The origin of overpressure in the Carnarvon Basin, Western Australia: implications for pore pressure prediction

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ABSTRACT: Porosity–effective stress analysis of 37 wells in the Carnarvon Basin, Australia, has identified 12 wells where the overpressure was generated by disequilibrium compaction and four wells where the overpressure was generated by fluid expansion. Disequilibrium compaction was identified as the dominant overpressure-generating mechanism in wells along the Rankin Trend as far south as Gorgon 1 and Spar 1. Fluid expansion was identified as the dominant mechanism of overpressure generation in wells along the Barrow Trend and around the Alpha Arch. Disequilibrium compaction-generated overpressures occur, as would be expected, where the Tertiary sediment thickness is greatest and fluid expansion overpressures where the Tertiary is thinnest. Indeed, where the N-1 (35 Ma) reflector is greater than c. 1500 m below seabed, disequilibrium compaction overpressures are observed and where it is shallower than c. 1500 m, fluid expansion overpressures are observed. Acoustic log-based pore pressure detection using Eaton’s (1975) method yielded accurate estimates with an exponent of three in Wilcox 1 where the overpressure was generated by disequilibrium compaction, and an exponent of six in Bambra 1 where the overpressure was generated by fluid expansion. If the Eaton (1975) technique is to be applied to seismic processing velocities for pore pressure prediction, then an exponent of three can be used where the N-1 horizon is greater than c. 1500 m and an exponent of six where the N-1 horizon is less than c. 1500 m.

KEYWORDS: overpressure, compaction, velocity, effective stress

INTRODUCTION

Knowledge of overpressure (pore fluid pressure greater than hydrostatic) is an important aspect of petroleum exploration with respect to drilling hazard and as a potential control on seal integrity. While drilling, it is important to use a mud weight in the ‘window’ between pore pressure and fracture pressure to prevent kicks (mud weight less than pore pressure) and mud loss (mud weight greater than fracture pressure). The ‘window’ is narrow in overpressured sediments and prior knowledge of the pore pressure is vital for safe and efficient drilling. Furthermore, the window between pore pressure and fracture gradient is an important indication of the maximum hydrocarbon column height that can be retained within a trap (Gaarenstroom et al. 1993).

There have been many mechanisms proposed to explain the generation of overpressure in sedimentary basins (see Osborne & Swarbrick 1998 for a detailed review). Overpressure-generating mechanisms can be separated into two categories – stress-related (e.g. disequilibrium compaction) and fluid expansion mechanisms. Fluid expansion mechanisms include hydrocarbon cracking to gas, aquathermal pressuring and mineral phase transformations. The most commonly cited mechanisms of overpressure generation are burial-related disequilibrium compaction and hydrocarbon generation (Law & Spencer 1998).

Pore pressure prediction relies on understanding the mechanism of overpressure generation. Most pore pressure prediction techniques assume overpressure is generated by disequilibrium compaction. Sediments which have become overpressured due to disequilibrium compaction have a higher porosity than sediments of otherwise identical chemical and textural composition, at a similar burial depth, that are subject to hydrostatic pore pressure (Bowers 1995; Osborne & Swarbrick 1998). Porosity-based pore pressure prediction is based on determining the difference between the measured porosity and the porosity for normally pressured sediment at that depth. However, sediments that have become overpressured via a fluid expansion mechanism may not be associated with a significant porosity anomaly (Bowers 1995; Teige et al. 1999). Hence, porosity-based pore pressure prediction techniques may underestimate overpressure generated by a fluid expansion mechanism (Bowers 1995).

Overpressure has been encountered in numerous wells in the Carnarvon Basin (Fig. 1). Horstman (1988) and Zaunbrecher (1994) concluded that the overpressure was generated by hydrocarbon generation (fluid expansion) because the top of overpressure is coincident with the hydrocarbon generation window and maximum thermal maturity. Conversely, Swarbrick & Hillis (1999) concluded that the mechanism of overpressure generation in the Carnarvon Basin was most likely...
disequilibrium compaction related to Tertiary burial, or possibly increasing horizontal stress, with only minor contributions from hydrocarbon generation. Tingate et al. (2001) observed that overpressure in the Carnarvon Basin was sometimes associated with a porosity anomaly and sometimes not, suggesting that overpressure in some areas was generated by disequilibrium compaction, while overpressure in other areas was generated by fluid expansion. However, to the authors’ knowledge, the nature of overpressure-generating mechanisms in the Carnarvon Basin has not been studied previously in detail using porosity–effective stress analysis.

The aims of this paper are to determine the overpressure-generating mechanisms that have operated in the Carnarvon Basin using porosity–effective stress analysis. The implications for pore pressure prediction using the widely accepted Eaton (1975) technique are then discussed, with examples from a well where the overpressure was generated by disequilibrium compaction and a well where the overpressure was generated by fluid expansion. The dominant mechanism of overpressure generation is then compared to the degree of Oligocene to Recent burial (depth to the N-1 horizon) to define a relationship which can be used potentially to predict the likely origin of overpressure and, thus, the appropriate Eaton (1975) relation prior to drilling.

**POROSITY–EFFECTIVE STRESS RELATIONS**

Sediments lose porosity as the mean effective stress acting on the rock matrix increases (Terzaghi 1948; Goult 1998). The porosity–effective stress path that sediments follow during mechanical compaction defines a loading curve (Fig. 2a). Disequilibrium compaction occurs when the rate of compaction exceeds the ability of the sediments to dewater, and the fluid supports some or all of any additional increase in applied stress. Sediment that is completely unable to dewater is subject to an increase of pore pressure of the same magnitude as any increase in applied stress and stays stationary at the same point on the porosity–effective stress plot (Point A, Fig. 2a). Hence, disequilibrium compaction does not alter the relationship between porosity and effective stress during mechanical compaction and sediments that have undergone disequilibrium compaction plot on the loading curve. Alternatively, sediments follow an unloading curve if they first compact under normal pore pressure conditions, and then become overpressured by fluid expansion (Point B, Fig. 2a). Compaction is a largely irreversible process (Magara 1980; Issler 1992). Porosity rebound associated with fluid expansion is limited to the elastic component of compaction and secondary porosity generation. Therefore, the unloading curve follows a different porosity–effective stress path than the loading curve (Fig. 2a). Bowers (1995) proposed that the origin of overpressure could be
identified as disequilibrium compaction if the overpressured sediments lie on the loading curve or as fluid expansion if the overpressured sediments lie on an unloading curve.

**Porosity and effective stress determination in the Carnarvon Basin**

Acoustic travel time from the acoustic log and density from the density log are used as proxies for porosity in this study. The acoustic travel time and bulk density of a rock are dependent on a number of variables, especially porosity, borehole condition and lithology. Acoustic travel time and bulk density are inversely related to porosity. Hence, once corrected/normalized for borehole conditions and lithology, bulk density--effective stress and acoustic travel time--effective stress data can be used to identify the origin of overpressure (Fig. 2b).

Intervals with poor borehole conditions were identified using the density correction log and caliper log, where available, and then removed from the acoustic and density logs. The acoustic and density logs were smoothed using a running average filter and resampled to minimize small-scale lithological effects associated with thin beds, and a despike filter was applied. Figure 3 shows a simplified stratigraphy of the Carnarvon Basin. Only shales were investigated in this study and were isolated for analysis using a gamma-ray cut-off filter. The gamma-ray filter for the Carnarvon Basin was devised by comparing cuttings lithology with the gamma-ray log; shales are defined by:

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

Vertical effective stress ($\sigma_v$) was calculated using Terzaghi’s (1948) relationship, modified to include Biot’s coefficient (equation (1)).

$$\sigma_v = \sigma_e - \alpha P_p$$

where $\sigma_v$ is vertical stress (MPa), $P_p$ is pore pressure (MPa) and $\alpha$ is Biot’s coefficient. Biot’s coefficient is assumed to be unity in this study (cf. Bowers 1995; Sayers et al. 2002).

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. Vertical stress does not vary significantly across the Carnarvon Basin and has been used in this study instead of mean stress. Hence, the effects of changes in horizontal stress on the generation of overpressure have not been considered.

Vertical stress was calculated in 30 of the 37 wells studied by integrating density values from the density log and from check-shot log velocities empirically transformed to densities. A vertical stress relationship was calculated (equation (2)) by fitting a regression line to these vertical stress estimates in order to estimate vertical stress in the seven wells where the density log was not run (Fig. 4).

$$\sigma_v = 20.4 \, \chi^{1.06} + (P_{\text{hyd}} \times WD)$$

where $\chi$ is metres below sea floor, $P_{\text{hyd}}$ is the hydrostatic pore pressure gradient and WD is the water depth. The excellent fit of the regression line in Figure 4 to the vertical stress estimates ($R^2=0.996$) suggests that there is little variation in vertical stress across the 30 wells. Hence, the vertical stress relationship defined in this regression line (equation (2)) is considered to be a good estimate of the vertical stress in the seven wells where vertical stress estimates were unavailable.

Pore pressure was estimated from drill stem tests (DSTs), wireline formation interval tests (WFITs) and kicks. Direct pressure measurements (DSTs and WFITs) are the most reliable measurement of pore pressure. However, direct pressure measurements can only be undertaken in sediments where the permeability is at least 1–10 mD (Swarbrick & Hills 1999).
Porosity–effective stress data have been separated into normally pressured and overpressured based on a pore pressure cut-off. The velocity–effective stress data have been obtained from the 37 wells included in the study (Table 1). The vertically effective stress was plotted against the average acoustic travel time and 619 edited bulk density values were used. In total, 649 edited acoustic travel time and bulk density data in shales within 100 m of the pore pressure measurement were used. No one well contained data which fell both ‘on’ and ‘off’ the loading curve. Hence, only one mechanism of overpressure generation was identified in each well. However, pore pressure measurements were only undertaken in target reservoirs and do not represent the full pore pressure profile in each well. Therefore, there may be relationships between the overpressure-generating mechanisms and age or stratigraphy that could not be identified from the pressure data in the study wells.

Figure 7 shows the geographical distribution of overpressure-generating mechanisms established in the porosity–effective stress analysis. Disequilibrium compaction is the dominant overpressure-generating mechanism in wells along the Rankin Trend as far south as Gorgon 1 and Spar 1. Fluid expansion is the dominant mechanism of overpressure generation in wells along the Barrow Trend and around the Alpha Arch.

Overpressure data which lie ‘on’ the loading curve were identified in sediments of all ages. Overpressured data which fall ‘off’ the loading curve were of Cretaceous and Jurassic age. The majority of these ‘off’ loading curve data are from sediments of Cretaceous age. Jurassic data that have been interpreted as ‘off’ loading curve clearly do not lie within the scatter of normally pressured points defining the loading curve (Fig. 5). It is inferred that ‘on loading curve’ overpressure data represent overpressure generated by disequilibrium compaction due to increases in vertical stress. Whereas, it is inferred that ‘off loading curve’ data represent overpressure generated, at least in part, by a fluid expansion mechanism. Wells where the overpressured sediments did not obviously fall ‘on’ or ‘off’ the loading curve were not classified.

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Fig. 5. Velocity–effective stress relationships in the Carnarvon Basin: (a) all data; (b) Cretaceous data; (c) Jurassic data; (d) Triassic data.
Fig. 6. Density-effective stress relationships in the Carnarvon Basin: (a) all data; (b) Cretaceous data; (c) Jurassic data; (d) Triassic data.
in sediments of Triassic age. However, there are no Triassic data in wells where 'off loading curve' data have been observed. Hence, the existence or origin of overpressure in the Triassic sediments around the Alpha Arch and Barrow Trend could not be determined from the study dataset.

The specific fluid expansion mechanism operating in the Carnarvon Basin could not be determined from the porosity–effective stress analysis. There are several possible fluid expansion mechanisms which may have contributed to the generation of overpressure in the Carnarvon Basin, e.g. hydrocarbon cracking to gas, thermal pressuring or lateral transfer of pressure. Lateral transfer is included as a fluid expansion mechanism for the purposes of this study. Swarbrick & Hillis (1999) provide a more detailed discussion on the potential fluid expansion mechanisms in the Carnarvon Basin.

It has been inferred that the origin of overpressure is fluid expansion in wells where the velocity and density–effective stress data fall outside the scatter of normally pressured points. However, an alternative explanation is that the 'off loading curve' data are uplifted compared to the 'on loading curve' data and normally pressured data. Uplift will cause sediments to be overcompacted relative to otherwise identical sediments that are at their maximum burial depth. Hence, uplifted sediments will also fall 'off' the loading curve. It may not be possible to distinguish between uplifted sediments and sediments where the overpressure was generated by fluid expansion in a velocity or density–effective stress analysis.

There has been up to 900 m of Late Cretaceous–Recent uplift in the Carnarvon Basin (Densley et al. 2000). However, the data in this study are from formations which were deposited before the Late Cretaceous–Recent uplift. Hence, this uplift should equally affect the normally pressured and overpressured data in each well. Thus, any difference between normally pressured and overpressured data in each well cannot be attributed to the Late Cretaceous–Recent uplift. There is also evidence of an earlier period of uplift in the Carnarvon Basin. Kaiko & Tingate (1996) concluded from temperature data that several wells along the eastern margin of the basin, including Chervil 1, show evidence of uplift prior to Jurassic to Mid-Cretaceous burial. However, this uplift pre-dates the deposition of the 'off' loading curve sediments and, thus, cannot explain the 'off loading curve' nature of study data. Furthermore, the normally pressured data from the eastern part of the study area, with the exception of Chervil 1, do not show evidence of uplift. Chervil 1 was omitted from the velocity and density–effective stress analyses.

The application of a single porosity-based technique will not accurately estimate pore pressure in all areas of the Carnarvon Basin. Along the Rankin Trend, where the overpressure is generated by disequilibrium compaction, standard porosity-based pore pressure prediction techniques can be used. The origin of overpressure along the Barrow Trend and around the Alpha Arch is fluid expansion. The standard pore pressure detection techniques may underestimate pore pressure in this area.

The following section outlines two examples of pore pressure detection in the Carnarvon Basin using the Eaton (1975) method on acoustic log data; an example from a well

![Fig. 7. Distribution of overpressure-generating mechanisms in the Carnarvon Basin. Disequilibrium compaction is the dominant mechanism of overpressure generation along the Rankin Trend as far South as Gorgon 1 and Spar 1. Fluid expansion is the dominant mechanism of overpressure generation along the Barrow Trend and around the Alpha Arch.](image-url)
where the overpressure was generated by disequilibrium compaction (Wilcox 1), and an example from a well where the overpressure was generated by fluid expansion (Bambra 1).

The acoustic log has been chosen for pore pressure prediction in this study. The acoustic log is preferable to the density log when estimating overpressure generated by a fluid expansion mechanism because acoustic travel time undergoes more elastic rebound during unloading than does density. The density log measures a bulk parameter of the sediment and is dependent on net pore volume. During unloading there is relatively little change in porosity. Hence, the density anomaly associated with unloading is small. Acoustic travel time is a transit property of the sediment and is related to pore size and geometry (Bowers 2002). Thin connecting pores open elastically during unloading, altering the acoustic travel-time properties of the sediment without significantly increasing the total pore volume (Bowers 2002). Hence, acoustic travel time undergoes a larger elastic rebound during unloading than density.

The Eaton (1975) method calculates pore pressure from the ratio of the normally compacted acoustic travel time to the observed acoustic travel time in the zone of investigation (equation (1)). The Eaton (1975) method assumes that the relationship between this ratio and pore pressure depends on changes in the vertical stress gradient (Eaton 1975; Mouchet & Mitchell 1989). Pore pressure is calculated using the following equation:

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

where \( x \) is an exponent, \( P_{\text{hyd}} \) is hydrostatic pressure (MPa), \( \Delta t_{\text{norm}} \) is the acoustic travel time from the normal compaction trend at the depth of investigation and \( \Delta t_{\text{obs}} \) is the observed acoustic travel time. The standard exponent of three was developed in sediments where the overpressure was generated by disequilibrium compaction (Eaton 1975; Mouchet & Mitchell 1989). The Eaton (1975) method was chosen in this study as the exponent can be changed easily to calibrate the method to estimate overpressure generated by different mechanisms.

The normal compaction trend is the average evolution of acoustic travel time with depth under hydrostatic pore pressure conditions. A normal compaction trend for shale acoustic travel time with depth in the Carnarvon Basin was established by fitting an exponential relationship to averaged acoustic travel times from the 17 normally pressured wells analysed in this study (Fig. 8). Wells were selected as normally pressured based on direct pressure measurements in sandstones, where available, and mud weight where direct pressure measurements were not available. An absence of lateral facies variation is assumed within the units analysed. The normal compaction trend used in this study is:

\[ \Delta t_{\text{norm}} = 225 + 391e^{0.00103z} \]  

Wilcox 1

Wilcox 1 lies along the Rankin Trend (Fig. 1). There are several overpressured direct pressure measurements in Wilcox 1 between 3386 m and 3536 m (Fig. 9). The top of the overpressure is not defined by direct pressure measurements. However, the well was drilled with 9.7 ppg mud weight from 3315 m to 3380 m without incurring a kick, suggesting the well is near normally pressured in this interval. The well is normally pressured again below 3588 m (as shown by direct pressure measurements). Porosity-effective stress data from the overpressured sediments in Wilcox 1 lie on the loading curve (Table 2), implying that the overpressure was generated by disequilibrium compaction. Therefore, standard porosity-based pore pressure detection techniques should accurately estimate pore pressure in this well.

Pore pressure prediction using the Eaton (1975) method was undertaken in Wilcox 1 using an exponent of three (Fig. 9). As expected, the pressure estimates correlate well with the direct pressure measurements in Wilcox 1. However, the Eaton (1975) pressure estimates are significantly higher than mud weight in the overlying Muderong Shale and Gearle Siltstone. No pressure measurements have been undertaken in the Gearle Siltstone and Muderong Shale in the study wells, although the predicted pressure anomaly corresponds to kicks taken in adjacent wells, suggesting that the Muderong Shale is indeed, overpressured in this region. However, the acoustic log response in the Muderong Shale and Gearle Siltstone also correlates with high smectite content (Tingate et al. 2001; Dewhurst et al. 2002). Hence, it is unclear whether this acoustic log anomaly is related to overpressure via undercompaction (the well was drilled underbalanced) or to shale mineralogy (i.e. high smectite content). None the less, the Eaton (1975) method, using an exponent of three, is a good measure of overpressure in Wilcox 1 in the formations where direct pressure measurements have been undertaken.

Bambra 1

Bambra 1 lies to the North of Barrow Island along the Barrow Trend (Fig. 1). Bambra 1 contains two overpressured direct
pressure measurements at 3098 m and 3608 m (Figs 10a, b). The porosity–effective stress data from these overpressured pressure measurements lie off the loading curve indicating that the overpressure was generated, at least in part, by a fluid expansion mechanism. Hence, the porosity anomaly associated with the overpressured sediments in Bambra 1 is relatively small compared to the porosity anomaly associated with overpressure generated by disequilibrium compaction. Therefore, an exponent of three will underestimate pore pressure in Bambra 1.

Figure 10a shows Eaton (1975) pressure estimates in Bambra 1 using an exponent of three. The pore pressure predictions are a good measure of pore pressure for the normally pressured sediments. However, the pressure estimates underestimate the overpressured pore pressure measurements in the well. A good match between predicted pore pressure and the overpressured pore pressure measurements was obtained using an exponent of six (Fig. 10b). These results suggest than an exponent of six may be used to estimate pore pressure where the overpressure was generated by a fluid expansion mechanism in the Carnarvon Basin.

Using an exponent of six will increase the amount of noise in the pore pressure prediction. An exponent of six will enhance all acoustic log anomalies, including those unrelated to porosity. Overpressure cannot be predicted accurately using a porosity-based pore pressure prediction technique if the porosity anomaly associated with fluid expansion cannot be isolated from the acoustic data. The scatter in the pressure estimates in Bambra 1 in the upper, normally pressured sediments is greater when using an exponent of six (Fig. 10). It follows that pore pressure prediction yields results that are more accurate where the overpressure was generated by disequilibrium compaction.

**BURIAL HISTORY AND OVERPRESSURE-GENERATING MECHANISMS**

The porosity–effective stress analysis in the Carnarvon Basin has identified regions where the overpressure was generated by disequilibrium compaction and regions where the overpressure was generated by fluid expansion. Therefore, a single porosity–effective stress relationship cannot estimate accurately pore pressure in all regions within the Carnarvon Basin. Pore pressure was predicted accurately in Wilcox 1, where the overpressure was generated by disequilibrium compaction, using the Eaton (1975) method with an exponent of three. Alternatively, pore pressure was predicted accurately in Bambra 1, where the overpressure was generated by a fluid expansion mechanism, using the Eaton (1975) method with an exponent of six. However, the origin of overpressure cannot be determined prior to drilling using the porosity–effective stress approach. Hence, a method of predicting the origin of overpressure prior to drilling is required in order to decide which Eaton exponent to use in pore pressure prediction and, therefore, gain accurate pre-drill pore pressure estimates in the Carnarvon Basin.

Overpressure generated by burial-driven disequilibrium compaction can be related to the amount of burial, the burial rate...
and the time since burial. Disequilibrium compaction occurs when the rate of compaction due to burial exceeds the sediments’ ability to dewater. The fluid then supports some or all of any additional increase in sediment load. Given the relationship between burial rate and disequilibrium compaction-generated overpressure, the thickness of Oligocene to Recent sediments has been compared to the mechanism of overpressure in the wells analysed. Specifically, the depth to the N-1 horizon (35 Ma), as mapped by Hull (1999) and Young (2002), was compared with the overpressure-generating mechanism.

There is no relationship between the depth to N-1 horizon and the occurrence of overpressure in the Carnarvon Basin (Fig. 11). Hence, depth to N-1 horizon cannot be used to map the distribution of overpressure in the Carnarvon Basin. However, there is a relationship between depth to N-1 horizon and the dominant overpressure-generating mechanism where overpressure is developed. The origin of overpressure is disequilibrium compaction in wells where the depth to N-1 is more than c. 1500 m below sea floor (mbsf). The origin of overpressure is either unclassified or is fluid expansion in wells where the depth to N-1 horizon is less than c. 1500 mbsf. Hence, the depth to N-1 horizon may provide a means of predicting the origin of overpressure in the study wells and could be used potentially to identify the origin of overpressure prior to drilling in the Carnarvon Basin.

**CONCLUSIONS**

Porosity–effective stress analysis of 37 wells in the Carnarvon Basin, Australia, has identified 12 wells where the origin of overpressure is disequilibrium compaction and four wells where the origin of overpressure is fluid expansion. The specific fluid expansion mechanism could not be determined from the porosity–effective stress analysis. Disequilibrium compaction is the dominant overpressure-generating mechanism in wells along the Rankin Trend as far south as Gorgon 1 and Spar 1. Fluid expansion is the dominant mechanism of overpressure generation in wells along the Barrow Trend and around the Alpha Arch. A single porosity-based pore pressure detection technique cannot estimate accurately pore pressure in all regions within the Carnarvon Basin. When undertaking pore pressure detection using the Eaton (1975) method an exponent of three yielded accurate pore pressure estimates in Wilcox 1, where the origin of overpressure is disequilibrium compaction; an exponent of six yielded accurate pore pressure estimates in Bambra 1, where the origin of overpressure is fluid expansion.

It may be possible to predict the origin of overpressure prior to drilling using depth to the N-1 horizon in the wells studied. The origin of overpressure was identified as disequilibrium compaction in areas where the N-1 horizon is greater than c. 1500 m. Hence, when undertaking pore pressure detection using the Eaton (1975) method an exponent of three can be...
used where the depth to N-1 horizon is greater than 1500 m. The origin of overpressure was identified as fluid expansion in areas where the depth to the N-1 horizon is less than 1500 m. An Eaton exponent of six may yield more accurate pore pressure prediction in these areas. However, increasing the exponent increases the amount of noise in the pore pressure prediction and care must be taken in pore pressure prediction in areas where fluid expansion is likely to be the dominant mechanism of overpressure generation.

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