Field Testing the Applicability of Borehole Gravity for Monitoring Geologic Storage of CO2 within Closed Carbonate Reef Reservoirs

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BACKGROUND
The Midwest Regional Carbon Sequestration Partnership (MRCSF) is evaluating the potential to use Silurian-aged reefs for the storage of CO2 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 CO2 storage. The project is being carried out across the pinnacle reefs in fields in different stages of their production lifecycle, including a highly depleted reef that has already undergone CO2-EOR (late stage reef), reefs currently undergoing CO2-EOR (active EOR reefs), and wells that have previously only experienced primary oil production (near EOR reefs). The pinnacle reefs are oil-bearing dolomites and limestone structures that are overlain by low-permeability carbonates and evaporites.

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 CO2 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 (g) and depth (d) differences measured between successive stations constitute the integral vertical gradient of gravity (dg/dz), which varies directly with the density of the rock layer bracketed by the measurements. BHG data are converted to apparent or internal density profiles, which can be used for reservoir evaluation, well log and core analysis/statistical, integration with surface gravity and seismic studies, or engineering and rock property investigations. For CO2 monitoring, time-lapse BHG surveys may be useful for detecting changes in density caused by the accumulation of CO2 within the pores 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 CO2 replacing brine in the pore space, the depleted pinnacle reef model scenario assumed the CO2 would be replacing low-pressure saline brine. Furthermore, the model assumed the CO2 would concentrate in the more porous zones connected by low-permeability barriers. 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 taken in 2016 following the injection of approximately 265,000 metric tons of CO2 into the reef and the reservoir pressures had increased from about 600 psi to 3,500 psi (4 MPa to 24 MPa). The largest sources of spatial gravity variations are the free-air effect, orbit effect, and regional and local geology, including terrain, lithology and structural variations. These time-statics 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 CO2 or other fluid injections or redistributions).

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.
• Satellite stations were visited to a few cm between the wells using gamma ray.
• BHG measurements were taken using a fluid level survey instrument inside the tubing or other fluid injections or redistributions.
• Station Spacing

ZONE 1 (Deep Reservoir Zone)
- Depth: 1,155-1,975 ft (352-603 m)
- 5 Stations: 10, 20, 30, 40, and 50 ft (3, 6, 9, 12, and 15 m) between stations
- 3 Sweeps (Repeat)

ZONE 2 (Intermediate Mesoreservoir)
- Depth: 530-1,155 ft (161-352 m)
- 5 Stations: 10, 20, 30, 40, and 50 ft (3, 6, 9, 12, and 15 m) between stations
- 3 Sweeps (Repeat)

ZONE 3 (Shallow)
- Depth: 290-530 ft (88-161 m)
- 5 Stations: 10, 20, 30, 40, and 50 ft (3, 6, 9, 12, and 15 m) between stations
- 3 Sweeps (Repeat)

ZONE 4 (Near Surface)
- Depth: 5-290 ft (1.5-88 m)
- 5 Stations: 10, 20, 30, 40, and 50 ft (3, 6, 9, 12, and 15 m) between stations
- 3 Sweeps (Repeat)

CONCLUSIONS
The injection of 265,000 metric tons of CO2 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 CO2 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 and storage of CO2 in the reef. The CO2 appears to have replaced the original gas zone in the upper portion of the reef. The red zone shows the area of greatest CO2 storage followed by the green zone, which indicates significant CO2 storage. The yellow and grey areas indicate minimal CO2 storage.

The results obtained at the MRCSF add to the growing knowledge base regarding the use of BHG surveys to monitor CO2 storage performance. This research is important because BHG surveys provide an effective method for demonstrating storage security, as well as provide valuable data to improve geologic models.

The work was a collaborative effort between Battelle, MGL, and Core Energy. Battelle leads the MRCSF, which is supported by the U.S. DOE-NETL under Cooperative Agreement No. DE-FC26-07NT41608. The BHG tools were deployed by MGL survey service, who also supplied the pre-survey modeling and post-survey data analysis modeling. Core Energy provided key data, access and field implementation support.