Quantified Detection of Carbonate Cementation in Sandstones using Standard Wireline Log Data

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SUMMARY

Carbonate cemented zones were identified within the lower Paaratte Formation of the eastern Otway Basin, Victoria, in southeastern Australia. A wireline log model trained on these zones can predict carbonate cementation within Late Cretaceous to Paleocene reservoir sandstones of the Latrobe Group, Gippsland Basin, 100s of km to the east. Predictions are supported by published evidence and match cementation facies interpreted for other data acquired there. These sandstones are thought to have once been heavily cemented prior to development of secondary porosity that produced the world-class petroleum reservoirs we see today. Cemented zones that remain must act as obstructions to reservoir fluid migration. They may also react with the mild carbonic acid that would be introduced by CO_2 storage (sequestration) operations of the future. Model predictions show that cemented zones are sparse, spatially sporadic and fall well below seismic survey resolution at modern-day reservoir depths. This study emphasises the challenge in mapping their distribution but provides predictions against which to measure future mapping attempts.

Key words: siliciclastic succession; carbonate cement; wireline logging; probability; modelling.

INTRODUCTION

The Otway Basin is a divergent rift and drift continental margin basin forming an eastern part of the much larger Jurassic-Cretaceous Australian Southern Rift System (Woollands and Wong, 2001). Carbonate cemented zones were identified within the lower Paaratte Formation, a heterolithic shallow marine siliciclastic succession deposited in a deltaic palaeo-environment during the Late Cretaceous (GSV, 1995; Partridge, 2001). It is the final wholly marine unit deposited under a broad sea level regression recorded by the Sherbrook Group supersequence (GSV, 1995; Partridge, 2001). It was accommodated within a transition zone from the Inner Otway Basin (onshore) to the Morum (South Australia) and Nelson (Victoria) sub-basins of the offshore Voluta Trough, Otway Basin (GSV, 1995; Partridge, 2001).

The lower Paaratte Formation constitutes a CO_2 storage reservoir target for the Otway Basin Pilot Project (the Otway Project), a CO_2 storage demonstration site developed at the Naylor field by the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) and operated by CO2CRC Ltd (see "Otway Panel" in Figure 1). It comprises a series of demonstration-scale trials to geologically store CO_2 under Australian conditions (Sharma et al., 2011). Carbonate cemented zones intersected by a purpose-drilled CO_2 injection well - CRC-2 - might act as chemically reactive, physically obstructive baffles to the free migration of injected supercritical CO_2 (Dutton et al., 2002; Johnson et al., 2004; White et al., 2004). Their presence therefore has implications for the injectivity, sweep and monitoring of CO_2 plumes as they form, develop and migrate (Dutton et al., 2002; Johnson et al., 2004; White et al., 2004).

Carbonate cemented zones intersected at CRC-2 are thought to have developed in the same way as those described in studies of analogue shallow marine systems (Dutton et al., 2002; Taylor and Gawthorpe, 2003; White et al., 2004; Lee et al., 2007; Taylor and Machent, 2010; Taylor and Machent, 2011). The locus of their development is argued to correspond to the highest permeability pathways – the most compositionally and texturally mature sandstones within the succession – through which meteoric fluids carrying the aqueous feedstock of ionic species had flowed most readily (e.g. Davis, 1999; Dutton et al., 2002; Taylor and Gawthorpe, 2003; White et al., 2004; Lee et al., 2007; Taylor and Machent, 2010; Taylor and Machent, 2011). Another possibility is formation within intervals rich in local feedstock and nucleation points provided by detrital carbonate lag (Morad et al., 2010).

It has not been possible to confidently correlate cemented zones interpreted in FMI data between the first two purpose-drilled injection wells at the Otway Project site (CRC-1 and CRC-2; Lawrence et al., 2013). Their well heads are separated by only 173 m, giving an indication that cemented zones are limited in lateral extent. By contrast, the reservoir geobody units that host them are expected to extend much further (e.g. Wellner et al., 2005). However, it is important to understand the distribution of carbonate cemented intervals throughout a siliciclastic fluid reservoir system. Such cementation may compartmentalise reservoir units, reducing bulk permeability and making reservoir sweep a complex process (Dutton et al., 2002; White et al., 2004). Their presence would also increase reactivity of the reservoir matrix with carbonic acid that develops in formation fluid surrounding free CO_2 injected for enhanced oil recovery (EOR) or dedicated CO_2 storage (Johnson et al., 2004; White et al.,2004; Ott and Oedai, 2015; Bickle et al., 2017). Dissolution of carbonate cements would be followed by secondary cement precipitation should thermochemical conditions change downstream (Johnson et al., 2004).

This study demonstrates a model that predicts the occurrence of carbonate cemented zones within reservoir sandstones using a standard suite of wireline log data. Predictions match interpretations of a range of other data: an Elemental Capture Spectroscopy (ECS) wireline log; core and cuttings samples; formation micro-imager (FMI) wireline data; Hylogger spectral classifications of core matrix minerals. The importance of this new model is that it provides a capability to leverage more widely available legacy datasets in order to predict the presence

of carbonate cementation across all previously explored sedimentary basins. Such predictions at wells provide a test dataset against which to compare future mapping systems.

METHOD AND RESULTS

When carbonate cemented zones of sandstone were first identified in the core acquired at CRC-2, it was established that their occurrence could be predicted accurately by reference to an ECS wireline log of $\%Ca^{2+}$ by atomic weight. Cemented intervals correspond to exceedance of a threshold value of 0.03%. A set of six conventional logs was tested for independent correlation but no one alternative could provide the same predictive accuracy as the ECS Ca^{2+} log. A subset of log data restricted to those coinciding with designated cemented zones was extracted. The value range of log data acquired within the Paaratte Formation was discretised into 19 equal value-width data bins. The number of data within each bin that coincide with cemented intervals as a proportion of the overall bin total, provided a measure of the probability that a particular log value was measured within a cemented interval. These coincidence frequency bin ratios were assumed to represent a cementation probability mass function (PMF; see Figure 2). Thus a ‘probability of cementation’ log could be generated independently from each test wireline log dataset. Combining probability distributions for each of these six conventional wireline logs produced a robust means of predicting the occurrence of carbonate cemented zones using well log data acquired elsewhere at the Otway Project site and beyond.

A linear weighted average of probability logs was optimised to produce a compound probability log that best matched predictions of cementation produced by the ‘ground truth’ ECS Ca^{2+} log. A threshold probability value was required to discriminate between cemented and non-cemented data points, this being equivalent to the 0.03% Ca^{2+} by weight threshold for the ECS log. The threshold compound probability value at CRC-2 was calculated to be just under 22%, which produced an optimised accuracy of 98.4% in predicting cementation or non-cementation at log data points that match those determined from the ECS log.

Figure 3 shows visual development of the cementation probability model across a CRC-2 well panel. There are a few notable features. Firstly, the GR probability log is visually the least diagnostic log for predicting the presence of cementation (see Table 1) and its value rarely exceeds 10%. Some spikes do coincide with cementation, others do not. In general, the gamma ray (GR) probability log value rises when the GR signal is low, demonstrating the association between cementation and clean, quartz-rich sandstone, but this isn’t always the case. This is the most expendable single data stream. Sonic velocity (DT_P), neutron porosity (ϕ_N), bulk density (ρ_B) and the logarithm of true resistivity ($\log_{10}R_t$) probability logs track well together. All four are responsive to porosity though the sonic velocity probability log is the least well correlated of the four. The logarithm of the ratio of deep and shallow resistivities ($\log_{10}RR$) probability log (used to detect permeability) often tracks well with the other porosity-dependent probability logs but occasionally does not. The relatively low reliability of DT_P and $\log_{10}RR$ probability logs gives an indication that a variety of matrix coupling and porosity occlusion styles is developed through cementation.

The first test of the model was make predictions in a forward sense for the nearby predecessor well, CRC-1, and compare these with interpretations made using an FMI facies scheme calibrated by core observations at CRC-2. The distribution of compound probability log values generated for CRC-1 differs slightly from that of CRC-2. Given this, it was recognised that the threshold probability applied to determine whether each log data point represents cementation at CRC-2 might not be appropriate for CRC-1. The sum of all occurrences of a particular cementation probability value within a raw probability log must equal the number of log data points falling within the corresponding log data value bin deemed to coincide with cementation. By extension, the sum of all values in a probability log will equal the total number of cemented zone data points, which is 342 points within the Paaratte Formation at CRC-2. So the sum of probability log values calculated for another well predicts the number of log data points recorded within cemented zones intersected there. These points must be those with the highest probability values so an ordered list of probability values can determine the appropriate threshold probability value used to predicts cementation. A compound cementation probability threshold of 22.48% was thus determined for CRC-1, almost three quarters of a percentage point higher than for CRC-2. This difference is the first indication that data conditions vary between these wells whose well heads are separated by a mere 173 m in map view (Figure 1). Lithostratigraphic variation – variation in cementation – could be responsible for the difference though there could be other reasons, including variation in wireline tool performance (tool technology vintage, tool calibration or sensitivity) and logging conditions (the borehole environment). These variations would have varying impact on signals recorded by different wireline tools owing primarily to their differing geometries of investigation (Rider and Kennedy, 2011).

Figure 4 shows a similar model development panel for CRC-1 as that shown in Figure 3 for CRC-2. This well lacks the ‘ground truth’ ECS log but similar characteristic responsiveness can be seen for respective probability log tracks. The lithostratigraphic interpretation panel in Track 8 provides independent test data for evaluating the performance of the cementation predictions shown in Track 7 to its left. Cemented zones are well predicted in the more sandstone-rich lower half of the Paaratte Formation. Up to five thin cemented intervals embedded within sand-rich sediments elicit a compound (weighted) probability response greater than background but insufficient to be predicted as cemented. DT_P and ρ_B probability logs appear well correlated, as does the ϕ_N probability log. The $\log_{10}R_t$ probability log seems effective in the lower half of the succession. The $\log_{10}RR$ probability log does not seem very diagnostic, as before. An interesting new type of carbonate cemented zone is interpreted within shales of the upper Paaratte Formation from FMI data (not shown in Figure 4). Though this has not been confirmed by core observation, both DT_P and ρ_B probability logs show low-level spikes at these locations. Spikes in these two probability logs alone occur occasionally for CRC-2 data in the upper Paaratte Formation (not shown in Figure 3) but were not associated with cemented zones predicted by the ECS log. A new resistive (perhaps cemented) facies may be involved here. In general, the model makes predictions that agree well with data or interpretations that were adopted as test criteria.

The model was run using standard wireline data acquired at a number of wells in the Gippsland Basin (for the list of wells, refer to Figure 1). This basin lies further eastward along the Australian Southern Margin and therefore shares many lithostratigraphic trends with the Otway Basin in a broad sense. By contrast, a simpler stratigraphic record developed owing to the relatively shallow shelf gradient and a restricted zone of

accommodation. Of the Gippsland Basin wells modelled, those drilled more recently were the most useful as acquisition of ECS and FMI wireline data provided a more robust dataset against which to test cementation predictions. Figure 5 provides a comparison of cementation predictions with the full statically normalised FMI log record for Basker-3 and Garfish-1. An ECS Ca^{2+} log is also shown for the latter. Three important features stand out over both log records. Firstly, cementation is predicted to coincide with many, but not all, highly resistive intervals as seen at CRC-1 & CRC-2. Resistive intervals are low in conductive matrix minerals (e.g. clay minerals or metalliferous intervals) and low in (connected) porosity. The model appears able to distinguish between resistive intervals perhaps on the basis of subtle variations in density. Secondly, cementation is occasionally predicted for intervals that appear only moderately resistive/sporadically conductive (again, as seen at CRC-2). The clearest example of this is the thickest continuous interval of predicted cementation for Garfish-1 at ~2,080 m depth. This interval features discontinuous stratigraphic fabric with some relatively conductive patches. What lends weight to the cementation prediction here is its correspondence with the upper half of a zone of elevated Ca^{2+} concentration as measured by ECS log (right hand curve). More generally, the third feature at this well is that the most continuous zones of elevated Ca^{2+} concentration are also predicted to be carbonate cemented by the model. This is perhaps the strongest support for validity of cementation predictions at Garfish-1 and thereby adds credibility to predictions made for other wells where ECS log data were not acquired.

CONCLUSIONS

The linearly weighted, locally calibrated 6-log fuzzy logic cementation probability and prediction model described in this paper appears robust in predicting the presence of carbonate cementation in sandstones where such cementation was recorded or interpreted by other means. To this point, evaluation of the accuracy of these predictions is made qualitatively for other wells. Confirming them directly or quantitatively would require either exhaustive sampling and analysis of core samples, or development of some independent evidence derived from other exploration data, e.g. seismic surveys. Perhaps the best evidence presented here is that of FMI data, which can be interpreted in terms of stratigraphy. This provides independent context against which to judge how sensible the predictions of cementation are, according to what is known about the likely stratigraphic relationship to cementation development. The model performed well in predicting carbonate cementation where stratigraphic carbonate zones were interpreted from FMI data for wells drilled at the Otway Project site. Corresponding FMI facies were also identified when the model was applied in the Gippsland Basin.

Predictions of carbonate cementation at the Otway Project site demonstrate how challenging it is to correlate this feature between wells less than 200 m apart. They also show how sporadic the occurrence of cementation is in the context of the local host stratigraphic unit. Though cementation is proven most likely to occur within particular lithostratigraphic units, the degree to which it develops is much less predictable. Model predictions in the Gippsland Basin reinforce this point. A detailed stratigraphic pattern associated with predicted cementation in the Gippsland Basin has not been explored in this study but initial impressions are of local sporadic occurrences, as seen in the Otway Basin case.

Given the importance of cementation as an operational risk in reservoir systems under development, the predictive model described here provides a vital tool for identifying its occurrence and predicting its likely stratigraphic distribution away from wells. The model thereby helps narrow the true range of utilisable reservoir space. In particular, it also provides some quantitative information on the likely volume of rock minerals that will provide reactive feedstock over the operational timescale of projects involving injection of CO_2 into conventional reservoir units, e.g. CO_2 EOR operations or dedicated CO_2 storage/sequestration.

Development of the model was an involved and data-intensive process. Similar results might be achieved by machine learning. An advantage of this model however, is generation of a 'probability' log that might provide a measure of the pervasiveness or maturity of cementation. Perhaps this might be adopted as a proxy for the degree of pore space occlusion within zones of reservoir rock predicted to have been cemented.

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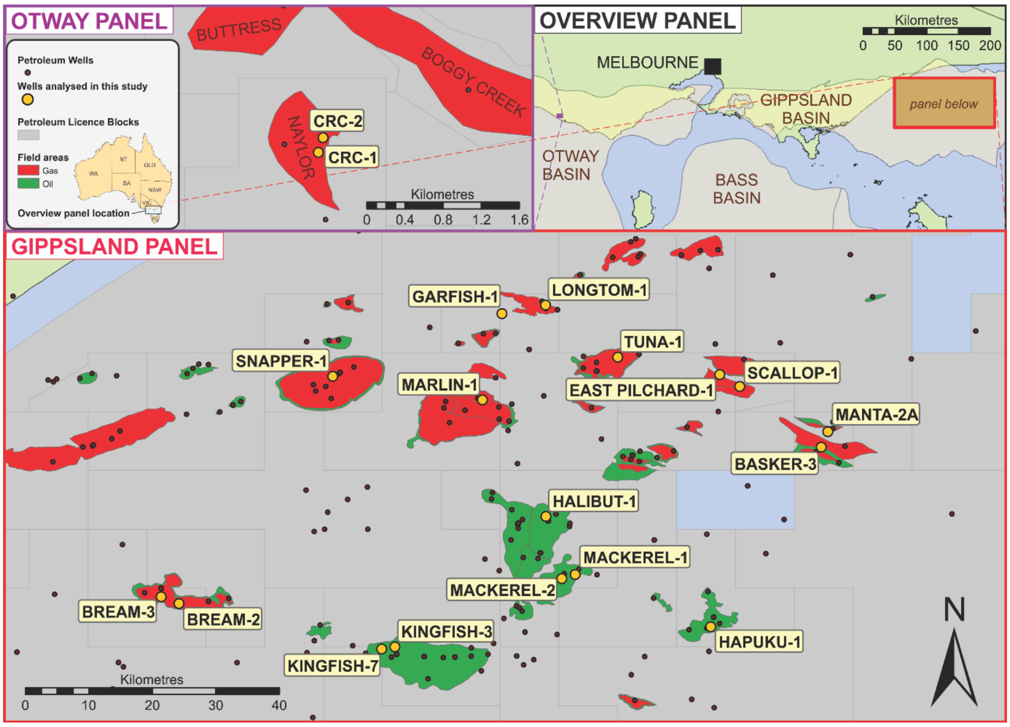

Figure 1. Maps showing the locations of wells where the data used in this study were acquired.

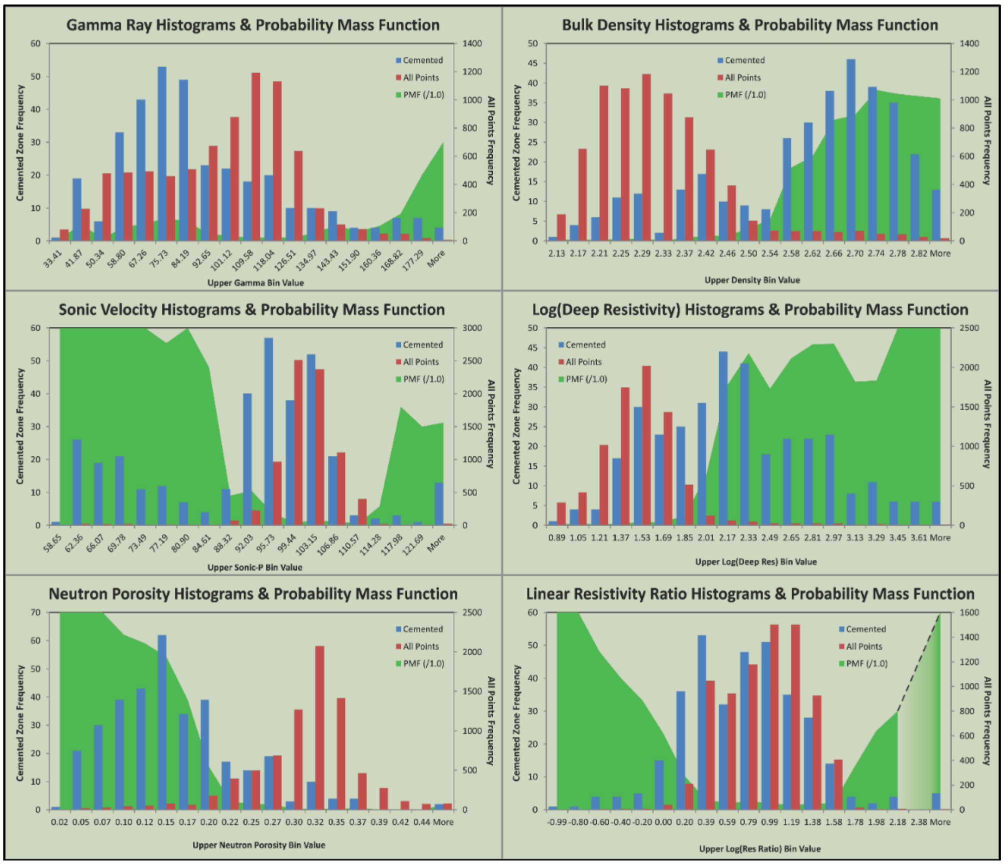

Figure 2. Frequency histograms for wireline log data values coinciding with cemented zones (blue) and within the Paaratte Formation as a whole (red) split into 19 data value bins covering the full value range of these data encountered at CRC-2. The green area chart in the background is the ratio of these two numbers and is assumed to represent a probability mass function (depicted in a continuous form here) that is used by look-up to generate a probability of cementation log from raw wireline log values.

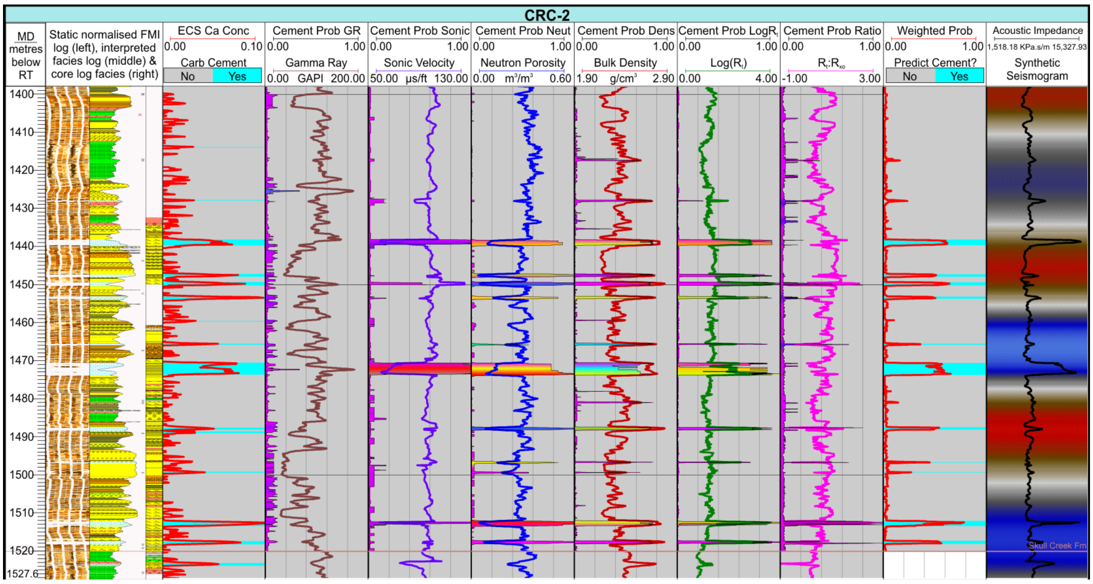

Figure 3. Wireline log tracks of CRC-2 in the lower Paaratte Formation. Track 1 (leftmost) shows statically normalised FMI data with interpreted lithostratigraphy to its right (cementation shown as white with light blue cross-hatching) on the basis of calibration with core logged lithostratigraphy (column on extreme right of track; Lawrence et al., 2013); Track 2 shows the ECS log for weight % of Ca^{2+} with blue blocks showing where this log exceeds the 0.03% threshold criterion used to diagnose carbonate cementation; Track 3 shows the raw gamma ray log (brown) and a colour-filled curve of cementation probability derived using the corresponding PMF of Figure 2; Tracks 4, 5, 6, 7, 8 show data corresponding to that of Track 3 but for raw sonic velocity, neutron porosity, bulk density, logarithm of true resistivity and logarithm of the ratio of true to flushed zone resistivity (raw log curve colours vary) respectively; Track 9 is equivalent to Track 2 but shows a weighted average probability log curve (combining the probability logs of tracks 3, 4, 5, 6, 7 & 8) with blue blocks where this log exceeds a threshold probability value calibrated by the occurrence of blue blocks in Track 2; Track 10 shows a synthetic seismogram (coloured) with a black curve of acoustic impedance calculated from sonic velocity and bulk density logs.

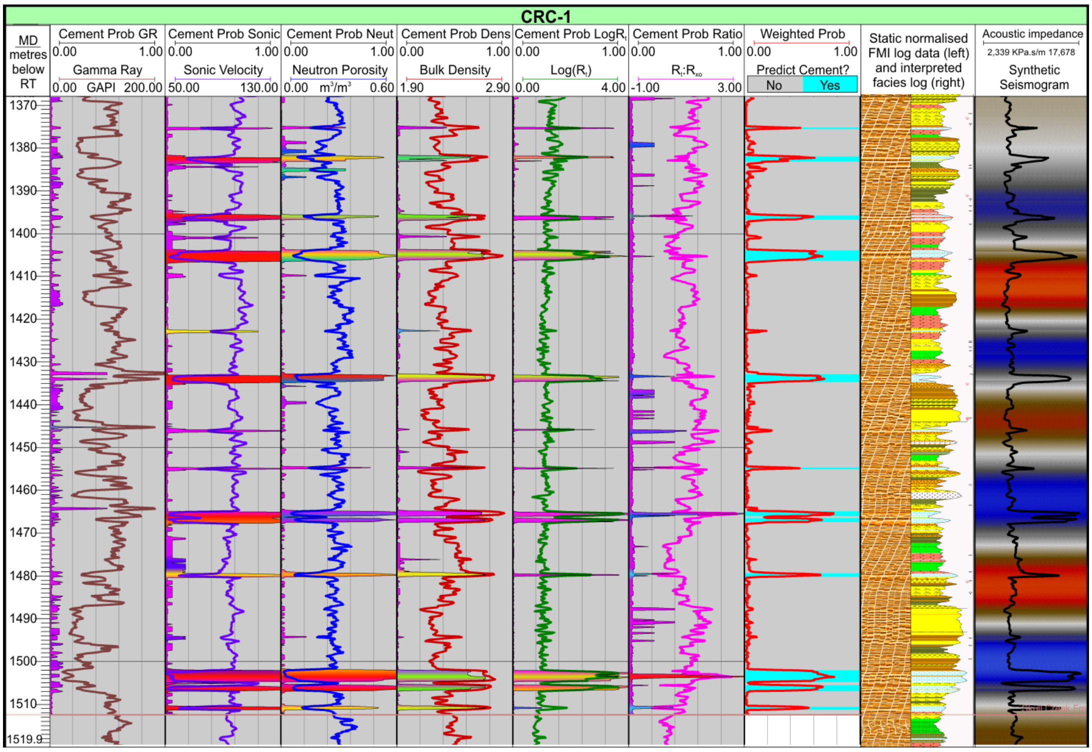

Figure 4. Wireline log tracks of CRC-1 in the lower Paaratte Formation. Tracks 1 (leftmost) to 7 are equivalent to tracks 3-9 of Figure 3, respectively; Track 8 shows statically normalised FMI data (left) with a lithostratigraphic interpretation of these data (right) using the facies scheme developed for CRC-2 (see Track 1 of Figure 3; Lawrence et al., 2013); Track 9 is equivalent to Track 10 of Figure 3.

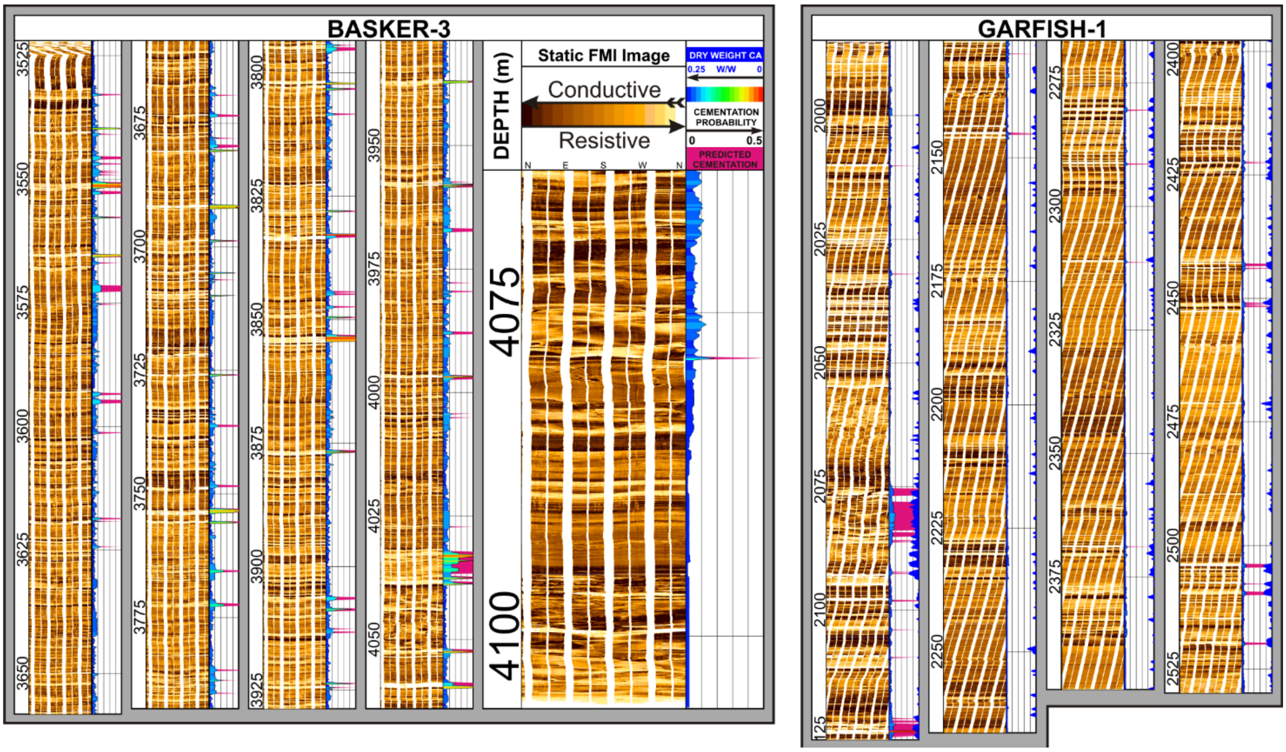

Figure 5. This figure shows statically normalised FMI data acquired at Basker-3 and Garfish-1 wells in the offshore Gippsland Basin, SE Australia. To the right of these data is a log track showing the probability of carbonate cementation (grows from the left) calculated by the model presented in this study. For each well, a threshold probability of cementation was calculated, exceedance of which designates cementation (pink blocks). This 2nd log track for Garfish-1 also shows an ECS wireline log curve for the atomic weight %Ca^{2+} (grows from the right), which is equivalent to the 'ground truth' log used to develop the model at CRC-2 in the Otway Basin.