OVERPRESSURES IN THE CENTRAL OTWAY BASIN:
THE RESULT OF RAPID PLIOCENE-RECENT SEDIMENTATION?

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ABSTRACT

This paper reports the first evidence for significant overpressures in the Otway Basin, southern Australia, where most previous studies have assumed near-hydrostatic pore pressures. Overpressures are observed within the Upper Cretaceous Shipwreck supersequence in several wells in the Voluta Trough, such as Bridgewater Bay-1, Normanby-1 and Callister-1. One of these wells penetrated successions of Pliocene-Recent marine clastic sediments nearly 700 m thick that were deposited rapidly in submarine channels that were probably carved during the late-Miocene to early-Pliocene. Wire-line and drilling data suggest that overpressures present in Upper Cretaceous shales and sandstones within the Belfast Mudstone and Flaxman and Waarre formations developed either due to disequilibrium compaction - where there is no evidence of hydrocarbon generation and thick Pliocene stratigraphy is present - or due to fluid expansion where there is evidence of hydrocarbon generation and the Pliocene stratigraphy is thin to absent. The two key factors that may indicate abnormal pore pressures in Upper Cretaceous sediments in the central Otway Basin, are the thickness of Pliocene stratigraphy and whether or not hydrocarbons are actively generating from source rocks.

KEYWORDS

Overpressure, sonic velocity, disequilibrium compaction, net exhumation, Otway Basin

INTRODUCTION

Accurate estimates of formation pore pressures are an essential requirement for safe, economically successful exploration and drilling in overpressured regions (Tingay et al., 2009; Sayers, 2010). During the exploration phase, estimates of pore pressure can be used to develop fluid-migration models, to study the effectiveness of seals and to rank prospects for reservoir planning and reserve estimation (Mouchet and Mitchell, 1989; Law and Spencer, 1998; Tingay et al., 2009; Sayers, 2010). During the drilling phase in overpressured regions, accurate pore pressure prediction is imperative in order to ensure safe drilling operations through the selection of appropriate mud weights and optimization of well and casing designs (Sayers et al., 2002; Teige et al., 2007; Tingay et al., 2009; Sayers, 2010).

Although overpressures are known to be present in the central Otway Basin, most geomechanical investigations basin have assumed that pore-pressures are near-hydrostatic (Hillis et al., 1995; Nelson et al., 2006) and there have been no systematic studies of the nature, distribution and origin of the overpressure.

The purpose of the present study was to characterise the distribution and origin of overpressures in the central Otway Basin. The study investigated 5 offshore wells (Fig. 1) and used petrophysical wire-line data such as sonic velocity and bulk density logs and drilling and formation test data compiled from Well Completion Reports (WCR). All wells are located south of the Tartwaup-Mussel fault zone, along which late-Cretaceous extension produced thick NW–SE trending depocentres and widespread, pervasive, mainly south-to-southwest-dipping faults (Palmowski et al., 2001; Noll and Hall 2003).

MECHANISMS FOR OVERPRESSURE GENERATION

In order to accurately predict pore-pressures, it is necessary to understand what mechanisms are responsible for its generation (Bowers, 1995; Tingay et al., 2009). Osborne and Swarbrick (1997) provide a comprehensive overview of the mechanisms that can generate abnormally high formation pore pressures within sedimentary basins; they separate overpressure generation into two general categories: disequilibrium compaction mechanisms and fluid expansion mechanisms (Fig. 2).

In a perfect hydrostatic environment, any increase in compressive stress will be balanced by the normal compaction of the sediments and the expulsion of fluids in the pore space; thereby pore pressure remains hydrostatic and in equilibrium. Increases in compressive stress, brought about by rapid burial and the vertical loading of sediments or by changes in horizontal stress driven by tectonic forces, requires the rapid expulsion of fluid if the rock is to compact and the pore pressure remain hydrostatic. The expulsion of fluids in sediments with low permeability can be considerably slower, which may cause the pore fluids, rather than the compacting sediments/sediment matrix, to bear some of the compressive load. This process is known as *disequilibrium compaction* (Fig. 2) and it can generate considerable overpressures in tight, impermeable sedimentary sequences such as thick shales, mudstones, clays and marls. It can also produce overpressures in adjacent, highly permeable reservoir rocks, through stratigraphic isolation of the reservoir within finer grained, low permeable sections (Terzaghi and Peck, 1948; Yassir and Bell, 1996; Osborne and Swarbrick, 1997; Tingay et al., 2009). Stress-related mechanisms are the most likely causes of overpressure in many sedimentary basins (Osborne and Swarbrick, 1997).

Fluid expansion mechanisms of overpressure generation (Fig. 2) involve an increase in pore-fluid volume within a confined rock framework. The three primary processes by which fluid expansion can generate overpressure are aquathermal expansion, mineral diagenesis (e.g. smectite-to-illite and gypsum-to-anhydrite dehydration transformations, cementation) and the release of hydrocarbons from kerogen (Osborne and Swarbrick, 1997; Tingay et al., 2009). These processes result in overpressure generation because the mechanical compaction of sediments is largely irreversible, except for a slight elastic component (Magara, 1980). This does not allow pore volume to increase in a response to fluid expansion, thus increasing pore pressure (Mouchet and Mitchell, 1989; Neuzil, 1995). Perfect sealing is essential for these types of overpressures to occur and aquathermal expansion, clay diagenesis, osmosis and other fluid expansion mechanisms have been hypothesized to generate high magnitude overpressures (e.g. Barker, 1972; Perry and Hower, 1972; Mouchet and Mitchell, 1989). However, modelling under ideal conditions indicates that these mechanisms can generate only minor amounts of overpressure, although they may be mechanisms for creating hydrodynamic seals that promote disequilibrium compaction overpressures (Osborne and Swarbrick, 1997; Tingay et al., 2009). Depending upon the kerogen type, abundance of organic matter, temperature history, and rock permeability, hydrocarbon generation and the cracking of oil to gas can possibly produce overpressures, although since hydrocarbon generation is partially-pressure dependent, the subtle build-up of pressure may inhibit further organic catagenesis in a sealed system (Osborne and Swarbrick, 1997).

It has been argued that the movement of fluids and processes related to density differences between fluids and gases can 'transfer' overpressures (Osborne and Swarbrick, 1997). For example, fluids and overpressures can be transferred laterally within one or more hydraulically linked pressure compartments (Traugott, 1997; Tingay et al., 2007) by pressure redistribution within inclined, isolated reservoirs to maintain a hydrostatically parallel gradient (Yardley and Swarbrick, 2000). Overpressures may also be vertically transferred, as is the case in the Baram Delta (e.g. Tingay et al., 2009), via either cap-rock fracturing or active faulting (Grauls and Baleix, 1994; Tingay et al., 2007).

GEOLOGICAL SETTING OF THE OTWAY BASIN

The Otway Basin is one of several extensional basins located along the southern Australian margin that developed following initial rifting in the late Jurassic to early Cretaceous; rifting eventually resulted in the continental separation of Australia and Antarctica in the mid-Eocene (Krassay et al. 2004). The basin contains up to approximately 13 km of post-Jurassic sediments and trends broadly NW-SE, encompassing onshore and offshore parts of South Australia and Victoria, and offshore Tasmania (Krassay et al., 2004). There have been commercial gas discoveries within the Penola Trough in onshore South Australia and in the Port Campbell area and Shipwreck Trough in Victoria and many other hydrocarbon shows throughout the basin. Comprehensive overviews of the structure and stratigraphy of the basin are provided by Perineck and Cockshell (1995), Gallagher and Holdgate (2000), Boult and Hibburt (2002), Duddy (2003) and Krassay et al. (2004). The basin is divided into several structurally-controlled depocentres. This paper focuses on the Voluta Trough (which has been subdivided further into the Morum and Nelson sub-basins (Fig. 1; Moore et al., 2000)), where overpressured units occur within upper Cretaceous Sherbrook Group shales and sand units.

The Voluta Trough is a major depocentre separated from platform areas by the Tartwaup-Mussel fault zone, which comprises a series of major northwest-southeast striking *en-echelon* normal faults (Geary and Reid, 1998). Individual faults can be traced for between 30 to 80 km and generally display shallow to moderate dips (~40º), with very large displacements at the earliest late-Cretaceous levels, a result of major crustal extension at this time (Geary and Reid, 1998). Structural growth on these faults continued throughout the Late Cretaceous, with variable amounts of offset observed within the upper Cretaceous Sherbrook Group; many faults propagate upwards to a regional intra-Maastrichtian unconformity where they are commonly truncated (Geary and Reid, 1998). Structural closures south of this fault zone are associated mainly with titled fault blocks; large structures that have been targeted by wells include Bridgewater Bay-1, Voluta-1, Discovery Bay-1 and Normanby-1. A major, NE-SW trending structural culmination, variously named the Bridgewater High (Lavin and Mein, 1995), the Bridgewater Arch (Krassay et al., 2004) or the Discovery Bay High (Moore et al., 2000) effectively separates the Morum and Nelson sub-basins and is thought to have developed during the late-Maastrichtian (Lavin and Mein, 1995). Comparatively little structural activity occurred during the Cenozoic within this area, with relatively few normal faults observed; there is, however, evidence for localised inversion along the Tartwaup-Mussel fault zone (Geary and Reid, 1998). The intensity of Cenozoic inversion (i.e. fault reactivation and folding of Cenozoic sediments) increases to the east of the present study's focus area, with wells around the Port Campbell Embayment such as Minerva-1, Ferguson Hill-1 and Loch Ard-1 drilled into large mid to late-Cenozoic anticlines (Tuitt et al., in press).

The sedimentary succession of the Otway Basin is subdivided into a series of supersequences that accumulated under distinct structural and environmental conditions and which are bound by regional unconformities (Krassay et al., 2004; Fig. 3). The Upper Cretaceous Shipwreck supersequence and the Neogene Heytesbury and Whalers Bluff supersequences are the primary focus of this study.

The Turonian-Santonian Shipwreck supersequence is equivalent to the basal parts of the lithostratigraphic Sherbrook Group (i.e. the combined Copa, Flaxman, Waarre and Mt Salt formations, the Argonaut Member, Belfast Mudstone and Nullawarre Greensand (Fig. 3) (Krassay et al., 2004)). This supersequence contains both the most important proven reservoir (Waarre Formation) and the regional seal (Belfast Mudstone) in the eastern parts of the basin (Krassay et al., 2004). The base of the supersequence is marked by a major mid-Cretaceous (Cenomanian) unconformity, often referred to as the Otway Unconformity (Krassay et al., 2004). The supersequence comprises a series of distinct tectonostratigraphic packages. The basal package, which is of Turonian age, is equivalent to the Copa and Waarre formations and deposition was controlled strongly by extensional faulting. This package is represented by syn-rift growth wedges containing interbedded non-marine coarse sands, shales and silts (Krassay et al., 2004). The Waarre Formation displays an upward gradation from fine grained lithic sandstones to extremely quartzose, fine to very coarse grained, pebbly sandstones that are thought to have been deposited by a series of prograding deltaic complexes (Geary and Reid, 1998). The Turonian package is overlain by a Coniacian to early-Santonian package that is time equivalent to both the Flaxman Formation in South Australia and the Belfast Mudstone in Victoria (Krassay et al., 2004). The Flaxman Formation comprises interbedded mudstone, siltstone and fine to coarse grained sandstone that were deposited in near-shore to offshore marine environments (Geary and Reid, 1998). Although marine sands in the Flaxman Formation contribute to total gas reservoir sections at the Minerva and La Bella fields in the Shipwreck Trough, reservoir development is poor compared to the Waarre Formation, and, in general, the Flaxman Formation does not itself constitute a reservoir target in the Victorian parts of the Otway Basin (Geary and Reid, 1998). Pressure data from La Bella-1 indicate that the Flaxman reservoir is not in pressure communication with the underlying Waarre reservoir, implying that the formation has some sealing capacity (Geary and Reid, 1998). The Belfast Mudstone comprises grey-black silty mudstones with occasional sandstone interbeds that were deposited rapidly during a period of increased extension on syn-depositional faults (Geary and Reid, 1998). The thickness of the Belfast Mudstone increases rapidly into the Voluta Trough, with Bridgewater Bay-1 penetrating a 1,294 m thick succession that was deposited in relatively deep marine conditions (Geary and Reid, 1998).

The Upper Oligocene to Miocene Heytesbury supersequence comprises relatively shallow water carbonates of the basal Upper Oligocene Clifton Formation, overlain by Lower Miocene Gellibrand Marl and the Lower to Middle Miocene Port Campbell Limestone in Victoria, and the equivalent Gambier Limestone in South Australia (Fig.3). The Lower Miocene marls and Lower to Middle Miocene limestones represent a shallowing-upward sequence that records a prograding depositional system and the reduction of siliclastic sediment input as cool water carbonate sedimentation became established along the southern Australian margin (McGowran et al., 2004; Leach and Wallace, 2001; Hill et al., 2009). Widespread folding of the Lower to Middle Miocene limestones is primarily the result of northwest-southeast compressional shortening during the late-Miocene, which was accompanied by localised uplift and erosion (Hill et al., 1994; Perincek and Cockshell, 1995; Sandiford, 2003). This tectonic uplift was accentuated by a glacio-eustatically controlled fall in sea-level, which resulted in a widespread late-Miocene to early-Pliocene (~10-6 Ma) depositional hiatus across the basins along the southeastern Australian margin (Dickinson et al., 2001; Hill et al., 2009).

The Pliocene-Recent Whalers Bluff supersequence includes the Whales Bluff Formation, Hanson Plain Sand, Moorabool Viaduct Formation, Grangeburn Formation and Newer Volcanics (Krassay et al., 2004). These stratigraphic units primarily consist of mixed clastic/carbonate sediments indicative of open shelf carbonate sedimentation and record a period of mild compressional tectonism that begin during the late-Miocene (Dickinson et al., 2001; Leach and Wallace, 2001). In the northwestern parts of the Voluta Trough, around the Morum-1 well and the Lacepede Shelf, thin (6-10 m) Lower Pliocene-Recent shallow-water marine transgressive sand overlies the Heytesbury supersequence (Hill et al., 2009). In the central Voluta Trough (offshore Portland and Cape Bridgewater), however, Pliocene to Recent sediments are considerably thicker. Bridgewater Bay-1, Discovery Bay-1 and Voluta-1 each encountered thick Pliocene-Recent successions of 690 m, 544 m and 169 m, respectively (Fig.4). The stratigraphy above the Wangerrip Group (~800 m MDbMSL) in Callister-1 is reported as undifferentiated marls and therefore the distinction between the Miocene and Pliocene-Recent sediments in this well cannot be made. Furthermore, no sampling was made above 131 m MDbMSL in Normanby-1; the stratigraphy is assumed to be Miocene (Heytesbury Group) in age all the way to the seabed. Correlation with the onshore Whalers Bluff Formation with the sections penetrated by Voluta-1 and Discovery Bay-1 illustrates a clear seaward-thickening of the Pliocene-Recent succession, with an increase in sediment accumulation rate by some 30 times (Discovery Bay-1 WCR). The localised spatial distribution of this thick Pliocene-Recent succession is confirmed by wells located in the southeastern Voluta Trough (e.g. Triton-1, Nautilus-1), where Pliocene-Recent sediments are thin or absent (Fig.4).

OVERPRESSURES IN THE OTWAY BASIN

Evidence from formation testing and drilling parameters, such as connection gas, trip gas and dc-exponent, indicates the presence of overpressures in the basal sections of the Upper Cretaceous Sherbrook Group in a number of petroleum wells in the Otway Basin, including Breaksea Reef-1, Fahley-1, Normanby-1, Bridgewater Bay-1, Calister-1, Triton-1 and La Bella-1. The present study is focussed on overpressured wells within the Voluta Trough, namely Breaksea Reef-1, Normanby-1, Bridgewater Bay-1 and Calister-1, and in the Shipwreck Trough, La Bella-1 (Fig. 1). Brief drilling operation descriptions pertaining to overpressures were extracted from their respective WCRs and are included in Appendix A to highlight some of the evidence of overpressures in the Otway Basin. There have been no other systematic studies on the nature, distribution and origin of these overpressures. Boult et al. (2005), however, postulate that the cause of large-scale shelf collapse near Breaksea Reef-1 may be due to overpressures generated by the maturation of hydrocarbons, which reduces the effective stress and provides the necessary slip mechanism. Given that Breaksea Reef-1 had shows of migrated oil and these overpressures occur late in its burial history, which is typical of fluid expansion mechanisms (Gutierrez et al., 2006), this is a reasonable assumption.

Direct pore pressure measurements, such as Repeat Formations Tests (RFTs), were conducted in three of the five wells, but were only successful in two wells (Normanby-1 and La Bella-1). Formation fracture pressure measurements such as leak-off tests (LOTs) were also available for all the wells in this study. In the absence of more direct and reliable pore-pressure measurements, drilling mud weight data were also used as a proxy for pore pressure since these data are available for all five wells. These data provide an independent measure of pore pressure and are often just in excess of pore pressure to avoid drilling problems and to maximise drilling efficiency. Mud weight data can only be used as a proxy for pore pressure when increases in mud density are due to pore pressure changes, and not for other reasons, such as to improve wellbore stability (van Ruth and Hillis 2000; Reynolds et al. 2006). All available pore and fracture pressure data (i.e. RFTs, LOTs and mud weights) are plotted in Figure 5. The RFT measurements in La Bella-1 show that the magnitudes of overpressure are relatively small, following a pressure gradient of 12 MPa/km, whereas the single RFT measurement in Normanby-1 is higher, at around 14 MPa/km. LOT measurements vary between ~15 MPa/km to ~ 19 MPa/km, and mud weight data imply that the greatest magnitudes of overpressure occur within the Belfast Mudstone below ~3 km in Bridgewater Bay-1 and Callister-1 (Fig. 4). The discrepancy between the RFT pressure measurement and the equivalent depth mud weight pressure in Normanby-1 (Fig. 5) is most likely due to the well being drilled underbalanced for up to 250 m towards the bottom of the hole. Although underbalanced, the well did not suffer flows or a kick due to the low permeability of the formation (Templeton and Peattie, 1986). A hydrostatic pressure gradient of ~10.863 MPa/km (ρ_f, = 1.105 g/cm^3) has been assumed, based on mud weight data from Copa-1, which is interpreted to be normally pressured. This gradient is within the upper limit of a saturated brine (~11.44 MPa/km; Swarbrick and Osborne, 1998).

Excluding the effective stress approach of Bowers (1995), all other overpressure prediction models imply that undercompaction is the dominant cause of overpressures and, therefore, are likely to underestimate pressures associated with unloading such as fluid expansion and vertical transfer (Gutierrez et al. 2006). Unfortunately, due to the lack of direct pore pressure measurements inside and outside the overpressured sections, a definitive determination of the cause of overpressures reported in the Otway Basin is not possible. However, in the absence of reliable, direct formation pore pressure data (e.g. RFT), the mechanisms generating overpressures have been investigated by analysing the results of pore pressures predicted using the commonly applied Eaton (1972) pore pressure prediction method. This method uses wire-line data (i.e. sonic velocity and bulk density log data) and by observing whether or not this analysis yield results typical of either disequilibrium compaction or fluid expansion, the cause of the overpressures can be assessed. Sonic velocity and bulk density wireline log data are available for Breaksea Reef-1, Normaby-1, Bridgewater Bay-1 and La Bella-1; unfortunately, no wireline log data were available for Callister-1.

PORE PRESSURE PREDICTIONS USING WIRE-LINE LOG DATA

The Eaton (1972) method

The Eaton (1972) method is used in this study to predict pore pressures from wire-line sonic velocity log data. Overpressures generated by disequilibrium compaction typically have an Eaton (1972) exponent of 3.0 (Tingay et al., 2009). The Eaton (1972) method can therefore be used to determine the cause of overpressure generation. Pore pressure, P_P, is calculated by rearranging Terzaghi (1943)'s equation relating effective stress and overburden:

$$P_P = \sigma_V - \sigma_V{}' \qquad (1)$$

where σ_V = vertical, overburden stress or lithostatic pressure
σ_V' = effective vertical stress estimated by (Eaton, 1972);

$$\sigma_V' = (\sigma_V - P_h)\left(\frac{\Delta t_{norm}}{\Delta t}\right)^x \qquad (2)$$

where P_h = hydrostatic pore pressure (~10.863 MPa/km)
Δt = observed sonic velocity measurement
Δt_{norm} = sonic velocity from a normal compaction trend at a specified depth
x = Eaton (1972) exponent generally assumed to equal 3.0 for overpressures generated by disequilibrium compaction.

Raising the Eaton (1972) exponent to values greater then 3.0 empirically allows the Eaton (1972) method to be used in sequences overpressured by either fluid expansion or vertical transfer mechanisms by amplifying the reduced sonic log response associated with such overpressures (e.g. Hermanrud et al., 1998; Tingay et al., 2009).

Vertical stress estimates

The vertical stress, σ_V, in offshore wells is defined as the pressure exerted by the weight of the water column from the surface to the seabed plus the weight of overlying rocks at a specified depth, z, and is expressed as (Sayers, 2010):

$$\sigma_v = \rho_w g z_w + \int_z^{z_w} \rho(z) g dz \qquad (3)$$

where $\rho(z)$ = density of the overlying rock column at depth z
ρ_w = density of the fluid
z_w = water depth
g = accelation due to gravity.

In order to calculate accurate vertical stress estimates, the bulk density log data (RHOB) was carefully filtered to remove spurious data that result from poor contact between the tool and the borehole wall, caused by rugose borehole conditions (Tingay et al., 2003). Filtering involved application of the procedure of Tingay et al. (2003), where bulk density data were assumed to be affected by rugosity if the density error log, DRHO > $|\pm 0.1|$ g/cm3 and the caliper log is ≥ 5 % of the bit or hole size. Any wells that did not have all or some of these additional data were nevertheless still analysed, but considered less reliable. Filtered (and non-filtered) logs were then also manually edited and ‘de-spiked’ to remove anomalous measurements, prior to calculating the vertical stress (Tingay et al. 2003). Since it is uncommon for bulk density to be logged from the surface, check-shot velocity data was used to determine the average density from the surface to the top of the density log using the Nafe-Drake velocity/density relationship (Ludwig et al., 1970).

The vertical stress profiles for Breaksea Reef-1, Normanby-1, Bridgewater Bay-1 and La Bella-1 are shown in Figure 6 and each well has been assigned a power-law relationship that is used to estimate pore pressures. Breaksea Reef-1 has the lowest vertical stress magnitudes for any given depth, but the vertical stress gradients for all wells are broadly similar, at approximately 21-22 MPa/km.

Normal compaction trends

SONIC VELOCITY LOG DATA

The Eaton (1972) method relies heavily upon the use of reliable sonic velocity data and, more importantly, the ratio of sonic velocities in normally pressured and normally compacted sediments to measured sonic velocities (Tingay et al., 2009). A reliable normal compaction trend is therefore vital to constrain estimates of pore pressure. The Otway Basin has experienced several phases of uplift and erosion (i.e. exhumation) in the mid-Cretaceous, Paleocene to mid-Eocene and Miocene-Pliocene (Teasdale et al., 2003). Apatite fission track analyses (AFTA) and vitrinite reflectance data (VR) indicate that ~1,000 m of additional section has been removed from the top-Nirranda Group unconformity in Bridgewater Bay, and ~850 m of additional section has been removed from the top-Wangerrip Group unconformity in Breaksea Reef-1 (Duddy, pers. com.). This makes determining a normal compaction trend for these sequences problematic because both exhumation and overpressures can cause anomalous porosity/depth relationships (van Ruth and Hillis, 2000).

Overpressures cause sediments to be undercompacted with respect to a normal compaction trend, whereas exhumation causes sediments to be overcompacted with respect to a normal compaction trend (Corcoran and Doré, 2005). Normal compaction trends in exhumed basins must therefore be corrected to remove any log measurement effected by exhumation, so that the 'apparent' normal compaction trend fits the upper, normally pressured part of the sequence (van Ruth and Hillis, 2000). Lithology (e.g. mineralogy and composition) and/or diagenetic effects (e.g. smectite-illite transition or cementation) can have a profound effect on the position of a normal compaction trend and should also be taken into consideration when estimating pore pressure and exhumation (Mondol et al., 2007).

In order to remove common sources of noise in sonic velocity log data, such as cycle skipping caused by poor borehole conditions (Rider, 1996; van Ruth and Hillis, 2000), a de-spike filter was applied to the log data (Fig. 7).

ESTABLISHING NORMAL COMPACTION TRENDS

To establish a normal compaction trend for the Upper Cretaceous Shipwreck supersequence, normally pressured sonic velocity log data were selected from the thick and laterally extensive Belfast Mudstone using data from wells that are thought to be presently at their maximum burial depth on the basis of AFTA and VR data (i.e. the maximum palaeotemperatures of rock units indicated by these data are close to measured present-day temperatures) (Duddy, 1997; Duddy pers. com.). Even though the overpressured units in the Voluta Tough occur in the Belfast Mudstone and below (Fig. 3), normal compaction trends were constructed for the overlying Paaratte Fomation, which is a thick and regionally extensive stratigraphic unit. Wells used to constrain normal compaction - and thus normally pressured - trends for the Paaratte Formation and Belfast Mudstone include Argonaut-1, Voluta-1 and Discovery Bay-1. Shales and mudstones exhibit relatively simple compactional trends: porosity decreases rapidly with depth, they are often more homogeneous in terms of grain size and mineralogy, and they do not act as aquifers with the consequent porosity variations (Japsen et al., 2007). For this reason, shaly lithologies were identified using gamma-ray logs (as a proxy for shale volume; e.g. Rider, 1996) and used to filter sonic velocities where the equivalent gamma-ray responses are greater than 90 API units. A best-fit exponential curve was then fitted to normally pressured sonic velocities from the Paaratte

Formation and Belfast Mudstone (Athy, 1930; Tingay et al., 2009), yielding:

Paaratte Formation: $$\Delta t_{norm} = 496.22e^{-0.0002186z} \tag{4}$$

Belfast Mudstone: $$\Delta t_{norm} = 468.26e^{-0.0001881z} \tag{5}$$

where z is in metres and Δt_{norm} is in µs/m.

The Upper Cretaceous formations below the Belfast Mudstone (i.e. the Flaxman and Waarre formations) are relatively thin and generally contain less shaly lithologies. For these reasons it was difficult to construct a highly reliable normal compaction trend for these formations; it has been assumed that they follow a similar normally pressured and normally compacted trend to that of the Belfast Mudstone, despite their varying lithologies.

CORRECTING FOR NET EXHUMATION – 'APPARENT' NORMAL COMPACTION TRENDS

The displacement of the observed normally pressured sonic velocity values, on the depth/vertical axis, from the normal compaction trend gives an estimate of net exhumation (Hillis, 1995; Corcoran and Doré, 2005). Net exhumation magnitudes were calculated and filtered for the Paaratte Formation and the normally pressured sections of the Belfast Mudstone (Table1), which corresponds to exhumation event(s) that occurred after the late-Cretaceous. The normal compaction trends for the Paaratte Formation and Belfast Mudstone therefore now represent an 'apparent' normal compaction trend (herein referred as 'uplift-corrected NCT') and follow the form:

$$\Delta t_{norm} = ae^{-b\left(z - E_{N_i}\right)}$$

where a and b are calibrated parameters in Equations 4 and 5, and E_{Ni} is the amount of net exhumation in well i, represented by a negative number. The net exhumation estimates for the Belfast Mudstone were also used to correct exhumation in the Flaxman and Waarre formation sections of the wells prior to estimating pore pressure.

Table 1. Net exhumation estimates for the Paaratte Formation and the normally pressured sections of the Belfast Mudstone which were corrected for the estimate of pore pressure. Since a gamma ray cut-off of 90 API units yielded no shale lithologies in the Paaratte Formation, the gamma ray cut-off was lowered to 70 API units in order to estimate exhumation for this section.

Well	Paaratte Formation Net Exhumation (m)	Belfast Mudstone Net Exhumation (m)
Breaksea Reef-1	-309 ± 140	-164 ± 133
Normanby-1	-654 ± 119	-1000 ± 192
Bridgewater Bay-1	-150 ± 98	-290 ± 108
La Bella-1	n/a	-578 ± 250

As can be seen in Figure 7, the observed velocity trends for some of the wells (e.g. La Bella-1, Normanby-1) vary in slope significantly in comparison to the normal compaction trends and do not correctly represent the compaction trends for those wells. This consequently impacts the accuracy of net exhumation estimates with depth and yields a less confident pore pressure estimate.

The complex burial history of the basin necessitated that the approach of Bowers (1995) be employed to determine the power-law function relationship between the effective vertical stress and sonic velocity for the normally pressured section of the Upper Cretaceous stratigraphic units. This effectively calculates the 'apparent' normal compaction trend (herein referred to as 'effective-stress NCT') for the equivalent depth, but disregards the consequence of exhumation, and when applying it to the entire Upper Cretaceous Sherbrook Group, assumes the same normal compaction trend for all formations regardless of lithology. An advantage of this approach is that it treats each well's sonic velocity response uniquely, which may effectively compensate for calibration discrepancies of the logging tools used in different wells. The calibrated power-law functions used to determine the alternate Δt_{norm} values can be seen in Figure 8.

Results of pore pressure prediction

Figure 8 shows the results of the Eaton (1972) pore pressure prediction method for both normal compaction trends and using an Eaton (1972) exponent of 3.0 for Breaksea Reef-1, Normanby-1, Bridgewater Bay-1 and La Bella-1. RFT, LOT and mud weight data have also been plotted as well as the vertical and hydrostatic stresses. The Eaton (1972) method indicates that all the studied wells are overpressured. The mud weight data and Eaton (1972) method suggests a similar magnitude of overpressure in Bridgewater Bay-1's Belfast Mudstone at depths below 3,500 m MDbMSL for both normal compaction trends used. The Eaton (1972) method gives similar pressures in Normanby-1 to the RFT measurement in the Waarre Formation using the uplift-corrected NCT and slightly underestimates pore pressures using the effective-stress NCT. In Breaksea Reef-1, the uplift-corrected NCT overestimated pore pressures with respect to the mud weight data, whereas the effective-stress NCT values underestimated pore pressures with respect to the mud weight data. Finally in La Bella-1, (although the Eaton (1972) pore pressure values vary to some extent due to scatter of the sonic velocity response) the overall the magnitudes predicted using the effective-stress NCT overestimates the RFT measurements where as the uplift-corrected NCT matches the RFT measurements over selected intervals.

With the exception of Bridgewater Bay-1, the depth at which mud weights and RFT measurements (in La Bella-1) begin to show overpressures is very well predicted using the Eaton (1972) method, which corresponds to the depth at which the sonic velocity response reverses (Fig. 7). However, drilling information in the Bridgewater Bay-1 WCR states that overpressures were encountered from ~3,028 m MDbMSL but did not manifest themselves until a depth of 3,526 m MDbMSL had been reached due to an 82 hour delay caused by weather issues. This depth correlates very well with the depth predicted using the Eaton (1972) method and, therefore, accounts for the discrepancy observed between the mud weights which, appears typical of a fluid expansion overpressure response (see Fig. 2), and the predicted pore pressure between ~3,028 and 3,526 m MDbMSL.

Given that the uplift-corrected NCTs poorly represent the observed sonic velocity trend in Breaksea Reef-1 and La Bella-1 (Fig. 7), and shows similar estimates of pore pressure in Bridgewater Bay-1 and Normanby-1 with the effective-stress NCT (Fig. 8), we consider the effective-stress NCT as the better representation of pore pressures.

DISCUSSION

Origin of overpressures in the Otway Basin

The Eaton (1972) method using an exponent of 3.0 has had some success in predicting pore pressures in the Otway Basin (Fig. 8), as well as providing an insight into the origin of these overpressures. The accuracy of the pore pressure prediction in Bridgewater Bay-1 suggests that the sonic velocity anomaly associated with the overpressure is consistent with the overpressures being generated by disequilibrium compaction. The predicted pore pressures are slightly underestimated in Breaksea Reef-1 and Normanby-1, which indicates that an increase in the Eaton (1972) exponent will yield a better pore pressure prediction. This may indicate that overpressures are likely to be associated with an unloading mechanism, such as fluid expansion (e.g. maturation of hydrocarbons) or vertical transfer, rather than, or in combination with, disequilibrium compaction (Bowers, 1995; Teige et al., 2007). This conclusion is further supported by the oil leg interpreted to exist within Breaksea Reef-1 and a weak hydrocarbon (gas) show from the Waarre Formation in Normanby-1 (Geary & Read, 1998; O'Brien et al., 2009). Hydrocarbons in both cases are thought to be sourced from Aptian to Albian fluvial and coaly facies of the Eumeralla Formation, that are assigned to the Austral 2 petroleum sub-system (Bradshaw, 1993; Summons et al., 1998). In contrast to Breaksea Reef-1 and Normanby-1, however, the predicted pore pressures in La Bella-1 are overestimated with respect to the RFT measurements in the Waarre Formation sandstones. Van Ruth & Hillis (2000) observed a similar situation in Moomba-55 in the Cooper Basin and suggested that the discrepancy between the Eaton (1972) method and the mud weight and formation pressure data may be explained by enhanced lateral transfer pressures that occur at the crest of isolated overpressured permeable reservoir units (Yardley and Swarbrick, 2000). A similar situation may exist in La Bella-1, where the Eaton (1972) method accurately predicts higher overpressures in the low permeability shales but not the permeable, less overpressured sandstones from which the RFT data were acquired. Furthermore, the RFT and drilling data showed that two overpressured, isolated gas sand intervals were not in pressure communication with each other, nor in pressure communication with nearby wells (e.g. Eric the Red-1), which are not overpressured. These observations support the notion of enhanced lateral transfer of pressures in permeable reservoir units.

The occurrence of overpressures generated by disequilibrium compaction in the Upper Cretaceous sediments as a result of initial rapid sedimentation is doubtful, especially given that significant exhumation is likely to reduce pore pressures (van Ruth & Hillis, 2000; Swarbrick & Osborne) and the Otway Basin has experienced several exhumation events (Cooper & Hill 1997). The occurrence of overpressure in the offshore Otway Basin, therefore, requires that the overpressures have either been adequately sealed to preserve high pressures since initial (rapid) deposition in the late-Cretaceous (during multiple exhumation phases and possible seal breach resulting from fault reactivation), or, more likely, that the overpressures post-date compaction (van Ruth & Hillis, 2000). A robust fault-seal evaluation would be required to dismiss the possibility that overpressures have been retained since the late Cretaceous in spite of fault reactivation and seal breach, though the geological evidence for Cenozoic fault reactivation throughout the Otway Basin makes this scenario unlikely. As a result, a fluid expansion mechanism seems more plausible to explain the overpressures observed in the wells analysed in this study, and fluid expansion is commonly invoked to explain overpressures that are relatively minor or occur late in the burial history (Gutierrez et al., 2006). An alternative possibility is that the recent, rapid sedimentation has resulted in another phase of disequilibrium compaction. There is ~700 metres of post mid-Pliocene section at Bridgewater Bay-1, which equates to a sediment accumulation rate of ~130-190 m/Ma. Such geologically recent and rapid burial as is witnessed in Bridgewater Bay-1, where no hydrocarbons have been reported, may be sufficient enough to generate high overpressures in the low permeable Upper Cretaceous Belfast Mudstone as a result of disequilibrium compaction. Discovery Bay-1 also has a considerably thick Pliocene section similar in nature to that of Bridgewater Bay-1, though no overpressures were reported in this well. This may due to the fact that Discovery Bay-1 was only drilled into the upper ~78 m of the Belfast Mudstone (Fig. 4), the occurrence of overpressures in deeper parts of the Belfast Mudstone cannot be discounted.

Predicted pore pressures and drilling data indicate that the onset of overpressures occurs in the Belfast Mudstone in Breaksea Reef-1, Bridgwater Bay-1 and Normanby-1, and in the Waarre Formation in La Bella-1. Drilling data from Callister-1 also show that the onset of overpressure in this well occurs in the Belfast Mudstone. Recent geochemical analyses have found that the gas composition in wells along, or immediately inboard of the Mussel-Tartwaup Fault Zone (Fig. 1), such as La Bella-1, contain significantly wetter components to the dominant Austral 2 reservoired hydrocarbon inventory in comparison to the drier, completely Austral 2 hydrocarbon accumulations in the Port Campbell region (O'Brien et al., 2009). Preliminary results from δTLogR analyses in La Bella-1 have shown that the Turonian interval (i.e. the Flaxman and Waarre formations) contains significant enrichment in total organic carbon (TOC) compared to that observed from conventional down-hole analytical TOC data. This has led to the suggestion that a late-Cretaceous fluvio-deltaic facies from the Austral 3 petroleum sub-system (Bradshaw, 1993; Summons et al., 1998) has the potential to generate hydrocarbons in the Otway Basin (O'Brien et al., 2009). No previous discoveries in the Otway Basin have been attributed to an Austral 3 source, though temporally equivalent stratigraphic intervals in the Gippsland Basin (i.e. the Upper Cretaceous to Lower Palaeocene Latrobe Group) are widely recognised as the major source interval in that region (O'Brien et al., 2009). O'Brien et al. (2009) suggest that this wetter, geochemical distinction in the La Bella-1 reservoired hydrocarbon inventory, may indicate a source within the basal (Turonian) part of the Austral 3 sub-system. If TOC enriched, low permeability shales in the Waarre Formation are indeed making some contribution to the hydrocarbon accumulation at La Bella-1, this may further support the notion that the Eaton (1972) method over-predicts pore pressure in the low permeability, unloaded, Waarre Formation shale units, but not the sandstones.

The hydrocarbon shows in Breaksea Reef-1 and Normanby-1 are known to be sourced from the Austral 2 sub-system (O'Brien et al., 2009). It thus seems improbable that overpressures in the shallower Belfast Mudstone are generated by fluid expansion of an Austral 2 source in these wells. Since the predicted pore pressures are more typical of an unloading mechanism, it is possible that overpressures have been vertically transferred along breached late-Cretaceous faults (Tingay et al., 2009). However, new δTLogR data in Normanby-1 have revealed the presence of organically-rich intervals in high-stand sequences as shallow as the Upper Cretaceous Paaratte Formation (Fig. 3; O'Brien et al., 2009). If the Belfast Mudstone contains similar TOC-enriched units that have sufficient thermal maturity in Breaksea Reef-1 and Normanby-1, it may be possible that the overpressures in the Belfast Mudstone can be attributed to fluid expansion of hydrocarbons generated from an Austral 3 source. Since the proposed Austral 3 source in La Bella-1 is wetter and more liquid-prone (O'Brien et al., 2009), it may be reasonable to conclude that moderate (<14 MPa/km) overpressures are in fact generated by fluid expansion of an Austral 3 source, given that the minor hydrocarbon show in Breaksea Reef-1 was oil.

Drilling data from Callister-1 show significantly high pore pressures (exceeding 15 MPa/km; Fig. 5) that are associated with overpressures as opposed to wellbore stability issues. Although there is evidence for a weak Austral 2 gas show in this well (O'Brien et al., 2009), it is difficult to determine whether these overpressures were generated by an unloading mechanism or disequilibrium compaction, given that sonic velocity and density data were not available for pore pressure prediction, and the stratigraphy of the well above (i.e. younger than) the Lower Eocene to Paleocene Wangerrip Group is poorly defined (Fig. 4). However, given the close proximity of Callister-1 to Bridgewater Bay-1 and large canyons filled with Pliocene sediments (Fig. 9a), it is reasonable to infer the presence of a moderately thick Pliocene succession in this well, though thinner than that encountered by Bridgewater Bay-1. This inference is supported by seismic data adjacent to the well (Fig. 9b). It may be possible that both unloading and disequilibrium compaction overpressure generating mechanisms are contributing to the observed overpressures in Callister-1, though it is difficult to conclude with certainty based on available data.

Canyon development and source of sedimentation

Descriptions of cuttings indicate that the thick Pliocene stratigraphy in Bridgewater Bay-1 comprises coarse clastic limestone, with minor or no fossils (Bridgewater Bay-1 WCR). Seismic mapping in the central Otway Basin (e.g. Leach & Wallace, 2001) indicates that these sediments contribute to the sedimentary infill of canyons in the vicinity of Bridgewater Bay-1 (Fig. 9). Erosion that accompanied submarine canyon development is the most likely explanation for the incomplete, ~70 m thick Miocene succession at Bridgewater Bay-1, compared with the ~543 m thick Miocene section encountered in Voluta-1. Seismic data reveal at least two phases of Pliocene canyon incision and fill, and a seismic section oriented parallel to the strike of the canyons that ties Voluta-1 and Bridgewater Bay-1, shows features characteristic of shelf progradation (Fig. 9b; Leach & Wallace, 2001).

The origin of these canyons, and the cause of subsequent rapid sediment accumulation, are poorly understood fully understood. The Pliocene-recent canyons have regular, even spacing that may be suggestive of a slope-controlled process (Leach & Wallace, 2001). Recent research into recent geological evolution of the Murray Basin (Miranda et al. 2009), has presented evidence that the major drainage system in the Murray Basin during the late-Pliocene was a southward-flowing river system through western Victoria, along the line of Wimmera and Glenelg, represented by the Douglas Depression palaeo-drainage system (Miranda et al. 2009). If this was the case, then a proto-Murray

River transporting large volumes of sediments that had been recently uplifted and eroded in the late-Miocene, may have deposited sediments at a sufficiently rapid rate to cause disequilibrium compaction in Bridgewater Bay-1. The sudden generation of overpressures may have caused sufficient reduction in effective stress to trigger shelf collapse (cf. Boult and Hibburt, 2002) which may have influenced the development of the canyons near Bridgewater Bay-1.

Overpressure prediction in the Otway Basin

In order to predict the distribution of overpressures within the Otway Basin, comprehensive 3D basin modelling (e.g. Sayers et al. 2002) would be required, which is beyond the scope of this study. Nevertheless, we have shown that by integrating wire-line and drilling data with stratigraphic constraints and our knowledge of hydrocarbon occurrences in the basin (O'Brien et al., 2009), it is possible to identify areas that are likely overpressured. We suggest that the two key factors that may be suggestive of abnormal pore pressures in Upper Cretaceous sediments in the central Otway Basin are the thickness of Pliocene stratigraphy, and whether or not hydrocarbons are actively generating.

Thick (e.g. >500 m) Pliocene sequences suggest rapid recent sediment accumulation, which may cause disequilibrium compaction in low permeable rocks such as those of the Upper Cretaceous Belfast Mudstone. The thickness and distribution of areas of thick Pliocene sedimentation can be relatively easily assessed using existing seismic data to generate sediment isopach maps.

Around 94% of the discovered hydrocarbons in the entire Otway Basin, and 99% of the gas discoveries in Victoria are sourced from the Austral 2 sub-system (O'Brien et al., 2009). Hydrocarbon shows in the central onshore Otway Basin (e.g. Caroline-1, Lindon-1) may potentially have mixed Austral 2 and Austral 1 (i.e. fluvio-lacustrine shales of the Casterton Formation and Crayfish Subgroup) source rocks (O'Brien et al., 2009). However, it is likely that the majority of any undiscovered resources in parts of the basin such as the outer shelf, will be related to the Austral 2 sub-system (O'Brien et al., 2009). The zones of greatest prospectivity in the basin are located where source rocks did not exhaust their entire generative capacity during the Cretaceous, but have been actively generating and expelling remaining hydrocarbons throughout the late-Cenozoic following sediment loading by Upper Oligocene to Miocene Heytesbury Group carbonates (O'Brien et al., 2009). The peak hydrocarbon generation window for the Austral source systems is located between approximately 2,500 and 3,500 m (sub-surface or sub-seafloor), and all significant Austral 2 sourced accumulations in the basin are located either directly within, or within less than approximately 3 km of an actively generating Austral 2 source rock kitchen (O'Brien et al., 2009).

The majority of the observed overpressures reported in this study occur in the late Cretaceous Belfast Mudstone. Recent investigations into the petroleum systems of the Otway Basin (e.g. O'Brien et al., 2009) have provided evidence for the potential importance of Austral 3 system source rocks of late Cretaceous-earliest Paleocene age. Understanding the distribution and generation potential of this system may therefore have implications for predicting overpressures related to fluid expansion, especially in relatively unexplored parts of the basin. Figure 9a shows the distribution and magnitude of overpressures (using mud-weight as a proxy) identified in this study overlain on the approximate distribution of peak, thermally mature, Austral 3 (i.e. Flaxman and Waarre formation) source rocks (O'Brien et al., 2009). This peak maturity map was produced by taking the top Eumeralla Formation or top Otway Group depth and subtracting 500 m from it produce a pseudo Flaxman-Waarre horizon (O'Brien et al., 2009). Where the combined Flaxman-Waarre thickness does not exceed 500 m this map might represent a pseudo

Belfast Mudstone horizon. It should be noted that this map does not take into account potentially important factors such as differential exhumation, variations in heat flow across the area and variations in Kerogen type. As previously discussed, thermal history data from Bridgewater Bay-1 and Breaksea Reef-1 indicate a considerable amount of post-late-Cretaceous exhumation (Duddy pers. comm.), which is not taken into account in the peak maturity Austral 3 fairway map shown in Figure 9a. Nevertheless, this map does provide a useful, first-order means of assessing how generation fairways are distributed regionally across the basin (O'Brien et al., 2009) and, could be used a general guide to possible areas that may potentially contain abnormal pressures as a result of fluid expansion (i.e. unloading). We note that according to Figure 9a, Normanby-1, Callister-1, Triton-1 and La Bella-1, which all contain Austral 2 hydrocarbon shows and small to moderate overpressures, lie within or near the zone of postulated active generation from Austral 3 source rocks. Bridgewater Bay-1, which has no hydrocarbon shows but the greatest observed overpressure lies in the blue shade away from the active generative zones. This observation supports the pore pressure prediction analyses, and that overpressures within the Belfast Mudstone in wells located in actively generating Austral 3 zones, without Pliocene stratigraphy are likely caused by an unloading mechanism, whereas, overpressures in the Belfast Mudstone in non-actively generating Austral 3 zones, with thick Pliocene stratigraphy are likely caused by disequilibrium compaction.

Finally, if Austral 2 hydrocarbons have migrated to Upper Cretaceous sediments, then mapping of late Cretaceous faults in or near actively generating Austral 2 hydrocarbon zones may also be useful to predict overpressures if overpressures are caused by an unloading mechanism as a result of vertical transfer along faults rather than in situ fluid expansion.

CONCLUSIONS

The key conclusions of this study of overpressures in the offshore central Otway Basin are:

- Overpressures occur in the Upper Cretaceous stratigraphy and appear to have been generated late in the history of the basin. Sonic velocity data record porosity anomalies associated with both overcompaction caused by uplift and erosion, and undercompaction caused by overpressures.

- The Eaton (1972) pore pressure estimation method using sonic velocity and density data successfully predicted the occurrence of overpressures in all the studied wells.

- The depth at which overpressures commence, in comparison with RFT and mud weight data, was accurately predicted using the Eaton (1972) method.

- The magnitudes of observed overpressures are greatest in Bridgewater Bay-1 (~ 18 MPa/km) and least in La Bella-1 (~ 12 MPa/km).

- An Eaton (1972) exponent of 3.0 accurately estimates pore pressure in Bridgewater Bay-1, underestimates pore pressure in Normanby-1 and Breaksea Reef-1, and overestimates pore pressure in La Bella-1 with respect to RFT and mud weight data. It is suggested that overpressure in the low permeability basal Upper Cretaceous sediments of Bridgewater Bay-1 may be caused by disequilibrium compaction resulting from rapid early to mid-Pliocene sediment accumulation rates (~130-190 m/Ma). The origin of overpressure in Breaksea Reef-1 and Normanby-1, where hydrocarbon shows have both been recorded, is more likely to be an unloading mechanism such as fluid expansion or vertical transfer, either in isolation from or in combination with disequilibrium compaction. The origin of overpressure in La Bella-1 is difficult to determine, but one possible explanation for the anomalously high predicted pore pressure in this well is the lateral transfer of overpressures into the crest of isolated permeable reservoir units.

- The two key factors that may be suggestive of abnormal pore pressures in Upper Cretaceous sediments for which explorers should be aware of in the central Otway Basin are the thickness of Pliocene stratigraphy, and whether or not hydrocarbons are actively generating. First, the existence of thick (e.g. >500 m) localised Pliocene sedimentary successions suggests rapid recent sediment accumulation, which may have caused disequilibrium compaction in low permeability rocks such as the Upper Cretaceous Belfast Mudstone. The onset of initial overpressures generally occurs in the Belfast Mudstone, and the Upper Cretaceous fluvio-deltaic facies of the Belfast, Flaxman and Waarre formation that belong to the Austral 3 petroleum sub-system have been shown to be a TOC-enriched and liquids-prone source contributing to known hydrocarbon accumulations (e.g. La Bella-1). Thus, the approximate distribution of the peak, thermally mature, Austral 3 source rocks may be a good guideline to explorers of potential areas where overpressure exist as a result fluid expansion. In addition, mapping of late Cretaceous faults may also be useful if Austral 2 hydrocarbons have migrated to Upper Cretaceous sediments causing overpressure as a result of vertical transfer.

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APPENDIX A

Table 2. Brief drilling operation descriptions pertaining to overpressures extracted from their respective WCRs to highlight some of the evidence of overpressures in the Otway Basin.

Well	Description
Breaksea Reef-1	Drillers relied on a deviation of the dc-exponent trend to indicate overpressure, formation changes or major changes in drilling or mud properties. This indicated a formation pressure gradient (FPG) of 10.5 peg at 3400 bib increasing to between 11.0 and 11.3 ppg by 4000 mbKB which then remained constant to 4360 mbKB.
Normanby-1	The Waarre Formation was found to be overpressured at ~ 3084 mbKB and due to a number of influxes; the mud weight was raised to 1.42 sg (~11.83 ppg) by 3306 mbKB in order to prevent pressure control problems. One RFT was sampled in Normanby-1 at 3178 mbKB which showed their 1.43 sg mud weight to be just on balance and that the hole was drilled underbalanced for up to 250 m, however, although underbalanced, the well did not flow due to the low permeability of the formation.
Bridgewater Bay-1	Overpressures existed from 3050 m to the wells total depth of 4200 mbKB with the degree of overpressuring in the order of 15.5 ppg at 4042 mbKB, however, this condition did not manifest itself until a depth of 3548 m had been reached due to an 82 hour delay caused by weather issues. Nevertheless, the data interpreted from the electronic logs indicate overpressuring which caused problems with respect to casing design.
Calister-1	Relied upon drilling parameters couple with hole conditions observed while drilling to predict changes in pore pressure, from which abnormal pore pressures were indicated. An increase in pore pressure was observed from 2770 to 2890 mbKB and at 2890 mbKB, there is a rise in mud weight of 1.15 sg (9.58 ppg) increasing to 1.26 sg (10.50 ppg) at 3016 mbKB. Between 3370 and 3500 mBKB there are several severe cut backs in the dc-exponent and signs of overpressure and at the appearance of the first major sand beds, the mud weight was increased to 1.44 sg at 3630 mbKB, then 1.46 sg at 3652 mbKB, then 1.54 sg at 3788 mbKB, and finally 1.56 sg before the end of the well and total depth at 3914 mbKB
Triton-1	The presence of overpressure is supported by drilling parameters such as connection gas, trip gas, dc exponent and general hole conditions. From 1700 to 2200 m bKB, pore pressure increases from 8.3 to 15.7 ppg mud weight equivalent (MWE), with the maximum indicated pore pressure of 15.7 ppg MWE at 2200 m. Between 2200 to 3500 mbKB (sloughing and caving between 2000 and 2803 m), the pore pressure remains constant at ~ 15.0 ppg MWE, however, there is uncertainty from the log data to whether the overpressure is present to total depth or if there is a return to normal pressure at ~ 3404 mbKB.
La Bella-1	RFT data in the Upper Shipwreck Group showed that two isolated gas sand intervals where not in pressure communication with each other and furthermore, the Lower Shipwreck Group was overpressured with respect to the Upper Shipwreck Group by ~410 psi. In comparison with nearby wells such as Eric the Red-1, which do not show overpressures, have any signs of overpressure, this indicates that both the Upper and Lower Shipwreck Groups are not in pressure communication with the Shipwreck Groups in these other nearby wells

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Figure Captions

Figure 1. Bathymetry map overlain by a schematic map of the Otway Basin (modified after Mehin & Constantine, 1999) showing the Early and Late Cretaceous depocentres, structural elements (after Moore et al., 2000) and the wells used in this study. The wells used for pore pressure predictions are bold. The well correlation in Figure 4 follows the blue line. Hydrocarbon shows are modified after O'Brien et al. (2009).

Figure 2. Idealised (a) sonic velocity (porosity)-depth plot, (b) pressure-depth plot, and (c) effective stress-sonic velocity plot showing the paths in which overpressures are generated by disequilibrium compaction and fluid expansion or vertical transfer (Modified after Tingay et al., 2009). Overpressures generated by disequilibrium compaction plot on the loading curve in (c), whereas overpressures generated by fluid expansion or vertical transfer follow an unloading curve (Bowers 1995).

Figure 3. Stratigraphic column of the Otway Basin with the litho-stratigraphy of interest in this study highlighted (i.e. Late Cretaceous Sherbrook Group, Miocene Heytesbury Group and Whalers Bluff supersequence (modified after Krassay et al. 2004).

Figure 4. Well litho-stratigraphic correlation form Morum-1 in the northwest part of the basin to Mussel-1 in the southeast part of the basin showing the variation in formation thicknesses. Refer to Figure 1 for well locations wells and Figure 3 for entire Otway Basin Stratigraphic succession. Formation tops picked using PGS' SAMDA database except for Calister-1 which was picked using its Basic Data Report (Subramanian, 2005) where no post-Wangerrip Group sediments were differentiated. Note well distance is not to scale and formation. Hydrocarbon shows and the approximate interval of the peak hydrocarbon generation window are modified after O'Brien et al. (2009).

Figure 5. Available RFT, LOT and mud weight data for the Breaksea Reef-1, Normanby-1, Bridgewater Bay-1, Callister-1 and La Bella-1.

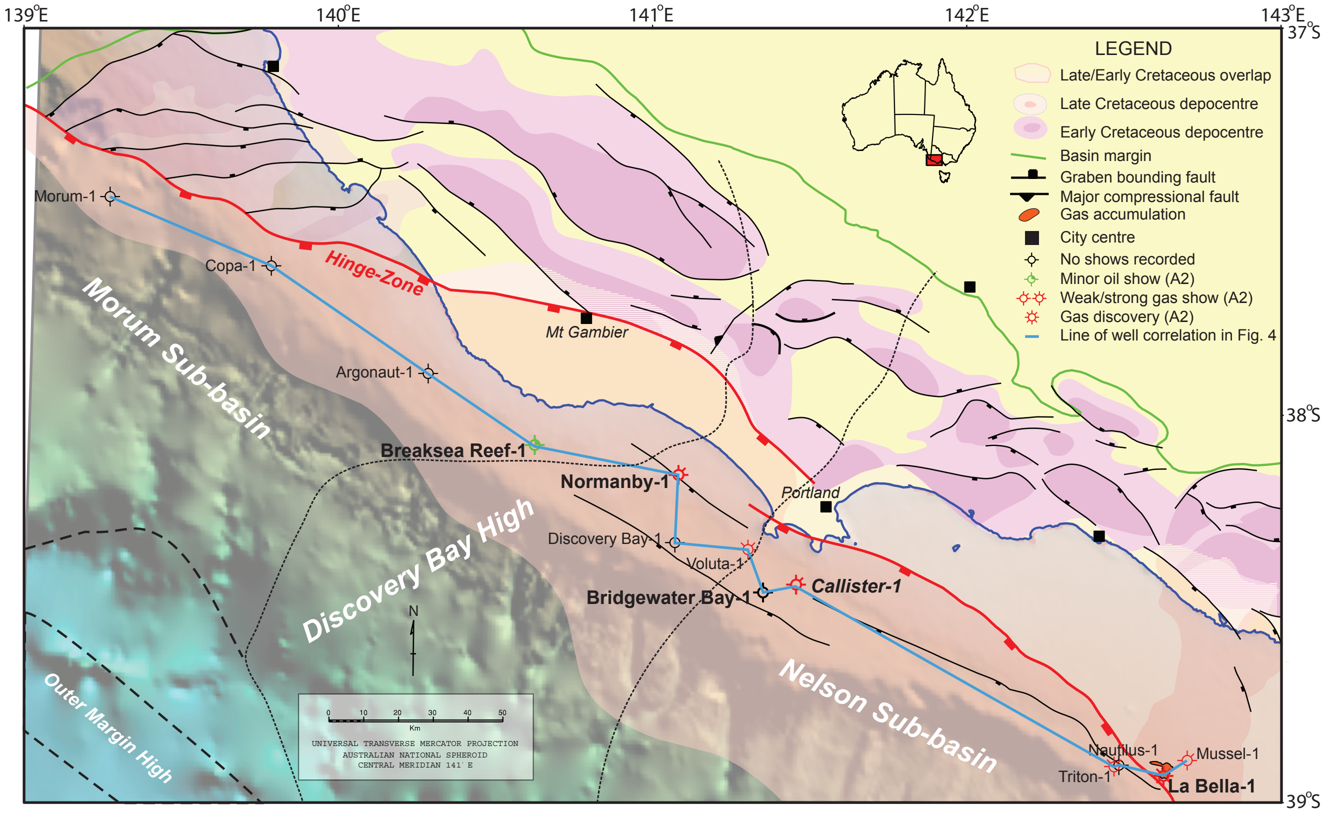
Figure 6. Vertical stress profiles for Breaksea Reef-1, Normanby-1, Bridgewater Bay-1 and La Bella-1 with their corresponding stress-depth relationships shown.

Figure 7. (a) Sonic velocity-depth plot showing the measured sonic velocity response in relation to the constructed normal compaction curves for the Paaratte Formation (black curve) and Belfast Mudstone (grey curve) for the Late Cretaceous Sherbrook Group shales in Breaksea Reef-1, Normanby-1, Bridgewater Bay-1 and La Bella-1.

Figure 8. The pressure profiles of Upper Cretaceous sediments established using the Eaton (1972) method for when Δt_{norm} values derived from corrected normal compaction trends (black curve) and normally pressured vertical effective stress relations (grey curve) for Breaksea Reef-1, Normanby-1, Bridgewater Bay-1 and La Bella-1. RFT, LOT and mud weight values in each well are also shown for comparison. Inserted in the top right corner of each profile shows the effective stress-sonic velocity relationship for the normally pressured overlying Upper Cretaceous section which effectively determines an apparent normal compaction trend for the Late Cretaceous sediments.

Figure 9. (a) Fairway map showing the approximate distribution of peak, thermally mature, Turonian Austral 3 source rock (modified after O'Brien et al., 2009) overlain with the location of various modern, Pliocene and Miocene canyons that have been mapped using seismic and bathymetry data (modified after Leach and Wallace, 2001) and magnitudes of pore pressure. (b) Seismic section showing the geometry of at least two phases of canyon incision and filling (C1 and C2), and the seaward thickening progradation features (Pro). The section between Voluta-1 and Bridgewater Bay-1 trends parallel to canyon and the section from Bridgewater Bay-1 towards Callister-1 cross-cuts the canyon. The position of seismic profiles can be seen (a).

Figure 1



139°E
140°E
141°E
142°E
143°E
37°S
38°S
39°S
LEGEND
Late/Early Cretaceous overlap
Late Cretaceous depocentre
Early Cretaceous depocentre
Basin margin
Graben bounding fault
Major compressional fault
Gas accumulation
City centre
No shows recorded
Minor oil show (A2)
Weak/strong gas show (A2)
Gas discovery (A2)
Line of well correlation in Fig. 4
Morum-1
Copa-1
Hinge-Zone
Mt Gambier
Morum Sub-basin
Argonaut-1
Breaksea Reef-1
Normanby-1
Portland
Discovery Bay-1
Voluta-1
Callister-1
Bridgewater Bay-1
Discovery Bay High
Nelson Sub-basin
Outer Margin High
N
0 10 20 30 40 50
Km
UNIVERSAL TRANSVERSE MERCATOR PROJECTION
AUSTRALIAN NATIONAL SPHEROID
CENTRAL MERIDIAN 141° E
Nautilus-1
Mussel-1
Triton-1
La Bella-1

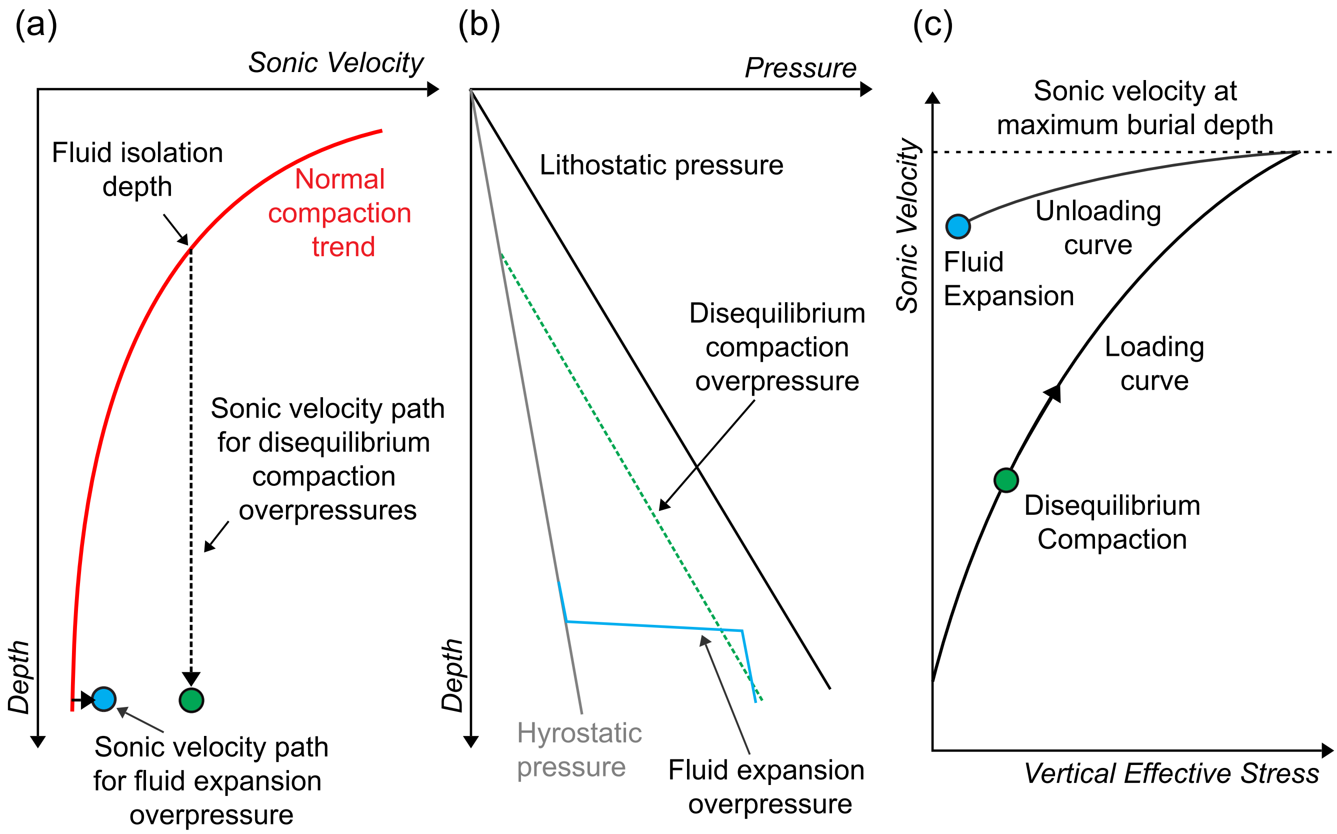
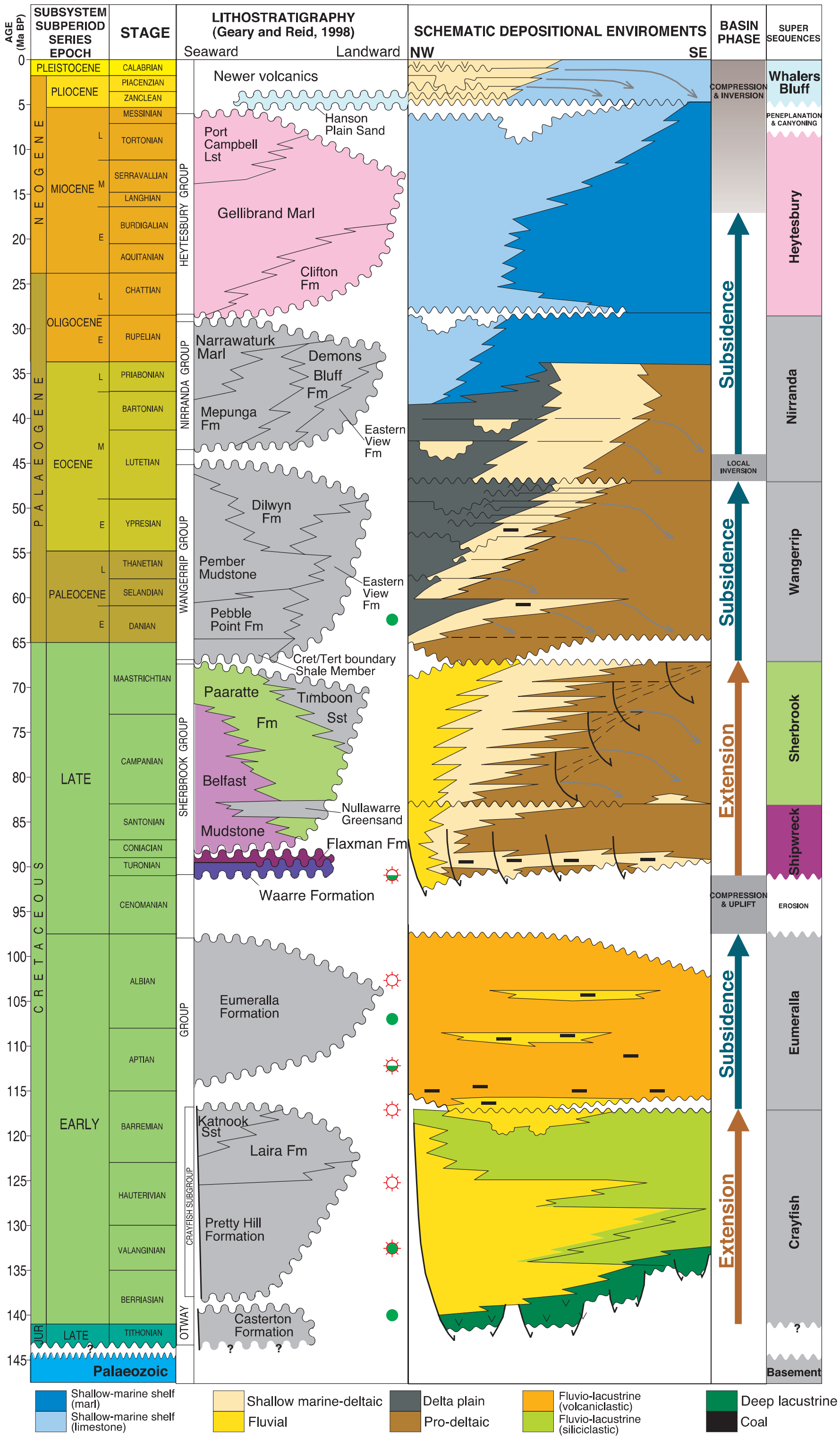
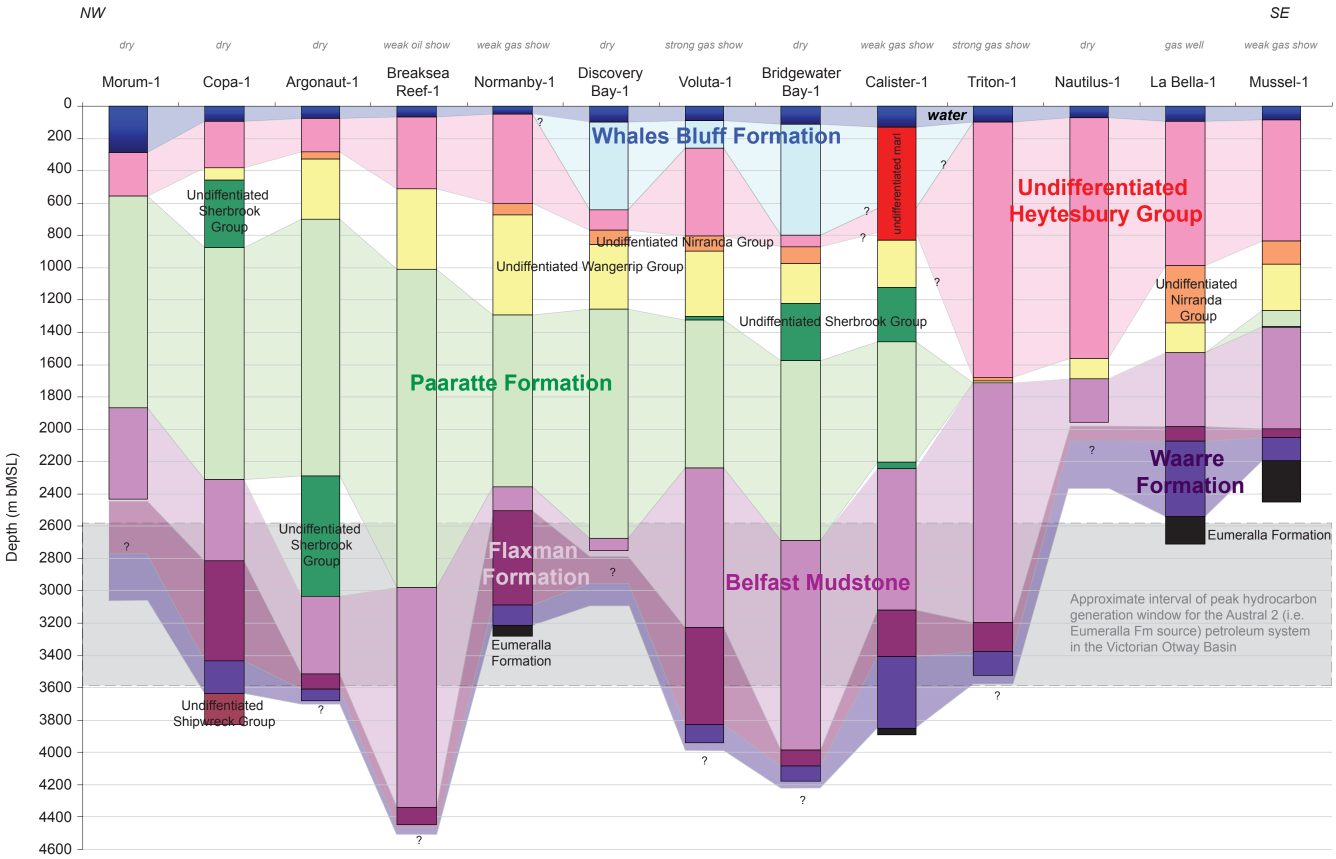

(a)
Sonic Velocity
Fluid isolation depth
Normal compaction trend
Sonic velocity path for disequilibrium compaction overpressures
Depth
Sonic velocity path for fluid expansion overpressure
(b)
Pressure
Lithostatic pressure
Disequilibrium compaction overpressure
Depth
Hyrostatic pressure
Fluid expansion overpressure
(c)
Sonic velocity at maximum burial depth
Sonic Velocity
Unloading curve
Fluid Expansion
Loading curve
Disequilibrium Compaction
Vertical Effective Stress

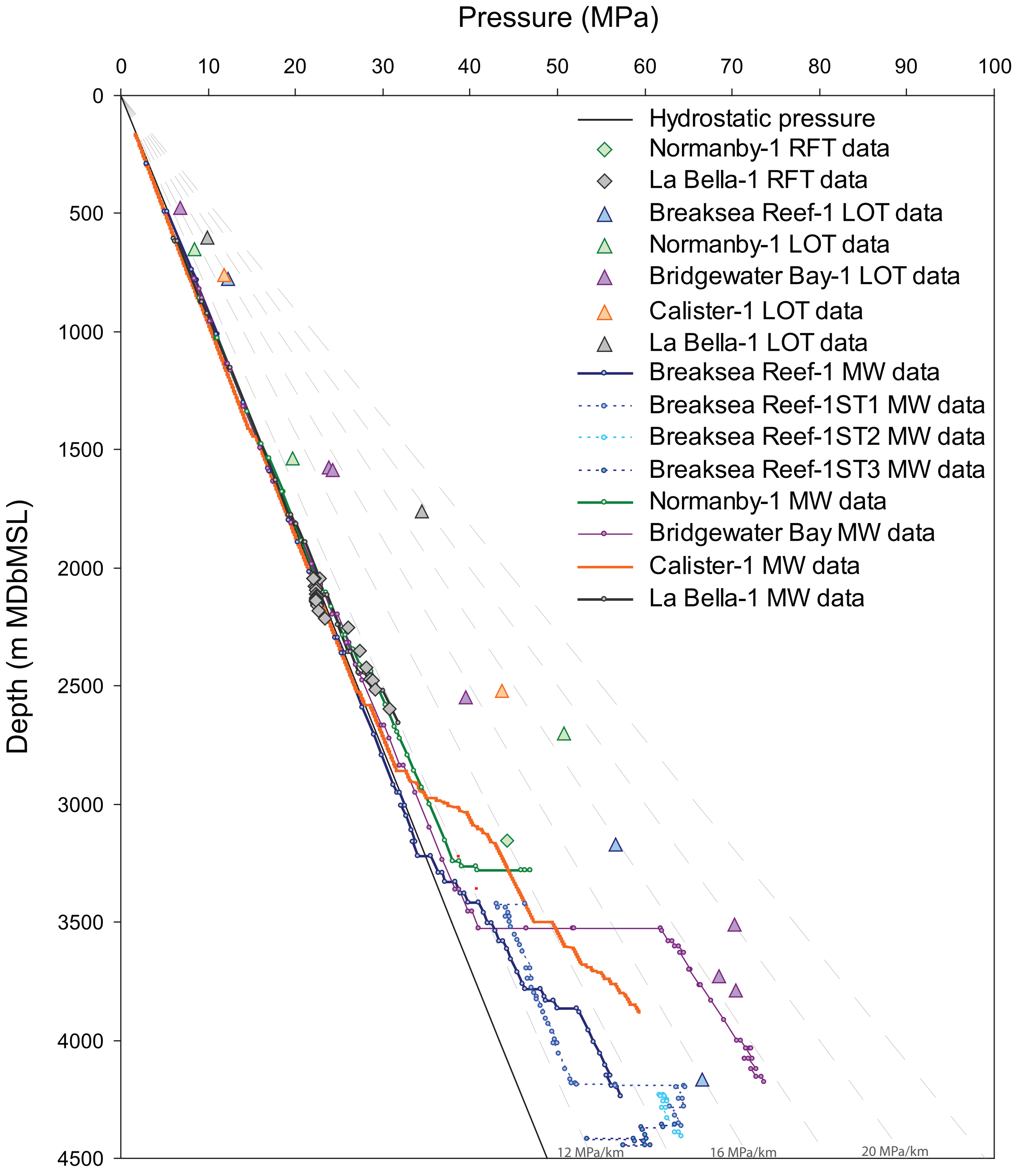
Figure. 3

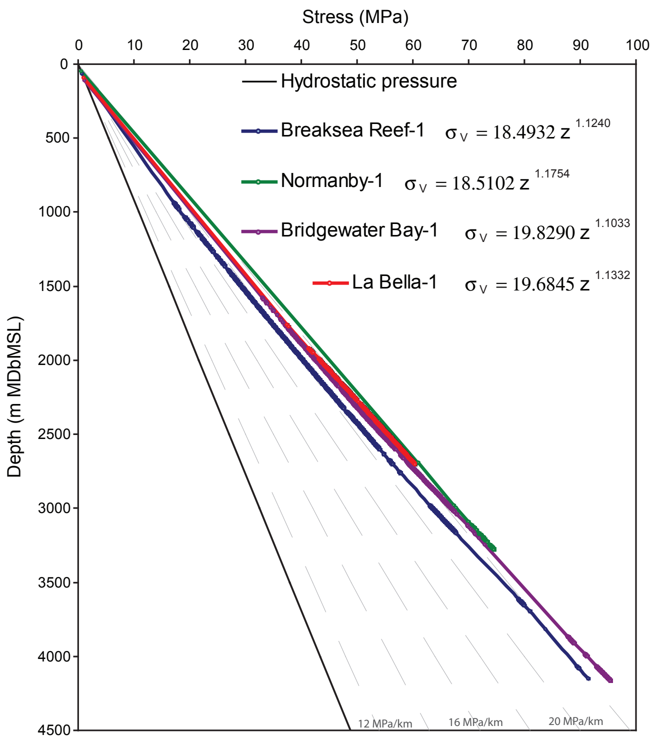


AGE (Ma BP)
SUBSYSTEM SUBPERIOD SERIES EPOCH
STAGE
LITHOSTRATIGRAPHY (Geary and Reid, 1998)
Seaward
Landward
SCHEMATIC DEPOSITIONAL ENVIROMENTS
NW
SE
BASIN PHASE
SUPER SEQUENCES
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
NEOGENE
PALAEOGENE
CRETACEOUS
LATE
EARLY
JUR
Palaeozoic
CALABRIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YPRESIAN
THANETIAN
SELANDIAN
DANIAN
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
TITHONIAN
Newer volcanics
Hanson Plain Sand
Port Campbell Lst
Gellibrand Marl
Clifton Fm
HEYTESBURY GROUP
Narrawaturk Marl
Demons Bluff Fm
Mepunga Fm
Eastern View Fm
NIRRANDA GROUP
Dilwyn Fm
Pember Mudstone
Pebble Point Fm
WANGERRIP GROUP
Cret/Tert boundary Shale Member
Paaratte Fm
Timboon Sst
Belfast Mudstone
Nullawarre Greensand
Flaxman Fm
Waarre Formation
SHERBROOK GROUP
Eumeralla Formation
Katnook Sst
Laira Fm
Pretty Hill Formation
CRAYFISH SUBGROUP
Casterton Formation
OTWAY GROUP
COMPRESSION & INVERSION
LOCAL INVERSION
COMPRESSION & UPLIFT
Subsidence
Extension
Whalers Bluff
PENEPLANATION & CANYONING
Heytesbury
Nirranda
Wangerrip
Sherbrook
Shipwreck
EROSION
Eumeralla
Crayfish
Basement
Shallow-marine shelf (marl)
Shallow-marine shelf (limestone)
Shallow marine-deltaic
Fluvial
Delta plain
Pro-deltaic
Fluvio-lacustrine (volcaniclastic)
Fluvio-lacustrine (siliciclastic)
Deep lacustrine
Coal

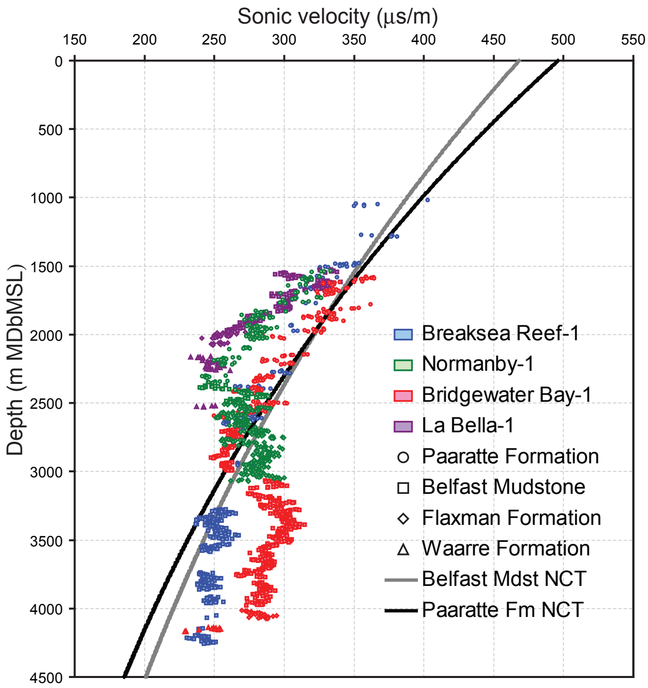


NW
SE
dry
dry
dry
weak oil show
weak gas show
dry
strong gas show
dry
weak gas show
strong gas show
dry
gas well
weak gas show
Morum-1
Copa-1
Argonaut-1
Breaksea Reef-1
Normanby-1
Discovery Bay-1
Voluta-1
Bridgewater Bay-1
Calister-1
Triton-1
Nautilus-1
La Bella-1
Mussel-1
water
Depth (m bMSL)
Whales Bluff Formation
Undifferentiated Heytesbury Group
undifferentiated marl
Undiffentiated Sherbrook Group
Undiffentiated Nirranda Group
Undiffentiated Wangerrip Group
Undiffentiated Sherbrook Group
Undiffentiated Nirranda Group
Paaratte Formation
Waarre Formation
Flaxman Formation
Belfast Mudstone
Undiffentiated Sherbrook Group
Eumeralla Formation
Eumeralla Formation
Undiffentiated Shipwreck Group
Approximate interval of peak hydrocarbon generation window for the Austral 2 (i.e. Eumeralla Fm source) petroleum system in the Victorian Otway Basin

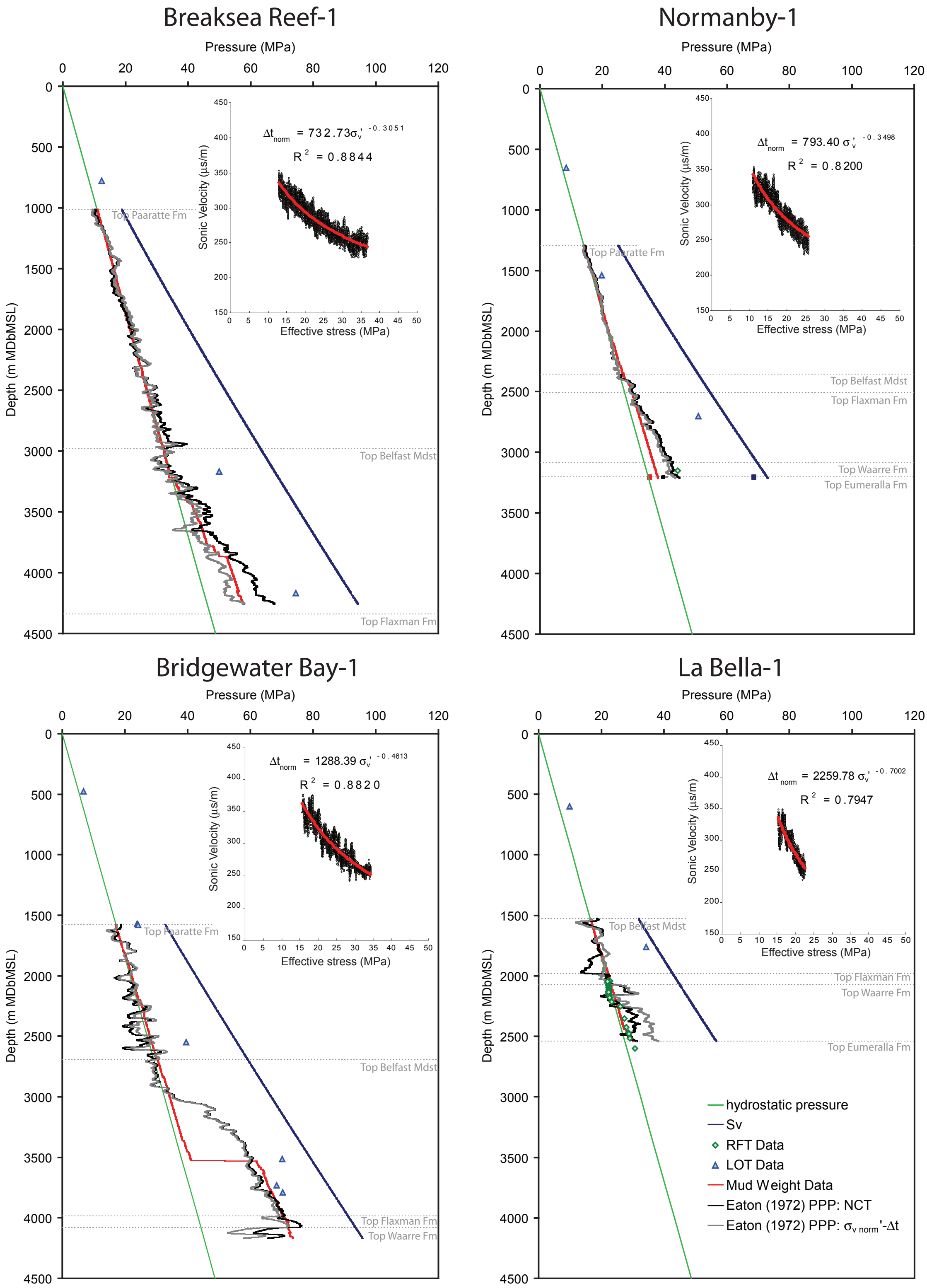

Pressure (MPa)
0
10
20
30
40
50
60
70
80
90
100
Depth (m MDbMSL)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Hydrostatic pressure
Normanby-1 RFT data
La Bella-1 RFT data
Breaksea Reef-1 LOT data
Normanby-1 LOT data
Bridgewater Bay-1 LOT data
Calister-1 LOT data
La Bella-1 LOT data
Breaksea Reef-1 MW data
Breaksea Reef-1ST1 MW data
Breaksea Reef-1ST2 MW data
Breaksea Reef-1ST3 MW data
Normanby-1 MW data
Bridgewater Bay MW data
Calister-1 MW data
La Bella-1 MW data
12 MPa/km
16 MPa/km
20 MPa/km



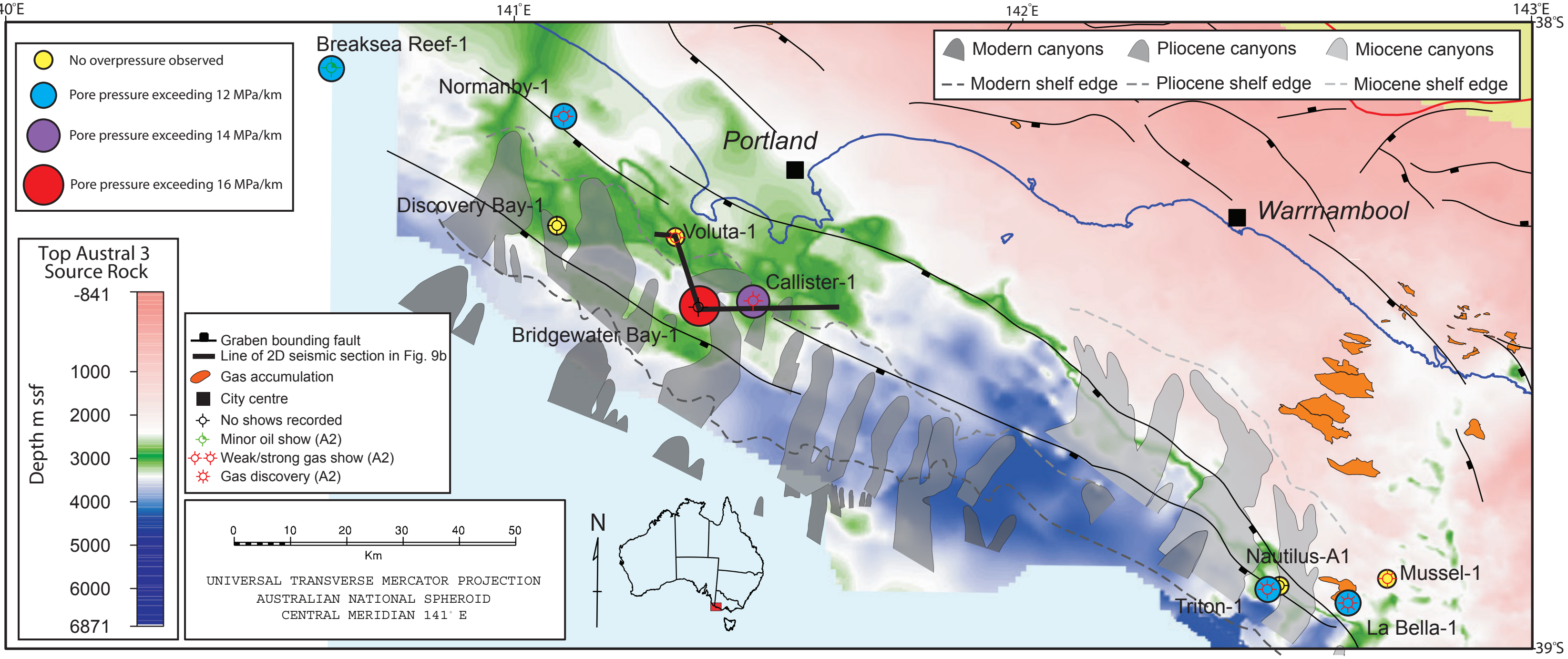
Stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Depth (m MDbMSL)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Hydrostatic pressure
Breaksea Reef-1 $\sigma_V = 18.4932\ z^{1.1240}$
Normanby-1 $\sigma_V = 18.5102\ z^{1.1754}$
Bridgewater Bay-1 $\sigma_V = 19.8290\ z^{1.1033}$
La Bella-1 $\sigma_V = 19.6845\ z^{1.1332}$
12 MPa/km
16 MPa/km
20 MPa/km



Sonic velocity (µs/m)
150
200
250
300
350
400
450
500
550
Depth (m MDbMSL)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Breaksea Reef-1
Normanby-1
Bridgewater Bay-1
La Bella-1
Paaratte Formation
Belfast Mudstone
Flaxman Formation
Waarre Formation
Belfast Mdst NCT
Paaratte Fm NCT

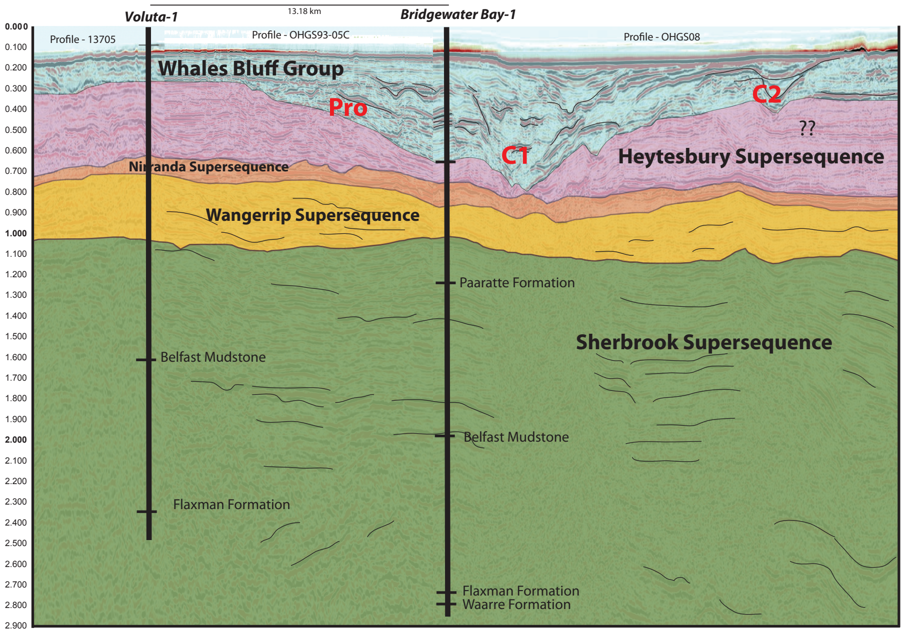

Breaksea Reef-1
Normanby-1
Bridgewater Bay-1
La Bella-1
Pressure (MPa)
Depth (m MDbMSL)
Sonic Velocity (µs/m)
Effective stress (MPa)
Δt norm = 732.73σv' -0.3051
R 2 = 0.8844
Δt norm = 793.40 σv' -0.3498
R 2 = 0.8200
Δt norm = 1288.39 σv' -0.4613
R 2 = 0.8820
Δt norm = 2259.78 σv' -0.7002
R 2 = 0.7947
Top Paaratte Fm
Top Belfast Mdst
Top Flaxman Fm
Top Waarre Fm
Top Eumeralla Fm
hydrostatic pressure
Sv
RFT Data
LOT Data
Mud Weight Data
Eaton (1972) PPP: NCT
Eaton (1972) PPP: σv norm'-Δt

(a)



140°E
141°E
142°E
143°E
38°S
39°S
No overpressure observed
Pore pressure exceeding 12 MPa/km
Pore pressure exceeding 14 MPa/km
Pore pressure exceeding 16 MPa/km
Top Austral 3 Source Rock
Depth m ssf
-841
1000
2000
3000
4000
5000
6000
6871
Graben bounding fault
Line of 2D seismic section in Fig. 9b
Gas accumulation
City centre
No shows recorded
Minor oil show (A2)
Weak/strong gas show (A2)
Gas discovery (A2)
0 10 20 30 40 50
Km
UNIVERSAL TRANSVERSE MERCATOR PROJECTION
AUSTRALIAN NATIONAL SPHEROID
CENTRAL MERIDIAN 141° E
N
Modern canyons
Pliocene canyons
Miocene canyons
Modern shelf edge
Pliocene shelf edge
Miocene shelf edge
Breaksea Reef-1
Normanby-1
Portland
Discovery Bay-1
Voluta-1
Callister-1
Bridgewater Bay-1
Warrnambool
Nautilus-A1
Triton-1
Mussel-1
La Bella-1

(b)



Voluta-1
13.18 km
Bridgewater Bay-1
Profile - 13705
Profile - OHGS93-05C
Profile - OHGS08
Whales Bluff Group
Pro
C2
??
C1
Heytesbury Supersequence
Nirranda Supersequence
Wangerrip Supersequence
Paaratte Formation
Sherbrook Supersequence
Belfast Mudstone
Belfast Mudstone
Flaxman Formation
Flaxman Formation
Waarre Formation
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
1.400
1.500
1.600
1.700
1.800
1.900
2.000
2.100
2.200
2.300
2.400
2.500
2.600
2.700
2.800
2.900