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Gravity monitoring of CO_2 storage in a depleted gas field: A sensitivity study

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Key Words: CO_2, sequestration, gravity, monitoring and verification

ABSTRACT

In 2006, the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) plans to undertake (subject to receiving the necessary approvals) a Pilot program for CO_2 storage within a depleted gas reservoir. The Otway Basin Pilot Program (OBPP) aims to demonstrate that subsurface CO_2 storage is both economically and environmentally sustainable in Australia. This will be the first CO_2 storage program in the world to utilise a depleted gas reservoir and, hence, the experience gained will be a valuable addition to the range of international CO_2 storage programs that are underway or being planned.

A key component of the OBPP is the design of an appropriate geophysical monitoring strategy that will allow the subsurface migration of the CO_2 plume to be tracked and to verify that containment has been successful. This paper presents the results from modelling the predicted gravity response to CO_2 injection into the Otway Basin reservoir, where the goal was to determine minimum volumes of CO_2 that may be detectable using non-seismic geophysical techniques. Modelling results indicate that gravity measurements at 10 m spacing within the existing observation well and the planned CO_2 injection well would provide excellent vertical resolution, even for the smallest CO_2 volume modelled (10 000 tonnes), but resolving the lateral extent of the plume would not be possible without additional wells at closer spacing.

INTRODUCTION

This paper summarises the results of a geophysical forward-modelling project carried out to determine the feasibility of gravity measurements for monitoring the injection and migration of the CO_2 plume in the Otway Basin Pilot Program (OBPP), and to determine minimum volumes of CO_2 that will be detectable. The goals of this project were to provide recommendations on optimum measurement systems and geometries for gravity data acquisition. This work is complemented by a companion paper that examines the feasibility of electrical resistivity monitoring techniques within the same environment (see Christensen and others, this issue). The monitoring program must provide essential information about the downward movement of the gas-water contact, areal coverage of the CO_2 movement, and provide early warning of any potential loss of containment.

The Otway field is a depleted methane reservoir, and as a CO_2 storage site it has the advantages of a demonstrated seal and some existing infrastructure. However, the limited vertical extent of the reservoir unit (only ~29 m) and the presence of multiple in-situ fluids (brine and methane) lead to significant challenges for monitoring and verification. The presence of residual methane means that the sensitivity of seismic methods to the presence of injected CO_2 in the supercritical state will be much lower than it would be if injection were to take place in a depleted oil reservoir or saline aquifer. For this reason, 4D seismic is not necessarily the obvious choice for geophysical monitoring, and an investigation of the feasibility of alternative geophysical methods is warranted.

An existing well, Naylor-1, is situated close to the crest of a tilted fault-block closure in the Otway Basin (Figure 1). The Waarre C reservoir unit is approximately 29 m thick and is located at a depth of 1977 m below sea level at Naylor-1. The Waarre formation is a friable sandstone interbedded with a thin shale unit, and represents deposits laid down in a low-sinuosity braided fluvial environment. The Naylor structure is a relatively complex tilted fault-block structure dipping to the south-east, with the thick Belfast Mudstone providing both vertical and cross-fault seal. Mature source beds may be located in the underlying Eumeralla and Crayfish Groups, with either direct migration into the reservoir or migration via fault conduits. Approximately 5 BCF of methane were produced from the Waarre C sand at Naylor-1 before it watered out. The estimated original gas in place is somewhere between 7 and 10 BCF, with the original gas-water contact projected at 2020 m from history matching.

The current plan is to inject CO_2 into the Waarre C sand at a rate of 3 mmscfd (1.8 kg/s). The proposed injection well location (at the time of modelling) is around 400–620 m downdip (SE) from Naylor-1, with the duration of injection expected to be around 18 months for a total injected volume of up to 100 000 tonnes. This represents approximately half the volume of gas that was produced from the reservoir. The results are helping guide the final selection of monitoring technologies, with further more-detailed and better-constrained modelling to be performed once additional data become available.

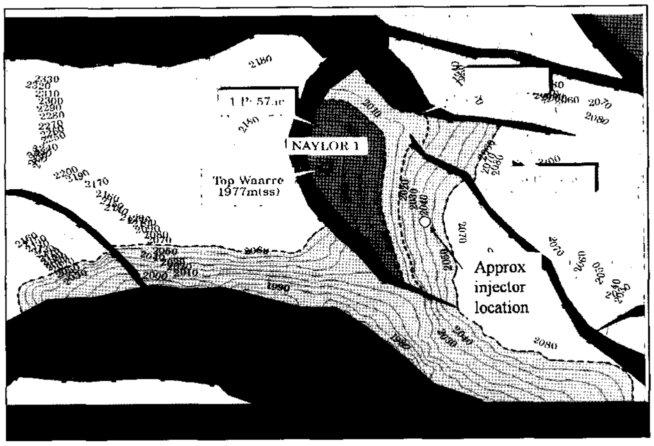

Fig. 1. Map of Naylor block (courtesy of Santos).

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We used log data from the Naylor-1 well and horizon interpretations from 3D seismic data for the Waarre C reservoir to construct a three-dimensional geophysical model of the proposed sequestration site. Log data from Naylor-1 were used to derive a rock properties model that links the reservoir parameters (porosity, saturations, pressure) to geophysical parameters (velocity, density, electrical resistivity). The changes in the model geophysical parameters caused by CO_2 injection were then calculated by combining the saturation data from three-dimensional TOUGH2 flow simulations with the rock properties model. The flow simulations assumed 84 000 tonnes of CO_2 injected over 18 months. Smaller volumes of CO_2 were also modelled by applying a rule-of-thumb for how the saturation values in the reservoir change per month of CO_2 injection, based on these simulation results. We then carried out forward modelling of the seismic and gravity response using the different models. Surface seismic, surface gravity, and borehole gravity response were calculated and the relative sensitivities of each method were compared. The seismic models require further refinement before the results can be considered reliable, because of the complex response to multiple fluid phases in the reservoir, and these results will be published at a later date.

Rock Properties Modelling

The Naylor-1 log data were used to derive a rock properties model for the Waarre C reservoir. This model allows us to relate the reservoir parameters (porosity, saturation, pore pressure, salinity) to geophysical parameters (velocity, density, resistivity), and thus calculate the anticipated changes in seismic velocity, density, and electrical resistivity in the reservoir when CO_2 is introduced.

The bulk density is found from the constituent grain and fluid densities, the fluid saturations, and the porosity. We then used an L_1-norm minimisation of the misfit between the log and calculated densities. The minimisation was constrained by fixing the values of known parameters; 0.632 for gas gravity and salinity estimated to be 14 000 ppm. Archie's law was used to calculate the bulk resistivity from the water saturation and reservoir porosity. L_1-norm minimisation was used to find the brine resistivity, and porosity and saturation exponents that give the best fit between observed bulk resistivity and the log bulk resistivity. Additional details on the rock properties modelling, including the seismic and electrical properties that are not discussed further here, are given in Hoversten and others (2003).

Figure 2 shows the results of the regression fit to the log resistivity, sonic velocity, and density. The best-fit values are in the expected range for a poor to moderately sorted sandstone.

Flow simulation inputs

A flow simulation for the Waarre C reservoir was carried out by Jonathon Ennis-King (CSIRO) using TOUGH2 (Pruess and others, 1999), which is a compositional flow simulator (Figure 3). Results show CO_2 mixing with the methane as it migrates up-dip and accumulates under the remaining free gas cap at the Naylor-1 crestal structure. Complex mixing of the three fluid phases provides a challenge for both forward modelling and analysis of geophysical monitoring data. The flow simulation model used to build the geophysical models was necessarily simplistic because of the limited data that were available when this study was initiated.

Saturation data were provided for before and after methane production, 18 months after the beginning of CO_2 injection (end of injection), and two and five years after the beginning of injection. Mass fractions of the various components, computed by TOUGH2, were converted to molar fractions and then to saturations. The data were then interpolated onto a finer grid and the flow model was draped over the seismic surface so that it followed the same contours as the reservoir. The resultant saturation data was used to determine geophysical properties of the reservoir at various times during the CO_2 injection experiment.

The TOUGH2 data for 18 months of injection allowed us to infer that the CO_2-water contact moves down by 0.5 m for every month of injection. This rule-of-thumb allowed us to generate additional (simplistic) models of the CO_2 saturations for shorter time periods of injection. For these additional models, the CO_2 plume at the injection well was ignored, as there was no easy way to estimate how this plume changes for different volumes of CO_2 injection. Table 1 shows the saturation values used in different intervals of the reservoir for the gravity modelling. Reservoir pressures were modelled as hydrostatic (19.5 MPa), but changes in pore-pressure were not considered, as the flow simulations predicted only very minor increase in pore pressure (~0.1 MPa) that quickly dissipated after injection stopped. Production history matching that was performed after these models were built indicates that present-day reservoir pressure is likely to be significantly depleted from hydrostatic, perhaps as low as 15 MPa. This is considered to be of minor significance for the gravity and electrical modelling, but is important for the seismic modelling that is now being revisited with this updated

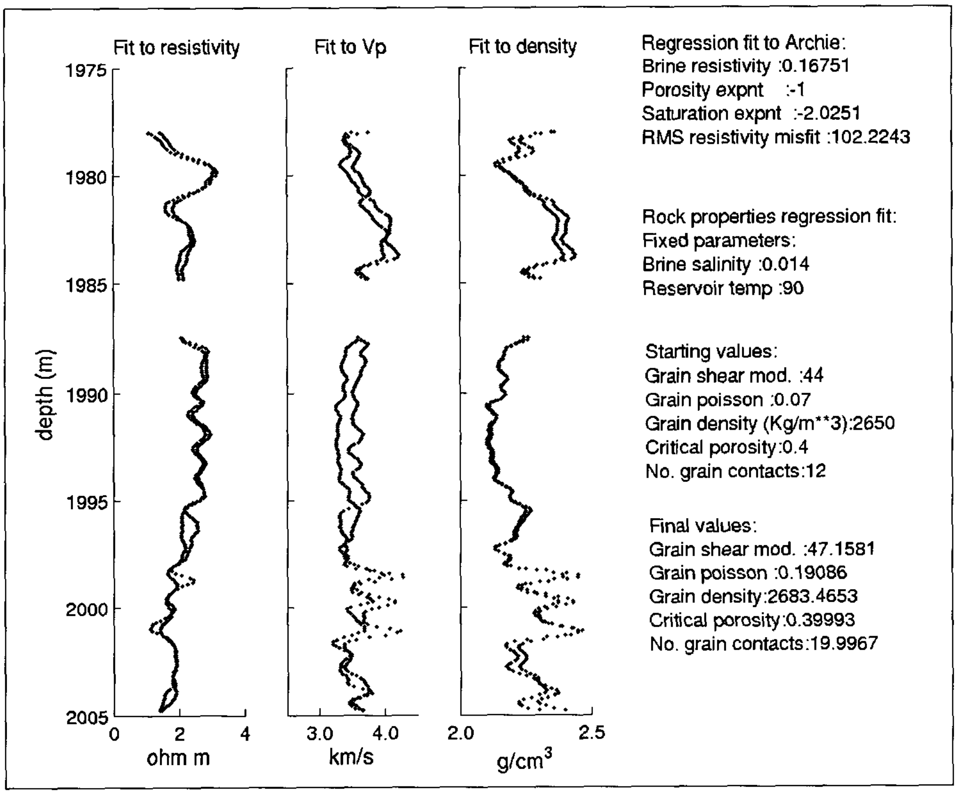

Fig. 2. Naylor-1 log data (blue) and the best fit to the log data (red). The gap in the data coincides with a 2 m thick shale unit.

information.

Gravity modelling

We carried out forward modelling and inversion of the changes in surface and borehole gravity induced by changes in CO_2 saturation in the reservoir. Gravity monitoring has lower spatial resolution than seismic methods, but accurate time-lapse gravity data could potentially be very complementary to 4D seismic because of the direct response of gravity to changes in subsurface density, rather than the more complex relationships between density and seismic response. Supercritical CO_2 has a density higher than that of methane but lower than that of water. Thus, replacing water with CO_2 in the reservoir will result in a net decrease in density, but the remaining free methane at the crest of the reservoir becomes enriched with CO_2, resulting in a net increase in density in this region.

The combined result is a change in the gravity response. The total change must be greater than the background noise (typically around 1–2 μGals) to be detectable in repeat gravity surveys (Hare and others, 1999). We investigated how much CO_2 must be injected to elicit a detectable change in the gravity response at the surface, in a dense network of boreholes, and in the existing boreholes. We also investigated whether and how well the change in gravity response can be modelled to locate the CO_2 plume.

The gravity models described below were constructed using GEM (Geophysical Earth Modelling) software developed at Lawrence Berkeley National Laboratories, and used a horizontal grid spacing of 25 m, with vertical grid spacing ranging from 100 m above and below the reservoir to 5 m in the reservoir interval. Total dimensions of the models are 3000×2500×3000 m. We constructed models corresponding to 10 000, 37 000, 84 000, 147 000 and 227 000 tonnes of CO_2. The bottom of the methane layer was placed at 1992 m, and the bottom of the CO_2 layer was moved down by 0.5 m for every month of injection. The saturation values used for each of the fluid phase intervals are shown in Table 1. Figure 4 shows a cross-section of the modelled changes in density between the beginning and end of injection.

We investigated three different field configurations:

- gravity meters located on the surface at 100 m spacing (total of 806 gravimeters)
- gravity meters located at 1900 m depth in a grid of boreholes at 500 m spacing (42 boreholes)
- gravity meters located at 10 m vertical intervals in the four existing boreholes and in the proposed injection well.

Modelling of the surface gravity response showed a change in vertical gravity (Gz) of around 0.1 μGal, which is an order of magnitude lower than the detection limit for gravimeter field data and the results are not shown here. Surface gravity monitoring will only be viable under the most favourable circumstances of large volumes of fluid displaced by CO_2 in the gas phase at shallow depths. The reduced density contrast when CO_2 is in the supercritical phase means that changes will be below the sensitivity of current measurements, and surface gravity monitoring will not be feasible in most applications within the foreseeable future (Lewis and Shin, 2001)

Figure 5 shows the change in gravity recorded at 1900 m depth (~80 m above the reservoir) in a network of boreholes spaced 500 m apart, which is not unreasonable for a producing oil or gas field (although impractical in this case as additional observation wells will not be drilled at Otway, the modelling is relevant for potential application in other fields). Placing the gravimeters in boreholes allows the gravity measurements to be made closer to

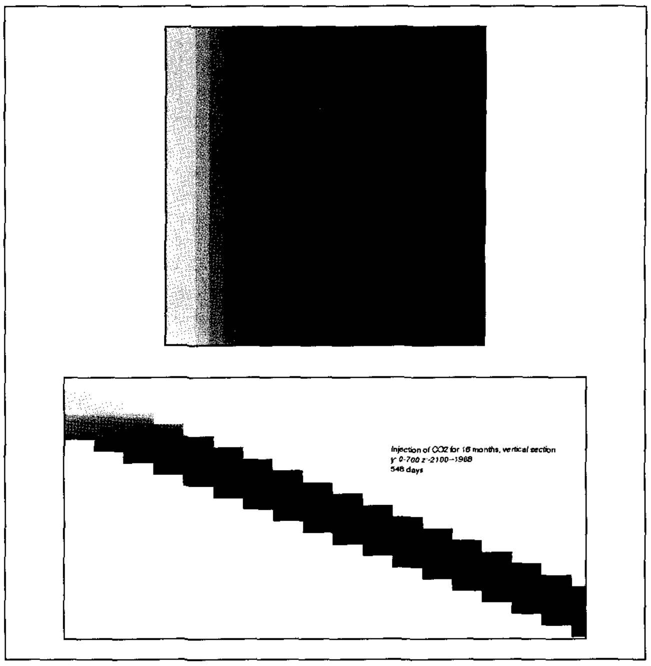

Fig. 3. Reservoir flow data from TOUGH2 simulations, provided by Jonathon Ennis-King (CSIRO). CO_2 saturations after 18 months of injection (left: plan view of the reservoir; right: vertical slice through the injection well and Naylor-1). Red represents CO_2, green represents methane, black represents water. The CO_2 injection plume can be seen 620 m downdip from Naylor-1. The density contrast between the CO_2 and water causes the CO_2 to rise to the top of the reservoir and migrate up-dip, where it sinks below the residual methane cap. The end result is a layer of CO_2 enriched in methane, capped by methane enriched in CO_2.

	Methane cap	CO_2 layer	Water leg
S_w	0.12	0.232	1.0
S_g	0.72	0.345	0.0
S_{CO2}	0.16	0.423	0.0

Table 1. *Saturation values used in the geophysical models. These saturation values were taken from the mean saturation values in each leg in the TOUGH2 data for two years after the beginning of injection.*

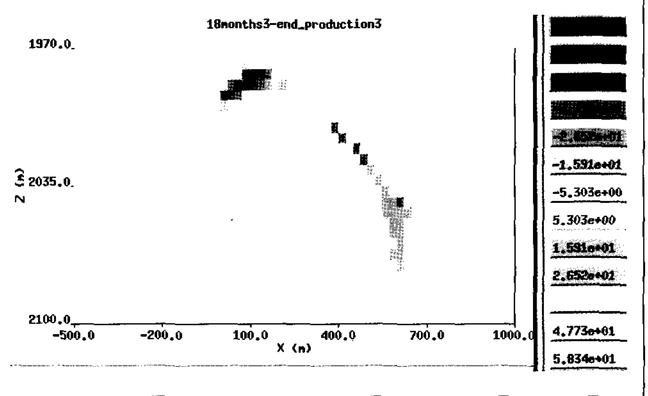

Fig. 4. Cross section of density changes in the reservoir between the beginning and end of CO_2 injection (84 000 tonnes). The maximum density change is of the order of about 60–70 kg/m³. Naylor-1 is located at *x* = 0 *in this figure, and the injection well is located at* *x* = 620.

the reservoir, strengthening the signal compared to observations made on the surface. The calculated change in *Gz* is on the order of 5 to 6 μGals, which is above the limit of detection. Figure 5 shows that the area over which the gravity change will be detectable at this depth is probably around 1 km × 800 m.

Modelling the gravity response between the end of injection and 6 months after injection ceases showed a maximum change in gravity response at the crestal structure from -5.8 μGals at the end of injection to -6.5 μGals 6 months later, as the CO$_2$ continues to migrate away from the injection well and towards the Naylor-1 crestal structure. There is little further change in gravity response after an additional three years.

Gravity inversion

Inversion of the gravity data was performed for 18 months (i.e., end of injection), two years, and five years after the beginning of CO$_2$ injection. For reasons of space, only the inversion results for the end of injection (18 months) are shown here. The gravity inversion algorithm used in this study solves for density changes within the reservoir. That is, changes in the inversion are constrained by the horizons that define the top and base of the reservoir. The inversion result is a cumulative density change in the reservoir as a function of *x* and *y*. Because the model space and inversion domain space are different, in order to compare inversion results with a true model, we need to calculate a parameter that is equal in both of these domains; such a parameter is the product of a cumulative cell density change and its volume. This is illustrated in Figure 6. The true model is displayed in colour, and the inversion results are displayed as contours. The inversion agrees very well with the true model in the *y*-direction. There is about 500 m difference between the true model and the inversion results in the *x*-direction. This is because of the presence of two anomalies; one at the injection well and one at the crestal structure. The two anomalies are separated by only 500 m, which is equal to the borehole spacing used for these simulations. Hence, the inversion finds a broad smooth anomaly instead of two more localised anomalies. Tighter borehole spacing in a 1 km × 800 m region would allow better resolution of the CO$_2$ plume geometry.

Since it is more reasonable to assume that access will be available only to the existing boreholes at Otway, we calculated the gravity response for a string of detectors (at 10 m spacing, down to a depth of 2100 m below sea level) in each of the five existing boreholes that are located within a 2 km range of Naylor-1: Naylor South-1 is located about 850 m SSE of Naylor-1; the proposed injection well (at the time of this modelling) lies 620 m SE; Boggy Creek lies 1.6 km NE; and Buttress-1 lies 1.4 km North of Naylor-1.

Figure 7 shows the change in gravity response recorded in the Naylor-1 well and the proposed injection well. A decrease in vertical gravity (*Gz*) after CO$_2$ injection is observed at the top of the reservoir. This is because the net density in the reservoir is reduced so the vertical gravitational force is decreased. Below the reservoir we see an increase in *Gz* after CO$_2$ injection. This is because the gravitational force is the sum of the attraction to the mass everywhere. After CO$_2$ injection there is less mass above these gravimeters to exert an upwards gravitational force, with the result that the downwards gravitational force is increased. In both wells the change in *Gz* is well above the background noise and indicates that gravimeters at 10 m spacing in Naylor-1 and the injection well would allow very accurate resolution of the vertical location of the CO$_2$ plume.

Modelling of the gravity response in the other three wells showed a maximum change of less than 0.5 μGal and would not be feasible for gravity monitoring. This is illustrated in Figure 8,

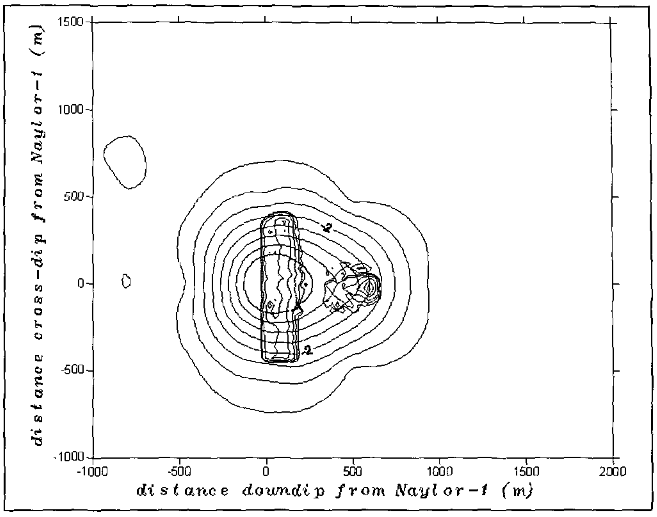

Fig. 5. Modelled change in vertical gravity (*Gz*) between pre- and post-injection, measured by gravimeters at 500 m spacing at 1900 m depth. The modelled change in gravity response has been contoured and overlaid on a plot of the cumulative density change determined from flow simulations.

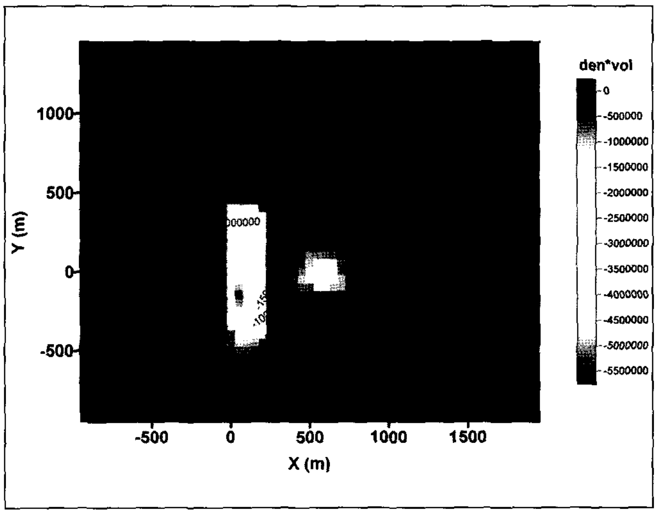

Fig. 6. True density model overlaid by contours of inversion results for the changes in density between the beginning and end of CO$_2$ injection.

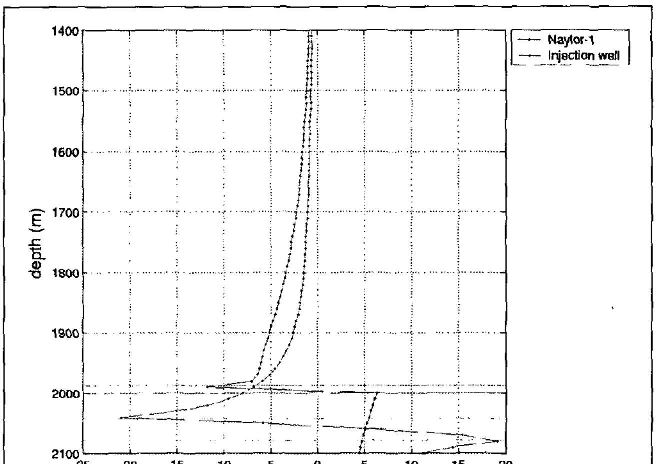

Fig. 7. Comparison between the change in *Gz* recorded at Naylor-1 and at the proposed injection well, after 18 months of CO$_2$ injection. Solid lines mark the vertical extent of the CO$_2$ plume at Naylor-1 and the injection well.

where the results for all five wells were used to contour the range of a potentially detectable response. In general, a density contrast can be detected by borehole gravity measurements if the observation well is within a distance not more than twice the thickness of the zone of density contrast (Popta and others, 1990). Our reservoir thickness is about 30 m, which suggests that only wells within about 60 m of the CO$_2$ plume will show a response. This supports the conclusion that the gravity anomaly will be detectable only in the injection well and in Naylor-1.

Gravity response as a function of CO$_2$ volume

For the second suite of gravity modelling we used the saturation data inferred for different CO$_2$ volumes. The CO$_2$ volumes investigated correspond to 10 000, 37 000, 84 000, 147 000, and 227 000 tonnes. Results indicated that even a 227 000 tonne injection volume, which is more than double the maximum volume that will actually be injected, will not be detectable by surface gravimeters. Conversely, borehole gravimeter data (Figure 9) suggests that even the lowest volume of CO$_2$ modelled, 10 000 tonnes, will be detectable at Naylor-1 (and by inference, also at the injection well, although CO$_2$ saturations at the injection well were not included in these additional models). Interestingly, the results obtained from these simulations suggest that for very small volumes of injected CO$_2$ (10 000 tonnes), a net increase in gravity may occur. The rule of thumb for saturation values derived from the flow simulations suggested that for very small volumes of injected CO$_2$ there will be little or no change in the level of the gas-water contact, with the injected CO$_2$ instead mixing with the remaining methane and causing a net increase in density in the reservoir. However, this result for 10 000 tonnes must be considered questionable in the absence of more accurate flow simulation data. With that in mind, based on these results, the 37 000 tonne injection case is the minimum that can be confidently expected to produce a detectable response.

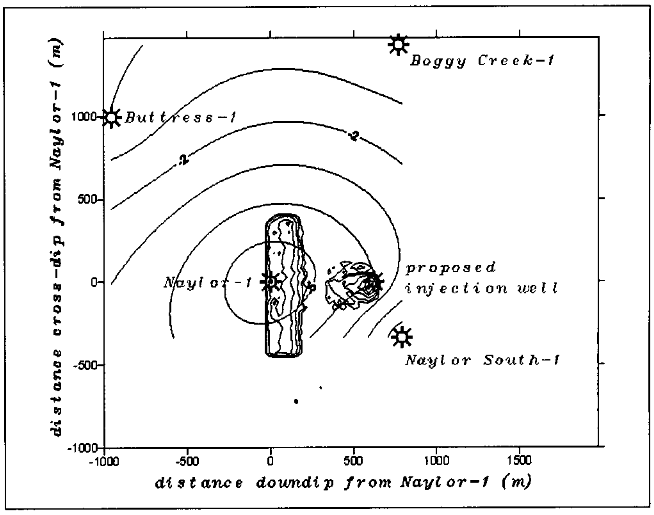

Fig. 8. Change in Gz recorded at 1950 m in all of the existing wells (Naylor-1, Naylor South-1, Buttress-1, Boggy Creek-1, and the injection well), after 18 months of injection. Contours shaded in blue indicate a detectable gravity anomaly. The well locations and the location of the density anomaly from flow simulations are also shown. This figure suggests that the anomaly caused by the CO$_2$ plume will be detectable only at Naylor-1 and at the injection well. (Note: the computed anomaly is sampled only at the 5 wells – contours in between represent an interpolation of the data by kriging). The range of detectable gravity change shown by blue-shaded contours is possibly overestimated, due to the interpolation algorithm.

CONCLUSIONS

Effective monitoring and verification of CO$_2$ storage requires measurement of many different parameters at many locations and scales. We need be able to determine the phase state and track the migration paths of the CO$_2$. For many CO$_2$ storage sites, time-lapse surface seismic methods will form the basis of geophysical monitoring efforts as they are cost effective and cover the whole area of interest. However, in the case of depleted gas fields, the sensitivity of seismic methods to the injected CO$_2$ is much reduced due to the presence of residual gas that remains trapped in the pores. Alternative geophysical methods may be required in place of, or to complement, seismic monitoring. The desire for multiple independent geophysical measurements to reduce uncertainty in the data analysis must be balanced against costs and, ultimately, the regulatory requirements for storage verification.

Gravity modelling indicates that surface gravity techniques will

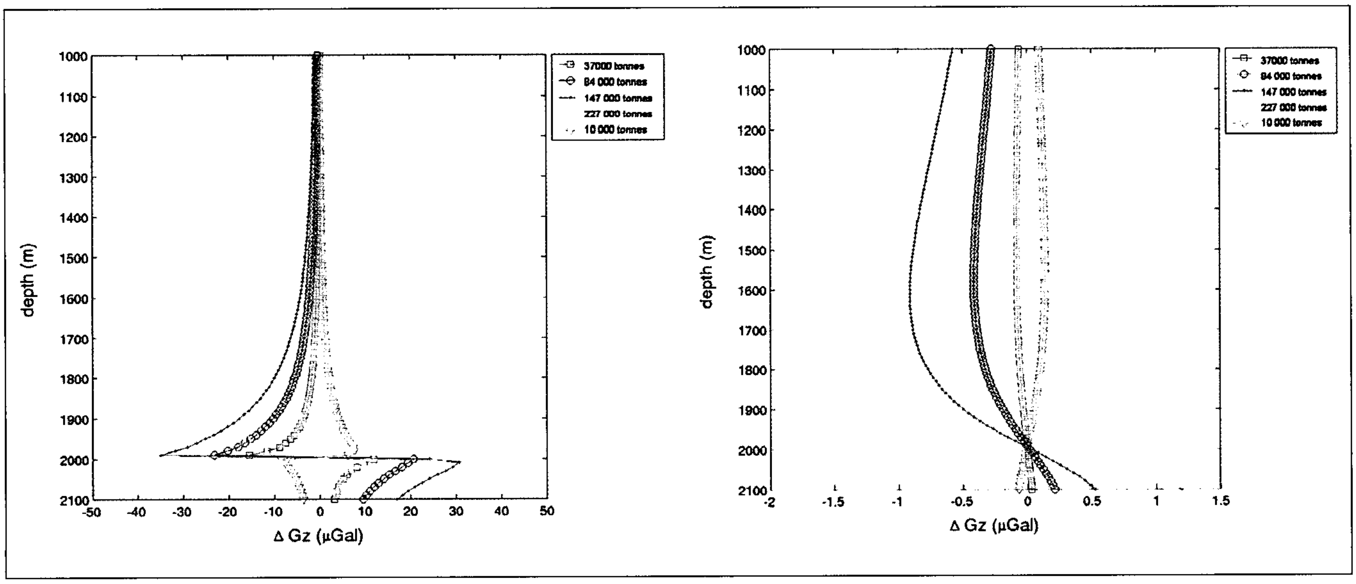

Fig. 9. Comparison of Gz anomaly for different CO$_2$ volumes in: a) Naylor-1, and b) the closest existing borehole, Naylor South-1. Data from the injection well is not shown here as the CO$_2$ plume at the injection well was not included in these models.

not be able to detect any changes as a result of CO_2 injection into the 2 km deep Waarre C reservoir, but borehole gravity monitoring could provide good resolution of the CO_2 plume. A network of boreholes at 500 m spacing would allow good vertical resolution of the CO_2 plume. However, horizontal resolution is only as good as the borehole spacing, so distinguishing the two anomalies at the crest of the reservoir and at the injection well would require closer borehole spacing. If only the existing boreholes were used, gravity measurements at 10 m spacing within Naylor-1 and the injection well would provide excellent vertical resolution, even for smallest CO_2 volume modelled of 10 000 tonnes, but resolving the lateral extent of the plume would not be possible.

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枯渇ガス田での CO_2 貯留の重力モニター: 感度試験

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要　旨： 2006年、Cooperative Research Centre for Greenhouse Gas Technologies (CO_2CRC)は、(必要な承認を待って)生産の終わったガス貯留層に CO_2 貯留するパイロット・プログラムを計画している。 Otway Basin Pilot Program (OBPP)は、CO_2 地下貯留がオーストラリアにおいて、経済にも環境配慮面においても持続可能であることを示すことを目的とする。これは世界初の、枯渇ガス貯留層を利用する CO_2 貯留プログラムである。従って、このプロジェクトで得られる経験は世界中で進行中あるいは計画中の広範な CO_2 貯留プログラムへの貴重な貢献となるであろう。

OBPP の主要な要素として、地下の CO_2 プリュームの移動を追跡し、さらに、それがきちんと貯留されているかを確認するための、地球物理探査的モニタリング手法の確立を挙げることができる。 本論文では、モデリング結果より予測される、Otway Basin 貯留層中へ CO_2 圧入を行った場合の重力応答結果を示す。その目標は地震探査以外の物理探査法で検出可能な CO_2 の体積の最小値を決定することである。モデルリングの結果、現存の観測井と計画中の CO_2 圧入井の中を 10m 間隔で重力測定すれば、最もわずかな CO_2 量(10000 t)の場合でも、大変良い垂直解像度を得られることがわかった。しかし、CO_2 プリュームの水平分布範囲を特定するには、孔井をより小間隔で追加しなければならない。

キーワード： CO_2 地層処分、重力、モニタリング、CO_2 貯留確認

채굴후 가스전내 CO_2 저장소의 중력 모니터링: 감도 연구

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요　약： 2006 년도에 호주 온실가스 기술에 대한 협력연구센터(CO_2CRC)는 채굴 후의 가스 저류층내에 CO_2 를 저장하는 시험 연구의 수행을 계획하고 있다 (승인이 필요함). Otway Basin Pilot Program (OBPP)은 지하 CO_2 저장이 경제적이며 환경적으로 지속가능함을 보이는 것이 목표이다. 이는 CO_2 저장 프로그램으로는 세계에서 처음으로 채굴 후 가스 저류층을 활용하는 것 이므로 여기서 얻어질 경험은 현재 수행중이거나 계획중인 국제적 CO_2 저장 프로그램에 귀중한 하나의 분야를 더할 것이다.

OBPP 의 중요한 요소는 주입된 CO_2 의 거동을 추적하고 지하 저장이 성공적임을 입증하기 위해 적절한 지구물리학적 모니터링 전략의 설계이다. 이 논문은 Otway Basin 저류층에 CO_2 를 주입할 때의 중력 반응을 예측하는 모델링 결과를 보여주며, 그 목적은 탄성파탐사가 아닌 물리탐사 방법으로 탐지가능한 최소 CO_2 부피를 결정하는 데에 있다. 모델링 결과는 계산된 CO_2 부피가 최소 10,000 ton 일 경우에도 기존 관측정과 계획된 주입정내에서 10 m 간격으로 중력을 측정하면 훌륭한 수직 해상도를 제공할 것임을 말해주나, 수평적인 연장에 대한 해상도는 더 좁은 간격의 추가 시추공이 없다면 불가능한 것으로 나타났다.

주요어： CO_2, 지하저장, 중력, 모니터링과 입증

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