Space Geodesy and Geochemistry Applied to the Monitoring, Verification of Carbon Capture and Storage

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ABSTRACT

This award was a training grant awarded by the U.S. Department of Energy (DOE). The purpose of this award was solely to provide training for two PhD graduate students for three years in the general area of carbon capture and storage (CCS). The training consisted of course work and conducting research in the area of CCS. Attendance at conferences was also encouraged as an activity and positive experience for students to learn the process of sharing research findings with the scientific community, and the peer review process. At the time of this report, both students have approximately two years remaining of their studies, so have not fully completed their scientific research projects.

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Course Requirements

As this was a training award and PhD students were recruited, the students (Student 1 and Student 2) were required to take 36 course credits (approximately 12 courses within the first two years of the funding period (2010-2011 and 2011-2012). However, one of the students had a MS degree prior to arriving at the University of Miami and therefore needed a smaller number of courses. A list of courses taken by the students is included in the Appendix at end of this report.

Research

The students involved in the project worked with the Principal Investigators (Professors Swart and Dixon) to develop an integrated, low cost methodology for assessing the fate of CO2 pumped into various classes of geologic reservoirs. In particular, one student worked on the risk assessment of potential CO2 leaks from sequestration sites, while the second investigated the use of satellite technology in detecting ground deformation.

Exposure to National Scientific Meetings

Students involved in this award have attended numerous national and international meetings as well as workshops on CCS. This is considered an integral portion of their training. A list of meetings and workshops attended is included in the Appendix of this report.

OVERVIEW

This was a training grant awarded by the U.S. Department of Energy (DOE). The purpose of this award was solely to provide training for two PhD graduate students for three years in the general area of carbon capture and storage (CCS). The training consisted of course work and conducting research in the area of CCS. Attendance at conferences was also encouraged as an activity and positive experience for students to learn the process of sharing research findings with the scientific community, and the peer review process. At the time of this report, both students have approximately two years remaining of their studies, so have not fully completed their scientific research projects.

The following discussion focuses on the research component of the students' training. The components comprised of coursework training and conference participation is incorporated into these discussions, and also provided in the Appendix.

RESEARCH

Introduction

This project was funded in conjunction with a second still ongoing project (DE-FE0001580). The original, primary research project (DE-FE0001580) was designed to examine methods of monitoring the fate of CO_2 injected into underground reservoirs for the purposes of mitigating atmospheric CO_2 levels.

Five general areas of research were proposed to be combined into an integrated monitoring system for carbon storage operations; a similar number of graduate students was needed. These areas were:

1. The use of GPS (Global Positioning System) to detect ground deformation signals related to injecting CO_2 into the subsurface for carbon storage;
2. The use of InSAR (Interferometric Synthetic Aperture Radar) to monitor ground deformation using X-band satellites;
3. The application of seismic studies to detect activity associated with the injected plume;
4. The modelling of the fate of CO_2 in the subsurface reservoir and the possible leakage from the intended containment zone;
5. The monitoring of atmospheric sources of CO_2 using cavity ring down spectrometry.

Of these five areas of research, the students for this project (DE-FE0002184) only worked on items 2 and 4.

Students working on the other areas were supported either by the second DOE grant (DE-FE0001580) or by scholarships from the University of Miami.

While this report will not include any discussion of these other elements, some background information has been included relevant to the larger project (DE-FE0001580), as the work flow of these students has been guided by work on the second project.

SITE SELECTION

At the initiation of both projects the first task was the selection of a site at which the various methods could be tested. The initial criteria for site selection were as follows.

First, the site had to be actively injecting CO_2 at moderate to high rates (~ 1 million Tons per year) for at least one year. This would insure that there is a reasonable chance of a surface deformation signal, a seismic signature, and the potential for significant geochemical changes. It also better mimics realistic conditions in future commercially viable carbon capture and storage (CCS) operations compared to smaller demonstration projects.

Second, the site had to be located on land, easily accessible for study. Offshore sequestration projects are a viable option for CCS operations, however the monitoring techniques proposed are less expensive to implement and more precise on land. For example, sea floor geodetic techniques are typically one order of magnitude less accurate and one order of magnitude more expensive compared to terrestrial geodesy. Similarly, ocean bottom seismometers (OBS) are more expensive to deploy than their on-land equivalents, and typically have higher noise, since they rest on the ocean bottom, rather than in seismic vaults.

Third, the site had to be located in North America, to minimize travel costs associated with establishment and maintenance of the monitoring facility.

Initially the project considered locations at Cranfield and the Farnham dome. To this end, the project team met with researchers from the University of Texas at Austin and visited the Cranfield site. The team considered the Cranfield site unsuitable because injection had been going on already for some period of time, and the vegetation coverage made it difficult to apply the InSAR method.

After considering numerous other locations the team decided on a site south of Houston TX. This is an enhanced oil recovery location (EOR) operated by an industrial partner. Installation and activities at this site were coordinated with the Bureau of Economic Geology (BEG) at the University of Texas at Austin. This project team is grateful for this cooperation.

InSAR DATA

Prior to the site selection (see previous section) a comprehensive ground deformation survey was carried out by Student 1 of current and past CCS sites and sites utilizing CO_2 in North America using archived InSAR data . Archived SAR data (several hundred images from the ERS, Envisat, Radarsat-1 and ALOS satellites) were ordered for all the relevant sites. For most sites the imagery goes back to 1995 with reasonably good coverage starting in

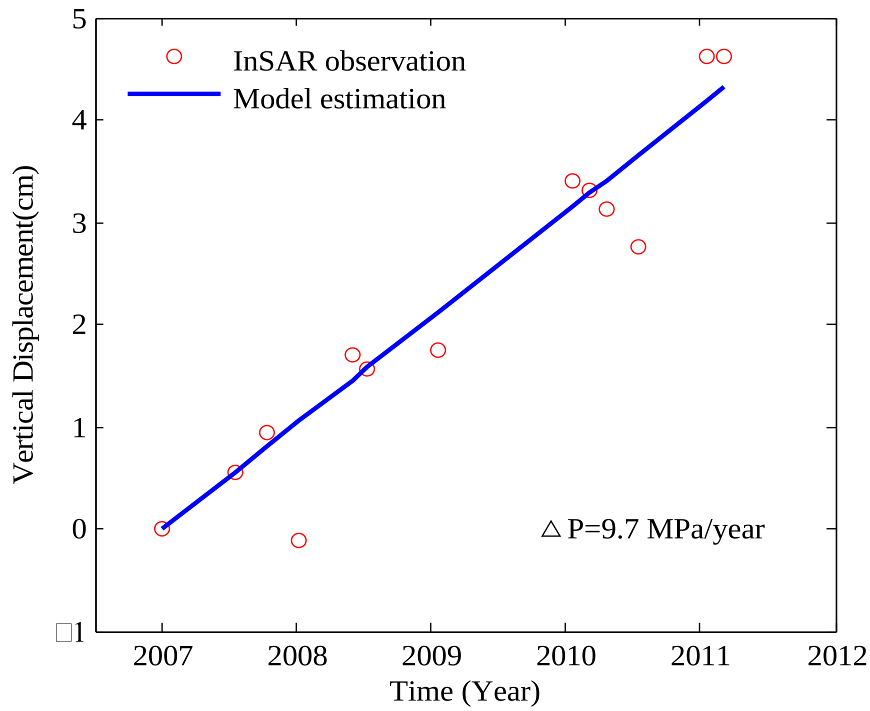


Figure 1: Modeled data from interferograms generated during the first phase of the project, at the SACROC site near Snyder, Texas

2005. Obtaining the imagery is commonly very time-consuming. Most data centers do not have the imagery available online and it first must be produced from archived telemetry files which sometimes take several months because of long queues. The survey results were critical for the final selection of the project's test sites. Figure 1 shows an example of the first phase analyses.

Once the site had been selected, the satellite was tasked to collect images of the south Texas site. The student involved in the project has been developing new methods for the time-series analysis of InSAR data which will be applied to the project. The project started to acquire TerraSAR-X high-resolution spot light imagery for the south Texas site on Jan 21, 2012. The sensor is operated by DLR (German Aerospace Center). The ground resolution is about 1 m for a full look product. Temporal resolution of the project's data is 11 days. At the time of this report, 35 images have been acquired. Individual interferograms contain significant high frequency noise because of the decorrelation of vegetation and atmospheric noise. Therefore researchers decompose the signal to remain the low pass part related to the ground response due to injection. Using small baseline time series analysis, the ground velocity from the initial result indicates apparent uplift in part of the study area (Figure 2). The project continues to process new data and expects more stable results with a denser temporal network.

A total of 30 scenes were received for period: 01/27/2012 – 05/03/2013. This represents very good coverage except for a 2 month gap during July-Aug 2012. All processing problems have been resolved, but the (expected) challenge will be the vegetation which causes significant background noise. The project expects to better resolve surface deformation once a few more images are available to filter out noise, and compare it to a set of GPS-determined time series of surface deformation.

An earlier set of interferograms generated during the first phase of the project, at the SACROC site near Snyder, Texas, has now been modeled (Figure1). This is a simple case to model, since during the monitoring period, only fluid injection was occurring (simultaneous injection and extraction occur at the south Texas site). The SACROC InSAR results show a clear deformation signal over a relatively small area. This site has been the locus of enhanced oil recovery activities for several decades, involving injection of CO2 into a relatively deep reservoir, and concurrent extraction of oil and natural gas. In addition, waste water is being injected at shallowed levels. The InSAR signal most likely results from the the shallower waste water injection, and is currently being modeled. Results will be presented at a professional meeting in Spring 2014.

Student 1 is currently processing and working with these images.

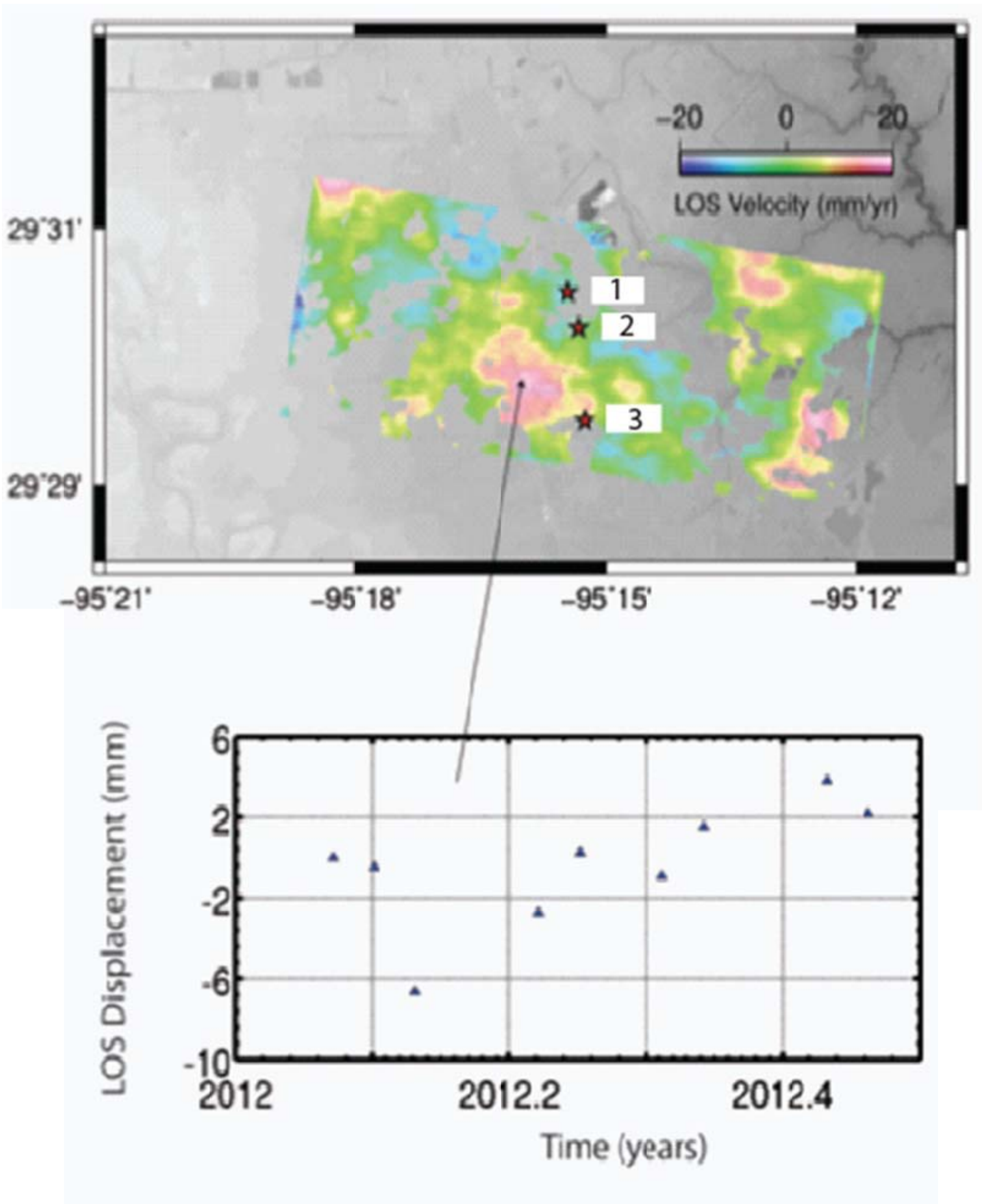


Figure 2: Line-of-sight velocity retrieved from TerraSAR-X high resolution spot light InSAR. Red stars are the injection sites. The reference point is close to site DEN2. Red color represents uplift and blue represents subsidence. Indicated motions are within the uncertainty of the technique and are not believed to be significant.

Student 2 on the project is pursuing an interdisciplinary PhD with equal focus being placed on geochemistry, mathematics, and political science. This student has taken extensive coursework in these three areas (See Appendix for course list).

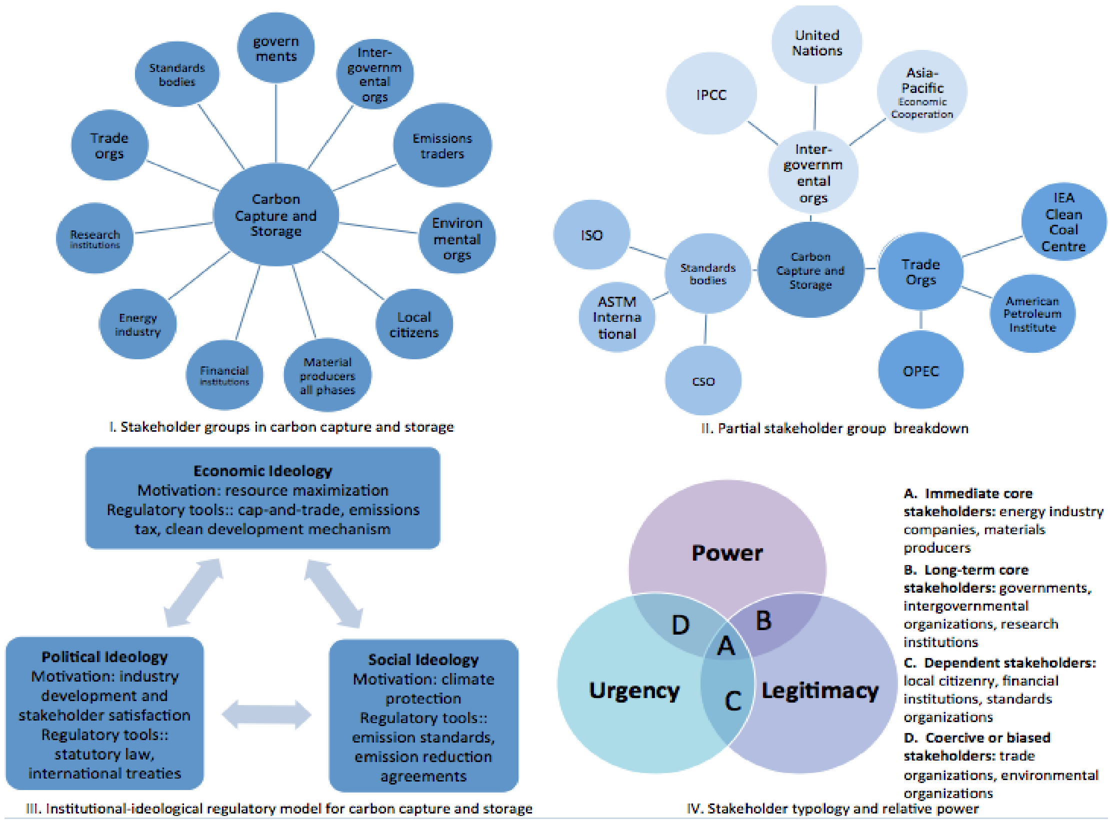
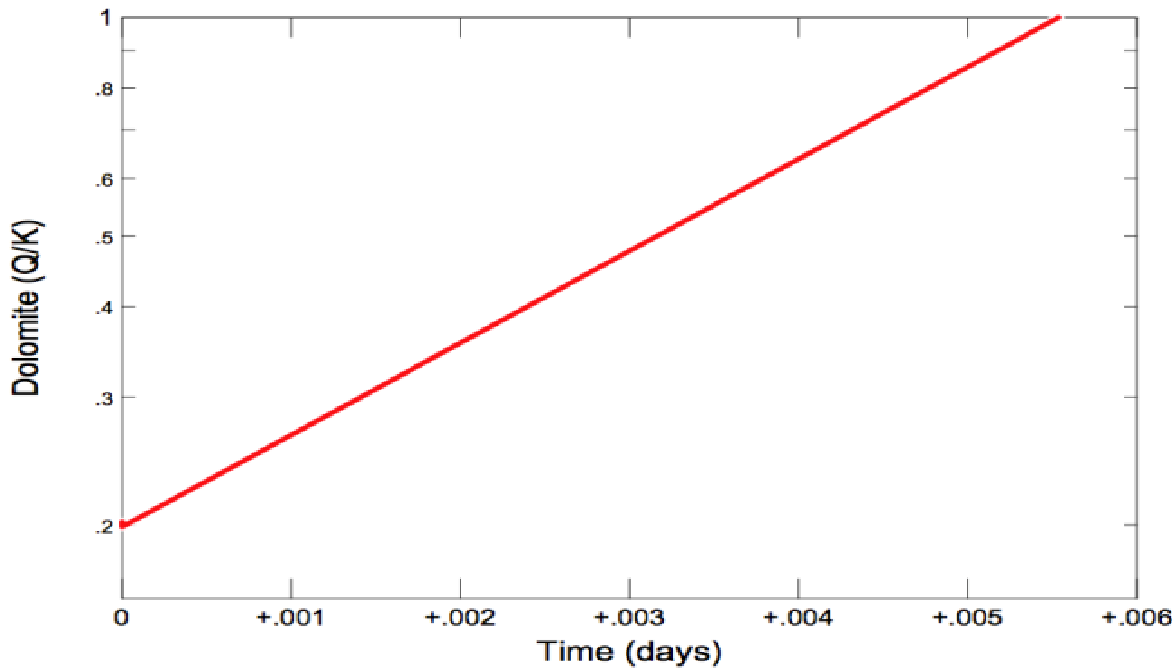


Figure 3: Stakeholder analysis from American Geophysical Union meeting poster in 2011

Her first task was tabulating and characterizing potential sites for the project team to begin pre-injection monitoring. This deliverable was met in Fall 2010, and she presented a site characterization poster at the American Geophysical Union Fall 2010 meeting. She also presented a research plan at the annual Carbonate Sedimentology Laboratory Sponsors meeting in fall 2010. She was selected for a travel grant and was invited to participate in the January 2011 IODP CCS-Oman Workshop (hosted by Peter Keleman of Lamont-Doherty Earth Observatory) where she presented preliminary site characterization models for sites selected from the literature review. She also attended a two-day field course on basalts while in Oman.



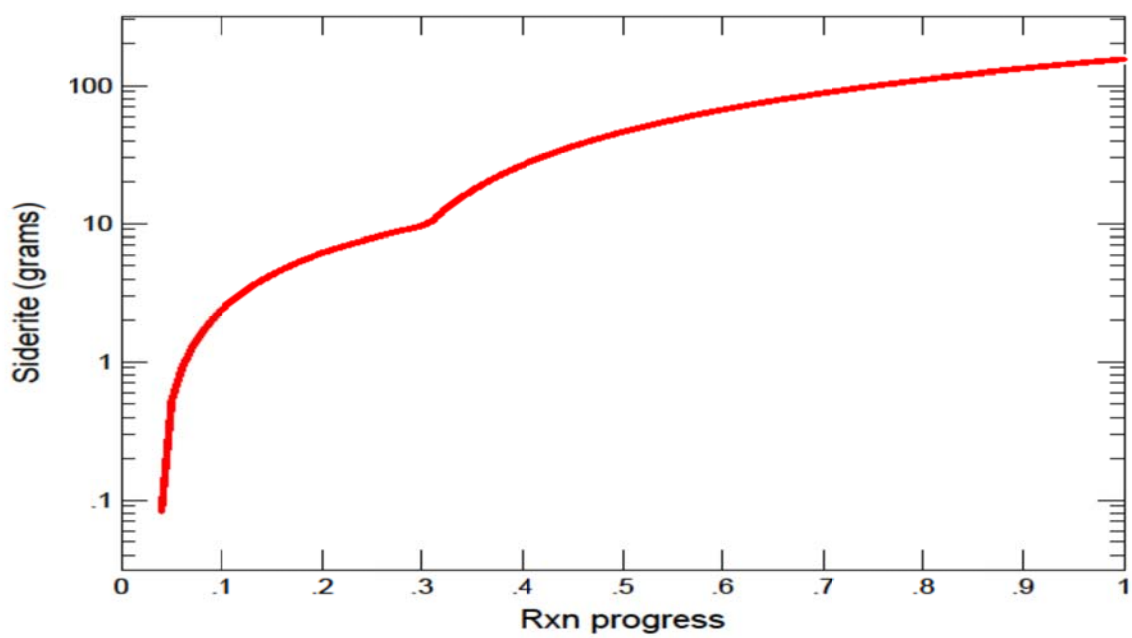


Figure 4: Outputs of a Geochemist's Workbench model injecting 10 kg of CO_2 into a mixed mineral assemblage reservoir formation. The upper graph shows the approach of the reservoir to saturation with respect to dolomite. The lower graph shows the precipitation of siderite.

Her next task focused primarily on research in the political science arena and drafting two proposed industry standards with members of ASTM (American Society for Testing and Materials) International's Committee E60 on sustainability. She presented these standards and led a round table discussion at the 2011 biannual ASTM International Committee Week meetings. In the summer of 2011, student 2 was a delegate to the IEAGHG CCS Summer School, the premier international short course on CCS where she was an active participant in multiple group activities and she greatly benefited from this experience and gained many excellent research contacts. She also received National Science Foundation funding to attend the American Meteorological Society's Summer Policy Colloquium where she learned about both national climate change policy and atmospheric modeling techniques. At the same time the student was working on a project involving stakeholder analysis which was presented at the 2011 Fall American Geophysical Union meeting (Figure 3).

During spring and fall semesters of 2012, the student worked with legal scholars at the University of Miami's School of Law to begin cataloging the 150 US state, regional, and national laws that are potentially applicable to CCS. She also attended a Lawrence Berkeley National Laboratory short course on modeling using the TOUGH2 software, and attended a research meeting at Bureau of Economic Geology (BEG) in Austin with the project Principal Investigators, Dr. Swart and Dr. Dixon, to consult with other persons working at the Texas injection site. The student also participated in a winter 2012 dissertation writing workshop and submitted a draft of her dissertation proposal. The project's latest efforts have been using a version of the TOUGH2 code integrated with a more user friendly interface (Petrasim).

In spring 2013, student 2 was awarded a grant to organize and host an interdisciplinary research workshop under the NSF SEEDs program. She worked with administrators in the Abess Center for Ecosystem Science and Policy to bring six interdisciplinary researchers to host a daylong workshop and mentoring event. She presented a poster at this event of her dissertation project and progress to date. Also in spring 2013 the student captained a research team for AAPG's Imperial Barrel Award program. The team received significant praise for their site exploration and drilling approach because they incorporated EOR technologies using captured carbon dioxide. The student also took certificate courses in basin modeling and CCS through the AAPG education program.

In order to model surface leaks coursework was carried out in Bayesian statistics and a research problem was developed centered on modeling surface leaks at CCS sites. A thorough literature review for leakage from CCS sites was conducted and the data collected used to build a predictive Bayesian risk analysis model that assigns a probability to leakage counts and leakage sizes (in tons.) This work was first presented at the Summer 2013 Goldschmidt meeting, and has been revised and extended into a paper for the IIE Transactions Journal – Annual Conference Proceedings issue (currently under review.) An oral presentation on risk modeling at the Summer 2014 Annual Institute of Industrial Engineers Conference will be presented and the student has been invited to participate in the IIE Doctoral Colloquium event attached to the conference. A figure from this paper which shows theoretical changes in the saturation state and mineralogy in shown in Figure 4. The student has further extended this risk analysis research to include modeling the risks of seismic events at CCS sites.

SUMMARY

This project was a training award which partially supported two graduate students in studies focused on CCS. Although this is a final report for this project, it is actually very much a progress report in that most of the actual research will not mature until 2015-2016.

The goal of the project was to train the next generation of students in understanding the challenges of CCS, and the goal was successfully met. Students involved in the project received traditional classroom training, hands-on research experience through a study investigating monitoring of carbon storage sites, attendance and participation in relevant conferences, and other numerous training activities.

APPENDIX

Meetings Attended and Presentations

2010 1) Student 2 attended Goldschmidt geochemistry meeting in Tennessee.

2) Student 2 attended the carbon capture and storage workshop in Oman organized by the International Ocean Drilling Program.

3) Both students attended the American Geophysical Union

in San Francisco and presented posters (i) on the work completed to date compiling CCS sites, (ii) Glacial Rebound at the Vatnajokull ice cap, and (iii) Monitoring Carbon Sequestration Reservoirs from InSAR in North America

2011 1) Students attended American Geophysical Union in San Francisco and presented posters.

2) Student 2 attended IEAGHG summer school. This is a school which trains students in the early stages of their PhD in all facets of carbon sequestration.

Student 2 attended the 2012 TOUGH2 training course hosted by LBNL (9/14/11).

3) Student 1 attended European Space Agency Fringe workshop 2011: 1) Glacial Rebound at the Vatnajokull ice cap; 2) Monitoring Carbon Sequestration Reservoirs from InSAR in North America

2012 1) Student 2 attended the American Association of Petroleum Geologists course on CCS (http://www.aapg.org/education/online/details.cfm?ID=217) and the American Association of Petroleum Geologists Basin modeling course (certificate course in Giant Oil Fields and Reservoirs).

2) Student 1 attended UNAVCO Science workshop 2012 and presented a) Two Methods for the InSAR Time-Series analysis, and b) Rapid ice loss at the Vatnajokull ice cap, Iceland

2013 1) Student 2 attended Goldschmidt geochemistry meeting in Florence Italy

2) Student 2 attended Research Experience in Carbon Sequestration (RECS program http://www.recsco2.org/)

3) Student 2 attended workshop on Geochemists workbench with advisor.

4) Student 1 attended American Geophysical Union in San Francisco. He presented initial results of a survey of bedrock responses due to ice mass loss in the North Atlantic Region using InSAR and bedrock deformation due to the present day ice loss on the Greenland ice sheet and the Canadian Arctic Archipelago observed by synthetic aperture radar interferometry.

5) Student 1 attended Wagner Meeting 2013. Student presented material on rapid ice loss at Vatnajokull, Iceland, since the late 1990s, constrained using InSAR.

Courses Taken

Student 1 **(Student had a MS degree and therefore only needed 24 credits)**

1. Plate Tectonics
2. Geophysics
3. Paleoclimatology
4. Crustal Deformation
5. Geophysical Inverse Theory
6. Physical Volcanology
7. Geodynamics

Student 2

1. Interdisciplinary Environmental Theory
2. Political Environments of Business (stakeholder analysis)
3. Introduction to Geochemistry
4. Computer Simulation Systems
5. Interdisciplinary Environmental Law and Policy
6. Interdisciplinary Environmental Research Methods
7. Risk Analysis
8. Structural Geology
9. Petroleum Geology
10. Accident Prevention Systems
11. Failure Time Analysis
12. Judgment and Decision Making
13. Climate and Energy Law
14. International Environmental Law
15. Property Law
16. Decision Support Systems