Estimating pore pressure in the Cooper Basin, South Australia: sonic log method in an uplifted basin

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ABSTRACT

The use of sonic log data to analyse overpressure in the Cooper Basin, South Australia is complicated by the occurrence of Tertiary uplift in the basin. Uplift and overpressure are both associated with anomalous porosity/depth relationships: the former being witnessed by overcompaction and the later by undercompaction. Hence uplift may mask overpressure effects on log data. A normal compaction trend was determined for the Cooper Basin by averaging sonic log data from 29 wells. The Maree Subgroup was omitted from the normal compaction trend because it has a markedly different sonic log signature. Shale sequences were isolated for study by applying a gamma ray filter (API > 100). In order to remove the effects of uplift, the normal compaction trend was adjusted to fit the trend of the upper, normally pressured part of the sequence in each well. Quantitative pore pressure analysis was undertaken on shale sequences from 8 wells using the Eaton (1972) method once the effect of uplift had been removed. The predictions of the Eaton (1972) method are consistent with pressure measurements (DSTs and mud weights) in sandstones in 7 of the 8 wells, suggesting that both uplift and overpressure have been successfully determined. Assuming that the shales at Moomba 55 are overpressured, as suggested by the Eaton (1972) method, these shales must be isolated from adjacent near normally pressured sandstones. Furthermore mud weights, which are only at best an approximation of formation pressure, are especially unreliable in overpressured shales adjacent to near-normally pressured sandstones.

INTRODUCTION

The Cooper Basin lies in the north eastern corner of South Australia and the south western corner of Queensland, Australia (Figure 1). The Cooper Basin is an area of known overpressure where mud weights as high as 17 MPa/km have been used to balance pore pressure. Overpressures have significant implications for drilling safety and for the primary migration and sealing of hydrocarbons in sedimentary basins (Mouchet and Mitchell, 1989). The Cooper Basin has also been subjected to significant Tertiary uplift (Rodgers et al, 1991; Mavromatidis, 1997).

Fig. 1. Cooper Basin location map.

Log based overpressure analysis in uplifted basins is complicated because overpressure and uplift each affect porosity / depth relationships in a different manner. Overpressure is commonly associated with undercompacted (higher than normal porosity) sediments. In a constant lithology, zones of high sonic travel time may be interpreted as overpressured with respect to a normal compaction trend (Pennebaker, 1968). However, uplift results in sediments being overcompacted with respect to their maximum burial depth (Rodgers et al., 1991). Hence, the effects of uplift must be removed in order to enable accurate pore pressure estimates. Many authors have considered the effects of overpressure and uplift separately (e.g. Pennebaker, 1968; Rodgers, 1991). However, only a few recent studies have taken both overpressure and uplift into account in the analysis of sonic log trends (e.g. Japsen, 1998; Poix, 1998).

This paper aims to establish a technique to perform quantitative pore pressure analysis in the Cooper Basin by considering both overpressure and uplift. Eight wells were chosen as representative of the different pore pressure regimes in the basin (Figure 2).

BASIN SETTING

Figure 3 shows a simplified stratigraphy of the Cooper / Eromanga Basins. The Permian-Triassic Cooper Basin unconformably overlies the Cambrian-Divonian beds of the Warburton Basin or Carboniferous igneous rocks. The Cooper Basin sediments are non-marine, characterised by fluvial, lacustrine and swamp deposits with occasional coal measures (Toupin et al., 1997). The Eromanga Basin contains fluvial, lacustrine and shallow marine deposits (Toupin et al., 1997). The uppermost unit of the Eromanga Basin is the Late Cretaceous non-marine Winton Formation, which was deposited rapidly with...
Overpressured intervals can only be recognised on the sonic log data with reference to a normal compaction trend. Errors in the normal compaction trend will either mask or overemphasise overpressure. A curve was picked through smoothed sonic log data from 29 wells in order to establish a normal compaction trend for the sonic log (Figure 4). The Maree Subgroup was edited out of the pressure analysis due to its significantly different log signature. The different log signature of the Maree Subgroup was interpreted to be due to variations in shale mineralogy. No detailed analytical analysis is available to support this interpretation. However, the Maree Subgroup sediments are the only marine sediments in the Cooper / Eromanga sequence (Alexander and Hibburt, 1996), and Japsen (in press) argues that marine and terrestrial shales in the North Sea display different normal compaction relationships.

The construction of a normal compaction trend in the Cooper Basin was complicated due to the Tertiary uplift in the basin. During uplift only the elastic component of compaction is...
Fig. 4. A normal compaction trend in the Cooper Basin was established by hand picking a curve through smoothed sonic log values. These values were taken from 29 wells in and around the study area. As the log character of the Maree Subgroup is significantly different it was ignored when picking the normal trend.
recovered. Hence the porosity rebound is small relative to porosity reduction during compaction, and uplifted sediments are overcompacted (anomalously low porosity) with respect to sediments at a similar depth that are at their maximum burial depth (Figure 5). The effect of uplift on the normal compaction trend is a bulk shift in depth, which corresponds to the amount of exhumation.

It was assumed that the sections above the Top Toolachee Formation were all normally pressured in order to allow for the effects of uplift. The effect of uplift was then removed by using the upper part of the sequence as a reference and applying a bulk shift to the normal compaction trend so it fitted the upper, normally pressured sections in each well (Figure 6). After fitting the upper, normally compacted section, any deviation from the normal compaction trend in the sections below the Top Toolachee Formation in each well was interpreted as being due to overpressure. The relative uplift between wells was estimated from the amount of adjustment applied to the normal compaction trend in each well.

Quantitative pressure analysis using the sonic log is based on calibrating the observed sonic log value and an expected or normal sonic log value with known pressure measurements. In this study the Eaton (1972) method was used for quantitative pressure estimation. The Eaton (1972) method is based on the principle that the relationship between the observed sonic log value / normal sonic log ratio and the pore pressure depends on changes in the overburden gradient (Eaton, 1972; Mouchet and Mitchell, 1989). The formula for the Eaton (1972) method is:

\[
Pp = OB - (OB - Pn) \left( \frac{\Delta t_{\text{norm}}}{\Delta t_{\text{obs}}} \right)^{3.0}
\]

(1)

where

- \(Pp\) = Pore Pressure Gradient (MPa/km);
- \(Pn\) = Hydrostatic Pressure Gradient (MPa/km);
- \(OB\) = Overburden Stress Gradient (MPa/km);
- \(\Delta t_{\text{norm}}\) = Normal sonic log value (us/ft);
- \(\Delta t_{\text{obs}}\) = Observed sonic log value (us/ft).

The accuracy of the Eaton (1972) method is dependent on the extent to which the velocity anomalies are related to changes in the overburden stress gradient.

ACCURACY OF THE EATON (1972) METHOD PRESSURE ANALYSIS

Mud weights and reliable drill stem test (DST) measurements have been compared with the pressure profiles determined by the Eaton (1972) method in order to determine its accuracy. DST measurements were only considered reliable where the pressure versus time curve established during the test had been extrapolated to give a pore pressure estimate. Mud weight is used as an approximate indicator of pore pressure because it is generally slightly in excess of pore pressure to avoid the danger of a kick. Hence mud weights are usually raised in overpressured zones. However, mud weights may be raised for reasons other than overpressure (eg. to stabilise the wellbore). Although not always reliable indicators of pore pressure mud weights are widely available and provide the only available independent measure of pore pressure in shales. Furthermore, log-based pressure prediction, at least as an aid to drilling safety, is concerned with replicating / predicting mud weight. The extent to which mud weight is a reasonable approximation for pore pressure is discussed later.
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Fig. 7. Pressure profiles established using the Eaton method. Mud weight and DST values are also shown for comparison. DST measurements were only used where pore pressures have been extrapolated.
Figure 7 shows the results of the Eaton (1972) method for the eight wells in the study area. Mud weights and DST measurements have also been plotted. The sonic log and mud weight data indicate that Darmody 1, Snake Hole 1 and Three Queens 1 are normally pressured. The sonic log data indicates that McLeod 1, Bullyeroo 1, Kirby 1, Bulley 2 and Moomba 55 are overpressured. In the overpressured wells the mud weight and Eaton (1972) method suggest a similar magnitude of overpressure, with the exception of Moomba 55, where mud weights suggest near hydrostatic pore pressure. Given the success of the technique in 7 of the 8 wells analysed, the technique appears to be generally successful in predicting pore pressure in the uplifted Cooper Basin.

Although insufficient wells have been studied to map overpressure in the region, the overpressured wells analysed are restricted to the Nappamerri Trough (Figure 2). Overpressured units occur below the Toolachee Formation. Nappamerri Group sediments are the primary vertical seal to the overpressured compartments. Lateral seals to the overpressured compartments must also exist.

The maximum amount of uplift indicated by fitting the normal trends to the upper, normally pressurised part of the sequence was 632 m in Moomba 55 relative to Snake Hole 1. The few hundreds of metres of uplift indicated by the wells analysed is broadly consistent with the magnitudes of uplift indicated by Rodgers et al. (1991).

**DISCUSSION**

The Eaton (1972) method appears to have been successful in predicting pore pressure in 7 of the 8 wells analysed. Hence it is interesting to speculate on the discrepancy in Moomba 55 where the Eaton (1972) method suggests that the shales are overpressured but mud weights, and DST measurements in adjacent sandstones, indicate near hydrostatic pore pressures. It is possible that the sonic log based Eaton (1972) method did not accurately predict formation pressure in Moomba 55. However, given that the Eaton (1972) method successfully predicted mud weight in 7 out of the 8 wells studied, it is suggested that the deeper shales in Moomba 55 are indeed overpressured. The discrepancy between the Eaton (1972) method and the mud weight and DST data may be explained if the sandstones are vertically isolated from the adjacent shales such that pore pressures have not equilibrated between them. Hence the Eaton (1972) method may be correctly predicting overpressure in the shales while the direct pressure measurements in the sandstones indicate near hydrostatic pore pressure. If this interpretation is correct, mud weights in the shales are considerably underbalanced. It is tentatively suggested that mud weights better reflect pore pressure in the sandstones than shales because the low permeability of the shales prevents kicks. In the wells where mud weights are elevated and consistent with the predictions of the Eaton (1972) method, the sandstones are overpressured as witnessed by the DST measurements. Unlike the sandstones at Moomba 55 these overpressured sandstones in the deep Nappamerri Trough are interpreted to be undrained.

This analysis has some implications for the origin of overpressure in the Cooper Basin. The successful use of an undercompaction-based technique to accurately predict pore pressure in 7 of the 8 wells studied suggests that the magnitude of the porosity anomaly associated with the overpressure is consistent with overpressure having been generated by disequilibrium compaction (Yassir et al., 1996). However, the occurrence of overpressure generated by disequilibrium compaction in an uplifted basin, where the last significant depositional event was 90 Ma, is puzzling. It seems unlikely that the pressure compartments would be adequately sealed to preserve overpressure over 90 My since the deposition of the Winton Formation, especially given that the significant recent uplift is likely to have reduced pore pressure (Swarbrick and Osborne, 1998). Hence the origin of overpressure is likely to postdate compaction. For this reason a fluid expansion mechanism seems more probable than disequilibrium compaction. The cracking of hydrocarbons producing gas is a fluid expansion mechanism that can produce significant amounts of overpressure and significant porosity anomalies (Yassir et al., 1996).

Alternatively, the sonic anomalies, which mark the overpressure in this study, may not reflect high porosity. Traditionally it is thought the sonic log velocity anomalies marking overpressure are caused by porosity anomalies associated with disequilibrium compaction (Pennebaker, 1968). However, recent studies have shown that the sonic log may be responding directly to textural changes due to overpressure, rather than indirectly via porosity anomalies (Hermanrud, 1998; Teige et al., 1999). Thus it is possible that the overpressure witnessed in the study may have been generated by a fluid expansion mechanism where there is little porosity change.

**CONCLUSIONS**

(1) There are significant overpressures in the Toolachee Formation and deeper units of the Nappamerri Trough, Cooper Basin, South Australia.

(2) The Cooper Basin has also been subject to Tertiary uplift, and prior to quantifying overpressure from log data it is necessary to remove the effect of uplift. This was done by fitting the normal compaction trend to the upper, normally pressurised part of the sequence.

(3) Once the effect of uplift has been removed, the Eaton (1972) method appears to have been successful at predicting pore pressures in 7 of the 8 wells analysed. The predicted pore pressure match mud weights and DST-based pressures measurements in adjacent sandstones.

(4) In Moomba 55 the Eaton (1972) method suggests shales are overpressured but mud weight data, and DST based pressure measurements in the adjacent sandstones suggest near normal pore pressures. These observations may be consistent if the shales are isolated from adjacent sandstones and mud weights are underbalanced in the shales.

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**REFERENCES**


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