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A live test of automated facies prediction at wells for CO_2 storage projects

Mark Bunch[a,]*

[a]Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), Australian School of Petroleum, University of Adelaide, Adelaide, South Australia, Australia

Abstract

At least 900 m of image log data have been interpreted in detail through the Late Cretaceous and Cenozoic succession intersected at two purpose-drilled injection wells of the CO2CRC Otway Project. Interpretations have been calibrated against core observations where possible. Natural clusters for the combined signature of a common suite of coincident well log data were determined using an unsupervised Naïve Bayesian classification algorithm called Autoclass. A deterministic relationship between these modelled clusters and interpreted image log facies provides a two-step facies prediction algorithm that can be applied using well log data acquired at other wells intersecting sedimentary successions prospective for CO_2 storage.

Earlier this year the Division of Resources & Energy, Department of Trade & Investment, of the Australian state of New South Wales drilled a new stratigraphic test well within the Pondie Range Trough of the Darling Basin. The new well, Mena Murtee-1, was drilled close to a 2D seismic tie line linking the Pondie Range Trough depocenter with an old petroleum exploration well, Pondie Range-1, that is sited on a flanking high. Analyses and interpretation of data acquired at Mena Murtee-1 is the latest step in reducing the uncertainty surrounding CO_2 storage potential within the Darling Basin. Interpretation of core and image log data acquired at the new well has provided a means by which to test facies predictions made on the basis of the models developed within the Otway Basin.

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Keywords: CO_2 storage; well log data; facies; Bayesian; modelling; Otway Project; Darling Basin; New South Wales, Australia

* Corresponding author. Tel.: +61-8-831-34292; fax: +61-8-831-38026.
E-mail address: mbunch@co2crc.com.au

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1. Introduction

The Darling Basin is an inactive frontier basin that underlies parts of the modern-day Murray River Basin in western New South Wales (NSW), south-eastern Australia. The basin comprises mostly Devonian sediments, small sections of which may have potential for storing supercritical CO_2. The majority of the succession has been interpreted as terrestrial (fluvial) with some marine influence scattered throughout and becoming more persistent from the north-east in the uppermost part [1,2]. In general the age and depositional characteristics of this succession differ from the majority of other more recent successions interpreted to have CO_2 storage potential in south-eastern Australia [3]. In particular, the Late Cretaceous succession tested by CO_2 injection and storage operations of the CO2CRC Otway Project (Otway Basin of western Victoria) is exclusively marine in origin. To date, two sections of this sequence remain the only reservoir systems utilized to demonstrate CO_2 storage at field scale in Australia [4,5,6].

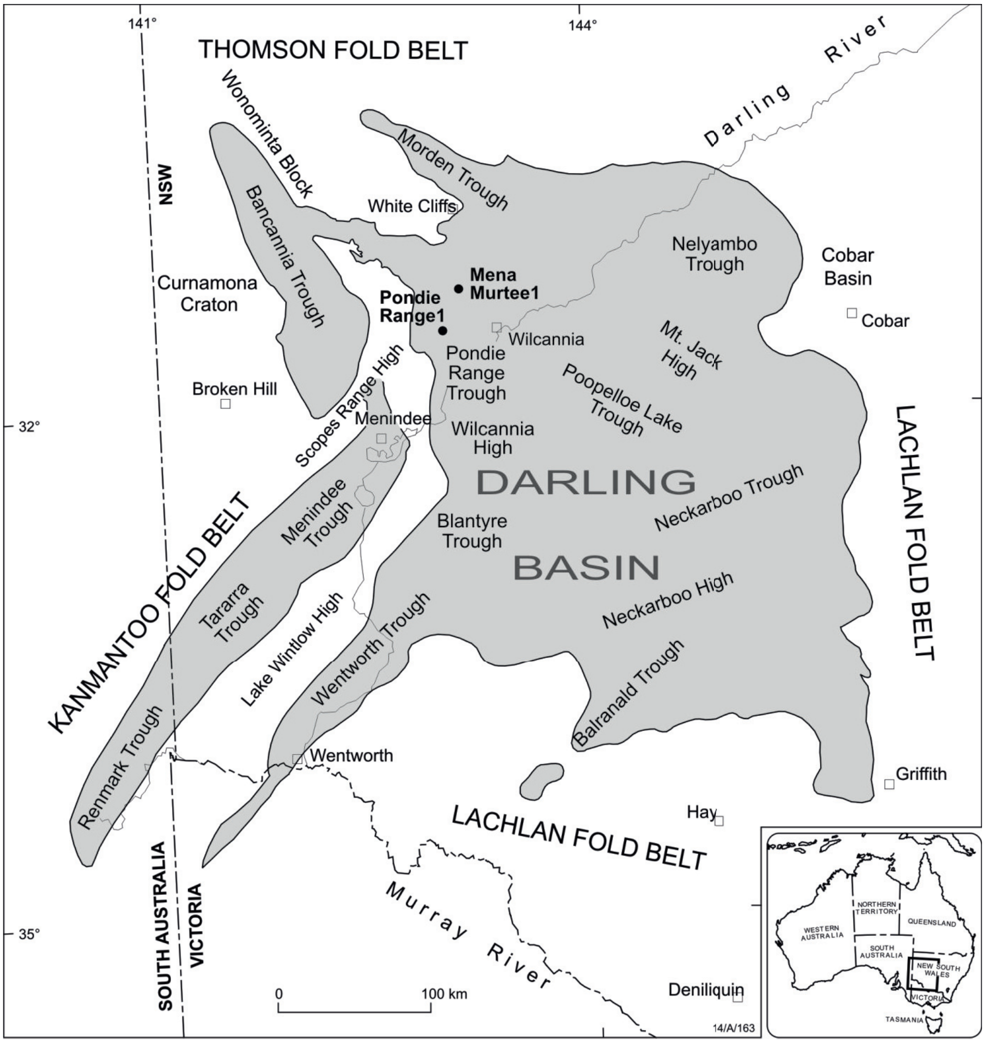

Figure 1: A map of the Darling Basin in western New South Wales, south-eastern Australia (after [1]). Labels indicate local depocentres and intervening basement highs (see [7,8,9]). Two wells within the Pondie Range Trough (north-western sector) are the focus for this paper.

Sedimentary rocks that define the CO_2 storage system encountered at Otway Project injection wells are classified according to a suite of characteristics. Classification schemes may describe their sedimentary characteristics, their depositional origin or their CO_2 storage system performance. For the purposes of this paper, these collections of defining characteristics are termed facies and are used to guide upscaling and attribution of petrophysical properties of the fluid (CO_2, water) flow medium [10]. Facies models calibrated for the Otway Project are not necessarily suitable for predicting facies within the Darling Basin given the differences in general depositional setting between the sedimentary successions and differing post-depositional basin changes. However, collapsing the set of ten observed facies classes adopted for Otway Project modelling into geologically coherent groupings has produced a set of models that predicts a smaller number of classes covering more general rock types. Adopting this approach has enabled Otway-calibrated models to predict general CO_2 storage system facies using well log data acquired at the Pondie Range-1 well within the Darling Basin.

Earlier this year the Division of Resources & Energy (DRE), NSW Department of Trade & Investment, drilled a new stratigraphic test well – Mena Murtee-1 – within the Pondie Range Trough to begin the process of reducing the uncertainty surrounding CO_2 storage potential within the Darling Basin. This well indicates the possibility of prospective reservoir intervals within an appropriate range of depth but at this stage, further exploration is required before suitable sites for CO_2 storage within the Darling Basin can be identified and characterized. Datasets generated as a result of drilling Mena Murtee-1 have, however, provided two important opportunities for CO_2 storage system facies prediction. The first was a direct test of facies predictions made by the generalised models calibrated using Otway Project well data. Facies logs generated at Pondie Range-1 and Mena Murtee-1 were compared for the stratigraphic section with possible CO_2 storage potential (i.e. reservoir potential) identified at the latter. This section was correlated manually to Pondie Range-1 using the general trend of coherent reflection events apparent on the seismic tie line and key stratigraphic boundaries expressed as significant excursions on a number of well logs.

The second opportunity is to be the focus for future work. Stratigraphy within the Darling Basin inevitably features rock types that were not observed or interpreted as part of the original Otway Project facies classification scheme. Future interpretation of image log data acquired at Mena Murtee-1 will provide supplementary type data for which associated well log responses will provide an additional set of facies classes to augment the existing model dataset. A newly expanded model will be better able to predict facies using well log data acquired from both marginal marine and terrestrial sedimentary successions. These general depositional settings together represent the majority of siliciclastic sedimentary successions with CO_2 storage potential within both onshore and offshore Australia.

2. Development of the Otway Project facies model

An objective of field experiments at the CO2CRC Otway Project is to define and demonstrate safe, reliable CO_2 storage systems under Australian geological conditions. Future commercial-scale storage activities in Australia will be widespread and will require detailed storage system characterisation at greater spatial scales. Datasets acquired at Otway Project wells (CRC-1 and CRC-2) represent the most comprehensive and detailed stratigraphic information anywhere in the Otway Basin. An important step is therefore to develop an approach that can relate models of CO_2 storage systems developed using detailed Otway Project well data to less comprehensive exploration well datasets acquired elsewhere in the past.

Otway Project storage systems are defined by facies related to rock types interpreted in core logs, image logs and other well logs. These facies are regarded as the end point for a general model that must be able to predict them using only basic well log data. Four basic, widely available 1D well logs – compressive sonic velocity, density, gamma and formation resistivity – were combined to generate a fifth log of clay volume using a standard model. Taken together the five logs respond to basic lithology (gamma, resistivity and clay volume) and key petrophysical properties, i.e. porosity and permeability (density, sonic velocity and resistivity). Natural data clusters for coincident responses at each logging point were discovered probabilistically by a Naïve Bayesian classification algorithm called Autoclass [11,12,13]. Two assumptions were made:

- There is a relationship between rock types and coincident well log responses;

- Natural data clusters of combined well log response are related to particular rock types.

It therefore follows that natural data clusters of combined well log response should be diagnostic of particular rock types, i.e. of facies interpreted from core, image and other well logs. Thus, an automatic algorithm designating appropriate natural data clusters also predicts stratigraphic facies that are otherwise inherently difficult to perceive and interpret reliably using multiple well log data streams [12].

Natural data clusters are transformed into one of the 10 facies of depositional environment interpreted manually from image log data (termed here "image facies") using a matrix populated by the frequency of occurrence of each image facies for each data cluster. The number of natural data clusters determined by Autoclass for the Otway Project wells dataset is 132, which is far greater than the number of image facies classes identified manually (10). Figure 2 gives an example of an earlier model featuring nine-dimensional data space (nine well logs) that produced 197 natural data clusters for CRC-2 alone. Predictive accuracy was high but the number of well logs required would have constrained use of the model to just a few of the most recent wells within the basin.

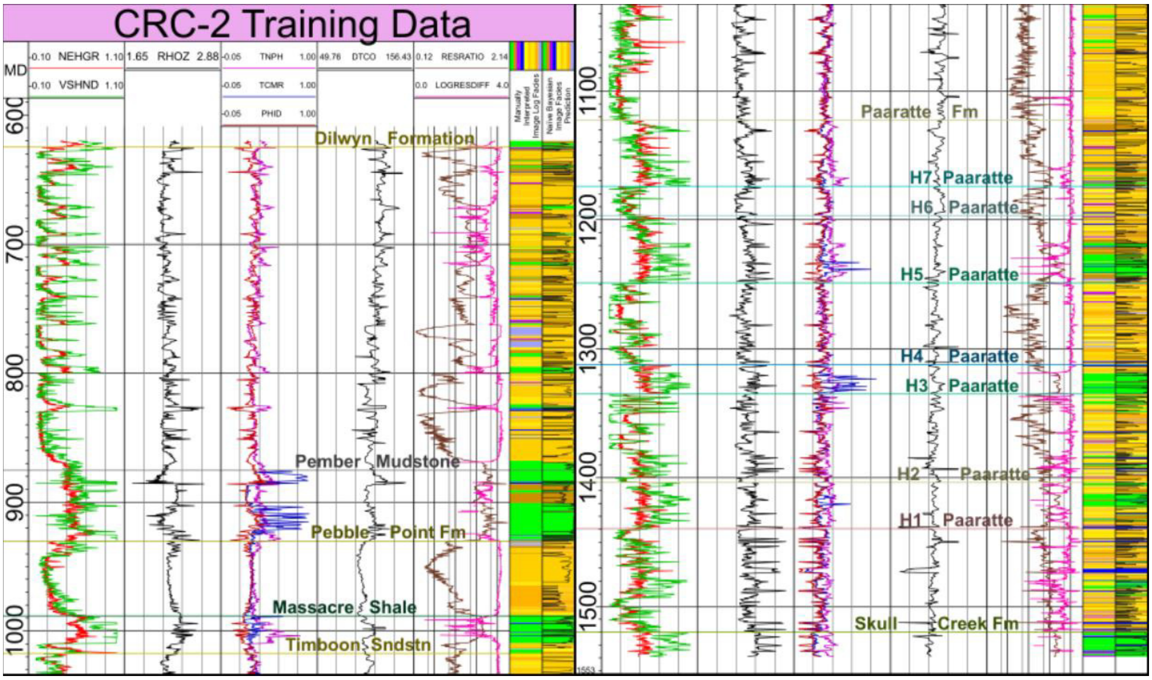

Figure 2: Image log training data for a previous version of the facies prediction model. Tracks 1-5 show well log data used to train facies classification models. Track 6 is a nine-class discrete log of facies manually interpreted from image logs and calibrated by results of core analysis. Track 7 shows image log facies predicted by a supervised Naïve Bayesian classifier overlain by a continuous log of class member probability. Formation tops are labelled for stratigraphic context [14,15].

Deploying this system at many wells across the region of the Otway Project has reduced uncertainty in attempting to map the distribution and geometry of facies geobodies that form the discrete reservoir and non-reservoir components of the stratigraphic CO_2 storage system. This possibility is already implied by our current ability to correlate reservoir and non-reservoir units over several kilometres between these wells (e.g. [16]).

3. Refinement for wells away from the Otway Project

A key advantage of the Bayesian approach is that all data points are assigned a finite probability of existing in all identified data clusters [11,12]. It therefore differs from the majority of classification algorithms that seek to discretise multidimensional data space using definite data separation hyperplanes. A practical outcome is that Bayesian classification models are not too tightly fitted (‘over-fitted’) to their conditioning dataset, meaning they are flexible to be applied to other data settings, for example, log datasets from a different well. This was a key objective given that the Otway Project remains unique for CO_2 storage activity within Australia and being the national test case must produce outcomes that can be made more general.

In testing the Bayesian facies model and more general variants at Otway Project wells it was recognised that the fewer the number of manually assigned facies classes, the more accurate the Bayesian-matrix facies prediction modelling became. In particular, a tripartite system produced high predictive accuracy with some range or flexibility in the rock associations represented by the three facies classes. Two geologically coherent ways of generalising the original 10 Otway Project image facies classes into sets of three are by general depositional environment and by reservoir/seal characteristics. These two systems can be combined to form a three-by-three matrix (Figure 3) that can discriminate six facies classes of the original 10, two sets of two original classes and an additional ”Indeterminate” class assigned to all data points most likely to represent a Terrestrial Environment and a Seal – this combination was not observed at Otway Project wells. The two paired sets are separated by applying probabilities again. The facies class selected is a random variate generated from the discrete frequency distribution for the corresponding couplet of Environment and Reservoir/Seal classes derived from image facies manually interpreted at Otway Project wells.

Facies Discrimination Matrix

Environment	Reservoir or Seal		
	Reservoir	Mixture	Seal
Terrestrial	Fluvial Channel	Abandonment	Indeterminate
Estuarine	Est Channel Sand Estuarine Sand	Estuarine Heterolithics	Tidal Flat
Deltaic	Distributary Channel Proximal Mouthbar	Distal Mouthbar	Delta Front

Figure 3: Classification matrix expressing the ten manually interpreted image facies in terms of their Environment of deposition (Terrestrial, Estuarine or Deltaic) and their CO_2 storage system function (Reservoir, Seal or a Mixture).

A key feature of this matrix classification system is that prediction errors (inaccuracies) can be considered as being either critical or non-critical. Critical errors from a CO_2 storage point-of-view predict a Reservoir instead of a Seal or vice versa. Non-critical errors mistake the Environment of a Reservoir/Seal type or mistake a Mixture Reservoir/Seal type for a Reservoir or a Seal, or vice versa. Model upscaling eliminates the influence of local outliers [10] but regardless, applying these criteria shows the model to produce less than 10% critical errors for data from Otway Project wells.

4. Application to Darling Basin wells

Prior to the drilling of Mena Murtee-1, well log data acquired at Pondie Range-1 was quality checked and normalised (de-trended using a linear function of depth and transformed to produce a mean of zero) ready for the process of natural cluster prediction. The natural well log cluster model conditioned on CRC-1 and CRC-2 data was applied to predict the likeliest Otway natural cluster for each Pondie Range-1 well logging data point. The deterministic frequency transform developed for CRC-1 and CRC-2 was then used to predict the likeliest of the ten original image log facies classes from the attributed natural data cluster. The two three-class transforms corresponding to the matrix classification system were also applied and their predictions used to back-determine the original image log facies class via the matrix (Figure 3). Thus, directly and indirectly predicted 10-class image facies logs were produced. Predictions of the latter (the "Matrix Facies" log) were preferred to those of the former (the "Image Facies" log) when discrepancies arose between them because the two three-class transforms generating Environment and Reservoir/Seal facies were more accurate when tested against manual interpretations at CRC-1 and CRC-2. Direct method predictions (the direct approach first described) were adopted in cases where a recognised facies had been predicted and the matrix method predicted the Indeterminate facies class. A composite image facies log – "Combined" – was thereby produced to represent the maximum likelihood image facies prediction for Pondie Range-1.

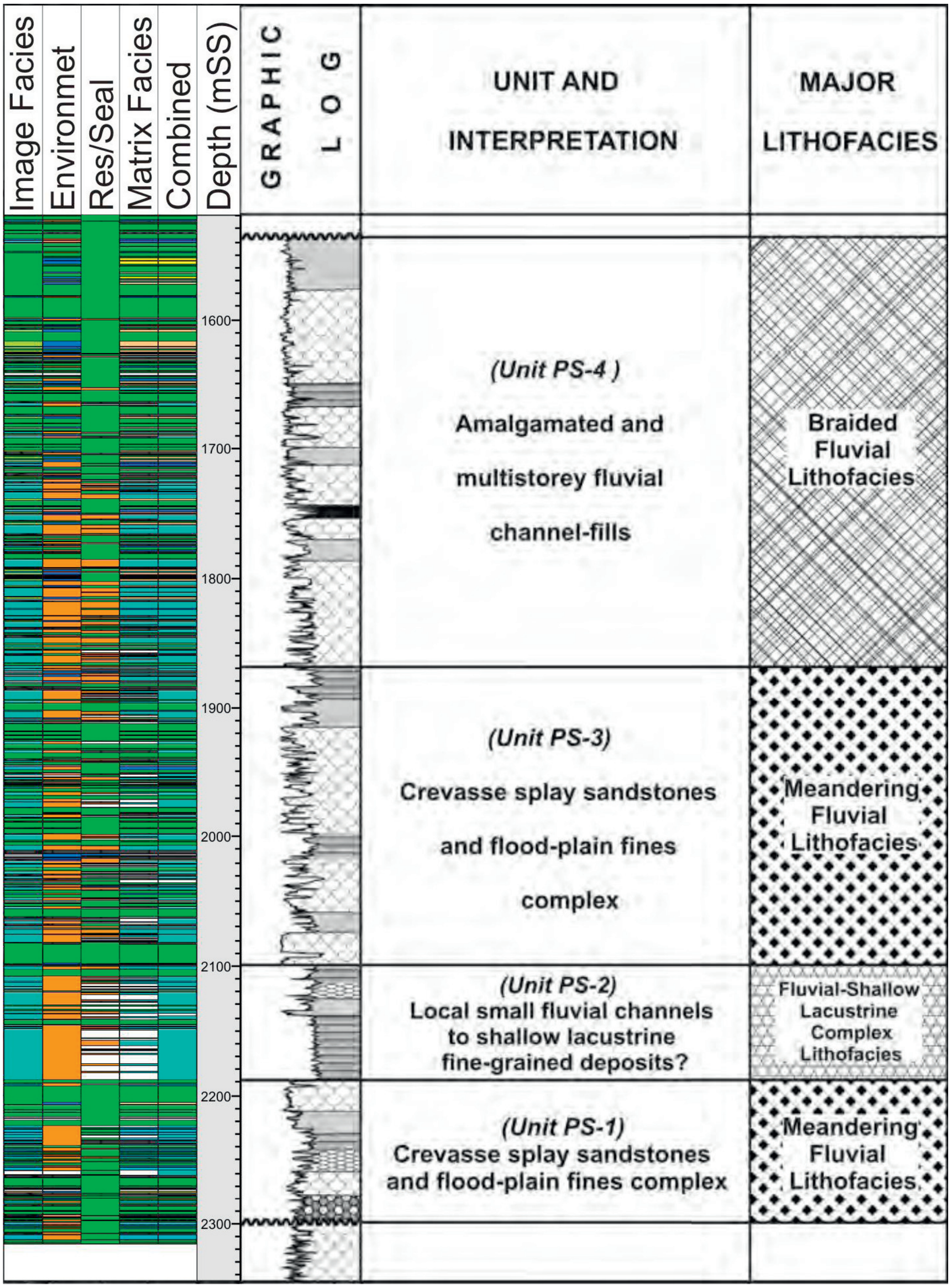

Figure 4: Predicted discrete facies logs (left) plotted alongside lithofacies interpretations of [2] for sub-units of the Snake Cave Interval of the Mulga Downs Group intersected at Pondie Range-1. See Figure 3 for facies log colour schemes. The Graphic Log is bound by a gamma ray log curve (data range is -27.5 to 97.5 GAPI units from left to right). Depth is in metres sub-sea.

Figures 4 and 5 show all five facies logs plotted alongside lower (Snake Cave Interval) and upper (Ravendale Interval) members of the Devonian Mulga Downs Group interpreted at Pondie Range-1 by [2]. A few key features of correspondence are immediately obvious. The general suite of Combined facies appears to transition sharply at three of the seven encapsulated unit boundaries (PS-1=>PS-2; PR-1=>PR-2; PR-3=>PR-4). In addition a pseudo-sequence break in Combined facies coincides with unit boundary PS-2=>PS-3. Where there is no major step in gamma ray log response at a unit boundary, there is no apparent transition in Combined facies (PS-3=>PS-4; PS-4=>PR-1; PR-2=>PR-3). A general observation of note is to recognise the strong predominance of Fluvial Channel image facies predicted at Pondie Range-1 – a well penetrating terrestrial stratigraphy – by a model conditioned on data from stratigraphic sections predominated by shallow marine sediments. This is a clear indication that the model was not over-fitted to observations at CRC-1 and CRC-2.

A more detailed comparison with the major lithofacies and facies units of [2] reveals some correspondence and some mismatch. The Early Devonian Snake Cave Interval represents a coarsening upward terrestrial succession of fluvial channel sandstones and heterolithic channel abandonment facies. Unit PS-1 represents crevasse splay sandstones and flood-plain fines complexes of a meandering fluvial channel system. The sediment log shows fining up from a basal conglomerate through sandstone to shaly siltstone, before recoarsening to sandstone at the top. Given this interpretation, the Abandonment image facies (a Terrestrial Mixture) would be expected to predominate. Predicted image facies, however, are predominantly Fluvial Channel with minor estuarine facies (Sand, Heterolithics and Tidal Flat) and only occasional Terrestrial Abandonment. In particular, the appearance of marine-influenced facies is out of step with the general geological interpretation for the Snake Cave Interval (though brakish-marine influence is noted by [1]) and may represent a best fit made by the model in the absence of appropriate facies classes interpreted at Otway Project wells. In any case, the expectation would be for Mixture Reservoir/Seal facies so classification errors here would be considered non-critical.

Unit PS-2 is interpreted to represent small fluvial channels and fine-grained sediments of a shallow lacustrine environment [2]. The images facies prediction model does not feature a lacustrine Environment class as no such sediments were observed in image logs at CRC-1 or CRC-2 [17]. Instead predicted image facies are predominated by Estuarine Heterolithics with minor Fluvial Channel coinciding with coarser shale intervals. From this outcome it seems that the model may default to substituting Estuarine facies for lacustrine intervals, which may be regarded a sensible approximation in terms of the general style of sedimentation and the appearance of deposits these two environments produce. In terms of the geometry of storage system components (geobodies) that lacustrine and estuarine environments would produce, these could both be geographically extensive with low geographic aspect ratio (e.g. [18]). Sedimentary structures would be simple (horizontal lamination) and would not be diagnostic of a longitudinal axis of orientation, if at all present. The impact of this misclassification on static storage system modelling would therefore be limited.

Unit PS-3 is interpreted to represent a thicker repeating sequence as seen for PS-1 less the basal conglomerate [2]. The predicted image facies are again split between Fluvial Channels, which predominate the coarser sections indicated by the gamma ray log, and Estuarine Heterolithics, which predominate the finer sections. It now becomes possible to broaden the applicability of the Estuarine facies to fine-grained sections representing shallow angle/horizontally laminated sediments.

Unit PS-4 is described as multi-storey channel fills of a braided fluvial system [2]. The unit coarsens upwards and predominantly consists of sandstone with some siltstones and minor shale. The image facies prediction suggests a bottom half dominated by Estuarine deposits and a top half dominated by Fluvial Channel sandstone. There are sporadic appearances of shallow marine lower delta plain (Deltaic) deposits (e.g. [19,20]), more so in the upper half.

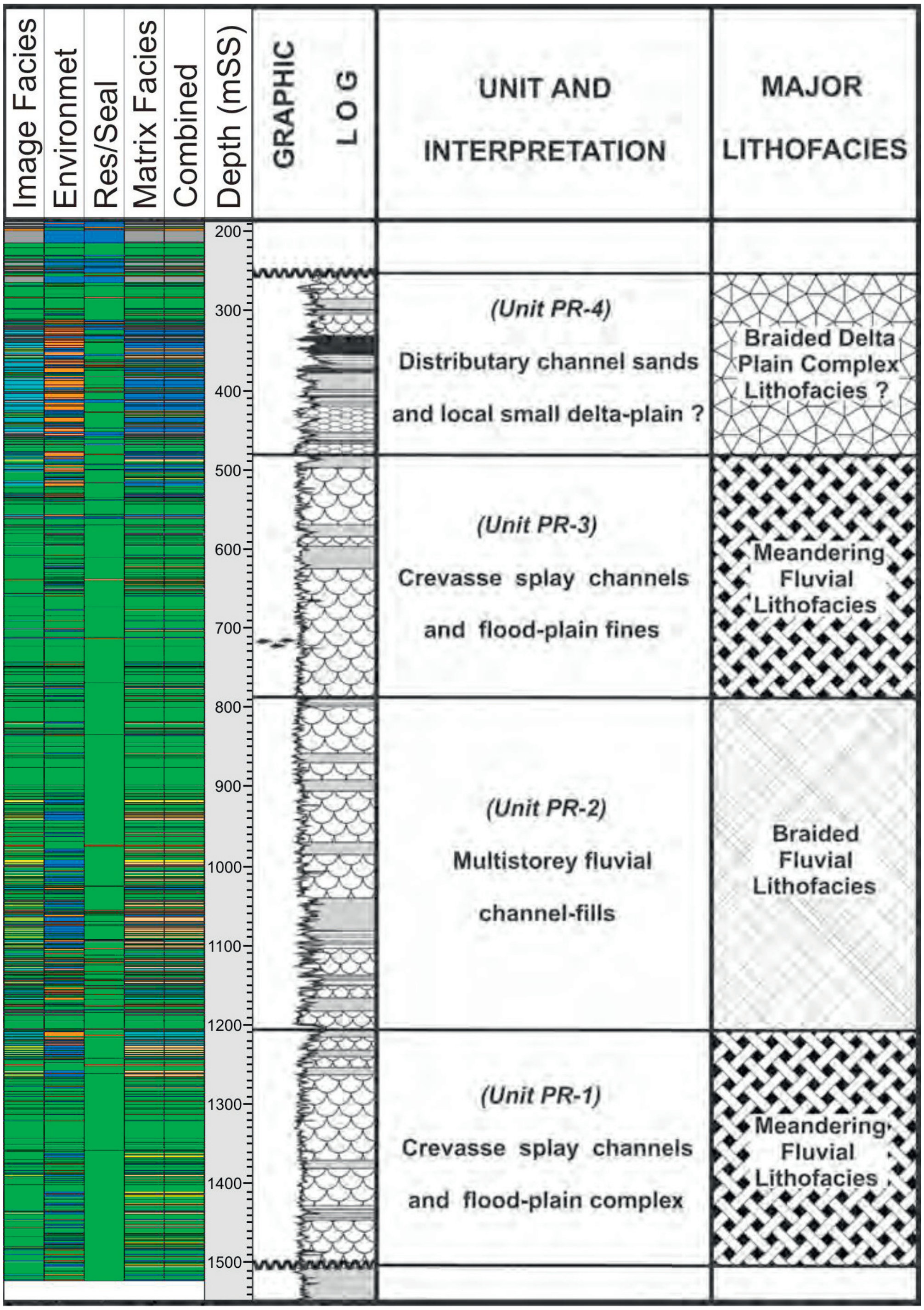

Figure 5: Predicted discrete facies logs (left) plotted alongside lithofacies interpretations of [2] for sub-units of the Ravendale Interval of the Mulga Downs Group intersected at Pondie Range-1. See Figure 3 for facies log colour schemes. The Graphic Log is bound by a gamma ray log curve (data range is -22.5 to 102.5 GAPI units from left to right). Depth is in metres sub-sea.

The Late Devonian Ravendale Interval unconformably overlies the Snake Cave Interval and represents a relatively coarse fluvial succession with some semi-persistent shallow marine sediment observed across large areas [1]. The system is characterised by relatively reduced accommodation and perhaps also reduced sediment supply. Unit PR-1 is dominantly crevasse splay channel sands of a fining upward meandering fluvial system. Some flood-plain shales are present. The predicted image facies are almost entirely of Fluvial Channel sandstone. Shaly intervals are registered as marine-influenced Reservoir facies.

Unit PR-2 sees a return to braided fluvial sandstones. The unit coarsens upward and comprises sandstones and siltstones with some minor shale. The majority of predicted image facies is again Fluvial Channel sandstones. A thick siltstone is erroneously attributed shallow marine Reservoir facies. Other sporadic occurrences of marine facies are predicted in the lower two thirds of the unit.

Unit PR-3 comprises crevasse splay sandstones and some channel abandonment siltstones signifying a return of the meandering fluvial system. The predicted image facies log does not recognise the PR-2 to PR-3 unit boundary with a continuation of the dominantly Fluvial Channel sandstone facies for the lower four fifths of Unit PR-3. The upper fifth of the unit is predicted to comprise mostly Estuarine and some shallow marine Deltaic sandstones that continue, after a pseudo-sequence break at the upper boundary, into the unit above.

Unit PR-4 is interpreted as the first genuine appearance of marine-influenced sediments [2]. The unit is a coarsening upward sequence of silty shales, shaly siltstones and sandstones of a braided lower delta plain complex (i.e. [19]). Likewise, predicted image facies are dominantly Estuarine (confined mid-lower delta plain; [20]). There are some genuine Deltaic facies predicted in the form of isolated Delta Front muds but the sequence break these imply with Estuarine Sandstones and Tidal Flat mudstones must be spurious (a 'non-critical error').

Frequency analysis of predicted indices of the facies discrimination matrix (Figure 3) is shown in Figure 6. This gives a clearer indication of the modal response of the image facies prediction model. Generally it can be seen that Terrestrial facies and Reservoir facies co-dominate throughout the succession at Pondie Range-1. Clear exceptions occur: (a) Unit PS-2 registers as being distinctly Estuarine (so perhaps lacustrine) with largely Indeterminate Reservoir/Seal. Where classified, the dominant Reservoir/Seal type is a Mixture; (b) the base of Unit PS-4 registers as Estuarine (so perhaps lacustrine) and a combination of Reservoir and Mixture; (c) a point one third of the thickness from the base of the Unit PR-2 registers as Marine (and Reservoir); (d) the majority of Unit PR-4 is a combination of Estuarine and Deltaic facies (so perhaps genuinely estuarine at this stage) with the first persistent appearance of genuine Seal facies. Deltaic Seal facies continue ~100 m into the overlying stratigraphy before a return to Terrestrial Reservoir. Other general statements are that Reservoir/Seal Mixture is confined to units PS-2 to PS-4, Seal facies are confined to Unit PR-4, Estuarine facies (likely representing both lacustrine and estuarine sediments) are most prominent in units PS-2 to PS-4 and Unit PR-4, while Deltaic facies are most prominent in units PR-2 and PR-4.

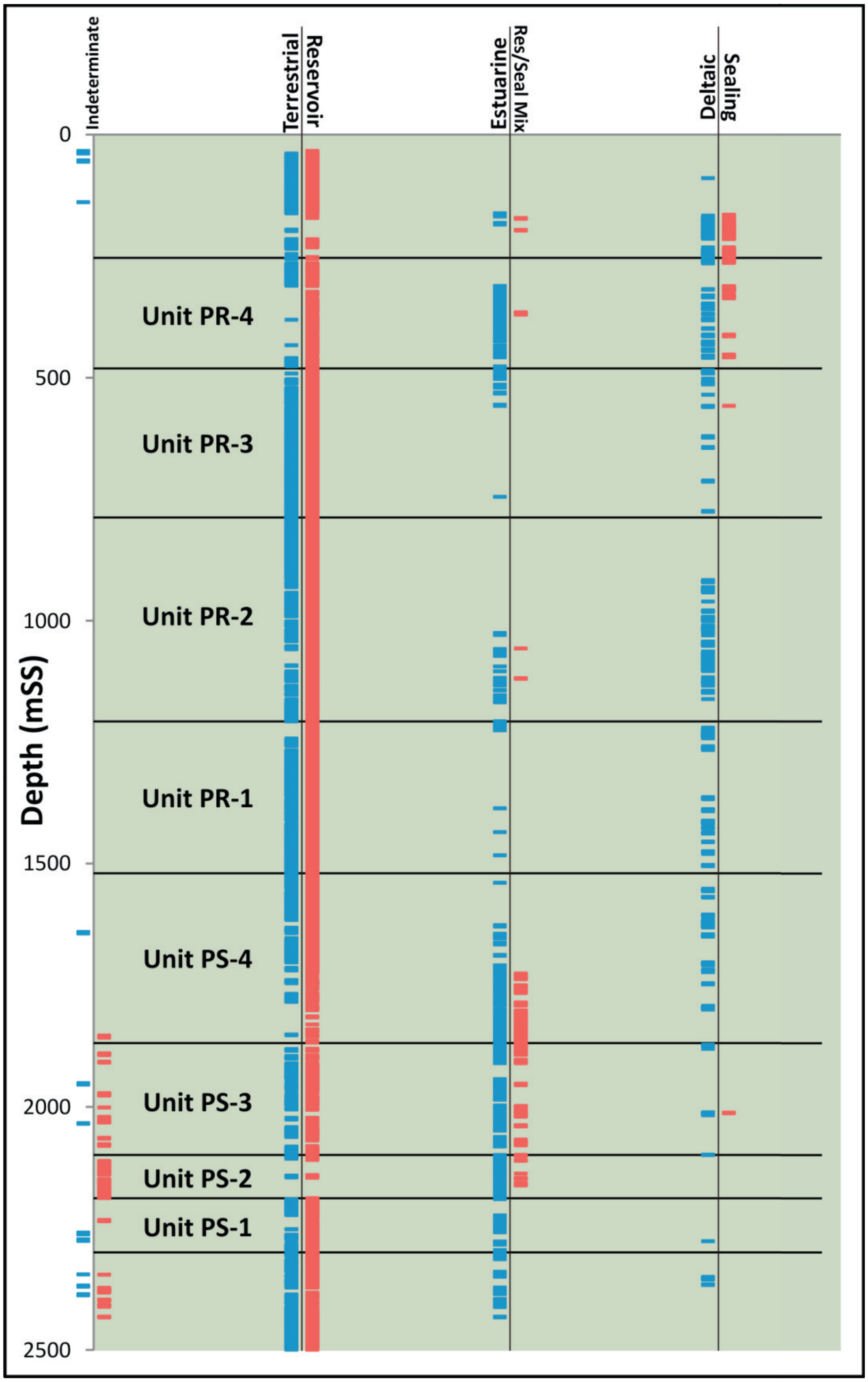

Figure 6: Prevailing facies predicted at Pondie Range-1 for each of the generalised tripartite systems that constitute indices of the image facies discrimination matrix (Figure 3). Unit boundaries are those published by [2]. Depth is in metres sub-sea.

5. Stratigraphy encountered at Mena Murtee-1

Mena Murtee-1 was drilled close to a 2D seismic reflection profile line that also passes close to the location of Pondie Range-1. Tracking of reflection events between the projected locations of Pondie Range-1 and Mena Murtee-1 shows that ~1150 m of overburden stratigraphy was intersected by the new well that is absent at Pondie Range-1. The mud log indicates that this consists exclusively of shaly formations. Preliminary well log analysis revealed prospective reservoir intervals centred at ~1300 mSS TVD (~30 m thick), ~1385 mSS (~10 m thick), ~1425 mSS (~10 m thick) and ~1490 mSS (~90 m thick). These were correlated using the seismic reflection event tracking with well log signatures to a Pondie Range-1 depth range of 130-310 mSS (Figure 7).

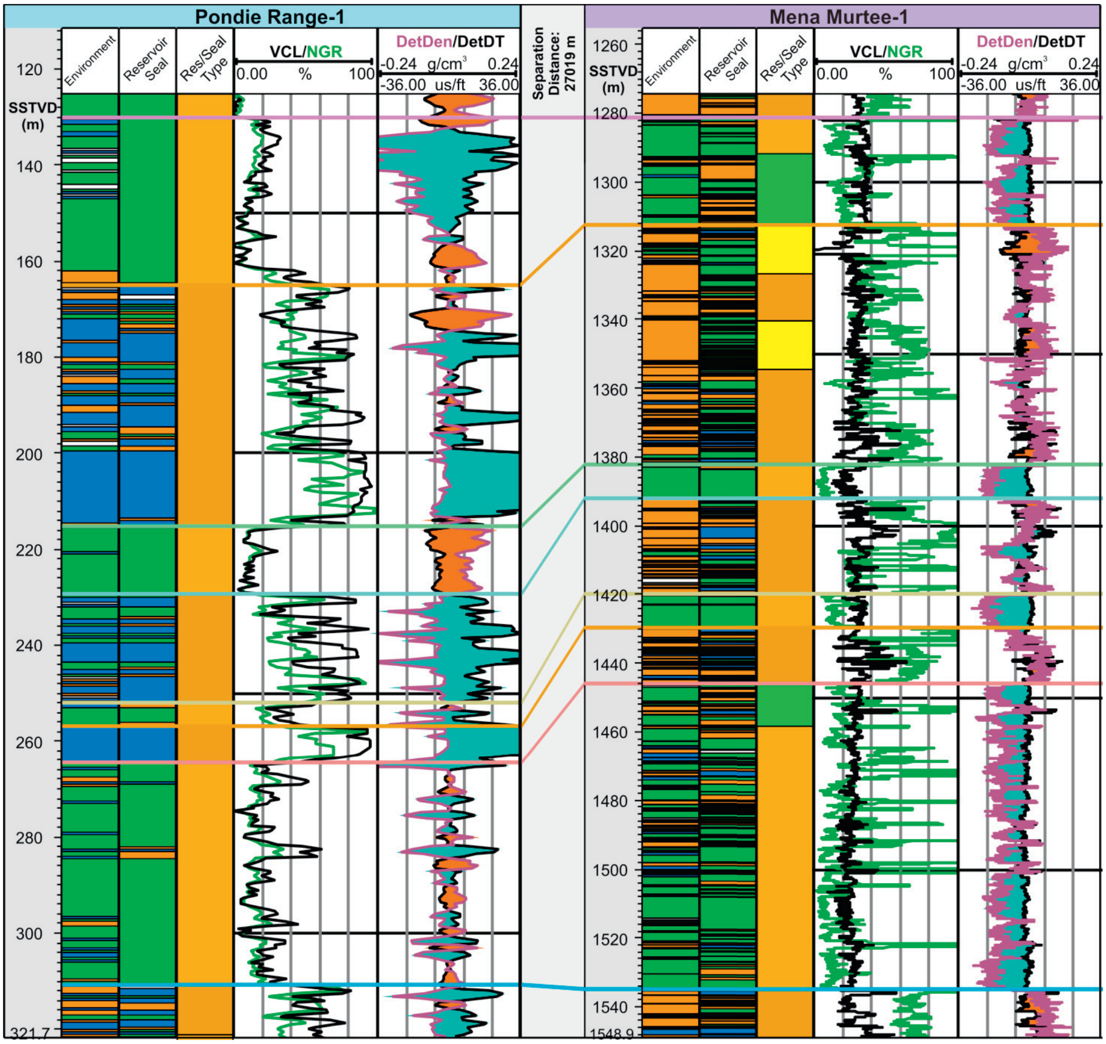

Figure 7: Correlation between Pondie Range-1 and Mena Murtee-1 for the most prospective reservoir intervals intersected at the latter. Tracks 1-3 are predicted facies logs, the last of which shows a new geometric Reservoir/Seal Type (see below and Figure 8). Track 4 shows clay volume (VCL) and the normalized gamma ray log (NGR). Track 5 shows separation between the de-trended and transformed density log (DetDen) and the de-trended and transformed sonic log (DetDT).

Correlation between Pondie Range-1 and Mena Murtee-1 was not possible on the basis of the Environment facies log alone (Figure 7). Consideration of Reservoir/Seal facies revealed a more obvious correlation but did not represent a classification scheme that offered particular advantages over manual interpretation of well log data. The most significant contribution a facies classification could make towards static modelling would be to imply likely 3D geometries of connected storage volumes associated with facies at wells. Thus the image facies discrimination matrix (Figure 3) was simplified in terms of a geometric reservoir/seal classification system (Figure 8). Five Reservoir/Seal Type classes were defined to guide their characterisation by geostatistical models. Tabular bodies – either Reservoir or Seal – were regarded as having a geographic aspect ratio of one with no preferred longitudinal orientation. Axial bodies were geographically long and narrow with a preferred orientation (azimuth) parallel to the sediment dispersal direction as interpreted from image log data and corrected for structural tilt.

Storage System Component Matrix

Environment	Reservoir or Seal		
	Reservoir	Mixture	Seal
Terrestrial	Axial Reservoir	Axial Seal	Indeterminate
Lacustrine/ Estuarine	Axial Reservoir Tabular Reservoir	Tabular Seal	Tabular Seal
Deltaic	Axial Reservoir Tabular Reservoir	Tabular Seal	Tabular Seal

Figure 8: The image facies discrimination matrix (Figure 3) simplified to produce just four genuine geometric Reservoir/Seal Type facies for the purposes of static modelling.

6. Summary

The image facies prediction model conditioned using well log data acquired at Otway Project wells has proven somewhat transferable to a much older, sedimentologically different succession within the Pondie Range Trough of the Darling Basin, NSW. The major shortcoming is an over-prediction of Estuarine facies, which are thought in this case to correspond to lacustrine sediments. Image log data acquired within the Pondie Range Trough at a new well, Mena Murtee-1, provides an opportunity for the original set of images facies to be supplemented with new types, particularly lacustrine facies. A Reservoir/Seal Type facies system adjusts the current image facies log prediction to suit its ultimate use, that is, to guide the population of reservoir properties – principally porosity and permeability – into virtual 3D space. In doing so, it remedies the spurious (for the most part) attribution of the Estuarine environment facies by replacing them with a general geometric facies type that can represent both lacustrine and estuarine geobodies within static reservoir models. The current approach therefore seems competent to predict rock types with particular CO_2 storage performance properties for stratigraphy within untested sedimentary basins. Its application has the potential to enhance previous studies that screened prospective CO_2 storage sites in Australia (e.g. [3]) and beyond whilst providing important guidance to optimise the acquisition of costly new high quality CO_2 storage exploration datasets.

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