Feasibility of time-lapse gravity monitoring of producing gas fields in the Northern Carnarvon Basin, Australia

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SUMMARY

Aquifer influx and pressure depletion are key variables during the production and development of a natural gas field. To obtain an understanding of how aquifer influx and pressure depletion varies across the reservoir, remote geophysical monitoring techniques are commonly used, particularly in offshore environments where well data is geographically sparse. The seafloor time-lapse gravity technique is a candidate technique for remote reservoir monitoring of water influx into producing gas fields in the Northern Carnarvon Basin.

We have developed a method to quickly assess the sensitivity of time lapse gravity measurements to water influx or pressure depletion using a vertical cylinder model for gas reservoirs. In strong water-drive gas reservoirs, a field-wide height change in the gas-water contact greater than 5m may produce a detectable gravity response depending on the reservoir depth and rock quality. In depletion-drive gas reservoirs, large pressure changes between 6MPa (~870psia) throughout the reservoir can produce a detectable response. Applying this technique to Carnarvon Basin gas fields where the primary reservoir is the Mungaroo Formation suggests that gravity monitoring of production related changes may be feasible but needs to be assessed on a field-by-field basis.

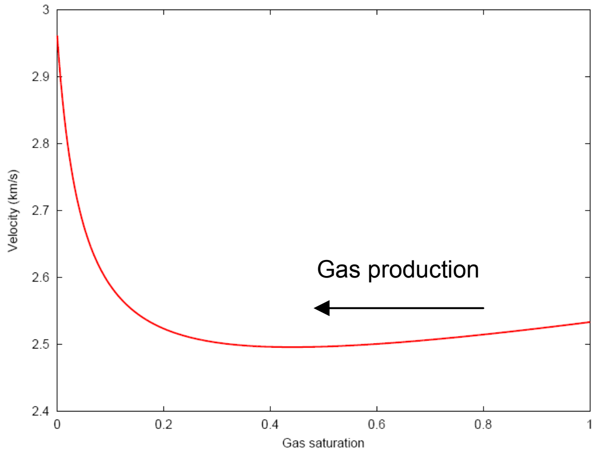
The method employed is both flexible and practical. It can be used in a range of applications, and provides a quick assessment of the feasibility of time-lapse monitoring of subsurface density changes.

Key words: time lapse gravity, gas production, water influx, reservoir management and monitoring

INTRODUCTION

The timing of water breakthrough in producing gas wells is a key uncertainty impacting ultimate gas recovery. Water production in a gas well reduces production rates until the well cannot lift the water volumes and will no longer produce. Therefore early detection is important, especially in offshore environments where intervention is expensive (e.g. $50M+ per well).

The degree of water influx depends strongly on the reservoir rock permeability and the size of any adjacent aquifer, among other factors. In a producing gas reservoir with strong water support, the gas saturation will decrease in zones of water influx. This may lead to modest changes in seismic velocities and more significant changes in density (Figure 1).



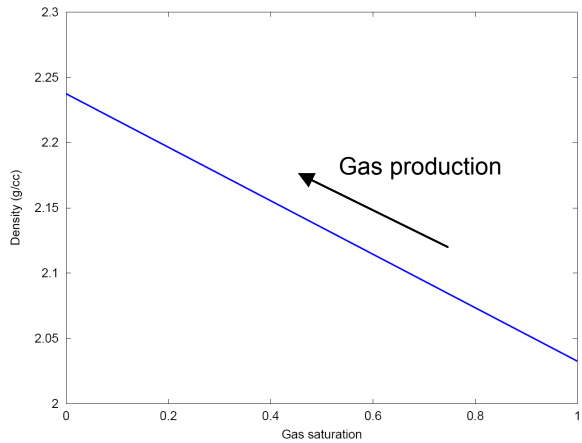


Figure 1. Model of P-wave velocity (above) and density (below) verses gas saturation for a sandstone reservoir with a porosity of 25%. The velocity was modelled using Gassmann's equation (1951) with the Reuss average moduli of the fluids. For a gas saturated reservoir, a decrease in gas saturation causes a negligible change in the P-wave velocity for saturations above 20% and more significant changes to density.

Repeat (time-lapse) geophysical surveys, especially gravity, seismic or electromagnetic methods, may remotely detect changes in gas saturation over time (Lumley, 2009, Lumley, 2010). Gravity data has the benefit of being directly related to changes in subsurface density, which is a strong linear function of gas saturation (Figure 1). In contrast, the seismic response is a highly non-linear function of the gas saturation making it difficult to quantify changes in gas saturation until low saturations (~20% or less) are reached (Figure 1).

A high-precision seafloor gravimeter was developed by Statoil and Scripps for monitoring of water influx into natural gas fields. A detailed description on this method and the ROVDOG instrument is provided by Sasagawa et al. (2003) and Zumberge et al. (2008). The inter-survey repeatable noise is in the range of 3 to 5 μGal (Zumberge et al., 2008). At these precision levels, time-lapse gravity is capable of tracking height changes in the gas-water contact (GWC) within a few metres, depending on the strength of water influx and the reservoir properties (Zumberge et al., 2008).

The large undeveloped gas fields in the Northern Carnarvon basin may be good candidates for gravity monitoring given the size of fields (typically multiple Tscf) and the nature of the reservoirs involved. Although many have moderate target depths (~2-3km depth below mudline (BML)), the presence of thick gas columns (on the order of 100's of meters) and high porosities (20-30%) should create reasonably large gravity changes above water-flooded zones. To the best of our knowledge, no feasibility studies on gravity monitoring of gas production in the Northern Carnarvon Basin have been published to date, and therefore this is the subject of our study.

To assess the feasibility of gravity monitoring of gas fields, we developed a rapid and practical method to predict the peak gravity change response above producing gas reservoirs (both aquifer-driven and depletion-driven). We used a vertical cylinder model to represent zones of density change in a gas reservoir. Our results show that it may be possible to detect a change in the gravity field after a 5m rise in the GWC or a 6MPa decline in reservoir pore pressure in Carnarvon Basin gas reservoirs.

THE VERTICAL CYLINDER GRAVITY MODELLING METHOD

The change in the vertical component of gravity Δg_z along the axis of a vertical cylinder with density contrast $\Delta\rho$ to the laterally equivalent material can be calculated from the equation given by Telford et al. (1990),

$$\Delta g_z = 2\pi\,\gamma\,\Delta\rho\left(L + \sqrt{z^2 + R^2} - \sqrt{(z+L)^2 + R^2}\right)$$

where $\gamma = 6.672 \times 10^{-3}\ \mu Gal\,\frac{m^2}{kg}$ is the gravitational constant, z is the distance from the centre of the cylinder to the observation point, R is the cylinder radius and L is the cylinder height (Figure 2). The calculated gravity response is a maximum value directly above the centre of the cylinder. This equation can be simplified by approximating the gravity effect of a vertical cylinder by the effect of a horizontal disk located at the centre of the cylinder multiplied by the cylinder height (Stenvold et al., 2008). The simplified equation is

$$\Delta g_z = 2\pi\,\gamma\,\Delta\rho_{bulk}\left(1 - \frac{1}{\sqrt{1 + \left(\frac{R}{z}\right)^2}}\right)L$$

The gravity anomaly is now a function of the ratio of the cylinder radius R to the cylinder depth z and a range of reservoir settings and dimensions can be captured for a given anomaly. The relative error in Δg_z is less than 1% when the simplified equation is used instead of Telford's Equation if $\frac{R}{z} > 0.2$ and $\frac{L}{z} < 0.2$ (Stenvold, 2008). Typically, these criteria are met in economical gas fields because the overburden thickness is usually less than the reservoir width and much greater than the reservoir thickness.

To model the time-lapse gravity response it is necessary to estimate the change in bulk reservoir density $\Delta\rho_{bulk}$ resulting from gas production. Two primary drive mechanisms were considered: (1) water-drive and (2) depletion-drive. In a strong water-drive gas reservoir, water displacing gas dominates the density change.

In a water-drive gas reservoir the change in bulk density $\Delta\rho_{bulk}$ between production times $t = 1$ and $t = 2$ is given by,

$$\Delta\rho_{bulk} = NTG\ \varphi\ (S_{g1} - S_{g2})(\rho_w - \rho_g)$$

where NTG is the net reservoir to gross volume ratio, φ is the fractional porosity of the net rock volume, S_{g1} and S_{g2} are the gas saturation values at times $t = 1$ and $t = 2$, and ρ_w and ρ_g are the density of water and the density of gas in the reservoir, respectively. The fluid densities are considered constant because isobaric conditions are assumed. Other assumptions are that the gas saturation is the complement of the water saturation and that the GWC remains horizontal during water influx (Figure 2).

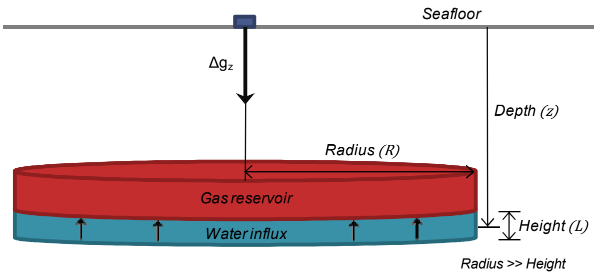


Figure 2. A schematic illustration of the model used to represent a gas reservoir undergoing uniform base water influx. The zone of water influx was approximated by a vertical cylinder with radius R, height L and depth z.

In a depletion-drive reservoir, there is little or no water influx and reservoir pressure declines linearly with increasing gas recovery (Dake, 1983). Other pressure effects such as connate water expansion and reservoir compaction are herein assumed to be negligible since the rock matrix and water compressibility are much smaller than the gas compressibility.

Assuming constant fluid saturations for small pressure changes, the change in bulk density $\Delta\rho_{bulk}$ in a depletion-drive gas reservoir between production times $t = 1$ and $t = 2$ is given by,

$$\Delta\rho_{bulk} = NTG\ \varphi\ S_g\ \Delta\rho_g$$

where the difference in gas density, $\Delta\rho_g = \rho_{g2} - \rho_{g1}$, is negative for a pressure decline. Methane can be approximated as an ideal gas over the pressure range under consideration. Therefore, the change in bulk density $\Delta\rho_{bulk}$ becomes,

$$\Delta\rho_{bulk} = NTG\ \varphi\ S_g\ \frac{M_w}{RT}\Delta P$$

where M_w is the molecular weight of methane, R is the gas constant, T is the reservoir temperature, and ΔP is the difference in reservoir pore pressure between $t=1$ and $t=2$.

ROCK AND FLUID PROPERTIES OF THE MUNGAROO FORMATION

We collected petrophysical data from 17 wells that intersected gas bearing sands in the Mungaroo Formation. These wells are located in 15 large, undeveloped gas fields in the Northern Carnarvon Basin. The data was sourced from well completion reports and journal publications. Moderate variations in petrophysical properties exist across the 15 fields. To capture these variations in the gravity modelling, we defined low, mid, and high values of each of the properties (Table 1).

Table 1. Low, mid and high values of rock and fluid properties established from petrophysical data collected in gas bearing sands in the Mungaroo Formation. Net to gross sand ratio and porosity values are expressed as a fraction of bulk reservoir volume. The initial gas saturation and the residual gas saturation are expressed as a fraction of pore volume. Properties and values highlighted in bold were calculated.

PROPERTY	LOW	MID	HIGH
Net to gross sand ratio	0.40	0.60	0.80
Porosity	0.15	0.23	0.30
Initial gas saturation	0.70	0.80	0.90
Residual gas saturation	**0.12**	**0.16**	**0.20**
Depth BML (m)	2000	2500	3000
Pore pressure (MPa)	32	35	39
Temperature (°C)	80	100	120
Gas density (kg/m^3)	**181**	**192**	**203**
Water salinity (ppm)	10,000	20,000	30,000
Brine density (kg/m^3)	**983**	**989**	**993**

Land's equation (Land, 1971) was used to predict the residual gas saturation, the fraction of gas remaining in the pore space of a reservoir rock after water influx has occurred, given the initial gas saturation and a trapping parameter (C). The trapping parameter is a function of the reservoir rock quality and was calculated in the range of 3.5 to 4.5. The resulting residual gas saturation ranges from around 0.12 to 0.20 for initial gas saturations ranging from 0.70 to 0.90.

Average reservoir pore pressures and temperatures in the majority of the gas fields considered in this study are between 32-40 MPa and 80-120°C, respectively. Over this pressure and temperature range, methane (the predominant species in dry gas) can be approximated as an ideal gas. Therefore, we calculated the density of methane using the ideal gas law (Himmelblau and Riggs, 2004). We calculated the density of brine in the Mungaroo Formation to be in the range of 983-993 kg/m^3 using the equations of Batzle and Wang (1992).

PRODUCTION SCENARIOS

To assess the feasibility of gravity monitoring of gas production, we modelled two primary drive mechanisms: (1) water-drive (Figure 2) and (2) depletion-drive. Reservoir pressure data collected from wells in the Northern Carnarvon Basin indicates there is a common water pressure gradient in the upper Mungaroo Formation across a number of fields (Jenkins et al., 2008). Depending upon the degree of connectivity between the gas reservoir and the aquifer, a reduction in reservoir pressure during gas production may lead to aquifer influx. In the water-drive production scenario, we assumed piston-like water sweep at the base of the reservoir with no pressure change. In the pressure depletion scenario, we assumed there is no water influx leading to a uniform decrease in pore pressure throughout the gas reservoir. In reality, a gas reservoir will normally experience a degree of both water influx and pressure depletion during production.

For brevity, gravity anomalies resulting from gas production from a reservoir with mid Mungaroo-range values of porosity and NTG only are shown in Figures 3 and 4. The threshold of detect (noise limit) was assumed to be ±10 µGal.

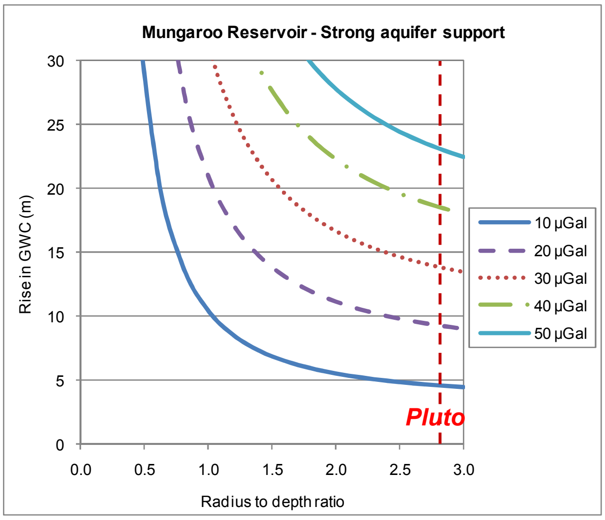


Figure 3. Vertical gravity anomalies resulting from base water influx in a Mungaroo-type gas reservoir. Mid porosity and NTG values were used. The threshold of detection corresponds to a 10 µGal gravity anomaly (blue solid line). The red dashed line indicates the approximate $\frac{R}{Z}$ ratio for the Pluto field.

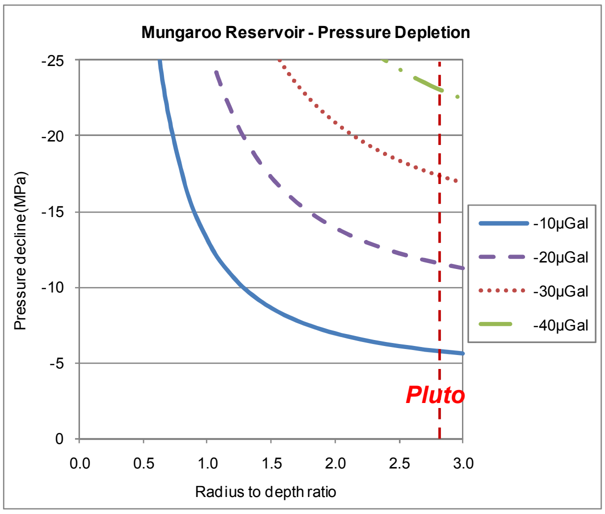


Figure 4. The vertical gravity anomaly caused by pressure depletion in a Mungaroo-type gas reservoir 100m thick. Mid porosity and NTG values were used. The threshold of detection corresponds to a -10 µGal gravity anomaly (blue solid line). The red dashed line indicates the approximate $\frac{R}{z}$ ratio for the Pluto field.

The magnitude of the positive gravity anomaly increases with both a rise in the gas-water contact or an increase in the radius to depth (volumetric extent of aquifer influx) (Figure 3). In the pressure depletion case, the magnitude of the negative gravity anomaly decreases with both a decrease in pore pressure and an increase in the radius to depth ratio (Figure 4). The results in Figures 3 and 4 demonstrate that gravity monitoring of gas fields may be feasible but needs to be assessed on a field-by-field basis.

EXAMPLE APPLICATION OF FEASIBILITY CONTOUR PLOTS

The contour plots in Figure 3 and Figure 4 can be a useful tool for conducting a quick feasibility test of using time-lapse gravity data to monitor production related changes in a gas field. We demonstrate this process with the Pluto gas field.

The Pluto field is located in the Northern Carnarvon Basin and, together with the nearby Xena gas field, has a dry gas recoverable volume of about 5Tcf (Conroy et al., 2008). The area of the Pluto gas field is approximately 100 km^2 and the target depth is about 2 km BML. A cylindrical reservoir with an equivalent area has an $\frac{R}{z}$ ratio of around 2.8 (Figure 3 and Figure 4). We assume a reservoir thickness of 100 m, an average porosity of 0.23 and an average NTG of 0.65 for this study.

Given the parameters above, we can use Figure 3 and Figure 4 to assess the sensitivity of gravity data to (1) a vertical height rise in the GWC across the field, and (2) uniform pressure depletion throughout the reservoir, respectively. The results are given in Table 2.

If there is strong aquifer support at Pluto, it may be possible to detect a 5 m rise in the GWC across the field with time-lapse gravity data. Alternatively, if depletion-drive is likely to be the dominant drive mechanism then a pressure decrease of 6MPa (870 psia) is required throughout the gas reservoir to produce a detectable gravity response.

Table 2. Minimum changes throughout the Pluto gas field for 1) a vertical height rise in GWC and 2) uniform pressure depletion to produce a detectable gravity anomaly. The modelled reservoir has an R/z ratio of 2.8, porosity of 0.23, NTG of 0.65 and is 100 m thick.

Case	Description	Minimum detectable change
1	Strong aquifer drive	5 m rise in GWC
2	Pressure depletion	6 MPa depletion

CONCLUSIONS

We have developed a method to quickly assess the feasibility of using repeat gravity measurements for gas field monitoring. We have applied this method to large, undeveloped Mungaroo gas fields located offshore in the Carnarvon Basin. Possible drive mechanisms for these fields range between strong aquifer drive and depletion drive. The feasibility of gravity monitoring of fields with strong aquifer support is more likely compared to depletion drive fields because the potential density change is greater. For a Mungaroo gas field with strong aquifer support a gas-water contact rise in the range of 5-6m may produce a detectable change in the gravity response, whilst a pressure change of greater than 6MPa is required in the pressure depletion scenario. These results suggest that gravity monitoring of Carnarvon Basin gas fields may be technically feasible, pending economic and technical evaluation on an individual field basis.

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