Evidence for overpressure in the Belfast Formation, Shipwreck Trough, Otway Basin

Andrew J. Aouad
Origin Energy Resources Ltd.
135 Coronation Drive
Milton, 4064
Andrew.aouad@originenergy.com.au

David I. Close
Origin Energy Resources Ltd.
135 Coronation Drive
Milton, 4064
David.close@originenergy.com.au

SUMMARY

The Late Cretaceous Belfast Formation is a fine grained, regionally extensive mudstone unit that provides the regional seal for a number of gas discoveries in the Otway Basin. A distinct decrease in sonic velocity and resistivity through the Belfast Formation is observed in wells on the western (down thrown) side of the Sorell Fault Zone. The velocities are anomalously low relative to expected velocities based on depth trends and/or petrophysically estimated velocities. Analysis of conventional log data in conjunction with bulk rock x-ray diffraction (XRD) data from rock chips through the interval illustrate that the velocity reversal is not a function of changes in lithology or porosity. We interpret the observed log response to be a function of increased pore pressure gradient, overpressure, through the Belfast Formation.

Increased drilling mud weights through this interval in a number of wells supports this conclusion. There have been no attempts to pressure test the Belfast Formation, however, there are abundant pressure test data for the underlying reservoir rocks. Pressure tests do show evidence of overpressure in reservoir intervals in Triton-1. It is not surprising that higher overpressures are not observed and/or recorded in the reservoir interval as the overpressure in the Belfast Formation is likely a consequence of disequilibrium compaction. Such overpressure has limited opportunity to create overpressure in adjacent formations. The disequilibrium compaction is likely caused by rapid sedimentation during the Late Cretaceous.

Using the Eaton Method (Eaton, 1975) and sonic log data, a maximum pore-pressure approximately 30% higher than hydrostatic is calculated in the shale. This prediction, however, cannot be made without an implicit assumption regarding a ‘normal’ compaction trend; we utilise a Gardner density-derived velocity prediction in addition to a standard depth trend extrapolation method. Observations in this paper are consistent with recently published evidence for overpressure in Otway Basin west of the Shipwreck Trough.

The occurrence of overpressure has implications for velocity analysis of seismic data and depth conversion in and around the Shipwreck Trough. Overpressure effects on velocity are not readily observable during velocity analysis of CMP gathers, which is partly due to the lack of reflectivity through the Belfast Formation and partly as the velocity of any reflector in this shale section will have a slower than expected velocity and can be potentially dismissed as multiple energy. This results in stacking velocities that are over-predicted through the shale, which can limit their use in detecting overpressure and cause depth conversion errors.

Key words: Otway Basin, overpressure, velocities, sonic logs, resistivity logs

INTRODUCTION

The Shipwreck Trough, located in the eastern Otway Basin, contains the majority of offshore commercial hydrocarbon discoveries in the basin. The Shipwreck Trough is a north-south trending depocentre, formed during Late Cretaceous rifting (Figure 1).the main reservoirs are the Turonian aged fluvial and deltaic sands of the Waarre Formation, the deltaic to shallow marine Flaxman Formation, and the primarily deltaic sands (Thylacine Member) of the lower Belfast Formation (Krassay et al. 2004) (Figure 2). In the Shipwreck Trough there is a rapid change from deltaic sands of the Thylacine Member to the marine mudstones of the Belfast Formation (Krassay et al. 2004). The thickness of the marine mudstone increases into the centre of the trough and thins to the east over the Prawn Platform. This thinning is also associated with an eastward gradation from clay rich mudstone to clay poor sandstones, such as those encountered through the equivalent interval at Prawn-A1.

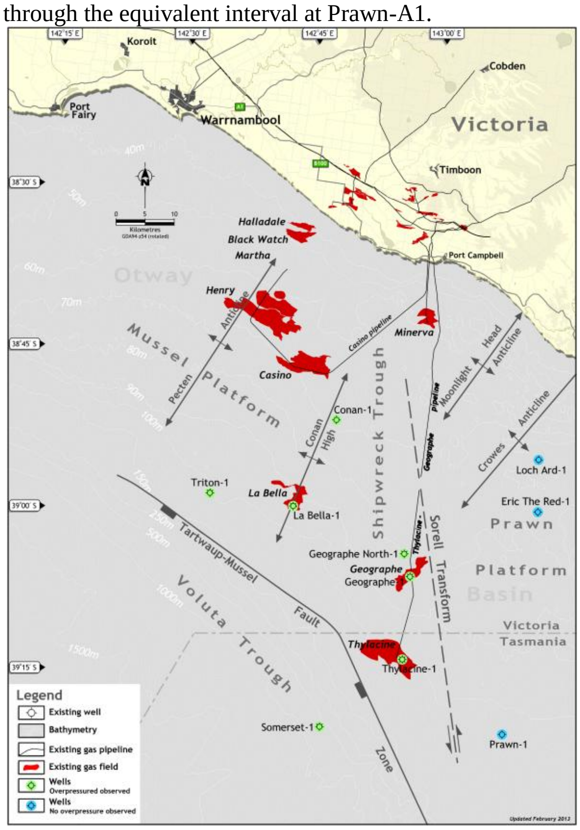

Figure 1: Main structural components of the Otway Basin. The wells used in this study are highlighted, those in green, all to the west (down thrown) side of the Sorell Fault Complex display overpressure, whereas those to the east, on the Prawn Platform are normally pressured.

Well log data across the Belfast mudstone in Thylacine-1, Geographe-1 and Geographe North-1, in the central Shipwreck Trough are characterised by distinct petrophysical responses. Both the p-wave sonic log and resistivity log show a distinct reversal in their depth trends through the Belfast mudstone (Figure 2). Such reversals are recognised as indicators of overpressure (e.g. Eaton ,1975)

Overpressure is defined as a pore pressure greater than the hydrostatic pressure and is often documented in Tertiary basins with high sedimentation rates (Swarbrick, 2011). In older sequences, such as the Cretaceous Belfast Formation, preservation of overpressure is less common. Accordingly, the magnitude, or even occurrence, of overpressure in the Belfast Formation within the Shipwreck Trough has remained equivocal. The only direct measurement of overpressure in the Shipwreck Trough is from a formation test in the Waarre Formation at Triton 1 (CSIRO pressure database, PressurePlot www.pressureplot.com). Overpressure is also reported in the well completion report (ESSO, 1982). We interpret well log data from other wells in the Shipwreck Trough to support a more widespread presence of overpressure in the Belfast mudstone.

This paper reviews the evidence for overpressure in the Shipwreck Trough and investigates its magnitude, and briefly discusses its causes and implications on seismic velocities and time-to-depth conversion.

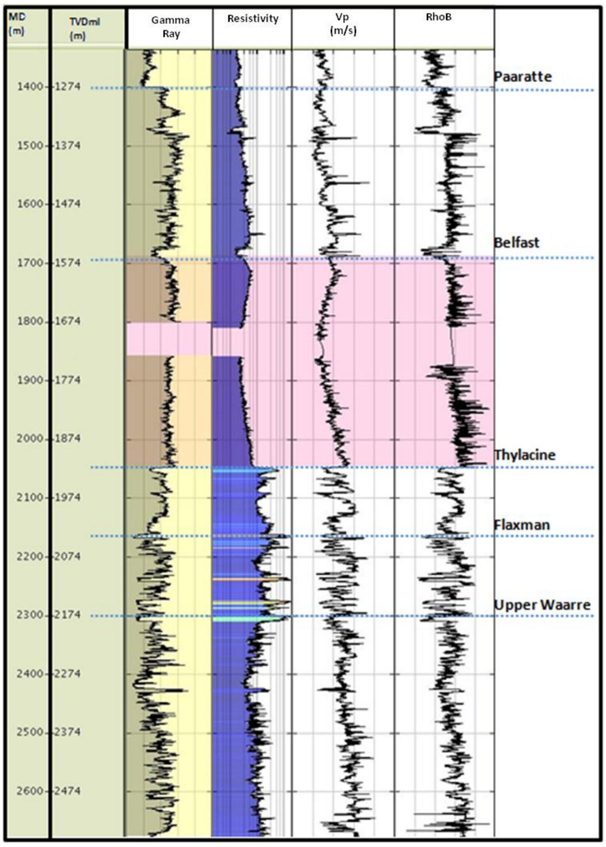

Figure 2: Well log data from Thylacine-1 showing the stratigraphy of the Shipwreck Trough. The pink highlight shows the Belfast mudstone section, where both the Vp and Resistivity logs show a characteristic bow shape.

METHOD AND RESULTS

Two characteristic manifestations of overpressure are identified in sonic velocity data, these can be summarised as either:

i) A velocity reversal: where velocities decrease with depth from the top of the Belfast mudstone towards the middle of the formation before increasing towards the base, creating a distinct bow shaped log response (e.g. Figure 3a);

ii) A near constant velocity: where the velocity departs from the trend of increasing velocity with depth and stays almost constant over the entire Belfast mudstone before rapidly increasing in velocity towards its base (e.g. Figure 3b).

A similar trend is observed in resistivity log data over the same interval (e.g. Figure 2).

Sonic velocities return to a normal trend at the base of the Belfast mudstone where adjacent permeable sands allowed for effective pore fluid escape during compaction.

All wells where these distinctive log patterns occur are located west of the Prawn Platform (Figure 1) where the Belfast mudstone is thickest. Although the overpressure is largely confined to the Belfast Formation through the central Shipwreck Trough, towards the outer Shipwreck Trough (e.g. Triton 1 and Somerset 1) the overpressure is also observed within the overlying Paaratte Formation. In this part of the basin the Paaratte Formation and Belfast Formation are effectively a continuous mudstone sequence, indicative of a distal marine environment, which has resulted in an extended section of overpressured shales.

No full or sidewall cores are available for study from the Belfast Formation, however, X-Ray Diffraction (XRD) results from cuttings taken from two wells indicate a remarkably consistent mineral composition laterally and vertically (Figure 4). The average composition of the Belfast Formation can be summarised as approximately: 38% quartz, 29% kaolonite, 12% mica/illite minerals and 20% other minerals (feldspar, plagioclase, chlorite, siderite, illite, smectite, pyrite). Critically, the XRD data confirm there is no systematic variation with depth from the top to the middle, and the middle to the base Belfast that can explain the characteristic log response observed.

Quantifying overpressure from logs

Eaton (1975) proposed a method of pore pressure prediction from sonic velocity and resistivity logs. The method utilises the ratio of measured velocity to 'normal' velocity for a given depth. Accordingly, a velocity-depth trend that defines 'normal' for a given depth is required to quantify the amount of overpressure observed in the Shipwreck Trough wells using Eaton's method

Calculating such a trend is not trivial, particularly in a basin that has undergone several episodes of erosion, uplift and reburial since the deposition of the Belfast mudstone. Several methods to predict a 'normal trend' exist (see Tassone 2011). The most basic method is to manually or statistically extrapolate a trend for sonic and resistivity data using all the wells in and around the Shipwreck Trough. The second relatively simple method is to apply a conversion based on other measured log properties, for example the Gardner technique (Gardner 1974) provides a means of predicting velocity using measured bulk density.

Bulk density measurements are impacted by overpressure, but the effect is minimal relative to the large impact of overpressure on sonic velocities. Taking this into account, we tested using an inverse Gardner relation (Gardner, 1974) to convert the measured bulk density to an expected/normal sonic velocity. Where pore pressure is interpreted to be hydrostatic (e.g. the Tertiary section), the Gardner estimated sonic velocity accurately predicts the measured sonic velocity. This is also observed in wells to the east of the Shipwreck Trough, such as Prawn A1 and Eric The Red 1, which display no log reversals or overpressure indications.

In the Belfast mudstone, and in some wells the Paaratte Formation, there is a significant departure between the measured sonic velocity and the Gardner predicted sonic velocity (Figure 5). The sonic velocity obtained from the inverse Gardner relationship is also a close fit to a simple extrapolated depth trend, which supports the conclusion that using the inverse Gardner relation is a reasonable approximation for the 'normal' sonic trend. This predicted velocity can now be consistently calculated for all wells where density data are available and used as the basis for pore pressure prediction using Eaton's method.

Cause of Overpressure

The processes for creating overpressure can be broadly classified into two categories, 1) stress applied to a compressible rock and, 2) fluid expansion (Swarbrick et al., 2002). Vertical compressive stress is the obvious result of sediment deposition or loading, this depth proportional compaction is a constant in all sedimentary basins (although the principal stress direction need not necessarily be vertical).When sediments with low permeability comprised of grains with large surface areas, such as in clay rich shales, are rapidly buried, pore fluid can be prevented from escaping. This results in the pore pressure increasing above hydrostatic pressure. This is known as disequilibrium compaction and is the cause of considerable overpressure in many basins around the world (Swarbrick et al., 2002).

Fluid expansion mechanisms increase the volume of fluid in the pore, without changing the pore size. A number of mechanisms can cause this, such as dehydration, smectite to illite transformation or hydrocarbon generation (Swarbrick et al., 2002). XRD data confirm that there are negligible quantities of smectite and illite in the Belfast mudstone

From the available evidence we believe that the most likely cause of the overpressure in the Shipwreck Trough is disequilibrium compaction. Tassone et al. (2011) suggest that fluid expansion due to hydrocarbon maturation may cause the overpressure west of the Shipwreck Trough, however, this explanation is contradicted by the lack of hydrocarbon charge in areas where overpressure effects are clear in log data(e.g. Geographe North 1).

Although sedimentation rates have not been rigorously calculated for the Belfast formation, a combination of palynology data and section thickness from the wells gives an indication. The rates in Table 1 are calculated from current thicknesses and can be taken as the minimum rate as no attempt has been made to compensate for compaction. Additionally, wells with thicker Belfast section (also implying higher rates of sedimentation) have correspondingly higher overpressure (e.g. Somerset 1, Triton 1)

Table 1: Sedimentation rates calculated from current well thickness and palynology data for the Belfast mudstone.

Well	Sedimentation rate
Thylacine 1	0.14 mm/yr
Geographe 1	0.13 mm/yr
Somerset 1	0.21 mm/yr
Triton 1	0.24 mm/yr

Effect on seismic velocities

Considering the effect overpressure has on measured velocities in wells, the question naturally arises, is there an effect on the seismic velocity? Numerous vintages of seismic data (3D and 2D) have been acquired and reprocessed in the Otway Basin. To investigate if the overpressure makes a measurable difference to seismic velocities, depth conversions were undertaken at some well locations.

The Dix interval velocity (from V_{rms} to V_{int}) between the base Tertiary and the base Belfast mudstone was calculated and used to predict the thickness in this interval. At Prawn A1, this method gives a thickness 94% of the actual well interval (i.e. under predicted). Using this same method at Somerset 1, the thickness is 106% of the well interval (i.e. over predicted).

This is in contrast to the interval between the water bottom and base Tertiary in both wells. At Prawn A1 the seismic velocities give a thickness of 99.0% of the actual and at Somerset the seismic gives 99.6% of the actual (in both cases the seismic under predicts the depth by a few metres). There are a number of vintages of 2D lines that cross the Prawn A1 location, the various vintages of seismic data and their respective velocities give a similar result.

Although it is well known that there is a difference between seismic velocities and measured well velocities due to anisotropic effects and differences in the frequency of seismic and sonic sources, these differences are amplified by the overpressure through the Belfast mudstone. These effects are important as they have operational impacts for well planning away from structural highs and for predicting depth surfaces used to predict gross rock volumes for reserves estimation.

The velocity trend observed in the wells through the Belfast mudstone is not readily observed in seismic velocities in this area. This is most likely caused by the lack of reflectors in the shale and/or that any reflectors observed have a slower velocity than anticipated, thus appearing as multiples. Future velocity modelling and depth conversions in the Otway Basin, specifically the Shipwreck Trough should consider the effect that overpressure has in decreasing seismic and sonic velocities through the Belfast mudstone.

CONCLUSIONS

Observations from log data are consistent with overpressure in the Belfast mudstone in the Shipwreck Trough. The overpressure is interpreted to be a function of disequilibrium compaction during the rapid deposition of the Belfast Mudstone.

Using an inverse Gardner relationship to calculate sonic velocities from density provides a reasonable approximation to a 'normal' sonic depth trend. Further investigation is needed

to compare this method to other methods for calculating normal trends.
Seismic velocities have thus far not captured the effect of overpressure and as a result over predict depth estimates and cannot be considered a reliable prediction of pore pressure ahead of drilling in the Shipwreck Trough.

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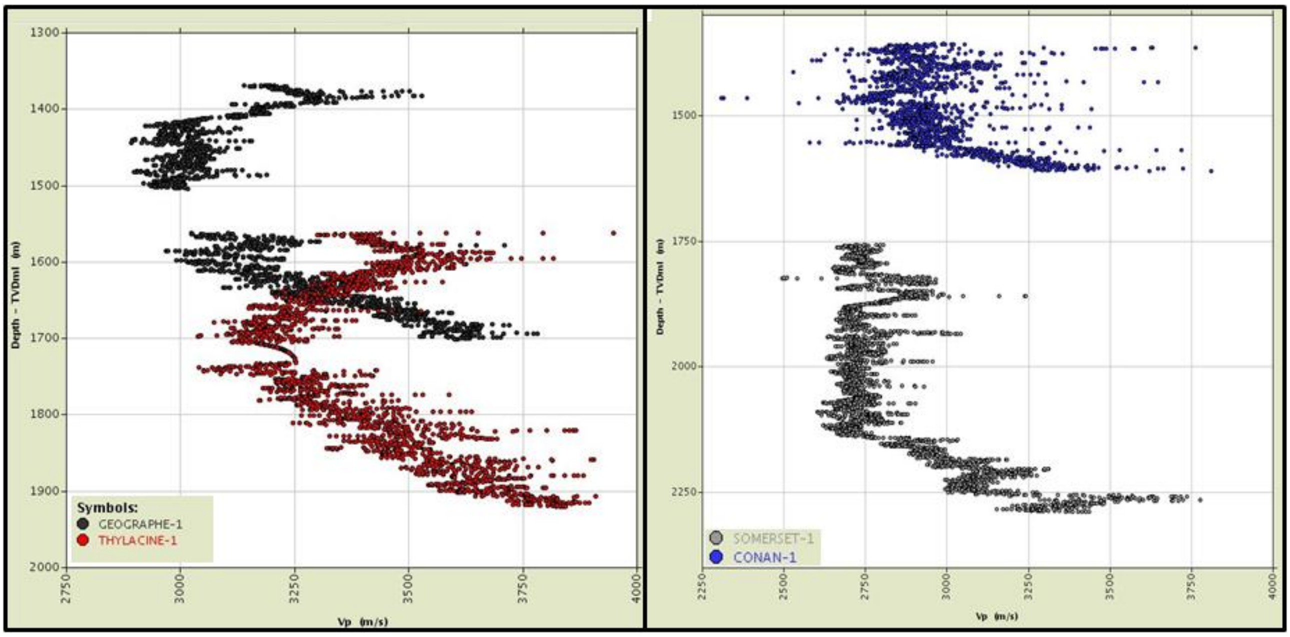

Figure 3: Crossplot of Vp vs Depth through the Belfast mudstone. a) Geographe-1 and Thylacine-1. These wells show a characteristic "bow" shape. b) For Somerset-1 and Conan-1, Both these wells show an almost constant depth to Vp trend before speeding up at the base of the Belfast. It should be noted that the Vp and Depth scales are different for each plot.

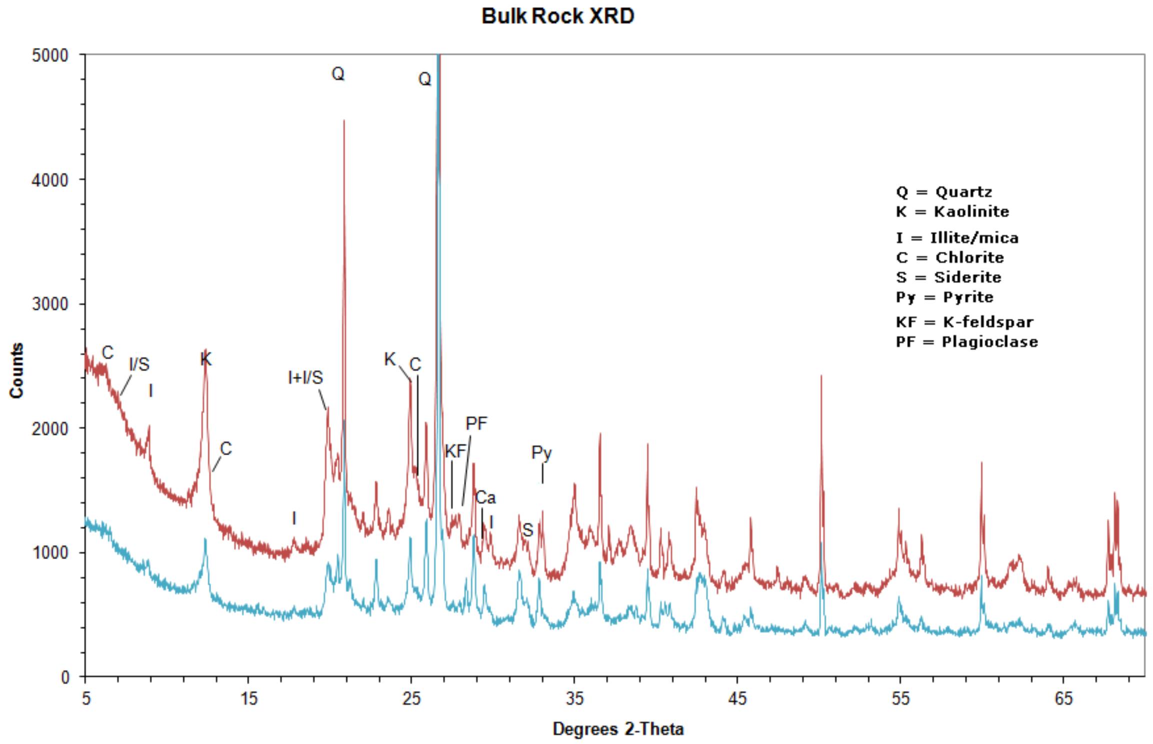

Figure 4: Bulk rock XRD results from the Belfast mudstone at two well locations. The coincident peaks demonstrate the same mineral assemblage in both wells. Data at other depths in the same wells show the same result.

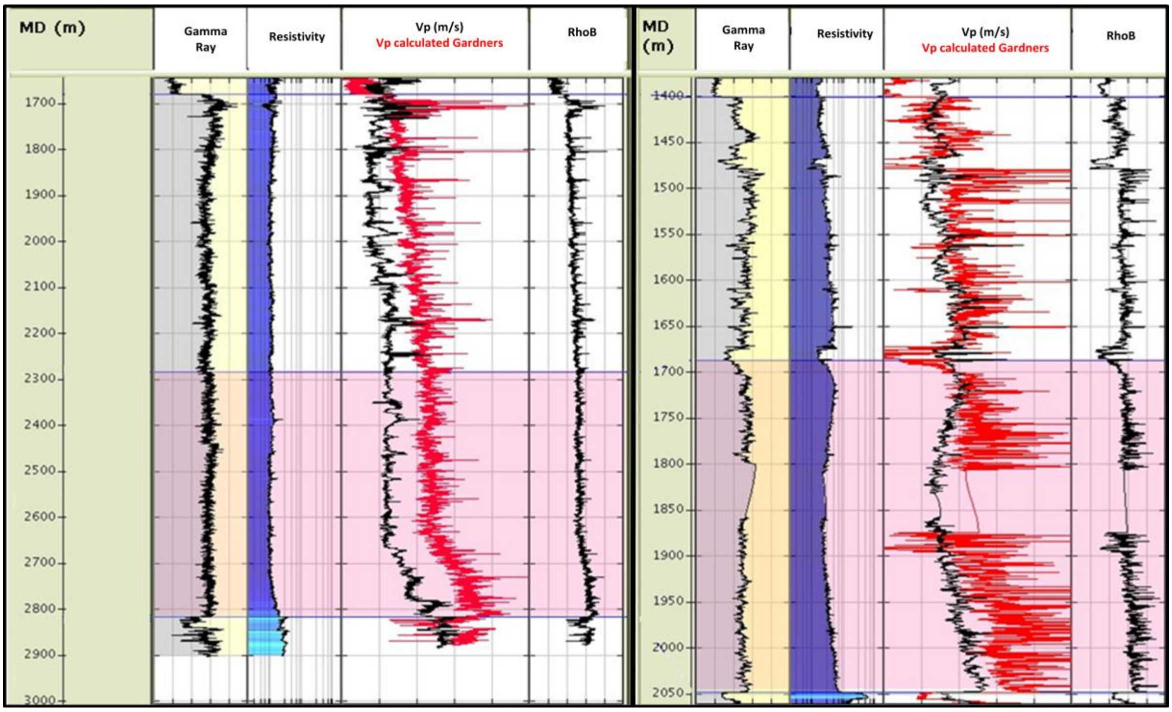

Figure 5: The inverse Gardner sonic (red) against the measure sonic (black) for two wells. The depth scale is measured depth from rotary table and the scale is different for each well.