DETECTING OVERPRESSURE USING POROSITY-BASED TECHNIQUES IN THE CARNARVON BASIN, AUSTRALIA

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ABSTRACT

Overpressure has been encountered in many wells drilled in the Carnarvon Basin. Sonic logs are used to estimate pore pressure in shales in the Carnarvon Basin using the Eaton and equivalent depth methods of estimating pore pressure from velocity data with reference to a normal compaction trend. The crux of pore pressure estimation from the sonic log lies in the determination of the normal compaction trend, i.e. the acoustic travel time (Δt)/depth (z) trend for normally pressured sediments. The normal compaction trend for shales in the Carnarvon Basin was established by fitting an Athy-type exponential relationship to edited sonic log data, and is:

Δt = 225 + 391exp(-0.00103 z)

Vertical stress estimates are also needed for the Eaton and equivalent depth methods used herein. A vertical stress (σv) relationship was obtained by fitting a regression line to vertical stress estimates from the density log, and is:

σv = 0.0131 z 1.0462

The Eaton and equivalent depth methods yield similar pressure estimates. However, the equivalent depth method can only be applied over a limited range of acoustic travel times, a limitation that does not apply to the Eaton method.

The pressure estimates from the Eaton method were compared to pressures measured by direct pressure tests in adjacent permeable units. There is a good correlation between Eaton and test pressures in normally pressured intervals in three wells and overpressured intervals in two wells. Eaton pressure estimates underestimate overpressured direct pressure measurements in four wells by up to 13 MPa. This is consistent with overpressure being generated (at least in part) by a fluid expansion mechanism or lateral transfer of overpressure. The Eaton pressures in one well are, on average, 11 MPa lower than hydrostatic pore pressure recorded in direct pressure measurements below the Muderong Shale. The sediments in this well appear to be overcompacted due to exhumation.

Mud weights can be used as a proxy for pore pressure in shales where direct pressure measurements are not available in the adjacent sandstones. The Eaton pressure estimates are consistent with mud weight in the Gearle Siltstone and Muderong Shale in 4 of the 8 wells studied. The Eaton pressures are on average 10 MPa in excess of mud weight in the Muderong Shale and Gearle Siltstone in three wells. It is unclear whether the predicted Eaton pressures in these three wells accurately reflect pore pressure (i.e. the mud weights do not accurately reflect pore pressure), or whether they are influenced by changes in shale mineralogy (because the gamma ray filter does not differentiate between shale mineralogy). Several kicks have been recorded in adjacent wells within the Muderong Shale and Gearle Siltstone, and this interval is overlain by significant sediment thickness in these three wells. These observations are consistent with the existence of overpressure due to rapid burial-related disequilibrium compaction in the Muderong Shale and Gearle Siltstone.

KEYWORDS

Overpressure, Carnarvon Basin, vertical stress, Eaton method, equivalent depth method, normal compaction trend, undercompaction.

INTRODUCTION

The Carnarvon Basin is located along the Western Australia coastline (Fig. 1), and overpressure has been encountered in many wells drilled in the basin. An understanding of the distribution of overpressured sediments in a sedimentary basin is of importance both in terms of drilling cost and safety, and in terms of understanding fluid flow in the basin. In particular, understanding the relationship between pore pressure and velocity provides a framework in which pore pressure can be estimated pre-drill using seismic processing velocities.

The most reliable pressure measurements in sedimentary basins are drill stem tests (DSTs) and wireline formation interval tests (WFTs). Many authors have described the distribution of overpressure in the high permeability aquifers of the Carnarvon Basin using direct pressure measurements (DSTs/RFTs) and/or drilling data (Nyein et al, 1977; Horstman, 1988; Zaunbrecher, 1994; van Ruth et al, 2000; Tingate et al, 2001; Otto et al, 2001). DST and WFT tests, however, cannot be performed in low permeability sediments,
where mud weights are unreliable indicators of pore pressure (van Ruth et al, 2000). Few authors have attempted to describe the distribution of overpressure in the less permeable claystone sequences of the Carnarvon Basin (Vear, 1998; Tingate et al, 2001). Low permeability sediments strongly influence the movement of fluids in sedimentary basins, and it is within low permeability sediments that overpressure is generated (Aplin et al, 1995; Otto et al. 2001).

Overpressure is commonly associated with undercompacted (higher than normal porosity) sediments. In a constant lithology, zones of anomalous acoustic travel time may be interpreted as overpressured with respect to a normal compaction trend (Pennebaker, 1968). The aim of this paper is to estimate the pore pressure in the low permeability lithologies in the Carnarvon Basin using acoustic travel time from the sonic log in 38 wells (Fig. 1). This paper firstly outlines a methodology for performing quantitative pressure analysis in the Carnarvon Basin and compares the Eaton (1972) and equivalent depth methods of estimating pore pressure from velocity data with reference to a normal compaction trend. Secondly, the distribution of overpressured shales in the wells analysed, as determined by the Eaton (1972) method, is discussed and compared to direct pressure measurements.

**QUANTITATIVE PORE PRESSURE DETERMINATION FROM THE SONIC LOG**

The origin of overpressure in the Carnarvon Basin is thought to be predominantly disequilibrium compaction, with minor contributions from hydrocarbon generation and horizontal stress (Vear, 1998; Swarbrick and Hillis, 1999; Tingate et al, 2001). Sediments compact during burial due to an increase in the mean effective stress (Goulty, 1998). If fluid loss from compacting sediments is impeded, some or all of any additional increase in mean stress is borne by the fluid, retarding compaction and causing overpressure. Thus, sediments that have become overpressured via disequilibrium compaction have a higher porosity than sediments at a similar burial depth that are subject to hydrostatic pore pressure. In this study overpressure was evaluated in shale sequences...
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using acoustic travel time data by detecting undercompaction (abnormally high porosity) with reference to a normal compaction trend. Sediments that have become overpressured from fluid expansion mechanisms (e.g. hydrocarbon generation, lateral transfer) may not be associated with a significant porosity anomaly (Bowers, 1994; Teige et al, 1999). Hence, the techniques presented in this paper under-estimate overpressure generated by such mechanisms.

Quantitative pressure analysis using sonic logs is based on determining the difference between an observed acoustic travel time and the acoustic travel time value for a normally compacted sediment. In this study the Eaton (1972) method and the equivalent depth methods were used for quantitative pressure estimation.

Sediments compact as the mean effective stress acting on the rock matrix increases (Goulty, 1998). However, mean effective stress is difficult to determine, mainly due to uncertainty in the maximum horizontal stress magnitude. Vertical effective stress, however, can be calculated from the density log and the lithostatic stress profile does not vary significantly in the Carnarvon Basin. In this study vertical stress has been used as an approximation of mean stress. Hence, the effects of changes in horizontal stress on the generation of overpressure have not been considered in this study.

Eaton Method

The Eaton (1972) method requires determination of the ratio of the normally compacted acoustic travel time to the observed acoustic travel time in the zone of investigation (Equation 1). The method is based on the principle that the relationship between this ratio and pore pressure depends on changes in the vertical stress gradient (Eaton, 1972; Mouchet and Mitchell, 1989). Pore pressure is calculated using the following equation:

\[ P_p = \sigma_v - (\sigma_v - \sigma_h) \left( \frac{\Delta t_{\text{norm}}}{\Delta t_{\text{obs}}} \right)^{3.0} \]  

Where:
- \( P_p \) = pore pressure (MPa);
- \( \sigma_v \) = vertical stress (MPa);
- \( \sigma_h \) = hydrostatic pore pressure at the equivalent depth (MPa), and;
- \( \Delta t_{\text{norm}} \) = normal compaction trend (µs/m), and;
- \( \Delta t_{\text{obs}} \) = acoustic travel time (µs/m).

Equivalent depth method

The equivalent depth method relates pore pressure to the difference in vertical stress between the observation point and the equivalent depth (Equation 2). The equivalent depth is the depth at which the normally compacted acoustic travel time is the same as that in the zone of investigation (Fig. 2; Mouchet and Mitchell, 1989). Pore pressure is calculated using the following equation:

\[ P_p = P_{eq} + (\sigma_v - \sigma_h) \]  

Where:
- \( P_{eq} \) = hydrostatic pore pressure at the equivalent depth (MPa), and;
- \( \sigma_h \) = vertical stress at the equivalent depth (MPa).

The accuracy of the Eaton (1972) method and the equivalent depth method is dependent on the extent to which the acoustic travel time anomalies are related to overpressure via changes in porosity. Hence it is important to remove effects from the sonic log that are not related to changes in porosity.

Log editing/lithology filter

The sonic log measures acoustic travel time in a formation. Acoustic travel time in a formation is dependent on a number of variables such as hole condition and lithology. In this analysis an attempt is made to normalise the sonic log in order to make it dependent upon porosity alone. The most common source of noise in the sonic log is cycle skipping (Rider, 1991). Cycle skipping is caused by poor borehole conditions and results in noise spikes (Rider, 1991). A despike filter was applied to the sonic log to remove noise associated with cycle skipping. Intervals with poor borehole conditions were identified using the DRHO and caliper logs where available, and then removed from the sonic log.

Figure 2. The equivalent depth is the depth at which the normally compacted acoustic travel time is the same as that in the zone of investigation. (Modified after Mouchet and Mitchell, 1989).
Acoustic travel time also varies with lithology. The sonic and gamma ray logs were smoothed and resampled to minimise small-scale lithological effects associated with thin beds. Coals were removed by applying a sonic log cut-off filter of 330 µs/m. Only shales were investigated. They were isolated for analysis using gamma ray cut-off filters.

The Triassic to Lower Cretaceous sequence in the study wells consists of interbedded siliciclastic shales and sandstones (Fig. 3). The Upper Cretaceous – Tertiary sequence is a mixed carbonate/siliciclastic sequence that progressively changes to pure carbonate. The sediments are dominantly carbonate in the Upper Cretaceous and totally carbonate in the Oligocene (Young et al, 2001; Fig. 3). Both the carbonates and sandstones have low gamma ray responses and thus a gamma ray filter is generally effective in differentiating them from shales. However, shales above the Muderong Shale have significant kaolinite (low K) clay content and exhibit relatively low gamma ray values. Hence, in sediments above the Muderong Shale a lower gamma ray cut-off was required so that shales were not filtered out of the analysis. The gamma ray filters for the Carnarvon Basin were devised by comparing cuttings lithology with the gamma ray log. The gamma ray filters used to identify shales in this study are:

- Surface to Muderong Shale: GR>40 API, and;
- Muderong Shale to total depth: GR>80 API.

Normal compaction trend for shale acoustic travel time

The normal compaction trend is the average evolution of acoustic travel time with depth under hydrostatic pore pressure conditions. An accurate normal compaction trend is vital to determining overpressure, as overpressure might be identified by deviations from the normal compaction trend. Errors in the normal compaction trend either mask or over-emphasise overpressure.

A normal compaction trend for shale acoustic travel time in the Carnarvon Basin was established by fitting an exponential relationship to averaged acoustic travel times from the 16 normally pressured wells analysed in this study. Wells were selected as normally pressured based on direct pressure measurements in sandstones where available, and mud weights where no direct pressure measurements were available. The sonic logs, however, were edited to remove the sandstones where the direct pressure measurements were undertaken. Therefore it is assumed that the low permeability lithologies in the normally pressured wells are in pressure equilibrium with the adjacent sandstones and can be used to establish a shale normal compaction trend. An absence of lateral facies variation is also assumed within the units analysed.

The normal compaction trend established in this study is based on the Athy (1930) relationship (Equation 3):

\[ \phi = \phi_0 \exp^{(1-Cz)} \]

Where;
- \( \phi \) = porosity;
- \( \phi_0 \) = initial porosity;
- \( C \) = compaction coefficient (m⁻¹), and;
- \( z \) = depth (m).

![Figure 3. Simplified stratigraphy of the Carnarvon Basin (Modified after Hocking, 1988; Woodside, 1988; Stagg and Cowell, 1994; Mildren 1997).](image)
To establish a normal compaction trend for the sonic log the Athy (1930) relationship was expressed in acoustic travel time using the time average equation suggested by Wyllie et al (1956). The Wyllie et al (1956) time average equation is:

\[
\phi = \frac{1}{C_p} \left( \frac{\Delta t_{ma} - \Delta t_{fa}}{\Delta t - \Delta t_{ma}} \right) 
\]

(4)

Where:
\( \Delta t_{ma} = \) matrix travel time;
\( \Delta t_f = \) fluid travel time, and;
\( C_p = \) Wyllie correction factor.

By substituting Equation 4 into Equation 3 the following relationship between acoustic travel time and depth is obtained (Bulat and Stoker, 1987):

\[
\Delta t = \Delta t_{ma} + \left( C_p (\Delta t_f - \Delta t_{ma}) \phi_0 \exp \left(-\frac{C}{C_p}\right) \right)
\]

(5)

Values for \( C_p, \Delta t_{ma}, \Delta t_f, \phi_0 \) and \( C \) were obtained by fitting Equation 5 to shale acoustic travel time values from the 16 normally pressured wells (Fig. 4).

The values obtained for the Carnarvon Basin are \( C_p = 1.65, \Delta t_{ma} = 225 \mu s/m, \Delta t_f = 620 \mu s/m, \phi_0 = 0.6 \) and \( C = 0.00103 \). Substituting these values into Equation 5 yields Equation 6, the normal compaction trend for acoustic travel time in shales used in this study:

\[
\Delta t_{ma} = 225 + 391 \exp \left(-\frac{C}{C_p}\right)
\]

(6)

**Determination of equivalent depth**

The equivalent depth is the depth at which the normally compacted acoustic travel time is the same as that in the zone of investigation. The equivalent depth relationship (Equation 7) was obtained by solving Equation 6 for depth. Equivalent depth was then calculated from acoustic travel time using the following equation:

\[
z_{eq} = -\frac{\left( \frac{\Delta t_{ma} - 225}{391} \right)}{0.00103}
\]

(7)

Where:
\( z_{eq} = \) equivalent depth (m).

**Determination of vertical stress**

Mildren (1997) calculated vertical stress in 20 wells in the Carnarvon Basin by integrating the density log. A vertical stress relationship was calculated (Equation 8) by fitting a regression line to these vertical stress estimates (Fig. 5).

\[
\sigma_v = 0.0131 z^{1.0642}
\]

(8)

The excellent fit of the regression line in Figure 5 to the vertical stress estimates (\( R^2 = 0.996 \)) suggests that there is little variation in vertical stress across the 20 wells. Hence the vertical stress relationship defined by this regression line (Equation 8) is considered to be a good estimate of the vertical stress in wells where there is either no density log, or the vertical stress has not been previously calculated. There is a significant difference between the vertical stress relationship for the Carnarvon Basin presented in this paper and the 1 psi/ft (22.6 MPa/km) assumption that is commonly used (Mouchet and Mitchell, 1989). The Carnarvon-specific relationship, for example, yields a vertical stress 10% less at 1 km depth (20.4 MPa as opposed to 22.6 MPa).
The Eaton (1972) and equivalent depth methods yield similar pore pressure estimates in all wells. An example of this is shown in Figure 6. The Eaton (1972) method estimates are more scattered than the pressure estimates from the equivalent depth method. This scatter is interpreted as residual noise in the edited sonic log rather than actual pressure variations. Therefore the equivalent depth method is considered to be less susceptible to noise than the Eaton (1972) method. However, the relationship used to calculate equivalent depth (Equation 7) is only defined for acoustic travel time values between 225 and 616 µs/m. Hence, the equivalent depth method can only be used where the acoustic travel time data fall inside this interval. Additionally, the equivalent depth method exaggerates deviations towards underpressure below 2,500 m. Due to these limitations we have chosen to use the pore pressure estimates calculated using the Eaton (1972) method when discussing the distribution of pore pressure in the Carnarvon Basin.

**Upper Cretaceous to Recent (Toolonga Calcilutite to Recent).**

The interval above the Top Gearle Siltstone contains no direct pressure measurements, and is usually drilled with low mud weights. Kicks were taken, however, in the Toolonga Calcilutite below 2800 mbsl in Fisher–1, Haycock–1 and West Dixon–1 (Tingate et al, 2001). The high permeability sediments in this interval are usually normally pressured, with the exception of the aforementioned kicks. Only Wells D, E, H and G contain edited sonic log data in this interval. The pressure estimates are normally pressured in all these wells with the exception of Well H (Fig. 7). The pressure estimates in this interval in Well H range from overpressured immediately above the Gearle Siltstone to underpressured around 2000 mbsf. The depth of the overpressured interval estimated in Well H correlates with the kicks observed in this interval in other wells. However, the estimated pressure anomaly may not be reflecting actual changes in pore pressure. As a gamma ray filter of 40 API was used in this interval, it is possible that the edited sonic log values represent mixed lithology sediments. Hence, the non-hydrostatic pressure estimates in this interval may reflect changes in lithology rather than actual changes in pore pressure.

**Lower to Upper Cretaceous (Gearle Siltstone/ Muderong Shale).**

This interval comprises the thick shale sequences of the Gearle Siltstone and the Muderong Shale (Fig. 7).
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There are no direct pressure measurements in this interval. Kicks have been recorded, however, in the Muderong Shale in Venture–1 and West Tryal Rocks–1 (Tingate et al, 2001). Mud weights are usually raised when drilling this interval to combat drilling problems. Normal pressures are estimated in Wells A, C, D and E. In Wells F, G and H, pressure estimates indicate high overpressure, even in excess of the mud weight used while drilling the formations (Fig. 7). This suggests that either the pressure estimates are overestimating the pore pressure, or that the Muderong Shale and Gearle Siltstone were drilled under balanced in these wells.

**Total depth to Lower Cretaceous (total depth to base Muderong Shale)**

There are many direct pore pressure measurements in the interval from the Base Muderong Shale to total depth. The sediments immediately below the Muderong Shale are generally normally pressured with the exception of Well H. An upper normally pressured compartment, underlain by an overpressured compartment was encountered in this interval in Wells A, B and F. In the Mungaroo Formation in Well G the WFIT measurements form a gradient steeper than hydrostatic gradient defining a pressure transition zone. This implies that the intervals where the measurements were undertaken are not in pressure communication, and are therefore compartmentalised. There are several hydraulically isolated gas gradients in Well H giving further evidence of pressure compartmentalisation. The pressure estimates correlate with normally pressured direct pressure measurements in Wells A, E and H, and with overpressured direct pressure measurements in Wells G and H (Fig. 7). The pressure estimates are up to 13 MPa lower than overpressured direct pore pressure measurements in Wells A, B, F and G. This underestimation of pore pressure is consistent with overpressure generated (at least partly) by fluid expansion or chemical processes which reduce porosity (Bowers, 1994; Teige et al, 1999). In Well C, the pressure estimates are underpressured, while the direct pressure measurements are normally pressured.

**ACCURACY OF POROSITY-BASED PORE PRESSURE PREDICTIONS**

The Eaton (1972) pressure estimates presented in this paper correlate with the pressure estimates from direct pressure measurements in adjacent sandstones in some wells, and are different in others. The difference between shale estimates and sandstone measurements suggests either that the pressure estimates are inaccurate, or that the sandstones and shales in these wells are not in pressure equilibrium. Several potential explanations for the differences between the pressure estimates and values from direct pressure measurements are outlined below.

If the pressure estimates are indeed correct then observed differences in pressure between shales and adjacent sandstones indicate that these shales and sandstones are not in pressure equilibrium. Such a pressure regime can occur when there is lateral transfer of pore pressure in permeable units that is not reflected in adjacent shales, or when the generation of abnormal pressure is isolated within certain lithologies (e.g. the generation of hydrocarbons in source rocks). Well G is a potential example of lateral transfer: in the upper Mungaroo Formation in Well G the RFT pressure measurements indicate near normal pressures whereas the pressure estimates indicate approximately 13 MPa of overpressure (Fig. 7). The RFT pressure measurements define a transition zone in the middle Mungaroo Formation with moderate overpressure at the base of the Mungaroo Formation. A possible explanation for the difference in pore pressure estimates in the upper Mungaroo Formation is that the permeable units in this interval have good lateral connectivity allowing excess pressure to bleed off. Lateral transfer may also act to increase pore pressure in permeable units relative to the non-permeable strata where the rocks become pressured from adjacent highly overpressured sediments. This could be validated by investigating the lateral distribution of high-resolution seismic interval velocities estimated from tomographic inversion.

The presence of any exhumed sediments (sediments not at their maximum burial depth) in the Carnarvon Basin is another potential source of error in the Eaton
Figure 7. Pressure profiles established using the Eaton method. Direct pressure measurements, hydrostatic gradient and mud weights are also shown for comparison. DST measurements were only used where pore pressures have been extrapolated.
(1972) method. Log-based overpressure analysis in exhumed basins is complicated because overpressure and exhumation each affect porosity/depth relationships in a different manner. Overpressure is commonly associated with under-compacted (higher than normal porosity) sediments. Exhumation results, however, in sediments being over-compacted with respect to their current burial depth. Densley et al., (2000) estimated that up to approximately 900 m of exhumation has occurred in the Carnarvon Basin since the Late Cretaceous. This estimate is inferred from sonic anomalies in the Muderong Shale, Gearle Siltstone/Haycock Marl and the Toolonga Calcitrite. Kaiko and Tingate (1996) concluded from temperature data, however, that the majority of wells in the Carnarvon Basin are currently at maximum temperature (and hence maximum burial depth), with only the wells along the eastern margin of the basin being exhumed. The section below the Muderong Shale in Well C may be overcompacted, possibly accounting for an interval where the pressure estimates are underpressured while the direct pressure measurements are normally pressured (Fig. 7).

Changes in shale mineralogy, in particular in the smectite content, can cause significant changes in the acoustic properties of shales (Tingate et al, 2001). The gamma ray log lithology filters used in this study do not differentiate changes in shale mineralogy (with the exception of kaolinite). The pressure estimates suggest that the Gearle Siltstone and Muderong Shale are overpressured in Wells F, G and H. However, the only actual evidence of overpressure in the Muderong Shale and Gearle Siltstone are kicks taken in Venture 1 and West Tryal Rocks–1 (Tingate et al, 2001). Hence, it is unclear whether the sonic log anomaly witnessed in Wells F, G and H is related to overpressure via undercompaction, or changes in shale mineralogy. The sonic log response in the Muderong Shale and Gearle Siltstone correlates with smectite content (Tingate et al. 2001; Dewhurst et al, this volume). The pressure anomalies in Wells F, G and H, however, correspond to kicks taken in adjacent wells suggesting that the Muderong Shale is indeed overpressured in this region. Additionally, the magnitude of the pressure anomaly in the Muderong Shale and Gearle Siltstone increases with increasing depth to top Gearle Siltstone, i.e. the largest sonic log anomalies in the Muderong Shale and Gearle Siltstone are overlain by the thickest sequence of sediments and hence, have been subjected to the largest cumulative burial. This observation is consistent with the existence of overpressure due to rapid burial-related disequilibrium compaction in the Muderong Shale and Gearle Siltstone. Moreover, the sonic log anomaly would be expected to decrease with depth if smectite content was the primary control on the sonic log response. This will occur as smectite content decreases with burial (increasing stress and temperature) when smectite transforms to illite. Nonetheless, it is likely that the sonic log anomaly in the Muderong Shale and the Gearle Siltstone is related to both overpressure and shale mineralogy. More sophisticated analysis might involve detailed lithological determination of clay mineralogy types and the creation of normal compaction relationships for shales with different clay mineral composition.
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Detecting overpressure using porosity-based techniques in the Carnarvon Basin, Australia

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