Feasibility study of gravity gradiometry monitoring of CO_2 sequestration in deep reservoirs using surface and borehole data

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Summary

Geophysical monitoring of carbon dioxide (CO_2) injections in a deep reservoir has become an important component of carbon capture and storage (CCS) projects. Until recently, the seismic method was the dominant technique used for reservoir monitoring. However, the cost of seismic surveys makes this method prohibitive in monitoring sequestration projects where there is not a direct profit. Moreover, some environments present challenges for seismic acquisition as in urban areas. In this paper we present a feasibility study of permanent gravity gradiometry monitoring of CO_2 sequestration in a deep reservoir using a novel approach involving both borehole and surface measurements. The interpretation is based on joint iterative migration imaging of the surface and borehole data. The advantage of this method is that the surface data provide a good estimate of the horizontal extent of the injection zone, while the borehole data control the depth of the target, which increases the sensitivity and resolution of the method. We illustrate the effectiveness of the gravity gradiometry method by computer simulating CO_2 injection monitoring in the Kevin Dome sequestration site in Montana, USA.

Introduction

The majority of approaches currently proposed for CCS rely on storing CO_2 in a supercritical state in deep saline reservoirs where buoyancy forces drive the injected CO_2 upward in the aquifer until a seal is reached. The CO_2 is stratigraphically and structurally trapped below an impermeable rock layer.

The Big Sky Carbon Sequestration Partnership (BSCSP) is one of the seven partnerships initiated by the U.S. Department of Energy. BSCSP along with the other partnerships is created to develop the technologies, infrastructures, and regulations required to implement large-scale carbon dioxide (CO_2) capture and storage within the nation. The BSCSP has chosen the Kevin Dome, north central Montana, among many potential CO_2 storage sites. The flanks of the Kevin Dome are saline-saturated and have the potential to store more than 1.5 billion tons of CO_2 (U.S. DOE, 2010).

Government regulations require continuous monitoring of CO_2 sequestration sites to ensure seal integrity. There is always a slight possibility of leakage even with a good seal characterization. A leakage of CO_2 to shallow water aquifers will alter the geochemistry, water quality, and ecosystem health. Also, monitoring fluid movements within the reservoir will lead to informed reservoir management decisions (Bruant et al., 2002).

Reservoir monitoring is dominated by seismic methods. However, seismic monitoring is usually expensive and sometimes difficult or prohibitive to acquire, as in urban or industrial areas. Therefore, an alternative or complimentary geophysical method is essential.

The advancement in gravimeters and gravity gradiometers technologies, has made these tools capable of monitoring the subtle changes in the surface gravitational field due to subsurface change in the fluid contents in the deep geological structures. Bradly et al. (2008) successfully monitored the movements associated with gas cap water injection (GCWI) at Prudhoe Bay using time-lapse gravity. AlJanobi (2017) examined a possibility of using the time-lapse airborne gravity and gravity gradiometry data for monitoring CO_2 sequestration.

In this paper, we present feasibility studies of time-lapse gravity and gravity gradiometry monitoring of CO_2 sequestration in the deep Duperow formation in the Kevin Dome project using the surface and borehole data. The interpretation is based on joint iterative migration imaging of the surface and borehole data (Wan and Zhdanov, 2013; Wan et al., 2016; Zhdanov, 2002, 2015). The advantage of this method is that the surface data can be used to estimate the horizontal extent of the injection zone, while the borehole data control the depth of the target, which increases the sensitivity and resolution of the method.

Kevin Dome project, Montana

The numerical study of the application of the gravity gradiometry for the permanent monitoring, verification, and accounting of CO_2 in deep reservoirs has been conducted for the Kevin Dome sequestration site located in northern Montana. This site is operated by the Big Sky Carbon Sequestration Partnership (BSCSP), which is part of Montana State University's Energy Research Institute. The partnership is supported by the U.S. Department of Energy as one of seven regional carbon sequestration partnerships (U.S. DOE, 2015a, 2015b).

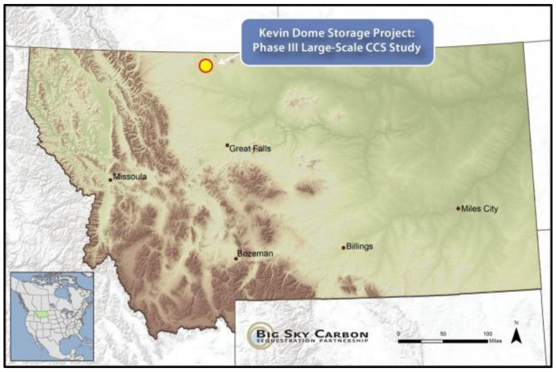

Figure 1: Location map of the Kevin Dome project site.

Kevin Dome is a large underground geologic feature that covers roughly 700 square miles in Toole County, Montana (Figure 1). This area is an excellent study site for several reasons. First, there is an abundance of naturally occurring CO_2 that has been trapped in place for millions of years indicating strong cap rock formations. Second, CO_2 can be extracted from the top portion of the dome and piped a relatively short distance (six miles) down the dome's flank and outside the natural CO_2 accumulation to the injection site. This short distance helps keep costs low and reduces environmental impacts. Kevin Dome's geology allows for the comparison of rocks that have been previously exposed to CO_2 to rocks freshly exposed through CO_2 injection. Lastly, this area has an active oil and gas industry that may be able to provide practical and economical applications of the study's findings. Figure 2 shows a schematic model of Kevin Dome.

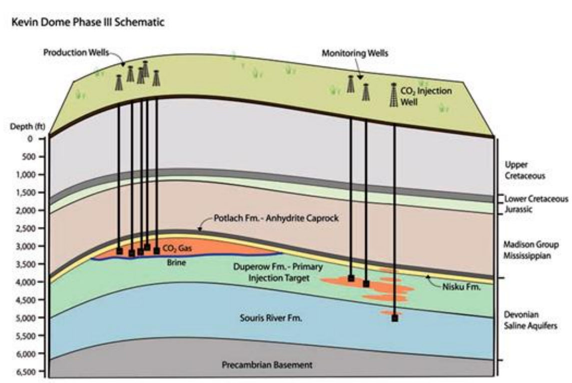

Figure 2: Schematic view of the Kevin Dome project.

In 2014, BSCSP drilled, cored and logged two wells and conducted and analyzed 3D seismic surveys in the project area. Using this valuable geological and geophysical information, a 3D static geologic model was constructed and will be updated as more data becomes available.

The BSCSP is planning to produce 1 million tons of naturally occurring CO_2 in the Duperow Formation in the Kevin Dome. Then, transport it north of the dome in an underground pipeline of 2-inch diameter and approximately 6 miles in length to the injection site. The CO_2 will then be reinjected back into the Duperow formation at the edge of the dome (Figure 2). The Nisku and Souris River formations above and below the Duperow formation, respectively, will be tested for additional storage during the process.

The Duperow formation is located at depths ranging from 1000 to 1900 m within the Kevin Dome. The upper Duperow formation is about 90 m in thickness of tight carbonates interbedded with anhydrites, which serves as the primary seal for the middle Duperow reservoir. The Potlatch formation serves as a secondary seal which consists of anhydrites 50 m thick. The core test results, showed that the density of the anhydrites in the Potlatch formation is 2.5-2.83 g/cm^3 close to the theoretical density of anhydrites of 2.97 g/cm^3 indicating nearly pure anhydrites with poor porosity (Spangler, 2015).

The middle Duperow consists of carbonate rocks with a thickness ranging from 20 to 58 m. It has high porosity and permeability ranging from 5% to 25% and 1 to 210 mD, respectively. The expected depth of the middle Duperow formation at the injection site is 1100 m (Dai et al., 2014).

Kevin Dome model study

We computer simulated the synthetic gravity gradiometry data for the Kevin Dome reservoir assuming using the anomalous density for the water-filled area is -0.74 g/cm^3 and the anomalous density of the area with injected CO_2 gas is -1.24 g/cm^3. The density contrast is negative because the injected CO_2 is lower in density that the in-situ brine in the reservoir. These data were used for a feasibility study monitoring carbon dioxide (CO_2) injections in a deep reservoir using gravity method.

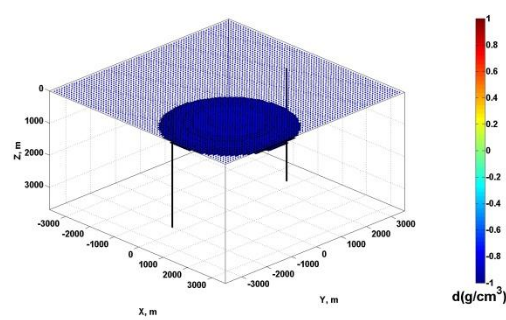

Figure 3: A simplified model of the Kevin Dome reservoir.

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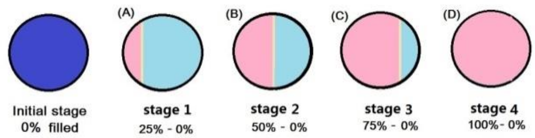

Figure 4: Schematic representation of four different stages of CO_2 injections in the reservoir

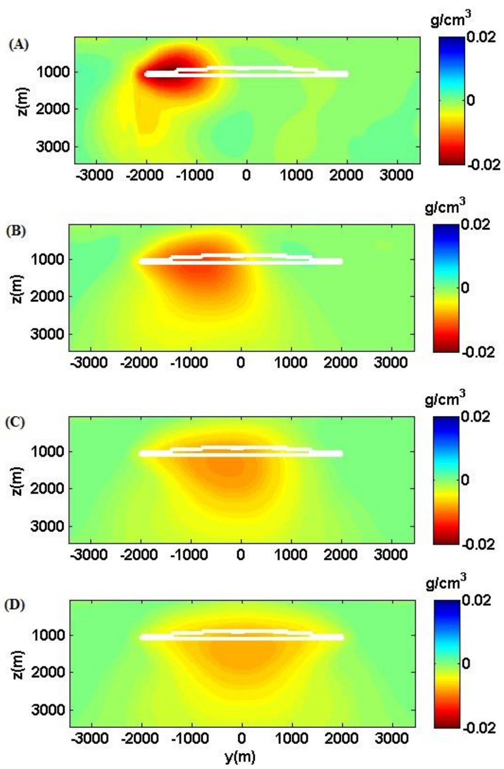

Figure 5: Images produced by the migration of the fields calculated as the differences between the data observed at the current stage of CO_2 injection and at the initial stage before the start of the injection.

A simplified model of the reservoir is shown in Figure 3.

Modeling of the time-lapse reservoir monitoring using surface and borehole gravity gradiometry data

We have considered four different stages of CO_2 injections in the reservoir, as shown in Figure 4.

For each of these stages we computer simulated the surface and borehole gravity gradiometry data.

We then calculated the differences between the fields observed at the current stage and the reference fields corresponding to the initial stage before the CO_2 injections.

These data were migrated back toward the location of the reservoir. Figure 5 presents the migration images for all four different stages of the CO_2 injections. It clearly shows the propagation of CO_2 during the different stages of injection.

We also calculated the differences of the gravity gradient data between the different stages of CO_2 injections and migrated these difference fields as well.

We jointly migrated the surface and borehole difference fields to produce the images representing the changes within the reservoir for the different phases of the CO_2 injection (Figure 6). These images manifest how the front of the injected CO_2 moves from the left to the right.

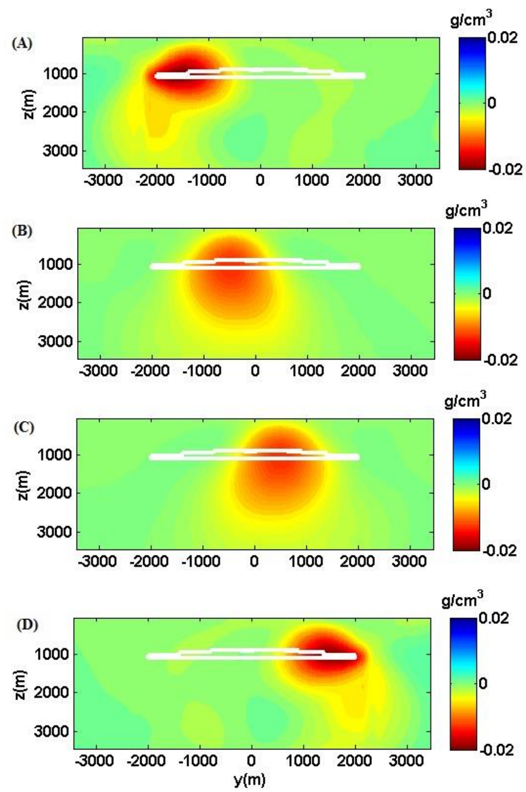

Figure 6: Images produced by the migration of the fields calculated as the differences between the data observed at the subsequent stages of CO_2 injection.

Kevin Dome leakage model

One of the important goals of monitoring the CO_2 sequestration process is to prevent a leakage of CO_2 from a deep reservoir. In order to study the detectability of leakage of CO_2 in the Kevin Dome model, we considered a leakage

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scenario of CO_2 from the main CO_2 reservoir with a radius of 2000 m. We assumed that the CO_2 escaped through the upper, 90 m thick Duperow formation of tight carbonate interbedded with anhydrites and through the Potlatch formation of 50 m thickness of anhydrites. We modelled the escaped CO_2 when it reached the dolomitic limestone in the Madison formation at a depth of about 500 m, forming a relatively small gas-filled (leaking gas) structure located above the main gas structure, about 500 m in diameter (Figure 7).

The synthetic surface and borehole gravity gradiometry data were migrated toward the reservoir. The corresponding migration images for models with and without leakage are shows in Figure 8.

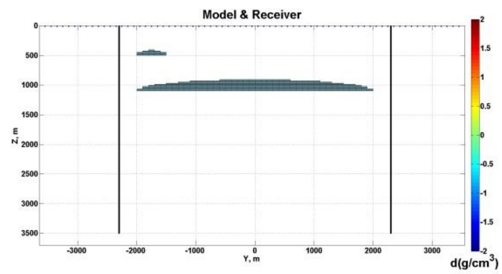

Figure 7: A cross section of the leakage model.

Comparing results (a), (b), and (c) in Figure 8, one can clearly see that the joint migration of surface and boreholes g_{zz} and g_{yz} data helps identify the presence of leakage from the CO_2- filled gas reservoir.

Conclusions

The most widely considered approach to carbon capture and storage is the one based on storing CO_2 in deep, natural saline reservoirs. An important problem arising in this case is monitoring and verification of the injection process and the long-term geological integrity of the reservoir seal. Thus, geophysical methods of reservoir monitoring should play a critical role in the CCS process.

In this paper, we have proposed a novel approach to monitoring CO_2 sequestration, which involves both the borehole and surface measurements of the gravity gradiometry data. We have demonstrated that gravity gradiometry data, especially collected both on the surface and within the borehole, may represent an effective indicator for monitoring CO_2 injection in deep reservoirs. Computer simulation has shown that the gravity gradiometry data provide a clear indication of the location of the CO_2 plume in the underground formation and of the movement of the front of the injected CO_2. This technique can also be used for controlling the leakage of CO_2 from a deep reservoir.

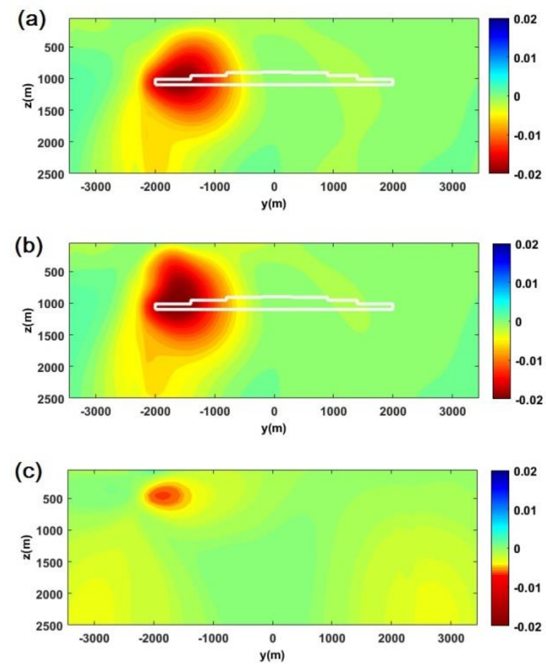

Figure 8: Comparison of the migration images for the leakage model at the 25% gas-injected stage: (a) no leakage; (b) with leakage; (c) difference between the two images.

Acknowledgments

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