Field Testing the Applicability of Borehole Gravity for Monitoring Geologic Storage of CO_2 within Closed Carbonate Reef Reservoirs

Lydia Cumming[1], Matthew Place[1], Jennifer Hare[2], Andrew Black[2], Neeraj Gupta[1], Allen Modroo[3], and Rick Pardini[3]
([1]Battelle, Columbus, Ohio; [2]Micro-g LaCoste, Inc, Lafayette, Colorado; and [3]Core Energy LLC, Traverse City, Michigan)

BACKGROUND

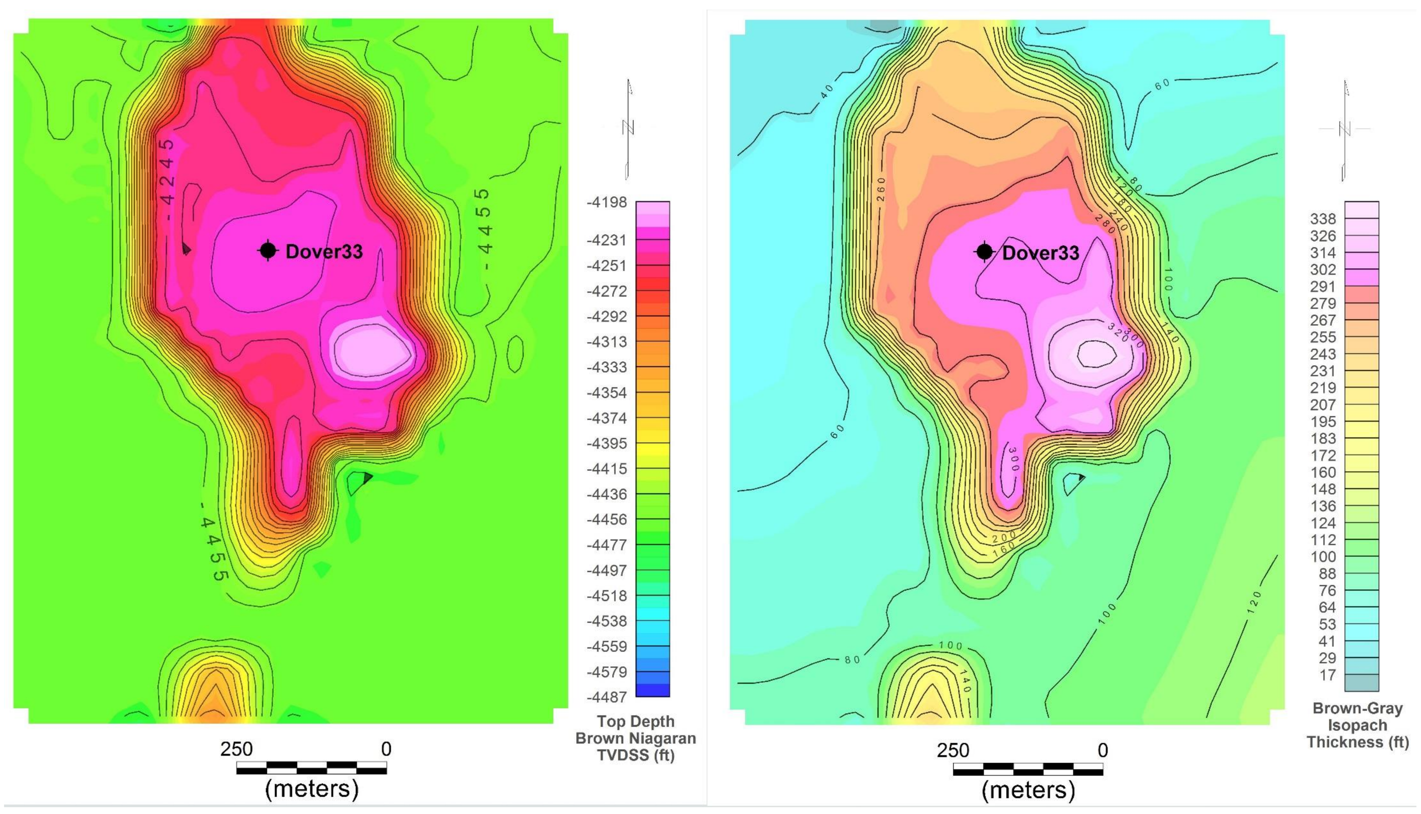
The Midwest Regional Carbon Sequestration Partnership (MRCSP) is evaluating the potential to use Silurian-aged reefs for the storage of CO_2 as part of enhanced oil recovery (EOR) operations. The Niagaran Pinnacle Reef Trend on the northern flank of the Michigan Basin is a regionally significant potential resource for hydrocarbon production and CO_2 storage. The project is being carried out across the pinnacle reefs in fields in different stages of their production life-cycle, including a highly depleted reef that has already undergone CO_2-EOR (late-stage reef), reefs currently undergoing CO_2-EOR (active EOR reefs), and reefs that have previously only experienced primary oil production (new EOR reefs). The pinnacle reefs are oil-bearing dolomite and limestone structures that are overlain by low-permeability carbonates and evaporates.

The use of borehole gravity (BHG) was tested in the late-stage reef (referred to as Dover 33) to assess the capability of this technology for monitoring CO_2 movement and storage within the reef structure. BHG surveys are conducted by performing gravity measurements at a series of downhole stations within the well or borehole being tested. Gravity (Δg) and depth (Δz) differences measured between successive stations constitute the interval vertical gradient of gravity ($\Delta g/\Delta z$), which varies directly with the density of the rock layer bracketed by the measurements. BHG data are converted to apparent or interval density profiles, which can be used for reservoir evaluation, well log and core analysis/correlation, integration with surface gravity and seismic studies, or engineering and rock property investigations. For CO_2 monitoring, time-lapse BHG surveys may be useful for detecting changes in density caused by the accumulation of CO_2 within the pore spaces of the rock layer.

TECHNICAL APPROACH

Using existing well log and seismic data provided by Core Energy, LLC, Battelle and Micro-g LaCoste, Inc. (MGL) developed a model to predict the change in density of the reef. Unlike a saline reservoir scenario that has CO_2 replacing brine in the pore space, the depleted pinnacle reef model scenario assumed the CO_2 would be replacing low pressure/density gas. Furthermore, the model assumed the CO_2 would concentrate in the more porous zones connected through high permeability pathways. The model predicted that the mass added to this closed reef structure would result in a measurable positive density change over time.

Two BHG surveys were performed within an injection well located in Dover 33 to generate time-lapse data. A baseline gravity measurement was performed in early 2013 while the reef was in a depleted, low-pressure condition. Repeat measurements were made in the well in 2016 following the injection of approximately 265,000 metric tons of CO_2 into the reef and the reservoir pressures had increased from approximately 600 psi to 3,500 psi (4 MPa to 24 MPa).
The largest sources of spatial gravity variations are the free-air effect, latitude effect, and regional and local geology-including terrain, lithology and structural variations. These time-static sources of gravity variation are cancelled by time-differencing survey data, and the remaining time-lapse gravity signal is representative of temporal changes in formation densities (such as those due to CO_2 or other fluid injections or redistributions).

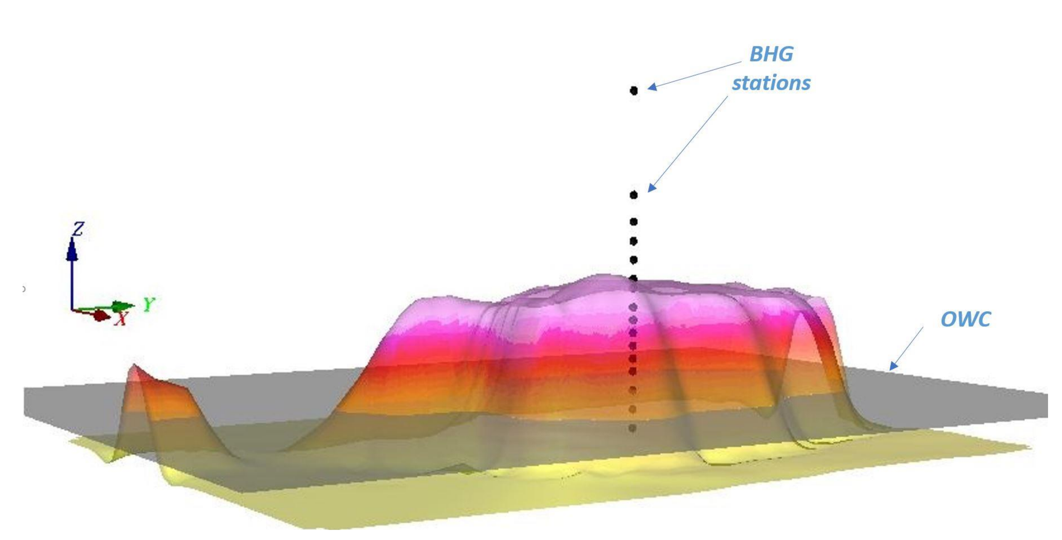


Map View of Late-Stage Reef Used for the BHGM Surveys

TESTING METHODS

- Two gravity surveys (2013 and 2016) were performed in the same well with the same configuration parameters.
- The same 39 gravity-measurement stations were quantified during each test.
- Station depths were verified to within a few cm between the tests using gamma ray.
- BHG measurements were made using a finer, vertical station interval near the zone of interest (reef/reservoir) with more widely-spaced stations near the surface:

Zone 1 (Deep, Reservoir Zone) ▪ 20 to 40 ft (6 to 12 m) Station Spacing ▪ Depths between 5,176 and 5,540 ft (1,577 and 1,658 m) ▪ 4 Sweeps (well passes, or "Repeats")	Zone 3 (Shallow) ▪ 190 to 380 ft (58 to 116 m) Station Spacing ▪ Depths between 660 to 3,253 ft (201 and 991 m) ▪ 3 Sweeps (Repeats)
Zone 2 (Intermediate, Above Reservoir) ▪ 120 to 280 ft (36 to 85 m) Station Spacing ▪ Depths between 3,253 and 5,176 ft (991 and 1,577 m) ▪ 3 Sweeps (Repeats)	Zone 4 (Near Surface) ▪ 3 Stations at Depths of 10, 34 and 240 ft (3, 10, and 73 m) ▪ 1 Sweep (Repeat)



Side View of Reef with Locations of Deepest Borehole Gravity Stations

TEST EQUIPMENT

- 2.4-inch diameter Gravilog – deployed by MGL (2013)
  - 7 microGal average station accuracy
  - Bubble leveling system
- 1.9-inch diameter Gravilog – deployed by MGL (2016)
  - 3 microGal average station accuracy
  - Micro-Electromechanical System (MEMS) tilt sensors
- L-M 1-33 Well with sealed (closed-ended) 2-7/8 inch tubing
- Tubing was filled with light-weight (9.6 lb/gal) Na-Cl Brine

Preparation of the Well for BHGM Surveying 2016

Gravilog Meter 2016

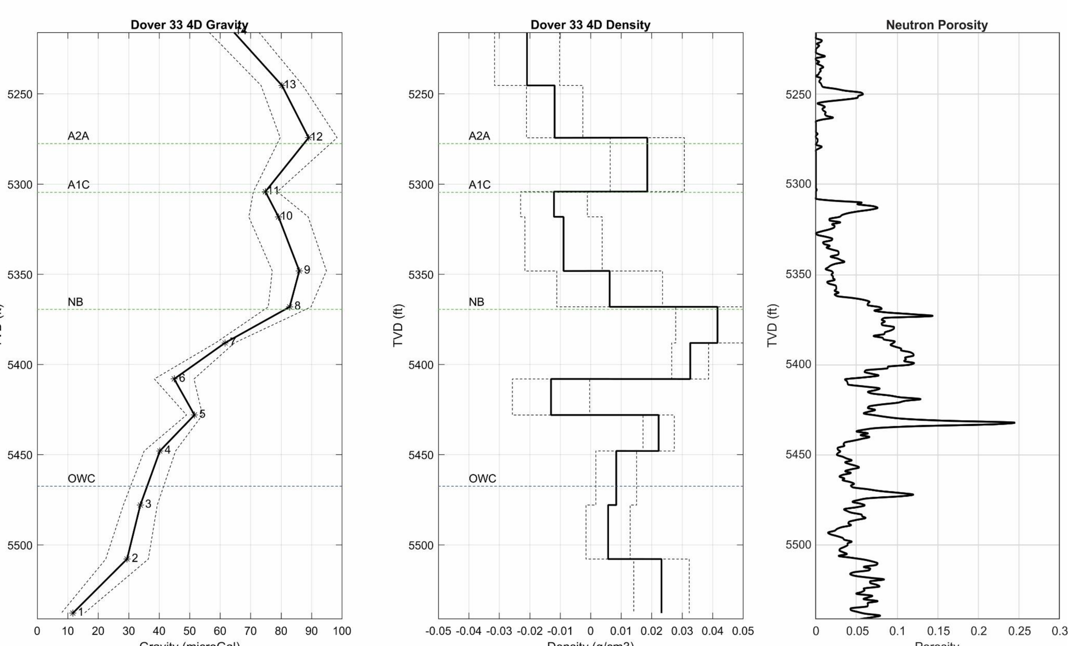
RESULTS

The time-lapse gravity signal over the whole well survey shows the change in gravity as small, variable and centered around 0 (zero change) in the shallowest zone (Zone 3) and upper part of the intermediate zone (Zone 2). Below this, the signal is positive and generally increasing down to the top of the reservoir (Zone 1), then positive and generally decreasing down through the reservoir toward the base of the well. In Zone 1, the gravity difference between 2013 and 2016 clearly shows a broad, approximately 90 microGal peak signal change above the Niagaran Brown (NB) reservoir (Stations 9 through 12). This signal is consistent with the forward models of CO_2 injection in a closed structure.

Formation Name	Station #	Depth 2013 (ft)	Depth 2106 (ft)	Δ Gravity (mGal)	Δ Density (g/cm3)
SBS	15	5176.0	5176.6	0.079	-0.014
A2C	14	5217.0	5217.2	0.064	-0.021
A2C	13	5247.0	5246.9	0.080	-0.012
A2A	12	5276.0	5275.9	0.089	0.019
A1C	11	5306.0	5306.0	0.075	-0.012
A1C	10	5320.0	5320.0	0.079	-0.009
A1C	9	5350.0	5350.0	0.086	0.006
NB	8	5370.0	5370.0	0.083	0.042
NB	7	5390.0	5390.0	0.062	0.033
NB	6	5410.0	5410.0	0.045	-0.013
NB	5	5430.0	5430.0	0.052	-0.022
NB	4	5450.0	5450.0	0.040	0.008
NB	3	5480.0	5480.0	0.034	0.006
NB	2	5510.0	5510.0	0.029	0.023
NB	1	5540.0	5540.1	0.012	-

Change in Gravity and Measured Density between the 2013 and 2016 BHG Surveys in Zone 1

The change in density between the two BHG surveys provide an indication of the distribution of CO_2 within the reef. The largest BHG survey density change is observed in the upper, approximately 40 ft of the Niagaran Brown formation (Stations 7 and 8), where a density change from 0.033 to 0.042 g/cm³ is indicated by the computed BHG slab density. These density changes indicate that CO_2 has filled the pore spaces in this portion of the reef where the porosity is generally greater, and that the injected CO_2 has been contained within the reef (Brown Niagaran formation).



Observed BHGM Gravity Change (2016 – 2013) (left), Computed BHGM Slab Density Change (middle) with Error Bars, and Neutron Porosity (right)

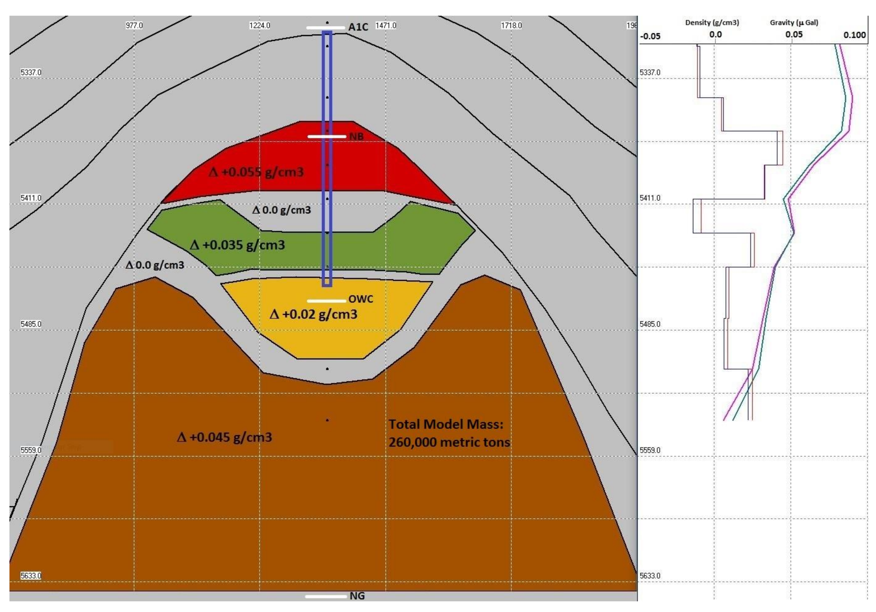
*The estimated error bounds are indicated by dashed black lines on both panels. Formation tops were provided by Battelle: OWC= Oil water contact; NB= Niagaran Brown (reservoir); A1C= A1 Carbonate (reservoir); A2A= A2 Anhydrite (seal). The well perforations are from 5,309 to 5,460 ft.

CONCLUSIONS

The injection of 265,000 metric tons of CO_2 into this sealed, depleted reservoir was expected to result in an increase in the average density of the reef, and a greater increase in density in zones of the reef that CO_2 accumulated. The data collected during the time-lapse monitoring agree with these hypothesized results.

The geologic framework and pore-fluid distribution models can be combined with the time-lapse gravity monitoring to substantiate the movement of the injected CO_2 in the reef. The CO_2 appears to have replaced the original gas zone in the upper portion of the reef. The red zone shows the area of greatest CO_2 storage followed by the green zone, which indicates significant CO_2 storage. The yellow and grey areas indicate minimal CO_2 storage.

The results obtained at the MRCSP adds to the growing knowledge base regarding the use of BHG surveys to monitor CO_2 storage performance. This research is important because BHG surveys could provide an effective method for demonstrating storage security, as well as provide valuable data to improve geologic models.



Time-Lapse Density Model Showing Heterogeneous Distribution of CO_2 (left) with Modeled (Red/Magenta) and Observed (Black/Blue) Density and Gravity Curves (right)

The work was a collaborative effort between Battelle, MGL, and Core Energy. Battelle leads the MRCSP, which is supported by the U.S. DOE-NETL under Cooperative Agreement No. DE-FC26-0NT42589. The BHG tools were deployed by MGL survey services, who also supplied the pre-survey modeling and post-survey data analysis/modeling. Core Energy provided key data, access and field implementation support.