Gravity Gradiometry for Emerging Applications

Dan DiFrancesco
Lockheed Martin
Niagara Falls, USA
dan.difrancesco@lmco.com

Bruce Kohrn
Lockheed Martin
Niagara Falls, USA
bruce.kohrn@lmco.com

Chloe Bonet
GeoIntrepid
Melbourne, VIC
chloe@geointrepid.com

Helen Gibson
GeoIntrepid
Melbourne, VIC
helen@intrepid-geophysics.com

SUMMARY

Gravity surveys have become an accepted part of the geophysical exploration process for hydrocarbons and minerals. Both scalar gravity and gravity gradient surveys are commonly conducted on land, sea, and in the air. The positive reception to these capabilities provides the backdrop for looking at other applications for emerging needs. Scenarios where gravity and gradiometry may have significant benefit include the detection and characterization of aquifers, monitoring of CO2 storage sites, geothermal exploration, and enhanced oil recovery monitoring. This paper will review modeling and analysis scenarios that evaluate the use of gravity in non-traditional applications.

Key words: Gravity, gradiometry, geothermal, aquifer, CO2

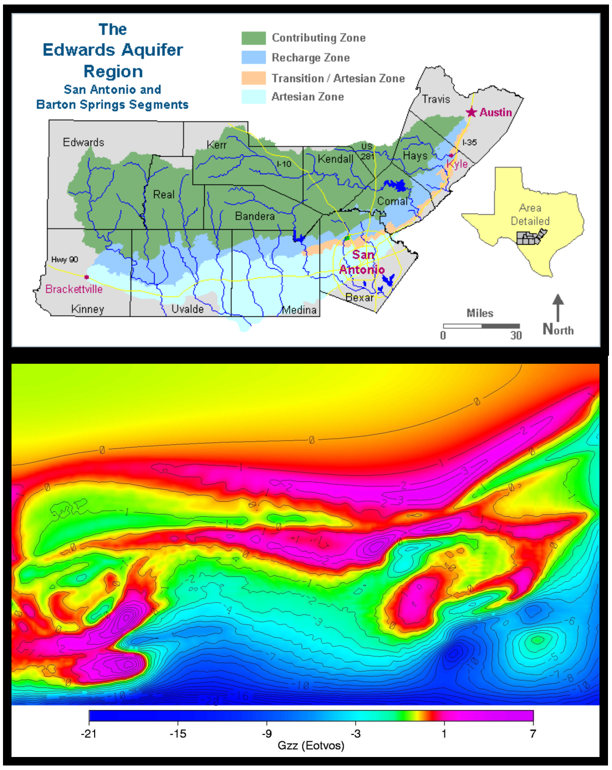
INTRODUCTION

The use of gravity gradiometry for purposes beyond exploration is a natural extension of the recent success and acceptance of this technique. Airborne gravity gradiometer surveys have been conducted for over 13 years, and ground-based gravity and gradiometry surveys go back much farther. Based on the accomplishments to date, a variety of applications for gravity measurement can now be considered, including the identification of global water resources, exploration for renewal energy sources, global warming control, and more efficient production of hydrocarbons. The approach used in this paper was to model known and representative targets for each of these emerging applications and make an assessment of gravity's ability to provide meaningful data to the problem. The investigation of these targets yields the conclusion that gravity measurements have a significant role to play in each case.

EMERGING APPLICATIONS

Aquifer Detection and Characterization

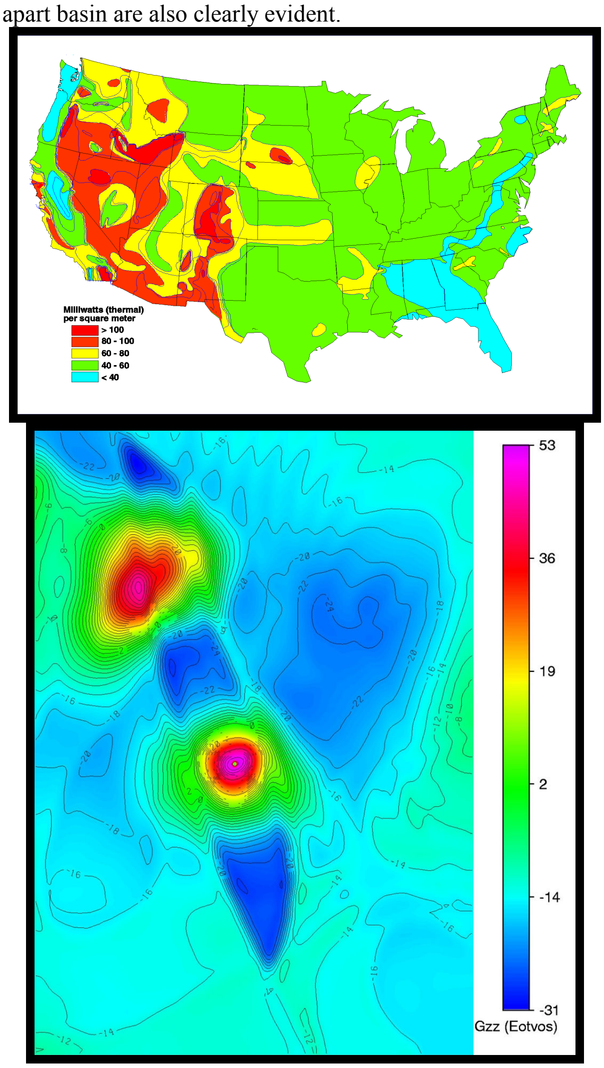
The first scenario investigated is the detection and characterization of aquifers. With world-wide water shortages affecting economic growth and human life, it is critically important to find techniques to help discover new reserves. The Edwards Aquifer in Texas was chosen as representative of this opportunity and simulated using 3D GeoModeller software to determine the gravity and gradient signals associated with the feature (Maclay and Small, 1986), (Stein and Ozuna, 1995), and (Pantea and Cole, 2004). A Miocene uplift created the Edwards plateau and the region is characterized by karst lithology with high permeability and porosity. The local structure is distinguished by numerous faults running along the length of the reservoir, and normal faults that provide for discontinuities in the sections (See Figure 1a). In the developed model, the gravity signature is driven by the depth of the sedimentary package, which is conformable with the denser Glen Rose formation - taken as the basement for the model. Where the aquifers and their confining layers outcrop in the north of the area, the gravity signal is higher than where these units are at greater depth. The Gzz response (see Figure 1b) shows that the faults which control the depth of the aquifer can be accurately mapped. The resulting analysis showed that indicative characteristics of the aquifer were discernable from the gravity signature.



Figures 1a and 1b. The Edwards aquifer located in south central Texas with strata dipping slightly south and southwest (1a). The karst lithology yields high permeability and porosity. Gravity gradients (1b) reveal the structure of the aquifer and can be used to map depletion and recharge over time.

Geothermal Exploration

The next scenario evaluated was the exploration of geothermal systems. The geothermal potential for energy is huge in many regions of the world, particularly in Australia, Western USA, Eastern Africa, and along the Pacific "Ring of Fire". For example, it is estimated that the geothermal potential in the Great Rift Valley in Africa approaches 15,000 MW. One of the biggest challenges is to accurately locate and characterize fault structures that supply geothermal systems. In this example, the Salton Sea geothermal field in California was modeled with the intention of characterizing the geologic structures that are typically found in geothermal settings (Brothers et al, 2009) and (Kasemeyer and Hearst, 1988). The Salton Sea geothermal field resides at the southern extent of the San Andreas fault and produces steam from natural processes (See Figure 2a). This region is characterized by local zones of extension that allow mantle-derived magmas and fluids to intrude. The lateral permeability – below the cap rock – is also much higher than the vertical permeability, allowing for wide-ranging flow and multiple heat/steam pathways. The geological model built for this area contains higher density alteration zones spatially correlated with basement highs. These are clearly visible in the calculated gravity gradient response (See Figure 2b). This is not surprising as the Salton Sea geothermal area does produce a known gravity anomaly. The faults associated with the pull apart basin are also clearly evident.



Figures 2a and 2b. The Salton Sea geothermal field is located in southern California's Imperial Valley about 80 miles east of San Diego (2a). The gravity gradients associated with the geothermal system (due to hydrothermal alterations of the rock and pore space filling) are evident in 2b.

CO2 Sequestration Monitoring

Global warming has been postulated as tightly correlated with the atmospheric release of CO2. Measurement, monitoring, and verification (MMV) of CO2 storage systems is becoming a significant component of the carbon capture process. The proposed introduction of carbon taxes and carbon credits makes the validation of sequestered CO2 a key element of the control process. Geologic sequestration of CO2 in saline aquifers, depleted oil and gas reservoirs, and in other naturally occurring underground voids is considered a viable methodology for reducing atmospheric carbon emissions. The In Salah storage site in Algeria was selected as representative of a CO2 storage system and modeled to determine if gravity can assist in the detection of escaping CO2 along a simulated thief zone. The In Salah site is a deep saline aquifer, adjacent to producing gas fields, with fractures at the aquifer and reservoir levels (Cavanagh and Ringrose, 2010), (Gasperakova and Hoversten, 2005 and 2008), (Ringrose et al, 2009) and (Haddadji, 2006). An effective seal is formed over the region by the thick mudstone cap rock (See Figure 3a). A simulated pocket of escaped CO2 was modeled against an added fault, the escape path. In this model the reservoir is evident in the gravity response; however it is unlikely that the presence of the escaped CO2 would be detectable (See Figure 3b). The value of gravity here would be more likely in monitoring changes over time. With regard to the pocket of escaped CO2, the gravity signature is dominated by the density contrast across the fault. In the presence of real geological noise this target would not be detectable. Again modeling changes over time would potentially be of value. A further assessment of the presence of the thief zone yielded a change signal (over time) less than 1 E measured in the reservoir by a borehole sensor. This signal is not currently detectable by any available instrument.

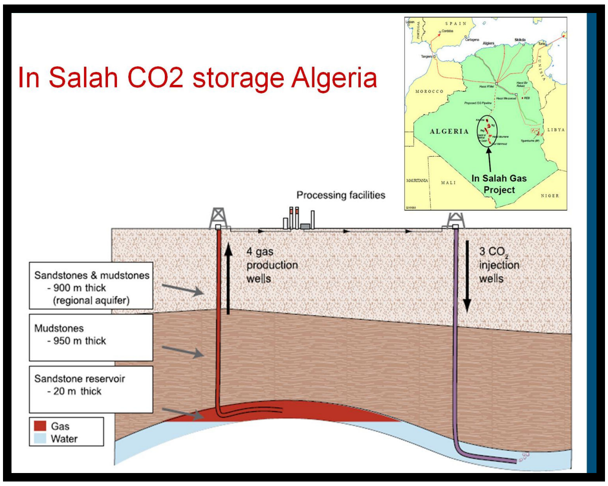


Figure 3a. The In Salah CO2 sequestration project located in central Algeria is hosted in a deep saline aquifer adjacent to gas production fields.

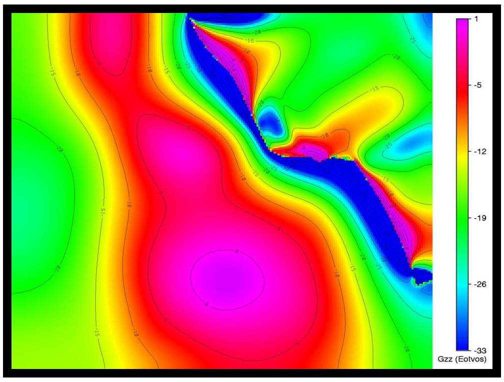
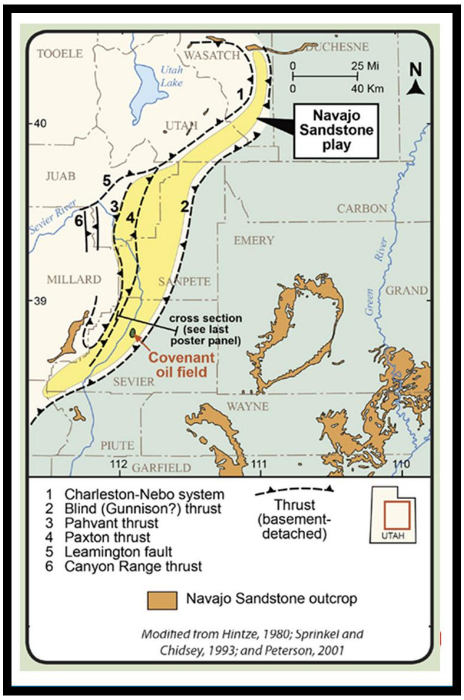


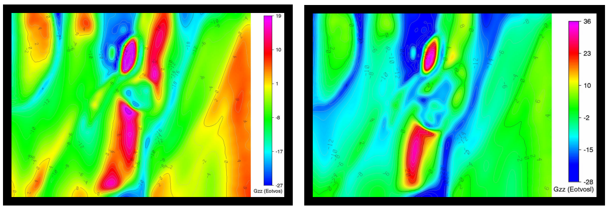
Figure 3b. A simulated fault that provides an escape path for CO2 is modelled and the associated gravity gradient is seen above.

Enhanced Oil Recovery (EOR) Monitoring

The last scenario examined addresses the application of fluid flow monitoring in EOR settings. It is estimated that 60% to 70% of known oil reserves are deemed unrecoverable due to operational and economic factors. The amount of bypassed oil that remains in known reservoirs provides a significant motivation to improve recovery factors and 'squeeze' out the remaining fluids from identified assets. The production, introduction, and management of the drive fluid (e.g. brine, steam, or CO2) in an EOR field makes up roughly 70% of the cost for the reservoir production operation. The management of this fluid, including the knowledge of the fluid front position, is critical to optimal recovery in the reservoir.

The Covenant Oil Field in Utah was modeled for this scenario (Moulton and Pinnell, 2005) and (Chidsey et al, 2007). The field is hosted in Navajo limestone and has been under EOR processes for some time (See Figure 4a). In the gravity gradient model, Time 1 represents the reservoir when only oil is present and Time 4 when the oil has been partly replaced by brine as it is forced north towards the extraction well. This study indicates changes in overall volume as the brine is added can be detected.





Figures 4a, 4b and 4c. The Covenant Oil Field in Utah (USA) is representative of enhanced oil recovery operations (4a). The gravity gradient change over time in the producing field (as measured from the surface) is seen in the Time 1 view at left (4b) and the Time 2 view at right (4c).

CONCLUSIONS

The examined applications each reveal an opportunity for gravity measurements to provide significant information. The Edwards aquifer example shows that gravity gradients can provide a useful tool for mapping the sedimentary package which contains the aquifer. For the CO2 sequestration scenario based on the characteristics of the In Salah field, the gravity response is too weak to be detected by surface or airborne surveys, however monitoring over time, particularly using borehole systems, could be effective as more sensitive sensors come to market. The geothermal scenario depicted by the Salton Sea geothermal site is readily detectable using gravity. The faults associated with the pull a part basin are clearly evident in the gravity gradient data. This may have significance for the exploration of blind geothermal systems, given that the faults do not have surface expression in the cover geology. Finally, the use of gravity gradiometry for monitoring fluid flow in a producing EOR field is validated by the Covenant example. Gravity capabilities are positioned to provide a significant measurement enhancement in the near future.

REFERENCES

Brothers, D.S., et al, 2009, Tectonic evolution of the Salton Sea inferred from seismic reflection data: Nature-Geoscience, Letters.

Cavanagh, A. and Ringrose, P., 2010, In Salah High-Resolution Heterogeneous Simulations of CO2 Storage: Search and Discovery Article #80092 (2010).

Chidsey, T. et al, 2007, Covenant Oil Field, Central Utah Thrust Belt: Possible Harbinger of Future Discoveries: U.S. DOE, NETL contract number DE-FC26-02NT15133 report.

Gasperakova, E. and Hoversten, M., 2005, Geophysical Techniques for Monitoring CO2 Movement During Sequestration: DOE Contract Report No. DE-FC26-03NT41984.

Gasperakova, E. and Hoversten, M., 2008, Gravity monitoring of CO2 movement during sequestration: Model studies: Geophysics Vol. 73, No. 6, Pages WA105–WA112.

Haddadji, R., 2006, The In-Salah CCS experience Sonatrach, Algeria: Presented at The First International Conference on the Clean Development Mechanism, Riyadh, Saudi Arabia.

Kasemeyer, P. and Hearst, J., 1988, Borehole gravity measurements in the Salton Sea Scientific Drilling Program Well State 2-14: Journal of Geophysical Research, V. 93(b11), P. 13037-13045.

Maclay, R. and Small, T., 1986, Carbonate Geology and Hydrology of the Edwards Aquifer in the San Antonio Area, Texas: Texas water Development Board Report #296.

Moulton, F. and Pinnell, M., 2005, Stunning Utah oil, gas discovery focuses spotlight on Hingeline: Oil and Gas Journal, January 17, 2005.

Pantea, M. and Cole, J., 2004, Three-Dimensional Geologic Framework Modeling of Faulted Hydrostratigraphic Units within the Edwards Aquifer, Northern Bexar County, Texas: Scientific Investigations Report 2004-5226, U.S. Geological Survey

Ringrose, P. et al, 2009, Plume development around well KB-502 at the In Salah CO_2 storage site: First Break, Vol 27, pages 85-89.

Stein, W. and Ozuna, G., 1995, Geologic Framework and Hydrogeologic Characteristics of the Edwards Aquifer Recharge Zone, Bexar County, Texas: U.S. Geological Survey Water Resources Investigations 95-4030.