


Figure 20. Stacking patterns during different system tracts (after Allen et al, 1996).

Phase I: Tectonic Setting

The knowledge of the type of basin in which the sedimentary succession which consist object of the study was deposited, is an elementary step in the construction of a sequence stratigraphic framework and geological model. Each tectonic setting, type of basin, and the position of the basin in different periods of time is unique in terms of subsidence patterns and represents controls on the depositional environment and the stratigraphic architecture of the bodies that fill the basin.

The interpretation of the tectonic setting must be based on regional data, including seismic lines, well-log correlation calibrated with core, and biostratigraphic information. For this study previous research by Marshall et al (1989), Mory and Iasky (1996), Song and Cawood (1999), Crostella and Backhouse (2000) and Iasky and Lockwood (2004) have been used to determine the regional tectonic setting in the South Perth Basin.

In addition, the knowledge of the tectonic setting may also help with the prediction of depositional systems that build the sedimentary succession, and their spatial relationships within the basin.

Phase II: Paleodepositional Environments

The definition of a chronostratigraphic context and the interpretation of paleodepositional environments are very important for the construction of a sequence stratigraphic framework (Strong et al, 2002). The success of paleoenvironmental interpretations depends on the integration of multiple data sets (i.e. seismic, well log data, core, depositional analogues) and their quality and quantity. The inclusion of 3D seismic horizon slices, when available, can be of major assistance in the interpretation of depositional environments. However, the lack of 3D seismic data is arguably overcome by integrating knowledge of the tectonic setting, and by applying a well-log motif scheme, and using the direct information supplied by core and depositional analogues.

The interpretation of depositional environments is a key part in the construction of sequence stratigraphic surfaces and systems tracts. Additionally, the recognition of lateral and vertical facies distribution and their relationships, permit the interpretation of the depositional trends and the geometry of the sand bodies.

However, Leeder and Gawthorpe (1987) pointed out that interpretation of paleo-depositional environments in extensional basins, such as Perth Basin, is more difficult to predict because they may cover most of the existing depositional setting; from continental (alluvial, fluvial to lacustrine) to shallow and deep water conditions.

Phase III: Sequence stratigraphic Framework

As with the depositional environment, the construction of a sequence stratigraphic framework depends on the availability and quality of the data and the integration of all direct and indirect geological information compiled so far. The integration of all data allows confident prediction of trends and patterns of facies, giving reliability to the sequence stratigraphic model and, as a result, a more confident geological model may be constructed and the most efficient exploration and production of Whicher Range Field may be achieved.

The construction of the sequence stratigraphic framework involves the definition of strata terminations, identification of the key stratigraphic surfaces and finally subdivision of the study interval into sequences and classification of systems tracts.

Sequence Stratigraphic analysis of the Permian sequence

In this study, stacking patterns of sand bodies (aggradational, retrogradational and progradational) and main depositional styles were defined in each well using core data and wireline logs. The use of Sue 1 well (located about 20 km south of the Whicher Range field) is important for this study because, it is the only well in the South Perth Basin penetrating the entire Permian sequence. Sue 1 provided an overview of the depositional processes occurring through the Permian section and therefore helped to constrain the sequence stratigraphic framework of the Willespie Formation in the Whicher Range area.

The chronostratigraphic framework of the Permian section is based on the palynological data available in Whicher Range 1 (Balme, 1966, 1968), Whicher Range 2 (Poyton, 1980), Whicher Range 3 (Ingram, 1982) and Sue 1 and studies developed by Backhouse (1991), Crostella and Backhouse (2000) and Eyles et al. (2002). These works were the basis for identification of palynostratigraphic markers and therefore the definition of some key stratigraphic boundaries. Based on this information, two major regional unconformities, representing depositional hiatuses, were identified within the South Perth Basin.

A total of four third-order depositional sequences were interpreted within the Permian, including the Moswood Formation and Sue Group, with a total thickness of 1839 m in Sue1 (Figure 21 and Figure 22).

Depositional Sequence 1 (DS1)

The first sequence boundary (defined here as SB1) is represented by a nonconformity that separates the Precambrian basement from the Early Permian glaciogene Mosswood Formation, which is recognized by biostratigraphic control to belong to *Pseudoreticulatispora confluens* zone. This non-conformable surface is interpreted in Sue 1 well at about 3055m depth.

The depositional sequence 1 (DS1) comprises the 356m thick section deposited between sequence boundary (SB1) and the sequence boundary 2 (SB2) and is represented by the following three systems tracts:

Low Stand Systems Tract 1 (LST1)

This consist on the succession deposited above SB1, about 2814.67m, up to the coal seam representing the transgressive surface 1 (TS1). LST1 displays an aggradational stacking pattern, which represents sedimentation within a low-accommodation setting. This tract contains the Mosswood Fm, Woodynook Sandstone and the base of the Rosabrook Coal Measures, and is characterized by an increase in sediment flux, development of amalgamated fluvial channels and poor preservation of floodplain deposits.

Transgressive SystemsTract 1 (TST1)

The overlying TST1 deposits are characterized by more accommodation space than in the LST1 and rapid base level rise that generated isolated channels, flood plains, splay complex facies and thin coal seams. At the top of transgressive sequence 1 (about 2782m), a MFS1 is defined by a distinctive shale interval (~5m thick) recognized from the GR log response.

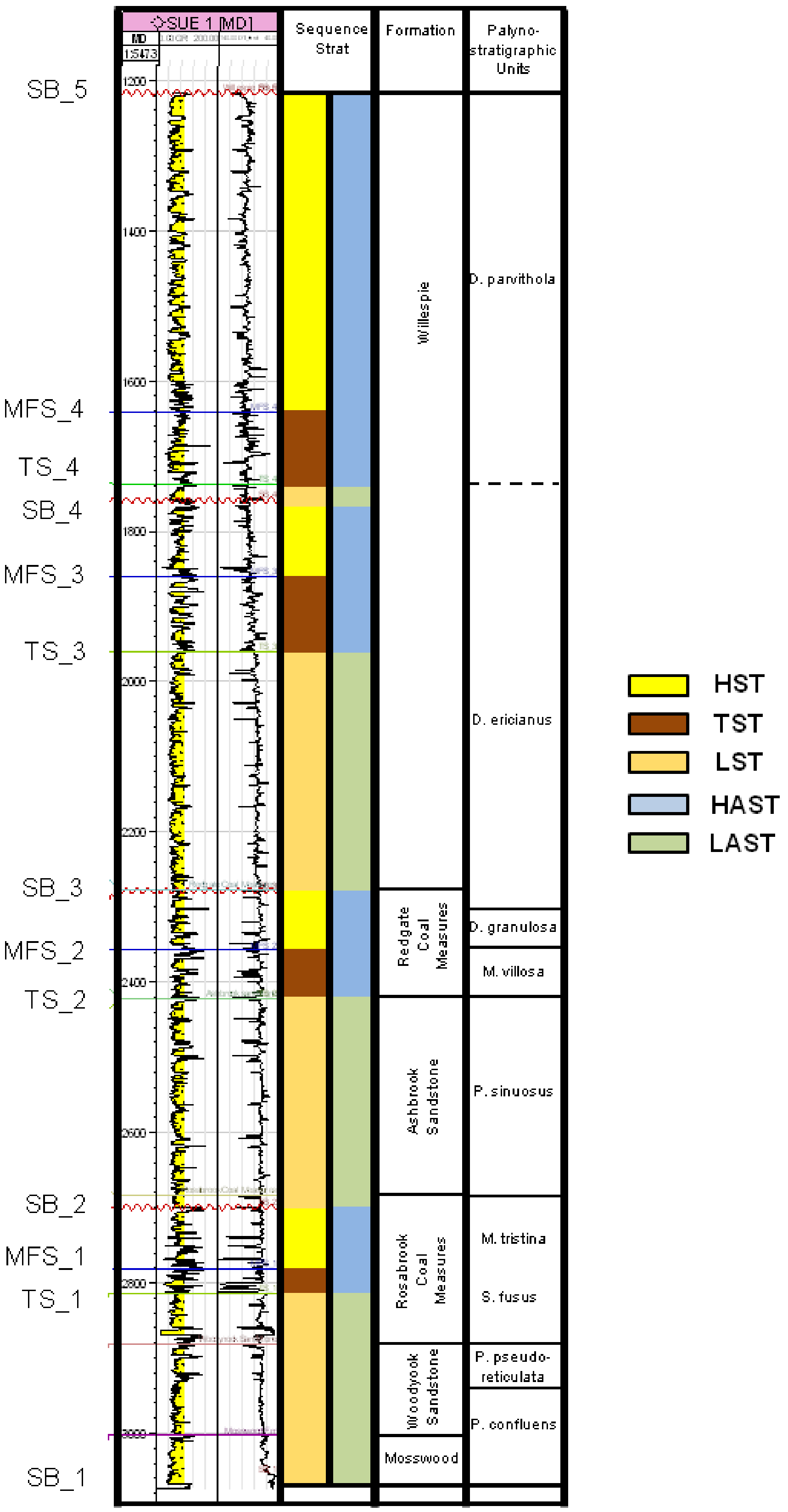


Figure 21. Permian section of South Perth Basin showing stratigraphic key surfaces, systems tracts, formation tops, and palynological zone of Sue 1.

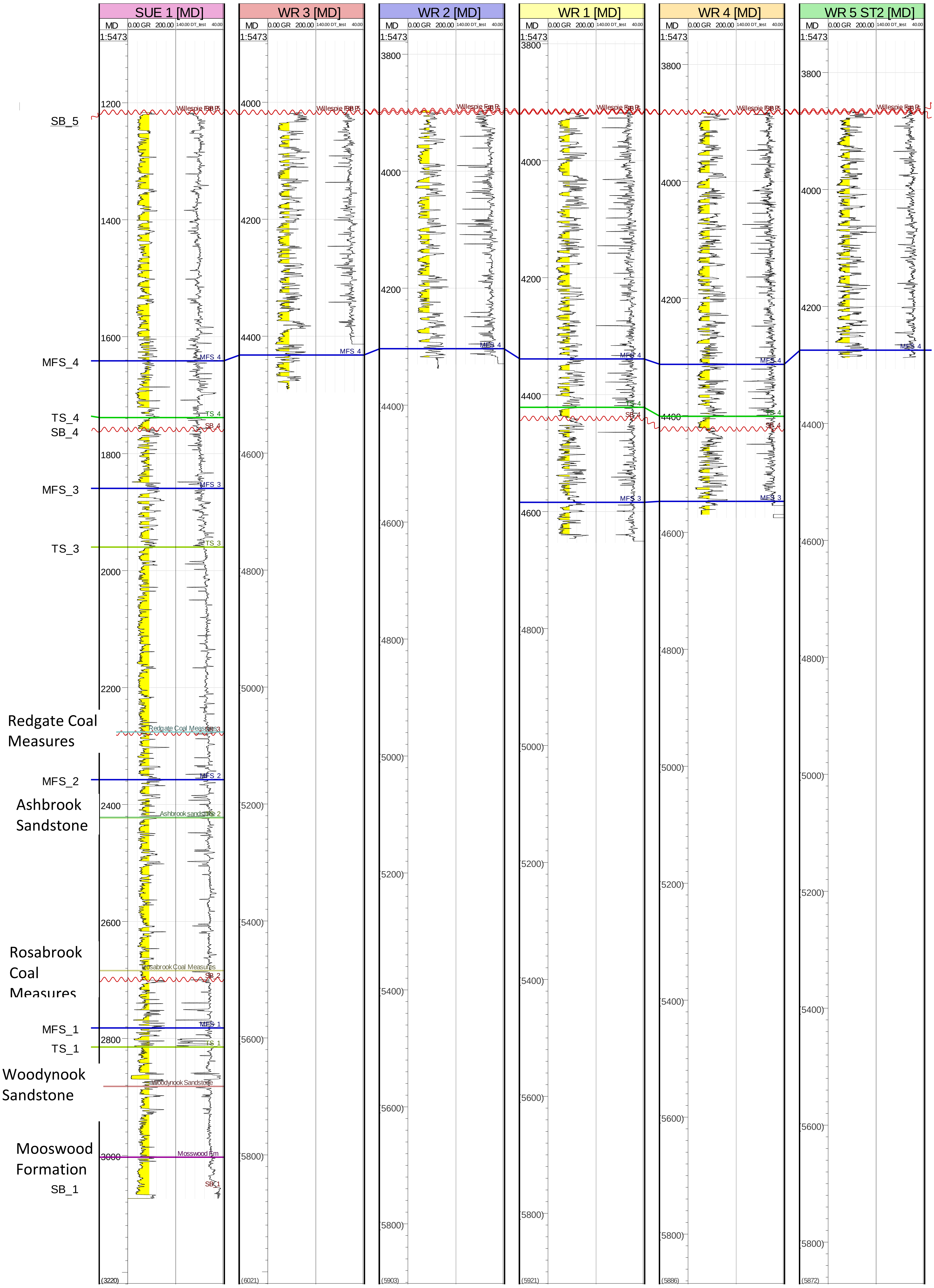


Figure 22. Third order sequence stratigraphy framework for the Permian within the area of study, showing the key stratigraphy surfaces (SB, TS and MFS)

High Stand Systems Tract 1 (HST1)

HST1 is characterized by a progressive reduction in accommodation space resulting in the sedimentation rate becoming greater than rate of creation of accommodation space. The HST1 is represented by a marked aggradational stacking pattern deposited during early stages and a slightly progradational one in to the late stages. Therefore, the HST deposition in this sequence is characterized by two different styles, an early one, characterized by sedimentation of isolated channels and crevasse channels enclosed in well-developed floodplains, and a final one displaying a fewer floodplain deposits and a much greater degree of channel amalgamation. HST1 is topped by sequence boundary 2 (SB2) that coincides with the top of the Rosabrook Coal Measures.

Depositional Sequence 2 (DS2)

Sequence boundary 2 (SB2) is the conformable surface that marks the base of depositional sequence 2. This is interpreted at 2699m in Sue 1 well, at the sharp contact across which a change in the depositional style and an increase in amalgamation thickness is observed.

Depositional sequence 2 (DS2) is 421m thick and consist of the amalgamated sands of the Ashbrook Sandstone and the Red Gate Coal Measures. DS2 overlies sequence boundary 2 and is topped by the sequence boundary 3, and is represented by the three systems tracts detailed below:

Low Stand Systems Tract 2 (LST2)

This contains sediments deposited above SB2, and is topped by a conformable transgressive surface 2 (TS2) that represents the beginning of the Redgate Coal Measures. LST2 is characterized by a distinctive aggradational stacking pattern, representing deposition within a low-accommodation setting. This covers the entire Ashbrook Sandstone Formation which is characterized by the development of amalgamated fluvial channels and poorly preserved floodplain deposits.

Transgressive Systems Tract 2 (TST2)

TST2 covers the 65m of deposits located between transgressive surface 2 (TS2), found at the top of Ashbrook Sandstone, and maximum flooding surface 2 (MFS2). This transgressive systems tract is demarcated by a change in the depositional trend from an aggradational to a retrogradational stacking pattern, and is represented by isolated channel deposits, splay complexes and thin coal seams engulfed in floodplain deposits.

High Stand Systems Track 2 (HST2)

The base of HST2 is marked by a shaly interval located at about 2357.5m in the Sue 1, which represents the MFS2. This surface was defined as the highest gamma log spike which is most likely to represent the maximum lacustrine inundation. MFS2, marks the beginning of a progradational and aggradational patterns in the HST and the occurrence of interpreted stacked channels with an increase in sand connectivity. HST2 is characterized by fining upward stacking patterns comprising mostly amalgamated channel deposits.

Depositional Sequence 3 (DS3)

In Sue 1, sequence boundary 3 (SB3) has been defined at 2278m and interpreted as a conformable surface topping depositional sequence 2 and marking the beginning of depositional sequence 3, which corresponds to Willespie Formation. This surface is defined palynostratigraphically between the *D. ericanus* (Kazanian) and *D. parvithola* (Dorashamian to Midian) zones.

Depositional sequence 3 (DS3) consists of 520m of sediment corresponding to the lower part of the Willespie Formation. The top of this stratigraphic unit is marked by sequence boundary 4 (SB4). DS3 consists of the three systems tract listed below:

Low Stand Systems Tract 3 (LST3)

Consists of an aggradational interval overlying the sequence boundary 3 (SB3) and topped by transgressive surface 3 (TS3). This is characterized by amalgamated channels (low accommodation systems) with poorly developed fine-grained overbank facies, which may have been deposited during a period of continuous sedimentation. Poor development of coal seams is observed in LST3 and may indicate limited accommodation creation within the floodplains.

Transgressive Systems Tract 3 (TST3)

At about 1960m, transgressive surface 3 (TS3) is defined by a change in the depositional trend from the aggradational LST3 to an overall retrogradational pattern. This surface represents the depth across which the GR blocky pattern changes to a fining-upward bell pattern.

The sequence overlying TS3 is interpreted as transgressive systems tract 3 (TST3) and is mainly characterized by the development of multiple isolated channels, crevasse splays and floodplain deposits.

High Stand Systems Tract 3 (HST3)

The deposition of high stand systems tract 3 occurs above maximum flooding surface 3 (MF3). This key surface is observed in Sue 1 but also in Whicher Range 1 and 4, and it is represented by a fine grained deposit ranging in thickness between 10 and15m. This event marks a change in the general stacking pattern from more progradational to more aggradational upward.

HST3 is aggradationally deposited above MFS3. A lateral variation in facies characteristics is observed between Sue 1 and the Whicher Range wells, although the general stacking pattern remains the same. In Sue 1, this interval is characterized by an increase in magnitude of channel amalgamation, commonly seen in High Stand Systems Tracts, whereas in Whicher Range wells (1 and 4) channel amalgamation is less developed and few coal deposits are found. The reason for this lateral facies variation may be related to proximity to the source area. Whicher Range 1 and 4, seem to be more distal than Sue 1, and as a consequence, they are more prone to the development of wet floodplain deposits.

Depositional Sequence 4 (DS4)

Sequence boundary 4 (SB4) is recognizable in Sue 1 at about 1758m, and in Whicher Range 1 and 4 at 4440.5m and 4423m respectively. This is the conformable surface that marks the beginning of depositional sequence 4 (DS4). No palynostratigraphic data is available to constrain this surface but It has been defined through a sharp erosional contact and sudden upward increase in sand content inferred from the GR and DT logs.

Depositional sequence 4 (DS4) comprises ~542m of sediment belonging to the upper part of the Willespie Formation. This stratigraphic unit is topped by, the sequence boundary 5 (SB5), which is a conformable surface between the Late Permian (Willespie Formation) and the Early Triassic (Sabina Sandstone).

According to Crostella and Backhouse (2000), SB5 is a conformable contact formed by a short break in sedimentation. However, this is not clear in the palynological records. It is worth mentioning, that the definition of this unconformity is based on a sharp change in wireline log signatures and, since this is not visible in seismic reflectors, it has been considered as a paraconformity.

The DS4 consist of the three systems tract which are described in more detail below:

Low Stand Systems Tract 4 (LST4)

LST4 comprises the thin (~21m) aggradational to retrogradational interval developed between sequence boundary 4 (SB4) and transgressive surface 4 (TS4). This interval mainly consists of stacked channel fills and represents deposition within a low accommodation system with limited creation of accommodation space and a sediment rate greater than the rate of creation of accommodation space.

Transgressive Systems Tract 4 (TST4)

TST4 is developed above TS4 and is identified in Sue 1 (at about 1738m) and Whicher Range 1 and 4 (at 4421.6m and 4401.6m, respectively). This transgressive system tract is characterized by a distinct retrogradational stacking pattern indicating deposition under higher accommodation conditions. Although this general stacking pattern is common within the entire interpreted area, a change in fluvial style is observed between Sue 1 and Whicher Range 1 and 4. In Sue 1, fluvial bodies are more thickly amalgamated and sand rich whereas in the Whicher Range wells, channel bodies are more isolated due to better preservation of the floodplain deposits. This may be related to changes in the slope impacting on the fluvial style and degree of sinuosity, i.e. changing from a straighter river to a more sinuous river as the slope reduces.

High Stand Systems Tract 4 (HST4)

The deposition of high stand systems tract 4 started with the development of maximum flooding surface 4 (MF4), which is interpreted from a change in the depositional style from the retrogradational TST4 to a more progradational to aggradational pattern upward. This key surface is recognizable in Sue 1 (at ~1641m) and in Whicher Range 1 to 5 (at ~4339m, ~4303.5m, ~4438m, ~4312m and ~4284m, respectively).

As in the case of HST3, a lateral change in facies is recognized from Sue 1 to Whicher Range area. More aggradational patterns, higher channel amalgamation and less preservation of floodplain deposits are characteristic of deposition in the southern areas, while northward to the Whicher Range area, a group of fining upward sequences embedded in a general aggradational pattern and an increase in floodplain and coal deposits are observed. This facies variation is most likely to be related to an increase in accommodation space towards the north in comparison with the southern study areas.

In this study, the recently developed HAST/LAST systems tract was also evaluated Figure 21 displays the Sue 1 well log with both the standard and the HAST/LAST systems tracts terminology. From the plot it may be observed that High accommodation systems tracts, seem to involve the standard High Stand and Transgressive Systems tract, whereas the Low Accommodation Systems tract correspond to the standard Low Stand Systems tract.

Additionally, results obtained by using the HAST/LAST terminology give a broad view of the main depositional changes. However, these seem to lack detail, particularly when looking for changes in depositional pattern on a finer scale (fourth order sequence stratigraphic framework).

Reservoir Stratigraphic analysis

The framework for the Whicher Range field area

An understanding of the sand quality distribution as well as lateral and vertical connectivity in the Permian section of the Whicher Range Field is a key focus area of this research. A detailed internal correlation and log facies definition of the Permian Willespie Formation in the Whicher Range area is needed to have a better control of the facies distribution and possible lateral and vertical connectivity of the geobodies in this field. However, based on the limited quality and quantity of the available well and seismic data, the level of control is poor which impacts on the level of confidence placed in these investigations.

To reduce the uncertainty, the use of the previously defined sequence stratigraphic framework (key surfaces) and expected stacking patterns during different system tracts, in conjunction with the core and log facies interpretation, can help to predict the sand body distribution.

Given the necessity of building up a model that reflects the connectivity of the channels (which will be mentioned further ahead in this document), and taking advantage of the availability of local stratigraphic markers such as coal seams, a more detailed intra-Willespie stratigraphic correlation was attempted. The third order sequences comprising the Willespie Formation were internally subdivided into fourth order ones, also by applying a sequence stratigraphic approach.

The internal correlation of the Whicher Range field involved the five wells (Whicher Range 1, 2, 3, 4 and 5) and the suite of logs available in each well. A key for the detailed internal correlation was to pair the sequence stratigraphic surfaces with more useful local markers (coal) and shaly intervals to help identify periods of poor sediment supply. The identification and interpretation of the coal markers was made based on core data, well completion and wellsite geological reports in conjunction with the log interpretation using the GR and Sonic logs.

This correlation also uses the log motif facies schema for the fluvial facies of the Sue Group. The already defined fourth-order sequences in the Willespie Formation in the Whicher Range area were, at the same time, split in eight groups of parasequences (named from top to base Groups A-H).

Permian section sequences and parasequences

The Permian Willespie Formation in the Whicher Range field was divided into eight fourth order sequences (A, B, C, D, E, F, G and H) starting from the top of the section. Each sequence was defined by cyclic changes marked by the fourth order erosional surfaces defined along the entire sedimentary succession. These sequences were then subdivided into a total of 37 parasequences, bounded by small mud-dominated intervals representing minor flooding surfaces and 40 internal coals recognized in the section. This detailed correlation helps to elucidate the internal 3-D architecture of the reservoir.

Facies observations in cores recovered from the Whicher Range wells suggest that there is not a characteristically significant facies variation between parasequences within the Willespie Formation. The top of this stratigraphic unit is well defined by the development of a 10 m thick shale interval, correlatable across the entire Whicher Range area, which is most likely to constitute the main reservoir seal. This shale represents a marker bed and an important allostratigraphic surface which was used as a datum in the correlation panels (Figure 23).

The Willespie sequence is capped by a sequence boundary (SB5) across which the change in composition and facies from the Permian Willespie to the overlying Triassic Sabina Sandstone occurs.

Figure 23 shows the fourth order sequences and their respective parasequences within the Permian Willespie Formation. Well defined intra-formational siltstones and shale intervals, with average thicknesses of 5 meters, and thin coal beds, are most likely to be laterally extensive in most areas of the field and therefore are useful to dissect the parasequences. A summary is presented in Table 2.

This detailed correlation based on parasequences, together with the results obtained from the petrophysical evaluation, can give an idea of the possible productive areas in the field. However, care should be taken when performing such projections since there are multiple factors that can impact on these predictions.

Electrofacies and facies associations distribution for the fourth order sequences

A similar approach to that displayed in Chapter 3, is applied to electrofacies and facies association distributions to elucidate sand distribution within fourth order sequences in the Willespie Formation.

Facies interpreted between SB_5 and SB_4_0 for all Whicher Range wells are represented on average by 40 percent CH1 FA, 7 percent FA CH2, 11 percent FA CHAB, 10 percent FA CS, 28 percent FA FP and 4 percent FA C. (Figure 24a). From this statistical analysis it is observed that, on average, 58 percent of the interpreted interval contains possible reservoir facies and the 38 percent corresponding to FP and CS CH facies, is most likely to represent intra-formational seals. The facies associations proportions interpreted for the five Whicher Range wells are alike. This is most likely to indicate that not major lateral or vertical changes in facies are

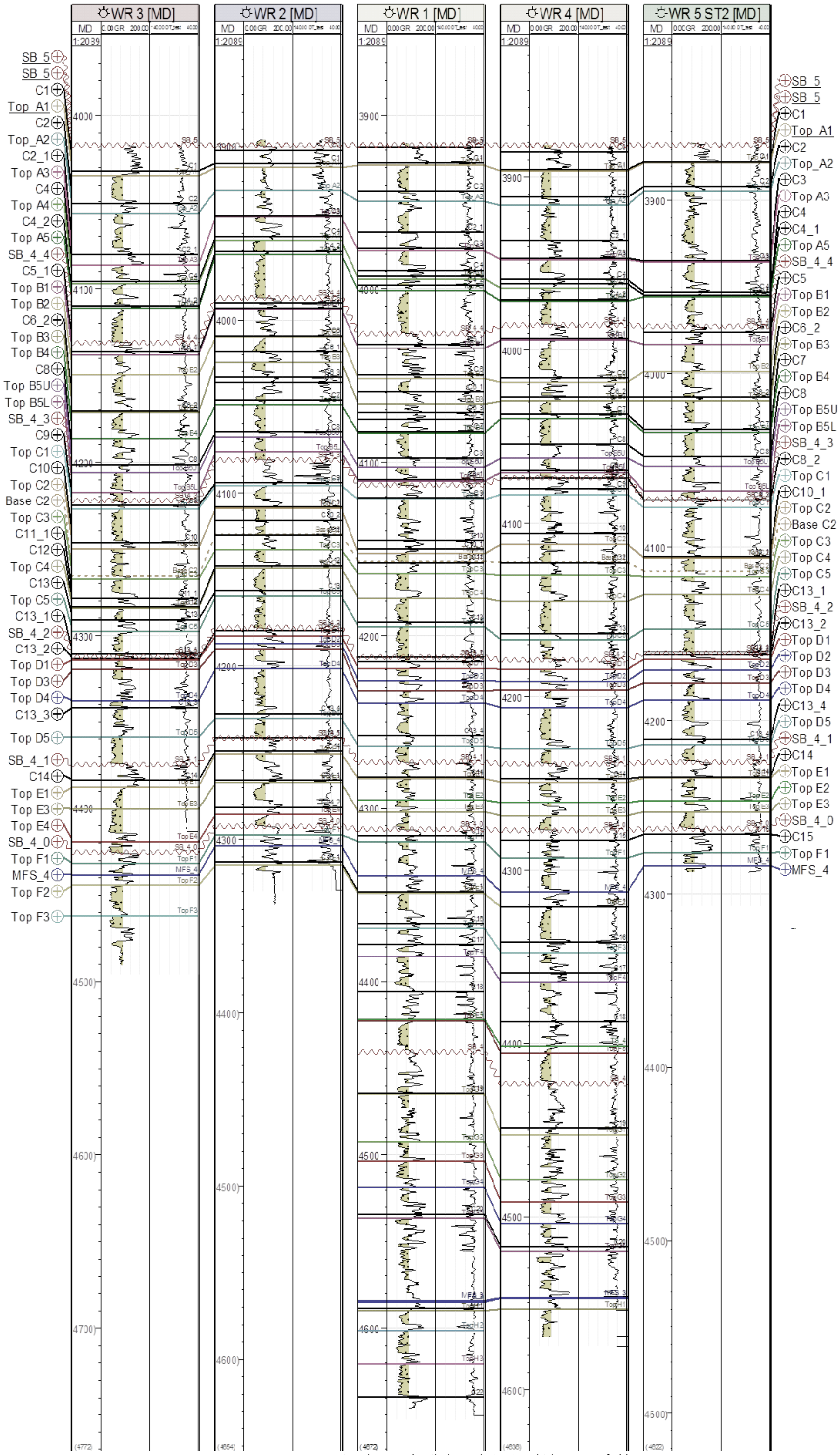


Figure 23. Cross section showing detailed correlation in Whicher Range field.

occurring between wells. Individual statistical proportions for each studied Whicher Range well are displayed in Figure 24b-f.

The section between from SB_5 to SB_4_0, which was drilled in all the Whicher Range wells is thickest in Whicher Range 4 followed by WR 2, 3, 1 and finally WR5, which display the lowest (Figure 25).

Similar statistics and charts as presented in Figure 24, were generated for individual fourth order sequences in order to study local lateral changes in facies and to evaluate the proportions of reservoir and non-reservoir facies (FP and CS) in each interval. These are shown in Enclosure 2.

Table 2.Willespie Formation Sequences and Parasequences classification for Whicher Range field

Willespie Formation Whicher Range Field			
4 Order Sequences	Sequences Group	Parasequences	Coals
SB_5	A	A1	C0
			C1
		A2	C2
			C2_1
		A3	C3
		A4	C4
			C4_1
		A5	C4_2
SB_4_4	B	B1	C5
			C5_1
		B2	C6
			C6_1
			C6_2
		B3	C6_3
			C6_4
		B4	C7
		B5U	C8
		B5L	C8_1
SB_4_3	C	C1	C9
		C2	C10
			C10_1
		C3	C11
			C11_1
		C4	C12
		C5	C13
			C13_1
SB_4_2	D	D1	13_2
		D2	
		D3	
		D4	
		D5	13_4
SB_4_1	E	E1	C14
		E2	C14_1
		E3	C14_2
SB_4_0	F	F1	C15
		F2	C15_1
		F3	C16
		F4	C17
		F5	C18
SB_4	G	G1	C19
		G2	
		G3	
		G4	
		G5	C20
FS_3	H	H1	C21
		H2	
		H3	C22

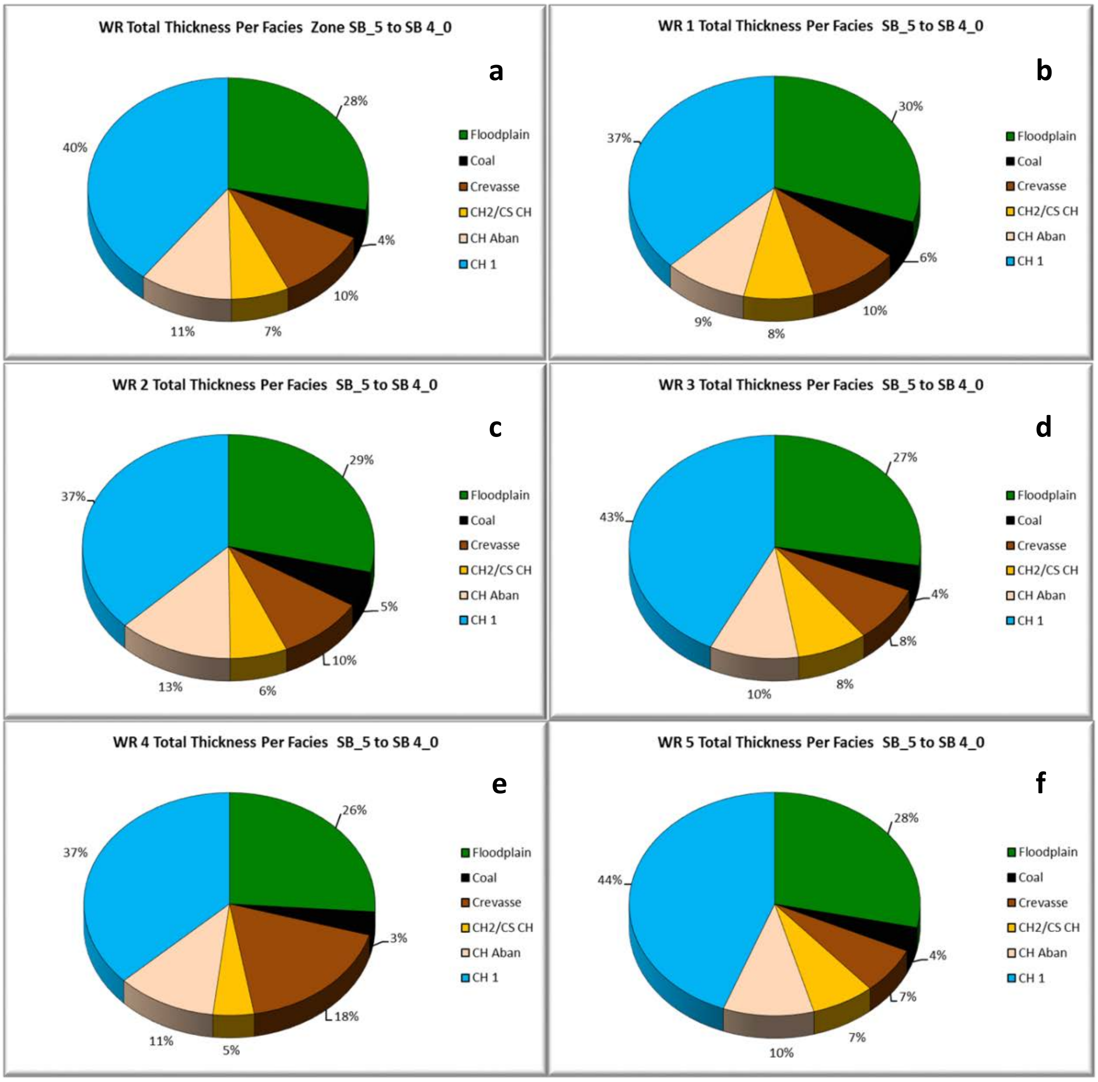


Figure 24.Pie Chart showing thickness and facies distribution over the interval SB 4_0 to SB 5_0 in overall and for each well.

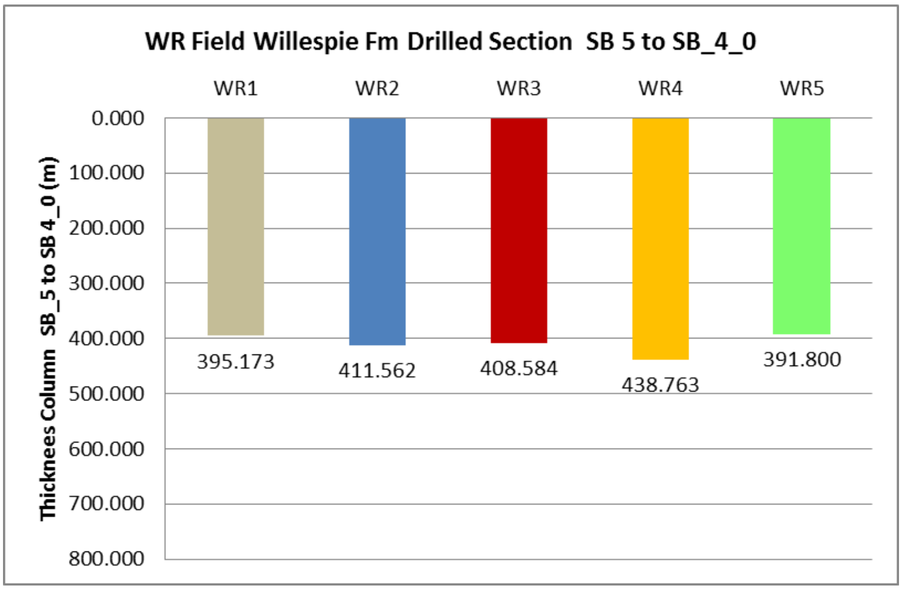


Figure 25. Gross thickness of the common section drilled for all Whicher Range wells

The sand/ shale ratio estimated from facies identified between SB_5 and SB_4_0 within the Willespie Formation shows values ranging from approximately 1.12 to 1.59 (Figure 26). Overall, WR4 (1.12) & WR1 (1.19) show the lowest sand / shale ratios followed by WR2 (1.3), WR3 (1.53) and finally WR5, which displays the highest value (1.59).

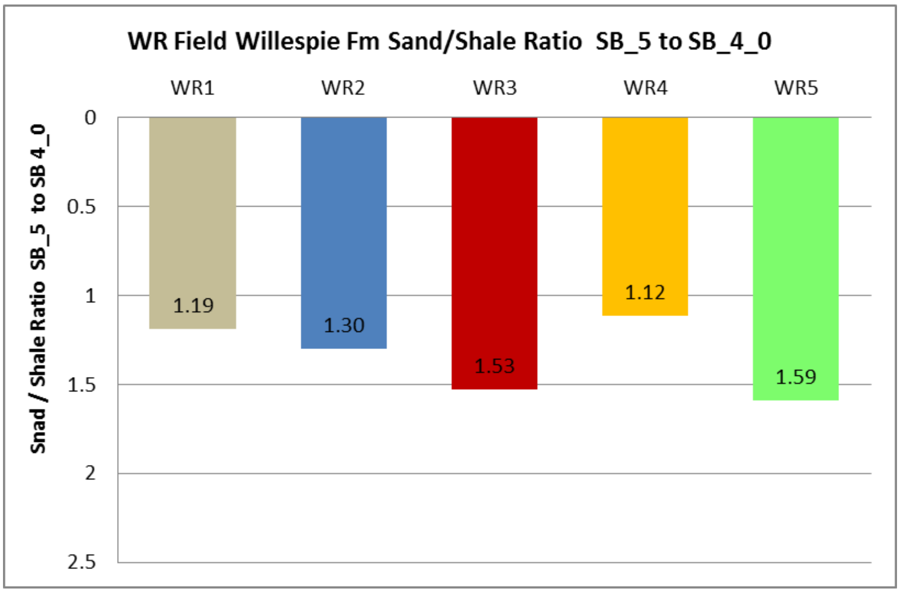


Figure 26. Comparison between sand/shale ratio estimated, in the interval SB 4_0 to SB 5_0, in the five Whicher Range wells.

The highest sand - shale ratios are found in WR3 and WR5 followed by WR2. WR4 and WR1 display the lowest net to gross and are located close to each other (Figure 27).

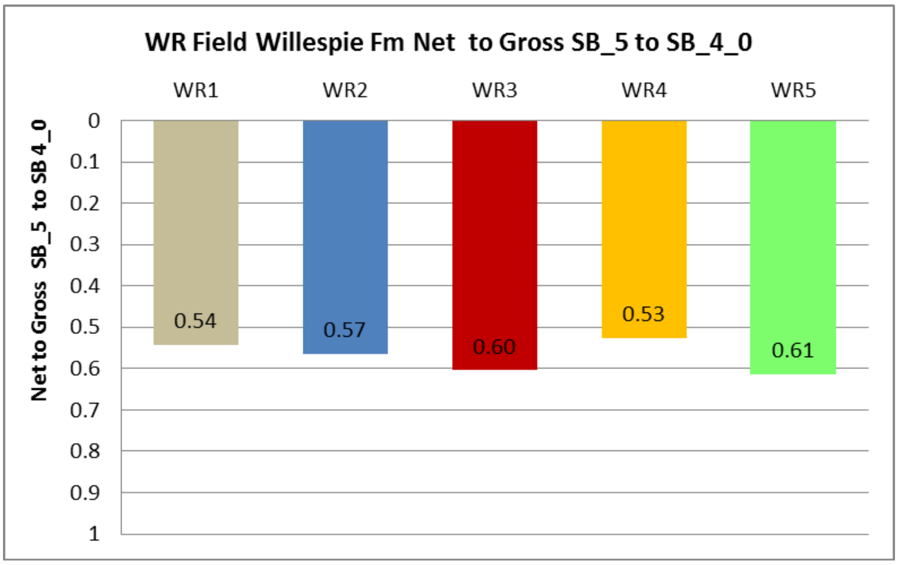


Figure 27. Net to Gross estimated in the SB-5 to SB_4_0 within the Whicher Range wells.

Discussion

Key surfaces recognized in this study provided the closest approximation to timelines which are required to perform an optimal cross correlation.

Independent time control information such as biostratigraphy and lithological time markers are recommended to be used when available (Catuneanu, 2006). In the case of the Whicher Range study, the unconformable contact between the Precambrian and the Permian Mooswood Formation and the top and bottom of the Willespie Formation were defined based on palynostratigraphic zones. The remaining interpreted surfaces were established from changes in depositional stacking pattern observed in well logs. These interpreted sequence stratigraphic surfaces provided the basis for the Permian chronostratigraphic framework from which the fourth order depositional sequences were constrained.

Based on the fourth order sequence stratigraphic interpretation developed for the type Permian section in Sue 1, four third order depositional sequences including 12 systems tracts were defined. Each depositional sequence varies upward from coarser grained aggradational intervals to finer grained more retrogradational patterns and finally to progradational stacking patterns representing LST, TST and HST, respectively.

Changes occurring within the Permian represent cycles of fluctuation in accommodation space and sedimentation rate which, in this non-marine fluvial environment, are most likely to be related to tectonic movements occurring during the Permian as a consequence of the active rift and paleo-climate (energy flux).

Distinct changes in depositional styles and stacking patterns, together with the definition of key surfaces (TS, MFS and SB), helped to elucidate the fluvial architecture in the Permian section of the Whicher Range area and into some extent, to predict the degree of sand body connectedness.

Also, changes in rock properties were found to occur across some of the sequence stratigraphic surfaces, i.e. SB 4_0 marking the surface across which a main change in hydrocarbon saturation and reservoir quality occurs. Increase in water saturation observed from this key surface upward, through HST3 is most likely to be related to an increase in the smectite content up-section.

In order to address the geobody distribution and connectedness within the distinctive varied third order depositional sequences, a fourth order sequence stratigraphic correlation was required. The definition of these sequences (8) and their respective parasequences (37) was based on recognition of erosional surfaces, flooding surfaces and intra-formational coal seam development within the Willespie Formation by using well log motifs and changes in stacking pattern.

The interpreted third order sequences allowed the generation of a more robust geological model that provides a better representation of the reservoir architecture and facies distribution than achieved by using fourth order depositional sequences.

Flooding events can be correlated through the Willespie Formation in the Whicher Range area. These surfaces represent periods where the rate of fluvial accommodation (formed by subsidence and/or base level rise) rapidly exceeded the rate of sediment supply, resulting in lacustrine inundation. Although these events may not necessarily be of regional lateral extent, they are most likely to be relevant surfaces within the Whicher Range field area.

A lateral change in facies represented by an increase in floodplain preservation occurs from the most southern well, Sue 1 towards the northernmost well, Whicher Range 1. This change may be related to a variation in the distance between the alluvial source (footwall uplands) and the location of the well within the axial where the fluvial system was deposited (Figure 18). In agreement with this, and as mentioned by Leeder and Gawthorpe (1987), peat/coal accumulation and soil development are most likely to be accentuated up the hanging wall dip slope away from the axis of maximum deposition.

This may be represented in the study area by the increase of coal development towards the north, but also may have an impact on the fluvial style, accretion type and therefore in the degree of sinuosity associated to the fluvial system.

Based on the sequence stratigraphic framework generated in this study, an increase in lateral continuity of the sand bodies may be expected to occur up-section toward the HST interval in the Willespie Formation. Based on the fluvial system interpretation, the tectonic setting and the sequence stratigraphic framework, it may be inferred that in the Sue area, the fluvial units within the Permian section are transiting from amalgamated LST braided stream through mudstone prone isolated meandering deposits in the TST. On the other side, Whicher Range area displays a mudstone prone meandering rivers with better floodplain and coal preservation. The aforementioned changes in interpreted fluvial style may be related to a variation in the slope profile between the Sue and the Whicher Range areas.

The sand count ratios performed in the WR wells, indicate that wells displaying the lowest sand/shale ratios are the ones showing the best performance in production tests (DST). At first thought, a direct proportional relationship between gas flow/production and sand thickness, and therefore higher sand/shale ratios, may be expected. However, in this case, not only are the sand reservoir facies critical in the development of the reservoir but also intra-formational non reservoir facies. This may be related to the intra-formational seal role played by the fine grained floodplain/overbank facies as the only effective gas trapping mechanism available, due to the lack of regional seal seen within the Whicher Range area. Having said that, it may be inferred that within this field there exists a direct relationship between intra-formational seal development and reservoir performance.

Also, the increase in channel facies upward across SB_4.1, observed on the facies distribution charts of each third order depositional sequence, most likely represents an increase in the connectivity of sand bodies, as theoretically expected within the HST.

Enclosure 2 contains results for all facies distributions within the third order sequences and also for the entire drilled section for each one of the Whicher Range wells.

Chapter 4 - WHICHER RANGE FIELD STRUCTURAL FRAMEWORK

Introduction

In this chapter, the structural setting of the South Perth Basin is discussed, including regional tectonic, fault and fracture systems and the structural control of the rift-related extensional features on the deposition of the Permian section sedimentary.

A local structural model was generated based on regional tectonic information and 2D seismic interpretation at the Willespie Formation stratigraphic level. This allowed the production of a geological model that honours the structural variables controlling deposition during the Permian. The objective of this model was to construct a faulted grid that characterizes the Willespie Formation reservoir in 3D space.

In the case of the Permian section of the Whicher Range field, a set of tilted fault blocks has created the reservoir compartments and is delineated by the grids used for the 3D geological model. The structural framework of the Whicher Range area is based on previous published regional work developed in the southern Perth Basin including regional tectonic studies and previously published structural models of the basin i.e. Crostella and Backhouse (2000).

The definition of the structural setting is supported by the interpretation of seismic reflection data comprising 17 2D seismic lines acquired in the Whicher Range field, from which seven (representing the most useful dataset within the area) were recorded at similar locations to some of the previous acquired surveys (Figure 28).

For the structural interpretation, the key formation markers were defined for the five WR wells, based on previously established picks (Cockleshell Gully Fm, Lesueur Sandstone, Sabina Sandstone and Willespie Formation) reported in the well completion reports. Because seismic data is in time and well data are in depth, the use of a time-depth relationship was necessary to tie well data to seismic.

Seismic Line Name	Type
aa2k-07	2D
aa2k-06	2D
aa2k-05	2D
aa2k-04	2D
aa2k-03	2D
aa2k-02	2D
aa2k-01	2D
81-47	2D
81-41	2D
80a-17	2D
80a-16	2D
80a-15	2D
80a-14	2D
80a-12	2D
80a-08	2D
80a-07	2D
80a-03	2D

Seismic lines used for the Inset A

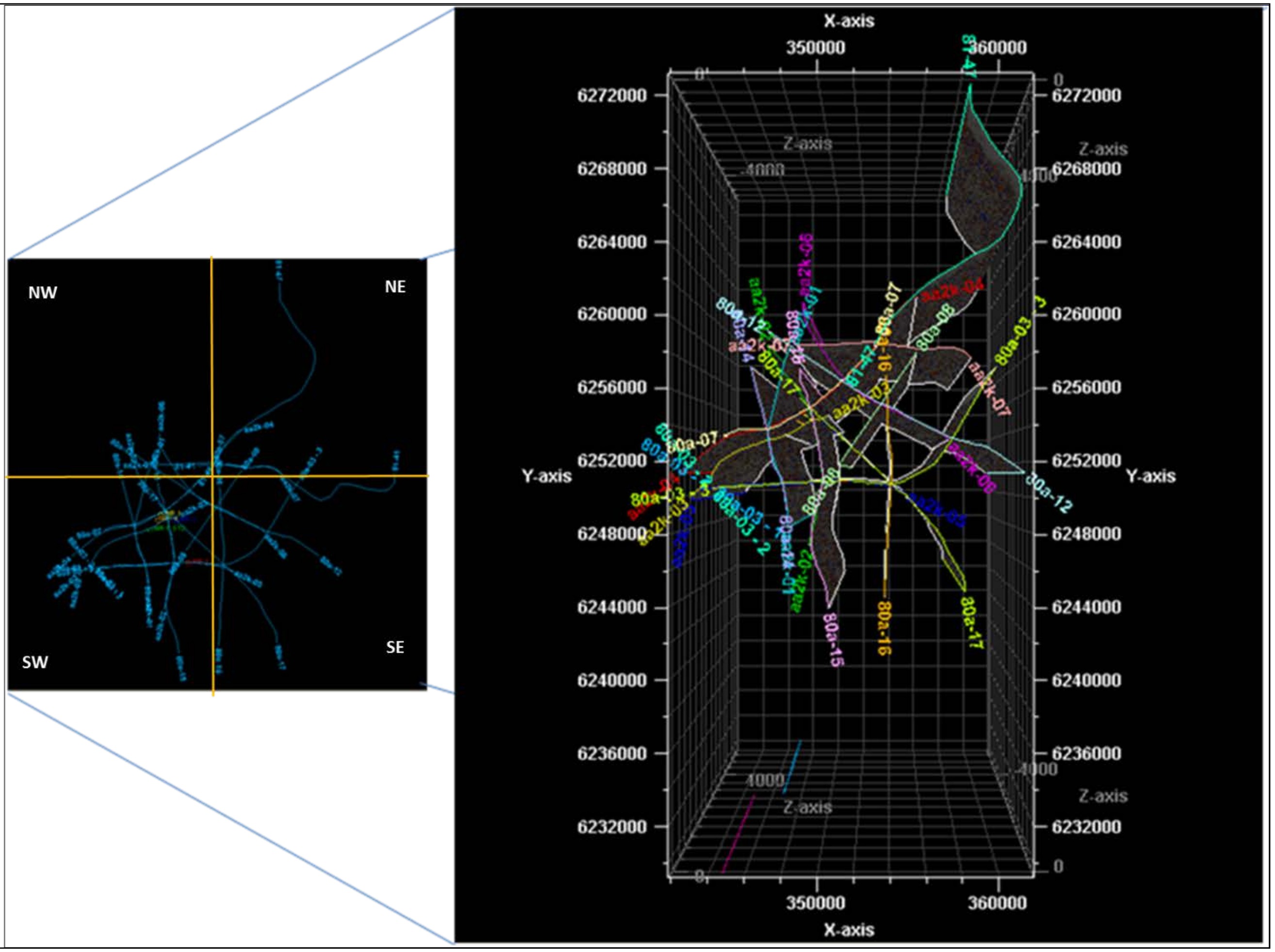


Figure 28. Location and name of the 17 seismic lines of Whicher Range field with the seven lines used on inset A

This time-depth relationship was obtained from checkshot and sonic data for each of the five WR wells.

Fault interpretation and tracking of seismic horizons was performed simultaneously for the entire survey. Faults were identified along with their extention, trend and correlation. These were tracked and correlated by using different methods but mainly manually due to the poor quality of the seismic data. The horizon picking was performed for the four main horizons and some intra-formational horizons.

Finally, a detailed re-interpretation of the faults and focus horizons in the Permian section was performed to create the structural model of the area, which was used to construct the 3D geological model of the Whicher Range Field.

Regional tectonics of the South Perth Basin

The regional tectonic setting of the Perth Basin is mostly linked to Permo-Cretaceous rifting of Greater India and Australia and the final break-up of Gondwana. This major structural events are two main rifting phases, occurred during the Permian and, during the Jurassic to Early Cretaceous.

The Permian-Triassic sinistral transtensional regime, developed during the first NE-SW extensional rifting phase, delineates the main architecture of the basin whereas the NW-SE shortening, occurring during the Late-Early to Middle Triassic, caused the development of sinistral transpressional features (Harris, 1994).

The younger Jurassic events, coinciding with the final break-up of Gondwana, entail dextral strike –slip deformation, and basin inversion as well as marginal orthogonal extension. The northwest-striking transfer faults divide the basin into multiple compartments with similar structural styles (Song & Cawood, 2000).

Overall, structures related to the rifting events are well represented in the basin by north-striking sub-basins, troughs and ridges enclosed by faults showing mostly normal and possibly strike-slip movement. Block rotation and tilting related to syn-sedimentary depositional thickening of rock units toward the faults are also commonly developed within the basin (Song & Cawood, 2000).

According to Song and Cawood (2000), the main structural features are: rift related extensional structures (including listric and planar faults); Strike slip deformation (en echelon fold arrays and local compressive deformations in the vicinity of major faults); transfer zones (transfer faults) and basin inversion (uplift, erosion and folding of the pre-breakup strata in major depocentres).

The dynamic behaviour of the structures caused by the unceasing extensional events, also had an impact on the sedimentation patterns, causing syn-depositional generation of local accommodation and shifting of the depositional environments along the basin.

Structural setting of the Whicher Range Field

The Whicher Range field is located within the Bunbury Trough, which is dominated by two major structural features, the Darling and the Busselton faults (Iasky et al. 1991), as shown in Figure 18A and Figure 29. Three periods of tectonism are described within the Perth Basin, which reactivated these major faults, firstly, sinistral strike slip motion, secondly, left lateral motion and finally, some oblique – transcurrent style of faulting (Iasky and Mory, 1993).

The tectonic setting of the Perth Basin is well represented by the horizon and structural features interpreted in all the available seismic profiles, as shown in Figure 30. In this figure, the four interpreted horizons are displayed together with the possible Redgate Coal Measure horizon. The new faults interpreted in this study, within the Whicher Range area have a major trend NNE–SSW, similar to the 2 major faults bounding the Bunbury Trough (Busselton and Darling Faults), as shown in Figure33.

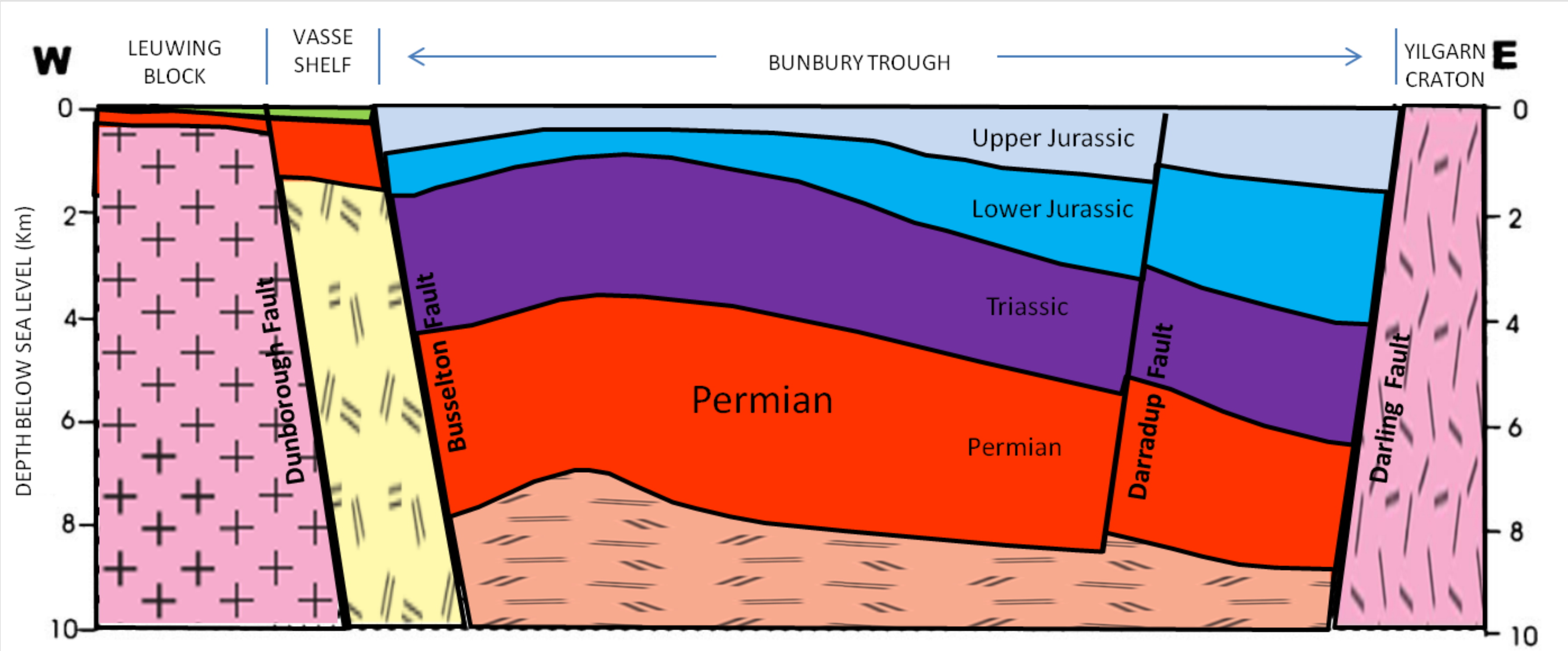
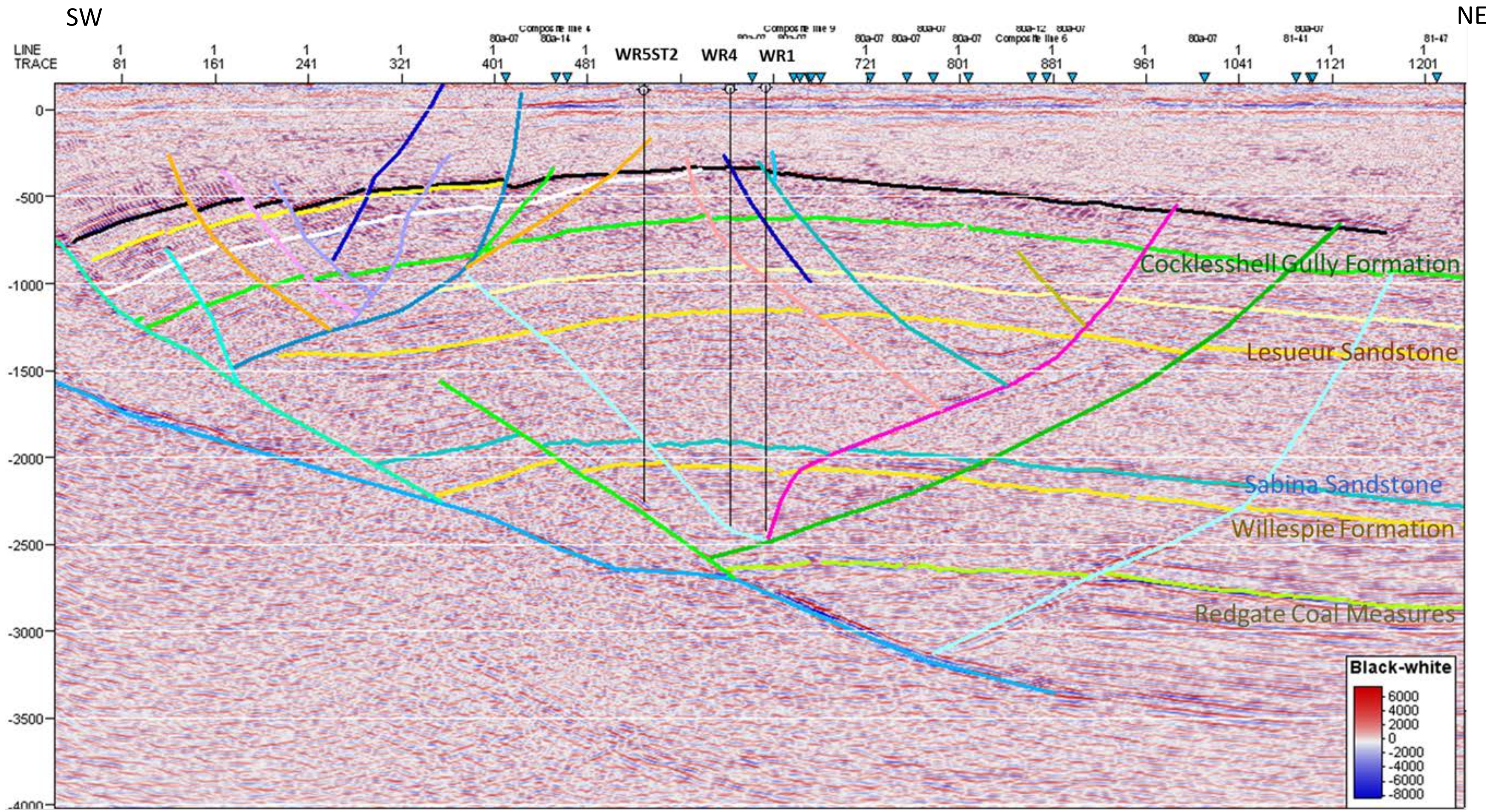


Figure 29. Cross section of the Bunbury Trough displaying the planar geometry of the Busselton and Darling normal faults (Modified from Song and Cawood (2000).



**Wells are projected to the seismic section*

Figure 30. Seismic section SW-NE direction across the Whicher Range field showing faults and horizons (line aa2k-04).

The rift basin area corresponding to the Whicher Range Field display an asymmetrical geometry (the basin is deeper along the eastern Darling Fault side, Figure 31). According to Bosworth (1995) the rift asymmetry occurs as a consequence of the role played by a low angle normal fault in the overall rift geometry.

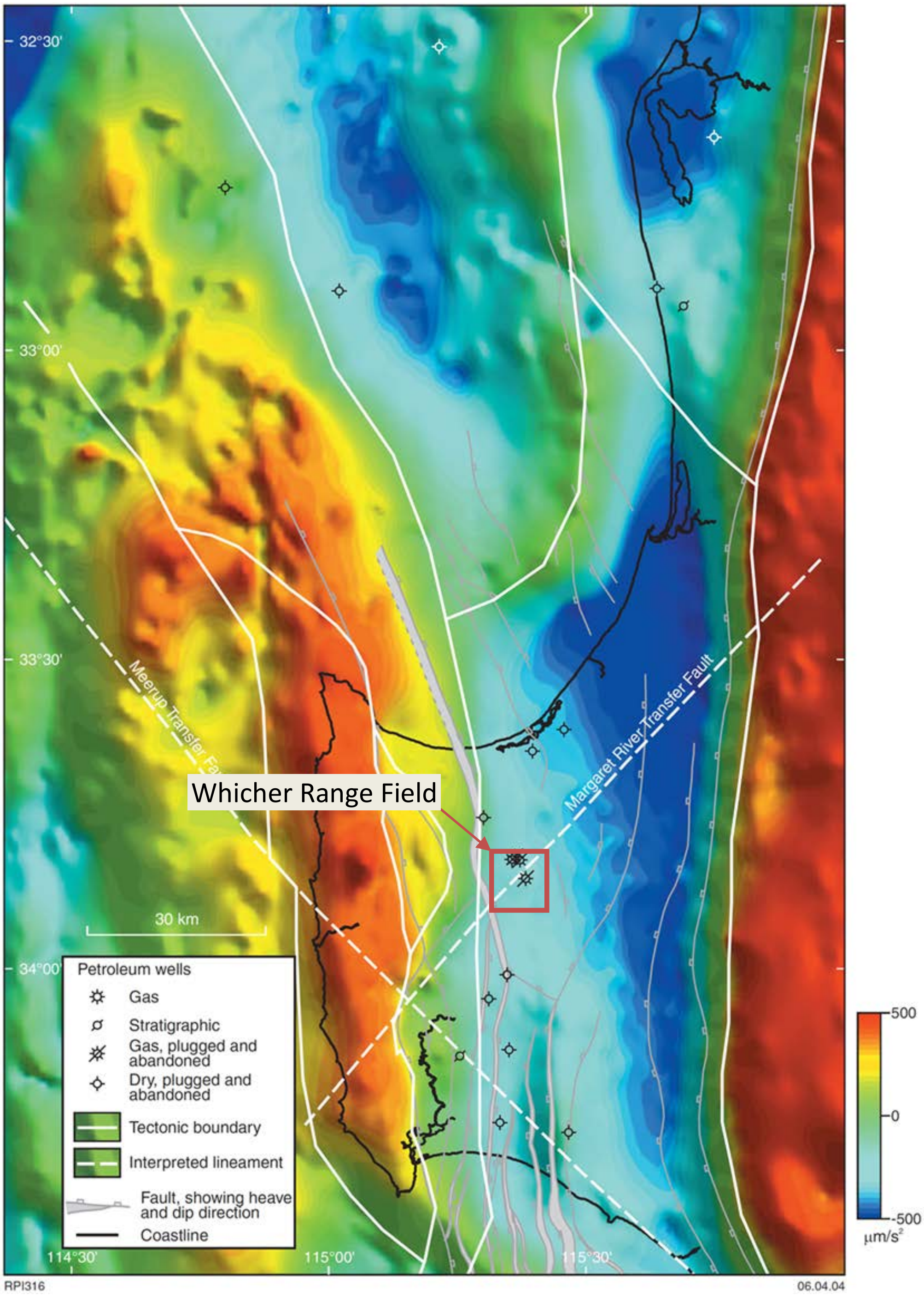


Figure 31. Isostatic residual gravity image of the southern Perth Basin with faults interpreted from seismic data showing the top-basement horizon (Iasky and Lockwood, 2004)

2D seismic interpretation and structural modelling

The workflow implemented to interpret the seismic data available in this project and the results obtained from it are presented and detailed in this section. There are different approaches that can be applied to interpret seismic data but the definition of the most appropriate, depends on the quality of the available data and the interpreter.

The basic seismic interpretation workflow followed in this project includes:

- Well Tie
- Fault Interpretation
- Tying and Tracking Seismic Horizons
- Generation of two way time (TWT) contour maps for each of the four horizons (mapping, gridding and contouring).
- Creation of isochron and isopach maps.

Well Tie

Seismic to well ties have been conducted by using Top markers, checkshot and wireline log data. Well ties were performed for the Top of Willespie Formation marker (TWF) for all wells within the onshore 2D seismic using the latest acquired data.

Five wells within the 2D seismic data have both top markers and checkshot data. They also have full logs recorded through the Cockleshell Gully Formation, Lesueur Sandstone and Sabina Sandstone to Top Willespie Formation. The TWF marker on all wells was consistently tied to the seismic peak-to-trough event or positive to negative zero crossing (Figure 32).

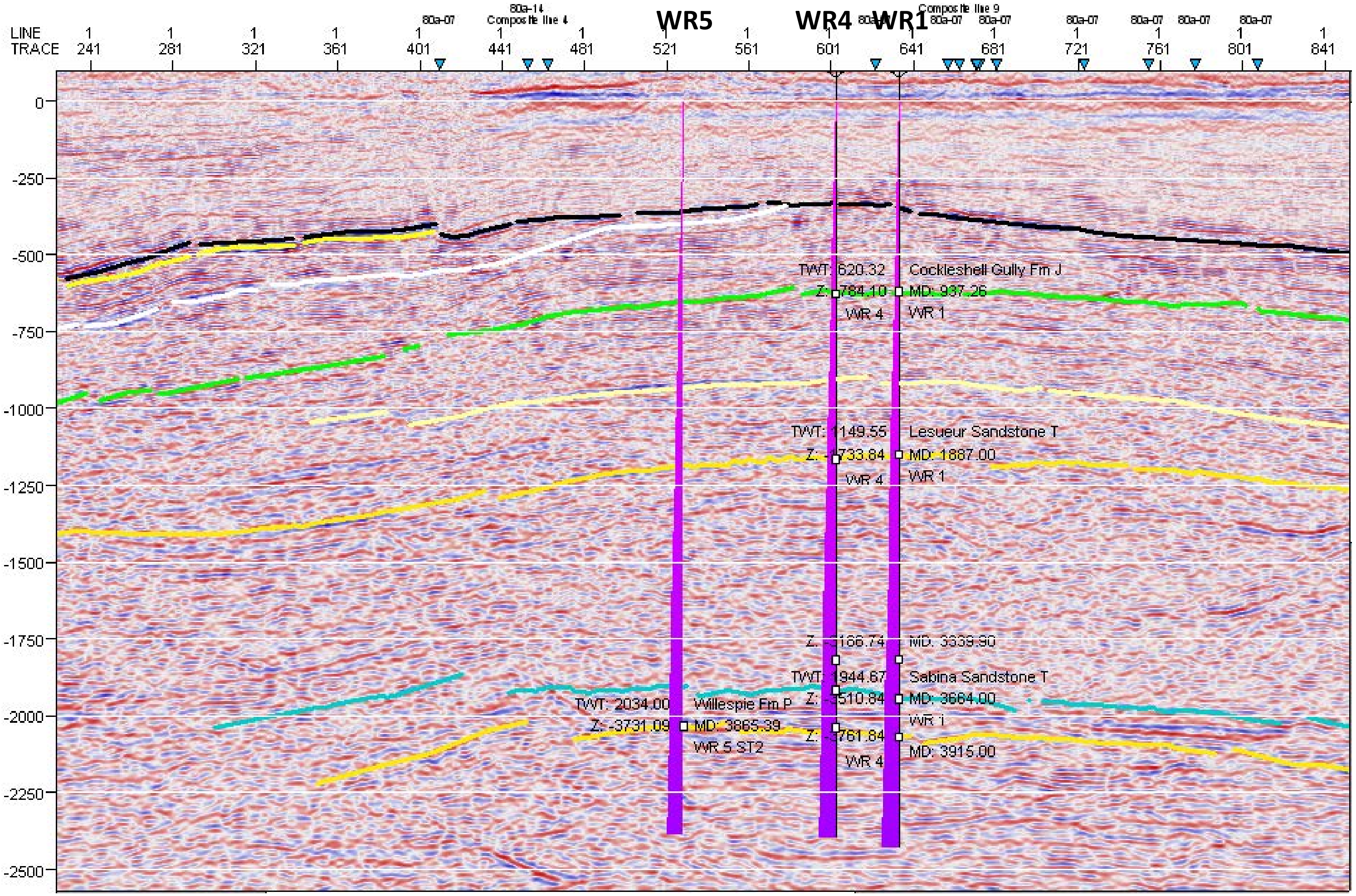


Figure 32. Seismic well tie displaying WR1, WR4 and WR5. The composite line include lines aa2K04

Fault Interpretation

A basic interpretation on the main and most obvious faults through the entire area was developed honouring the regional structural background of the basin. A number of faults were identified and the extention, trend and correlation of these faults are defined through the entire area across the seismic survey.

A quality control used during the fault interpretation stage is to check that fault displacement does not vary abruptly across the study area. This can be done by displaying horizon cut-off lines on the fault hanging wall and footwall. Also, vertical variations across the faults are reviewed by looking at layer thickness variation on both sides of the faults and assuring its compatibility with fault kinematics (Walsh et al., 2003).

The fault sets within the Whicher Range area are identified on the best quality seismic data available. A major fault, possibly corresponding to the Busselton Fault is interpreted at the west side of the field. This is a planar NNE-SSW fault which displaces the depositional sequence of interest (Permian to Jurassic). The main faults mapped observed in the Whicher Range area have a major trend NNE–SSW, similar to the 2 major faults bounding the Bunbury Trough (Busselton and Darling Faults), shown in Figure 1 and Figure 2.

Additionally, there is a second set of faults comprising a few planar, normal faults, striking ~EW. The lack of availability of reliable seismic data along the NS direction makes it difficult to get a detailed interpretation of this set of faults. A view of the fault network projected to the top of the Willespie Formation is displayed in Figure 33.

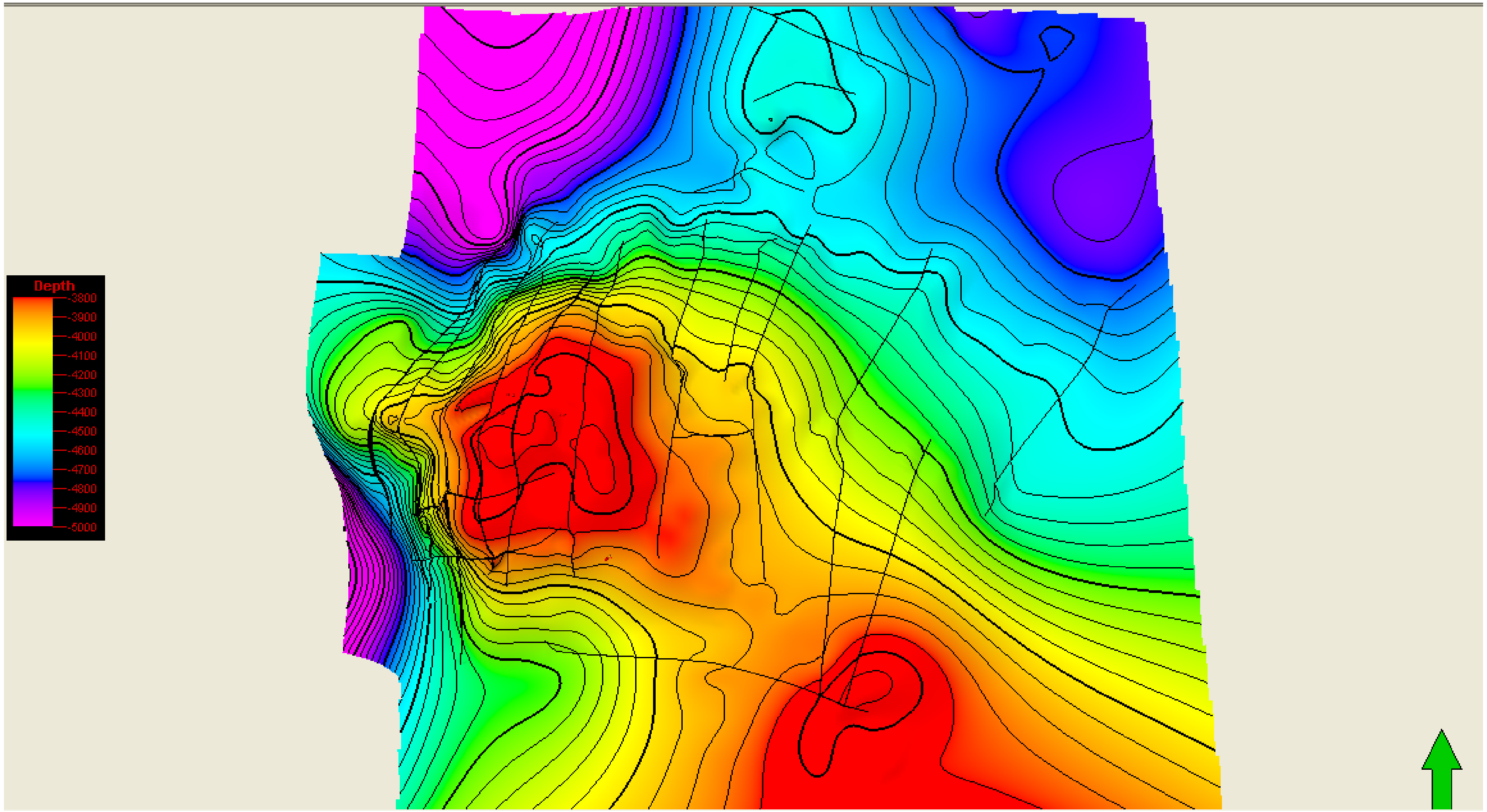


Figure 33. Plan view of the fault interpretation developed in the Whicher Range area, showing 2 main set fault network oriented NNE-SSW and to EW

Tying and picking Seismic Horizons

For this study, five wells were provided to tie the seismic data (Table 3). Once the wells were tied, top reservoir was tracked throughout the entire survey area.

The interpretation of all the 2D data was strictly done by applying a detailed manual picking. This was mainly because the auto tracking engines from Schlumberger Petrel software were unsuccessful in reliably picking horizons within the poor quality seismic data available in the Whicher Range area.

Four horizons were picked across the study area which correspond to the Tops of the Willespie Formation, Sabina Sandstone, Lesueur Sandstone and Cockleshell Gully Formation. The results obtained from the manual horizon picking are displayed in Figure 30.

Table 3. Well data locations, depths and results

Well identifier	Surface	Z	MD	TWT
WR 1	Cockleshell Gully Fm J	-784.1	937.26	620.32
	Lesueur Sandstone T	-1733.84	1887	1149.55
	Sabina Sandstone T	-3510.84	3664	1944.67
	Willespie Fm P	-3761.84	3915	2067.24
WR 2	Cockleshell Gully Fm J	-640.81	800	586.34
	Lesueur Sandstone T	-1657.81	1817	1138.49
	Sabina Sandstone T	-3495.81	3655	1946.47
	Willespie Fm P	-3736.81	3896	2060.64
WR 3	Cockleshell Gully Fm J	-653.42	791	522.06
	Lesueur Sandstone T	-1663.42	1801	1137.99
	S Sandstone	-3623.51	3761.09	2082.93
	Sabina Sandstone T	-3658.42	3796	2154.7
	Willespie Fm P	-3879.42	4017	2207.5
WR 4	Cockleshell Gully Fm J	-791.88	932	625.23
	Lesueur Sandstone T	-1762.88	1903	1164.57
	Sabina Sandstone T	-3437.88	3578	1916.33
	Willespie Fm P	-3740.88	3881	2037.95
WR 5 ST2	Willespie Fm P	-3731.09	3865.39	2034

Contouring Horizons

A contour map of the horizon was generated once the horizon and faults around the entire survey were identified. A TWT contour map was produced for the top of the reservoir horizon from the two-way-time picks. This together with the contour polygons of faulted areas were used to identify the "structural highs" surrounded by faults.

The two-way time structural contour map for the Willespie Formation, the top of the reservoir, show a faulted four-way dip closed structure embedded within a NW-SE anticlinal trend (Figure 34).

Additionally, a minor closure was observed towards the southeast of the Whicher Range structure (Figure 35). However, the lack of seismic information in this area makes it challenging to perform a detailed evaluation of its potential as structural hydrocarbon trap.

Discussion

Seismic data available around the Whicher Range main structure provide a fair control for getting a general view of the main fault networks affecting the reservoir. However, existing information does not seems to be enough to perform a detailed fault interpretation; particularly in areas where the overall distance between seismic lines is longer i.e. in the eastern quadrant of the field (Figure 28).

A distinctive variation in the degree of confidence while picking horizon characterized the entire seismic survey interpretation; i.e. it was observed that, picks tied to markers have the highest degree of confidence, possibly due to the proximity existing between the 2D seismic lines and the well log data (this was particularly true around the Whicher Range wells). However, picks performed in areas with poor seismic quality and those located beyond well control present a lower degree in picking confidence.

The structure identified along the Whicher Range area is interpreted to be mainly an NW-SE trending anticline with double crests that may result in the development of different structural traps and possibly in different gas fields. However, lack of seismic data to the east of the Whicher Range make it difficult to reliably characterize this structure and its hydrocarbon potential.

Steeper longitudinal dips on the end of the folds indicates left lateral movement along the faults (possibly linked to the dextral transpressional event related to the final break-up of Gondwana. This interpreted structural closure is most likely to be generated during two different transpressional events occurred in the basin during the latest early to Middle Triassic (Harris, 1994) and in the latest Jurassic to Early Cretaceous (during the final break-up of the Greater India and Australia).

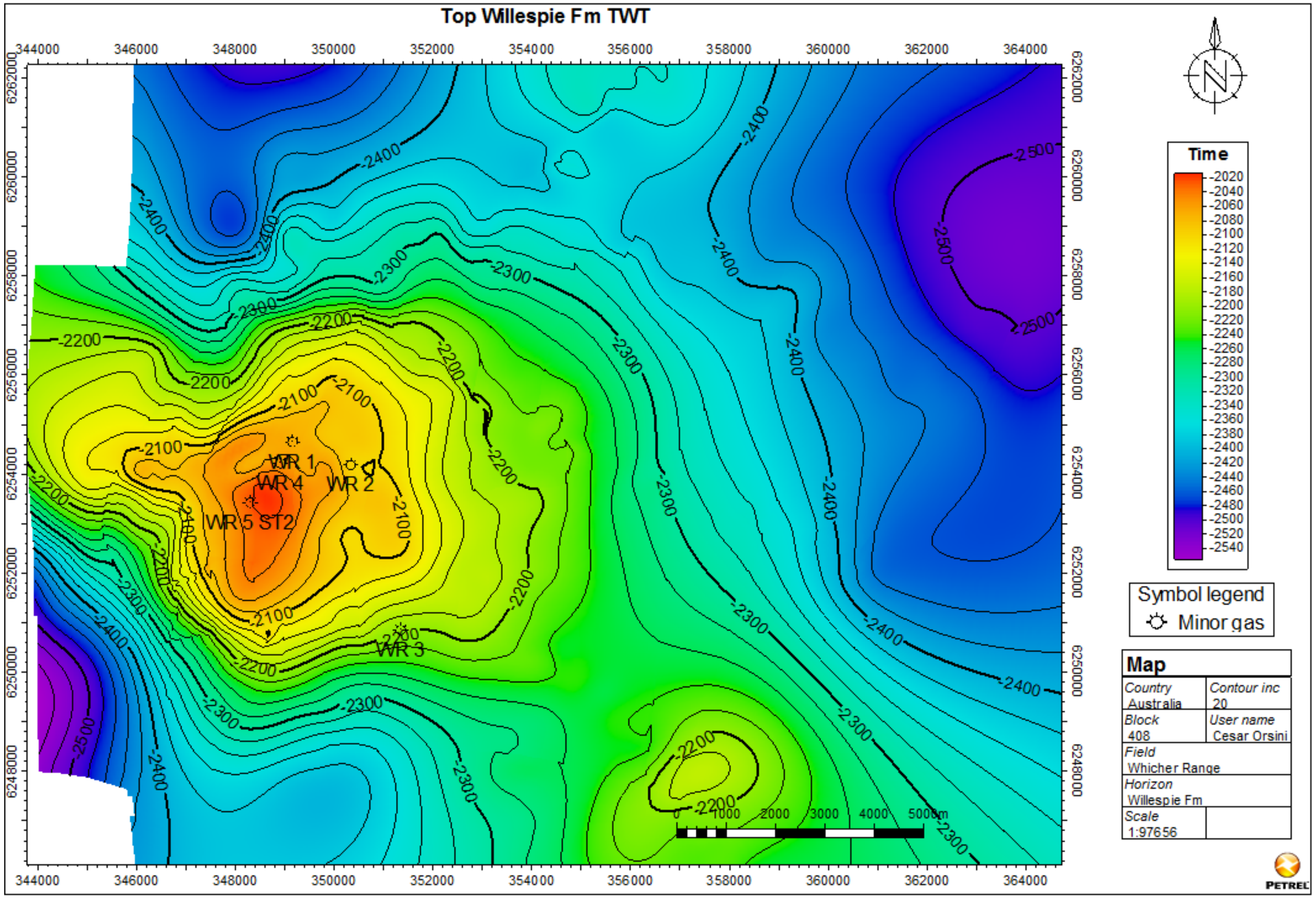


Figure 34. Contour map in TWT of the Top Willespie Formation displaying a four way closed reservoir structure

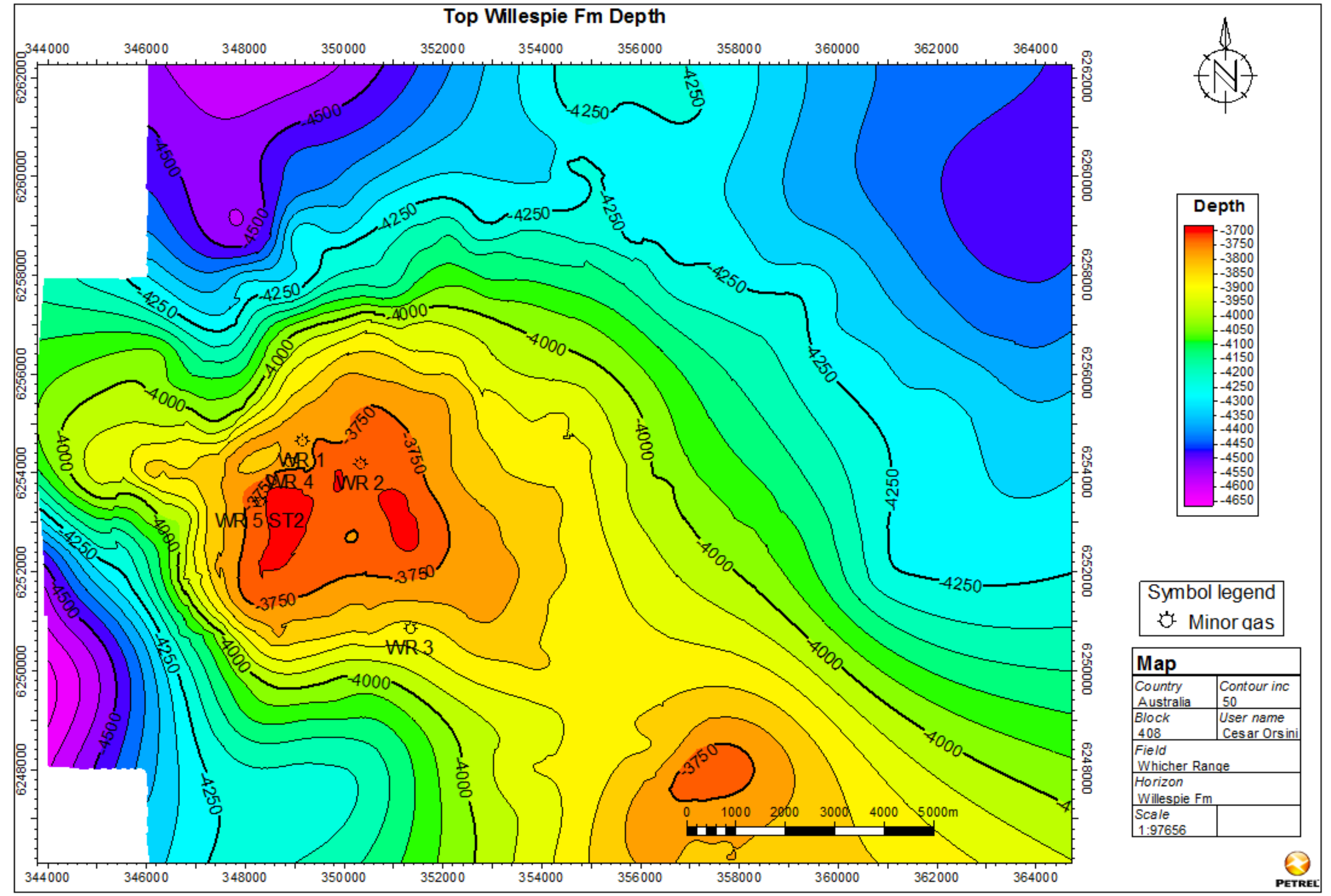


Figure 35. Map in depth of the contouring horizon of the Top Willespie Formation displaying a four way closed reservoir structure

Chapter 5 - PETROPHYSICAL EVALUATION

Introduction

Most commonly applied petrophysical interpretative methods are based on simple models that assume ideal clastic reservoirs displaying particular attributes, better described in Table 4. Rocks with these characteristics are called "Archie rocks", mainly because they match the requirements necessary for the application of the "Archie" fundamental equation for quantitative well log analysis (Archie, 1942).

The conventional "Archie" petrophysical procedures, summarized in Figure 36, have turned out to be the most used and useful tool for quantifying reservoir rock properties in low complexity formations. However, since the beginning of the development of complex conventional and unconventional reservoirs, a departure from these "Archie" conditions has brought the necessity of developing more complex petrophysical workflows that truly represent the reservoir character. In order to better quantify rock properties in complex conventional or unconventional reservoirs various modifications of a conventional petrophysical interpretation workflow have been made and specialized tools supported by special and advanced core analysis have been applied (Worthington, 2011).

Table 4.Archie vs. Non-Archie rocks compared against tight gas sands (TGS) reservoir rocks characteristics (Modified from Worthington, 2011).

Archie	Non-Archie	WR TGS rocks
Single rock type	Multiple electrofacies or petrofacies: Thin beds	Shaly/ Sands. Multiple facies
Homogeneous	Heterogeneous (variable mineralogy/texture)	Arkoses, Lithic-arkoses, Sub-LithicArkoses / variable mineralogy/texture
Isotropic at micro - meso scales	Anisotropic (elipsoidal grain shape, laminations)	Laminar Crevasse Splay facies
Compositionally clean	Clay minerals	Smectite, illite, kaolinite clay minerals
Clay/ Silt free	Argillaceous/ Silty	Clays and silts as main components
Non- metallic minerals	Pyrite and other minerals	Rare Pyrite and heavy minerals
Unimodal pore-size distribution	Multimodal pore size distribution including microporosity	Three different pore size distributions interpreted from CP and NMR logs
Intergranular porosity	(Micro) fractures/ fissures/ vugs	
High salinity brine	Fresh water	Fresh water (20000ppm)
Water-wet	Mixed wettability	Water-Wet
Ir is independent of Rw	Ir varies with Rw	

When applying conventional empirical approaches to characterize unconventional reservoirs, in this particular tight gas sands (TGS), is it important to define whether the rock follows the Archie conditions (see Table 4 for comparison between TGS properties and typical Archie/Non-Archie reservoirs), because a departure from these conditions could give rise to particular difficulties within the interpretative process, which would call for additional core and log information and for the development of a petrophysical database that is fit for purpose (Worthington, 2004).

As displayed in Table 4, the Whicher Range Tight Gas Sands (WR TGS) are characterized by a Non-Archie behaviour. Therefore, the critical petrophysical task in this analysis is to match the available data to the tight gas reservoir complexity and to use any external information (i.e. petrophysical analogue) to fill any gap existing between the reliable core/log data available and the dataset needed for a definitive petrophysical evaluation.

In this study, the petrophysical interpretation has been made by applying a more complex version of an Archie petrophysical Workflow (shown Figure 36), that has been modified to match the interpretation performed from well log data to the special core analysis data available (in most cases not performed in a complete fit-for-purpose manner). On the other hand, the lack of information caused by the absence of an extensive Fit-for-purpose petrophysical database for Willespie Formation in the South Perth Basin, has been approached by using the most recently compiled core data analysis information recorded for TGS reservoirs in the Mesa Verde Formation in the US (Byrnes, 2009). Comparison between the Mesa Verde TGS core data and the most reliable WR core data available, show a match in their petrophysical responses, and therefore the Mesa Verde TGS has been chosen as an analogue to the Whicher Range reservoir.

Within the aforementioned Archie modified workflow, gamma ray logs are used as the main shale volume indicator, mainly due to their availability in all the studied wells. Also, both total and effective porosity are calculated from acoustic logs instead of density/neutron logs; mainly due to the poor quality of the density data over most intervals within most WR wells.

Effective water saturation is estimated using the Modified Simandoux equation, which corrects for the clay effect on resistivity measurements characteristic of shaly sand TGS reservoirs. However, it is important to be aware that this approach does not account for the extra conductivity generated by high pore-surface areas commonly seen in TGS reservoirs, which according to Worthington (2011), is most likely to cause overestimation of water saturation in this type of reservoir.

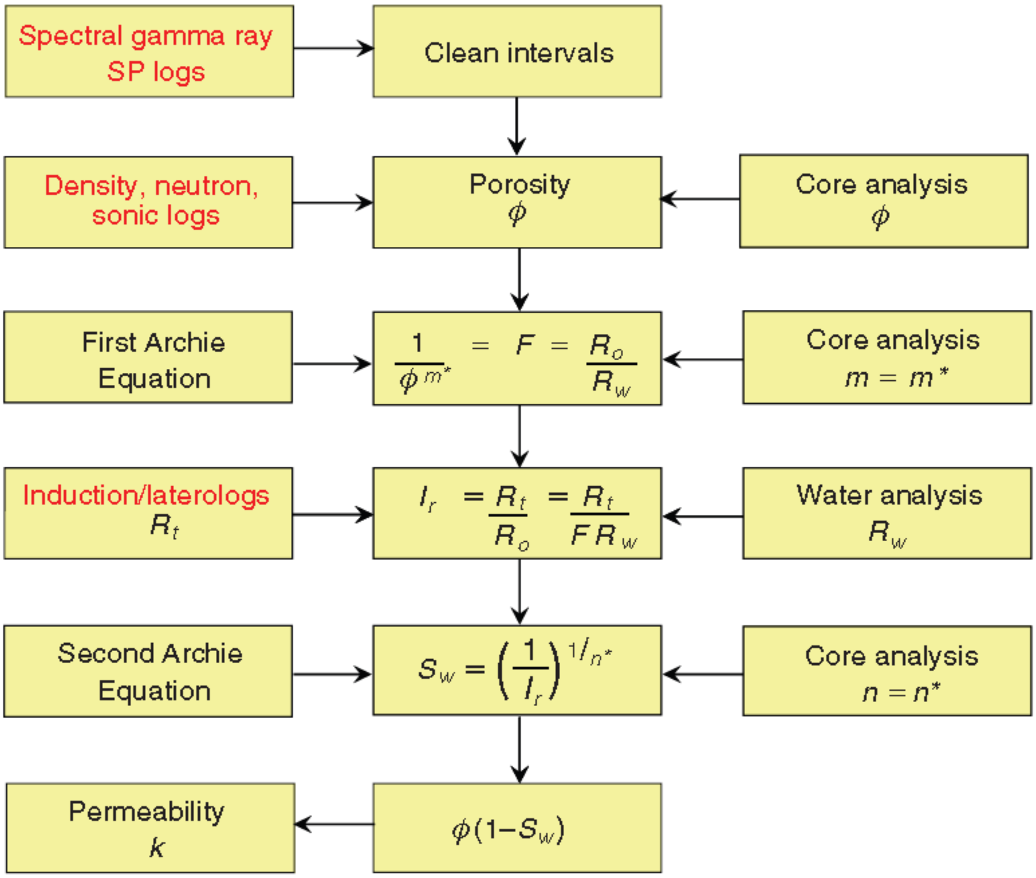


Figure 36. Standard Petrophysical workflow for complex conventional and unconventional reservoirs through standard logs (red) supported by core analysis. Note that m and n are required to be independent of water salinity (after Worthington, 2011)

This chapter discusses methods and results obtained from the petrophysical interpretation performed in the Whicher Range Field. Challenges, recommendations and uncertainties related to the application of conventional methods of evaluating unconventional TGS reservoirs are also discussed in this chapter.

Petrophysical Analysis

The main objective of performing a petrophysical analysis for each one of the five Whicher Range wells, is to better understand the main rock properties of the Willespie Tight Gas Sand (TGS) reservoir, including lithology volumes (sand/shale), porosity (total and effective), hydrocarbon saturation and matrix permeability. By developing a petrophysical analysis we not only aim to quantify properties and to improve our understanding of the vertical and lateral variations (rock heterogeneity), but also to identify intervals that enclose the best rock quality facies and to study their positions within different stratigraphic sequences.

We examine the complexity of characterizing the Whicher Range TGS reservoir by studying rock characteristic and comparing it to a typical "Archie rocks". We also examine theories behind the conventional petrophysical approach and the differences from the studied reservoir, and analogies with the Mesa Verde Tight gas reservoirs.

Gathering, validation and verification of the available data

A robust petrophysical model requires a complete set of information describing, in a direct or indirect way, the rock properties present within the reservoir. Most data required for the petrophysical analysis of the five Whicher Range wells was collected from Curtin University Department of Petroleum Engineering, WAPIMS (Western Australian Petroleum and Information Management System) and Whicher Range Energy. This dataset mostly comprises well completion reports, well log data (provided in LAS and DLIS format), geological well reports and core analysis reports.

Five well has been drilled in the Whicher Range Field using a water based mud system. Different combinations of open-hole wireline tools were run in each well from which most conventional well logs, including gamma ray, resistivity, density, caliper and compressional slowness were recorded for all five wells (Figure 37). Neutron log measurements were acquired in all wells with the exception of Whicher Range 1 and shear slowness measurements were recorded only within Whicher

Range 4 and 5. Also, a nuclear magnetic resonance log (CMR) was acquired in Whicher Range 4, but just a questionable quality CMRP (porosity from NMR) log was available for this study. Furthermore, a borehole image log (FMS) was acquired in Whicher Range 5 but this data was limited to good hole intervals or localized sections where some data could be recovered from the strong effects of stick and pull.

Additionally, core and core analysis data were available in Whicher Range 1, Whicher Range 2, Whicher Range 3 and Whicher Range 4. (Table 5). Core permeability profiles from permeametry (PDK-300), were also measured as part of the routine core analysis performed by CoreLab in 1997 (Whicher Range 4 well) and in 1998 (Whicher Range 1- Whicher Range 3 wells).

Table 5. Core Data available for Willespie Formation in the Whicher Range Field Study

Well #	Core Type	Depth mRT		# core	Samples	Test Conditions	Quality
WR 1	Conventional	**3946.3**	**4209.0**	6	55	Unconfined/ Amb?	poor(*)
WR 1	Sidewall	**4007.5**	**4057.5**		10	Unconfined/ Amb?	?
WR 2	Conventional	**3890**	**4178**	4	?	Unconfined/ Amb?	?
WR 3	Conventional	**3884**	**4431.9**	6	?	Unconfined & 800psi	?
WR 4	Conventional	**3915**	**4098**	3	?	Unconfined & 800psi	?

Wireline well log QA/ QC and log editing

Although different combinations of open hole wireline tools were run in each well, the standard acquisition of conventional well logs such as gamma ray, shallow and deep resistivities, density and compressional slowness (Figure 37), allowed a standard petrophysical analysis for all the drilled wells. Advanced wireline logs (i.e. Dipole sonic & FMS logs) run in the latest the wells, were used as calibration tools to provide robustness to the conventional petrophysical analysis. In despite of the availability of CMRP (NMR porosity) log in the Whicher Range 4 well, this was disregarded from the interpretation due to the questionable quality of this log given by the poor borehole conditions and the small DOI of the NMR tool.

Poor hole conditions including washouts, rugosity and breakouts were identified from calipers and borehole image logs (Figure 38). The majority of the enlargements found in the Willespie Formation are related to good porosity sand intervals and occur during drilling when the borehole wall (in weak sandstones) fails in compression, due to the regional tectonic stress. These features indicate high in-situ stress conditions that have been reported as “approaching mechanical limits of the rock fabric” (Pennzoil, 1998).

Wellbore ovalization (breakouts) commonly affect pad- based measurements (e.g. density logs and wireline resistivity images), mainly because wireline tools (run in vertical wells) tend to rotate freely along in-gauge hole intervals and get stuck in intervals where breakouts impede tool rotation. When the pad loses contact with the formation, bulk density measurements approach mud density, producing invalid data for computing porosity. A spiky saw tooth curve is generated as a consequence of this effect, as observed in Figure 39 at about 4495m.

As a result of the QA/QC phase, poor quality intervals were identified and highlighted for future editing. As expected, bulk density data was found to be the most affected log in all Whicher Range wells. Therefore, it has to pass strict editing before being used in any interpretation.

In the cases of Whicher Range 4- and Whicher Range 5, a dual bulk density measurement (two density tools with sensors orthogonal to each other) was acquired to target in-gauge areas within sand units affected by borehole breakouts, with the expectation that at least one density pad would always be in contact with the shorter borehole axis (De Koningh et al, 2008). This special set of information contributed to the improvement of density data, particularly in intervals affected by compressive wellbore failure, where in most cases good to moderate quality data was recorded by the tool seated in the direction perpendicular to the breakout (Figure 39).

Although enlargements were present along most intervals the Whicher Range wells, most of the conventional data recorded displays fair data quality. Near and far compressional slowness curves, when available, were used to verify sonic data quality and to correct cycle skipping. An example of the differences between near and far acoustic measurements is displayed in the last track of Figure 39.

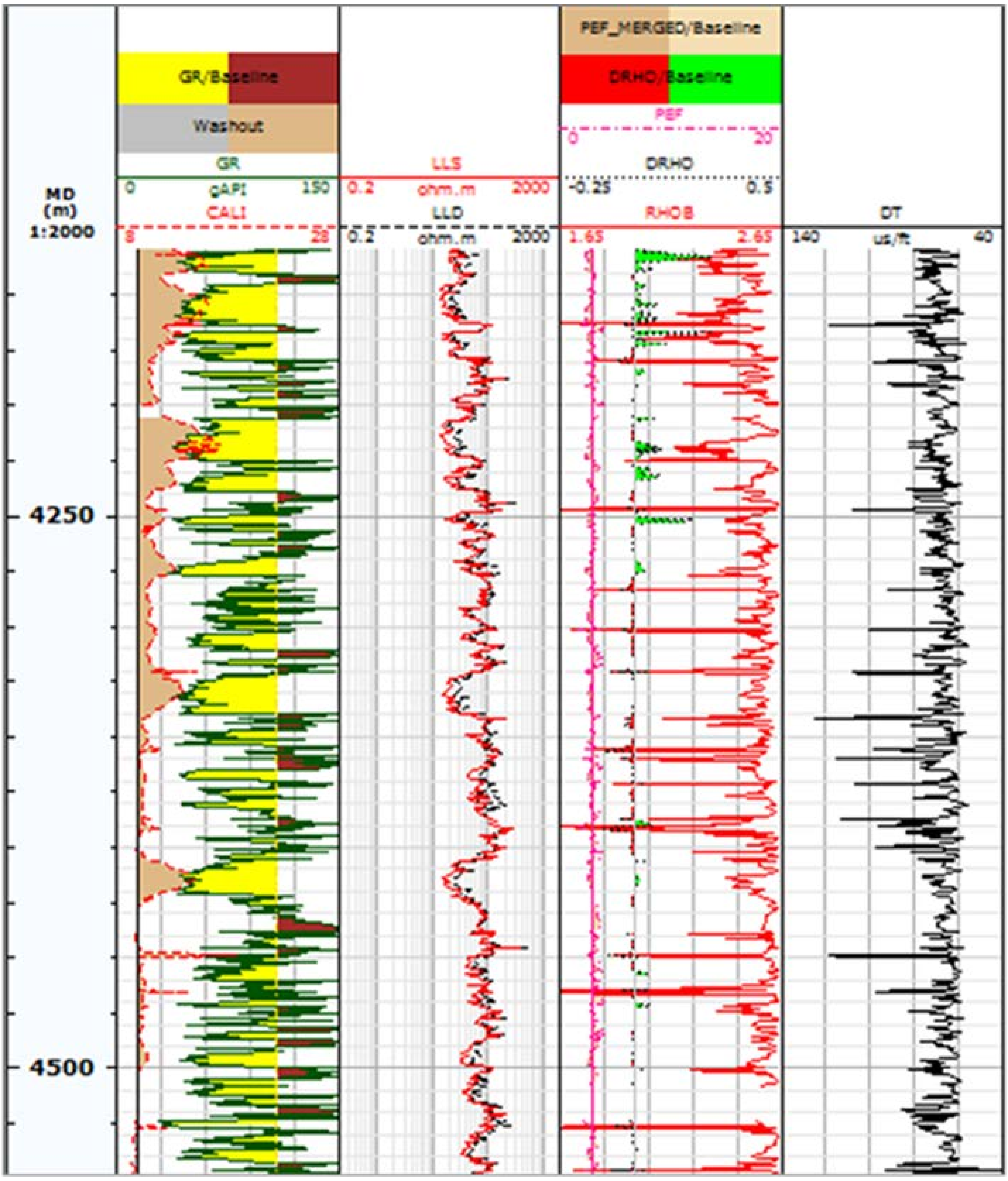


Figure 37. Most conventional logs were recorded in the five Whicher Range Wells. The example above shows well logs available for all Whicher Range wells

After the QA/QC stage was completed, a series of log editions were performed to condition the logs for the petrophysical interpretation. The log editing phase generally started with the log environmental correction and data normalization. The main aim of this phase is to reduce the effects of logging errors and other noises affecting the data set. These noises may be related to a variety of causes including technological changes in logging tools and the use of different processing algorithms depending on vendors and logging date.

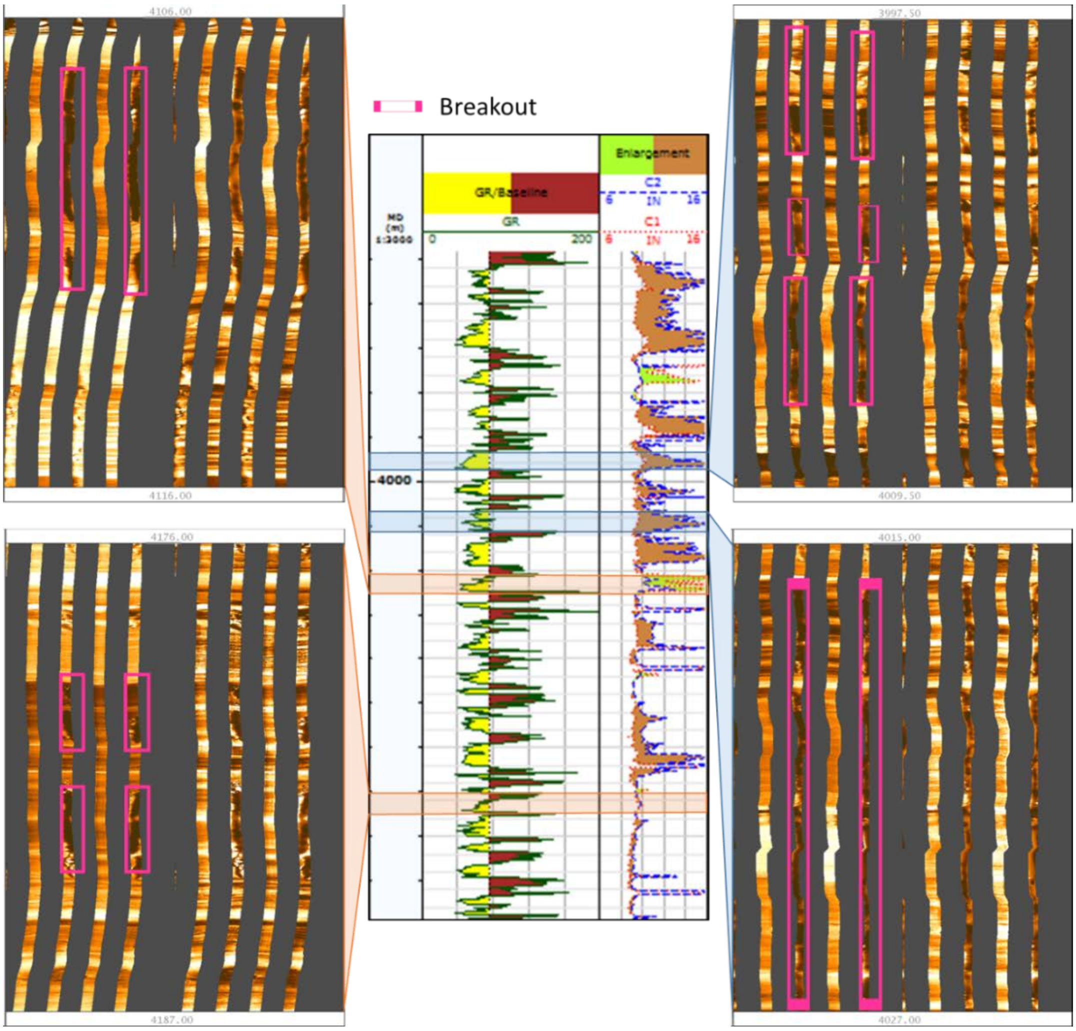


Figure 38. Borehole breakouts are present in the majority of the good porosity sand units. They has been recognized in all five drilled WR wells but has only been seen in the FMS log acquired in WR5.

In this study, all the open-hole wireline log data were recorded by the same service provider (Schlumberger), but with different acquisition dates (i.e. Whicher Range 1 recorded 1968 and Whicher Range 5 in 2003). Differences in acquisition date generally imply changes in tool generation and in processing methods, which may result in a mismatch between well log responses, which do not correspond to changes in rock properties.

Generally, environmental correction routines are the first method used to compensate for differences in environmental conditions present in a particular log acquisition. In theory, these corrections should remove all differences between logs due to varying logging environments such as (but not limited to) hole size, temperature, mud properties, anisotropy, etc. However, in practice, differences in well log responses usually still remain after such an exercise.

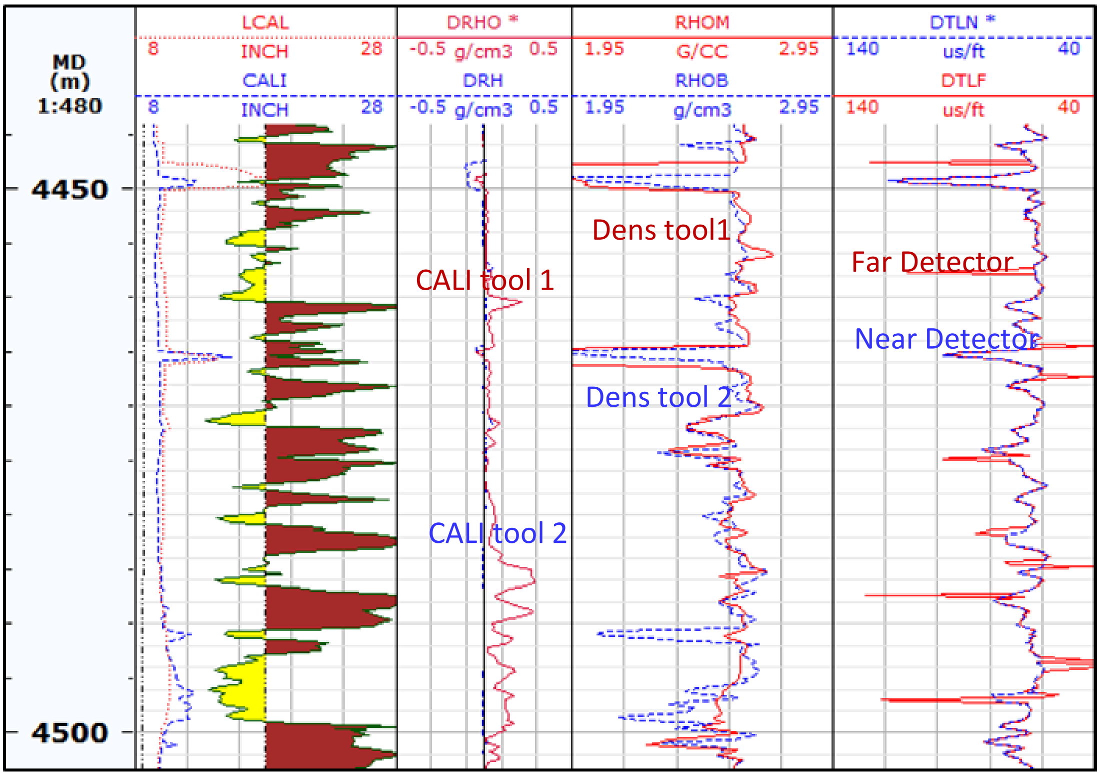


Figure 39. Example of the acquisition of dual bulk density measurements in Whicher Range 4. Blue and red curves in the first 4 tracks, correspond to measurements recorded by the short and long axis tool, respectively. Density log quality varies depending on each tool positioning in reference to the breakout orientation. Caliper data recorded from the dual density tool, in the short and long axis, display elliptical enlargements in sand intervals (4991m & 4495-4498m) indicating high stress conditions (2nd track). Bulk density logs recorded from different axes display significant differences at washed out section (track #3). Compressional slowness measured by the near and far detector are similar with exception of localized noise spikes and/or cycle skipping occurring at the far detectors.

Most of the time, the main challenge faced before applying any environmental correction, especially in vintage data, is reviewing and understanding the well log edition history, mainly because in most cases this information was never recorded or got lost along the years (Buffin, 2010). This is the case with the Whicher Range field study, which presented very limited well log edition history information, making it a challenge to determine if environmental corrections were needed.

Buffin (2010) argues that in cases where no log edition history is available, it is preferred not to correct than overcorrect, unless the correction is obviously required. For this reason and given the uncertainly around the curve history in the Whicher Range well log files, it was decided not to apply any environmental correction to the logs, but compensate for any irregularity by applying a standard normalization procedure when necessary.

Normalization aims to reduce uncertainty and provide consistency to well logs, particularly in areas/intervals of known and constant properties with the expected response in that lithology.

The normalization procedure may involve both applying an offset (bulk shift) to the log curve or applying a gain correction between two known end points.

In the case of GR normalization for Whicher Range 1 and Whicher Range 4, both adjustments were applied to the observed response in the entire Willespie Formation. The main assumption made during this process was the linearity in the log response and that it can be approximated by a simple slope-intercept method.

In order to verify consistency between wells, compare reservoir rock properties and investigate a possible occurrence of a lateral change in facies, multiwell frequency plots were generated for each curve type (see Figure 40). Good consistency and no visible change in facies is inferred from these plots as displayed in Figure 40. However, anomalous behavior of the GR logs in Whicher Range 1 and Whicher Range 4 is observed when compared to the other three wells. For this reason GR normalization was applied to Whicher Range 1 and Whicher Range 4 GR logs to represent the consistency of rock properties shown by the rest of the logs.

In the case of the Whicher Range study, considering that commonly nuclear tools (GR and neutron) are the first candidates for normalization (due to the strong impact that environmental conditions may have in this type of measurements) and that there is evidence that points toward a lateral/vertical consistency in rock properties (a total of 1999 rock properties core analysis" performed by STIM-LAB), confirmed by frequency plots of the conventional logs in all Whicher Range wells (Figure 40), a general assumption of defining a similar shale and clean response in the five studied wells has been made.

Volume of shale (Vsh) estimation from Gamma ray (GR) log

After the GR normalization, a shale volume (Vsh) was estimated using the gamma-ray curve. Shale content estimation from GR, similar to SP, is performed by scaling the GR log to shale volume units with respect to two endpoints: GR clean (0% Vsh) and GR shale (100% Vsh).

Quantitative estimation of shale content using GR logs assumes that shales and clays are the only radioactive minerals present in the rock. However, it is well known that this assumption may not always be true. Crain (2008) argues that some of the radioactive response in tight sands may correspond to uranium enrichment associated with phosphates and kerogen and that these are most likely to recognized by comparing all the spectra composing the gamma ray signal (thorium, potassium and uranium spectra). However, a spectral gamma log is only available in one of the five Whicher Range wells (see spectral curves displayed in the last track within the WR4 plot in Figure 41, Figure 43 and Figure 44). Therefore only an approximation of the impact of non-shale/clay radioactive material on our shale volume estimation can be made by using this data. Nevertheless, it is important to highlight that the GR response in the Whicher Range wells does not seem to be controlled either by uranium or potassium content (the latter one possibly associated to feldspar present in the rock), which makes the Gamma Ray log a good shale indicator.

Gamma ray index is estimated through Equation 1 and shale volume is calculated directly through a linear empirical relationship between the gamma ray index and shale content, which gives the upper limit of the shale content in any formation.

Equation 1 $$\boldsymbol{IGR = \frac{(GRC - GRcln)}{GRsh - GRcln}}$$

In Equation 1, GRC corresponds to the gamma ray curve environmentally corrected and normalized; GRcln is the normalized value for a clean sandstone and GRsh is the normalized value for shale.

Normalizing the GR curves allowed the definition of common end points to be applied for the shale volume calculation in all Whicher Range wells. The GR multiwell frequency plot including all WR wells is used to define GRclean and GR shale endpoints which are 60 GAPI and 180GAPI, respectively.

The SP could not be used for shale estimation in the Whicher Range wells because gas content has suppressed the SP response. An example of this gas effect can be observed in Figure 41 and Figure 44.

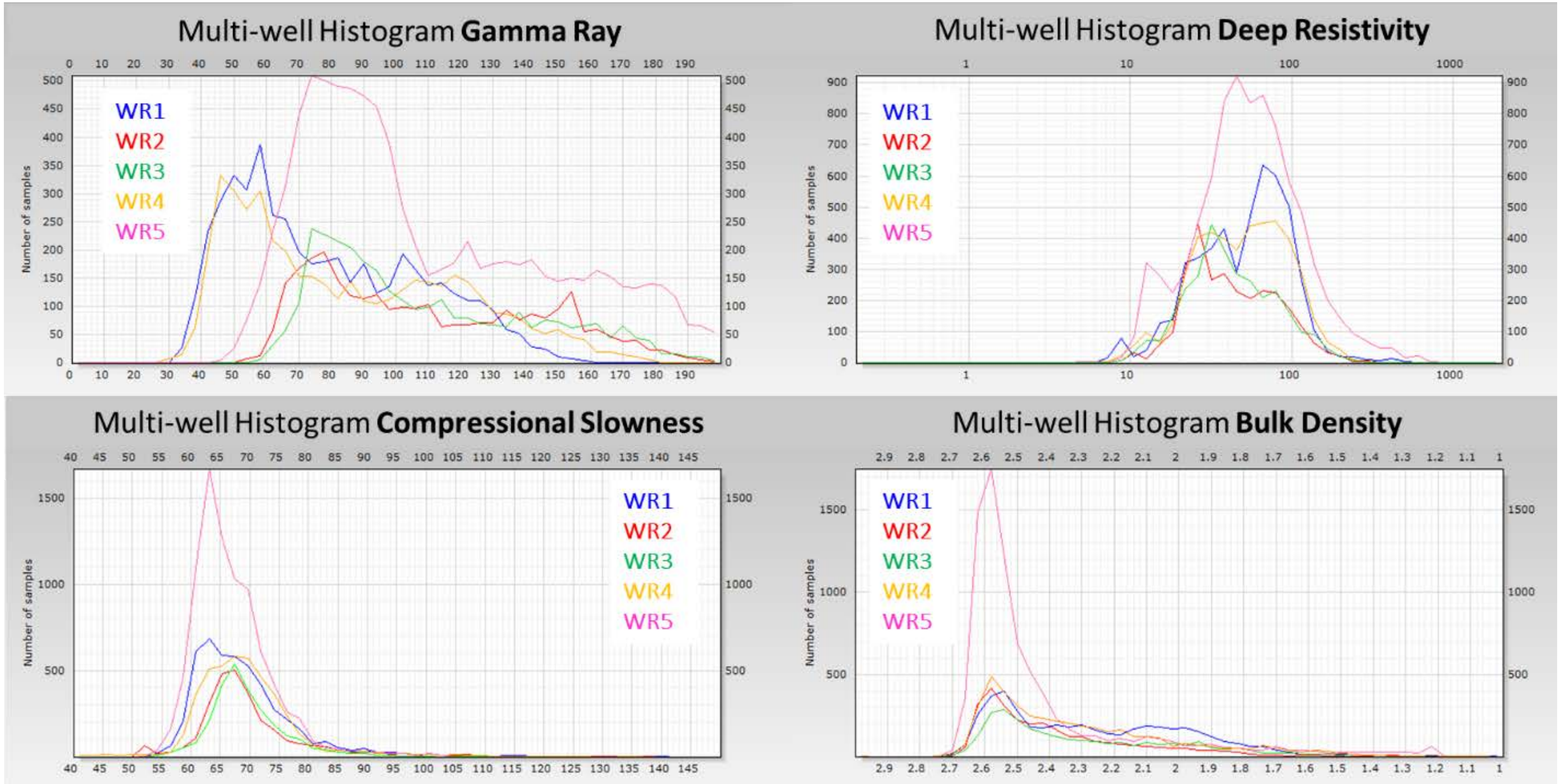


Figure 40. Frequency plots from five wells in Whicher Range Field. Well log responses in all of the five wells are very consistent with the exception of the GR log which show a distinct difference between Whicher Range 1 and Whicher Range 4 and the other wells. There is also an evident increase of sampling rate in all logs in WR5 when compared to the rest of the study wells.

On some occasions, additional corrections to the Gamma Ray index are needed to better correlate it to shale volume, particularly in young unconsolidated rocks. Some authors (i.e. Crain, 2008) argue that applying some of these may help to correct Vsh from uranium enriched zones typical in TGS. However, this is not the case in the Whicher Range Willespie Formation (see Figure 41), in which a high density matrix value increases the Gamma Ray absorption, providing a more linear relationship between gamma ray index and shale content. Considering the aforementioned reasons, no corrections were applied to the shale volume estimated from GR.

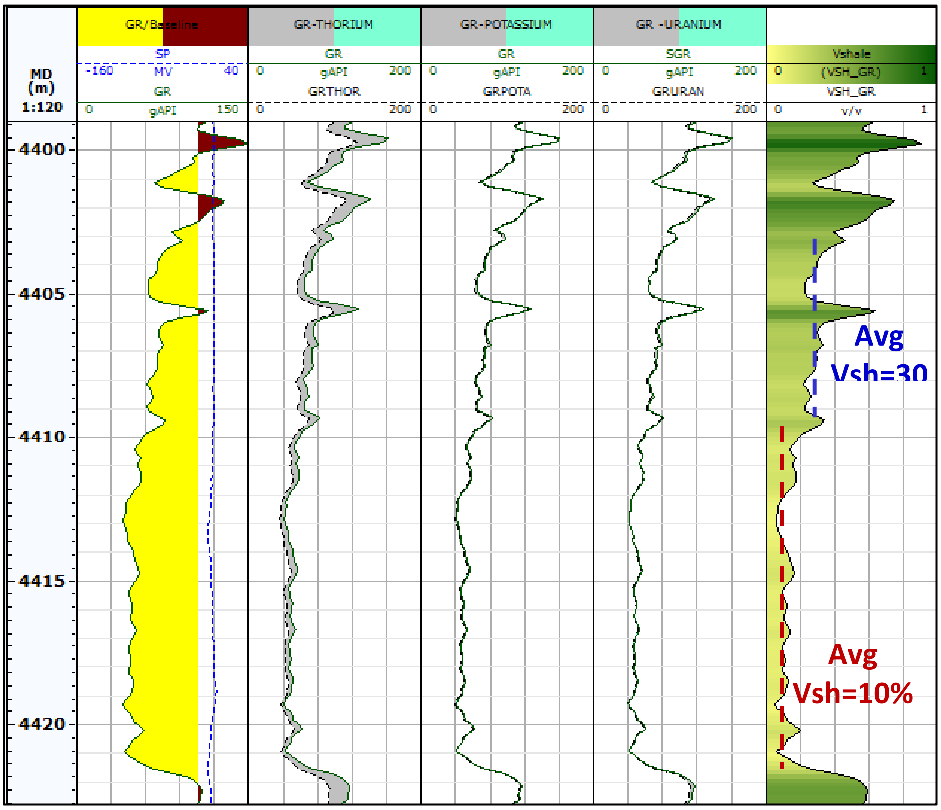


Figure 41. Average shale content varies within the main sandstone packages. Also, effect on uranium and potassium content on the GR response are shown to be minimum, therefore a linear relationship between GR and shale index may be applied to define shale volumes in the Whicher Range reservoir.

The frequency plot displayed in Figure 42 compares the shale volumes calculated in the five Whicher Range wells. The gamma ray multiwell frequency plot of shale volume, displays a log-normal distribution. Volumes below 30% Vsh are dominant within the interval in all wells. Furthermore, shale volumes in Whicher Range 1 and Whicher Range 4 are high in comparison to the other wells.

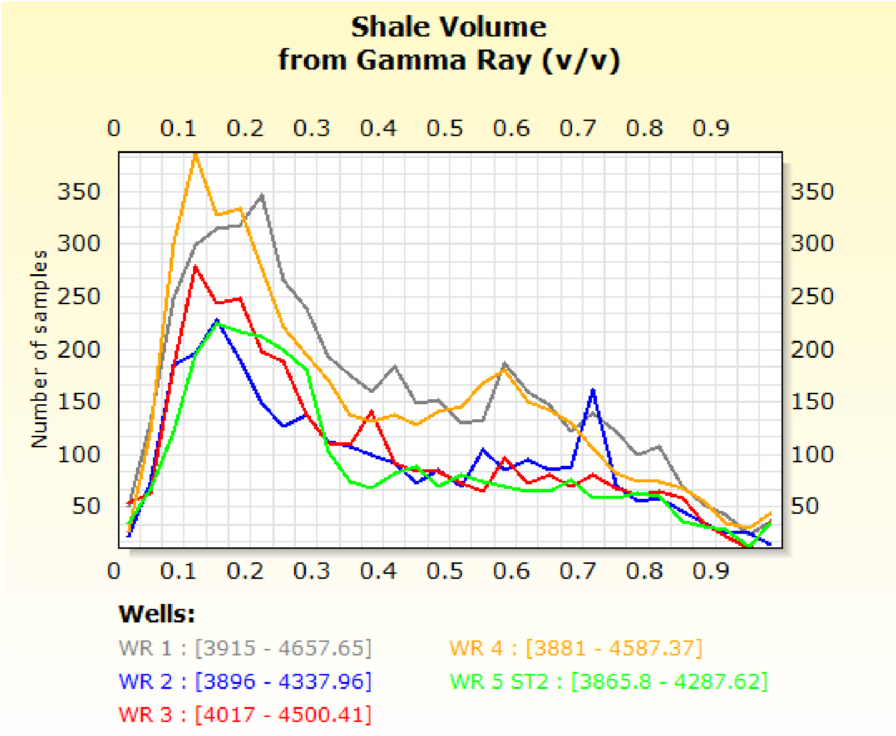


Figure 42. Frequency histogram showing overall comparison between GR calculated shale volume for the five Whicher Range wells. A distinct increment in number of samples is observed in the two deepest drilled wells (Whicher Range 1 and Whicher Range 4). A particular increment in shale content is observed in both wells when compared to the other 3 wells

Total and Effective porosity

Porosity estimation provides an indication of the storage capacity of the reservoir. Porosity is controlled by both syn-depositional and post-depositional diagenetic processes.

Unlike conventional sandstone reservoirs, effective porosity in TGS tends to be much lower than total porosity and may involve various types of porosity including primary, secondary, micro-porosity and grain fracture porosity (Newsham & Rushing, 2001).

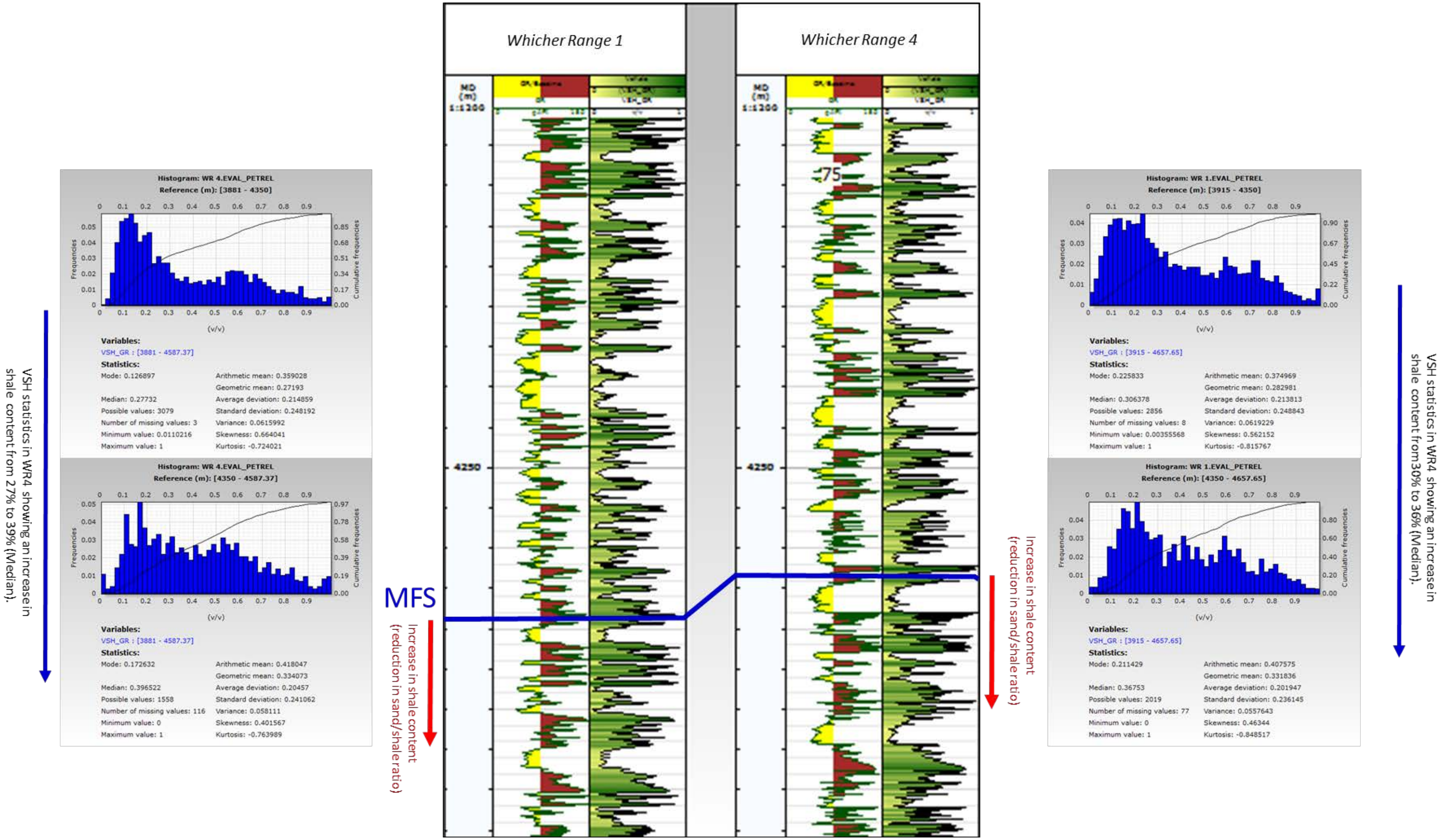


Figure 43.Comparison between Vsh estimation performed for the five Whicher Range wells in a correlated interval.

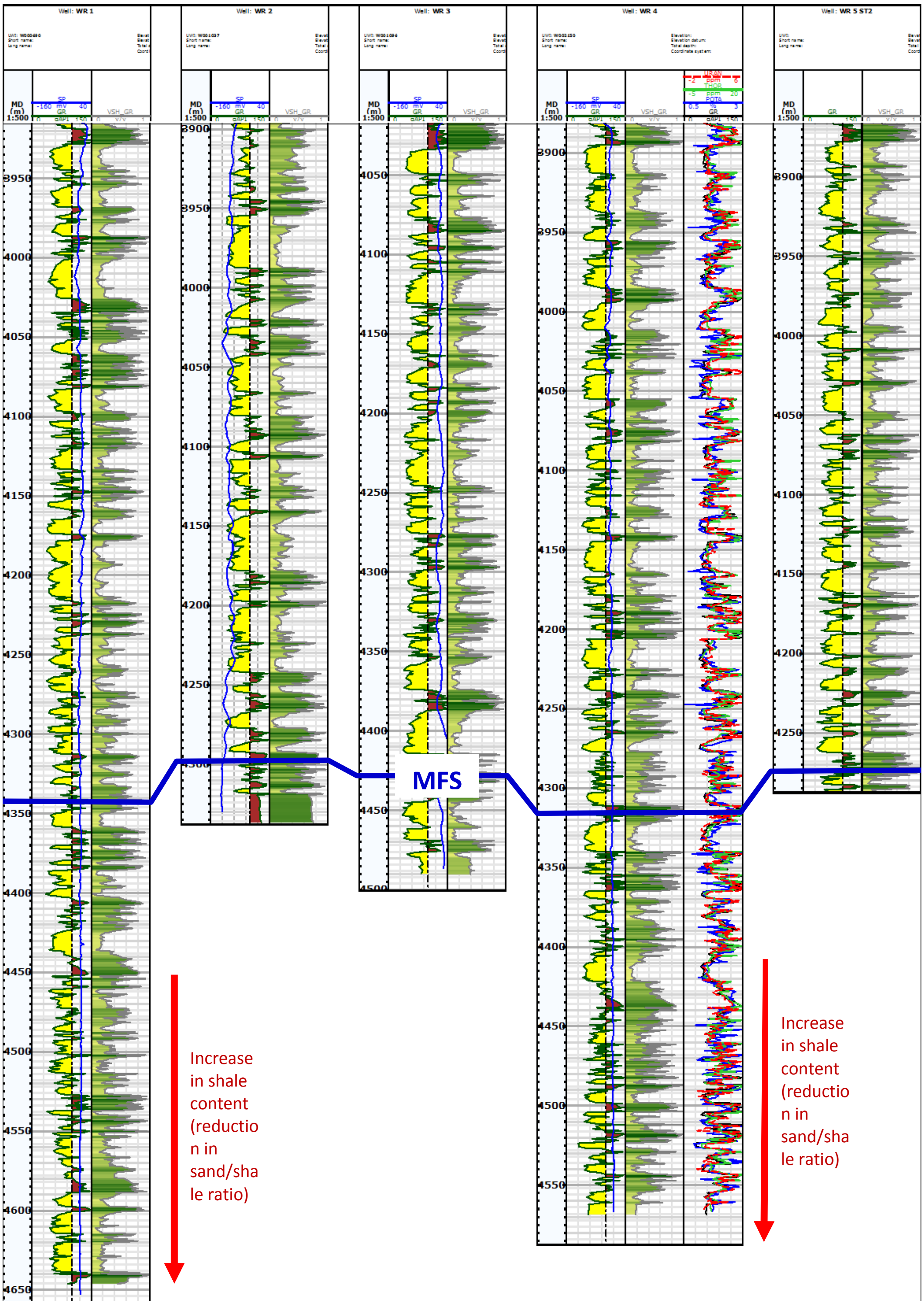


Figure 44. Vsh estimation for the five drilled Whicher Range wells. Gamma Ray (green) and Spontaneous Potential (blue) curves are displayed in the second track. There is no agreement between them due to the gas effect on the SP. Whicher Range 4 (WR4) is the only well with Spectral data.

Conventionally, the density log is preferred for porosity estimation, due to its similarity with the porosity measured from oven dried core plugs. Furthermore, density logs can be highly affected by rugosity and washouts, as is the case with the density logs acquired in the Whicher Range field. The poor quality of the density logs was the main reason for using other conventional logs available in all wells, such as acoustic logs (DTC), for porosity calculation.

Three methods were applied for porosity estimation:

Porosity calculation from acoustic logs, using the Raymer-Hunt-Gardner approach

Based on previous study by Dvorkin (1998), it has been demonstrated that the Raymer *et al,* (1980) velocity – porosity transform (Equation 2 & Equation 3) can be reliably used for cemented sandstones with porosity less than 35%. Therefore, this equation was used to calculate total and effective porosity. Equations related to this transform are displayed below:

Equation 2
$$\phi_t = 1 - C - \sqrt{C^2 - \frac{\Delta_{t_{ma}}}{\Delta_{t_f}} + \frac{\Delta_{t_{ma}}}{\Delta_t}}$$

Equation 3
$$\phi_E = 1 - C - \sqrt{C^2 - \frac{\Delta_{t_{ma}}}{\Delta_{t_f}} + \frac{\Delta_{t_{ma}}}{\Delta_{t_{cc}}}}$$

where

Equation 4
$$C = \frac{\Delta_{t_{ma}}}{(2 * \Delta_{t_f})}$$

and

Equation 5
$$\Delta_{t_{cc}} = \Delta_t - V_{sh} * (\Delta_{sh} - \Delta_{t_{ma}})$$

where Δt corresponds to the sonic log reading in the zone of interest; Δt ma is the sonic log reading in a 100% matrix rock; Δt fl is the sonic log reading in 100% water; Δsh is sonic log reading in 100% shale.

The acoustic Vsh parameters used for the analysis were established based on a Vsh vs. DT crossplot and afterwards adjusted to match the estimated porosity log to core porosity data. An example from Whicher Range 4 is given in Figure 45.

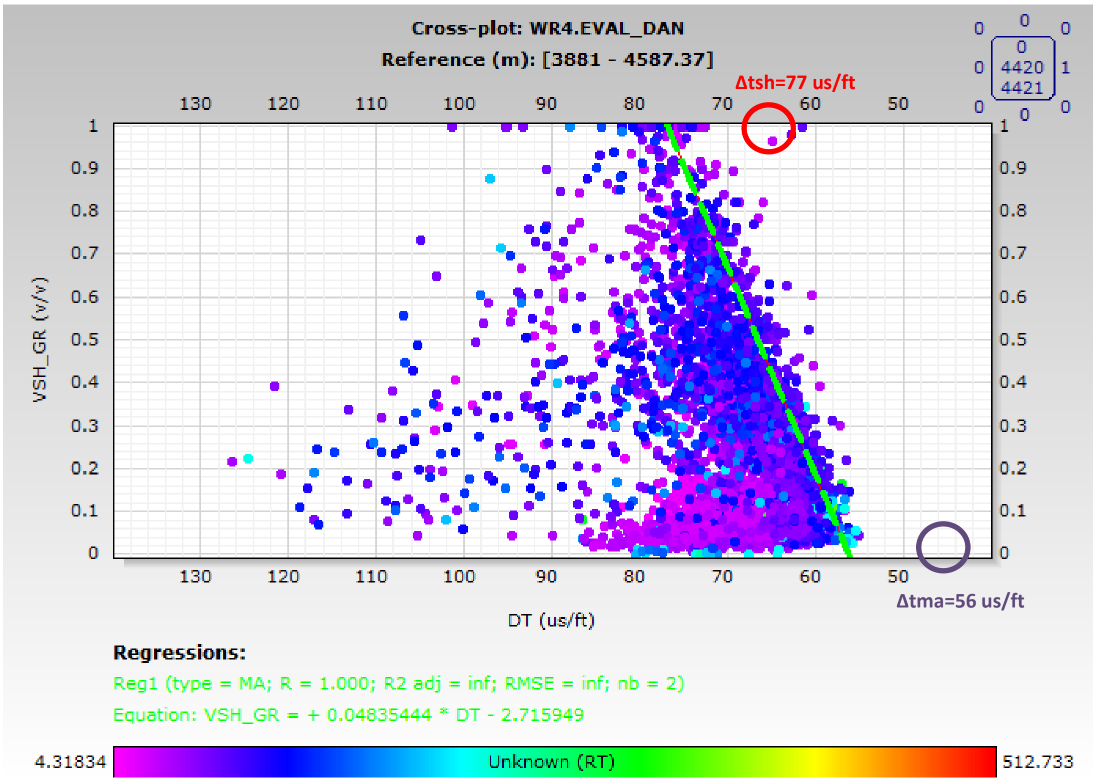


Figure 45. VSH vs. DTC crossplot used to define acoustic responses in Sand (0% vsh) and shales (100% vsh). A DTmatrix=77us/ft and DTsh=56 us/ft were predicted from this crossplot.

Porosity estimation from Density logs

Bulk density logs were used to calculate porosity within the Willespie Formation in the Whicher Range field. The standard density-porosity relations were applied to get total (Equation 6) and effective porosity (Equation 7).

Equation 6 $$\phi_T = \frac{\rho_{ma} - \rho_B}{\rho_{ma} - \rho_f}$$

Equation 7 $$\phi_E = \phi_T - (\phi_{T_{sh}} * VSH)$$

Equation 8
$$\phi T_{sh} = \frac{\rho ma - \rho sh}{\rho ma - \rho f}$$

where, *matrix density* (ρ_{ma}) was estimated to be 2.69 g/cc based on a Hingle plot. This matrix density coincides with the average obtained from core data; *bulk density* (ρ_B) is from density tool readings; *fluid density* (ρf) was assumed to be a constant 1.014 gr/cc. This value was obtained by averaging water density measurements performed in Whicher Range 1 and Whicher Range 4 Table 6.

Based on an statistical analysis of the total porosity values estimated from acoustic logs the Whicher Range reservoir porosities range between 2 and 15%, as represented in the box plot shown in Figure 46.

Table 6. Results from water sample analysis performed for WR1 and WR4

Water Analysis WR 1

Sample #	1	7	11	11	12	13
Container #	J/C1	P/B3	Base Gel	P/B6	J/C3	J/C4
Chloride, Cl (mg/l)	10000	8900	11000	10000	10000	10000
Resistivity ohmm@60˚F	0.352	0.444	0.281	0.360	0.365	0.360
Density g/cc @ 60˚F	1.017	1.014	1.019	1.013	1.012	1.014

Water Analysis WR 4

Sample #	2	3	4	5	6
Container #	P/B7	P/B8	J/C5	J/C6	P/B9
Chloride, Cl (mg/l)	9500	9800	8900	8800	8900
Resistivity ohmm@60˚F	0.453	0.432	0.478	0.475	0.465
Density g/cc @ 60˚F	1.012	1.016	1.013	1.011	1.012

Effective Water Saturation

Effective water saturation is estimated using the modified Simandoux equation (Equation 9), which corrects for the clay effect on resistivity measurements characteristic of shaly sand TGS reservoirs.

Equation 9
$$\frac{phi_e^m}{a*Rw*(1-Vsh)} * Sw^2 + \frac{Vsh}{Rsh} * Sw - \frac{1}{Rt} = 0$$

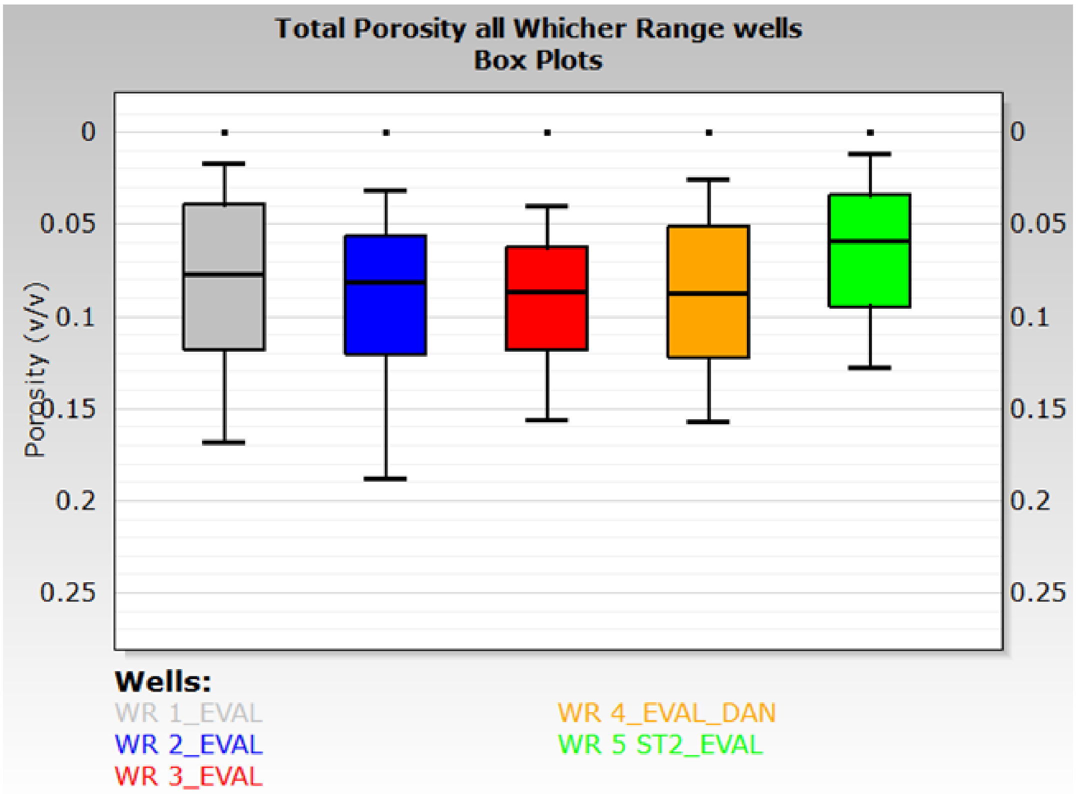


Figure 46. Box plots showing the distribution of total porosity in each Whicher Range well.

The necessary information for calculating water saturation from logs was gathered from available reports and analyses performed in the five Whicher Range wells. The first parameter investigated was the Archie cementation exponent (m). This was measured for 12 core samples, using a 200,000 ppm NaCl concentration brine in WR3 well. Analysis of this data shows a strong curvature when m decreases as a function of porosity, as is represented in Figure 47.

Due to the absence of an extensive database in the Whicher Range field, a comparison was made with an analog database from the Mesaverde tight gas sandstone. Similar to the result shown by Cluff and Byrnes (2008) the cementation exponent can be described as a function of the porosity using an empirical or dual porosity model relationship.

Equation10 $$m = \log\left[(\emptyset - \emptyset_2)^{m1} + {\emptyset_2}^{m2}\right] / log\emptyset$$

Where Ø = bulk porosity (fraction), $Ø_2$ = fracture or touching vug porosity, m1 = matrix cementation exponent, and m2 = fracture or touching vug cementation exponent.

The idea of considering a variable m for performing the petrophysical analysis was to compensate for the variable porosity found in tight sand intervals due to the high grain surfaces areas.

The second parameter defined was Water Resistivity (Rw). Based on water sample analysis performed for Whicher Range 4 and 1, the formation water resistivity at ambient conditions (Rw @ 75˚F) ranges between 0.23 and 0.453 ohm.m. Therefore, an average value of 0.36ohmm@75˚F, which is equivalent to 0.12 ohmm @ reservoir conditions (212˚F= 100˚C) was used for estimating water saturations in all five Whicher Range wells.

The final parameter needed to determine the saturation is Shale Resistivity (Rsh). This was estimated using a Resistivity (RT) versus shale volume (Vsh) crossplot. Value were picked at the top shales within the Willespie Formation because these were found to better represent shale in the reservoir. An average value of about 50 ohm-m was used for the water saturation analysis.

Figure 47 shows how parameters defined for the intermediate to low cases in the Mesaverde TGS allow a good approximation of the m value for the Whicher Range Field. Therefore, it was applied in the five Whicher Range wells to estimate the cementation exponent.

Finally, an estimation of water saturation was achieved by applying the modified Simandoux equation (Equation 9).

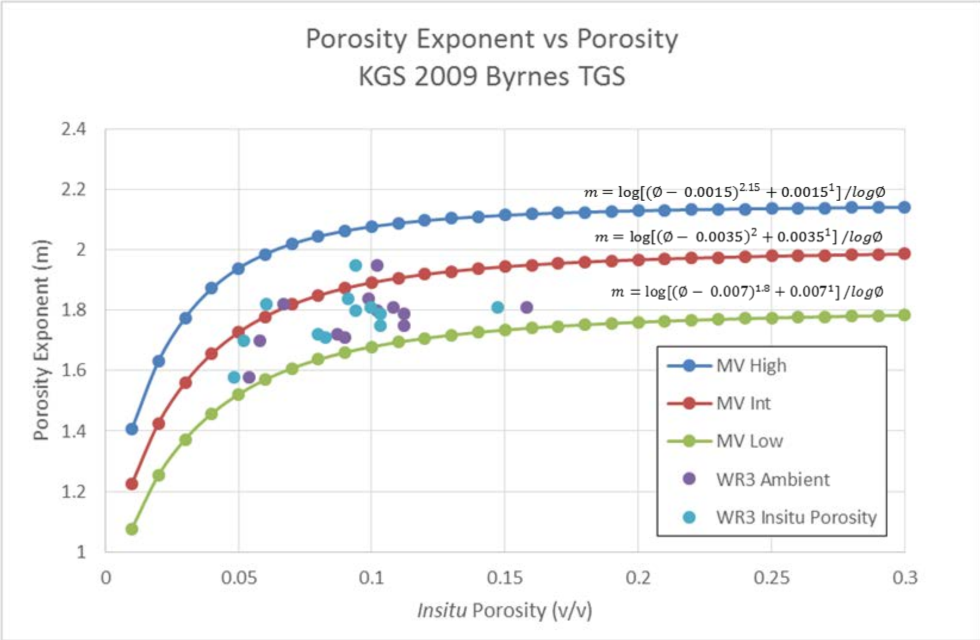


Figure 47. Crosplot of In-situ Archie cementation exponent, m (assuming a=1) vs Porosity showing a decrease in m with decreasing porosity in Whicher Range field. Blue, red and green curve correspond to dual porosity model from Mesaverde TGS after Cluff & Byrnes (2009). Whicher Range core data falls between the TGS Mesaverde "m" vs porosity relationship.

All the curves obtained from this analysis were used as an input to populate rock properties in the 3D reservoir model. An example of the final petrophysical interpretation is shown in Figure 48.

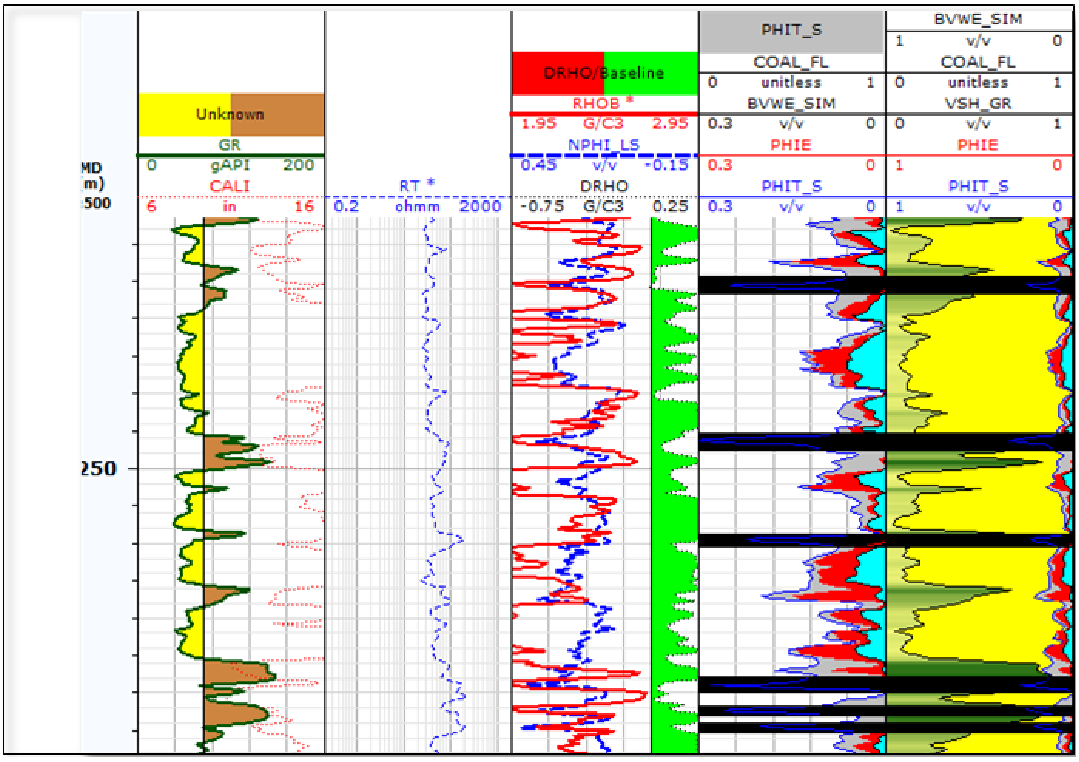


Figure 48. Results from the Petrophysical evaluation from WR Field, example from WR4.

Log porosity vs Core Porosity

One of the key steps to check the robustness of the log estimated porosity values is by calibrating log vs core porosity. The main assumption of this step is that the core data used for calibration is "the ground truth" and that all values measured from core are absent of any error or uncertainties.

However, core analysis data results depend on the methods applied during testing and general core conditions and test conditions. Key information, such as cleaning and drying methods, core preservation, test conditions, plug preparation and so on, will provide a clear indication about what the measurements represent (total or effective porosity), and the data reliability and uncertainty.

In order to perform accurate hydrocarbon estimation, a reliable value of the in-situ porosity and permeability is essential (Fjaer et al, 2008). Therefore, laboratory test results for Whicher Range 1 to 4 were catalogued, reviewed and analyzed in order to establish the quality of each set of data. In theory, the core should be preserved or reloaded to the in-situ stress state in a triaxial setup with controlled pore pressure and temperature. Also, the core must be oriented with respect to the earth stresses.

Considering that porosity changes are associated with variations in pore and bulk volume, therefore responding to mean stress, the confining pressure applied to the core should be the mean effective in-situ stress (Equation 11). The core should be loaded to a confining pressure equal to:

Equation 11 $$\overline{\sigma}' = \frac{\sigma h + \sigma H + \sigma v}{3} - pf$$

In the case of the Whicher Range field, based on the geomechanics analysis performed for Whicher Range 5 by Rasouli *et al.,* (2012), the effective stress needed to replicate the in-situ stress conditions should be:

$$\bar{\sigma}'@4160m = \frac{105000 + 80000 + 95000}{3} - 45000$$ = ~48333 Kpa

This means that about 7010 psi (48333 Kpa) confining pressure should have been applied during the Whicher Range 1, Whicher Range 2, Whicher Range 3 and Whicher Range 4 core porosity testing in order to get a representative value of the in-situ reservoir porosities. Reservoir test conditions are not always well defined at the time when the test is performed, therefore, a good approach taken by the companies is to execute the analysis applying different stress conditions to establish a general trend that can be used to adjust the core analysis data.

Core porosity measurements from Whicher Range 1 were not at in-situ stress conditions and as a consequence, the values measured do not truly represent the reservoir properties. Assuming the unlikely situation that no clay dehydration has occurred during the past 15 years and considering an effective confining reservoir pressure of less than 5000psi (different from that shown by Rasouli *et al.* 2011 and described above), the recent core analysis performed by Rezaee and Saeedi. (2012) for Whicher Range 4, would provide a better representation of the reservoir conditions than core analyses previously performed from Whicher Range 1 to Whicher Range 4.

The effect of increasing overburden stress on porosity in TGS reservoirs has been found to be significantly small. Previous laboratory tests have demonstrated that most pore volume compression/reduction tends to occur within the first 2000 psi net overburden pressure with a gradual additional decrease with increasing stress (Shanley *et al.,* 2004).

Routine helium porosity measurements conducted in the lab at reservoir conditions suggest that in-situ porosity values are within 95% of those measured at ambient conditions (Byrnes,1997). This low stress dependency on porosity is most likely to be related to the well-cemented and rigid framework characterizing TGS rocks and because the slot pores that do compress under stress make up a minor portion of the overall pore volume.

Despite the above remarks, core porosity results available in old reports were considered a good approximation to the reservoir properties for exploration purposes in Whicher Range field. Therefore, when available, core analysis data were used to calibrate the petrophysical model and in particular the log estimated porosity.

Comparison between core measured and log estimated porosities show a fair match between the two values along the entire cored interval, with the exception of localized shaly rich sections where log resolution may have reduced the accuracy of the log calculated porosity, as can be observed in Figure 49 and Figure 50.

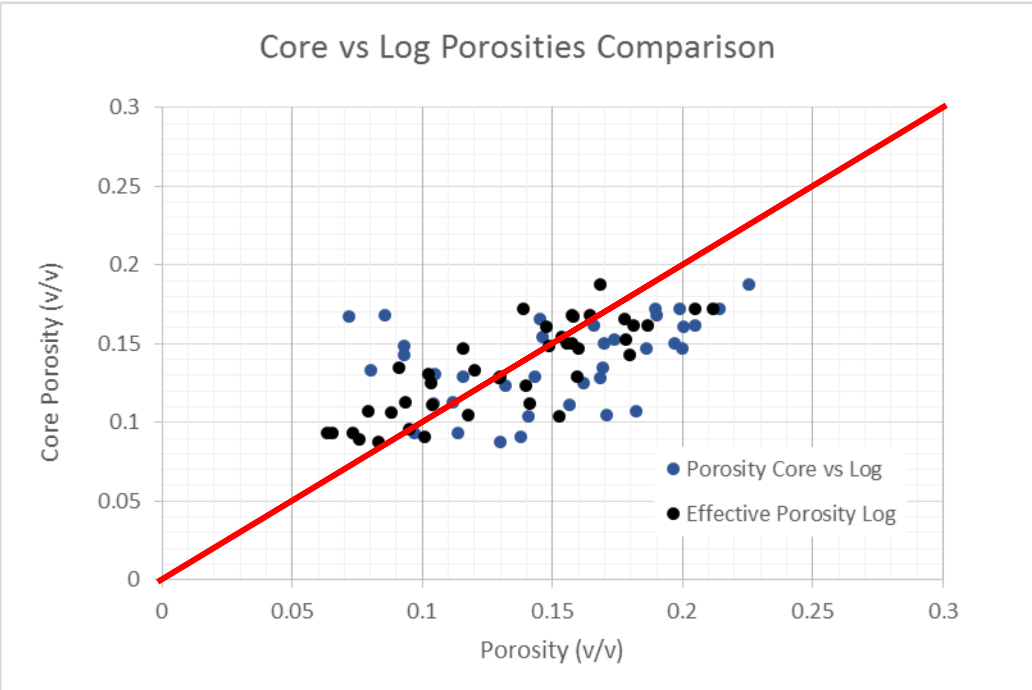


Figure 49. Cross Plot Log Porosity vs Core Porosity showing a good correlation between the three data sets. As expected for Humidity dried Core Porosity measurements, most data fall in between total and effective porosity range.

Permeability

Contrary to the porosity, permeabilities in Tight Gas Sands are well known for having a distinctive stress dependency. In low-permeability sandstone reservoirs, in-situ, high-pressure permeabilities relative to a gas phase range from 10 to 10,000 times less than routine gas-permeability values (Kg). These changes in permeabilities are found to be related to rock types, therefore they can only be defined by measuring a broad range of samples over the entire range of expected net stress conditions.

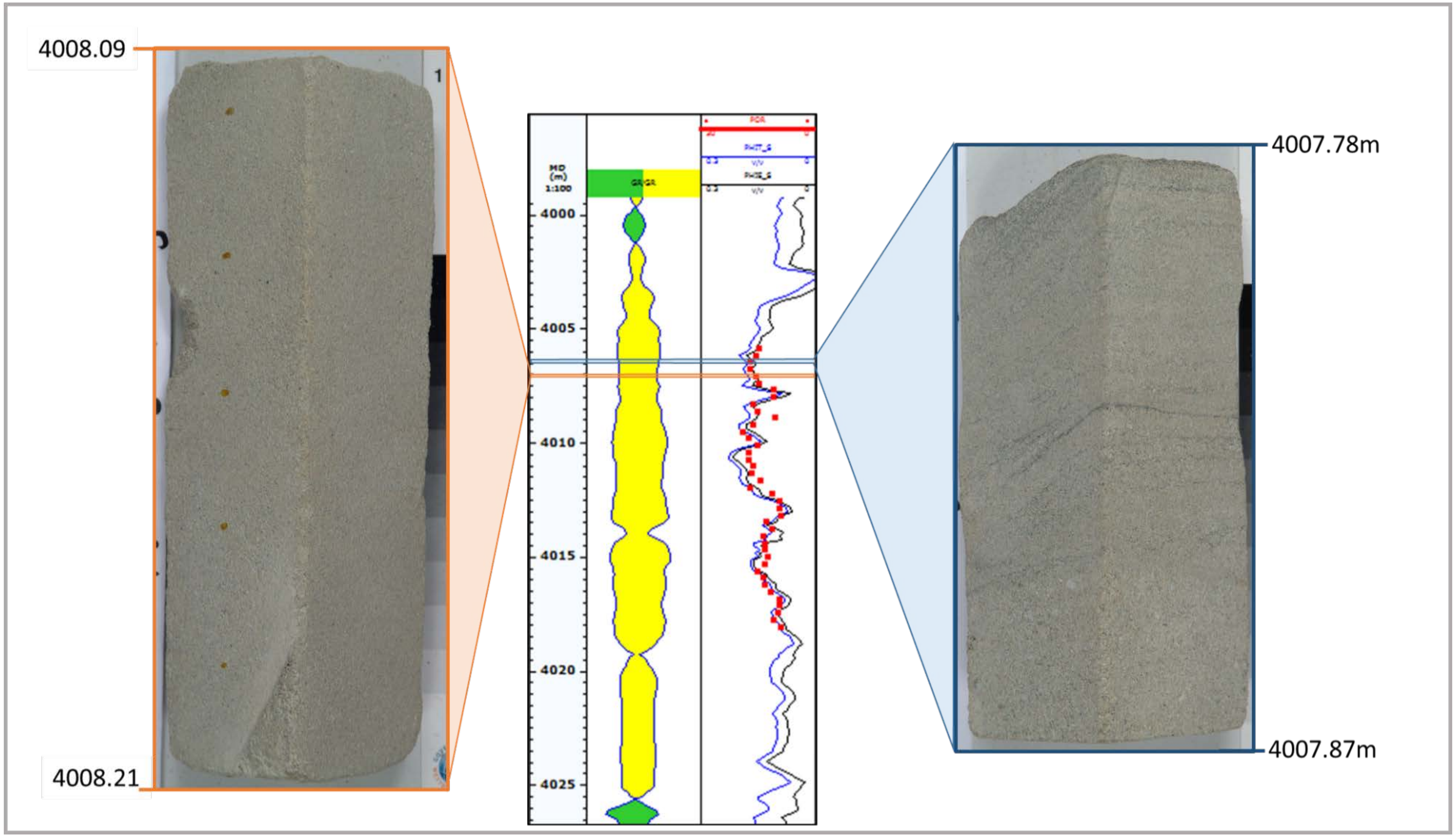


Figure 50. Log porosity calibration using core analysis data for Whicher Range 1. High porosity intervals correspond to massive sandstone observed in core (left image) whereas low porosity streaks coincide with more clay rich thinly laminated intervals (image at the right).

The in-situ mean stress conditions and stress history during depletion are the two key parameters to be defined in order to measure stress dependent properties (Newsham & Rushing, 2001).

Reactive clay minerals have been reported in various different petrological analyses and fluid sensitivity analyses performed for the Whicher Range wells (e.g. fluid sensitivity analysis performed by Poynton and Hollams (1980) for Whicher Range 1 and 2 wells).

Permeability estimation was based on an empirical relationship from the core porosity vs. core permeability crossplot (Figure 51). This relationship was evaluated for all the Whicher Range wells, but the Whicher Range 3 relationship was taken as the most valid value considering that the RCA humidity dried permeability test performed for this well was the only one to consider the swelling characteristics of the clay minerals contained in the Whicher Range reservoir.

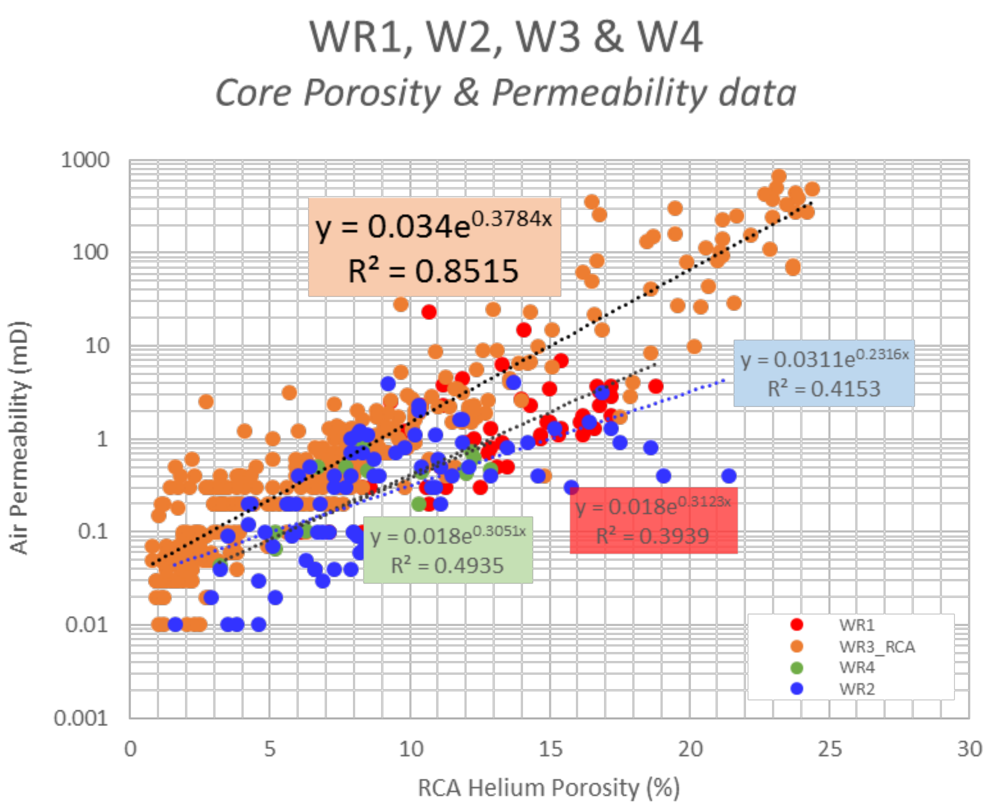


Figure 51. Poro-Perm crossplot displaying the results of the RCA and SCAL analysis performed for WR1 to Whicher Range 4. Whicher Range 3 regression (orange color) corresponds to humidity dried RCA analysis and therefore is considered the best approximation for Poro-perm relationship.

Discussion

The development of a petrophysical interpretation in a non-conventional reservoir has been demonstrated to be a challenge due to the poor applicability of conventional empirical relationships in this type of complex reservoir. As demonstrated in the first section of this chapter, the Whicher Range sandstones display a non-Archie behaviour and therefore several key considerations mentioned by Worthington (2011) had to be considered when performing the petrophysical interpretation.

The development of any reliable well log analysis and reservoir characterization relies on the input data used during the evaluation process, thus the importance of defining the quality of the input data.

In the case of the Whicher Range Field study, poor log quality data related to high stress anisotropy (breakouts), complex porosity (nano to micropores), multiple water arrangements (capillary, bound, movable), clay composition and distribution along the reservoir, reduces the reliability of the petrophysical evaluation of the field.

After going through a detailed QA/QC well log analysis, it has been found that the poor borehole condition characteristic of all Whicher Range wells has affected the overall log quality, and added a major degree of uncertainty to the petrophysical interpretation in the Whicher Range field. Short depth of investigation tools such as CMR (CMR porosity) and pad based logs such as density and resistivity image (FMS) are shown to be the most affected logs in the entire data set.

There is an improvement in the overall data quality with time i.e. sonic data acquired in Whicher Range 1 is much more affected by washout when compared to WR-5, as expected when considering the technological advances in logging tools and drilling operation over the years.

Although, the poor data quality was observed in most WR wells, it was found that the application of a more detailed quality control and log editing phase, helped to improve some of the petrophysical results, particularly in the newest wells, where merging with dual density logs produced a much more reliable density log which would also help calibrating sonic based porosity logs. Also, the core to log porosity comparison shows a good agreement and therefore shows the validity of using sonic logs for porosity estimation in this type of reservoir.

Routine and special core analysis data was *not fit for purpose* but given the lack of extra data was still used as a calibration tool, but a detail consideration of the main uncertainties was taken in account and it is recommended to be approached for the future core acquisition and analysis to be performed in this type of reservoir.

A detail analysis of the spectral gamma ray log in Whicher Range 5 demonstrated that GR is most likely to be a good shale indicator and that uranium enrichment seen in other TGS reservoirs does not seen to be affecting the capability of the GR as a shale indicator.

Application of the Simandoux equation when estimating water saturation in the field help to correct for the effect of clays in the resistivity logs and therefore in the saturations. Also, a variable m was applied in order to account for the multimodal pore size distribution verified by the magnetic resonance and seen also in parts of the petrophysical analogue the Mesaverde TGS reservoir.

By comparing the few SCAL (special core analysis) data points available for the Whicher Range field to the broad Mesaverde TGS reservoir database compiled by Byrnes *et al* (2009) it is found that the latter field is a good petrophysical analogue of the Whicher Range field, i.e similar exponential relationship is shown when plotting “m” vs porosity SCAL data in both wells (as shown in Figure 47).

From the petrophysical interpretation, it was found that the GR is a good shale indicator in the Whicher Range Field. The petrophysical interpretation shows a general increase in shale content with depth, coinciding with the results obtained from the sequence stratigraphic model, where a change from transgressive to a high stand systems tract is interpreted to occur from base to top of the reservoir section.

Also, an overall improvement in the petrophysical properties is observed up-section, and particularly from SB_4_2 upward. Permeability model generated from Porosity to permeability relationship detailed in Chapter 5, shows a distinct permeability reduction in the Whicher Range reservoir below SB_4_2. This model seems to be supported by flow information from DST test available in the Whicher Range Field which, when available, shows changes in flow behaviour across the aforementioned stratigraphy level.

Table below contains a summary of depth of the SB_4_2 stratigraphic surface and DST flow information that support a possible change in permeability across this level."

Table 7. DST flow data evidencing a possible reduction in flow rates below SB_4_2

Well	**SB_4_2** *Depth (m)*	**DST Flow information**
WR-1	4268	No flow below 4268m
WR-2	4241	No tested interval
WR-3	4380	No flow at 4408m (below SB_4_2)
WR-4	4240	Test over the entire Willespie Fm. Cannot be used to access changes in perm below SB_4_2.
WR-5	4222	No tested interval

A high degree of uncertainty in both core analysis data and well log based quantitative data still remains one of the main issues with this study. However, it is worth mentioning that one of the main purposes of the petrophysical interpretation performed in this study is to review the vertical and lateral distribution of the reservoir properties, which could be achieved by integrating all the available data and looking at it from a more qualitative point of view.

The final answer concerning the quality of the results of this study may be decided when *fit for purpose* data becomes available from future drilled wells.

Chapter 6 - GEOLOGICAL RESERVOIR MODEL

The development of a 3D geological model in oil and gas exploration and production aims to create an accurate, quantitative description of the subsurface, in order to provide reservoir engineers with models for dynamic numerical simulation.

This chapter presents the construction of a 3D geological model for the Permian section of the Whicher Range Field. This model aims to characterize the reservoir and predict the distribution of the features that control the fluid flow and the hydrocarbon recovery within the field. The final geological model is a combination of hard data and interpretations (structure, depositional environment, sand body architecture and petrophysical properties).

The construction of the model is based on the interpreted depositional setting enclosed within the structural and sequence stratigraphy framework. The latter holds the key for distributing the reservoir facies within this 3D geological model in a realistic manner giving better predictability of the reservoir properties and facies.

In this study, stochastic reservoir modelling has been used in order to capture the internal complexity of this fluvial TGS reservoir and the impact of the facies distribution on the flow units. Due to the lack of published analogue data for the Whicher Range tight gas reservoirs to constrain the modelling process, recent fluvial analogues (Lake Baikal in Russia and an outcrop/subsurface database (Gibling, 2005)) were used as a base to build multiple scenarios that would capture the uncertainties related to this complex tight gas reservoir.

This chapter starts with the construction of the structural/fault grid model. This model was generated from the integration of the fault interpretation and the main Permian horizons (Willespie Formation) presented in Chapter 4, cropped as a block along the area surrounding Whicher Range main closure. Then the estimation of the sedimentary body characteristics including size, length and width through application of empirical equations relating channel width to sand depth/thickness and the verification of estimated values through a published outcrop/subsurface database (Gibling, 2005) is discussed. This chapter is finalized by displaying the results obtained from the development of multiple 3D object based facies models and the population of petrophysical properties within the reference case scenario.

Structural/ fault grid model

Structural surfaces or horizons in the subsurface, which were modelled by computer grids, limit the top and base of the model and define the volume of rock being modelled. They also define the boundaries of zones within the model. These grids typically mark stratigraphic surfaces that define individual sequences.

The structural interpretation presented in Chapter 4 resulted in a 3D structural model of the entire area covered by the 2D seismic survey in the Whicher Range field. The model cell framework was constrained by two seismically derived horizons. The basis for inclusion/exclusion of seismic surfaces in building the model cells grid was to include only those horizons that could be interpreted with a reasonable degree of certainty so as not to introduce artifacts due to noisy seismic and speculative bias due to highly uncertain interpretation. The horizons used were the top Willespie Formation and the top Redgate Coal Measures.

Faults were trimmed between the two-way-time (TWT) contour maps to generate the 3D fault model and pillar gridding for the area of study as shown in Figure 52. The same were converted to depth using the depth-velocity model developed as explained in Chapter 4. However, a smaller area was selected for developing the structural grid to be used for the final 3D geological reservoir model. The idea was to cover just the faulted anticline closure, defined at the top of the Willespie Formation, and include the five wells and six faults interpreted within the Whicher Range Field.

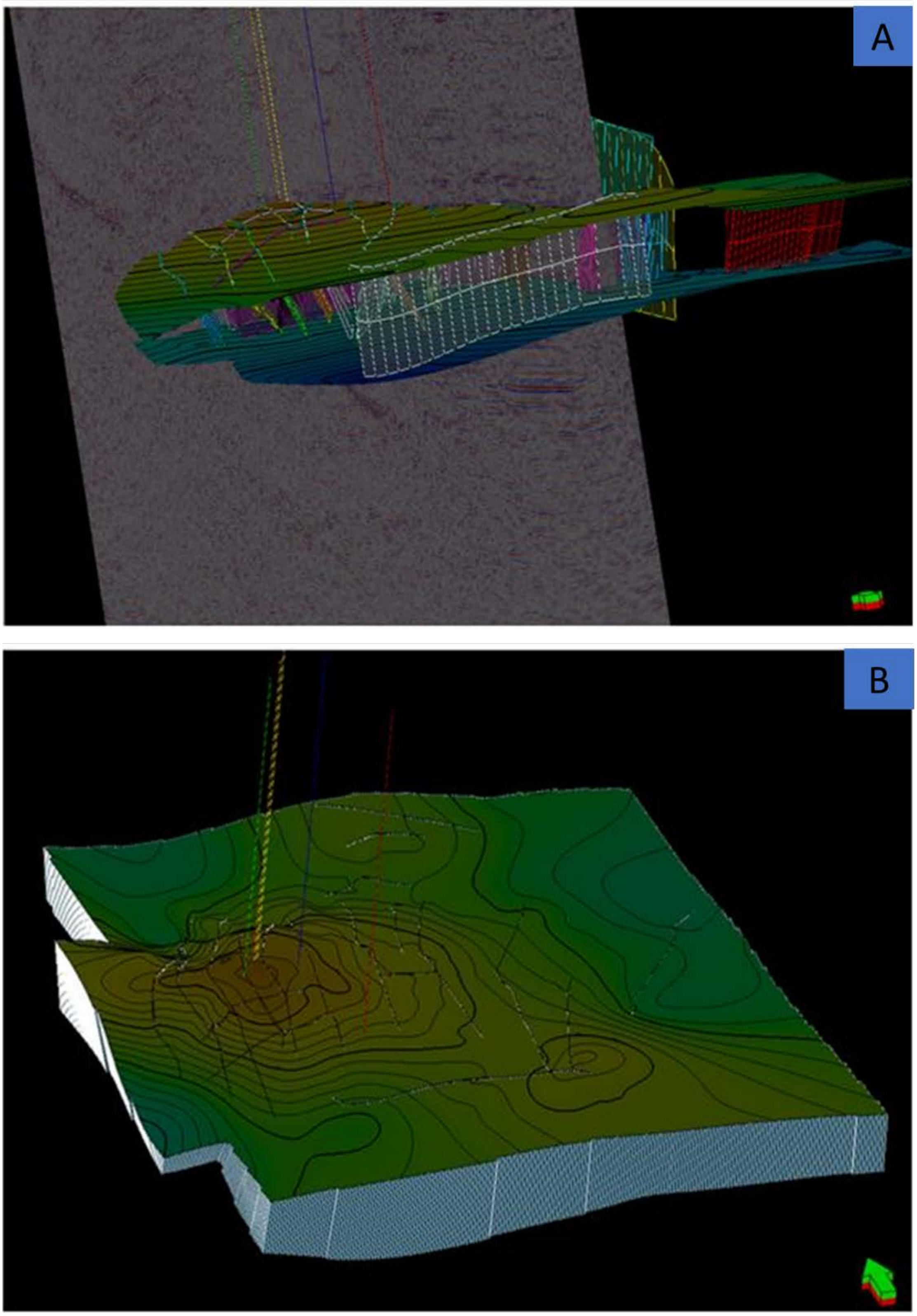


Figure 52. A) Structural surface honouring fault and top and base in TWT. B) TWT 3D model for the Permian section of Willespie formation in Whicher Range field.

Additionally, intermediate surfaces were constructed by hanging well marker isopachs from the seismically controlled surfaces, and scaling the isopachs proportionally so that inter-seismic surface isopachs were preserved. The markers defining the intermediate surfaces consisted of all the interpreted fourth order sequence stratigraphic surfaces presented in Chapter 3.

The intermediate surfaces were built conformable to the top Willespie Formation whereas the base of the model was built conformable to the top Redgate Coal Measures, passing through Whicher Range 1 total depth (Figure 53).

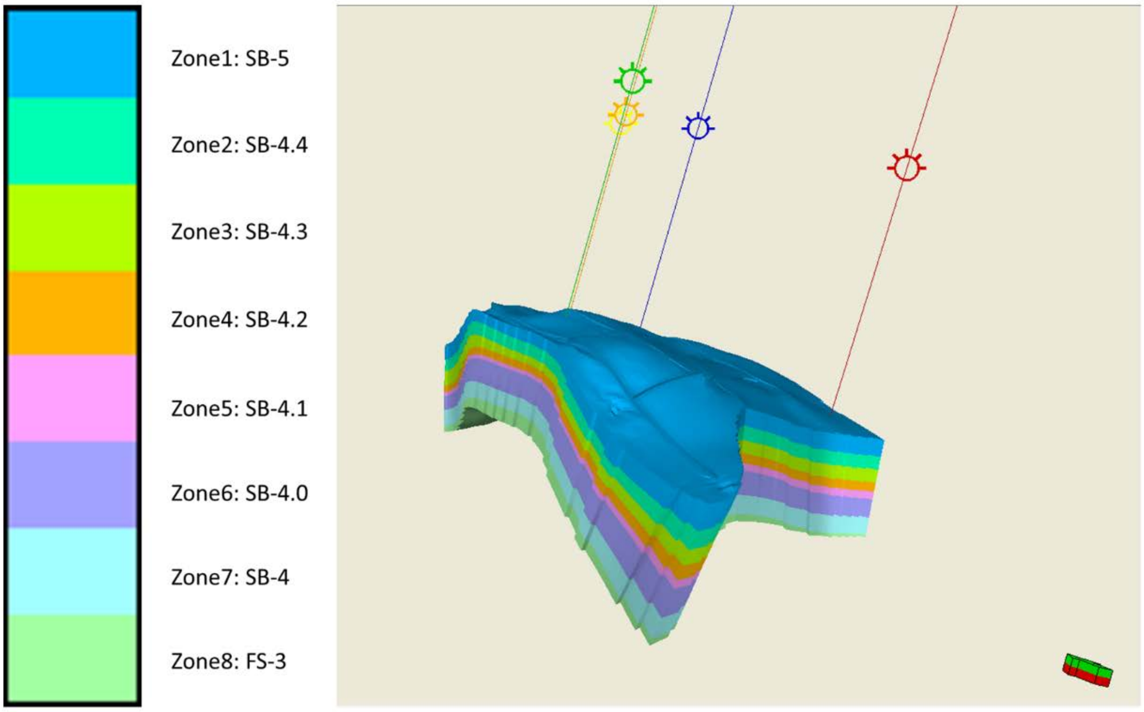


Figure 53. Fourth Order Sequence stratigraphic zone layering.

Channel and Channel Belt width and depth estimation

The prediction of the 3D geometry/architecture of fluvial deposits and its possible extent away from the single dimensional perspective provided by the wellbore is far from straightforward. There are multiple factors controlling the development of non-marine influenced channel deposits, including discharge, sediment supply, base level changes, sediment characteristics, structural controls, topography and climate.

The increase in development of 3D geological modelling applied to reservoir characterization has imposed the necessity of improving channel/width estimation models. From the early 70's, a number of authors started to develop relationships that attempted to predict and estimate the lateral extent of channel deposits. These models are mostly based upon channel width to channel depth correlations (e.g. Fielding and Crane 1987, Bridge and Mackey 1993, Leeder 1978 and Gibling 2006).

The recent work of Gibling (2006) provides not only an extensive public domain database of an "informed selection of analogues" to be used in subsurface applications but also offers an excellent review of published data related to width and thickness of fluvial channel bodies. For the purposes of this study, Gibling's work (2006) was used to compare the Permian Willespie Formation channel geometries to Quaternary analogues.

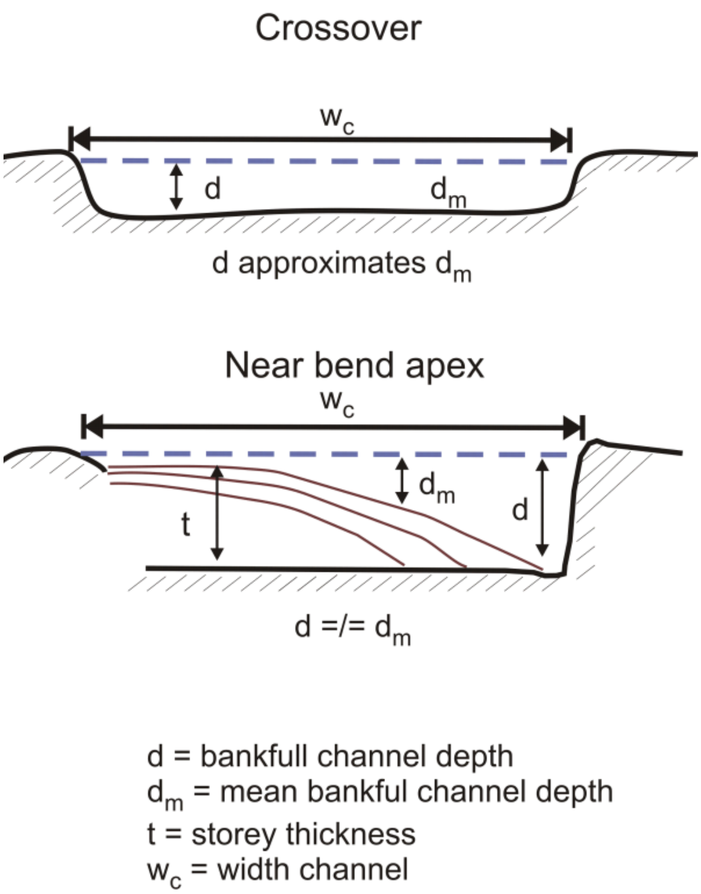
Estimation of channel widths for the Willespie Formation is based on the sand thickness estimated from wireline logs. Plots relating channel thickness to width (Fielding and Crane, 1987; Bridge and Mackey, 1993; Leeder, 1973; Gibling, 2006; Crane, 1987) provides estimations of channel geometrical parameters to be used for modelling the Permian Willespie Formation in the Whicher Range area.

During this study, simple models will be presented for channel width and channel belt width, which are based upon some of the most used published relationships. These models are also graphically compared to results obtained from a variety of other models, in order to have a broad idea about uncertainties related to this parameter and its impact of the predicted fluvial architecture interpreted from the 3D reservoir model.

Conversion of Channel sand thickness to channel depth

In their document, Bridge and Mackey (1993) include an illustration of the parameters used for channel modelling (Figure 54). They also argue that there are several factors that make accurate estimation of mean bankfull channel depth for the purpose of channel modelling very difficult. For example at channel crossovers, mean bankfull depth (dm) is approximately equal to bankfull depth whereas near a channel bend apex, maximum bankfull channel depth (d) may be up to three times greater than mean bankfull channel depth (dm).

Figure 54. Channel parameters used for modelling. From Bridge and Mackey 1993.



Additionally, storey thickness (ts) is to some extent less than maximum bankfull depth (about 10%). Therefore, in ancient deposits, storey thickness must be adjusted to compensate for the effects of compaction.

Workflow for the Channel Depth, Channel Width and Channel Belt Width estimation in the Permian Willespie Formation

The methodology for conversion of channel sand thickness to channel depth is detailed below:

- The channel sand thickness (maximum bankfull depth) were derived from visual examination of petrophysical logs and previously defined facies and facies associations together with Coal flags.
- Sand thickness adjustments of about +10% was applied to compensate for the effects of compaction (Lorenz et al., 1985)
- Calculation of mean bankfull channel depth (d_m) from the sand thickness (t) data sets was performed applying Fielding and Crane's (1987) relationship to compensate for aggradation of the channel. The regression used (d = 0.55 t) corresponds to the median line estimate through the data of Fielding and Crane (1987), which for the purposes of this study will be considered a reasonable estimate based upon their data (Figure 55).

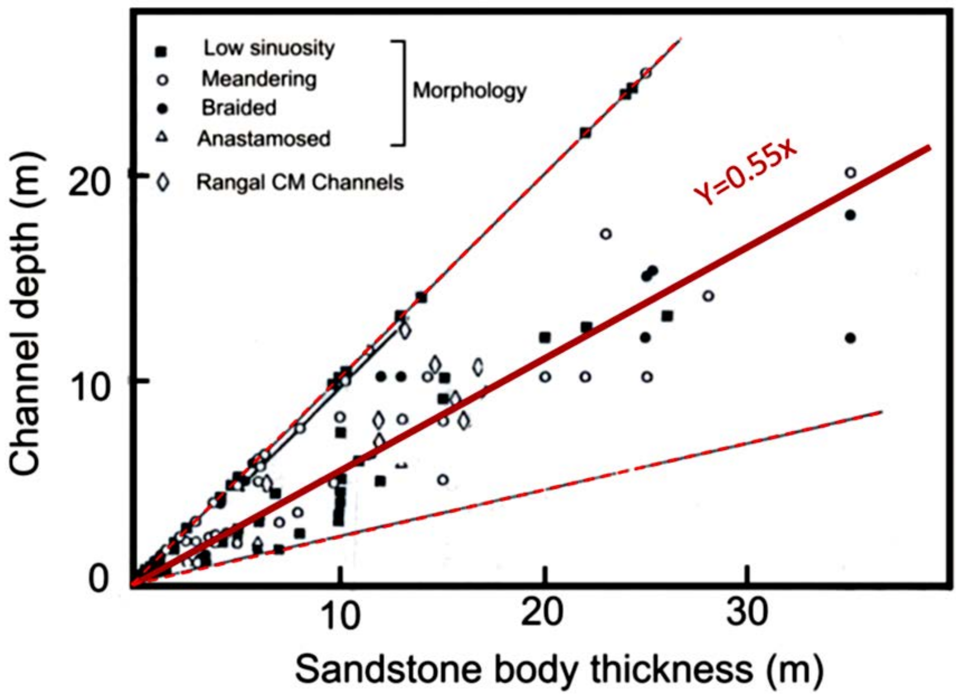


Figure 55. Channel depth versus sandstone thickness relationships for a variety of different channel types. From Fielding and Crane (1987).

Estimation of channel width (w) from the interpreted channel depths

The main relationships used for this study together with some information about their background are presented below:

- Bridge and Mackey (1993) provided two equations for estimation of channel width (w) from channel depth.

Equation 12 $w = 8.88\ dm^{1.82}$

Equation 13 $w = 15.85dm^{1.58}$

- Crane (1982), cited in Bridge and Mackey (1993) presented a further estimate of channel width from depth using the equation:

Equation 14 $w = 12.82dm^{1.59}$

- Leeder (1973) presented a relationship for channel width estimation based on bankfull channel depth. Therefore, an conversion factor of (0.55) needs to be applied in order to channel depths that can be compared to other authors studies.

Equation 15 $w=6.8dm^{1.54}$

- Williams in 1986 established two equations for estimating channel width based on channel depths:

Equation 16 $w=15.5dm^{1.4}$

Equation 17 $w=21.3dm^{1.45}$

Comparison between the aforementioned channel width to channel depth regressions developed by the different authors indicates that equation 14 may be used to generate a minimum estimate of possible channel width, whereas equation 13 can be used to generate a maximum channel width. Equation 11 is suggested as a useful average estimate. The relationship of Field and Mackey Combined equation (1993, Equation 13) can be seen to provide a very good *average* relationship over the range of interpreted channel depths.

Estimation of channel belt width (cbw) from the interpreted channel depths

Channel belt width (cbw) was interpreted from the estimated channel depths using multiple single regression equations developed by different authors (Bridge and Mackey, 1993; Fielding and Crane, 1987; Collinson, 1987; Williams, 1986).

The list of the equations applied for Channel Belt width estimation from Channel depth are as follows:

- Bridge and Mackey (1993) combined equation, which according to Bridge (2007) can be used to provide a useful minimum estimate of channel belt width

Equation 18 $$cbw = 59.9dm^{1.8}$$

and the Bridge and Mackey single regression that is presented as a good estimation of the maximum channel belt width

Equation 19 $$cbw = 192.01dm^{1.37}$$

- Fielding and Crane (1987) presented another empirical relationship used in this study, which provided the absolute minimum channel belt width when compared with all the other equations used

Equation 20 $$cbw = 12.1dm^{1.85}$$

- Collinson's (1987) regression which used maximum bankful channel depth, therefore has to be adjusted to be comparable to the equations developed by the other authors.

Equation 21 $$cbw = 65.6d^{1.57}$$

- Williams (1986) relates bankfull width to maximum bankfull depth including sinuosity in the regression.

Equation 22 $$cbw = 148dm^{1.52}$$

Channel belt width (cbw) was also interpreted from an estimated channel depth determined from Crane(1982, equation 11) and Leeder (1973; equation 12), using the regression equation of Bridge and Mackey (1993)

Equation 23 $cbw=6.89wc^{0.99}$

Also, and empirical relationship derived by William (1986) is applied for comparison purposes

Equation 24 $cbw=4.3wc^{1.12}$

Channel architecture in the Permian Willespie Formation

General channel width model

Several empirical relationships were used to estimate both channel width and channel belt width in this study. Graphical comparisons of the results obtained from Channel depth vs. channel width and Channel depth vs. sand thickness, estimated from the applied models, are displayed in Figure 56 and Figure 57.

As observed from the plots and considering an average channel depth of 9m, the two Williams regressions would represent the absolute maximum and minimum channel width values estimated from depth when compared with all the applied empirical models Figure 56 and Table 9).

Also, it may be observed that the Bridge and Mackey (1993) combined equation is a good representation of the average channel width estimated using all different models.

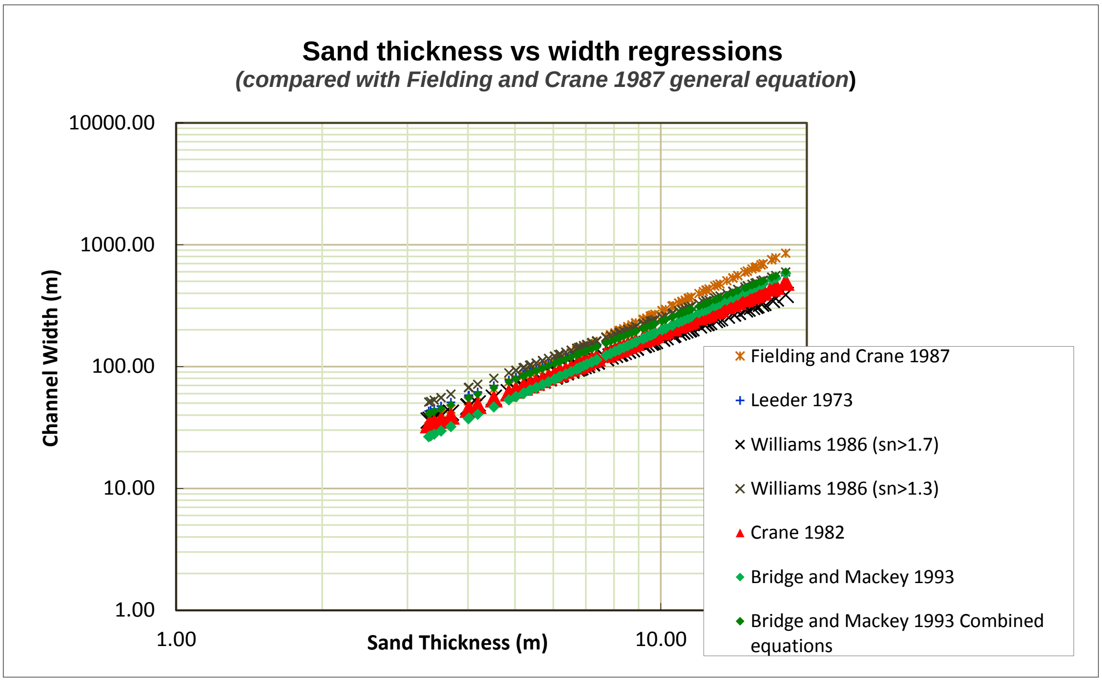


Figure 56. Channel width vs. channel depth estimation models comparison

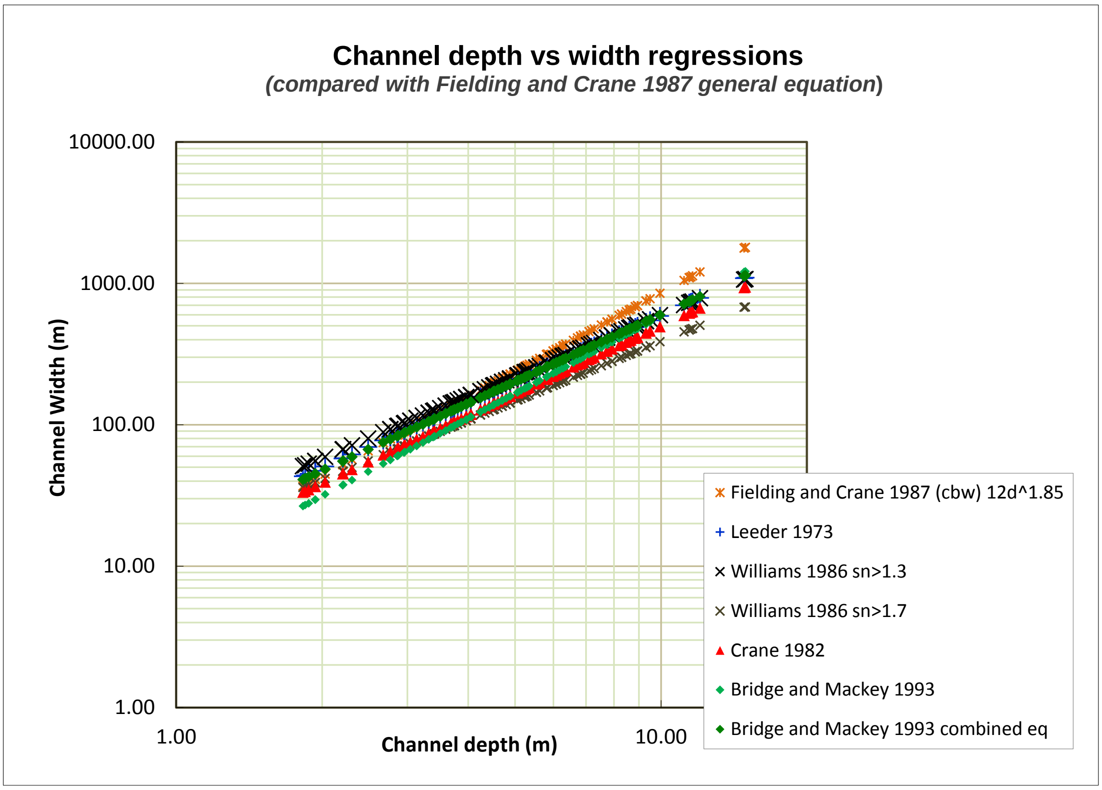


Figure 57. Plot Channel width vs. sand thickness using different authors regressions.

Table 8. Statistical summary of the channel width estimated from depth using different models, for CH1 FA

Maximun Bankfull depth (Channel sand thickness from vsh)	Statistics	Leeder 1973	Crane 1982	Williams 1986 (sn>1.7)	Williams 1986 (sn>1.3)	Bridge and Mackey (1993)	Bridge and Mackey (1993) Combined equations
3.02	min	43.20	33.43	36.04	51.04	26.60	41.08
24.69	max	1098.27	943.97	682.80	1074.13	1217.77	1135.95
9.04	average	255.25	210.96	177.55	268.21	228.72	255.85
4.35	St dev	196.53	168.37	122.96	193.09	212.91	202.75
8.13	geomean	198.54	161.43	144.20	214.59	161.30	196.43
8.08	Median	196.53	159.74	142.87	212.54	159.37	194.38
4.65	10 pct	83.93	66.36	65.92	95.39	58.31	81.20
8.08	50 pct	196.53	159.74	142.87	212.54	159.37	194.38
14.71	90 pct	494.59	414.24	330.62	506.80	474.36	501.07
5.94	25 pct	122.55	98.09	93.00	136.24	91.20	119.73

The statistics displayed in Table 8 **.**and Table 9 will be considered as input values for building up the 3D Geological model of the Whicher Range fluvial channels. Results shown in Table 9 were used to model CH1 FA channel geometries whereas statistics from Table 9 were applied to predict the architecture of CH2/CS channels.

Table 9. Statistical summary of the channel width estimated from depth using different models, for CH2/CS FA

Maximun Bankfull depth (Channel sand thickness from vsh)	Statistics	Leeder 1973	Crane 1982	Williams 1986 (sn>1.7)	Williams 1986 (sn>1.3)	Bridge and Mackey (1993)	Bridge and Mackey (1993) Combined equations
1.25	**min**	12.70	9.44	11.84	16.12	6.26	11.70
5.49	**max**	123.85	99.17	93.90	137.61	92.35	121.04
2.98	**average**	50.86	39.74	41.34	59.08	33.18	48.74
1.04	**St dev**	27.23	21.96	20.14	29.80	20.98	26.77
2.81	**geomean**	44.14	34.18	36.75	52.09	27.28	42.00
2.89	**Median**	46.28	35.89	38.37	54.46	28.85	44.09
1.83	**10 pct**	22.82	17.29	20.17	27.99	12.51	21.34
2.89	**50 pct**	46.28	35.89	38.37	54.46	28.85	44.09
4.72	**90 pct**	98.38	78.18	76.16	110.78	70.34	95.57
2.14	**25 pct**	29.02	22.17	25.10	35.09	16.62	27.31

In order to test the fluvial architecture interpreted for the Willespie Formation in the Whicher Range field, the estimated mean bankfull channel depths (thickness) and widths for CH1 FA and CH2/CS FA, using the Bridge and Mackey (1993) combined equation (Equation 13), were plotted in the Gibling (2006) database for Meandering Rivers and Avulsion deposits, respectively (Figure 58 and Figure 59).

From the Meandering rivers plot, it may be observed that the Whicher Range CH1 FA data is in good agreement with two modern analogues: a) Canyon Creek Mbr, Ericson Formation, Cretaceous, Wyoming and b) Joggins Formation, Pennsylvanian, Nova Scotia, Canada (Figure 58), whereas the CH2/CS channels have a good match with the Eocene avulsion deposits of the Wildwood Formation, in Wyoming (Figure 59).

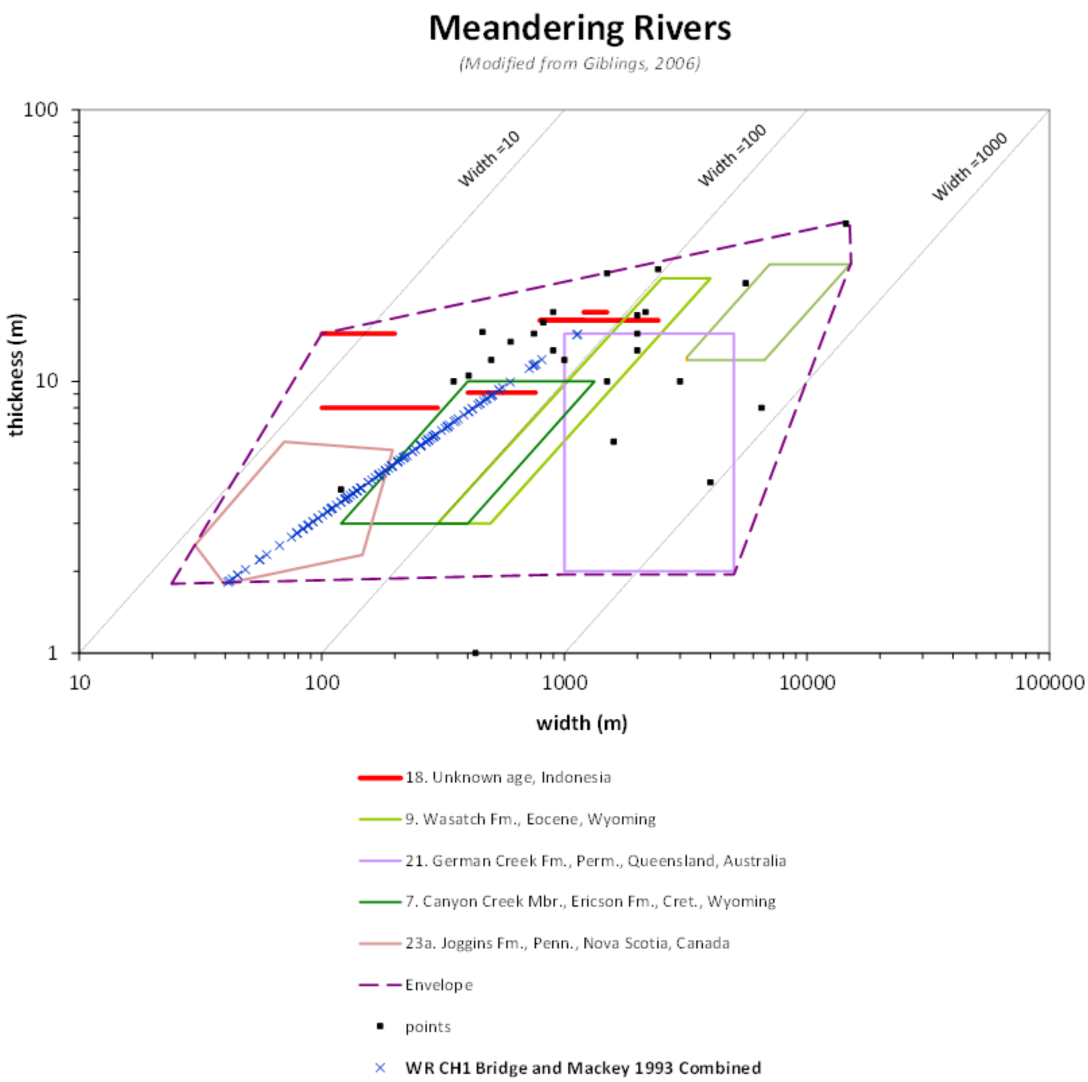


Figure 58. Whicher Range data plotted on the "Meandering Rivers Thickness vs. Width plots" from Gibling (2006).

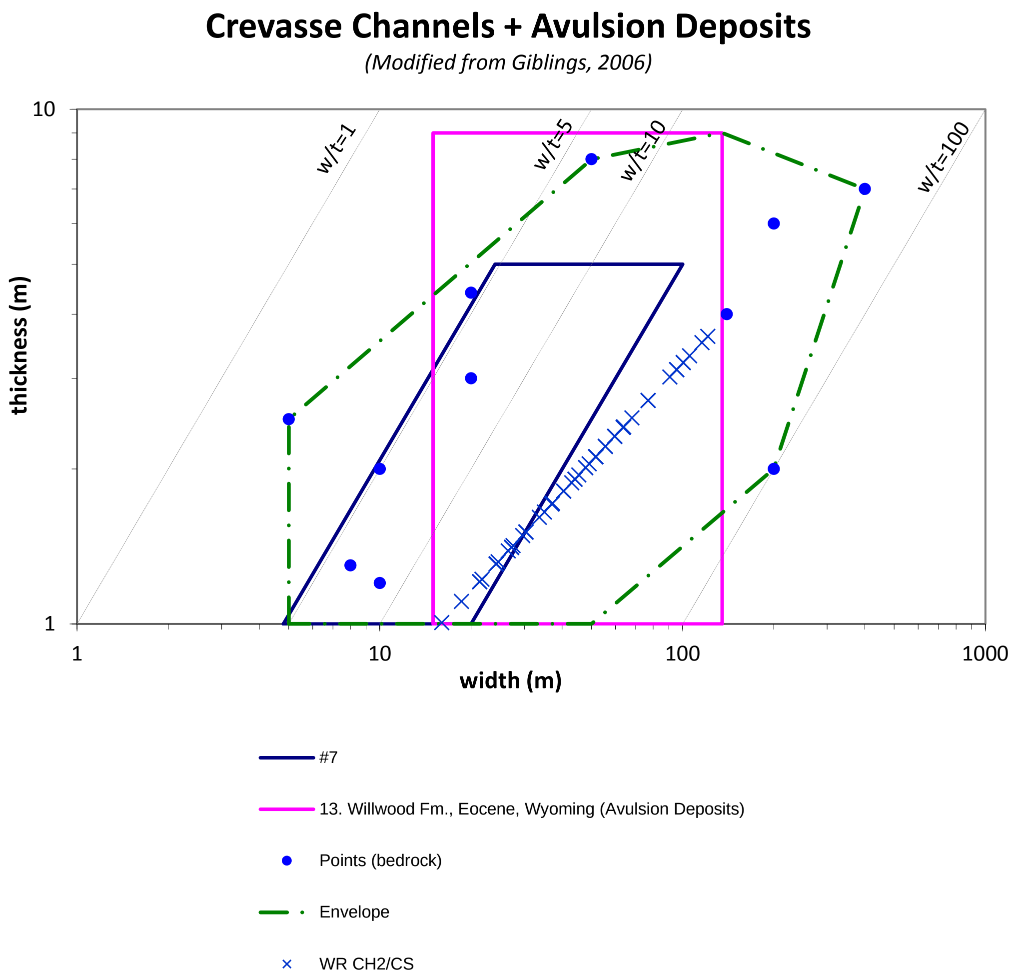


Figure 59. Whicher Range data plotted on the "Avulsion deposits Thickness vs. Width plots" from Gibling (2006).

General channel belt width model

A similar approach to that used to estimate channel width was applied to calculate channel belt width. Different published empirical equations presented by Bridge and Mackey (1993) were used to get a statistical approximation of the channel belt width in the Whicher Range area. All estimated values were compared with models generated by other authors/other scenarios.

For the purpose of this study the preferred model would be Bridge and Mackey (1993) combined with Leeder(2), which provides an average estimate. Plots including all different applied models of channel belt width estimation from channel depth and sand thickness are presented in Figure 60 and Figure 61, respectively.

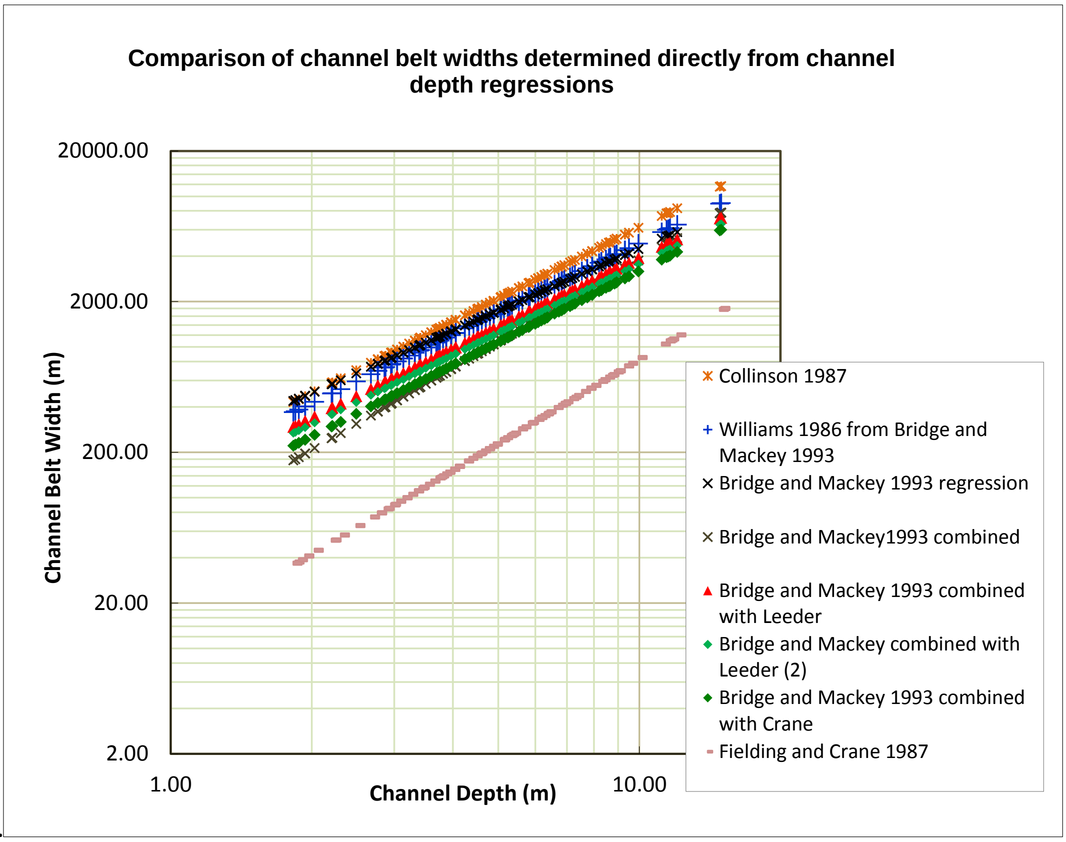


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Figure 60. Channel belt width vs. channel depth estimation models comparison

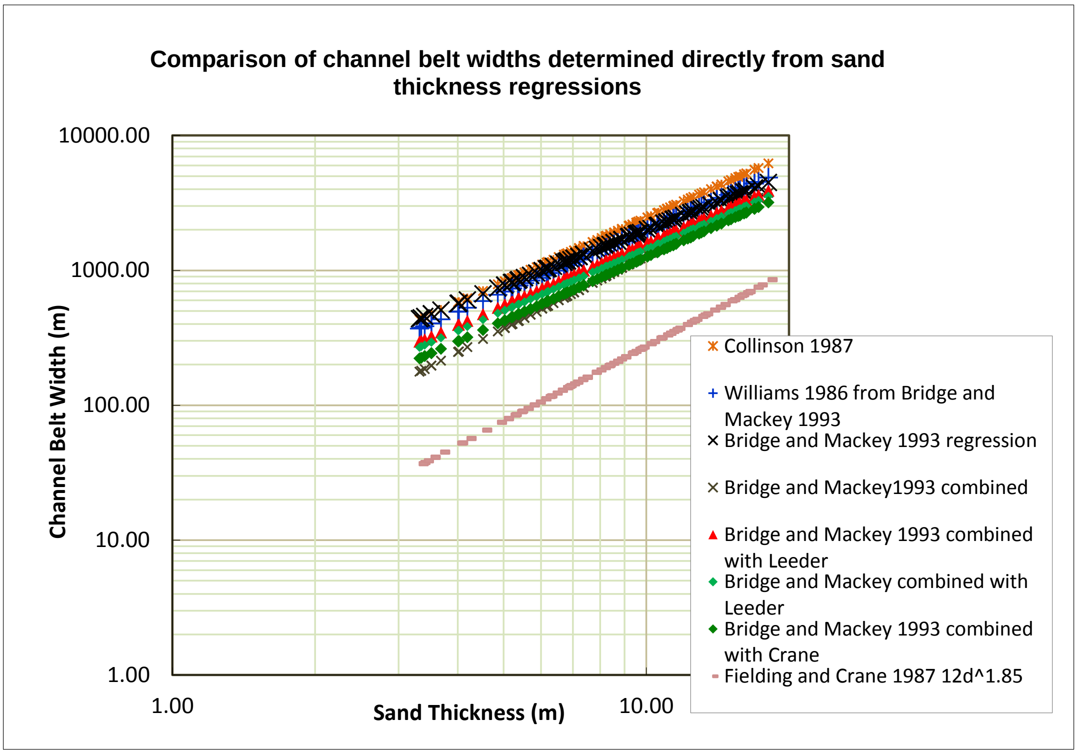


Figure 61. Channel belt width vs. sand thickness using different authors' regressions.

Table 10. Statistical summary of the channel belt width estimated from depth using different models, for CH1 FA

Statistics	Fielding and Crane 1987	Collinson 1987 (Uses maximum depth)	Williams 1986 from Bridge and Mackey 1993	Bridge and Mackey 1993 regression	Bridge and Mackey 1993 combined	Bridge and Mackey 1993 combined equations with Leeder (uses maximum depth)	Bridge and Mackey 1993 combined equations with Leeder (2)	Bridge and Mackey 1993 Combined equations with Crane
min	36.90	432.02	369.95	438.47	177.14	296.20	268.79	221.80
max	1799.55	11698.25	9018.52	7799.35	7776.83	7220.82	6552.44	6006.06
average	330.66	2655.48	2129.38	2078.54	1482.27	1704.92	1547.11	1363.36
St dev	313.67	2089.36	1615.72	1405.45	1362.38	1293.65	1173.91	1072.71
geomean	230.56	2045.49	1666.98	1702.98	1053.26	1334.69	1211.15	1050.19
Median	227.74	2024.29	1650.25	1687.57	1040.75	1321.30	1199.00	1039.30
10 pct	81.95	850.26	712.56	791.61	385.00	570.52	517.71	436.53
50 pct	227.74	2024.29	1650.25	1687.57	1040.75	1321.30	1199.00	1039.30
90 pct	690.18	5186.91	4103.66	3835.66	3060.89	3285.66	2981.53	2663.04

The statistics displayed in Table 10 and Table 11 are used to get the input values for building the 3D geological model of the Whicher Range fluvial channels belts. Results shown in Table 10 were used to model CH1 FA channel architecture whereas statistics from Table 11 were applied to predict the architecture of CH2/CSP channel belts.

Table 11. Statistical summary of the channel belt width estimated from depth using different models, for CH2/CSP FA.

Statistics	Fielding and Crane 1987	Collinson 1987 (Uses maximum depth)	Williams 1986 from Bridge and Mackey 1993	Bridge and Mackey 1993 regression	Bridge and Mackey 1993 combined	Bridge and Mackey 1993 combined equations with Leeder (uses maximum depth)	Bridge and Mackey 1993 combined equations with Leeder (2)	Bridge and Mackey 1993 Combined equations with Crane
min	8.48	123.98	110.48	147.53	42.34	88.46	80.27	63.66
max	130.79	1264.30	1046.25	1119.13	606.70	837.70	760.16	649.11
average	46.35	511.57	433.85	500.30	220.04	347.37	315.22	262.65
St dev	29.79	279.21	229.30	238.49	137.59	183.59	166.60	143.35
geomean	37.87	441.62	377.90	446.96	181.66	302.57	274.57	226.73
Median	40.09	463.45	395.98	466.18	191.99	317.05	287.70	237.94
10 pct	17.14	225.37	197.03	248.50	84.00	157.76	143.15	115.71
50 pct	40.09	463.45	395.98	466.18	191.99	317.05	287.70	237.94
90 pct	99.18	999.74	833.53	911.81	463.53	667.38	605.60	513.28

The presented figures, tables and statistics show the analysis of the channel geometries of the Whicher Range Field for all the stratigraphic intervals. However, a detailed channel width and belt analysis was also performed for each individual fourth order stratigraphic sequence.

Discussion of channel width and channel belt estimation

Empirical equations derived from studies of modern rivers (Fielding and Crane 1987, Bridge and Mackay 1993, Collinson 1987, Williams 1986,Leeder 1978 and Gibling

2006) were applied to relate channel width and channel-bar thickness to maximum paleo-channel depths. The results obtained by applying these empirical relationships are variable and depend upon several factors i.e. the applied sand compaction ratio, or even the model chosen for estimating sand thickness (maximum bankful depth or mean bankfull channel depth). At the same time, the interpreted channel thicknesses and calculated widths, are strongly dependent upon the quality of the logs and the cut-off used to define sand thickness.

The use of these multiple empirical relationships provided a broad range of possible channel widths, ranging from 27m to 1218m meters in the CH1 FA and from 6m to 137m for the CH2/CS FA. Overall, the Bridge and Mackey (1993) combined equation provided the best average among the 6 applied channel width/depth. On the other hand, Bridge and Mackey (1993) combined with Leeder (1973) provided an average value when compared to the other regressions applied.

These aforementioned averages are considered a good starting point for modelling the fluvial channels of the Permian Willespie Formation. Channel width and channel belt width estimation were also performed for individual stratigraphic sequences, interpreted from the fourth order sequence stratigraphic framework, and its statistics were used to give a different constraint to the 3D Geological model of the Whicher Range Field.

Comparison between the general and the fourth order sequence model will be presented further on in this chapter.

The channel belt width ranges from about 37 to 11700 m with the mean of 1235 m representing the majority of channels. The latter (1235 m) was used as a constraint in the generation of the 3D facies model.

The statistical summaries provided in the tables include the median values for channel width and channel belt width estimation. Considering these values instead of averages for building the 3D geological model may help to omit both over-thick sand successions where log data quality is reduced and the interpreter is unable to subdivide channels, or very thin successions which may reflect either truly small channels or truncated (i.e. eroded) incomplete channel fill successions.

3D Object-based Geological model

Stochastic reservoir modelling aims to statistically recreate the distribution of properties within a reservoir volume, by extrapolating available data through the use of a series of statistical algorithms. A *statistical realization* defines a model which honors both the input data and the algorithms. Considering that a single stochastic realization is unlikely to accurately represent the reservoir properties, multiple realizations are generated to statistically cover a wide range of scenarios, under the assumption that one of them will provide a good approximation to the subsurface reservoir characteristics. Stochastic modelling is used for predicting the petrophysical properties (porosity, permeability, fluid saturation) and facies. This approach has been previously proven by other authors i.e. Keogh et al., 2007.

Multiple facies modelling tools are available nowadays, and their preferred use and effectiveness in accurately predicting the subsurface, may vary depending on the reservoir characteristics and properties, data availability and the individual scope of the model. The most common facies model tools include object-based methods, indicator simulation methods, truncated Gaussian tools and Multipoint Statistics (MPS).

Object-based methods are based upon placing objects with a predefined shape in a background facies. These objects may have simple geometric shapes, but can also have more complex geological forms i.e. channels. An object-based approach was chosen for developing the 3D geological model in this study due to the lack of hard data available in the field and also for being one of the most effective stochastic methods in representing channelized fluvial reservoirs in areas where no seismic data is available (Holden et al., 1998: Stanley et al., 1990).

The Whicher Range 3D model was built using an object model stochastic approach, which was based on the six facies previously defined and shown in Chapter 2 (CH1, CHAB,CH2/CS, C, CSD and FP used as a background). At the same time, for the purpose of modelling, the reservoir interval was divided into eight zones representing the fourth order sequence stratigraphic zones separated by minor surfaces of erosion which were previously defined and presented in Chapter 3. The sequence stratigraphic zones defined for this model are displayed in Figure 53.

The parameters used to define the architecture of the channels and channel belts were estimated by applying several empirical regressions presented by different authors, as previously described in this chapter. The range of possible channel geometries and distributions applied to the model were constrained by setting an expected orientation and an average deviation from channel direction, both established from regional paleo-current information (FMS and dipmeter data).

Based on dipmeter interpretation (Griffiths, et al., 1982) for Whicher Range 3, and the paleocurrents direction interpreted from borehole image log for Whicher Range 5, an orientation of S-N or S-NW would be expected for the channels in this field. On this alignment some of the channel facies in well Whicher Range 3 would be connected to the same facies presented in Whicher Range 1, 2 and 4.

Also, channel sinuosity amplitude and wavelength were defined by using satellite images from a rift basin fluvial system (Lake Baikal, Russia) previously established as a modern analogue for the Whicher Range Field (Chapter 2). Each one of the aforementioned parameters defined a variety of possible sandbody dimensions and distributions which can be reproduced several times by using different parameters and therefore used for comparative purposes.

The model was upscaled with the fluvial facies and petrophysical properties derived from well logs, which workflow is documented in Chapter 5. A high resolution grid of 94i x 191j x 3402k cells (total = 48287988) with a 0.5m vertical resolution has been chosen to capture the complex heterogeneity of the rock and to achieve a better reservoir characterization. The total volume covered by each statistical realization is $20855\times10^6 m^3$.

For this study, multiple statistical realizations were performed assuming different parameters and seeds. Finally, one seed (25489) was chosen as the preferred one to be used because of its proximity to the previously developed conceptual geological model.

Once the *preferred* seed was defined, nine statistical realizations were run using, for each one, a single set of channel geometry parameters through the entire Permian section. These nine *simple models* were generated in order to pick the four most likely cases to use to better characterize the Whicher Range reservoir.

After selecting these models, a low case, a reference case and a high case were generated for each one of them, using as main constraints both the channel dimensions (width and length) for the facies elements statistically calculated for each one of the eight fourth order sequence stratigraphic zones and the proportion of facies per zone. The resulting reference case is represented by the average of facies from all wells, the low case corresponds to the well with lowest proportion of facies for each zone and the high case scenario is represented by the well with the highest facies proportion per zone. The previously described models are included as final output within the digital enclosures.

A hierarchy chart showing the total number of statistical realizations performed for the Permian section in the Whicher Range area is displayed in Figure 62.

Connectivity volume analysis was performed for each one of these final twelve statistical realizations in order to establish areas more prone to a higher degree of sand connectedness, which may be considered as future targets for geo-steered drilling and/or fracture stimulation.

In this section, a summary of the results obtained for the reference case will be displayed and some comparison between the three cases will be detailed. Also, the results from the populated petrophysical properties will be presented and discussed below.

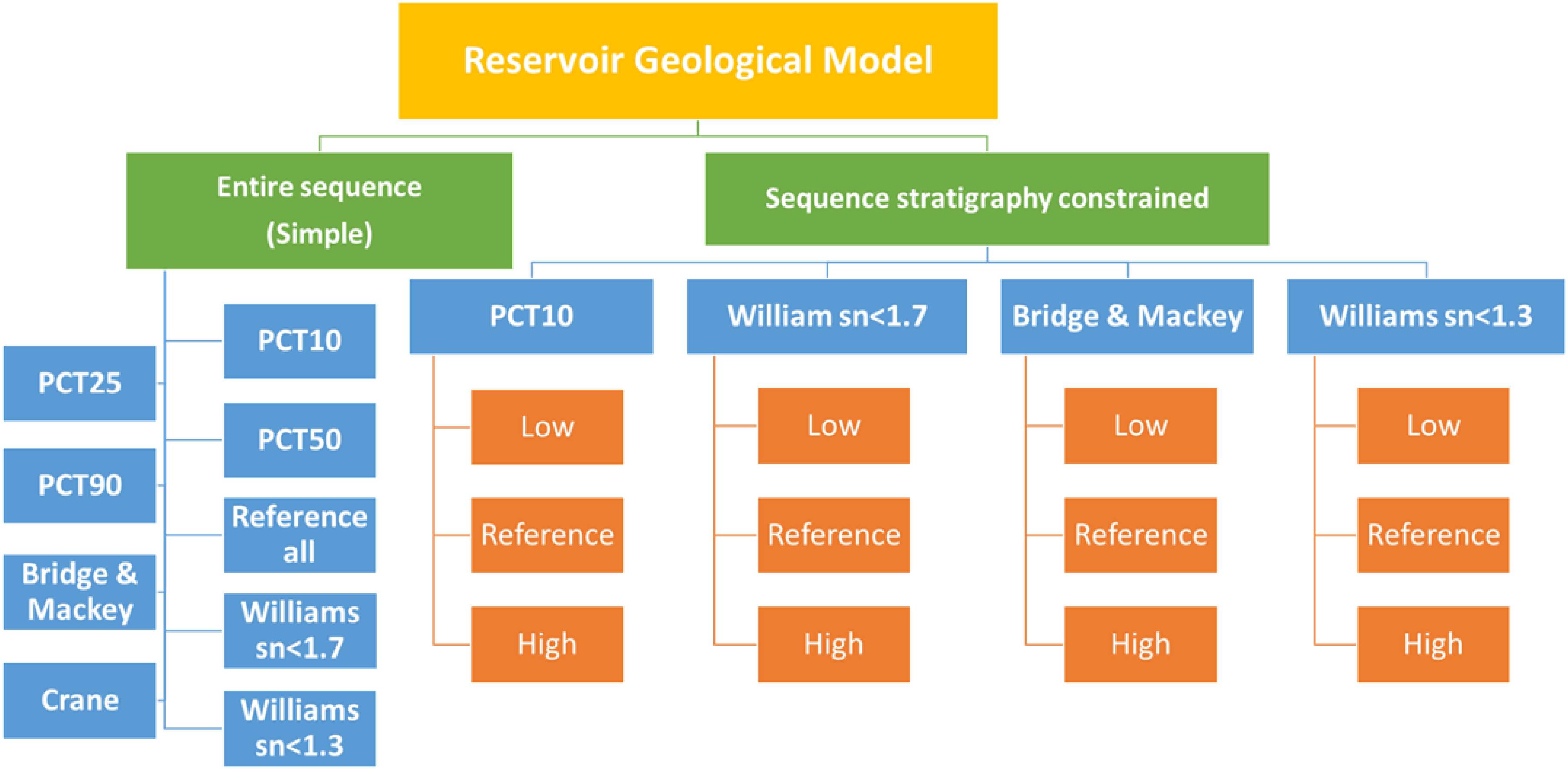


Figure 62. Hierarchy chart displaying the 21 statistical realizations perform as a part of the Geological Model of the Whicher Range Field

Whicher Range Field/ Willespie Formation Facies Model

A total of 21 facies models were generated as a final outcome from this study by using different channel parameters obtained from the statistical values estimated in the previous section together with some modern analogue information.

A constant seed (24589) was used to run all 21 models. The seed defines the start for the random number generation in the algorithm, implying that the same seed number will produce the same model. The early definition of the *preferred* seed number was useful in reducing the numbers of realizations for the final models and also to investigate the influence of each parameter on the results.

The stochastic modelling applied in this study was constrained by the well log facies data as well as the facies intersected by all the Whicher Range wells. The channel *wavelengths* (avg. distance between two consecutive same handed channel turns) and *amplitudes* (avg. transversal distance covered during one wavelength) were measured using Google satellite Images from the modern meandering channel system present in the rift Lake Baikal Rift basin, in Russia, whereas, the channel orientation was obtained from paleo-current information available for the Whicher Range Field (an azimuth range between 310 and 320deg). An example of the channel amplitude and wavelength measurements is displayed in Figure 63.

From the twenty one models, nine were run using a constant range of channel widths (min, median and max) applied over the entire Permian section (Figure 64). Another parameter used for construction of these nine statistical realizations was a maximum bankfull thickness estimated by using the Vsh log, which in the case of Whicher Range 5 was calibrated using the borehole image log (FMS). A summary of the statistical channel widths used for generating these nine models is shown in Table 8 and Table 9 and a display of each of the modelled blocks is included in Figure 64.

Overall, the main geometrical shape parameters modified between the nine simple realizations were channel width and thickness. The first model constructed was the "average reference all authors" in which an average from all authors minimum, mean and maximum channel width values was applied. The thickness was obtained from the absolute minimum, mean and maximum values interpreted from well logs.

Percentile 10 realization was performed by using the minimum, the average and the maximum *percentile 10* value estimated from the empirical regression developed by each author. A similar approach was applied to build up the models corresponding to the 25, 50 and 90 percentile. As for the thickness, these models use a unique deterministic value corresponding to each percentile.

The remaining four models were built using the channel width estimations obtained from the following regressions: Williams sn<1.7 (1986) , Williams sn<1.3 (1986), Fielding and Crane (1987) and Bridge and Mackey (1993). combined For all these the 10 pct, 50pct and 90pct were used as minimum, mean and maximum values, respectively, and a similar approach was applied for the thickness.

The channel abandonment facies, for all 21 realizations, were modeled using an oxbow lake geometrical shape, in which, a similar orientation and parameters as used for CH1 were assumed. After reviewing every realization and comparing all generated facies models in several K layers against the conceptual model established in chapter 2, and represented by Lake Baikal as a modern analog (Figure 63), it is was decided to choose the two Williams (1986) regressions for the upper and lower reference cases and the Bridge and Mackey (1993) combined equation as the main reference. An example of the observed facies distribution in K layers and in block view for the reference simple Bridge and Mackey (1993) combined model is represented in Figure 65.

The reference simple Facies model generated from channel width estimation obtained from the Bridge and Mackey (1993) combined equation chosen to model the final reference model including the fourth order sequence stratigraphic framework.

The final three models, which are believed to be the closest to the real geological case, were run by using different channel width ranges for each one of the eight fourth order sequence stratigraphic zones. The three aforementioned facies models are displayed in Figure 53, and a brief comparison between them is discussed below .

The three models chosen as reference cases (low, most likely and high), were built based on the channel width statistical data obtained from Williams sn<1.7 (1986), Bridge and Mackey (1993) combined and Williams sn<1.3 (1986), respectively. The ranges of channel widths applied for CH1, CHAB and CH2/CSP were the PCT 10, PCT50 and PCT90 calculated using an individual empirical regression presented by one author.

The applied thicknesses in these reference models were deterministically obtained by using a fraction of the width. Values used as a channel width for each reference case are included in Enclosure 3 and the resulting modelled blocks are displayed in Figure 66.

The main reason for using percentiles (10 and 90) instead of the minimum and maximum estimated channel widths is to statistically remove extreme values from the data. This may be related to either over-thick sand successions where Vsh log or poor image data quality prevent the interpreter from accurately subdividing channels, or the use of eroded or incomplete channel fill successions for the generation of the facies model.

Figure 67 shows a comparison between the three main facies models separated by the fourth order sequence stratigraphic zones defined in Chapter 3. The most distinct differences between them seem to be related to the channel development for each model.

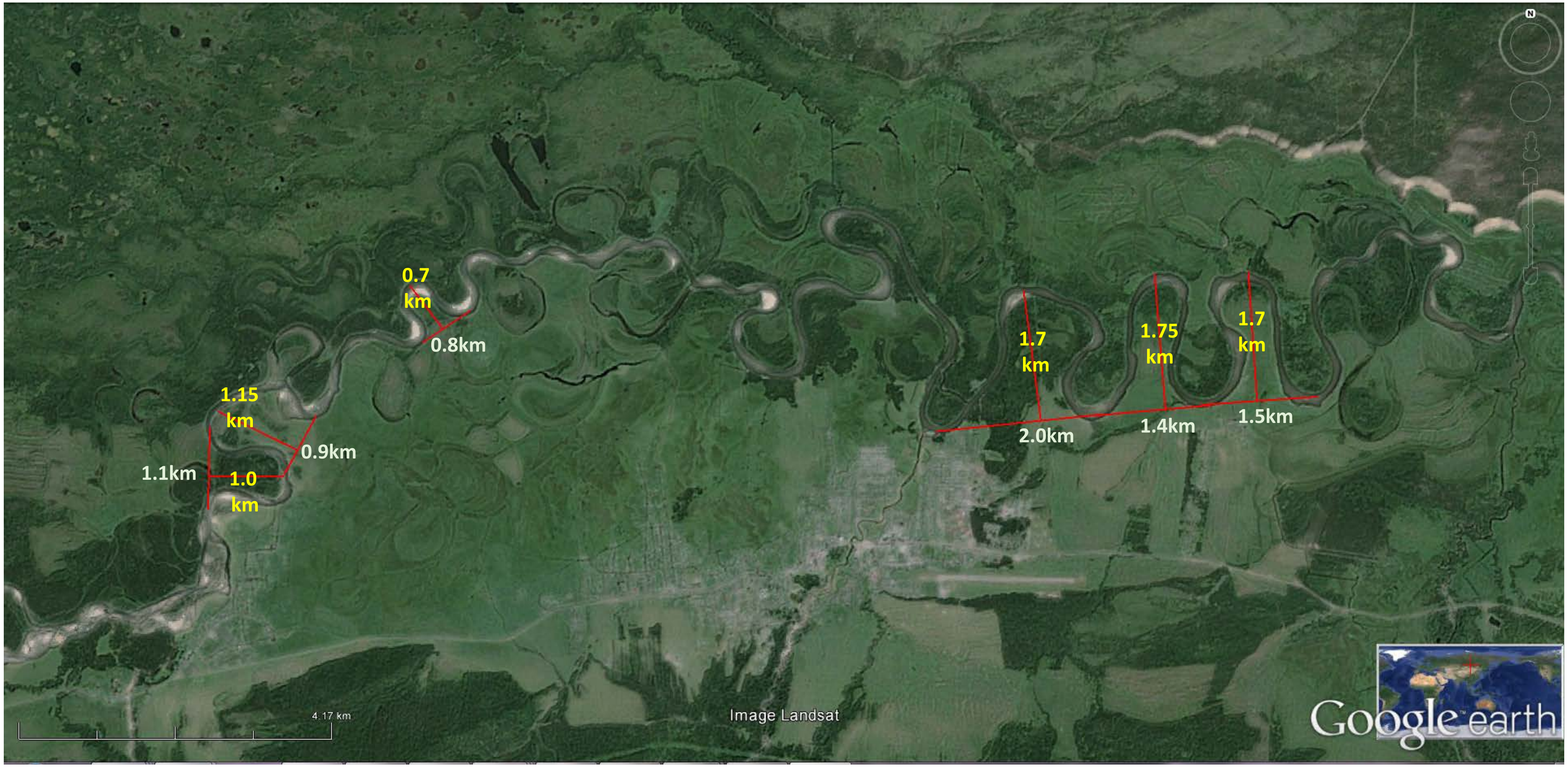


Figure 63. Satellite Image from Lake Baikal meandering system in Russia showing some of the measured channel amplitudes (yellow) and wavelengths (light green) used for modelling the 12 cases. Taken from Google Earth (2013).

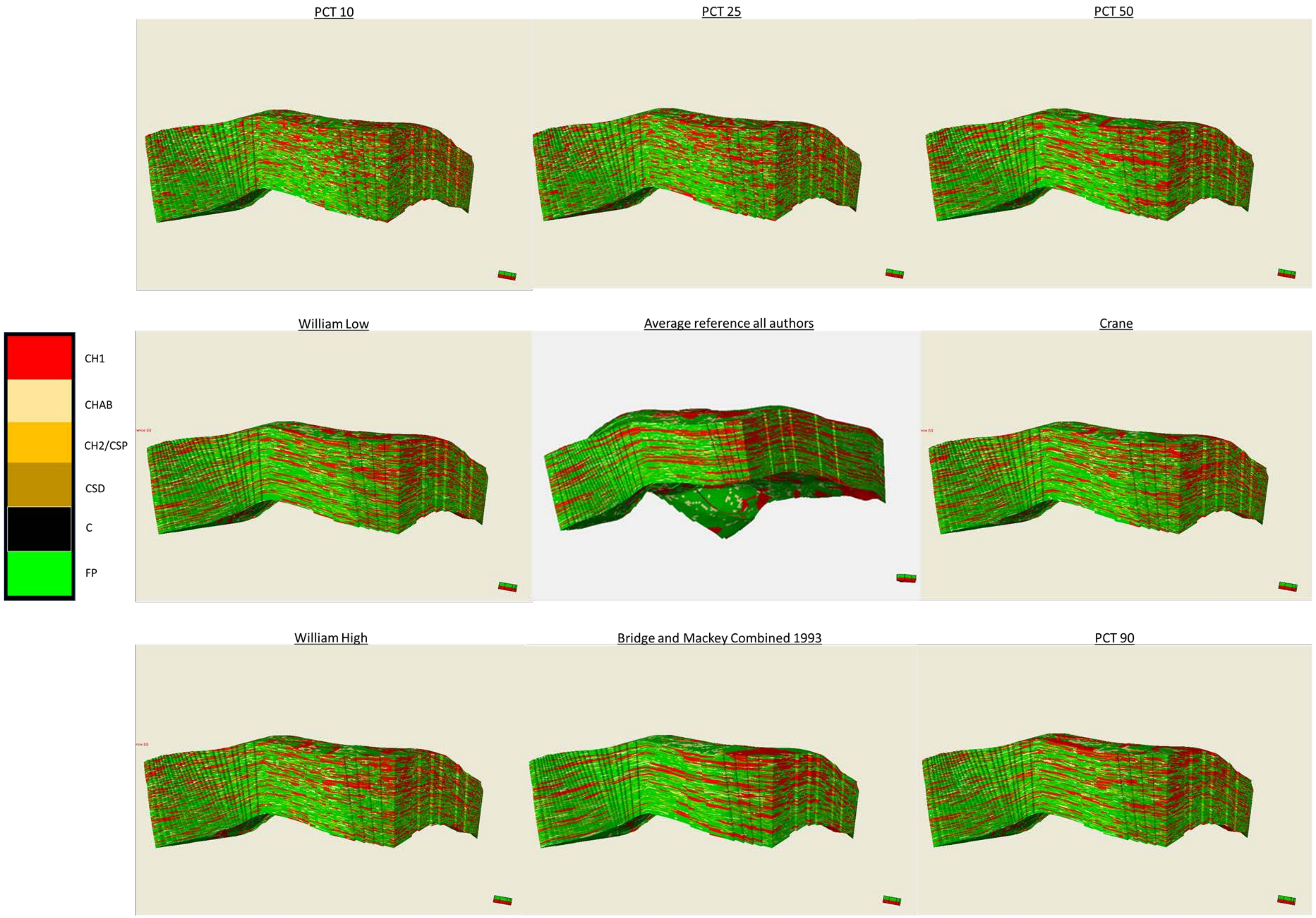


Figure 64. Comparison of the 9 blocks simple models developed for the Permian section of the Whicher Range area.

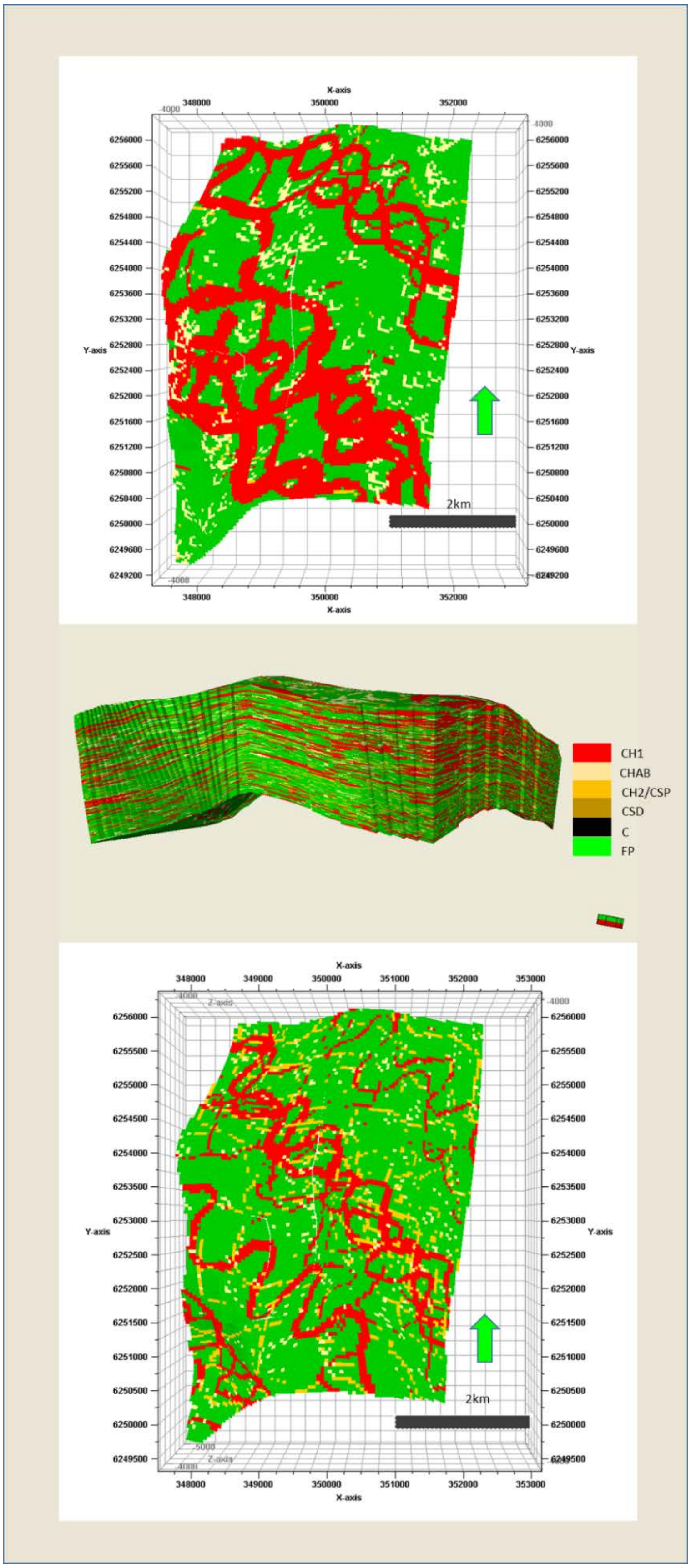


Figure 65. Reference simple Facies model generated from channel width estimation obtained from Bridge and Mackey(1993) combined equation chosen to model the final reference model including the fourth order sequence stratigraphic framework

Whicher Range Field/ Willespie Formation Petrophysical Model

The aim of the property modelling within this study was to build the most realistic petrophysical model incorporating the information provided by all the different disciplines and by extrapolating it to a 3D grid. The goal is to maximize the value of this data in a quantitative digital representation.

In a project with sparse data, such as that developed for the Whicher Range Field, a conceptual geological model plays an important role and therefore, analogue data (outcrops, fields with similar properties or even modern analogues) should be used as a source of information, at least in the first stages of the development of the reservoir model.

Reservoir properties are one of the main controls on production and therefore, maximizing information for an accurate prediction of these properties is a fundamental objective of the geological reservoir model. However, in areas where little data is available for building the properties model, important decisions have to be made based on limited data populated through the use of statistical methods.

In the case of the Whicher Range field, the lack of data does not allow a detailed calibration of the petrophysical model, which results in an increase of the level of uncertainty associated with the lateral propagation of the property models. The only condition used during petrophysical properties modelling was to make the model honour the well log information.

The petrophysical model was based on properties derived from logs and calibrated using the core data available for all the Whicher Range wells. The porosity model was also conditioned to the CH1 facies, mainly due to the strong relationship found between high effective porosity values and the CH1 facies during the petrophysical interpretation stage.

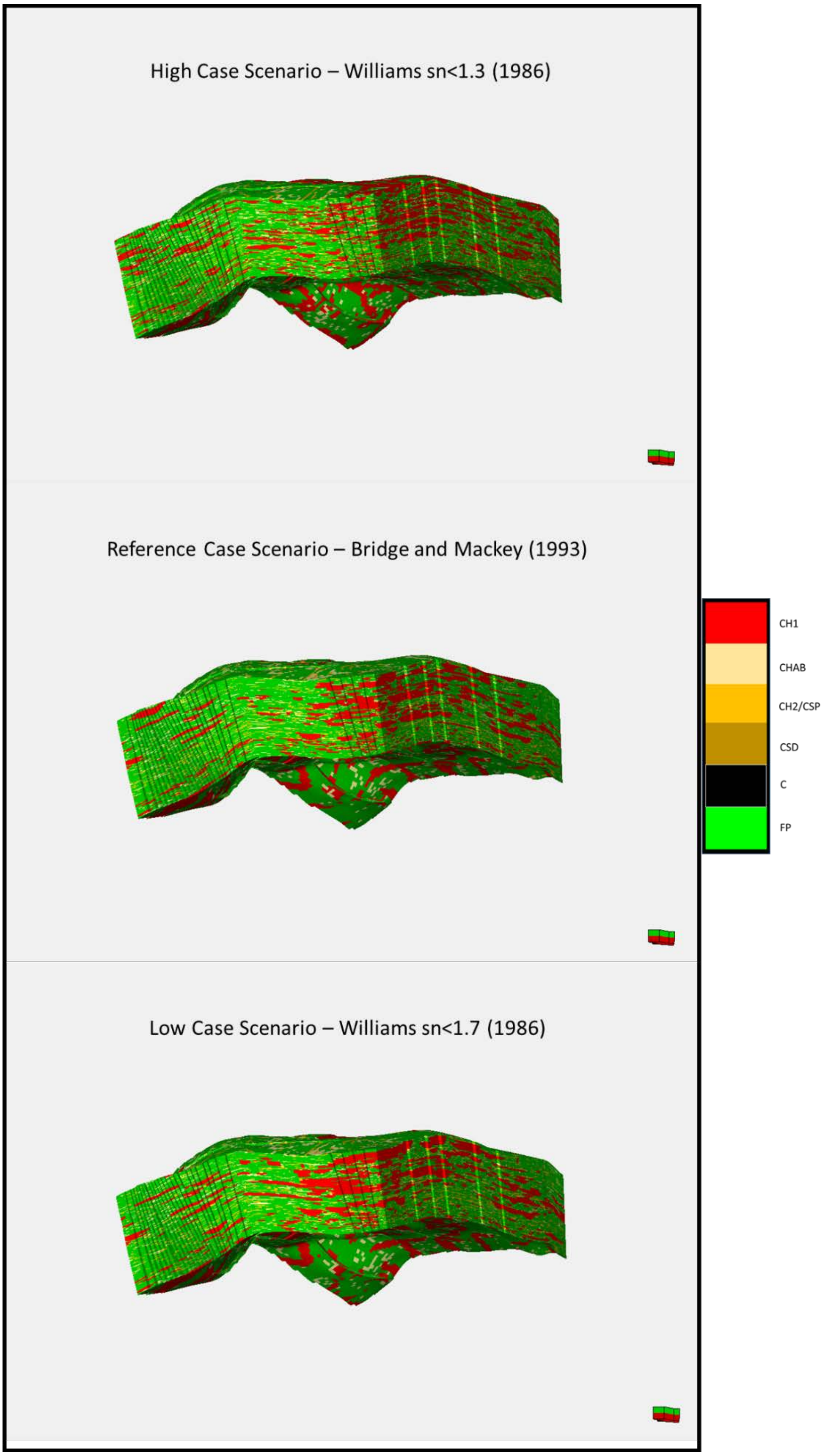


Figure 66. Low, reference and high sequence stratigraphic based facies model of the Whicher Range Field.

In the case of permeability modelling, an empirical relationship to the porosity previously described in Chapter 5 was directly applied for populating this property (Figure 51). Also, no facies conditioning was applied allowing more statistical freedom to a property strongly affected by post depositional diagenetic effects.

Pure statistical sequential Gaussian simulation with a distribution of the same seed used in facies modelling and an output data range using the absolute minimum and maximum values were applied to populate the water saturation.

The comparison between all the facies and petrophysical models obtained for three of the main reference scenarios is displayed in Figure 68.

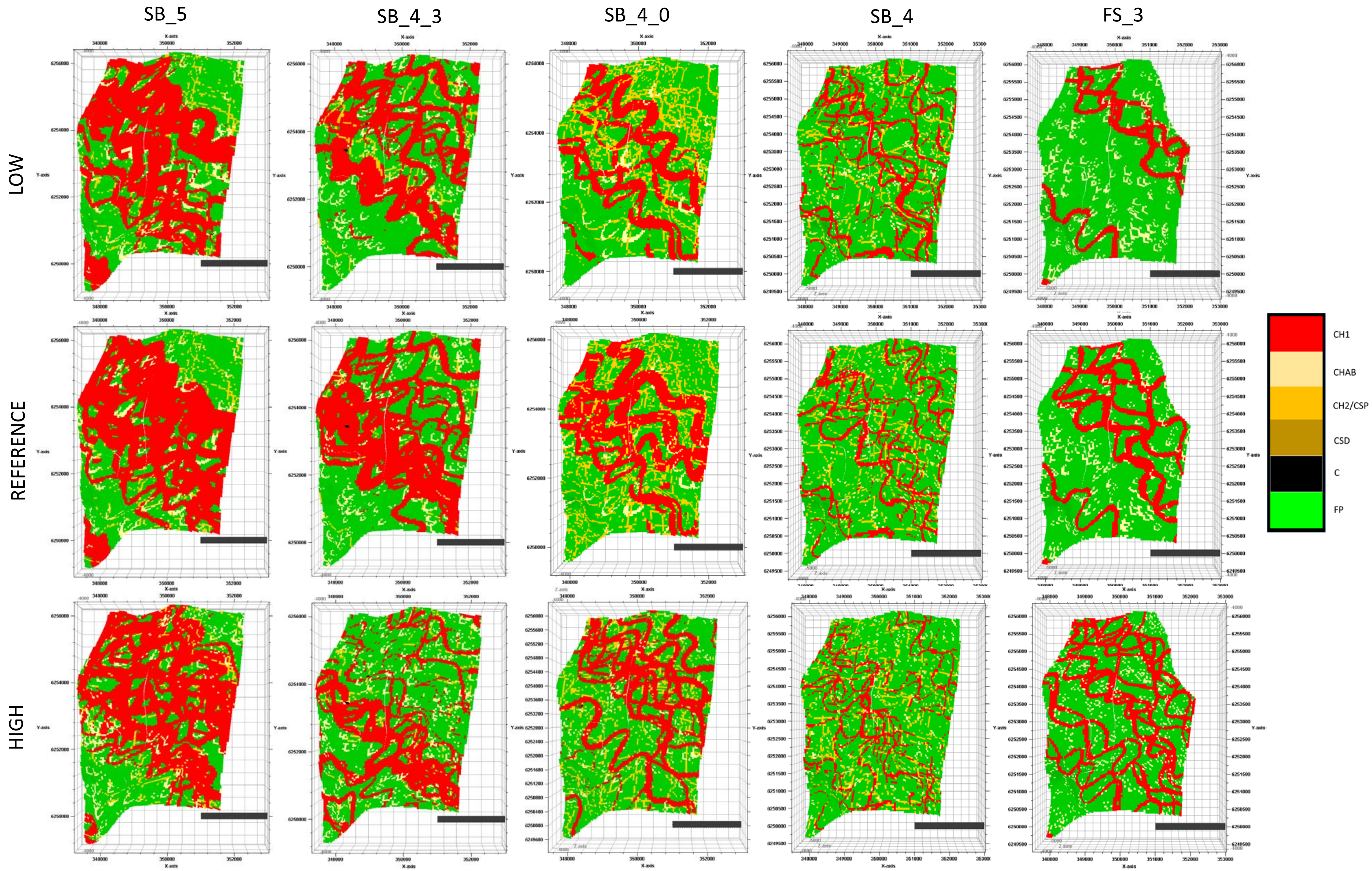


Figure 67. Comparison between low, reference and high facies model separated by fourth order sequence stratigraphy zones (only 5 of the 8 intervals are display in the image).

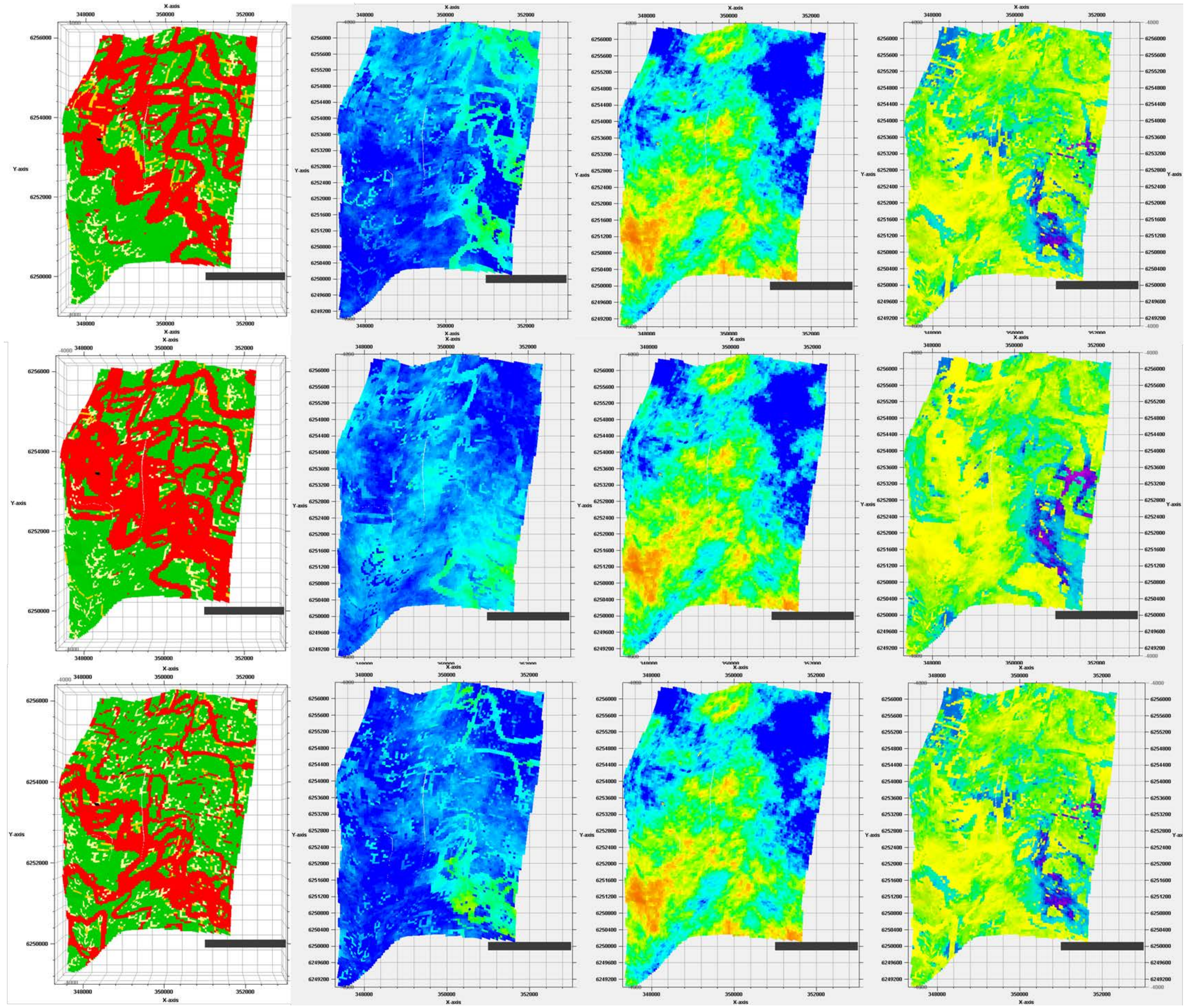


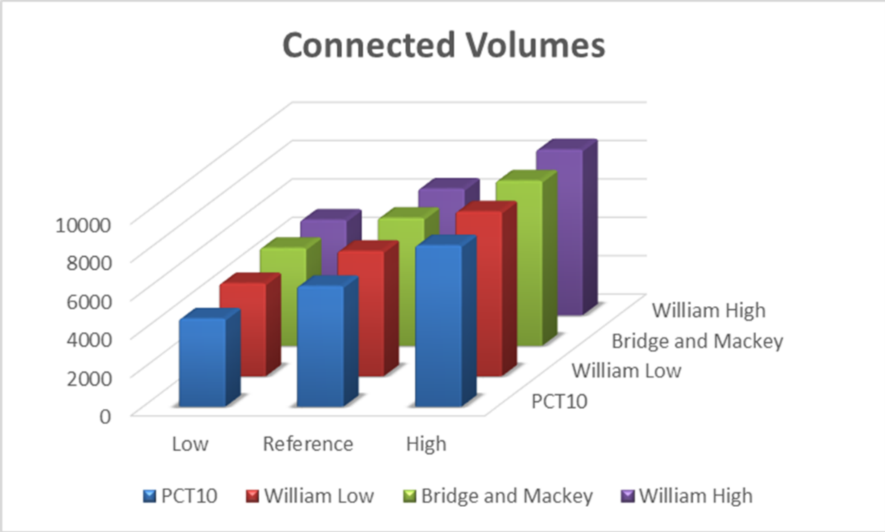
Figure 68. Comparison from the resulting facies and properties modelling population to the low, high and reference cases for the Whicher Range Field.

Whicher Range Field/ Willespie Formation sandbody connectivity

One of the objectives of this research was to address the connectivity in the field to better define key areas to focus on during the development of appraisal strategies in the Whicher Range Field. For this reason, connectivity analyses were carried out for each one of the 12 models generated and contained in the digital enclosures.

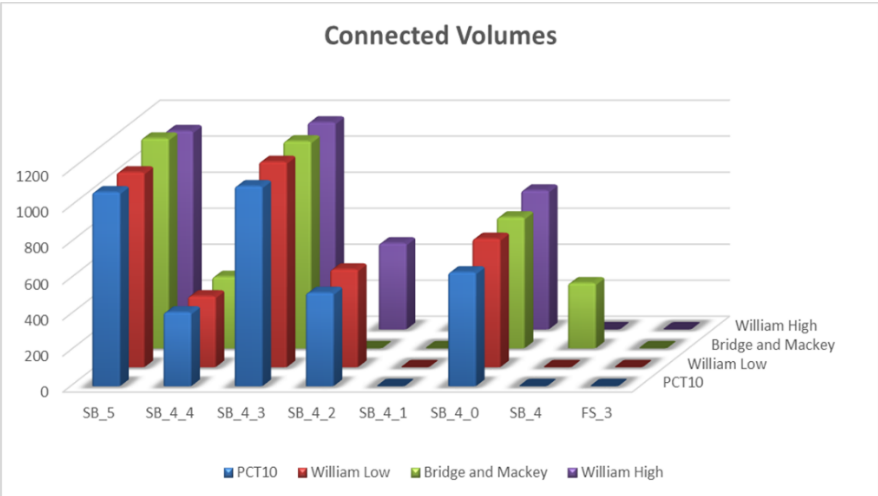
Considering that the CH1 facies has been found to be associated with intervals with the highest gas production during DST's and also, given that these seem to coincide with the best quality reservoir rock within the Whicher Range Field (based on petrophysical interpretation and reservoir quality analysis discussed in Chapter 5), it was decided to include just this facies within the connectivity analysis of the Whicher Range reservoir. For this reason, a net to gross estimation was performed by considering the CH1 FA as the only reservoir facies. After a connectivity volume estimation was performed for each one of the generated models, a total volume of connected CH1 sandbodies was estimated across the entire model using the Petrel software tool for volume calculation. An example of these volumes is shown in Figure 69.

Additionally, a separate estimation including just the five major volumes of connected sand was calculated, assuming the presence of a stratigraphic boundary (surface of erosion, shale layer, etc) that may be creating a disconnection of sand bodies across each stratigraphic surface. A summary of the distribution of connected volumes by stratigraphic zone, just including the main five channels, modelled for the four reference models (PCT10, Williams, and Bridge and Mackey) is displayed in Figure 70. Also, an example of a K layer view with differences in CH1 connectivity behavior for the reference case, William low, high and Bridge and Mackey is shown in Figure 71.



Net Volumes ALL [*10^6 m3]				
	PCT10	**William Low**	**Bridge and Mackey**	**William High**
Low	4597	4847	5100	4978
Reference	6292	6533	6668	6605
High	8413	8589	8610	8650

Figure 69. Chart comparing connected volumes estimated for the Low, reference and high cases for PCT10, William Low, Bridge and Mackey and William High facies models.



Net Volumes ALL [*10^6 m3]				
	PCT10	**William Low**	**Bridge and Mackey**	**William High**
SB_5	1078	1083	1166	1102
SB_4_4	411	395	398	395
SB_4_3	1111	1141	1150	1150
SB_4_2	519	544	0	479
SB_4_1	0	0	0	0
SB_4_0	633	714	728	772
SB_4	0	0	363	0
FS_3	0	0	0	0

Figure 70. Chart comparing connected volumes estimated by each fourth order sequence stratigraphic interval for the PCT10, William Low, Bridge and Mackey and William High facies models.

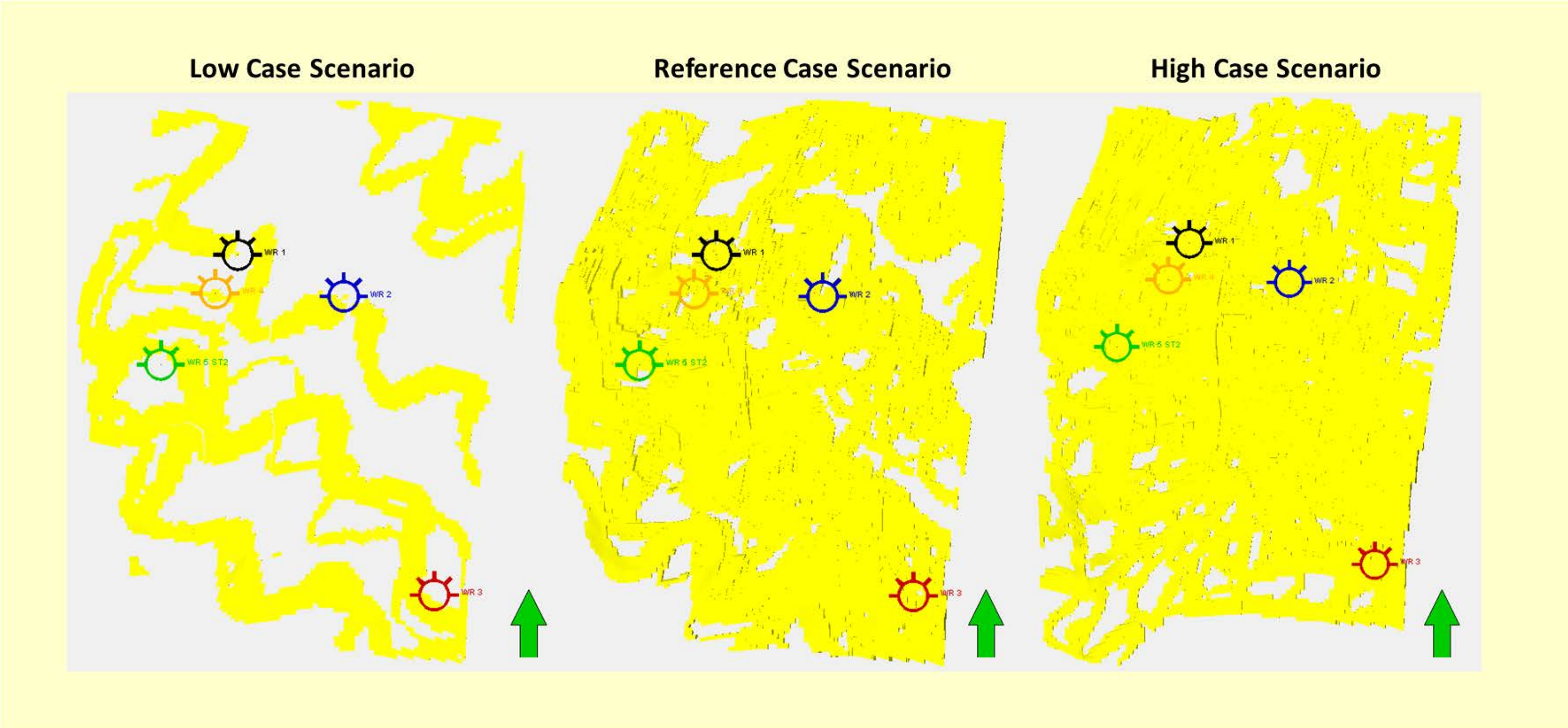


Figure 71. K layer view of the SB_4_2 where the major differences between connected volumes are displayed.

Discussion

After the generation of the nine simple models using a general channel geometry parameter, it may be observed that there exists a general variation in trends in the overall facies distributions and proportions. This vertical and lateral variation is more distinctive in CH1 FA , which shows a gradual increase in the volumes and proportion (wider and thicker) upward, as displayed in the modelled blocks presented in Figure 64. This increment in channel facies is accompanied by a decrease in floodplain and muddy facies, resulting in a higher degree of connectivity of the CH1 facies, but also in a reduction of the seal capacity of the reservoir.

Although an overall facies variation was observed, this doesn't seems to be completely representative of the geology or the magnitude of changes interpreted in the sequence stratigraphic model, because it tends to predict a high degree of channel facies through the TST and the start of the HST systems tracts.

The statistical models based on the PCT10, 25 and 50 channel estimation result in the prediction of multiple narrow channel bodies randomly distributed around the model area, which do not represent the expected facies geometries and inter-facies relationships previously interpreted from a modern analogue (Lake Baikal, Russia).

The remaining models produced a closer representation of facies proportions and distribution, therefore they were considered for the selection of the reference scenarios that would better represent the vertical and lateral facies. In terms of facies Williams sn<1.7 (1986), Bridge and Mackey (1993) and Williams sn<1.3 (1986) define the best range of possible facies proportions and distributions; however, PCT 10 was also consider a reference case but just for evaluating the impact caused by the reduction of channel facies proportions within the estimation of connected volumes.

To sum up, the results obtained from the comparison of the nine facies models provide certainty about the necessity for constraining the reference geological models to the fourth order sequence stratigraphic framework.

The results obtained from the integration of the facies dimensions (calculated per zone), facies proportions derived from logs, and the fourth order sequence stratigraphic framework were applied in the construction of all the reference 3D geological models. From this integration, a more realistic representation of the deterministic model was achieved for the Whicher Range Field, which was the key in achieving a more realistic model of the distribution of the reservoir architecture and therefore an improved connectivity estimation that aims to reduce the high degree of uncertainty about the connectivity of the bodies.

The impact of applying a sequence stratigraphy constraint on the prediction of the reservoir facies can be recognized in all the generated reference models (Figure 67) from a characteristic increase in channel dimensions occurring up-section, (from FS_3 to SB_5) as proposed in the sequence stratigraphic conceptual model presented in Chapter 3. These vertical and lateral variations imply marked changes in reservoir quality involving petrophysical properties and connectivity, therefore helping to define the main areas to target in further exploration and appraisal strategies.

Another objective of constructing a geological reservoir model in the Whicher Range field was trying to better extrapolate the petrophysical properties derived from core and well logs presented in Chapter 5, but also investigating the relationship (if any) between the petrophysical properties and facies. In the case of porosity, the property was populated applying a facies constraint. This was decided due to the linear relationship observed between the estimated porosities and predicted facies, as observed in Figure 67.

On the other hand, the poor relationship observed between permeabilities and facies, possibly related to the post-depositional diagenetic effects, was approached by upscaling the permeability log to the model and populating it with no facies constraint, applying sequential Gaussian simulation methods with a distribution given by the log data absolute minimum and maximum values. Although no facies constraint data was applied to populate this property, a good match between the distribution of the highest permeability values and the CH1 facies was observed for all reference cases (Figure 68).

One of the key observations obtained from the connectivity analysis was a distinctive increase in the total volume of connected reservoir facies (CH1), which shows the higher variation between the low case PCT10 and the Higher Williams case scenario, the latter being estimated to double the volume of the estimated lower case scenario. Also, it was observed that the best connected volumes were located above SB 4_0, as shown in Figure 66.

In relation to the distribution of connected bodies, when separating them by fourth order sequence stratigraphic intervals, it seem that volume estimates by stratigraphic intervals maintain the proportions in the main connected bodies and for all the reference case scenarios modelled.

The best areas in terms of petrophysical properties, including porosity, permeability and water saturation and connectivity, were observed to occur above SB 4_0 (Figure 72). Variability in reservoir quality is predicted by the geological reservoir model and has been recognized from the DST data acquired in some WR wells, as well.

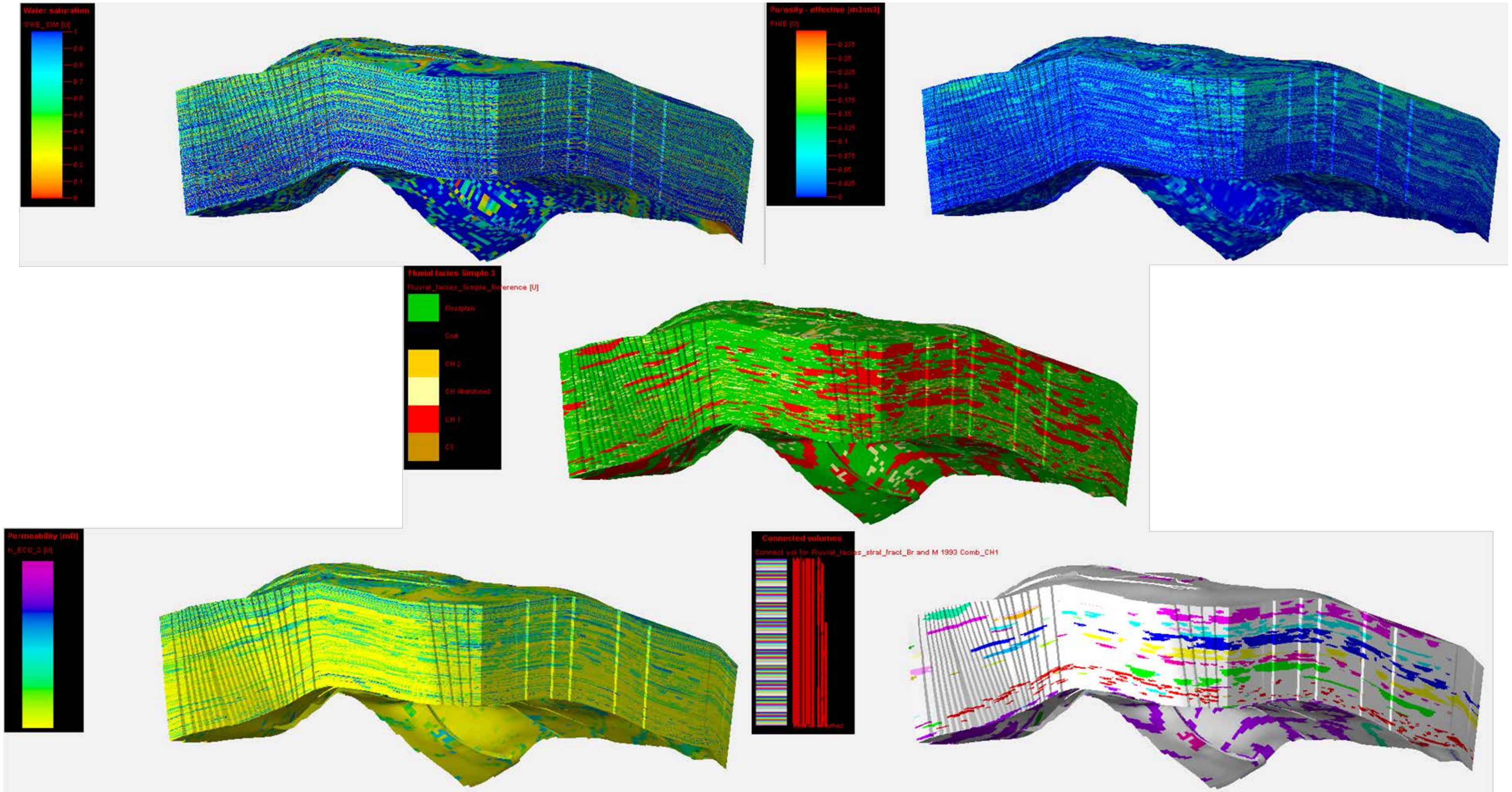


Figure 72. Block diagrams corresponding to the Geological reservoir modelling facies, porosity, permeability , water saturation and connectivity.

Chapter 7 - CONCLUSIONS AND RECOMMENDATIONS

Conclusions

- The Permian section of the Whicher Range field has been interpreted as an axial fluvial sinuous meandering system, with non-marine influence, flowing towards the north along the Bunbury trough and possibly migrating towards the Darling Fault.
- Six facies were identified from core in the Willespie Formation, which are embedded in three main lithology groups (Sand, Heterolitic and Mud). Also, six facies associations including channels, channel abandonment, CH2/crevasse splays, crevasse splay distal, flood plain and coal were recognized.
- The Permian section of the South Perth Basin evaluated in this study is defined by four, third order and eight fourth order depositional sequences. The transgressive Systems tract (TST) interval in the Whicher Range field is mostly characterized by floodplain shales and siltstones with proximal, medial and distal splay deposition. The Highstand Systems Tract (HST) is distinguished by isolated or multistorey sandstone channels and splays whereas the Lowstand Systems Tract (LST) is characterized by a thicker vertical section comprising amalgamated channel sandstone facies.
- The internal correlation of the Willespie Formation allowed the subdivision of this formation into eight groups of parasequences within the five wells drilled in the Whicher Range field.
- The key findings from the sand/shale ratio analysis were related to the apparent reverse relationship between the sand/shale ratio and reservoir performance, which is most likely to be related to the key role played by the fine grained facies (floodplains, distal crevasse splays and coals) as intra-formational seals.
- Faults in the Whicher Range area have a major trend NNE–SSW, a similar orientation to the two major faults that delimit the Bunbury Trough, a minor set of faults oriented E-W was also interpreted. All these faults influence structures and deposition within the basin.

- Based on seismic data, it was found that the structures and faults interpreted correspond to an extensional regional tectonic setting, as expected for this area.
- The structure within the Whicher Range area is interpreted as a NW-SE trending anticline with two culminations which may be different structural traps and with different gas accumulations. However, lack of seismic data makes it difficult to reliably characterize part of the structure and therefore its hydrocarbon potential.
- Poor well log data, particularly in density logs, and also core analysis data unfit for purpose give a high degree of uncertainty to the petrophysical data.
- Porosity estimation was based on acoustic logs and verified using density porosity in intervals where good hole conditions were observed. A good match between the log derived porosity and the measured core data was observed in most of the Whicher Range wells. The range of porosities interpreted varies from 2 to15%.
- The “m” versus total porosity trend observed from the Whicher Range core data, shows a good match to the extensive core data available for the TGS Mesaverde reservoir from the US. Therefore, this TGS reservoir was used as an analogue for the Whicher Range Field.
- Sandstones of the Willespie Formation in the Whicher Range Field are mostly classified as lithic arkoses and arkoses with rare feldespathic-litharenites. The main components of these sandstones are quartz and feldspar with minor rock fragments.
- Rock quality in the Whicher Range sandstones seems to be mostly controlled by type, morphology, abundance and distribution of clays, with minor control by deformation of ductile fragments, calcite and quartz cementation, compaction and grain rearrangement.
- Core data analysis indicates a diversity in clay content between the analyzed wells. Overall, smectite, chlorite and smectite/illite seem to be the dominant clays in Whicher Range 2 and Whicher Range 3 whereas kaolinite is more common in Whicher Range 1 and Whicher Range 4.

- The relationship between rock quality and the depositional environment suggests that low reservoir quality is mostly related to channel abandonments, floodplains and crevasse splays. The better reservoir quality is associated with channel barforms (CH1 FA).
- The channel belt across the field contains channel bodies of about 175 m width. This median value of channel width was applied as a constraint in the generation of the 3D facies model. The channel belt for the Whicher Range area has an estimated median width of about 1600m.The general trends given to the channels are NW-SE (310 ˚-320 ˚).
- The better connectivity of the channel sandstones in the upper section (from SB 4_0 to SB_5) of the Willespie Formation could be expected based on the interpretation of the available data from the Whicher Range field and the use of distinctive stacking patterns in relation to accommodation and sediment supply.
- Although the geological reservoir modelling predicts a high degree of connectivity between CH1 facies located within the Permian succession, the channel abandonment facies and floodplains are most likely to constitute permeability barriers and generate stratigraphic compartmentalization.
- The application of a sequence stratigraphic framework helps to better predict the facies proportions and the architecture of the sandbodies. The construction of this geological model within a sequence stratigraphic framework helps to demonstrate the possibility of building a robust model at an early exploratory stage where little and scattered data is available.
- The best areas in terms of connectivity and petrophysical properties, including porosity, permeability and water saturation, occur above SB_4_0.

Recommendations

- Acquisition of a 3D seismic survey may help to provide better control in the prediction of the architecture and structure through attribute extraction and accessing horizon slices.
- Acquire new core data and *performe fit for purpose* core data analysis to reduce the uncertainty related to the quality of the data available now.
- Study the possibility of drilling deviated or multilateral horizontal wells to access the channel sandstones.
- Focus the downhole perforations on targets from SB 4_0 to SB_5.
- Explore the hydrocarbon potential of the lead located to the southeast of the Whicher Range closure.
- Explore the possibility of drilling wells to the LST Permian sequence, no yet drilled in the Whicher Range area.
- Avoid drilling with fresh water based muds to avoid the swelling effect of clays on the drilling operations and therefore in quality of data.
- Acquire better coverage image log data to help the paleocurrent analysis, facies calibration and fracture study to look for better areas for applying fracture stimulation.

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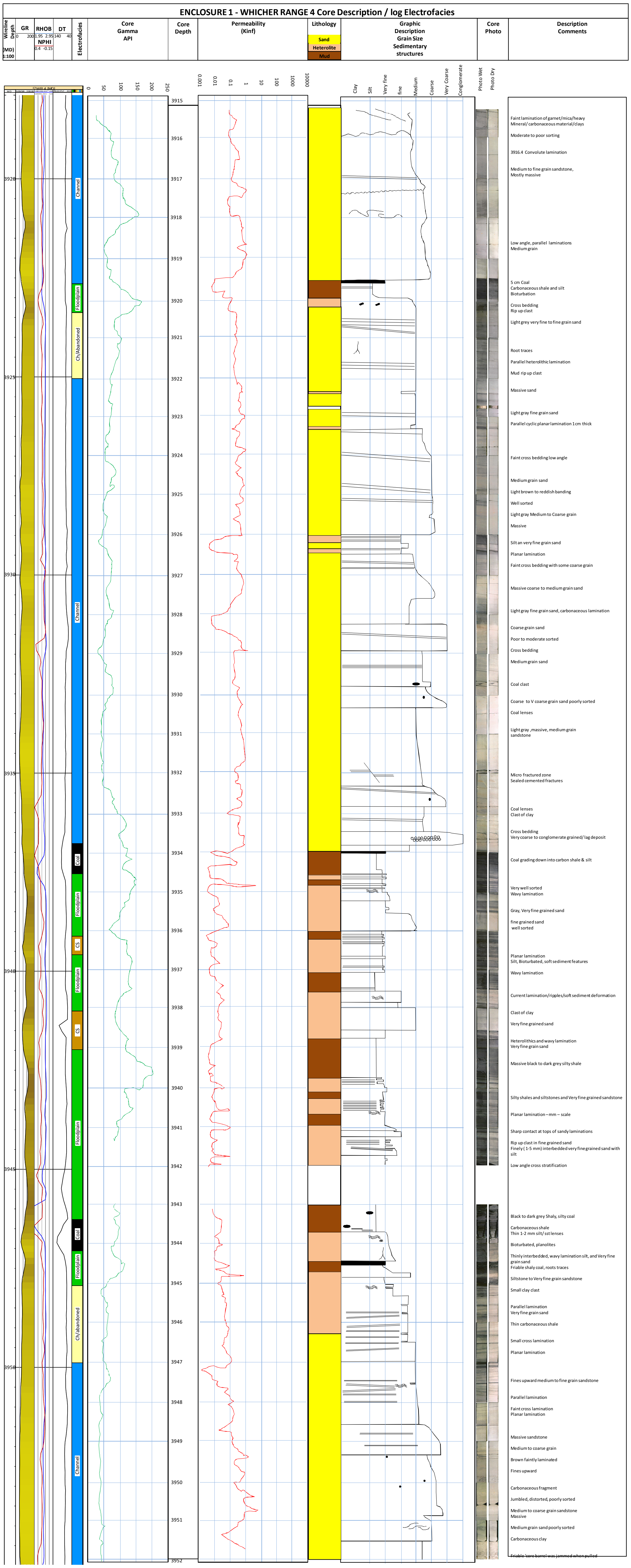
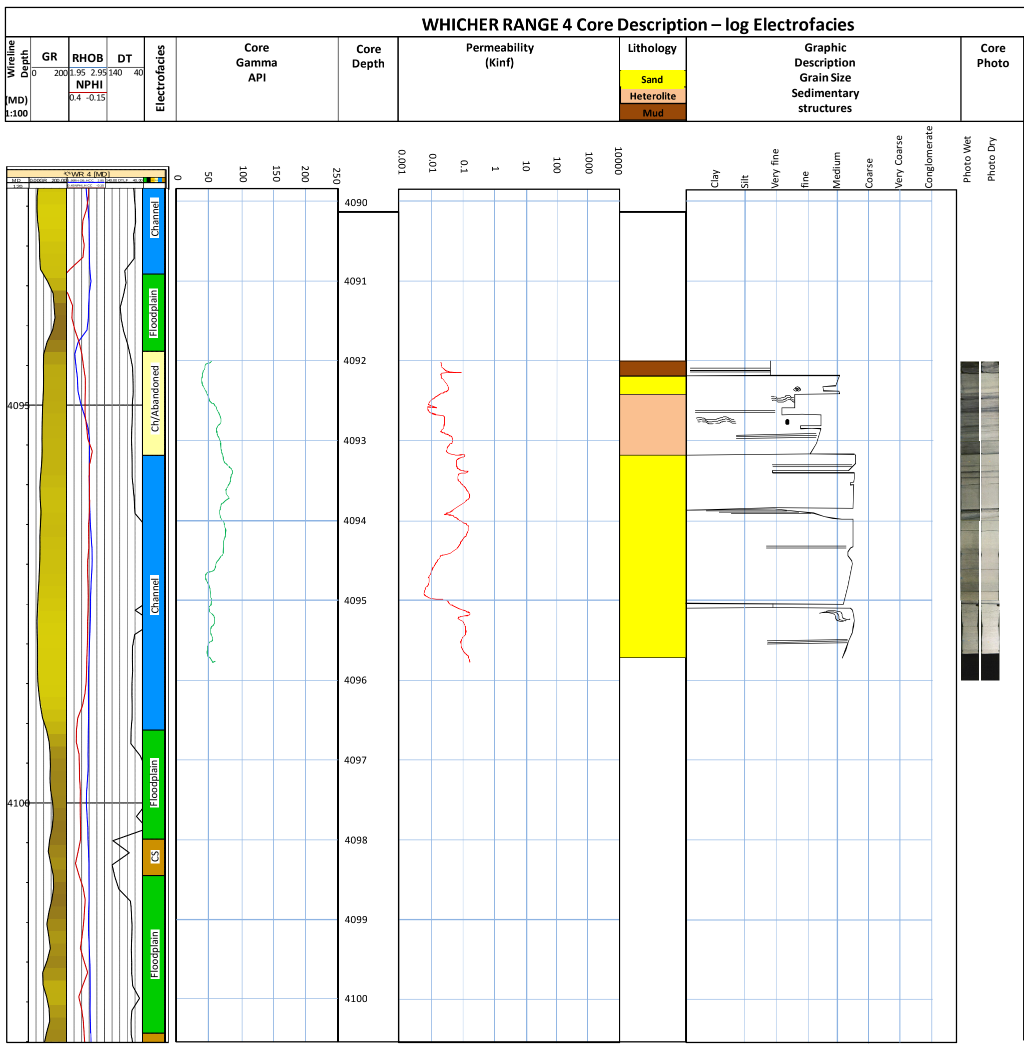
ENCLOSURES

ENCLOSURE 1 - WHICHER RANGE 4 Core Description / log Electrofacies



WHICHER RANGE 4 Core Description – log Electrofacies



Description Comments

Faint lamination of garnet/mica/heavy
Mineral/ carbonaceous material/clays

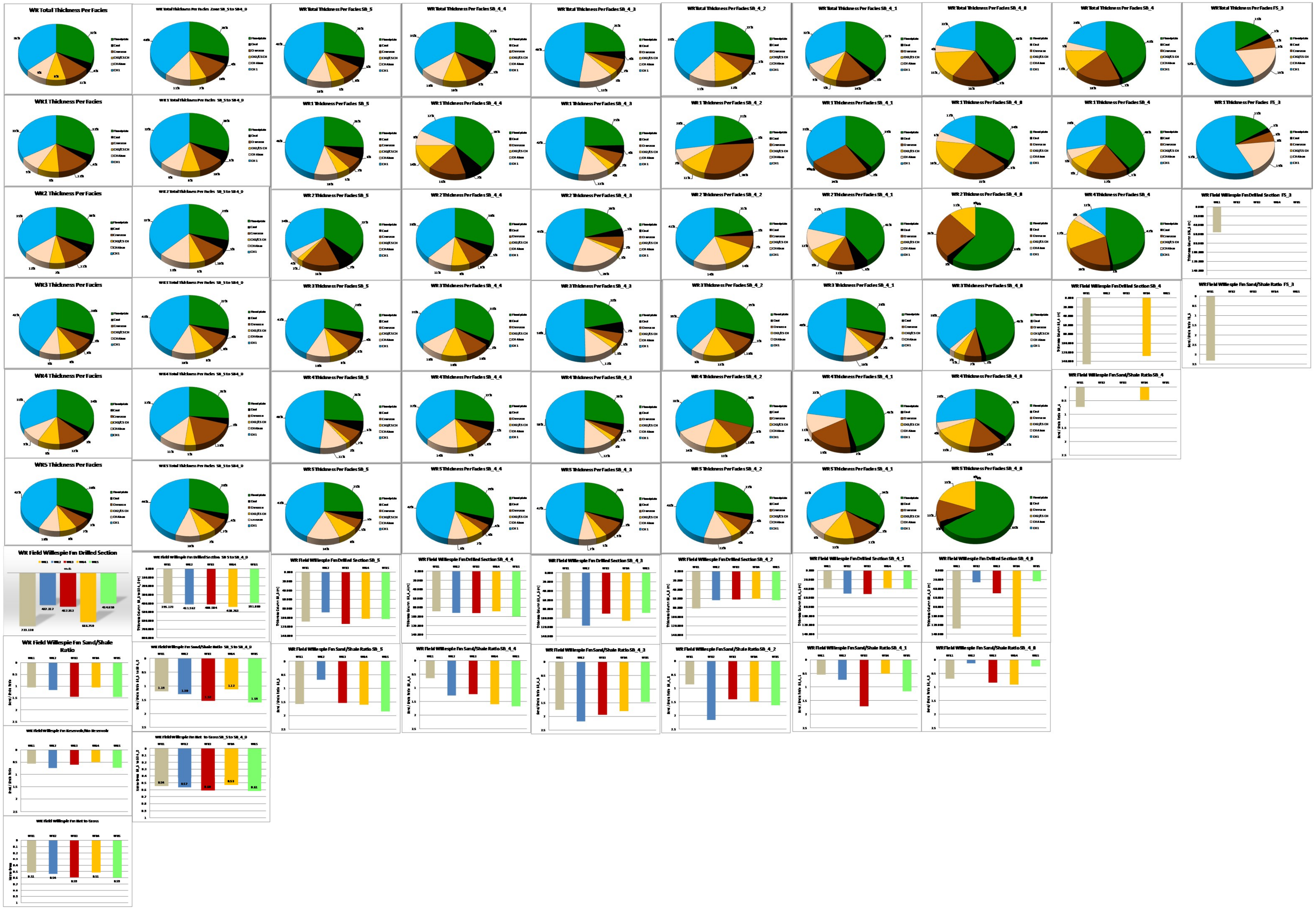
Moderate to poor sorting
Dark grey faintly laminated carbonaceous siltstone with very fine grain thin sandstone laminations (1-2 mm)
Very well sorted Very fine to fine grain sandstone / wavy lamination
Soft sediment features
Fine grain sandstone/ flaser bedding
Faint cross lamination

Massive medium grain sandstone
Faint carbonaceous lamination

Silty Carbonaceous shale 1 cm
Coarsening up cycle
Medium grain sandstone
Mostly massive with some faint laminations of gray carbonaceous fine grain sandstone
Medium grain sandstone
Faint cross lamination
Slightly friable toward the base

Carbonaceous silt

Enclosure 2



Equations taken from the paper published by Brigde and Mackey (1993)

Enclosure 3

Channel Width from Depth / Channel Belt Width from Depth

Zone	Facies	Maximun Bankfull depth (Channel sand thickness from vsh)	Statistics	Mean bankful channel depth (thick x 0.55 general Crane 1987)	Leeder 1973	Crane 1982	Williams 1986 (sn>1.7)	Williams 1986 (sn>1.3)	Bridge and Mackey (1993)	Bridge and Mackey (1993) Combined equations	Fielding and Crane 1987	Fielding and Crane 1987	Collinson 1987 (Uses maximum depth)	Williams 1986 from Bridge and Mackey 1993	Bridge and Mackey 1993 regression	Bridge and Mackey 1993 combined	Bridge and Mackey 1993 combined equations with Leeder (uses maximum depth)	Bridge and Mackey 1993 combined equations with Leeder (2)	Bridge and Mackey 1993 Combined equations with Crane
SB_5	CH1	3.35	min	2.03	50.75	39.47	41.72	59.40	32.17	48.46	44.78	1332.98	509.12	433.70	506.03	213.83	347.25	315.11	261.39
		24.69	max	14.94	1098.27	943.97	682.80	1074.13	1217.77	1135.95	1799.55	19740.90	11698.25	9018.52	7799.35	7776.83	7220.82	6552.44	6006.06
		10.90	average	10.90	345.42	288.67	233.00	355.84	329.45	349.31	479.51	6942.97	3617.52	2868.94	2709.96	2125.56	2297.07	2084.44	1857.29
		5.78	St dev	3.50	285.27	246.34	174.49	276.26	322.88	296.17	477.87	5008.96	3047.26	2337.74	1984.82	2059.75	1871.75	1698.50	1564.51
		9.58	geomean	9.58	255.64	209.57	181.46	272.25	217.46	254.59	312.36	5500.43	2646.74	2139.34	2132.39	1415.28	1712.90	1554.35	1358.88
		8.65	Median	5.23	218.40	178.13	157.26	234.75	180.54	216.61	258.53	4791.36	2254.27	1831.45	1853.71	1177.40	1466.38	1330.65	1157.38
		5.91	10 pct	5.91	121.61	97.32	92.34	135.25	90.39	118.79	127.97	2867.43	1240.95	1027.51	1100.97	593.95	822.69	746.54	637.12
		8.58	50 pct	5.23	215.50	175.69	155.36	231.81	177.71	213.66	258.53	4791.36	2254.27	1831.45	1853.71	1177.40	1466.38	1330.65	1157.38
		17.68	90 pct	10.70	659.67	557.93	429.10	664.19	668.57	673.56	978.55	12608.87	6958.83	5451.95	4949.37	4296.94	4365.19	3961.14	3572.77
		6.40	25 pct	3.87	137.36	110.36	103.17	151.70	104.37	134.61	148.11	3190.96	1405.07	1158.85	1227.12	684.77	927.85	841.97	721.39
	CH2/CSP	1.25	min	0.83	12.70	9.44	11.84	16.12	6.26	11.70	8.48	395.67	123.98	110.48	147.53	42.34	88.46	80.27	63.66
		3.81	max	2.51	70.64	55.54	56.36	81.11	47.56	68.04	66.63	1781.35	713.30	601.14	679.15	314.76	481.31	436.76	366.22
		2.51	average	1.66	38.38	29.67	32.14	45.45	23.54	36.47	32.66	1033.94	383.58	328.83	391.42	156.79	263.29	238.91	196.94
		0.71	St dev	0.47	16.37	13.04	12.54	18.32	11.74	15.93	16.54	389.83	166.59	138.55	149.63	77.40	110.94	100.67	85.53
		2.42	geomean	1.59	35.01	26.90	29.77	41.88	20.74	33.11	28.66	962.60	348.66	300.62	363.67	138.54	240.69	218.41	179.01
		2.50	Median	1.65	36.92	28.42	31.25	44.03	22.09	34.97	30.56	1008.60	368.12	316.84	381.31	147.44	253.68	230.20	189.00
		1.83	10 pct	1.21	22.82	17.29	20.17	27.99	12.51	21.34	17.14	661.44	225.37	197.03	248.50	84.00	157.76	143.15	115.71
		2.50	50 pct	1.65	36.92	28.42	31.25	44.03	22.09	34.97	30.56	1008.60	368.12	316.84	381.31	147.44	253.68	230.20	189.00
		3.20	90 pct	2.11	54.02	42.11	44.17	63.01	34.64	51.67	48.27	1408.11	542.65	461.32	534.98	230.05	369.36	335.17	278.60
		2.13	25 pct	1.41	28.92	22.09	25.03	34.99	16.56	27.22	22.79	814.29	287.01	248.99	306.87	110.84	199.36	180.91	147.35
SB_4_4	CH1	3.02	min	1.83	43.20	33.43	36.04	51.04	26.60	41.08	36.90	1157.43	432.02	369.95	438.47	177.14	296.20	268.79	221.80
		15.39	max	9.31	530.56	445.37	352.40	541.43	515.39	538.48	750.90	10432.14	5571.70	4398.06	4082.83	3322.60	3521.38	3195.43	2860.60
		8.48	average	5.13	223.07	182.94	158.39	237.55	190.88	222.22	274.49	4804.32	2309.98	1866.57	1861.96	1241.40	1494.50	1356.16	1185.98
		3.13	St dev	1.89	126.20	106.84	81.51	126.58	127.58	128.97	186.48	2384.78	1332.20	1042.35	937.82	820.58	834.57	757.32	683.97
		7.93	geomean	4.79	190.88	155.00	139.13	206.79	153.97	188.66	219.91	4257.76	1965.04	1603.46	1644.38	1005.90	1283.84	1165.00	1008.88
		7.85	Median	4.75	188.10	152.67	137.28	203.93	151.35	185.84	216.11	4202.77	1935.84	1580.34	1622.86	988.96	1265.33	1148.20	993.89
		5.49	10 pct	3.32	108.32	86.36	83.13	121.30	78.82	105.49	111.34	2591.09	1102.86	916.64	993.37	518.75	733.92	665.99	566.23
		8.08	50 pct	4.75	196.53	159.74	142.87	212.54	159.37	194.38	216.11	4202.77	1935.84	1580.34	1622.86	988.96	1265.33	1148.20	993.89
		12.51	90 pct	7.57	386.23	320.96	263.92	401.40	354.62	388.85	513.56	7892.45	4031.57	3214.67	3076.35	2295.33	2573.88	2335.63	2069.87
		6.27	25 pct	3.80	133.23	106.93	100.34	147.39	100.67	130.45	142.77	3106.49	1361.92	1124.37	1194.17	660.72	900.25	816.92	699.23
	CH2/CSP	1.30	min	0.86	13.49	10.05	12.51	17.06	6.72	12.44	9.11	417.18	131.86	117.26	155.67	45.44	93.89	85.20	67.70
		5.49	max	3.62	123.85	99.17	93.90	137.61	92.35	121.04	130.79	2914.05	1264.30	1046.25	1119.13	606.70	837.70	760.16	649.11
		3.15	average	2.08	55.23	43.26	44.59	63.88	36.53	53.04	51.10	1415.90	556.41	470.73	538.79	241.99	376.90	342.01	285.67
		1.10	St dev	0.73	29.43	23.80	21.63	32.07	22.99	28.99	32.69	662.56	302.24	247.63	255.80	150.61	198.27	179.91	155.17
		2.97	geomean	1.96	48.14	37.38	39.77	56.52	30.22	45.90	42.02	1272.61	482.41	411.65	482.78	201.02	329.59	299.09	247.68
		3.20	Median	2.11	54.02	42.11	44.17	63.01	34.64	51.67	48.27	1408.11	542.65	461.32	534.98	230.05	369.36	335.17	278.60
		2.03	10 pct	1.34	26.78	20.41	23.34	32.54	15.12	25.16	20.79	761.16	265.38	230.80	286.57	101.33	184.80	167.69	136.25
		3.20	50 pct	2.11	54.02	42.11	44.17	63.01	34.64	51.67	48.27	1408.11	542.65	461.32	534.98	230.05	369.36	335.17	278.60
		4.57	90 pct	3.02	93.81	74.46	72.89	105.89	66.61	91.04	93.85	2282.23	952.61	795.26	873.39	439.16	636.74	577.80	489.08
		2.44	25 pct	1.61	35.58	27.36	30.20	42.51	21.17	33.67	29.26	975.88	354.50	305.44	368.78	141.32	244.56	221.92	182.01
	CH1	3.05	min	1.84	43.82	33.92	36.51	51.73	27.05	41.68	37.54	1171.95	438.32	375.17	444.05	180.10	300.39	272.58	225.04
		19.89	max	12.04	787.56	669.65	504.66	785.37	822.02	807.58	1206.89	14748.98	8334.59	6495.12	5802.00	5272.25	5200.42	4719.06	4279.10
		8.93	average	5.41	251.30	207.63	174.95	264.20	224.71	251.82	324.78	5271.78	2613.86	2096.68	2048.51	1456.54	1678.74	1523.35	1341.99
		4.41	St dev	2.67	193.00	164.80	121.81	190.71	205.06	198.59	301.42	3535.73	2047.84	1588.75	1394.83	1314.08	1272.05	1154.31	1051.39
		7.96	geomean	4.82	192.13	156.05	139.96	208.06	155.17	189.93	221.64	4282.22	1978.18	1613.84	1653.97	1013.61	1292.15	1172.54	1015.63
		7.77	Median	4.70	185.21	150.25	135.37	201.00	148.59	182.91	212.09	4146.74	1905.58	1556.47	1600.88	971.08	1246.21	1130.86	978.35

		4.63	10 pct	2.80	83.30	65.85	65.47	94.72	57.79	80.58	[redacted]	81.22	2058.12	843.79	707.31	786.35	381.65	566.32	513.90	433.22
		7.77	50 pct	4.70	185.21	150.25	135.37	201.00	148.59	182.91	[redacted]	212.09	4146.74	1905.58	1556.47	1600.88	971.08	1246.21	1130.86	978.35
		14.45	90 pct	8.74	481.31	402.76	322.53	493.97	459.39	487.27	[redacted]	668.04	9577.81	5045.00	3994.86	3743.75	2965.29	3198.55	2902.49	2590.18
SB_4_3		5.98	25 pct	3.62	123.77	99.10	93.84	137.52	92.28	120.96	[redacted]	130.69	2912.34	1263.46	1045.58	1118.46	606.26	837.16	759.67	648.68
		1.85	min	1.22	23.22	17.61	20.50	28.45	12.77	21.73	[redacted]	17.51	671.71	229.44	200.48	252.42	85.75	160.52	145.66	117.80
		5.33	max	3.52	118.61	94.84	90.27	132.11	87.74	115.79	[redacted]	124.16	2805.58	1209.74	1002.51	1076.87	576.78	802.68	728.38	621.10
		3.18	average	2.10	56.43	44.27	45.39	65.11	37.65	54.25	[redacted]	52.72	1439.38	568.98	480.68	547.99	249.26	384.86	349.24	292.12
		1.28	St dev	0.84	35.04	28.39	25.61	38.06	27.62	34.57	[redacted]	39.31	782.96	360.25	294.62	302.54	180.86	235.89	214.06	184.96
	CH2/CSP	2.98	geomean	1.97	48.47	37.64	40.02	56.89	30.47	46.23	[redacted]	42.37	1280.31	485.80	414.46	485.74	202.64	331.84	301.12	249.42
		3.05	Median	2.01	50.57	39.36	41.50	59.12	32.22	48.32	[redacted]	44.87	1325.03	507.54	432.03	503.12	214.05	345.91	313.90	260.58
		2.00	10 pct	1.32	26.25	19.99	22.90	31.92	14.78	24.64	[redacted]	20.31	747.26	259.97	226.20	281.27	99.07	181.11	164.35	133.47
		3.05	50 pct	2.01	50.57	39.36	41.50	59.12	32.22	48.32	[redacted]	44.87	1325.03	507.54	432.03	503.12	214.05	345.91	313.90	260.58
		4.50	90 pct	2.97	92.48	73.45	71.76	104.29	65.96	89.79	[redacted]	92.98	2245.84	939.43	783.79	859.59	434.65	627.55	569.46	482.32
		2.26	25 pct	1.49	31.70	24.29	27.19	38.13	18.49	29.91	[redacted]	25.50	881.72	315.22	272.58	332.71	123.60	218.24	198.04	161.84
		3.64	min	2.20	57.66	45.04	46.86	66.99	37.42	55.25	[redacted]	52.21	1490.93	579.94	491.98	566.93	248.27	393.91	357.45	297.75
		19.05	max	11.53	736.70	625.05	474.94	737.52	759.66	754.11	[redacted]	1113.88	13910.58	7786.20	6080.93	5467.45	4876.49	4868.80	4418.13	3997.55
		9.65	average	5.84	274.72	227.03	191.01	288.62	245.51	275.35	[redacted]	354.73	5751.10	2857.93	2291.86	2235.49	1591.64	1835.02	1665.16	1467.30
		3.92	St dev	2.37	174.34	149.00	109.72	171.97	185.90	179.51	[redacted]	273.32	3180.92	1850.80	1434.62	1255.48	1191.10	1148.65	1042.33	950.23
	CH1	8.94	geomean	5.41	229.73	187.68	164.66	246.20	191.66	228.15	[redacted]	274.73	5008.59	2373.56	1925.20	1939.02	1249.11	1541.44	1398.76	1218.62
		8.76	Median	5.30	222.99	182.00	160.23	239.35	185.12	221.29	[redacted]	265.21	4878.23	2302.62	1869.33	1887.87	1206.87	1496.71	1358.17	1182.20
		5.89	10 pct	3.57	121.08	96.89	91.97	134.69	89.96	118.27	[redacted]	127.35	2856.17	1235.54	1023.13	1096.60	591.14	819.19	743.36	634.35
		9.14	50 pct	5.30	237.90	194.57	169.97	254.43	199.74	236.48	[redacted]	265.21	4878.23	2302.62	1869.33	1887.87	1206.87	1496.71	1358.17	1182.20
		14.25	90 pct	8.62	473.07	395.80	317.19	485.68	451.24	478.86	[redacted]	656.18	9421.84	4958.07	3926.72	3682.39	2912.74	3143.99	2852.98	2545.55
SB_4_2		7.23	25 pct	4.37	165.75	134.00	122.34	181.02	130.41	163.24	[redacted]	185.76	3760.79	1701.78	1394.87	1449.84	853.48	1116.82	1013.45	873.72
		1.52	min	1.01	17.23	12.94	15.63	21.48	8.97	16.00	[redacted]	12.23	517.05	169.24	149.32	193.55	60.49	119.55	108.49	86.89
		4.72	max	3.12	98.41	78.21	76.18	110.82	70.37	95.60	[redacted]	99.22	2382.01	1000.07	833.79	912.07	463.70	667.59	605.80	513.45
		3.04	average	2.01	53.06	41.56	42.86	61.39	35.09	50.95	[redacted]	49.09	1361.58	534.51	452.26	518.05	232.45	362.11	328.59	274.43
		1.22	St dev	0.81	31.57	25.42	23.44	34.64	24.08	30.99	[redacted]	34.15	720.66	323.38	265.99	277.84	158.05	212.97	193.26	166.03
	CH2/CSP	2.82	geomean	1.86	44.41	34.40	36.96	52.40	27.48	42.27	[redacted]	38.15	1185.96	444.43	380.23	449.44	182.98	304.44	276.26	228.18
		2.95	Median	1.95	47.64	36.98	39.39	55.96	29.86	45.42	[redacted]	41.52	1260.89	477.34	407.44	478.27	198.65	326.23	296.03	245.07
		1.83	10 pct	1.21	22.82	17.29	20.17	27.99	12.51	21.34	[redacted]	17.14	661.44	225.37	197.03	248.50	84.00	157.76	143.15	115.71
		2.95	50 pct	1.95	47.64	36.98	39.39	55.96	29.86	45.42	[redacted]	41.52	1260.89	477.34	407.44	478.27	198.65	326.23	296.03	245.07
		4.71	90 pct	3.11	97.89	77.79	75.82	110.27	69.94	95.09	[redacted]	98.60	2371.05	994.73	829.48	907.81	460.88	664.14	602.67	510.71
		1.94	25 pct	1.28	25.06	19.05	21.96	30.56	13.98	23.49	[redacted]	19.19	717.89	247.94	216.10	270.04	93.74	173.02	157.00	127.30
		3.66	min	2.21	58.01	45.32	47.12	67.37	37.68	55.58	[redacted]	52.58	1498.67	583.44	494.86	569.91	249.99	396.22	359.54	299.55
		14.22	max	8.60	469.64	392.68	315.42	482.70	446.21	475.15	[redacted]	648.57	9374.39	4920.29	3899.27	3663.05	2881.18	3122.02	2833.03	2526.15
		7.47	average	4.52	188.91	154.50	135.27	202.24	159.47	187.77	[redacted]	229.03	4116.57	1953.00	1582.52	1593.29	1037.97	1267.07	1149.79	1002.70
		3.57	St dev	2.16	136.89	115.35	89.59	138.48	134.73	139.37	[redacted]	196.36	2633.53	1440.98	1132.83	1033.71	868.24	907.02	823.06	739.82
	CH1	6.75	geomean	4.08	148.96	119.99	111.05	163.72	114.86	146.28	[redacted]	163.25	3425.83	1526.06	1255.32	1318.83	752.78	1005.09	912.06	783.50
		6.08	Median	3.68	127.13	101.91	96.10	140.98	95.39	124.35	[redacted]	135.19	2979.20	1298.61	1073.48	1144.62	626.41	859.50	779.94	666.73
		3.87	10 pct	2.34	63.37	49.66	51.05	73.21	41.86	60.87	[redacted]	58.51	1619.09	638.56	540.00	616.43	277.38	432.36	392.34	327.84
		6.08	50 pct	3.68	127.13	101.91	96.10	140.98	95.39	124.35	[redacted]	135.19	2979.20	1298.61	1073.48	1144.62	626.41	859.50	779.94	666.73
		12.24	90 pct	7.41	373.36	309.89	255.98	388.85	340.45	375.52	[redacted]	492.68	7663.99	3894.35	3109.00	2985.89	2204.75	2489.27	2258.86	1999.42
SB_4_1		4.65	25 pct	2.81	83.94	66.37	65.93	95.41	58.33	81.22	[redacted]	81.99	2071.95	850.46	712.71	791.72	385.15	570.64	517.82	436.64
		1.98	min	1.31	25.80	19.63	22.56	31.42	14.46	24.21	[redacted]	19.87	736.71	255.46	222.45	277.22	96.99	178.11	161.62	131.16
		4.72	max	3.12	98.38	78.18	76.16	110.78	70.34	95.57	[redacted]	99.18	2381.33	999.74	833.53	911.81	463.53	667.38	605.60	513.28
		2.91	average	1.92	49.50	38.68	40.24	57.51	32.35	47.44	[redacted]	45.19	1281.36	497.97	422.29	487.07	214.45	338.11	306.81	255.66
		1.29	St dev	0.85	34.14	27.55	25.20	37.32	26.33	33.58	[redacted]	37.38	773.16	350.22	287.47	298.35	172.72	230.17	208.86	179.81
	CH2/CSP	2.73	geomean	1.80	42.18	32.62	35.27	49.91	25.86	40.09	[redacted]	35.86	1133.55	421.67	361.37	429.29	172.28	289.33	262.55	216.49
		2.47	Median	1.63	36.91	28.46	31.13	43.91	22.29	35.00	[redacted]	30.86	1003.70	368.34	316.59	379.62	148.64	253.48	230.02	189.11
		1.99	10 pct	1.31	25.92	19.72	22.65	31.55	14.54	24.32	[redacted]	19.98	739.58	256.62	223.43	278.32	97.49	178.89	162.33	131.75
		2.47	50 pct	1.63	36.91	28.46	31.13	43.91	22.29	35.00	[redacted]	30.86	1003.70	368.34	316.59	379.62	148.64	253.48	230.02	189.11
		4.19	90 pct	2.77	83.15	65.82	65.13	94.34	58.20	80.52	[redacted]	81.88	2045.27	843.02	705.71	781.77	384.05	565.04	512.74	432.82
		2.00	25 pct	1.82	43.35	33.57	36.09	51.15	26.83	41.25	[redacted]	37.25	1158.16	433.75	371.12	438.86	178.62	297.14	269.64	222.69
		4.57	min	2.77	81.81	64.63	64.41	93.13	56.57	79.10	[redacted]	79.47	2025.96	828.43	694.85	773.88	373.67	556.34	504.85	425.33
		18.90	max	11.43	727.61	617.08	469.61	728.94	748.59	744.57	[redacted]	1097.39	13759.97	7688.24	6006.85	5407.38	4806.22	4809.48	4364.30	3947.26
		10.67	average	6.45	328.49	273.56	223.58	340.40	306.61	331.27	[redacted]	445.11	6681.62	3433.01	2731.98	2604.95	1981.58	2187.40	1984.93	1762.56

SB_4_0	CH1	5.24	St dev	3.17	233.57	199.60	146.98	230.40	248.75	240.48	[redacted]	365.65	4260.76	2479.47	1922.07	1681.80	1594.05	1538.93	1396.49	1273.00
		9.49	geomean	5.74	251.91	206.41	179.05	268.51	213.72	250.78	[redacted]	306.89	5429.99	2607.36	2108.52	2104.68	1391.17	1688.22	1531.95	1338.66
		9.91	Median	5.99	269.11	220.98	190.13	285.74	231.07	268.36	[redacted]	332.23	5753.74	2789.01	2250.58	2232.08	1502.84	1801.97	1635.17	1431.92
		4.94	10 pct	2.99	92.15	73.09	71.76	104.16	65.14	89.38	[redacted]	91.73	2248.41	935.36	781.47	860.20	429.59	625.70	567.78	480.23
		9.91	50 pct	5.99	269.11	220.98	190.13	285.74	231.07	268.36	[redacted]	332.23	5753.74	2789.01	2250.58	2232.08	1502.84	1801.97	1635.17	1431.92
		16.95	90 pct	10.25	616.07	519.74	403.55	623.10	615.47	627.78	[redacted]	899.42	11887.27	6489.11	5096.78	4661.55	3959.80	4080.82	3703.09	3331.61
		6.55	25 pct	3.96	142.42	114.56	106.61	156.95	108.93	139.69	[redacted]	139.71	3046.27	1333.88	1101.48	1170.86	646.63	881.92	800.29	684.84
	CH2/CSP	1.30	min	0.86	13.49	10.05	12.51	17.06	6.72	12.44	[redacted]	9.11	417.18	131.86	117.26	155.67	45.44	93.89	85.20	67.70
		5.03	max	3.32	108.33	86.36	83.13	121.30	78.83	105.50	[redacted]	111.35	2591.21	1102.92	916.69	993.41	518.78	733.96	666.02	566.26
		3.04	average	2.01	51.80	40.47	42.14	60.21	33.71	49.63	[redacted]	47.08	1341.60	521.01	442.00	509.99	223.61	353.89	321.14	267.50
		0.96	St dev	0.63	24.87	20.05	18.43	27.25	19.09	24.44	[redacted]	27.10	566.34	254.94	209.51	218.39	125.26	167.75	152.22	130.89
		2.89	geomean	1.91	46.13	35.77	38.26	54.30	28.75	43.95	[redacted]	39.93	1226.11	461.97	394.75	464.88	191.29	316.07	286.81	237.18
		3.07	Median	2.03	50.76	39.48	41.73	59.42	32.18	48.47	[redacted]	44.79	1333.24	509.25	433.80	506.13	213.90	347.33	315.18	261.45
		2.10	10 pct	1.39	28.50	21.77	24.65	34.47	16.34	26.83	[redacted]	22.50	802.04	282.85	245.34	302.26	109.39	196.44	178.25	145.22
		3.07	50 pct	2.03	50.76	39.48	41.73	59.42	32.18	48.47	[redacted]	44.79	1333.24	509.25	433.80	506.13	213.90	347.33	315.18	261.45
		4.02	90 pct	2.66	77.44	61.12	61.16	88.33	53.28	74.81	[redacted]	74.82	1926.07	783.70	658.02	735.37	352.03	526.85	478.09	402.36
		2.32	25 pct	1.53	33.01	25.32	28.22	39.62	19.36	31.17	[redacted]	26.72	914.25	328.43	283.70	345.14	129.38	227.15	206.12	168.62
SB_4	CH1	3.20	min	1.94	47.23	36.65	39.08	55.51	29.55	45.01	[redacted]	41.07	1251.53	473.12	403.98	474.66	196.59	323.45	293.51	242.91
		10.52	max	6.36	295.06	243.01	206.72	311.61	257.62	294.94	[redacted]	371.07	6237.14	3063.34	2464.58	2422.50	1673.51	1973.30	1790.65	1572.77
		6.18	average	3.74	135.06	108.83	100.70	148.43	104.66	132.67	[redacted]	148.90	3107.93	1383.94	1138.08	1196.20	685.56	911.22	826.88	710.54
		1.99	St dev	1.20	68.29	56.94	46.01	70.39	63.32	68.94	[redacted]	91.69	1366.44	714.29	567.46	534.16	409.81	454.34	412.29	366.73
		5.91	geomean	3.57	121.37	97.12	92.19	135.01	90.17	118.56	[redacted]	127.65	2862.84	1238.50	1025.58	1099.17	592.53	821.14	745.14	635.86
		5.64	Median	3.41	112.98	90.19	86.37	126.20	82.84	110.15	[redacted]	117.12	2688.47	1151.22	955.52	1031.26	544.91	765.05	694.24	591.05
		4.88	10 pct	2.95	90.37	71.62	70.50	102.27	63.63	87.60	[redacted]	89.56	2210.51	916.83	766.52	845.47	419.73	613.72	556.92	470.72
		5.64	50 pct	3.41	112.98	90.19	86.37	126.20	82.84	110.15	[redacted]	117.12	2688.47	1151.22	955.52	1031.26	544.91	765.05	694.24	591.05
		8.08	90 pct	4.89	196.53	159.74	142.87	212.54	159.37	194.38	[redacted]	227.74	4367.92	2024.29	1650.25	1687.57	1040.75	1321.30	1199.00	1039.30
		5.11	25 pct	3.09	96.98	77.04	75.17	109.30	69.17	94.18	[redacted]	97.49	2351.59	985.27	821.84	900.26	455.86	658.02	597.11	505.85
	CH2/CSP	1.52	min	1.01	17.23	12.94	15.63	21.48	8.97	16.00	[redacted]	12.23	517.05	169.24	149.32	193.55	60.49	119.55	108.49	86.89
		4.72	max	3.12	98.38	78.18	76.16	110.78	70.34	95.57	[redacted]	99.18	2381.33	999.74	833.53	911.81	463.53	667.38	605.60	513.28
		2.83	average	1.87	46.85	36.50	38.39	54.70	30.09	44.80	[redacted]	41.96	1225.45	470.48	400.14	465.33	199.74	320.37	290.72	241.55
		1.00	St dev	0.66	25.58	20.57	19.05	28.12	19.40	25.09	[redacted]	27.49	586.48	261.84	215.61	226.00	127.37	172.63	156.65	134.43
		2.68	geomean	1.77	41.00	31.67	34.37	48.60	25.01	38.94	[redacted]	34.66	1105.73	409.66	351.39	418.60	166.67	281.35	255.31	210.32
		2.67	Median	1.76	40.80	31.51	34.22	48.37	24.87	38.74	[redacted]	34.46	1100.82	407.60	349.67	416.72	165.73	279.97	254.06	209.27
		1.71	10 pct	1.13	20.55	15.52	18.34	25.35	11.06	19.17	[redacted]	15.13	603.22	202.57	177.68	226.33	74.38	142.26	129.09	104.00
		2.67	50 pct	1.76	40.80	31.51	34.22	48.37	24.87	38.74	[redacted]	34.46	1100.82	407.60	349.67	416.72	165.73	279.97	254.06	209.27
		4.31	90 pct	2.85	85.72	67.84	67.16	97.28	59.86	82.99	[redacted]	84.19	2109.05	868.90	727.54	806.16	395.11	582.52	528.60	446.11
		2.21	25 pct	1.46	30.58	23.40	26.32	36.86	17.70	28.82	[redacted]	24.39	854.67	303.82	263.06	322.34	118.40	210.63	191.13	155.98
SB_4	CH1	5.18	min	3.14	99.22	78.87	76.75	111.67	71.05	96.41	[redacted]	100.20	2399.16	1008.44	840.55	918.73	468.16	673.00	610.71	517.75
		9.91	max	5.99	269.11	220.98	190.13	285.74	231.07	268.36	[redacted]	332.23	5753.74	2789.01	2250.58	2232.08	1502.84	1801.97	1635.17	1431.92
		8.47	average	5.13	215.21	175.71	154.58	230.93	179.10	213.62	[redacted]	256.68	4706.24	2222.67	1803.97	1821.29	1167.34	1444.38	1310.68	1141.15
		1.88	St dev	1.14	66.74	55.76	44.69	68.53	62.43	67.48	[redacted]	90.47	1323.94	698.95	554.17	518.08	403.89	443.71	402.64	358.85
		8.27	geomean	5.00	203.62	165.69	147.55	219.75	166.19	201.58	[redacted]	237.65	4505.78	2098.78	1709.01	1741.63	1084.77	1368.34	1241.69	1077.55
		9.14	Median	5.53	237.90	194.57	169.97	254.43	199.74	236.48	[redacted]	286.51	5164.41	2459.66	1992.77	2000.25	1301.19	1595.54	1447.85	1262.82
		6.64	10 pct	4.02	149.85	121.07	110.89	163.89	117.75	147.50	[redacted]	167.75	3412.79	1537.90	1261.38	1315.01	770.54	1009.94	916.46	789.58
		9.14	50 pct	5.53	237.90	194.57	169.97	254.43	199.74	236.48	[redacted]	286.51	5164.41	2459.66	1992.77	2000.25	1301.19	1595.54	1447.85	1262.82
		9.66	90 pct	5.85	259.08	212.49	183.65	275.68	220.97	258.11	[redacted]	317.49	5564.50	2683.07	2167.69	2157.63	1437.86	1735.59	1574.94	1377.53
		8.84	25 pct	5.35	225.80	184.36	162.09	242.22	187.79	224.14	[redacted]	269.08	4933.23	2332.08	1892.62	1909.42	1224.11	1515.35	1375.09	1197.32

FACTORS CONTROLLING TIGHT GAS SAND QUALITY IN THE WHICHER RANGE GAS FIELD, SOUTHERN PERTH BASIN, WESTERN AUSTRALIA

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ABSTRACT

There are limited studies characterizing the Willespie Formation, a Permian tight gas sandstone in the southern Perth Basin of Western Australia. Consequently, the main factors controlling reservoir quality, lateral reservoir connectivity and fluid flow mechanisms remain unknown. Available data from 5 Whicher Range wells, including wireline logs, seismic, core data, well reports and petrographic data, were studied to define the syn-, and post-depositional events affecting the reservoir rock quality. On the basis of this data analysis, the Willespie Formation is interpreted to have been deposited under predominantly fluvial conditions in an ancient continental rift basin with no marine influence. The sedimentary environments were laterally varied as inferred from discontinuous facies formed by meandering channels, crevasse splay and flood plain deposits. The varied environments were mainly controlled by the Permian tectonic setting and allogenic factors. Extensive compaction, due to ductile grain deformation, as well as clay and calcite cements are the main post-depositional factors affecting the reservoir quality of the medium to coarse-grained, poorly-sorted lithic-arkose sandstones of the Willespie Formation. Combined syn-depositional parameters, controlling composition and texture of the sandstone, and post-depositional diagenetic events have had a critical control on the distinctive low porosity and permeability of this tight gas sand reservoir.

KEYWORDS

Tight gas sand, reservoir quality, petrography, depositional environment, diagenetic events, Whicher Range, Perth Basin.

INTRODUCTION

The Whicher Range gas field is located south of Busselton in the southern Perth Basin. The focus of this study is the Permian Willespie Formation that has been interpreted as a fluvial system with no marine influence. The formation shows typical tight sand characteristics represented by low porosity (<1-15%) and permeability (<0.01-10 mD). Five wells have been drilled in this field within an extensively faulted anticline. The focus of this paper is to outline factors controlling reservoir quality and lateral reservoir connectivity, and how these contribute to the evaluation of exploration and production potential of this field.

GEOLOGICAL SETTING

The Perth Basin is an onshore and offshore sedimentary basin located in Western Australia. The structural style developed through oblique rifting in a transtensional tectonic regime (Marshall et al., 1989), and the southern part of the basin is characterized by compressional anticlines with planar-geometry normal faults (Figure 1a). Sedimentation in the southern Perth Basin was near continuous during the Late Permian and Early Triassic. A possible short hiatus has been recognized at the top of the Willespie Formation (the focus of this work) within the Sue Group (Figure 1b). The depositional environment of the Willespie Formation was dominated by fluvio-lacustrine systems (Crostella and Backhouse, 2000). Sedimentation was influenced by faulting with seismic data indicating that Permian sequences thicken eastwards towards the Darling Fault (Iasky, 1993).

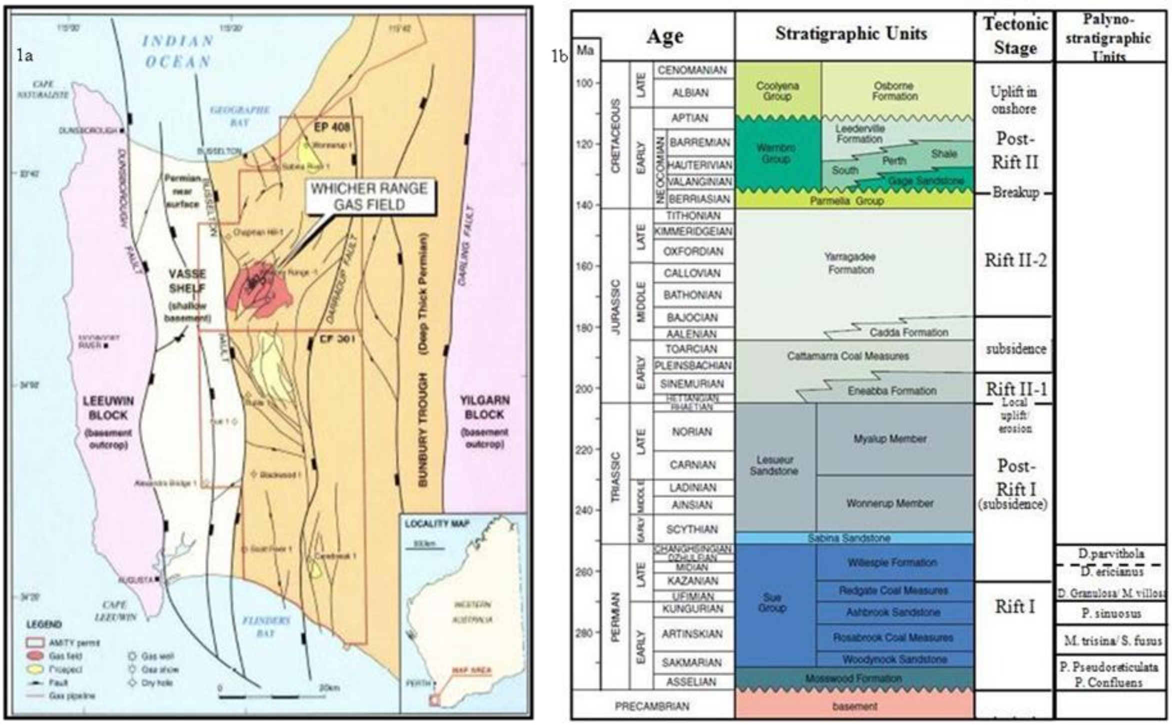

Figure 1. a: Location of the Whicher Range Field in the South Perth Basin, Western Australia (from Well completion Report Whicher Range #5 Amity Oil Limited 2004). b: Stratigraphy, tectonic stages and Permian palynology of the central and southern Perth Basin (Modified from Crostella and Backhouse, 2000).

FACTORS CONTROLLING RESERVOIR QUALITY

Depositional Environment and facies of the Willespie Formation

Changes in depositional environments influence reservoir properties through the linkage between environmental controls on sediment characteristics and geobody geometries (Weber, 1980). The effect of depositional conditions on rock quality may be recognized by classifying the reservoir unit in terms of depositional facies. A fluvial environment was defined for the Permian Willespie Formation through integrating core, palynological and well log data. Five fluvial-related facies have been defined, and their characteristics described below:

1) Meandering Channels (CH): Channel sandstones in the Willespie formation are highly variable, ranging from poorly-sorted pebbly conglomerates to very fine sands. The main stratigraphic features observed in core are parallel lamination, scours and cross-bedding. Deposits are characterized by low gamma ray (GR) values with an upward-fining, or blocky log motive interpreted as stacked and some single channels. Assuming the gamma response reflects grain size, the blocky pattern implies a near-constant energy level and perennial sedimentation flux in the clastic system.

2) Channel Margin (MCH): This facies is characterized by thinly bedded or laminated fine grained sandstone deposits and thinly laminated mudstone and siltstone. The main stratigraphic features are mostly thin parallel stratification and soft sediment structures.

3) Crevasse splay (CS): Crevasse splays form as broad, thin sheet or lens-shaped sand bodies usually overlying peat or organic-rich mud substrates. In the Whicher Range wells crevasse splay deposits are interpreted where very fine to medium grained sands and silts are present as isolated stringer sands encased in floodplain deposits, or as stacked splay successions. The main depositional structures are parallel-, or ripple-laminated sandstones and siltstone with coarsening-upward and spiky log motif. Upward-fining units are also present that may reflect moderate flow and then splay abandonment.

4) Crevasse splay channels (CSCH): These form when stable, incised anastomosing channels rework (and coalesce) the surface of splay deposits. Channel density is high per unit area with a branched pattern, including tabular but irregular and disconnected sand bodies. In the wells these units are characterized by medium to fine grained sandstone with cross bedding and ripple lamination. A fining-upward and blocky gamma ray log motifs (low GR but usually higher than the main channels) is common in the succession and characteristic of the channelized areas of the crevasse splay

5) Flood Plain (FP): Characterized by interbedded mudstone and carbonaceous siltstone. These are interpreted to be deposited in areas distal and proximal to channels (including levees) that may be affected by inundation during rising flow. Muddy floodplain deposits are generally interbedded with planar-stratified and small-scale cross-stratified fine to very fine sands representing individual flood events, and typically immediately overlie channel deposits. The wireline signature is characterized by high GR values for the mudstone and siltstone facies, but also medium GR values for the fine-grained sandstone. Spiky, but upward-fining log shapes indicate deposition during temporarily decelerating flows, whereas those that coarsen- and then fine-upwards reflect deposition during accelerating then decelerating flows.

Depositional facies interpreted from core and wire-line logs were compared to porosity and permeability core plug data to determine the relation between rock quality and the depositional environment. Low reservoir quality is mostly related to floodplain, crevasse splay and channel margin facies, whereas better qualities are associated with channel and crevasse channel facies (Figure 2). There are local exceptions, and some may relate to a shift in facies boundaries. Overall, lower reservoir quality intervals commonly relate to the more argillaceous facies, whose distribution is controlled by environmental conditions.

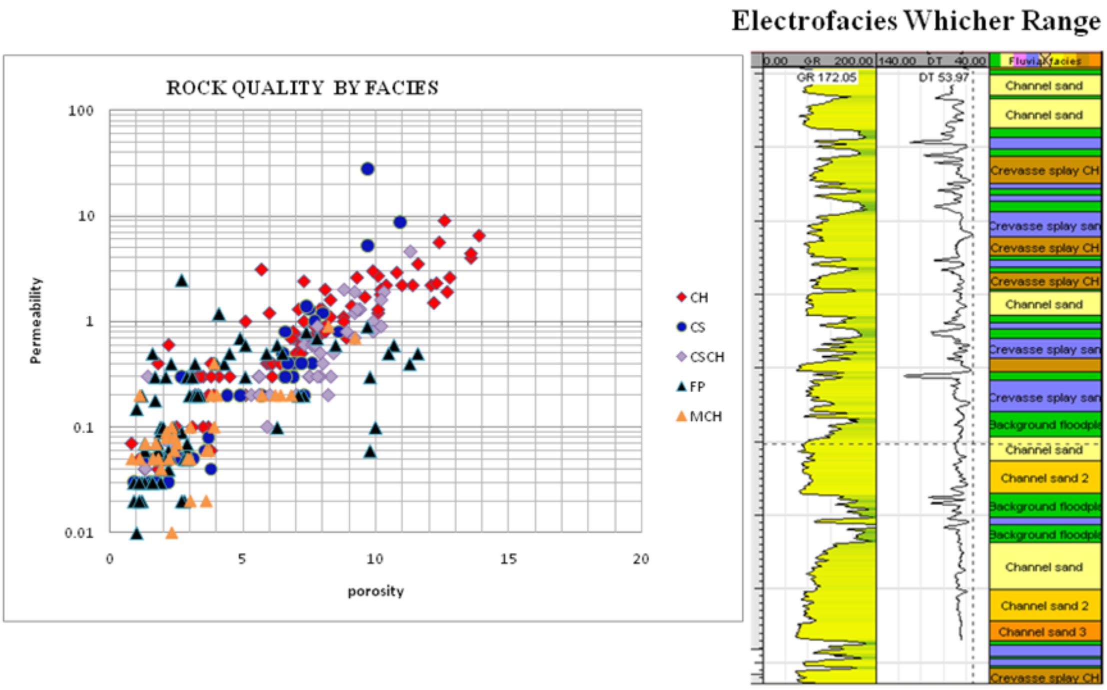

Figure 2. Rock quality vs electrofacies in the Whicher Range field

Rock composition, diagenesis and sedimentary characteristics

Composition & classification: Rock classification of the Willespie formation in the Whicher Range area is based on the thin section analysis by Poyton (1982). Using Folk's classification (1974), rocks in WR-1 (Whicher Range-1 Well) and WR-2 are classified mostly as lithic arkoses and arkoses with rare feldspathic litharenites (Figure 3). The major components of these sandstones are dominant quartz, abundant feldspar, and minor rock fragments. Rock fragments include polycrystalline quartz, metamorphic and igneous rock fragments and depending on the sample there are also lesser amounts of garnets and micas (biotite and muscovite). Detrital and authigenic clays such as kaolinite, illite/smectite, chlorite and minor amount of illite are also present together with calcite cement in lesser proportions. Some quartz and feldspar overgrowths are present (Figure 3).

Textures and compaction: According to Poyton (1982) and Irwin (1998) the fine- to coarse grained, poorly- to moderately-sorted sandstones have angular to subrounded grains with mostly long to point grain-to-grain contacts indicating moderate to heavy compaction. The entire interval appears to be highly stressed and the sandstone units are approaching a "ductile state". Cross-plots of grain size versus rock quality for the Sue Coal Measure sandstones appear to show a good correlation between increasing grain size and porosity-permeability. However, further data is required for a definitive conclusion. Based on comparisons between grain size, facies and cement data (WR-2 Well) grain size variations reflect depositional facies.

Feldspar alteration: Some feldspar grains are dissolved and others partially or totally altered to kaolinite clay booklets. Still others are shattered with 'microlineament' development, a feature also exhibited by rock fragments. In WR-2 well the upper cored intervals have less feldspathic components and contain more authigenic clays than the lower cored sections. However, there is no evidence of rock quality variation between those intervals suggesting that gross rock composition do not have a distinct effect on reservoir quality. Variations in lithology (particularly of the clays) are probably very important in interpreting the diagenetic history of these sandstones.

Calcite & micas: Calcite cements are more commonly associated with the larger grain sizes mostly found in the channel deposits. Thin section data suggests that micas may contribute to reduced porosity. When the percentage of mica increases in the samples the values of porosity decrease. According to Pittman and Larese (1991) the ratio between ductile and brittle grain is a good indicator of ductibility. Some of the crevasse splay facies are highly ductile, likely affected by the abundance of mica and clays as seen in the SEM and thin section data from WR-2 and WR-3 Wells (Linsley, 1982; Fanning et al. 1982)

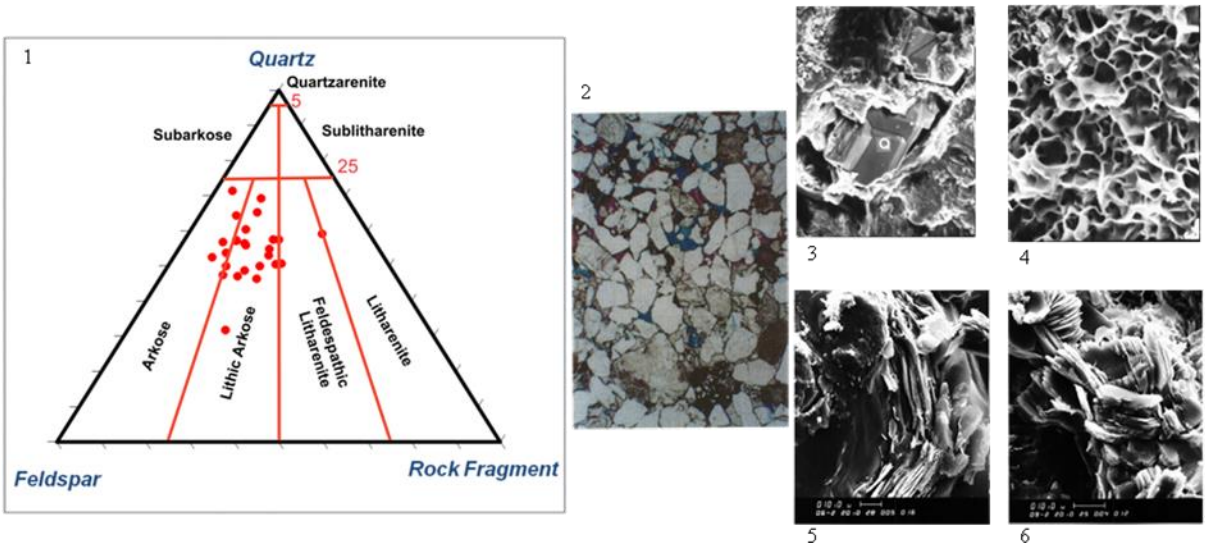

Figure 3. 1) Rock Classification using Folks' (1974) scheme for WR-1 &WR-2 wells; 2) Thin section showing Lithic Arkose from the Whicher Range. SEM images showing 3) Quartz overgrowths, 4) Smectite pore lining, 5) detrital mica curved around framework grain, and 6) Kaolinite and illite infilling pore space. (from Lynsley, 1982; Poyton, 1982 and Fanning et al., 1982).

Clays: Core data analysis indicates diversity in clay content between the analyzed wells. Overall, smectite, chlorite and smectite/illite are the dominant clays in WR-2 and WR-3, whereas kaolinite is more common in WR-1 and WR-4. Compaction of clays results in porosity reduction, whereas dispersed clays and their specific morphology may cause clogging of pore throats and therefore diminish permeability. Chlorites, smectites and smectite/illites when present as grain coatings have a strong permeability reducing effect (Neasham,1977) due to their large surface-area to volume ratios and the intricate micropore-creating morphologies (Wilson, 1994). Similar to tight gas sandstones in the Mesa Verde Group (Wilson, 1982) the rock quality in the Whicher Range sandstones units appears to be strongly controlled by the type, morphology, abundance and distribution of clays.

CONCLUSIONS

The Willespie Formation sand units are mainly composed of fine to medium coarse-grained lithic arkoses and arkoses, interbedded with silty claystones that have been grouped into five lithofacies. Each facies is the product of variations in a fluvial depositional system with no marine influence. The most important factors controlling the reservoir quality of the Whicher Range tight sandstones relate to depositional (lithologies, grain size, sorting and geobody geometries) and diagenetic factors. Better reservoir quality are associated with the coarser, better-sorted channel and crevasse channel facies compared with low reservoir quality of floodplain, crevasse splay and channel margin facies. Clay type, distribution and morphology, related to both deposition and diagenesis, strongly affect reservoir quality. Clay coatings and dispersed clays significantly reduce permeability. Authigenic clays, such as chlorite, kaolinite and smectite, are associated with the chemically unstable grain types (feldspar, siltstone and shale). Clay cementation is a major control on reservoir quality. Other more minor impacts on reservoir quality include deformation of ductile fragments, calcite and quartz cementation, compaction and grain rearrangement.

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His research has been focused on integrated solutions for reservoir characterization, formation evaluation and petrophysics. He has utilized expert systems such as artificial neural networks and fuzzy logic and has introduced several new approaches to estimate rock properties from log data where conventional methods fail to succeed. Currently, he is focused on unconventional gas including gas shale and tight gas sand studies, and is the lead scientist for the WA:ERA (EIS) Tight Gas research project.

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