Sequence Stratigraphy and Reservoir Characterisation
Of Permian fluvial-lacustrine successions,
Baryulah area, southwest Queensland, Australia

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9.1 Santos Ltd. news release 18th September, 2001

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References
Abstract

Gas exploration and reservoir development in the Baryulah area, Cooper Basin, southwest Queensland has focused on the Permian coal-bearing fluvial-lacustrine Patchawarra Formation, Murteree Shale, Epsilon and Toolachee Formations. The application of non-marine sequence stratigraphic concepts to wireline-log data, calibrated by available cores enabled the sub-division of litho-stratigraphic Formations into 17 chronostratigraphic intervals or time-rock units spanning a period of 35 million years.

This chronostratigraphic framework, from which log-motif based facies maps were constructed for systems tracts or combinations of systems tracts, is paramount to the preparation of geologically meaningful maps that depict changes of depositional style with time and space. Empirical data (eg. channel sandbody width, channel belt width) and spatial relationship information from appropriate modern and ancient depositional analogues were applied to chronostratigraphic intervals to assist facies mapping. Of particular conceptual value as analogues were the Siberian peatlands and fluvial systems. The following depositional facies were identified in the Baryulah area; fluvial channel, crevasse distributary channel, crevasse splay, overbank/floodplain, floodbasin, peat mire and lacustrine delta.

The facies maps were constructed partly in combination with available 3D seismic attribute maps, enabling suspected depositional morphologies (ie. meander belts, ox bow lakes) to be tested against the depositional interpretation for a specific interval.

Specific intervals, generally lowstand systems tracts of the Patchawarra Formation ‘VC40-Vu38’ & ‘Vu38-VC35’, and Toolachee Formation ‘basal PC50-PC40’, are the highest priority for targeting development wells because of the high net/gross and good reservoir facies (notwithstanding diagenesis). Some of the transgressive systems tract intervals; Patchawarra Formation ‘VC35-VC30’ & ‘VC20-VC00’ and Toolachee Formation ‘Daralingie Unconformity-PC60’ & ‘top PC50-PC40’, may be good stratigraphic trap candidates, especially if combined with a structural component. The relatively thin but extensive amalgamated lacustrine mouthbar sandstones of the Patchawarra Formation ‘VC30-VC20’ and the Epsilon Formation ‘Tu95-TC80’, ‘TC80-TC50’ & ‘TC50-Daralingie Unconformity’ represent potentially significant reservoir intervals.
Statement of Authenticity

The work contained in this thesis has not been previously submitted for a degree or diploma at any other higher education institution. To the best of my knowledge, this thesis contains no material previously published or written by another person except where due reference is made.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

NATHAN CEGLAR
6/12/2002
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Final thanks go to my family who has always been there.
Chapter 1  Introduction

1.1  Rationale

Future petroleum exploration and development in the Cooper Basin can benefit substantially from the application of high-resolution sequence stratigraphy, and the use of reservoir analogues to build sound geological reservoir models. Exploration in the Cooper Basin will increasingly rely on the recognition of stratigraphic traps. Pivotal to this process will be the development of a basin-wide chronostratigraphic framework that will enable the construction of high-resolution palaeogeographic maps.

A chronostratigraphic framework based on modern sequence stratigraphic concepts (using key surfaces as markers to subdivide a succession into sequences and systems tracts) allows the prediction of specific intervals with optimum reservoir connectivity and stratigraphic trapping potential away from structural highs.

A key driver for this study was the need for a better understanding of reservoir connectivity in the Baryulah complex. Litho-stratigraphic correlation of reservoir sandstones (Fig. 24) tended to over-estimate lateral connectivity, with pressure data from correlated reservoirs showing evidence of pressure compartmentalisation. Sequence stratigraphic correlation techniques use *key surfaces* to subdivide the succession into genetic chronostratigraphic units (Galloway, 1989). This approach highlights the lateral dis-connectivity between channel sand bodies within the same genetic interval because correlation focuses on mapping enveloping shale packages and then locating unconformities or erosion surfaces (within an interval), often within ‘sandy’ successions. As illustrated by Lang et al. (2001), this approach offers predictive insights into vertical connectivity and net-to-gross trends for a given genetic interval in a fluvial-lacustrine succession.

Stratigraphic traps comprising fluvial channel bodies do exist in the Permian interval of the Cooper Basin, but the scale, geometry, orientation and likely connectivity of these reservoirs is at present unknown. Answers to these questions lie in the
understanding of both the depositional style and stratigraphic position of the fluvial sandstones determined from available cores, log motifs and judicious use of depositional analogues.

Reservoir development of the key producing intervals within the Baryulah area depends significantly on the ability to build reliable reservoir models that underpin flow simulation models helping to optimise the number, spacing and type of development wells. Reservoir models need to be based on sound geological concepts that should incorporate our knowledge of the scale, geometry, orientation, heterogeneity and interconnectedness of reservoir flow units of differing qualities. As the number of wells to constrain these reservoir models must remain limited for obvious economic reasons, uncertainty between wells is high. To minimise this uncertainty, analogue models based on highly constrained datasets in similar geological settings need to be identified for comparative purposes. Analogues in non-marine basins include modern examples from comparable depositional settings, or ancient examples from outcrop, densely drilled coalmine datasets, or similar reservoirs elsewhere in the basin.

1.2 Aims

To develop a sequence stratigraphic framework for the Baryulah area of the Cooper Basin, incorporating nine wells; Winninia North-1, Baryulah -1, Baryulah-2, Baryulah East-1, Vega-1, Juno-1, Juno-2, Hera-1 and Juno North-1. Using appropriate analogues and seismic images, to produce facies maps that characterise reservoir geometries and thus the likely connectivity of sandbodies within the non-marine Patchawarra-Epsilon-Toolachee Formations.

1.3 Objectives

- To construct an internally consistent chronostratigraphic framework for the Patchawarra, Epsilon and Toolachee Formations within the Baryulah 3D seismic area based on sound sequence stratigraphic concepts applicable to non-marine basins.
• To ensure the constructed chronostratigraphic framework for the Baryulah area is consistent with established sequence analysis in other parts of the Cooper Basin, thereby linking the local chrono-stratigraphy to the basin-wide scheme used by Santos Ltd. and its joint venture partners in the Cooper Basin.

• To use the Dullingari Field as an analogue to help develop a log-motif based facies scheme for the Baryulah area, including the examination of available core from Dullingari and Baryulah area wells Juno North-1 and Winninia North-1.

• To provide a better understanding of reservoir distribution and connectivity through the use of modern and ancient depositional analogues, in conjunction with available Baryulah 3D seismic amplitude maps, to map facies distribution at various Patchawarra, Epsilon and Toolachee Formation sub-levels.

• To highlight specific chronostratigraphic intervals within the Baryulah area where future drilling may target reservoirs with good connectivity, and also identify/confirm possible stratigraphic traps.

1.4 Study area

The Baryulah complex is a cluster of gas fields lying approximately 40 km southwest of Ballera, in ATP 259P, Cooper Basin, southwest Queensland (Fig.1). A 3D seismic survey was acquired in 1999 to advance exploration and development, encompassing nine wells in the Baryulah, Juno, Juno North, Hera, and Vega gas fields within Aquitane ‘A’ of block ATP 259P. The seismic survey area (approximately 300 square kilometers) defines the study area, and is referred to as the Baryulah area (Fig. 2).

1.5 Data

Data was primarily supplied by Santos Ltd. Queensland and Northern Territory Business Unit (QNTBU), with input from South Australian Business Unit (SABU) and Santos Corporate.

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FIGURE 1 Location of the Baryulah complex in the Cooper Basin.
Outline of the Baryulah seismic survey (1999) that defines the Baryulah study area.

Contours show depth (ft) to Pre-Permian 'Z' marker horizon (Fig. 3).

The well correlation path used for this study is shown in black.
Wireline log suites were available for nine wells; Winninia North-1, Baryulah-1, Baryulah-2, Baryulah East-1, Vega-1, Juno-1, Juno-2, Hera-1 and Juno North-1. All measurements were originally recorded in feet and these units are retained for easy comparison with cores and sample depths. Core was available from two wells; a 51ft Patchawarra Fm. reservoir interval from Juno North-1 (9321-9372 ft) and a 58ft non-reservoir core interval from Winninia North-1 (7300-7358 ft). Several cores from the PIRSA Core Storage Facility (Burke-1, Burke-3, Dullingari-23, Dullingari-45, Dullingari North-1) were made available for use in this study.

Seismic data was provided by Santos Ltd. (QNTBU) consisting of a basement map (Fig. 2), and seismic amplitude maps of various horizons within the study area generated from 3D seismic data.

1.6 Background on Cooper Basin

The Cooper Basin is an intracratonic, north-east trending structural depression covering approximately 130,000 km² in northeastern South Australia and southwestern Queensland (Fig. 1). The basin contains Permian to Triassic strata interpreted as glacial, fluvial and lacustrine in origin (Apak et al., 1997). Permian formation descriptions are summarised in Table 1.

The Cooper Basin is divided into several individual blocks by northwest-trending lineaments. There is strong evidence to suggest that its evolution was associated with compressional tectonism as shown by the presence of compressional folds, thrust faults, strike-slip movements and inversions of the Permo-Triassic sequence (Apak et al., 1997).

Four tectonic events from the Permian to Triassic are recognised;

(1) First Sakmarian uplift (273 Ma) (middle Patchawarra Fm. unconformity)
(2) Second Sakmarian uplift (270 Ma) (upper Patchawarra Fm. unconformity)
(3) Late Permian uplift (258 Ma) (Daralingie unconformity – that occurred after deposition of the Daralingie Formation).
(4) Middle Triassic uplift (245 Ma) (occurred after deposition of the Nappamerri Group).

The Sakmarian uplifts resulted in coarse-grained sediment supply throughout the fluvial sediments of the Patchawarra Formation. The uplift which occurred after deposition of the Daralingie formation resulted in a return to fluvial style deposition to produce the Toolachee Formation (Apak et al., 1997).

Permian Cooper Basin palynostratigraphy (Fig.3) shows the relative position of lithostratigraphic units. In particular, the Patchawarra, Epsilon and Toolachee Formations are subdivided into chronostratigraphic units based on work done by Geoff Wood and Jim Benson of Santos Ltd. (1999).

**TABLE 1** Permian formation descriptions (after Gravestock et al., 1998).

| Toolachee Formation | The Toolachee Formation forms a blanket deposit over a regional unconformity (the Daralingie Unconformity) and is described as interbedded coarse to fine-grained sandstone, dark grey siltstone and dark grey to black carbonaceous shale, sometimes sideritic with thin coal seams (<3m thick), and conglomerates. It is thickest in the Patchawarra and Nappamerri Troughs. A mid-Toolachee unconformity divides the formation into two parts, with the lower part confined mainly south of the Challum-Wackett trend. |
| Daralingie and Roseneath Formations | The type section is 1792-1897 m in Toolachee-I (latitude 28°25′59.37″S, longitude 140°46′39.83″E). |

Shale prone Formations with coarsening upward successions interpreted as lacustrine to deltaic.

(Both Formations are absent in the Baryelah area either by non-deposition, or erosion beneath the Toolachee Formation).
### Epsilon Formation
(Early Permian - Artinskian to Kungurian - PP 3.2.2 – PP3.3)

Defined as the series of sandstones, shales and minor coals overlain by Roseneath Formation and underlain by Murteree Shale. It consists of thinly bedded, fine to medium grained, moderately to very well sorted, quartzose sandstone with dark grey-brown carbonaceous siltstone and shale and variable thickness coal seams (<2-20m). Depositional environments range from alluvial to deltaic plain, including distributary channels, crevasse splays, prograding lacustrine barrier-bar, delta mouth-bar, and shoreface sands. The Epsilon Formation reaches a maximum thickness of 150 m in the Nappamerri Trough.

The type section is 2095.2-2136.9 m in Epsilon-1, Queensland (latitude 28°8'48.3"S, longitude 141°9'11"E).

### Murteree Shale
(Early Permian - Artinskian - upper PP3.2.1)

Defined as the series of shales overlain by Epsilon Formation and underlain by Patchawarra Formation. It consists of black to dark grey-brown argillaceous siltstone and fine-grained sandstone. The Murteree Shale is relatively uniform in thickness averaging about 50 m, but ranges from absent over structural highs, to 80 m thick in the Nappamerri Trough. A relatively deep, fresh-water lake environment is interpreted for the Murteree Shale depositional envirnment, due to the absence of marine microplankton and invertebrate fossils. Rhythmites are deposited by episodic gravity flows, which may be related to seasonal infuxes of freshwater related to spring thaws in the hinterland.

The type section is 1922.9-1970.8 m in Murteree-1 (latitude 28°23'48.3"S, longitude 140°34'15.3"E), in the Patchawarra Trough in South Australia.

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<table>
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<tr>
<th>Patchawarra Formation (Early Permian – Asselian to Artinskian - PP2.1-PP3.2.1)</th>
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<td>The Patchawarra Formation is defined as the interbedded sandstone, siltstone, shale and coal beneath the Murteree Shale and above the Tirrawarra Sandstone/Merrimelia Formation or Pre-Permian rocks. The upper part of the formation reflects inundation of the Patchawarra floodplain environment and the onset of deltaic, lagoonal and lacustrine environments as the precursors to Murteree deposition. The Patchawarra Formation is the thickest formation of the Gidgealpa Group, up to 680 m thick in the Nappamerri Trough. It is likely that at least part of the upper Patchawarra is time equivalent to the Murteree Shale elsewhere in the basin (ie. the boundary is regionally diachronous).</td>
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The type section is 2741.4-2913.9 m in Moorari-1 (latitude 27°34'20.88"S, longitude 140°34'15.36E), in the Patchawarra Trough in South Australia.
### Late Carboniferous/Permian Palynostratigraphy of the Cooper Basin

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**NOTE:** The indicated vertical distribution of the lithostratigraphic units is the maximum extent known relative to the biostratigraphic units.

**FIGURE 3** Permian Cooper Basin Palynostratigraphy (Santos Ltd., 1999).

Study interval outlined in red.
Chapter 2  Sequence stratigraphy

2.1  The application of Sequence Stratigraphy to an intracratonic non-marine basin

Sequence stratigraphy is defined by Posamentier and Allen (1999) 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’.

For non-marine basin fill, the factors determining stratal architecture are the rate and nature of sediment influx and the rate of change of accommodation, in which sediment may accumulate. For non-marine basins such as the Permian Cooper Basin, regional scale accommodation is determined by tectonic uplift and subsidence, tilting of the fluvial equilibrium profile (Fig. 4) and climate.

The term fluvial equilibrium profile refers to the “graded or dynamic equilibrium surface wherein the slope is adjusted so that there is neither net sediment aggradation nor erosion through time and that the sediment load entering the system from upstream equals the load leaving the system from downstream” - Posamentier & Allen (1999). This concept lies at the heart of understanding alluvial stratigraphy as depositional response to changes in this profile with time results in changes to both alluvial style and stacking patterns.

An understanding of sequence stratigraphy as it applies to non-marine basins is valuable because predictable facies assemblages are developed within depositional sequences. A depositional sequence is a stratigraphic unit composed of a relatively conformable succession of genetically related strata, bounded at its top and base by unconformities or their correlative conformities (Shanley & McCabe, 1994). The bounding surfaces are referred to as sequence boundaries. Table 2 provides definitions for commonly used terms associated with the sequence stratigraphy of alluvial settings.
Fluvial Equilibrium Profile (FEP) - the alluvial gradient is such that there is neither net sediment deposition or erosion.

As a result of tectonic tilting or base level rise, the FEP is disrupted.

Hydro-dynamics dictates a return to the lowest possible energy system (FEP), therefore incision (erosion) and deposition will occur along the alluvial profile until the FEP is reached.
TABLE 2  Definition of selected sequence stratigraphic terms.
(after Posamentier & Allen, 1999)

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td>Accommodation</td>
<td>The potential space available for sediment to fill. For an alluvial environment, accommodation represents the space between the ground surface and a hypothetical surface known as the dynamic equilibrium fluvial profile.</td>
</tr>
<tr>
<td>Dynamic Equilibrium Profile</td>
<td>The graded or dynamic equilibrium surface wherein the slope is adjusted so that there is neither net sediment aggradation nor erosion through time and that the sediment load entering the system from upstream equals the load leaving the system from downstream. Back-tilting of this profile will result in extra accommodation being created in the alluvial plain (positive alluvial accommodation), whereas fore-tilting will result in widespread incision and erosion (negative alluvial accommodation).</td>
</tr>
<tr>
<td>Sequence Boundary</td>
<td>Surfaces that are formed when there is a significant downward shift of the fluvial equilibrium profile to a position below the actual fluvial profile. This produces negative accommodation, to which alluvial systems respond by downcutting.</td>
</tr>
<tr>
<td>Transgression</td>
<td>Landward migration of the shoreline.</td>
</tr>
<tr>
<td>Transgressive Surface</td>
<td>A surface marking the onset of a significant and extended period of transgression within a succession (the term 'significant' will depend upon the importance of the transgressive event within the section being studied).</td>
</tr>
<tr>
<td>Maximum Flooding Surface</td>
<td>Refers to the surface of deposition at the time the shoreline is at its maximum landward position (i.e. the time of maximum transgression).</td>
</tr>
<tr>
<td>Flooding Surface</td>
<td>A surface that separates older from younger rock and is marked by deeper-water strata resting on shallower water strata.</td>
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**Depositional Sequence**

A stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities. Where the hiatal breaks associated with the bounding unconformities narrow below resolution of available geochronologic tools, the time surfaces (i.e. chronohorizons) that are correlative with the 'collapsed' unconformities constitute the sequence boundaries.

**Systems Tract**

Distinct stratigraphic units that are deposited during specific phases of relative base-level change.

**Lowstand Systems Tract (LST)**

The sedimentary succession deposited during periods of falling relative base-level, subsequent stillstand, and slow initial rise of relative base-level constitutes the lowstand systems tract.

**Transgressive Systems Tract (TST)**

The sedimentary succession deposited as the rate of accommodation creation exceeds the rate of sediment supply.

**Highstand Systems Tract (HST)**

The sedimentary succession deposited when the sediment supply is equal to or greater than the rate of accommodation creation.

Based on the fundamental concepts of accommodation and sediment supply, Shanley & McCabe (1994) and Posamentier & Allen (1999) showed that sequence stratigraphy can be applied to intracratonic basins (with no marine connections), where there is no direct influence of eustacy. The application of sequence stratigraphy requires an understanding of the mechanisms and processes that control sedimentation patterns in sedimentary basins. In fluvial systems, changes in accommodation, are caused by modifications to the fluvial equilibrium profile (Fig. 4). In an intracratonic basin, the primary factors that will determine changes to the fluvial equilibrium profile are; tectonic tilting, modifications in fluvial discharge; and changes in sediment supply. It is the ratio between the rate of sediment supply and the rate of subsidence controlled accommodation that will determine changes in the style of non-marine sediment stacking patterns.
2.2 Non-marine sediment stacking patterns

Allen et al. (1998) proposed that predictable fluvial stacking patterns will result from the ratio of sediment supply to subsidence induced accommodation and produced a diagram of theoretical fluvial stacking patterns (Fig. 5). When the ratio of sediment supply to subsidence induced accommodation is high (meaning little or no subsidence) there is no significant increase in fluvial accommodation, resulting in a lateral migration of the fluvial channels. This produces a one channel thick, widespread sand sheet (Fig. 5a). If the ratio is very low, meaning there is very low sediment influx and rapid subsidence, a lacustrine system will develop (Fig. 5d). A rapid decrease in the ratio of sediment supply to subsidence induced accommodation will result in an increase in accommodation, promoting maximum lacustrine expansion that is marked by a maximum flooding surface.

In lacustrine settings, changes to lake water levels affect fluvio-lacustrine stratigraphy regardless of whether the lakes are open (ie with outflow) or closed. Lake levels exert a fundamental control on lacustrine and adjacent fluvial stratigraphy in much the same manner that marine and coastal plain environments respond to changes in relative sea level, however the fluctuations in lake level are likely to be of a higher frequency than eustatic fluctuations (Posamentier & Allen, 1999).

Stratal architecture within lacustrine strata reflects the interplay of sediment input and changes in lake levels. Accommodation space in interior basins or in areas far removed from the sea are largely driven by climatic or tectonic cycles that need not bear any particular relationship to changes in relative sea level (Shanley & McCabe, 1994).

2.3 Recognition of key surfaces in non-marine basins

In alluvial basins, three key surfaces can be recognised: sequence boundaries (SB), flooding surfaces (FS) and lacustrine maximum flooding surfaces (MFS). The formation of a sequence boundary is independent of sediment supply, rather a function of accommodation and changes in the fluvial equilibrium profile (Fig. 4). Maximum flooding surfaces are however very dependent on sediment supply.
(a) Negligible accommodation relative to sediment supply causes total reworking of fines and results in a sand 'sheet' with high interconnectivity.

(b) Low accommodation relative to sediment supply results in decreasing connectivity of fluvial channel bodies with the potential for coal to develop on the flood plains.

(c) Rapid accommodation relative to sediment supply produces increasingly isolated fluvial channel bodies therefore decreasing connectivity.

(d) Highest rate of accommodation relative to sediment supply produces a maximum flooding surface.

(e) Decreasing accommodation relative to sediment supply results in increased connectivity of fluvial channel bodies.

FIGURE 5 Fluvial channel stacking patterns resulting from varying accommodation rates for a constant sediment supply.

(modified from Allen et al., 1996 and Lang et al., 2001)
(Shanley & McCabe, 1994). Sequence boundaries will be produced when ‘negative accommodation’ is created, whereby tectonic tilting oversteepens a segment of the fluvial ‘equilibrium profile’ and causes the river to incise downwards (Posamentier & Allen, 1999). Unconformities are commonly expressed as coarse-grained channel fills deeply eroding into underlying lacustrine or floodplain dominant shale successions. On the interfluves between fluvial channels, the expression of an unconformity may be preserved as an extensive palaeosol, where the maturity of the palaeosols will give an indication of the length of sub-aerial exposure. An unconformity is a key surface marked by local erosion, and will have a correlative conformity that may lie downstream within a lacustrine prone succession or alternatively within an aggrading fluvial succession downstream from the tectonic hinge line. The presence of potential sequence boundaries can be recognised by an increase in channel clustering and amalgamation (Fig. 6). This is caused by a marked decrease in accommodation creation relative to sediment supply (Posamentier & Allen, 1999).

In lacustrine settings, the maximum flooding surface (MFS) is commonly represented by a shaley interval marked by the highest gamma ray and possibly resistivity/conductivity peak. Although the MFS is a well developed correlation marker in well logs and core due to its regional extent, it is dependent on sediment supply and therefore not a true chronostratigraphic surface. For example, in areas with a high sediment supply the MFS may be difficult to pick and often lies within in a broad interval of fine grained sediments. In order to specify the position of the MFS, high-resolution dating methods such as biostratigraphy are usually required.
An idealised fluvial depositional sequence for an alluvial basin (Allen et al., 1996), based on ideas from Legaretta et al., (1993) highlighting the position of key surfaces in relation to systems tracts and their relationship to the ratio of accommodation to sediment supply.

The lowstand systems tract (LST) typically amalgamated fluvial deposits representing low accommodation overlies the sequence boundary and is topped by a surface of transgression, typically marked by the onset of coal-prone or lacustrine sediments. The transgressive systems tract (TST) is marked by an upward increase in channel isolation and lacustrine deltas, topped by the maximum flooding surface (MFS). The highstand systems tract (HST) is marked by progradational stacking patterns associated with lacustrine delta infilling a decreasing rate of accommodation creation, topped by increasingly amalgamated channel belt sandstones and topped by the next sequence boundary.
Chapter 3  Fluvial-lacustrine depositional systems

3.1  Sedimentary facies

The Patchawarra, Epsilon and Toolachee Formations of the Cooper Basin are known to have been dominated by fluvial-lacustrine systems formed in a tectonically quiescent basin (Alexander (1993), Apak et al. (1997), Gravestock et al. (1998)). Figure 7 shows morphological elements and depositional facies associated with a meandering river system.

Fluvial-lacustrine facies identified in this study are recognised as follows:

Channels

Isolated or multistory fine-medium grained cross-bedded sandstones with blocky or fining upward log motifs are common especially in the Patchawarra and Toolachee Formations. They are interpreted as fluvial channel fill produced by channelised bedload traction deposits. The fining-upward log motifs are interpreted as abandoned channel fill mud plugs that may be capped by coal filling abandoned channels. Using seismic data as a guide, Toolachee Fm. channels are interpreted as meandering stream deposits. The high degree of sandstone amalgamation in the lowermost Toolachee Fm. is a result of low accommodation above the Daralingie Unconformity. The clarity of channel and channel belt imaging (see Chapters 5 & 6) is the direct result of an impedance contrast that occurs when highly sinuous meandering planform geometries (comprising channel fill sand) are abandoned and filled with mud plugs or coal. The sand-mud and/or sand-coal interface produces a seismic reflector. Most channels lie within broad channel belts, generally up to 2 km wide, with some ranging from 5 to 8 km wide (most likely laterally amalgamated). Some individual channels may show widths up to (but generally not exceeding) 1km wide within larger channel belts, although most individual channel widths are less than this. It is clear from seismic amplitude mapping that large rivers existed in this part of the Cooper Basin, and by comparison with modern analogues (see Chapter 5), shows that a significant fluvial system existed during various stages throughout ‘Patchawarra’ to ‘Toolachee’ time.
FIGURE 7

Block diagram showing fluvial depositional environments (modified from Walker, 1984):

**channels** - with lateral pointbar accretion and fining upward sequence, chute channels and channel abandonment capped with overbank fines. The channel belt is taken as the belt that delineates the maximum channel meander amplitude.

**crevasse splays** - shown with lobate morphology on outer river bend indicating levee breach as depositional mechanism.

**floodplain and floodbasin** - overbank areas of fine-grained sedimentation deposited during flood events. Typically a floodbasin is poorly drained, compared to a floodplain which is well drained and where soils may develop. Both may be vegetated.
Crevasse Splays

Isolated or stacked very fine to medium-grained parallel laminated or ripple-laminated sandstones with blocky, fining-upward and coarsening-upward log motifs are abundant in the succession. Supported by available cores (Figs. 12, 13) these have been identified as crevasse splay deposits and are commonly inter-bedded with floodplain deposits.

Individual crevasse splays are deposited from sudden influxes of sediment-laden floodwater and the upward fining of a single unit is characteristic, reflecting the waning flow during deposition. A succession of individual crevasse splays may show upward thickening within the overall package, indicating progradation of the splay system into the floodbasin, floodplain or inter-distributary area (Guion, 1984). The term crevasse splay distributary channel may be used to describe the proximal, channelised part of the crevasse splay. These can contain traction deposits (ie. dunes and hence cross-bedding) and usually have blocky, fining-upward log motifs but at a smaller scale to the main channels. Proximal crevasse splays are channelised flows (as indicated by cross bedding), void of basal lag with ripple cross lamination and flaser bedding towards the top (Fig. 12). Medial crevasse splays are characterized by a succession of constant grainsize (although may coarsen upward) with ripple cross-lamination and climbing ripples (Fig. 13). A coarsening upward profile may result from medial crevasse splay deposition into shallow lacustrine settings during flooding, with subsequent winnowing of fines from the uppermost portion due to wave agitation. Distal crevasse splay deposits are often represented as thin bands of sandstone inter-fingered with proximal floodbasin fines, and display flaser beds and laminations, rootlets and soft sediment deformation (Fig. 13).

Smith et al. (1989) suggests that there are three different, but inter-gradational forms of crevasse splays, each associated with a characteristic sandbody geometry (Fig. 8). Stage I splays are relatively small, lobate in plan, with shallow unstable distributary channels. They form sheetlike sand bodies, broadly wedge- or lens-shaped, that grade downward into fine-grained wetland deposits. Stage II and III splays exhibit stable anastomosing channels, which incise the underlying fine-grained sediment. Stage II
After Smith et al. (1989) summarising the three-stage evolution of a splay complex developed as the depositional response to avulsion of an alluvial channel. Channel morphology indicated refers to secondary channels reworking the surface of splay deposits.
splays have relatively high channel densities and form tabular but irregular and disconnected sand bodies, whereas stage III splays, with low density, well-stabilised channels, form isolated stringer sands encased in fine-grained floodplain deposits. It has been shown by Smith et al. (1989) in a study of an avulsion that took place in the Cumberland Marshes (Saskatchewan) in 1873 that crevasse splays can initiate the avulsion of a channel, leading to bifurcating and often anastomosing channel forms. These channels can be extremely narrow, with aspect ratios from as low as 1:10 – 1:25, results supported by studies of splays from several analogue studies; Avenell (1998), Lang et al. (2000), Jorgenson & Fielding (1996).

Floodplain/Overbank Deposits

Interbedded mudstone and siltstone, often with ripple cross-lamination, typically immediately overlying channel deposits are common with subvertical rootlets and occasional burrows. Plant debris is abundant. Convolute bedding; load casts and other soft sediment deformation structures can also be common in this facies. Possible interpretations include levees built as ridges on either side of a major channel especially on the outer margins of bends. They grow through the deposition of fine-grained, suspended load sediment during submergence from major floods. As floodwaters overtop levees, turbulence diminishes and suspended sediment is deposited, commonly becoming finer grained away from the channel (Reading, 1996). They are common in alluvial and delta plain settings and mark the edges of active channel belts.

Floodbasin Deposits

Grey mudstone, typically laminated with thin stringers of siltstone and very-fine sandstone are abundant in the succession. Fine-grained detrital plant debris is commonly preserved. These are interpreted as floodbasin lake deposits, accumulations in poorly drained areas of little relief located adjacent to or between active, but slightly higher, meander belt alluvial ridges. Floodbasins act as stilling basins in which suspended sediment fines can settle from overbank flows after coarser suspended debris has been deposited on levees or crevasse splays (Allen, 1965). They...
are typically poorly drained and contrast with floodplains that are well drained and subject to palaeosol development (Wright & Marriott, 1993).

**Lacustrine Deltas**

Lacustrine deltas consist of a prodelta, delta front, and distributary mouthbar. The prodelta deposits typically form a laterally extensive subaqueous lacustrine platform that underlies the entire delta complex. Delta-front sediments are transitional between the prodelta and distributary-mouth-bar environments and coarsen upward. Distributary-mouth bars overlie channel and delta-front deposits (Tye & Coleman, 1989).

Coarsening upward successions of tens of centimetres to a few metres comprising mm-scale laminations, ripple bedsets, parallel laminations, clay graded beds, rare lenticular beds, rare mudcracks, soft sediment deformation, wave-ripple cross-lamination and small-scale trough cross-bedding are together interpreted as lacustrine delta mouthbar deposits. Rooting in the uppermost portion is common and often destroys the stratification. Coal commonly marks the emergent surface of the delta, usually as a result of channel lobe switching.

Aquatic and subaerial vegetation accelerates the deposition of silt and clay. Burrows are rare. Disseminated organics and rounded wood clasts occur as drapes in ripple troughs or on scour surfaces (Hughes, 1999). Log motifs are typically cleaning/coarsening upward, and sometimes cyclical, with either progradational or retrogradational stacking patterns clearly evident. These are interpreted as individual mouthbar lobes that stack both vertically and laterally.

**Peat Mire environments**

Coals ranging from dull to bright, massive or delicately laminated can occur. They range in thickness from a few centimetres to over ten metres. In some cases they have siderite or pyrite mineralisation, and calcite along cleat faces. The coal is interpreted as peat, either detrital or insitu, forming in extensive peat mires. The mires can range from raised mires (low ash coal), able to form adjacent to, but more commonly away
from sediment influx on interfluves. Other coals have substantial silt (ash) content, grading into carbonaceous mudstone, and these are interpreted as abandoned channel fills or floodplain peats. A key feature of coal is the slow sonic response, with a variable gamma response depending on silt (ash) content. Coals that overly coarsening-upward log motifs are interpreted to represent an emergent surface above a delta mouthbar fingerling a lake.

3.2 Wireline log-motif facies scheme

A wireline log-motif facies scheme was needed to interpret sedimentological facies from wireline log suites in the absence of core data. The assumption is that gamma-ray log response represents grainsize ('hot' sands were not identified within the study interval), therefore reflecting the energy of erosive processes ultimately responsible for sediment deposition. A decrease in log gamma-ray response typically indicates increasing depositional energy as potassium rich clay fines (that produce a high gamma response) are increasingly winnowed from reworked sediments.

The development of a consistent facies scheme for use in the Cooper Basin is important for communicating key issues relating to reservoir characterisation. The facies scheme used in this study is based on the limited core from Juno North-1 and Winninia North-1 wells, and supported by data from previous studies on other Cooper Basin fields – Tartulla (Hughes, 1999); Dullingari (Integrated Reservoir Study, 2000). These facies schemes, in turn, build upon generic facies studies in fluvial systems (Miall, 1992 & Selley, 1978). Prior to application, the facies scheme was tested against numerous cores from fields in South Australia, in particular cores from Burke-1, Burke-3 (Fig. 9), Dullingari – 23 (Fig. 10), Dullingari – 45 and Dullingari North-1 examined at the PIRSA Core Storage Facility. The facies scheme used is summarized in Figure 11 showing a ‘rational association of facies’. Walther’s Law is then used where transitional contacts occur to predict the lateral distribution of facies based on the vertical successions.

3.3 Permian Baryulah sedimentary facies

Facies associations identified and interpreted for Baryulah area wells;
**Reservoir**
- Fluvial Channel
- Crevasse Distributary Channel
- Proximal Crevasse Splay
- Lacustrine Delta (mouthbars)

**Non-reservoir**
- Medial/Distal Crevasse Splay
- Overbank/Floodplain, Floodbasin
- Peat Mire (coal)

Direct application of the IRS facies scheme was tested on core from study wells Winninia North-1 and Juno North-1 at the Zillmere Core Storage Facility (QLD). The Juno North-1 core contains thick successions of stacked Patchawarra Fm. reservoir sandstones that would be interpreted as a braided fluvial deposit based solely upon wireline motif and the IRS facies scheme (Fig. 14). Core inspection revealed a series of stacked crevasse distributary channels and proximal crevasse splay sandstones (Fig. 12). Figure 15 shows such a succession of stacked splay sandstones in a ‘highwall’ at the South Blackwater mine. One of the implications is that Patchawarra Fm. depositional style at Juno North-1 is best characterized by meandering channels of moderate energy with associated crevasse splay deposits in a floodplain environment. This is dissimilar to the relatively high energy, low accommodation, braided fluvial style that would have been interpreted if no core were available from Juno North-1 and Winninia North-1 to ground-truth wireline log-motif based sedimentological interpretations.

Figure 14 shows how direct application of core data can aid the interpretation of depositional facies to produce a meaningful wireline log-motif facies scheme. Where possible, Formation Micro-Scanner / Formation Micro-Imager (FMS/FMI) data should be analysed to assist facies interpretation. FMS/FMI logs for wells Juno North-1 and Winninia North-1 were not especially helpful.
BURKE 3 - Log Motif Facies Association

<table>
<thead>
<tr>
<th>Core Depth (ft)</th>
<th>Gr log response</th>
<th>Grain Size and Sedimentary Structures</th>
<th>Photo</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7230</td>
<td>Low</td>
<td>G V C C M F VF ST MD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7240</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7250</td>
<td>sand bar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7260</td>
<td>(Santos, 2000)</td>
<td>(BEG, 1995)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Toolachee Formation core 1 (recovered section): 7220' - 7263')</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Disturbutary Channel Fill
- coarse to very coarse sandstone, planar cross-bedded, thin stacked fining upward units (~5cm) capped by organic stringers, interpreted as braided river deposits - traction currents in moderate to high energy environment

- coarse grained sandstone, planar cross-bedded at base overlain by laminated beds of organic stringers and floodplain fines

- matrix supported conglomerate with large (~4cm) intraclasts, rip-up clasts and stylolites - high energy traction deposition with basal lag
Baryulah reservoir facies
Juno North-1 (Core No. 1)

![Diagram showing sedimentary structures and depositional environment.]

**LEGEND**
- Parallel stratification
- Low-angle bedding
- Planar-bedded sandstone
- Cross-bedding
- Contact
- Carbonaceous shale

**FIGURE 12**
Baryulah reservoir facies from
Juno North-1 (core 1, 9354'-9366')

crevasse splay distributary channel
proximal crevasse splay
Baryulah non-reservoir facies
Winninia North-1 (Core No. 1)

**FIGURE 13**

Baryulah non-reservoir facies from
Winninia North-1 (core 1, 7330'-7342'')

*floodplain, floodplain lake/floodbasin
distal crevasse splay, medial crevasse splay*
Core from Juno North-1 (51' reservoir) interpreted for depositional facies.

Sedimentological information from core inspection was used to modify a generic facies scheme to emphasise crevasse splay deposition that is interpreted to have been prominent during various stages of sedimentation within the Baryulah area. Without core to verify depositional facies, the GR Log Lithology shown above for the cored interval could be interpreted as containing two channel sandstones (sharp base, fining upward motifs). This interpretation would lead to erroneous assumptions of mean bankfull channel depth (based on channel sand thickness) and incorrect channel sandbody width, channel belt width calculations (Fig. 21) and depositional style represented through facies mapping (Chapter 7).
FIGURE 15

Highwall from Ramp 11, South Blackwater Mine (courtesy of Dr. Simon Lang) showing 10 metres of stacked crevasse splay sands. These splays grade into distal splays of non-reservoir status. The splays overlie a regional coal at the top of the coal measures. Stacked splays like these produce wireline log signatures similar to that of pointbar channel sandstones, although stacked splays generally show a more 'ratty' gamma response.
Chapter 4 Chronostratigraphy

4.1 Baryulah chronostratigraphic framework

The chronostratigraphic framework for the Baryulah area in the southeastern Cooper Basin (Fig. 17) is based upon identification of the regional unconformities and on widespread lacustrine flooding surfaces and other marker horizons (eg. coal). Important criteria for selecting useful key surfaces is that they should be regional, and ideally even basin-wide, although it is also useful to pair these with more local markers (coal) that can help identify areas of local sediment supply (low sediment input favors coal, high sediment input precludes coal). Subdividing wireline log motifs into chronostratigraphic intervals is necessary to produce log motif facies maps of discrete time intervals. This enables the reconstruction of depositional history for an area and facilitates the development of palaeogeographic maps that characterize sedimentation within each interval. This approach is essentially an allostratigraphic methodology that divides the succession into genetically meaningful intervals.

In the Baryulah area, the regional unconformities include the intra-Patchawarra Fm. unconformity (VU45) and the Daralingie unconformity (UC00) at the base of the Toolachee Formation. Their identification is primarily based on depositional hiatuses resolved using Santos palynological data (Toolachee Fm. resting on Epsilon Fm. with the Daralingie Fm. and Roseneath Shale intervals removed by erosion - Fig. 3).

Widespread lacustrine flooding surfaces are indicated by maximum gamma-ray log spikes (high GR), commonly situated immediately above extensive coal markers. Significant flooding events are correlatable over the Baryulah area and 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 or in intervals characterized by extensive floodbasin/marshes/paleosols. Flooding surfaces are identified on the basis of wireline character, and are assumed to approximate timelines at the scale of this investigation. It should be emphasized that these flooding surfaces are probably actually diachronous events, however, as the initiation of lacustrine flooding was relatively rapid (a few thousands of years -

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responding to tectonic or climatic controls in the basin), these are for practical purposes geologically instantaneous, and approximate timelines.

The Cooper Basin chronostratigraphic nomenclature (Fig. 3) represents a rationalization of available palynological data with existing lithostratigraphic nomenclature. The key surfaces are labeled depending on whether they are local or regional, and whether they are unconformities or not. The system used by Santos Ltd. is alphanumeric and the prefix is based on traditional naming conventions in the basin. This scheme has been adopted for use in this study.

Chronostratigraphic type section wells and previous chronostratigraphic picks for Baryulah area wells were reviewed and implemented in constructing the overall framework. Minor revisions were made and modifications were done to some of the facies maps after a review of available pressure communication data. It is likely that minor adjustments may need to be made following further drilling.

Changes to the existing chronostratigraphic nomenclature included the addition of the Vu38 marker, which was added to enable more detailed facies mapping (Chapter 7). The inclusion of this surface (picked as a high-order unconformity) enabled the production of maps VC40-Vu38 and Vu38-VC35 (Patchawarra Fm.). The Vu38 unconformity may be an important marker to recognise elsewhere in the basin. Even finer chronostratigraphic subdivisions may be possible, for example the lacustrine shoreface near the top of the VC30-VC20 interval could be mapped out in more detail (and may even represent a higher order sequence boundary), but such a level of detail is the scope of future studies. An example of the chronostratigraphic subdivision (applied to all Baryulah area wells) is shown as Figure 16, an example from Juno-1.

4.2 Chronostratigraphic well correlation

Initial well correlations focused on regionally extensive flooding surfaces to define chronostratigraphic intervals. Biostratigraphic data was unavailable to assist flooding surface correlations. Type sections for the Patchawarra Formation (Kappa-1 – Appendix 3), Epsilon Formation (in Vega-1) and Toolachee Formation (in Hera-1) were provided by Santos Ltd. QNTBU for the purpose of identifying regionally
significant flooding surfaces and the genetic units they define. Flooding surfaces and key sequence stratigraphic surfaces were then correlated, providing a chronostratigraphic framework for the Baryulah area (Fig. 17).
FIGURE 16

Example from Juno-1 of picking sequence stratigraphic surfaces based on wireline character. This enables the construction of a chronostratigraphic framework for the Baryelah complex (Fig. 17) upon which facies maps for each chronostratigraphic interval can be produced.
Baryulah Chronostratigraphic Framework

FIGURE 17
Chronostratigraphic framework for the Baryulah area. Surfaces are picked based upon the principles of sequence stratigraphy for non-marine basins. The surfaces approximate time-lines and provide insight into the spatial variability of depositional environments throughout the Baryulah area in any one time interval. The construction of meaningful facies maps relies on the consistency of the chronostratigraphic framework. This framework was reviewed by Geoff Wood of Santos Ltd. (SABU) and found consistent with regional Cooper Basin chronostratigraphy, thus proving locally and regionally consistent.
Chapter 5  Depositional analogues

5.1  Modern Depositional Analogues

Modern depositional analogues provide ideal data for analogue studies. Channel belt dimensions and the relationships between depositional processes, facies and geometry are easily defined. By using modern analogues, both geoscientists and engineers can gain a greater understanding and appreciation for likely subsurface facies distribution. This should in turn lead to more realistic reservoir modeling.

5.2  Ob River

A useful analogue for Cooper Basin fluvial systems was identified by Lang (1997) and Lang et al., (2000) as the Ob River in western Siberia (Figs. 18, 19a, 19b, 19c). This is the largest peat forming environment on the planet today (70% of the world’s peat) lying in the cool-temperate Taiga forest-dominated region south of the Arctic permafrost zone in a vast flat marshy region over 4000km long, and up to 1000km wide. Western Siberia is closely comparable to the cool-temperate Gondwanan palaeogeography of Eastern Australia (Lang et al., 2000), lying between a fold thrust belt to the south and west and a stable craton to the north similar to the Permian Cooper-Galilee-Bowen-Gunnedah-Sydney basin system. The Cooper Basin could fit into one area of predominantly peat environments between major tributaries of the Ob River. The vast Ob River fluvial system is fed from river runoff from the northern side of the Altai Mountains (foreland thrust belt), as well as from melting of extensive winter snow that covers the region for up to 8 months of the year.

A potential pitfall with the Ob River analogue is the perception that it would be prone to permafrost structures. These have not been reported from the Patchawarra Fm.-Toolachee Fm. cores from the Cooper basin. Most of the Ob River floodplain however, lies well south of the permafrost zone. Further, river ice and surface ice/snow is not dominant in the spring and summer when all the sedimentation on the floodplain actually takes place. River and lake ice was likely during ‘Patchawarra’ and ‘Toolachee’ time, because rafted pebbles in the lacustrine facies are common,

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FIGURE 18
Ob River, western Siberia - useful as a modern analogue for depositional styles and the scale of fluvial-lacustrine features of the Baryulah area (Lang et al., 2000).
indicating river/lake seasonal ice was present up to mid Toolachee level at least. It should be understood that the process of ice-jams that is common throughout the Arctic and sub-Arctic zone may well be responsible for the high incidence of flood-generated sedimentation on the floodplain. This is because ice-jams cause rivers to spill out across their floodplain when the lower reaches of a river are ice-bound whilst the spring thaw has begun in the upper reaches. This would promote crevasse-splay deposition.

Anastomosing channel belts occur along the length of the Ob River plain, most >10km wide. These channel belts contain a vast area of floodplain sedimentation dominated by crevasse splays, floodplain lakes, and large but highly sinuous rivers (similar in scale to those imaged on the 3D seismic amplitude maps) that traverse the floodplain. The channel belt is flanked by extensive Taiga forest swamps and raised mires, which generally exist on slightly higher ground with raised water tables. In these areas sediment input is limited except during extreme flood events. Large floodplain lakes occur on the fringe of the system, fed by crevasse deltas that form part of a larger lacustrine delta. The Ob River floodplain has infilled extensive lake deposits developed during the climatic optimum (6000-3000 years ago), and it appears that cycles of fluvial, lacustrine and peat sedimentation dominate a region comparable in scale to the entire Cooper-Galilee-Bowen-Sydney Basin system (Lang et al., 2001).

Figure 19 shows an upper-Toolachee Fm. seismic amplitude map corresponding to the interval PC20-10 (Toolcahee). Modern Ob River images (inset A, B & C, Lang & Kassan) were used to interpret the geological significance of seismic features seen on the amplitude map and to determine depositional facies by way of analogy.

5.3 Other analogues

The Ob River is not the only useful analogue for the Baryulah study. The Cumberland Marshes in Canada is also useful because Smith et al. (1989) have undertaken extensive studies on the crevasse splay deposits (Fig. 8). Although the tectonic setting is different, the depositional processes were similar to that of the Permian fluvial deposits in the Cooper Basin. Crevasse splays develop following
FIGURE 19

Location of modern fluvial analogues from the Noyabrsk and Nizhnevartovsk areas in the cool-temperate, peat-forming Ob River basin of Western Siberia (courtesy Lang, Kassan), and comparison with seismic horizon amplitude slice map from the upper part of the PC20-PC10 interval (Toolachee Formation) in the Baryulah 3D seismic survey (Spencer).

The seismic slice clearly shows low amplitude channel fills in the southeastern part of the image (C) as well as high amplitude cut-off meander loops in the north (B).

Inset A  Abandoned channel of the Ob River near Nizhnevartovsk showing peat accumulation in abandoned channels. Note the distinct edge along the channel belt, similar in shape and scale to the seismic amplitude image from the Baryulah survey.

Inset B  Highly-sinuous meandering channel and meander cut-off in the early stages of being filled with peat, near Noyabrsk.

Inset C  Active sandy meandering channel (200m wide) in tributary of the Ob River near Nizhnevartovsk, showing well developed laterally accreting scroll bars with peat filling chute channels.
FIGURE 20

Atchafalaya River deltas in the Gulf of Mexico, showing highly constructive lobate fluvially-dominated deltas likely to be a useful analogue for deltas of the Tu95-TC80, TC80-TC50 and Tc50-Daralingie Unc. (Epsilon) intervals, that have used this delta as a modern analogue for depositional style and scale.
river avulsion during a major flood event. The crevasse splay begins as small lobe with a narrow, bifurcating distributary in the proximal zone, and this feeds the main splay lobe. They can build into shallow floodplain lakes, resulting in a crevasse delta a few meters thick (proportional to the depth of the floodplain lake).

As the splay channel diverts more of the river flow, it gets elongated and eventually forms an anabranch to the main river. In some cases it can merge with other splays to form an anastomosing network of high-energy, narrow, elongate splay distributary channels adjacent to the main river. These drain into a larger lake system, and form part of a lacustrine delta complex. The key to recognizing deposits such as these in the rock record is that they contain evidence of rapid deceleration of the current flow, typically producing a small fining-upward cycle in the proximal area, with high flow regime structures in medium to coarse sand (parallel lamination, with rip up clasts commonly) grading to climbing ripple lamination and laminated siltstone at the top. Small-scale cross bedding may be present (decimeter scale) but it is not dominant. In the medial area the splay becomes blocky (fine-medium sand with ripple and small scale cross-beds), and in the distal area may show coarsening upward facies from mudstone to fine ripple sandstone. The main difference between splays and lacustrine deltas is the relative dominance of root structures, common on top of splays, less common except on the topsets of deltas.

Epsilon Fm. fluvio-deltaic deposition in the Baryulah area also used analogue input from the Atchafalaya River deltas (Gulf of Mexico) for depositional style and dimension analysis (Fig. 20). Whilst the current climatic regime of the Atchafalaya deltas is probably dissimilar to that at Baryulah during Epsilon Fm. deposition, the depositional style and sedimentological processes are thought to have been similar, where crevasse splays and deltaic sedimentation predominates.
Chapter 6  Estimating channel belt width

6.1  Empirical equations

Prediction of subsurface channel-belt width using empirical equations (those based on observations) from modern rivers, relates maximum bankfull channel depth to channel width and channel-belt width. This method requires reliable estimates of maximum bankfull channel depth from one-dimensional data. Correctly estimating the maximum bankfull channel depth from wireline-logs is difficult because complete channel fill sequences may be difficult to identify. Bankfull channel depth will vary depending on what part of the channel is penetrated by the well ie. maximum bankfull channel depth will occur when the thalweg is penetrated (Fig. 7).

Depositional facies based upon wireline log character were assigned to the nine Baryulah area wells. The most complete channel fill sequences were interpreted for each chronostratigraphic interval within each of the wells. The resultant range of ‘assumed’ maximum bankfull channel depths was then plotted on a graph based on empirical observations of modern rivers compiled from published sources (provided by Whistler Research). Figure 21a shows a graph of bankfull channel depth vs channel belt width for truly meandering streams. Seismic images within the study intervals reveal truly meandering features such as necktie cut-offs that give confidence to using such a graph. The various gradients plotted from different sources provide a range of channel belt widths based on empirical data. Figure 121b shows the estimation of thickness for a complete fluvial channel fill sequence (sand and abandoned channel fill) from a package of stacked sands. For each chronostratigraphic interval these can be measured, providing a range of bankfull channel depths to produce a range for likely channel sandstone and channel belt widths for that interval. It is likely that the range of channel fill thicknesses for each interval, will produce a conservative estimate for channel sandbody width and channel belt width. This is because the likelihood of intersecting the thickest part of a preserved point-bar and abandoned fill package of a fluvial channel in each well is minimal.

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Published data:
- Collinson 1978
- Williams 1986
- Bridge & Mackey (A) 1993 - regression
- Bridge & Mackey (B) 1993 - total data set
- Bridge & Mackey (C) 1993 - with Leeder (1973) data
- Bridge & Mackey (D) 1993 - with Leeder (1973) data
- Bridge & Mackey (E) 1993 - with Crane (1982) data
- Fielding & Crane 1987 modern truly meandering streams
  (compiled by Whistler Research)

FIGURE 21

A Empirical data on modern truly meandering streams can be used to plot channel belt width against channel sandbody thickness. Such data in graphical form can be used to estimate appropriate ranges for channel belt widths for known channel sandbody thicknesses (Whistler Research).

B A worked example of using plot A to estimate minimum and maximum channel belt widths based on channel sandbody thickness (Strong et al., 2002)
It may be argued that sandstones identified in channel fill sequences should be decompacted before used to determine ranges for channel sand and channel belt widths (a decompaction of 10 percent is reasonable for the well-sorted sands of a pointbar succession), however, given the likely thickness variations in channel sandstones due to precise well location within a channel belt, decompacting the sands is a whimsical process.

The sandstone thickness range used as the measured input to derive width ranges was interpreted from well logs. Core studies showed that thick low gamma ‘blocky’ motifs of the Patchawarra Formation were most likely comprised of stacked fluvial channels and their proximal splays. In applying the facies scheme used for this study, each of the ‘blocky’ sand intervals were subdivided into channel and or proximal splay facies (Fig. 14), rather than a thick braided fluvial succession for which there is no evidence.

It was generally considered that the highest sand (or last deposited) represented the most complete (ie. not trimmed) ‘point-bar’ sand package from a single channel pass. Therefore, the thickness of each interpreted channel sandstone within a given interval was not suitable for calculating channel sandstone width and channel belt width. The pre-erosional thickness of now amalgamated channel sandstones is speculative. Only discrete sandstone and abandoned fill packages (interpreted from wireline motifs) thought to best represent actual fluvial channel bankfull thickness were used to define the maxima and minima for channel sandbody thickness for a given interval.

Application of this method for determining sandbody thickness from logs is not without uncertainty. The following list describes a particular uncertainty and its affect on determining channel sandbody and channel belt width.

1. Interpreting upper-bar deposits as overbank deposits, and not part of the bank-full depth of the channel. This will result in an underestimated channel depth and therefore an underestimated channel sandbody width and channel belt width.

2. Interpreting cross-bar channels (chute channels) as the most depositionally complete (ie. non truncated) uppermost true channel deposit. This will result in
channel sandbody thickness being underestimated, and therefore channel sandbody width and channel belt width will also be underestimated.

3. Interpreting channel sandbody thickness at a given well location as the maximum channel sandbody thickness within its associated channel. Within a single channel belt, channel depth and bar thickness can vary by at least a factor of two (Bridge & Tye, 2000). This would result in true channel sandbody thickness being underestimated and therefore channel sandbody width and channel belt width would also be underestimated.

In each of the above cases, possible interpretation pitfalls serve to underestimate channel sandbody width and channel belt width. Therefore, the uppermost limit of derived channel sandbody width and channel belt width should be considered a conservative estimate. Seismic amplitude maps enable us to check whether such estimates approximate what the seismic is imaging. An example of this is shown for interval PC50 - PC40 (Fig. 22) where the estimated channel sandbody width and channel belt width appear closely associated with sinuous features on the seismic amplitude map.

6.2 Amplitude analysis of 3D seismic horizon slices

The Baryulah 3D seismic survey area is the study area for this project. Numerous amplitude maps were generated by Santos Ltd. QNTBU to highlight suspected fluvial features within the Patchawarra Fm., Epsilon Fm. and Toolachee Fm. intervals. Seismic amplitude maps were used to check channel sand width and channel belt width determinations made by using sandbody thickness derived from wireline-log interpretation. Overall, fluvial features interpreted on the seismic amplitude maps had channel sandbody width and channel-belt widths within the ranges determined by plotting interpreted sandbody thickness (maximum bankfull channel depth) on a chart made up of empirical equations from published sources (Fig. 21a).

Below the P3 coal (a regional marker horizon), acoustic impedance contrasts on the seismic amplitude maps are subtle compared with those above. This is due to the reflection co-efficient of this thick coal being quite high. Where possible, amplitude

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contrasts delineating interpreted depositional features were used to assist facies mapping. This was achieved with greatest confidence for the PC intervals (Toolachee Fm. - above the P3 coal). Figures 22 and 23 show how seismic amplitude maps can be used in depositional facies mapping to constrain channel belts.
FIGURE 22

LEFT  Seismic facies classification map from *Stratimagic* (courtesy of Santos Ltd. QNTBU) for the mid-Toolachee Fm. interval PC50 - PC40, from the 3D seismic. Distinctive meander loops in the south of the Baryulah area are imaged.

RIGHT The resultant palaeogeographic map for the PC50-PC40 interval, integrating sequence stratigraphy, facies analysis and *Stratimagic* output.
FIGURE 23 LEFT: 3D seismic amplitude map showing sinuous channels in belt.

RIGHT: Facies map produced for the VC20-VC00 interval prior to receiving the 3D seismic amplitude map.
Chapter 7  Facies mapping

Facies maps were constructed for each chronostratigraphic interval identified between the Pre-Permian and PC10 horizons (Fig. 3), to characterize facies distribution and predict reservoir sandstone connectivity at various sub-levels throughout the Baryulah area.

7.1  Palaeogeographic setting

The palaeogeographic setting during deposition of each chronostratigraphic interval was first interpreted using available data. This included a review of Santos Ltd. QNTBU reports (Southern Margin Permian Stratigraphic Plays, 1997; Beaumont-Smith, 1999; Herdy, 1999; Kloss, 1999), personal communication with Steve Forder and Trinetta Herdy (QNTBU); basement maps generated by Doug Knowles (QNTBU) from previous 2D seismic data; seismic amplitude maps generated by Gregg Spencer (QNTBU) from 3D seismic data, along with the chronostratigraphic packages used to determine possible onlap edges during various intervals.

A depth to basement map of the Baryulah area based on 2D seismic data reveals a complex topography (Fig. 2). The Pre-Permian-VC00 (Patchawarra Fm.) succession was deposited by successive onlap over the basement, from north to the south (notwithstanding relatively minor fault reactivations and tilting). Log motif facies maps illustrate a depositional history of southward onlapping onto the basement high, progressively backstepping over this relief until commencement of widespread VC00-VC20 (Patchawarra Fm.) deposition.

It is assumed that the earliest recorded sedimentation within each of the nine wells studied in the Baryulah area indicates the time interval within which that location switched from an area of bypass/erosion to and area of sediment accumulation (refer to Fig. 4).

Structural control on sedimentation is most evident in the earliest Patchawarra Fm. interval with deposition occurring only in the vicinity of Juno North-1, off the flanks
of the basement high. As seen in the earlier Patchawarra Fm. facies maps the structural high provided a southern bounding margin to fluvial fairways.

Using analogues as a guide, facies distribution maps were constructed for the chronostratigraphic intervals with sedimentological information interpreted from log-motifs for each interval. Facies maps were compared to available seismic attribute maps corresponding to the same interval. In all cases a reasonable level of agreement was achieved between the two independently produced data sets. Some modifications to the facies maps were made based upon comparison with the seismically generated maps, usually resulting in the production of more tortuous river channel pathways than had been previously mapped. Figure 22 shows an example of the use of seismic amplitude maps for this purpose.

Most intervals have accompanying sand percent and isopach maps, their trends based largely upon the facies map of that interval. These are ideally suited for early stage integration of newly acquired well data from future wells.

7.2 Facies maps

A cautionary note about reading the facies maps: The following maps are not to be read as fixed, absolute maps of sand distribution. They represent a four-dimensional interval in which a suite of facies are deposited, eroded and amalgamated during a given time interval, and are based on the use of Walther's Law where vertical superposition of facies shown in each log motif at each well reflects lateral distribution of adjacent facies at any given time. Note that the key here is that the chronostratigraphic intervals must be conformable successions of genetically related strata. Assuming these intervals have been interpreted correctly (and they do not contain any hiatal breaks), then they can be useful as predictive tools. Also note that although an active channel is illustrated (usually in bolder red), all that really can be believed is the location and approximate orientation of the channel belts, and hence the illustration of other palimpsest channel deposits within the confines of the channel belt (generally shown as pale red). Where possible the 3D amplitude maps have been used as a guide, but there remains uncertainty as to the exact interval that these maps purport to reflect. There is a risk that the orientations and shapes of channel belts are
from an interval just below or above (and both together) the chronostratigraphic interval of interest although care has been taken to avoid this.

Another possible pitfall is that there has been an over- or under-interpretation of the thickness of actual channel deposits, or that interpreted channel deposits are actually stacked splays. Where uncertainty exists, estimates err on the conservative side (refer to Section 6.1 – Empirical Equations) when interpreting maximum bankfull channel depths that are then used for reconstructing channel widths and channel belt widths. This process will inevitably contain some errors and drilling should not be targeted in a precise fashion using only these maps for any single interval.
7.2.1 Pre-Permian - VU45 LST - TST (Patchawarra Fm.)

This unit represents the oldest recorded Permian deposition within the Baryulah area and is present only in Juno North-1. The basal portion has been interpreted as a succession of stacked proximal splays and channel sandstones, with overbank fines winnowed-out by fluvial reworking processes during lateral migration of fluvial belt(s). A transgressive surface is interpreted above the uppermost thick sandstone package, at the onset of transgressive deposition.

At 9650' in Juno North-1 there is a shaley interval above which there is a change in sediment style. Overbank fines and floodplain muds now separate channel sands. This indicates either a change in fluvial pathway (ie. river migrates away from well location) or an increase in accommodation due to base level rise. A transgressive surface is proposed at this level, above which there is an increase in accommodation resulting in an increase in overbank preservation. The VU45 erosion surface is placed at the base of the next major set of amalgamated channel sandstones that indicates a reduction in accommodation (refer to Fig. 6).
7.2.2 VU45 - VC40 Early LST (Patchawarra)

This interval is represented at Juno North-1 by stacked channel sandstones, at Hera-1 as distal crevasse splay sandstones, shale and overbank mudstones. Vega-1 shows a relatively thick succession of varied litho-facies, which represents predominantly proximal crevasse splays, and overbank fines with some coals. Abundant crevasse splays and overbank fines suggest Vega-1 is located within or close to an active channel belt.

Juno North-1, Vega-1 and Hera-1 are likely to be positioned on the downthrown side of a major northwest to southeast oriented fault in the area during this time. The VC40 surfaces is picked at the last flooding event (high GR) before the recommencement of stacked sandstone channel deposits of the VC40-Vu38 interval.
7.2.3 VC40 - Vu38 LST  (Patchawarra Fm.)

Vega-1, Hera-1 and Juno North-1 contain clean sandstones interpreted as channelised deposits. Baryulah East-1 and Juno-1 show crevasse splay sedimentation. Amalgamated channel sandstones with fining upward log motifs are restricted to the flanks off the high. Winninia North-1, Baryulah-1, Baryulah-2 and Juno-2 do not record sedimentation during this interval. Based on the depth to basement map (Fig. 2) these wells are situated on palaeo-highs during this time. This interval is interpreted as early lowstand deposition. The Vu38 marker represents a high order unconformity within the VC40-VC35 lowstand interval, and is placed at the base of the next amalgamated succession of channel sands.

The southern eastwest proposed channel belt results from an interpretation of the depth to basement map (Fig. 2), indicating sedimentation was at least possible if not probable over this 'palaeo-saddle' feature, as indicated by the highest onlap level shown by wells Juno-1 and Baryulah East-1.
7.2.4  Vu38-VC35  Late LST  (Patchawarra Fm.)

Juno North-1, Juno-2, Juno-1, Hera-1, Vega-1 and Baryulah East-1 record thick successions (up to 50m) of stacked fluvial sandstones. These are interpreted as amalgamated channel; crevasse splay distributary and proximal splay sandstones. This interval represents late lowstand deposition.

An interesting feature of the Vega-1 and Baryulah East-1 Vu38-VC35 is that a thick coal does not cap them. This is likely due to increasing accommodation relative to sediment supply being restricted to the north during this interval. Southward, less accommodation relative to sediment supply results in greater lateral migration of fluvial channels and hence the winnowing of fines.

The Vc35 surface is placed at the top of the first thick 'transgressive coal' in this interval (absent in Vega-1 and Baryulah East-1). The VC35 pick is a flooding surface assumed to have drowned the extensive coal to the north, where a relatively constant base level rise accompanied by a decrease in sediment supply enabled extensive peatmire development. The VC35 pick in Baryulah East-1 is placed at a shale break between two amalgamated sandstone packages.

![Isopach (ft) and Sand Percent Maps](image)
7.2.5 VC35 - VC30 TST (Patchawarra Fm.)

The lower part of the VC35-VC30 interval in all wells, except for Baryulah-1 and Winninia North-1, is characterised by clean sandstones of channel and splay origin, displaying 'ratty' block motifs. The VC35-VC30 interval thickens to the north where Vega-1, Juno-1, Juno-2, Hera-1 and Juno North-1 record increasingly overbank/peat mire sedimentation. Wells to the north show well-defined coals indicating that the rate of base level rise and rate of sediment supply was not consistent - rather, base level rise occurred as a number of small-scale relatively rapid flooding events consistent with that expected for transgressions. The sedimentary style of the northern part of the Baryulah area during this interval resembles the upper reaches of a delta plain. The VC30 marker is placed at a maximum flooding surface immediately above the fluvial-lacustrine succession. The MFS is significant in that it delineates when base level rise outpaces sediment supply, giving rise to a change in depositional style.
VC35 - VC30
Patchawarra Fm.

Scale 1: 75,000

- Peat Mire
- Overbank / Marsh
- Distributary Channels or Other Channels
- Crevasse / Splay Complex
- Lake / Floodplain Lake
- Mouthbars / Lake Shoreface
7.2.6 VC30-VC20 HST (Patchawarra Fm.)

Basal deposits of the VC30-VC20 interval in all wells except Winninia North-1 record abundant crevasse splay sedimentation and overbank fines. The abundance of crevasse splays suggests that the increase in accommodation is being met by sediment supply. Early Winninia North-1 records distal floodbasin/lake sedimentation with a thin coal at the top of a relatively fine-grained prograde. The uppermost portion of the VC30-VC20 succession shows strong progradation to the northeast, with Baryulah-1 and Baryulah-2 showing the wireline character of channelised flow.

The onset of progradational sedimentation and the preservation of thin sands (interpreted as deltaic progradation with associated deltaic distributary channels), marks the VC30-VC20 interval. This is a marked change in depositional style from the VC35-VC30 interval and is separated by the VC30 maximum flooding surface. During this highstand and based on log-motif analysis, deltaic sedimentation appears derived from the southwest or southeast of the study area possibly flanking a palaeo-high to the south, near Winninia North-1.
VC30 - VC20
Patchawarra Fm.

Scale 1 : 1:75,000
PALAEO-HIGH

Legend:
- Peat Mire
- Overbank / Marsh
- Distributary Channels or Other Channels
- Crevasse / Splay Complex
- Lake / Floodplain Lake
- Mouthbars / Lake Shoreface

Nth

27°4'0"S

27°5'0"S

GR (API) 20°

0 - 30 m.
7.2.7 VC20 - VC00 TST (Patchawarra Fm.)

The VC20-VC00 interval is characterised by overbank fines, crevasse splay sedimentation and stacked channel sandstones in Juno-1, Juno-2 and Hera-1, indicating their location within a channel belt.

The sandstones present in Juno-1 and Juno-2 show remarkably similar preserved thickness. It is interesting to note the different levels at which these sand bodies exist within their respective wells. The Juno-2 amalgamated channels were deposited first while Juno-1 recorded crevasse splay and overbank deposition. Subsequently, depositional style switched between these two locations, with Juno-1 recording amalgamated channels sandstones, whilst Juno-2 received overbank fines. This inter-relationship of depositional style between two relatively close wells (0.8km) may indicate that both locations were in the same active channel belt during this time.
7.2.8 VC00-Tu95 TST (Murteree Shale)

This interval is characterised by the finest grained sediments below the Daralingie Unconformity, indicating a period of base level rise and inundation of the Baryulah area, associated with a significant flooding event. Winninia North-1 displays fine-grained sedimentation with a progradational log-motif suggesting that the dominant sediment thoroughfare was located to the southeast of the study area and distal splay sedimentation reached Winninia North-1. The fine-grained sediments of the VC-Tu95 'Murteree Shale' interval provide a potential seal in this area.
7.2.9 Tu95-TC80 LST (Epsilon Fm.)

All wells, except Winninia North-1 (which does not appear to belong to the main depositional style of this interval) display progradational stacking patterns. Vega-1, Baryolah East-1, Baryolah-1, Juno-1, Juno-2, Hera-1 and Juno North-1 have two discrete progradational packages interpreted as separate delta lobes though not necessarily in hydraulic connectivity between wells. Juno North-1, Juno-2, Juno-1, and Hera-1 have relatively thick sandstone successions late in the interval, suggesting that progradation of the delta system south has resulted in distributary channel sedimentation at these well locations.

The interpreted progradational direction for the Tu95-TC80 delta system of north to south is in direct contrast to that interpreted for deltaic sedimentation during the Patchawarra VC30 - VC20 interval (south to north). Such a change in sediment Providence is most likely due to tectonic uplift to the north of the study area, re-establishing fluvial profiles (refer to Fig. 4). Deltaic sedimentation is evidenced by several cycles of progradational sedimentation at each well location. The progradational units of the deltaic system are capped by very low gamma 'sands' that may indicate wave-agitated, clean, high permeability sands with reservoir potential. Winninia North-1 appears separated from the major deltaic system which is sourced from the north, and is most likely 'fed' by sediments shed off highs to the south of the study area.
This interval shows a major progradation package thought to have formed by fluvially-dominated deltaic processes. Sandy mouthbar and channel deposits in the uppermost parts of progrades in Juno North-1 and Hera-1 suggest deposition from the north. Hera-1 shows an overall, large progradational package with a smaller prograde within the uppermost sandy 'mouthbar' portion of the deltaic package. This is interpreted as two amalgamated deltaic mouthbars resulting from lobe switching, stacking multiple sandstones, that are likely to be hydrodynamically connected. Also Juno North-1 shows evidence of amalgamated mouthbars, as well as a distinct fining upward package at the top of this interval interpreted as a distributary feeder channel for the delta lobes. Well log-motifs decrease in sand percent away from the north, indicating a north to south migration of the delta system.

The TC50 marker is interpreted as a flooding surface, picked at the top of the coal in TC80 - TC50 interval that separates the progrades of this interval from the ones above.
This interval is characterised by fluvial-deltaic deposition migrating from the north to the south. Wells Juno North-1, Juno-1, Juno-2 and Hera-1 display channel/crevasse splay character developed above a deltaic prograde indicating that the northern end of the area recorded sediment of an increasingly fluvial nature. Assuming a constant sediment supply this interval represents a highstand deltaic phase of basin sedimentation.

No deposition is recorded in Winninia North-1 for this interval, any sedimentation from this time period was probably eroded by the Daralingie Unconformity which overlies this interval.

The Daralingie Unconformity is picked where there is a change in depositional style from fluvio-deltaic progradation to fining upward channel deposits (except in Baryulah-1 and Winninia North-1). This depositional change is initiated by a base level fall and consequent exposure of deltaic sediment to fluvial processes. Sands on this sequence boundary are likely to be of excellent reservoir quality, as they probably represent fluvially reworked mouthbar sands. An example of this is seen in Baryulah-2 (Daralingie Unc. - Pc60) where a channel deposit is interpreted to exist directly above an eroded mouthbar.

This interval is a good reservoir target. High quality fluvial sandstones should produce well, with substantial pressure support from the underlying, extensive amalgamated mouthbar reservoir sandstones of slightly lesser reservoir quality.
TC50 - DARALINGIE UNC
Epsilon Fm.

Eastern Lobe of Larger Delta System

Scale 1: 75,000

- Peat Mire
- Overbank / Marsh
- Distributary Channels or Other Channels
- Crevasse / Splay Complex
- Lake / Floodplain Lake
- Mouthbars / Lake Shoreface

Nth

27° 0'S
27° 5'S
27° 0'S
27° 5'S

0 1000 2000 3000 4000 Metres

0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450 460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 610 620 630 640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880 890 900 910 920 930 940 950 960 970 980 990 1000 1010 1020 1030 1040 1050 1060 1070 1080 1090 1100 1110 1120 1130 1140 1150 1160 1170 1180 1190 1200 1210 1220 1230 1240 1250 1260 1270 1280 1290 1300 1310 1320 1330 1340 1350 1360 1370 1380 1390 1400 1410 1420 1430 1440 1450 1460 1470 1480 1490 1500 1510 1520 1530 1540 1550 1560 1570 1580 1590 1600 1610 1620 1630 1640 1650 1660 1670 1680 1690 1700 1710 1720 1730 1740 1750 1760 1770 1780 1790 1800 1810 1820 1830 1840 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020 2030 2040 2050 2060 2070 2080 2090 2100 2110 2120 2130 2140 2150 2160 2170 2180 2190 2200 2210 2220 2230 2240 2250 2260 2270 2280 2290 2300 2310 2320 2330 2340 2350 2360 2370 2380 2390 2400 2410 2420 2430 2440 2450 2460 2470 2480 2490 2500 2510 2520 2530 2540 2550 2560 2570 2580 2590 2600 2610 2620 2630 2640 2650 2660 2670 2680 2690 2700 2710 2720 2730 2740 2750 2760 2770 2780 2790 2800 2810 2820 2830 2840 2850 2860 2870 2880 2890 2900 2910 2920 2930 2940 2950 2960 2970 2980 2990 3000 3010 3020 3030 3040 3050 3060 3070 3080 3090 3100 3110 3120 3130 3140 3150 3160 3170 3180 3190 3200 3210 3220 3230 3240 3250 3260 3270 3280 3290 3300 3310 3320 3330 3340 3350 3360 3370 3380 3390 3400 3410 3420 3430 3440 3450 3460 3470 3480 3490 3500 3510 3520 3530 3540 3550 3560 3570 3580 3590 3600 3610 3620 3630 3640 3650 3660 3670 3680 3690 3700 3710 3720 3730 3740 3750 3760 3770 3780 3790 3800 3810 3820 3830 3840 3850 3860 3870 3880 3890 3900 3910 3920 3930 3940 3950 3960 3970 3980 3990 4000
7.2.12 Daralingie Unconformity - PC60 LST - TST (Toolachee Fm.)

All wells display channel sandstone and associated crevasse splay sandstone log-motifs. The basal sandstones although thin, are relatively clean, suggesting reworking of these fluvial deposits during lateral migration of channels (refer to Fig. 5a), indicating negligible accommodation relative to sediment supply. Within this interval there is a sharp boundary between the basal sands and overlying fines. This abrupt surface is interpreted as a transgressive surface. Sedimentation during the Daralingie Unc. - PC60 interval is prevalent throughout the entire study area and interpreted to be of similar depositional style.

Fluvial processes are dominant during this interval with sediment derived from the north. Constituent facies are fluvial channels, proximal crevasse splay and overbank fines. PC60 is picked as the first major flooding surface above the Daralingie Unconformity. The palaeo-flow from the northwest to the southeast is speculative, it is possible that the flow direction could be the other way around. This needs to be determined from detailed FMS/FMI palaeocurrent analysis.
7.2.13 PC60 - PC50  HST  (Toolachee Fm.)

Baryulah-1, Baryulah-2 and Baryulah East-1 are interpreted to be situated between fluvial channel belts. They record overbank and coal deposition. Wells to the north; Juno North-1, Juno-1, Juno-2, Hera-1 and Vega-1 show a variation in depositional facies from channel sandstones to overbank siltstones and splay deposition. These wells are interpreted to be situated within, or close to channel belt(s).

This interval contains two separated channel belts interpreted from seismic amplitude maps (of adjacent intervals PC50 - PC40) and sedimentological information interpreted from wireline log-motifs. The channel sandstone log-motif of Winninia North-1 suggests it is located within an active channel belt within this interval. Within the channel belt interpreted to the north, log-motifs show regular coals and channel abandonment fill. Such variation in wireline character is likely due to the influence of numerous fluvial channels active within the main channel belt.

As with the Daralingie Unconformity - PC60 interval, the palaeo-flow direction is speculative (shown here as west to east) and could be the other way around, flowing toward the Nappameri Trough to the west.
7.2.14  PC50 - PC40  LST - TST  (Toolachee Fm.)

All wells in this interval display log motifs consistent with truly meandering river deposits. This is consistent with features interpreted as meandering rivers imaged on seismic amplitude maps for this interval. Figure 22 shows a seismic facies classification map from Stratimagic (courtesy Santos Ltd. QNTBU) that reveals large meander loops in the southwest, and a tortuous channel belt to the north. Most wells show channel-fill sandstones topped by fine-grained abandonment fill, capped by coal. Juno-1 shows a particularly nice example of a complete channel fill sequence giving confidence to bankfull channel depth estimation and hence estimation of channel sandbody width and channel belt width (refer to Fig. 21).

This interval comprises fluvial channel, crevasse splay, overbank and floodplain deposits capped by a regionally extensive coal (P3), deposited during lowstand to early transgression. The Pc50 surface is picked as the next major flooding surface above the PC60 marker that separates the variable, somewhat 'ratty' character of the PC60-PC50 interval from the lithologically well-defined PC50-PC40 interval.
Wells Baryulah-1, Baryulah East-1 and Juno-2 display wireline motifs interpreted as containing channel deposits. The relatively thick sandstone in Baryulah-1 suggests that it is located within a channel belt. Winninia North-1, Baryulah-2, Hera-1, Juno-1 and Juno North-1 have log-motifs characteristic of overbank sedimentation with the occasional proximal/distal crevasse splay deposit.

This interval is interpreted as having a main channel belt in the west (evidenced by the channel sandstone of Baryulah-1), with a large associated splay complex on the outside of the bend, responsible for depositional styles in Juno-2, Juno-1, Vega-1, Baryulah East-1 and Winninia North-1. This interval is interpreted as representing transgressive sedimentation, consistent with the development of large splay complexes, as rivers are more likely to breach their banks during periods of rising base level.
Log motifs for this interval suggest relatively distal sedimentation away from fluvial fairways at all well locations except for Winninia North-1, whose motif suggests stacked splay deposition within/flanking an active channel belt(s). Sedimentation is believed to be derived from the north, consistent with the general depositional trend for Toolachee Fm. intervals of this area.
Based largely upon seismic amplitude analysis of this interval (below), facies map PC20-PC10 shows a broad (3-4km) channel belt, split in its 'upper' reaches to the north and converging before extending down the eastern margin of the study area. There are numerous 'ox bow' lakes that appear on the seismic amplitude map. These have been transferred to the facies map in order to convey fluvial sinuosity information within this interval. Most log-motifs show crevasse splay sedimentation, consistent with the abundance of active channels within belts that encompass well locations. Baryulah-1 and Baryulah-2 are void of substantial fluvial facies, primarily receiving overbank sedimentation.
Chapter 8 Conclusions

It has been demonstrated that the use of sequence stratigraphic concepts to build chronostratigraphic frameworks (comprised of genetically related intervals) can assist facies mapping, and thus delineation of channel belts with optimum reservoir facies and connectivity. Specific intervals, generally lowstand systems tracts, are clearly the highest priority for targeting development wells because of the high net/gross and good reservoir facies (notwithstanding diagenesis). Some of the transgressive systems tract intervals may be good stratigraphic trap candidates, especially if combined with a structural component.

The use of empirical data and modern and ancient depositional analogues is the key to understanding the spatial variability of depositional facies within fluvial-lacustrine settings. When appropriate analogues are applied correctly they are invaluable for communicating key reservoir issues (such as quality, lateral extent and connectivity) to geologists and engineers.

Permian intervals mapped for this study are characterised by the following:

1. Pre-Permian to VU45 (Patchawarra Fm.) LST - TST interval; a thick basal succession (~60m) of amalgamated channel sands upwardly becoming more isolated, restricted to the northern flank of an interpreted palaeo-high.

2. VU45 to VC40 (Patchawarra Fm.) Early LST interval; fluvial channel, crevasse splay, overbank and peat mire sedimentation - restricted to the northeast of the study area, possibly on the downthrown side of a northwest to southeast orientated fault.

3. VC40 to Vu38 (Patchawarra Fm.) LST interval; fluvial channel and crevasse splay sedimentation restricted to the northeast of the study area with multiple active channels within a 4km wide channel belt, oriented north/northwest to southeast.
4. Vu38 to VC35 (Patchawarra Fm.) Late LST interval; to the south - thick successions (up to 45m) of amalgamated fluvial sandstones (braided and/or meandering); to the north - fluvial meandering channel and crevasse splay sedimentation topped by widespread coal development marking the onset of transgression.

5. VC35 to VC30 (Patchawarra Fm.) TST interval; basal amalgamated sandstones of channel and splay origin - upward transition into channel sandstones and coals interspersed within overbank siltstones interpreted as true meandering fluvial conditions with wells displaying characteristic log-motifs.

6. VC30 to VC20 (Patchawarra Fm.) HST interval; basal channel and splay deposition with an upward transition into fluvio-deltaic conditions (the only deltaic deposition of the VC interval with characteristic progradational log-motifs). The uppermost five meters in Juno-1 may represent laterally extensive, clean mouthbar sandstones of reservoir potential.

7. VC20 to VC00 (Patchawarra Fm.) TST interval; mostly overbank siltstones with proximal, medial and distal splay deposition. There is an east-west trending channel belt intersected at Juno-1 and Juno-2.

8. VC00 to Tu95 (Murteree Shale) TST interval; widespread siltstone and mudstone deposition under lacustrine conditions. Winninia North-1 and Vega-1 receive slightly coarser sediments indicating their position closer to a southern sediment source.

9. Tu95 to TC80 (Epsilon Fm.) LST interval; deltaic sedimentation from a north to south (in contrast to the north-flowing fluvial systems of the underlying VC intervals). The change in sediment province is most likely the result of tectonic uplift to the north of the study area re-establishing fluvial profiles.

10. TC80 to TC50 (Epsilon Fm.) TST interval; a fluvially dominated deltaic system encroaching southward, from north of the study area with relatively
thick (10 to 30 meter) successions of sandstone interpreted as deltaic mouth-bars and superimposed incising distributary channels.

11. TC50 to Daralingie Unconformity (Epsilon Fm.) HST interval; further progradation of the delta system southward, with deltaic sediments overlain by distributary channel sandstones and s plays.

12. Daralingie Unconformity to PC60 (Toolachee Fm.) LST – TST interval; widespread fluvial channel activity within numerous channel belts up to 4 km in width. Interpreted palaeo-flow direction is from northwest to southeast, but speculative.

13. PC60 to PC50 (Toolachee Fm.) HST interval; fluvial, splay and overbank sedimentation with fluvial channel belts restricted to the north and south of the study area. Palaeo-flow direction from northwest to east is speculative.

14. PC50 to PC40 (Toolachee Fm.) LST – TST interval; truly meandering fluvial channels are active within the study area. Channel sandstones are overlain by channel abandonment siltstones and capped by coal.

15. PC40 to PC30 (Toolachee Fm.) TST interval; fluvial channel, proximal, medial and distal crevasse splay deposition amongst overbank siltstones, under transgressive conditions favoring channel avulsion and the development of extensive splay complexes.

16. PC30 to PC20 (Toolachee Fm.) TST interval; medial and distal splay sedimentation amongst overbank siltstones and mudstones deposited away from fluvial fairways - floodplain lakes common throughout the study area.

17. PC20 to PC10 (Toolachee Fm.) HST interval; characterised by meandering fluvial channels within broad channel belts to the north and in the east of the study area, sedimentation is mostly crevasse splay (proximal/medial/distal), with the development of thin coals and preservation of floodplain siltstones.
and floodplain lake mudstones. Palaeo-flow direction from north to south is speculative.

The key intervals with good connectivity that could be targeted for future drilling include the sand-prone VC40–Vu38, Vu38–VC35, VC35–VC30, Daralingie Unconformity–PC60 and PC50–PC40.

The VC20–VC00 interval contains a narrow channel belt with isolated fluvial channels within it that can be seen on the 3D seismic amplitude maps. The target of drilling in this interval should lie within the channel belt. The closer to the fringe of the channel belt the greater the likelihood of non-reservoir section being encountered.

The thin, but extensive amalgamated deltaic mouthbar sands of the VC30–VC20 (Patchawarra Fm.) and Tu95–TC80, TC80–TC50, TC50–Daralingie Unconformity (Epsilon Fm.) progradational cycles are potentially significant reservoir intervals due to the likely lateral extent of the sandstones.

A follow-up study should be undertaken post-drilling to check the reliability of this methodology and to ensure that major differences encountered in the future wells get rationalized within the chronostratigraphic framework.

It is recommended that future wells within the study area have detailed FMI/FMS analysis to constrain palaeo-flow direction (especially for the Toolachee Fm. intervals), and that reservoir quality studies be conducted, with the results linked to the facies and the systems tracts.
Chapter 9  Implications for petroleum development

Constructing an internally and regionally consistent sequence stratigraphic framework for a fluvial-lacustrine succession allows for the prediction of three-dimensional reservoir architecture from one-dimensional data. With the addition of seismic amplitude maps to constrain fluvial fairways, modeling sub-surface fluvial sand distribution at various levels becomes an issue of interpretation rather than direct analogue application.

An appreciation of fluvial-lacustrine reservoir architecture allows for more efficient planning of drilling programs, and greatly improves the construction of detailed reservoir models. This enables more successful secondary and tertiary recovery methods. Figure 24 compares the pre-study litho-stratigraphic well correlation of the Baryulah area (Santos Ltd. QNTBU - Fig. 24a), with the post-study chronostratigraphic well correlation (Fig. 24b). The most notable difference is the interpreted lateral connectivity of sandstone bodies. Figure 24b provides a realistic model of reservoir connectivity; wells located in the same channel belt at the same time interval are likely to be laterally connected through fluvial channel sandstones.

9.1  Santos Ltd. news release 18th September 2001

Key deliverables for this study were provided to Santos Ltd. QNTBU on the 10th of December 2000. The news release included as Appendix-1, detailing the discovery of gas in well Wellington-1 within the Baryulah area, was issued on the 18th of September 2001.
FIGURE 24

(a) ABOVE - Initial lithostratigraphic correlation (Santos Ltd. QNTBU) based on coal marker horizons - makes a sand correlation.

(b) BELOW - Revised correlation based on flooding surfaces and key sequence stratigraphic surfaces - builds a geologically meaningful chronostratigraphic framework.
APPENDICES

Appendix 1 Santos Ltd. News Release 18th September 2001

New Cooper Basin Exploration Play Discovery: Wellington-I.
New Cooper Basin Exploration Play Discovery: Wellington 1

Santos Ltd, as Operator for the South West Queensland Unit, announces the success of a new gas play in the Queensland sector of the Cooper/Eromanga Basins.

The Wellington 1 gas exploration well in Southwest Queensland has been cased and suspended as a Toolachee Formation gas producer.

Santos’ Managing Director Mr John Ellice-Flint said “The well successfully proved the existence of a stratigraphic trap in the Baryulah/Juno region 35 kilometres due south of the Ballera gas plant.

We intend to quickly complete connection of the well to the Baryulah trunkline before the end of November and follow-up appraisal activity is planned to assess the extent of the hydrocarbon accumulation.

This discovery fits well with Santos’ strategy of extracting additional value from its Cooper Basin assets.”

During an initial two-hour production test the Wellington 1 well flowed gas to surface at a calculated rate of 257,700 cubic metres per day (9.1 Million cubic feet per day) through a 12.5 millimetre (1/2 inch) choke.

The interests of the Producers in the South West Queensland Unit are:

- Santos Group: 60.0625% (Operator)
- Delhi Petroleum: 23.2000%
- Origin Energy: 16.5000%
- Oil Company of Australia: 0.2375%
Wellington I Discovery

Santos acreage
- Oil pipeline
- Gas pipeline
- Proposed Gas pipeline
- Oil Field
- Gas Field

Wellington I

Winninia North
Winninia

Press Release

Santos Ltd A.B.N. 80 007 550 923 17 September 2001 File No. CORINV P158
Appendix 2


NOTE:

This publication is included in the print copy of the thesis held in the University of Adelaide Library.
Appendix 3

KAPPA-1: Queensland Patchawarra Formation Type Section.
KAPPA 1, Queensland Patchawarra Formation Type Section (Santos Ltd., QNTBU)
References


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