The origin of overpressure in ‘old’ sedimentary basins: an example from the Cooper Basin, Australia

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ABSTRACT

Overpressure in ‘old’ sedimentary basins that have not undergone rapid, recent sedimentation cannot be easily explained using traditional burial-driven mechanisms. The last significant burial event in the Cooper Basin, Australia, was the Late Cretaceous deposition of the Winton Formation (98.5–90 Ma). Maximum temperature in the basin was attained during the Late Cretaceous, with cooling beginning prior to 75 Ma. Hence, overpressure related to rapid burial or palaeomaximum temperatures (e.g. hydrocarbon generation) must have developed prior to 75 Ma. Retaining overpressure for 75 Ma in ‘old’ basins such as the Cooper Basin requires extremely low seal permeabilities. An alternative explanation is that overpressure in the Cooper Basin has been generated because of an increase in mean stress associated with an increase in horizontal compressive stress since Late Cretaceous times. Structural observations and contemporary stress data indicate that there has been an increase in mean stress of approximately 50 MPa between Late Cretaceous times to that presently measured at 3780 m. The largest measured overpressure in the Cooper Basin is 14.5 MPa at 3780 m in the Kirby 1 well. Hence, disequilibrium compaction driven by increasing mean stress can explain the magnitude of the observed overpressure in the Cooper Basin. Increases in mean stress (tectonic loading) may be a feasible mechanism for overpressure generation in other ‘old’ basins that have undergone a recent increase in horizontal stress (e.g. Anadarko Basin).

Key words: Cooper Basin, disequilibrium compaction, fluid expansion, overpressure, tectonic loading

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INTRODUCTION

Many mechanisms have been proposed to generate overpressure in sedimentary basins (see Osborne & Swarbrick 1997 for a detailed review). The most commonly cited mechanisms of overpressure generation are disequilibrium compaction and hydrocarbon generation (Law & Spencer 1998). Overpressure in ‘old’ basins, which have not undergone rapid, recent sedimentation (e.g. Cooper Basin) is not readily explained by burial-driven disequilibrium compaction. The maintenance of overpressure generated by ancient (approximately 100 Myr) burial events requires seal permeabilities in the range of $10^{-23}$ to $10^{-25}$ m$^2$ (Deming 1994). The lowest measured permeability values on sedimentary rocks are in the range of $10^{-22}$ to $10^{-24}$ m$^2$ (Lee & Deming 2002). The same extreme pressure seals requirements preclude the origin of overpressure in ‘old’ basins that attained maximum palaeo-temperature prior to 100 Ma, and have since cooled, being readily attributed to temperature-driven processes (e.g. hydrocarbon generation).

An increase in horizontal stress (tectonic loading) is recognized as a potential overpressure-generating mechanism (Berry 1973; Yassir & Bell 1996). There is a strong relationship between the occurrence of overpressure and contemporary compressional tectonics worldwide (Yassir 1998). Tectonic loading can generate overpressure either by increasing mean stress and thereby causing disequilibrium compaction-related overpressure (Goultby 1998), or because of the process of tectonic shear (Yassir & Bell 1996). Recently, some overpressure models have taken increases in horizontal stress into account (e.g. McPherson & Garven 1999; Darby & Ellis 2001). However, horizontal stresses are often ignored when considering overpressure-generating mechanisms because the magnitudes of horizontal stresses, in particular
maximum horizontal stress, are difficult to constrain and because the relationship between pore pressure and horizontal stress is complex.

In this paper, we demonstrate that the origin of overpressure in the Cooper Basin, Australia is unlikely to be burial- or temperature-driven. We outline a major increase in horizontal stress in the Cooper Basin during the Tertiary using structural observations and contemporary stress measurements. We quantify this increase in horizontal stress and demonstrate that it is sufficient to generate the observed overpressure. We conclude that this increase in horizontal stress is the most likely cause of the observed overpressure in the Cooper Basin.

**THE ORIGIN OF OVERPRESSURE IN THE COOPER BASIN**

The Cooper Basin straddles the South Australia and Queensland border (Fig. 1). Drill stem test pressure measurements as high as 14.5 MPa in excess of hydrostatic pressure have been recorded (Fig. 2). The origin of overpressure is not related to hydrocarbon buoyancy alone, as the magnitude of excess pressure would require a hydrocarbon column extending into the basement (Hillis et al. 2001).

**Burial history and burial-driven overpressure mechanisms**

The Permian–Triassic Cooper Basin sediments are nonmarine, characterized by fluvial, lacustrine and swamp deposits with occasional coal measures (Alexander 1998). The Cooper Basin is overlain by the Late Triassic-Mid Cretaceous Eromanga Basin succession (Fig. 3), which contains fluvial, lacustrine and shallow marine deposits (Alexander 1998). The early nonmarine Eromanga Basin sediments were deposited at 5–25 m Myr⁻¹ (Moussavi-Harami 1996). Sedimentation rates increased during the deposition of the marine Maree Subgroup and reached a maximum of 113 m Myr⁻¹ during the Late Cretaceous deposition of the nonmarine Winton Formation (98.5–90 Ma). Winton Formation sedimentation terminated in the Late Cretaceous with a period of nondeposition or erosion that was followed by the deposition of the nonmarine Cainozoic Lake Eyre Basin. The Lake Eyre Basin consists of three unconformably bounded sequences deposited at less than 10 m Myr⁻¹ (Moussavi-Harami 1996). Tertiary sediments are thin or absent over much of the Eromanga Basin and the maximum preserved Tertiary thickness is only 300 m (Rodgers et al. 1991).

The largest increase in pore pressure that can be generated by disequilibrium compaction alone (without considering fluid redistribution by lateral and vertical fluid transfer) is equal to the magnitude of the increase in applied stress (Swarbrick et al. 2002). The increase in vertical stress because

![Fig. 1. Cooper Basin location map showing overpressured wells and major tectonic elements.](image)

![Fig. 2. Kirby 1 pore pressure profile. Contemporary mean stress, mean palaeostress, hydrostatic gradient, contemporary vertical stress, drill stem test shut in pressure (DST shut in) and extrapolated drill stem test pressure (DST P) are also plotted.](image)
of Tertiary sediment loading in the Cooper–Eromanga has been determined from vertical stress/depth relations calculated using density data (Engelder 1993) and check-shot log velocities empirically transformed to densities (Fig. 4). Vertical stress/depth relations determined in 25 wells in the Cooper Basin are described by:

$$\sigma_v = 19.3 e^{-1.101}$$  

where $z$ is the depth and $\sigma_v$ is the vertical stress. Hence, 1480 m of burial would be required to create an additional vertical stress of 29.8 MPa, or an overpressure of 14.5 MPa, if the sediments were undrained and all of the vertical stress transferred to the pore fluids. Therefore, if the overpressure was generated by burial-driven disequilibrium compaction then fluid isolation must have occurred during or prior to the Early Cretaceous deposition of the Wallumbilla Formation (117.5–101 Ma).

**Thermal history and thermally driven overpressure-generating mechanisms**

The thermal history of the Cooper Basin has been constrained by Geotrack (1997) using apatite fission track, zircon fission track and vitrinite reflectance data. The Cooper–Eromanga Basin sediments reached their maximum temperatures in the Cretaceous during a period of significantly elevated basal heat flow. The geothermal gradient at this time is estimated to be 89°C/km$^{-1}$. Cooling from maximum temperatures commenced between 75 and 98 Ma. The high geothermal gradients in the Cooper–Eromanga succession during the Cretaceous are consistent with temperature estimates in southern Australian basins prior to the onset of rifting between Australia and Antarctica (Geotrack 1997). Measured vitrinite reflectances in the sequence below the Nappermerri Group in the Burley 2 well are greater than 3%, with a maximum of 7% at 3495 m in the Patchawarra Formation (Geotrack 1997). These values cannot be explained using the present day geothermal gradient of 61°C/km$^{-1}$,
and the Permian–Cretaceous section in the Burley 2 well reached measured maturity prior to cooling between 97 and 75 Ma (Geotrack 1997; Fig. 3). If overpressure was generated by hydrocarbon cracking to gas, then overpressures must have been generated prior to 75 Ma. Therefore, like overpressure generated by burial-driven disequilibrium compaction, that generated by irreversible, temperature-dependent reactions (e.g. hydrocarbon cracking to gas) in the Cooper Basin must be at least 75 Myr old.

To maintain overpressure for approximately 100 Myr requires seal permeabilities in the range of $10^{-23}$ to $10^{-26}$ m$^2$ (Deming 1994), which is at or below the lowest shale permeability measurements. The sediments comprising the pressure seal in the Kirby 1 well are a maximum of 540 m thick between the deepest normally pressured drill stem test at 2717 m and the shallowest overpressured drill stem test at 3257 m (Fig. 2). This succession comprises dominantly siltstone with interbedded sandstone, shale, and occasional coal measures, and contains natural fractures (Alexander 1998; Sun 2001). Although no detailed analysis is presented herein, it is unlikely the sediments forming the pressure seal in the Kirby 1 borehole to have sufficiently low permeability to maintain overpressure generated prior to 75 Ma. It is further unlikely that overpressure generated 75 Ma could be maintained to the present day because the reduction in temperature that the Cooper Basin was subject to during the Tertiary is an underpressure-generating mechanism (Osborne & Swarbrick 1997). Hence, to retain overpressure generated prior to 75 Ma in the Cooper Basin requires extremely tight pressure seals or another mechanism to maintain the overpressure. The following section investigates whether overpressure may have been generated more recently by an increase in horizontal stress.

**Tectonic history and horizontal stress-driven overpressure mechanisms**

Numerous minifracture tests (Haimson 1993) have been run in the Cooper Basin to determine horizontal stress magnitudes prior to hydraulic fracture stimulation treatments. These tests indicate that contemporary minimum horizontal stress in the Cooper Basin is relatively high and approaches the vertical stress. Further, the occurrence of drilling-induced tensile fractures (DITFs) in vertical wells demonstrates that maximum horizontal stress is significantly greater than the minimum horizontal stress. Hence, the contemporary mean stress in the Cooper Basin is significantly higher than the vertical stress.

Minimum horizontal stress can be estimated from fracture closure pressure in hydraulic fracture tests (Engelder 1993), and the lower bound to leak off test pressure is considered to give a reasonable estimate of minimum horizontal stress (Engelder & Fischer 1994). A relationship between minimum horizontal stress and depth was estimated by fitting a power relationship to 17 leak off test pressures and 154 hydraulic fracture test closure pressures (Fig. 4):

$$\sigma_h = 16.8 \sigma_0^{1.14}$$  \hspace{1cm} (2)

where $\sigma_h$ is minimum horizontal stress. Contemporary maximum horizontal stress was constrained by modeling wellbore stress conditions required to replicate observed wellbore deformation, i.e. the formation DITFs witnessed on image logs in vertical wells the Cooper and Eromanga Basins. The minimum circumferential stress acting around an open borehole ($\sigma_\theta$) must be zero in order for DITFs to form (Brudy & Zoback 1999; Fig. 5). Assuming that the tensile strength of the rocks is zero (pre-existing zones of weakness), and ignoring temperature effects because of relatively cool drilling mud contacting warm wellbore wall rock (which tend to counteract any tensile strength), the magnitude of the maximum horizontal stress can be constrained such that $\sigma_h$ reaches zero. $\theta$ is the angle of the borehole with respect to the maximum horizontal stress (Fig. 5). The contemporary maximum horizontal stress gradient was thus estimated to be 45 MPa km$^{-1}$ in the Toolachee Formation in the overpressured region.

The stress state in the Cooper Basin during Cretaceous times was inferred from the presence of layer-bound, polygonal faults (LBPF) in the Cretaceous Eromanga succession (Oldham & Gibbins 1995). LBPF consist of densely packed, minor extensional faults with no preferential strike azimuth (Dewhurst et al. 1999). The absence of a preferential strike azimuth implies a low differential horizontal stress ($\sigma_{H} \approx \sigma_{\theta}$; Goulty 2001). It is assumed that stress state in the Cooper Basin was relaxed (no tectonic stresses) during the formation of the LBPF because of:

![Fig. 5. Wellbore stress conditions required for the formation of DITFs in vertical wells. The circumferential stress acting around an open borehole ($\sigma_\theta$) must reduce to zero in order for DITFs to form. Minimum horizontal stress ($\sigma_h$) is taken from equation (2) and wellbore pressure/mud weight ($P_w$) and pore pressure ($P_p$) are also known. Maximum horizontal stress ($\sigma_{H}$) is varied until $\sigma_h$ reaches zero; $\theta$ is the angle of the borehole with respect to the maximum horizontal stress.](image-url)
• low differential stress conditions associated with LBPF formation;
• LBPF occur predominantly in passive basin settings (Dewhurst et al. 1999); and
• there is no evidence for a zone of stress detachment between the Cooper and Eromanga Basins.

The horizontal stress magnitudes in the Cooper Basin in the Late Cretaceous have been approximated by the passive basin uniaxial strain reference state (Engelder 1993)

\[ \sigma_{HV} = \sigma_{HH} = \left( \frac{\nu}{1-\nu} \right) \sigma_V \]  

(3)

where \( \nu \) is Poisson’s ratio, \( \sigma_V \) is vertical effective stress, \( \sigma_{HV} \) is minimum horizontal effective stress, and \( \sigma_{HH} \) is maximum horizontal effective stress. The applied vertical stress is equal to the weight of the overburden. The vertical stress relationship in the Late Cretaceous was assumed to be the same as that of the present day (equation (1)). The horizontal stresses in the Late Cretaceous in the Cooper Basin was calculated as \( \sigma_{HV} = \sigma_{HH} = 0.33\sigma_V \) using a Poisson’s ratio of 0.25 and are summarized in Table 1.

The timing of the increase in horizontal stress in the Cooper Basin from relaxed during the Late Cretaceous to the contemporary high horizontal stresses is poorly constrained. The stress conditions required for LBPF formation must have existed at least until the deposition of the Winton Formation, the lower part of which contains LBPF. The LBPF probably formed during the deposition of the Winton Formation (98.5–90 Ma) because:

• LBPF occurs at shallow depths during burial (Goult 2001); and
• LBPF formation is compaction driven, and occurs in poorly consolidated sediments (Goult 2001).

Hence, the increase in horizontal stress in the Cooper Basin occurred during the last 90 Myr. The current compressional stress regime across Australia is believed to have originated during the Miocene (Dickinson et al. 2001). There is widespread evidence of reactivation in many Australian basins during this period, e.g. Gippsland Basin (Norvick & Smith 2001). This tectonism is related to a change in dynamics of the Australian plate, particularly along the New Zealand plate boundary (Dickinson et al. 2001).

Increasing horizontal stress may generate overpressure via disequilibrium compaction because of increases in the mean stress (Goult 1998) or via undrained tectonic shear (Yassir 1998). These processes involve a rearrangement of the rock matrix in response to an increase in applied stress, which results in the fluid supporting some or all of the additional applied stress.

In this paper, we relate overpressure generation to increasing mean stress. Mean stress \( (\sigma_m) \) is the average of the three principal stresses

\[ \sigma_m = \frac{1}{3} (\sigma_{11} + \sigma_{22} + \sigma_{33}) \]  

(4)

where \( \sigma_{11} \) is maximum horizontal stress. Given the present day and inferred Late Cretaceous stress conditions in the Cooper Basin, estimated mean stress has increased by 50 MPa at 3780 m (Table 1). This increase is sufficient to generate the observed 14.5 MPa of overpressure in Kirby 1 via disequilibrium compaction. Hence, tectonic loading resulting from changes in horizontal stress since the Late Cretaceous could have generated the overpressure witnessed in the Cooper Basin.

Overpressure generated by increases in horizontal stress is likely to have occurred during the Miocene, significantly later than overpressure generated by either burial-driven disequilibrium compaction or temperature-driven mechanisms. The time over which a seal can maintain overpressure is inversely related to sediment permeability (Deming 1994). Therefore, the seal permeability requirements are less extreme for overpressure generated by increasing horizontal stress. Furthermore, should the sediments be of sufficiently low permeability to maintain overpressure generated by burial or temperature-driven processes, significant overpressure is likely to have been generated during the subsequent increase in horizontal stress. Therefore, the overpressure witnessed in the Cooper Basin is likely to have been largely generated by increases in horizontal stress. However, we cannot rule out the possibility that overpressure generated by burial or temperature-driven processes in the Cooper Basin has been maintained to the present day.

### DISCUSSION

In this paper, we propose that increases in horizontal stress over geological time can generate overpressure. The occurrence of LBPF in the Cooper–Eromanga succession suggests a low horizontal stress environment in the Late Cretaceous, which has evolved to the present day high horizontal stress environment. Pore pressure has been shown to change in response to changes in horizontal stresses during tri-axial loading experiments (Yassir 1998). The ratio of pore pressure response to stress increase \( (\Delta P_p/\Delta \sigma_{11}) \) is usually greater than one (Yassir 1998). Minimum horizontal stress has also been shown to change in response to changes in pore pressure. Repeated pore pressure tests undertaken throughout the depletion of oil fields demonstrate that a reduction in pore pressure

| Table 1: Calculation of mean stress increase at 3780 m in the Kirby 1 well |
|-------------------|-------------------|-------------------|
|                  | Contemporary      | Late Cretaceous   | Difference  |
|                  | (MPa)             | (MPa)             | (MPa)       |
| Vertical stress  | 80                | 80                | 0           |
| Maximum horizontal stress | 170             | 50                | 120         |
| Minimum horizontal stress | 80              | 50                | 30          |
| Mean stress      | 110               | 60                | 50          |

pressure is accompanied by a reduction in minimum horizontal stress (Teufel et al. 1991). Furthermore, minimum horizontal stress has been shown to increase from shallow normally pressured sediments to deeper overpressured sediments (Engelder & Fischer 1994). The ratio of horizontal stress response to changes in pore pressure (Δσh/ΔPp) ranges between 0.46 and 1.18 in sedimentary basins (Hillis 2000). Many mechanisms have been proposed to explain the relationship between pore pressure and horizontal stress in sedimentary rocks. In particular, there is debate as to whether pore pressure drives changes in horizontal stress or vice versa (Bell 1996). It is not the purpose of this paper to discuss the driving mechanisms of pore pressure/stress coupling, rather to draw attention to the need for a greater understanding of these processes to allow more accurate pore pressure modeling and detection in compressional basins. In the Cooper Basin, we believe that an increase in horizontal stress is the only feasible mechanism of overpressure generation. The resultant increase in mean stress is sufficient to explain the observed overpressure purely because of disequilibrium compaction. However, we cannot discard the possible role of tectonic shear as described by Yassir (1998).

Tectonic loading may also be a feasible mechanism of overpressure generation in other ‘old’ basins. Lee & Deming (2002) modeled the generation of overpressure in the Anadarko Basin, Oklahoma, which has not experienced significant sedimentation for nearly 250 Myr. Lee & Deming (2002) concluded that the overpressure in the Anadarko Basin could not be easily explained by burial-driven disequilibrium compaction or gas generation because the average basin permeabilities required would be at or below the lowest shale permeabilities measurements. Moreover, the Anadarko Basin has been in a nearly continuous state of uplift and erosion for the last 50 Myr, and the dominant thermal change during this period has been cooling (Lee & Deming 1999). Although no detailed analysis is presented herein, uplift in the Anadarko Basin is likely to have been associated with a change in stress regime and an increase in horizontal stress. Tectonic loading associated with the uplift in the Anadarko Basin could potentially explain near lithostatic pore pressure observed in the deeper part of the basin. Additionally, tectonic loading provides a mechanism for overpressure generation in younger basins where the magnitude of observed overpressure cannot be explained by burial-driven disequilibrium compaction alone. Darby & Ellis (2001) modeled the generation of overpressure in the Taranaki Basin, New Zealand and concluded that the near lithostatic pore pressure must be generated, at least in part, by increases in horizontal stress.

CONCLUSIONS

Overpressure in the Cooper Basin cannot have been generated by burial-driven disequilibrium compaction or hydrocarbon generation and maintained for generations unless the average basin permeabilities are at or below the lowest known shale permeability measurements.

In the Cooper Basin, a change in stress regime from relaxed (σv > σh = σb) during Late Cretaceous times to one of contemporary high horizontal stresses (σh > σv > σb) has resulted in an estimated mean stress increase of approximately 50 MPa from the Late Cretaceous to that presently observed at almost 4 km in the Kirby 1 well.

Disequilibrium compaction driven by an increase in mean stress since the Late Cretaceous can explain the 14.5 MPa of overpressure witnessed in the Kirby 1 well. However, the role of tectonic shear cannot be discounted.

Tectonic loading may be a feasible mechanism for overpressure generation in other ‘old’ basins that have undergone a recent increase in horizontal stress (e.g. Anadarko Basin). The tectonic history of a basin, in addition to the burial and thermal histories, needs to be considered when assessing the origin of overpressure.

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**NOMENCLATURE**

$z$ depth

$P_p$ pore pressure

$P_w$ mud weight

$\sigma_0$ circumferential stress acting around an open borehole

$\theta$ angle of the borehole with respect to the maximum horizontal stress

$\sigma_m$ mean stress

$\sigma_v$ vertical stress

$\sigma_h$ minimum horizontal stress

$\sigma_{H}$ maximum horizontal stress

$v$ Poisson’s ratio

$\sigma_v'$ vertical effective stress

$\sigma_h'$ minimum horizontal effective stress

$\sigma_{H}'$ maximum horizontal effective stress

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