TIME-LAPSE SEISMIC MODELING & INVERSION OF CO_2 SATURATION FOR SEQUESTRATION AND ENHANCED OIL RECOVERY

Final Report

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ABSTRACT

Injection of carbon dioxide (CO_2) into subsurface aquifers for geologic storage/sequestration, and into subsurface hydrocarbon reservoirs for enhanced oil recovery, has become an important topic to the nation because of growing concerns related to global warming and energy security. In this project we developed new ways to predict and quantify the effects of CO_2 on seismic data recorded over porous reservoir/aquifer rock systems. This effort involved the research and development of new technology to:

- Quantitatively model the rock physics effects of CO_2 injection in porous saline and oil/brine reservoirs (both miscible and immiscible).
- Quantitatively model the seismic response to CO_2 injection (both miscible and immiscible) from well logs (1D).
- Perform quantitative inversions of time-lapse 4D seismic data to estimate injected CO_2 distributions within subsurface reservoirs and aquifers.

This work has resulted in an improved ability to remotely monitor the injected CO_2 for safe storage and enhanced hydrocarbon recovery, predict the effects of CO_2 on time-lapse seismic data, and estimate injected CO_2 saturation distributions in subsurface aquifers/reservoirs.

We applied our inversion methodology to a 3D time-lapse seismic dataset from the Sleipner CO_2 sequestration project, Norwegian North Sea. We measured changes in the seismic amplitude and traveltime at the top of the Sleipner sandstone reservoir and used these time-lapse seismic attributes in the inversion. Maps of CO_2 thickness and its standard deviation were generated for the topmost layer. From this information, we estimated that 7.4% of the total CO_2 injected over a five-year period had reached the top of the reservoir. This inversion approach could also be applied to the remaining levels within the anomalous zone to obtain an estimate of the total CO_2 injected.

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I. EXECUTIVE SUMMARY

Injection of carbon dioxide (CO_2) into subsurface aquifers for geologic storage/sequestration, and into subsurface hydrocarbon reservoirs for enhanced oil recovery, has become an important topic to the nation because of growing concerns related to global warming and energy security. In this project we develop new ways to predict and quantify the effects of CO_2 on seismic data recorded over porous reservoir/aquifer rock systems by means of a:

- Theoretical analysis of CO_2-saturated fluid and rock properties,
- Workflow and software modules to calculate the fluid compressibility and density of CO_2-oil-water mixtures, as well as the CO_2-saturated rock elastic moduli (P-wave and S-wave) and bulk density, for both miscible and immiscible cases with variable pressure and temperature,
- Workflow and software modules to generate the synthetic seismic data response to CO_2 injection from well logs,
- New inversion approach to estimate CO_2 pressure and saturation distributions in aquifers/reservoirs from time-lapse 4D seismic data, and
- Modeling and inversion example applied to a real data set from the Sleipner CO_2 sequestration project, Norwegian North Sea.

This work has resulted in an improved ability to remotely monitor injected CO_2 for safe storage and enhanced hydrocarbon recovery, predict the effects of CO_2 on time-lapse seismic data, and estimate injected CO_2 saturation distributions in subsurface aquifers/reservoirs.

The technical approach for this project consists of three phases, each of which represents a significant contribution to our main technical objectives of obtaining a better understanding of CO_2 effects on seismic data, and making quantitative estimates of time-lapse pore pressure and CO_2 saturation changes for enhanced oil recovery. In Phase I we researched a number of approaches for modeling the rock physics effects of CO_2 injection (both miscible and immiscible) in porous saline and oil/brine reservoirs. This required searching numerous publications and internet websites to understand the most recent techniques and limitations for calculating the effects of CO_2 on the density and bulk modulus of rock-fluid systems using currently available equation-of-state (EOS) and molecular dynamics modeling. In addition, a number of experts were interviewed and laboratory core and log databases were examined to determine the best theoretical approaches for calculating CO_2 fluid properties. As a result of this effort, we developed a practical rock physics workflow to calculate/predict the fluid compressibility and density of multi-phase oil-water-CO_2 mixtures (both miscible and immiscible), and the P-wave and S-wave elastic moduli and bulk density of porous rock saturated with these fluid mixtures, as a function of pressure and temperature. The resulting rock physics techniques from Phase I were coded up as new custom software tools in our existing proprietary rock physics software suite.

In Phase II we developed a practical seismic modeling workflow and algorithms to simulate the prestack seismic (AVO) response of CO_2 injection (both miscible and

immiscible) in a subsurface porous aquifer/reservoir. The workflow requires the integration of geologic properties, well log data, laboratory core measurements and fluid information, and engineering field data (such as well pressure, saturations, and CO_2 injection rates) acquired at different production times. These data are then used to derive the fluid-saturated bulk moduli, shear moduli, and densities for a particular horizon of interest in the reservoir, and for a particular set of CO_2 injection scenarios, using the tools developed in Phase I. The moduli and densities directly yield the P- and S-velocities, which, along with the densities, are used to model offset-dependent P-wave seismic amplitudes. The seismic data are generated by 1D convolution using either a synthetic wavelet or one extracted from field data. To test the modeling workflow, synthetic traces were generated using reservoir data from the Sleipner Field, an industry-standard dataset consisting of multiple vintages of 3D seismic data recorded over a shallow saline aquifer during CO_2 injection. After verifying that the synthetic traces adequately matched the Sleipner field data, a suite of synthetic datasets were generated for different scenarios of CO_2 saturation and temperature. These data were subsequently used in the inversion procedure of Phase III.

In Phase III we researched and developed new technology to perform quantitative inversions of time-lapse 4D seismic data to estimate injected CO_2 distributions within subsurface reservoirs and aquifers. The algorithm was based on our current pressure-saturation inversion method by forward modeling (Cole et al., 2003), which we modified to accommodate CO_2 effects. The new method works by first generating synthetic time-lapse changes in seismic attributes over a range of selected reservoir parameters, such as CO_2 saturation and temperature, using the seismic modeling workflow developed in Phase II. Next we extracted time-lapse seismic attribute maps of traveltime and amplitude from the uppermost layer at Sleipner and used them as input data for the CO_2 inversion. The seismic attributes were then inverted using the synthetic forward modeled data to yield CO_2 saturation and temperature values. The inversion algorithm was not able to discriminate between different temperature scenarios because of the lack of sensitivity of the time-lapse attributes on temperature. As a consequence, only maps of CO_2 thickness and its standard deviation were generated for the top reservoir layer. From this information we estimated that 7% of the total CO_2 injected over a five-year period had reached the top of the reservoir. This estimate is approximately equal to the ratio of the area of the seismic amplitude anomaly from the topmost layer to the total area of all amplitude anomalies seen in the reservoir.

We are not aware of any seismic inversion method that discriminates between time-lapse changes in multiple reservoir properties, such as oil saturation, water saturation, CO_2 saturation, and pressure, as ours does. Methods that do perform simultaneous pressure and saturation inversion using time-lapse reflection seismic amplitudes are primarily designed for oil-water systems (Cole et al., 2003). Others cannot invert simultaneously for these properties, and require extraneous (e.g., EM) data to obtain water saturation as a first step (Hoversten et al., 2002).

This effort has resulted in a novel, accurate, and robust fluid modeling and inversion capability that can be used for a variety of CO_2 injection scenarios for sequestration and enhanced oil recovery.

II. STATEMENT OF THE PROBLEM

It is widely recognized that CO_2 is an important agent in global warming, and much recent activity has focused on finding ways to reduce, eliminate, or sequester CO_2 in order to minimize its impact on the environment. Indeed, the Department of Energy's establishment of regional CO_2 sequestration centers is an indication of the nation's high level of interest in this important area. In addition, miscible CO_2 floods have become increasingly important, both as an EOR (Enhanced Oil Recovery) method for recovering residual or bypassed oil, and also as an effective means to sequester CO_2.

CO_2 floods have been used successfully throughout the U.S. since the first such application in Texas in 1972. CO_2 EOR and sequestration projects lend themselves naturally to time-lapse studies, but to date, few such studies have been performed for CO_2 operations. Today half the CO_2 floods (more than 40) in the world are located in the Permian Basin, producing more than 20% of the area's total oil production. It is estimated that more than 50 CO_2-floodable reservoirs still remain in the Permian Basin, representing additional oil reserves of 500 million to 1 billion barrels (West Coast Petroleum Technology Transfer Council Workshop, 9/20/01). With so much potentially recoverable oil at stake, and with the recent rapid increase in oil and gas prices, even a modest improvement in CO_2 flood management can have a significant economic impact. Clearly, an understanding of the effects of CO_2 on rock-fluid systems, together with an ability to accurately map CO_2 fronts during injection, are crucial for improving recovery rates, optimizing well patterns, locating bypassed oil, and minimizing the cost of injected CO_2. Our study directly addresses these concerns by improving the understanding of CO_2 effects in time-lapse seismic data, as well as by providing ways to track changes in CO_2 saturation during CO_2 injection (both miscible and immiscible) in saline and oil/brine porous rock systems.

Time-lapse seismic modeling of the effects of CO_2 injection in water aquifers and oil reservoirs is still in its infancy. Seismic modeling requires knowledge of the reservoir velocities and densities, which are functions of the rock and fluid properties. For CO_2 floods, a key step is the determination of the fluid bulk modulus (K) and density (ρ) of the CO_2-oil-brine or CO_2-brine mixture. At high pressures, CO_2 is a supercritical fluid with complex, liquid-like properties that can vary abruptly within narrow pressure and temperature regimes, particularly near the critical point. In oil reservoirs, this supercritical, CO_2-rich phase usually contains dissolved light hydrocarbons, complicating its behavior even further. Numerical instabilities often occur in algorithms that model CO_2 behavior near the critical point, creating large artifacts in modeled time-lapse seismic data. Furthermore, many equations of state are unable to predict the thermodynamic properties of CO_2 accurately over the range of temperatures and pressures typically found in reservoirs.

The current project has created a better understanding of how CO_2-brine and CO_2-oil mixtures affect seismic data through improved rock-fluid relations. Our improved seismic modeling technology can be used to predict accurately time-lapse seismic anomalies in real data. Unlike currently available inversion methods, our novel inversion approach solves for changes in multiple reservoir properties, such as CO_2 saturation, oil saturation, and pressure, from time-lapse seismic data.

III. EXPERIMENTAL METHODS

No experimental methods were used during this project.

IV. TECHNICAL APPROACH

[see Appendix I]

V. SLEIPNER DATA EXAMPLE

[see Appendix I]

VI. DISCUSSION

[see Appendix I]

VII. CONCLUSION AND RECOMMENDATIONS

[see Appendix I]

VIII. PROJECT ACTIVITIES AND CHALLENGES

Information was gathered during the project from a wide variety of sources, including books, journal articles (mainly from the Society of Petroleum Engineers, European

Association of Geoscientists and Engineers, and Society of Exploration Geophysicists), and a comprehensive series of publicly available reports on the Sleipner Field from the Saline Aquifer CO_2 Storage consortium. Additional useful information was obtained by personally interviewing experts in the fields of CO_2 fluid physics, reservoir simulation, and molecular dynamics modeling. One of the most important activities in this reporting period was a trip by the Principal Investigator to the 7th International Conference on Greenhouse Gas Control Technologies (GHGT-7) in Vancouver, Canada, September 5-9, 2004. The conference is held every two years and is focused primarily on CO_2 capture, sequestration, long-term storage, risk assessment, and legal and economic issues. Important information was gathered from various experts regarding the modeling of CO_2 fluid mixtures in a variety of environments, including those from two well-known case studies at Sleipner and at Weyburn Field, Saskatchewan.

In addition to this trip, the Principal Investigator attended an International Monitoring Workshop sponsored by the IEA Greenhouse Gas R&D Programme, Santa Cruz, California on November 8-9, 2004. The objectives of the meeting were to bring together the main research groups currently active in the field of CO_2 monitoring, and to review the current state of the art in monitoring technology. Several discussions of the Sleipner project pointed out that current estimates of the injected CO_2 volume obtained from time-lapse seismic traveltime and amplitude changes differ from actual injected amounts, indicating that further study is needed. This observation stimulated our own research into how such estimates can be improved using novel inversion technology.

Several challenges were encountered during the project which resulted in a reassignment of tasks and a rescheduling of priorities. Two employees involved in the project left the company, one in 2003 (Duncan) and one at the end of 2004 (Griesbach). Additional time was lost due a faulty tape drive. The tape drive was not yet operational by the last reporting period. For this reason, a four-month, no-cost extension was granted for the project. Additional barriers were encountered with regard to having limited access to research results from several groups involved in CO_2 research. This information (such as the particular CO_2 equation of state used in reservoir simulation or the fluid properties of CO_2/brine mixtures) was not forthcoming, most likely because of its proprietary nature or because the individual being questioned lacked the time to respond. Nevertheless, despite these barriers the project was successfully completed, and has provided an excellent base from which to continue development of novel CO_2 inversion methodologies.

IX. ACKNOWLEDGMENTS

We would like to thank Ola Eiken of Statoil, who kindly provided us with seismic data from Sleipner as well as a number of important reservoir parameters needed in our study. Peter Zweigel and Erik Lindeberg of SINTEF supplied well logs and other valuable information on CO_2 fluid physics and reservoir simulation.

X. REFERENCES

[see Appendix I]