Introduction

The Department of Earth and Planetary Science has long had investment and expertise in the study of biogeochemical cycles, in particular the carbon cycle and its relationship to the Earth’s climate system, and also has a deep history relating to the hydrocarbon industry. As part of our developing interest in a carbon management initiative (i.e., improving understanding of natural carbon cycle dynamics and resulting climatic effects, mainly through paleoclimate studies, and using insights gained to better guide human actions as we attempt to manage our impact on the global carbon cycle and climate), several actions have been undertaken to initiate research. This report addresses activities funded by an ISEN Booster grant, which provided support for three main efforts:

- Development of a comprehensive report on Carbon Capture and Storage (CCS), redacted from published sources: (1) as a follow up to the NSF-funded workshop on CCS that was hosted by NU faculty (Sageman) and others in association with the 2011 Geological Society of America meeting, and (2) in order to provide a foundation for strategic planning of how best to approach development of a carbon management initiative at Northwestern.
- Planning and implementation of outreach efforts, such as public symposia, designed to bring expert speakers to campus, educate relevant stakeholders about state-of-the-art research activities, and thus help guide decision making, while also informing the campus and local community about selected issues.
- Initiation of new basic research on carbon storage via the mineralization of CO₂ under elevated pressure and temperature conditions, which was facilitated by collaboration with mineral physics colleagues in the Department of Earth and Planetary Science who routinely study mineral dynamics at elevated temperature and pressure.

Much of the ISEN funding supported a post-doctoral scholar, Dr. Dorothee Husson, who worked with myself to accomplish the objectives listed above. It is worthwhile noting that Dr. Husson was drawn to Northwestern because of my work in the area of cyclical paleoclimatic phenomena and their use to refine and improve geologic time scales. Although not directly related to the focus of this ISEN funding, a paper on the work, co-authored by Sageman, was published during the period of ISEN funding (Husson et al., 2014).

It is prudent to note that the original proposals submitted for this work viewed it as part of the vision for development of a Northwestern Carbon Center. This resulted from several requests from higher administration officials to Sageman for a “white paper” outlining such a vision, which could be presented to potential donors for possible endowment support. The white paper described a center placed within the umbrella of ISEN that included basic research, education, and outreach spanning physical science and policy disciplines focused on carbon management. The first such white paper was provided in 2010, and revised at least once thereafter. Over four years there has been no response to this effort, which suggests that significant support for a carbon management initiative is unlikely to come soon. In some ways this is not a surprise because Northwestern lacks the full complement of tenure line faculty who would complete the team. For example, we lack social science expertise in economics and policy related to carbon management and we have no modern climate expertise (although Earth and Planetary Science expects approval for such a search any day now). Although endowment support could have provided the means to address these
deficiencies and help build the initiative, there are, of course, many other priorities competing for support within the institution. It is hoped that in the absence of significant funding the results described herein will help guide future investments of time and effort in order to best optimize our approach to carbon management.

1) Understanding the landscape of CCS

One of the key areas of carbon management is Carbon Capture and Storage (CCS). Relatively little specific work in this field had been started at Northwestern four years ago, so it seemed worthwhile to review the state-of-the-art in CCS science and compile this information into a report, which could also serve as a summary document for the CCS workshop supported by the NSF-SEES initiative (Science, Engineering, and Education for Sustainability) that Sageman co-hosted at the 2011 Geological Society of America meeting. The report also includes a description of research programs and carbon-related curricula offered by universities and national laboratories, and compiles information on large-scale field test developments. The report includes the following chapters:

- **Carbon capture**: details the various pre-, post- or oxyfuel combustion methods available or in development, among them membranes, adsorption or absorption technologies.
- **Geological carbon sequestration**: covers the physical and chemical behaviour of CO2 when injected underground, the various storage options (saline aquifers, basalts, coal...) and the enhanced-oil recovery projects, that are using injected CO2 to increase oil and gas production.
- **Biological carbon sequestration**: summarizes the results of research to understand the potential of agricultural sequestration approaches;
- **Risk assessment**: addresses the two major issues possibly encountered in a CCS project: leakage and induced seismicity.
- **Monitoring**: presents a large number of the geochemical and geophysical monitoring tools currently used or being developed (tracers, soil gas flux, seismic imaging, gravimetry...).
- **CCS projects in the USA**: compiles information on the small scale and large scale projects developed by the DOE-funded regional partnerships and the large-scale commercial projects that have been planned.
- **Academic research and teaching**: relies on a database gathering information on research projects funded in universities, and on curriculum information obtained through university websites.
- **Carbon management policy**: this chapter summarizes policy initiatives that address carbon management and may provide insight for how best to build such expertise at Northwestern in a way that does not duplicate others.

Among the areas identified above, some research relevant to capture and storage has begun at Northwestern (Metallo-organic frameworks or MOF’s; carbonation under geological conditions), but are not yet extensive – they should be supported. Areas with potential for growth include monitoring (e.g., ISEN has supported an small scale CO2 monitoring station on campus using the type of technology that would be required for larger scale efforts), induced seismic assessment (a current project by NU seismologists is looking at a possible induced seismic event related to quarry operation within the Chicagoland area), carbon management (if the talent and focus of Kellogg, Economics, and Political Science faculty were brought to bear on this issue I believe the results could be significant), and curriculum (the ISEN certificate provides an excellent framework for disseminating knowledge about carbon management).
2) CCS outreach efforts

- Northwestern continues to participate in a Research Coordination Network on CCS managed by Alissa Park of Columbia University (RCN-CCUS); the last meeting was held on October 4th, 2013.
- On August 5-6, 2013, Dr. Husson took part in the Climate Change and Sustainability workshop for K-12 teachers conducted by the Office of Stem Education Partnerships (OSEP) at Northwestern University. She conducted two sessions on the theme of Carbon Capture and Sequestration with high school and middle school teachers. These sessions included a presentation on CCS followed by exercises and analog experiments specifically designed for this workshop, aimed to promote understanding of the fate of carbon dioxide once injected into a reservoir rock. Working sessions followed, during which Dr. Husson worked with the teachers to develop a board game on CCS that could be used in various educational contexts. This CCS teacher workshop was advertised on the Northwestern website.
- Dr. Husson and Dr. Sageman, with support from staff in ISEN and the Department of Earth and Planetary Science, hosted the 2014 Climate Change Symposium titled The Future of Carbon. The event took place May 16, 2014 and the cosponsors included the NU Alumnae, the Environmental Science, Engineering and Policy/Culture Programs, the Plant Biology and Conservation Program, and the Medill School of Journalism. Seven nationally and internationally renowned researchers presented talks focused on different facets of carbon management including shale gas and fracking, CCS, biological sequestration, MOF’s and gas storage, and other topics. A capacity crowd was present throughout the day and feedback from the event was excellent.

3) Fundamental Carbon Sequestration Research

Research on carbon dioxide mineralization at subsurface pressure and temperature was also initiated in the mineral physics lab of Prof. Steve Jacobsen (Dorothee Husson and John Lazarz performed the experiments with guidance from Steve Jacobson, Craig Bina, Andrew Jacobsen and Brad Sageman, Department of Earth and Planetary Sciences). To perform the experiments, a new high-pressure and high-temperature diamond anvil cell was built, including a heater and temperature measurement tools. The cell was tested by forming high pressure phases of water ice at room temperature (H₂O VII) and then melting the ice. The cell was then used to study carbonation at elevated pressures and temperatures by charging it with CO₂ in the gas loader at Argonne National Lab. The first experiment sought to address the effects of carbon dioxide on dissolution of the mineral olivine ((Mg, Fe)₂SiO₄) and hypothesized precipitation of the mineral magnesite (MgCO₃) as a product. After the cell was charged and brought to pressure, the olivine dissolved but magnesite was never detected in the cell. Several possibilities exist to explain the negative result: (1) magnesite did precipitate, but did so as a thin film on the interior of the cell that was undetectable by Raman spectroscopy, which is the method used to measure mineral phases in the cell; (2) the reaction lacked sufficient H₂O to proceed; or (3) pressure conditions were too high and exceeded the range that would most effectively model subsurface conditions at which CO₂ would be stored. It is hoped that further experimental results may allow refinement of the thermodynamic database and models used to predict reaction rates of carbon dioxide in subsurface reservoir rocks. Bacterial activity may eventually be included to constrain the potential role of microbes in subsurface carbon mineralization. However, this will all require an apparatus that can achieve lower pressures than possible with the current type of diamond anvil cells being used in the Jacobsen lab. John Lazarz, a graduate student working with Jacobsen, may continue this work.
4) **Summary**

The development of a carbon management initiative at Northwestern faces significant challenges. It seems unlikely that it will attract internal funding support unless significant momentum in the form of external funding and major research results are achieved. This seems unlikely given the small number of faculty working on related problems, and the lack of cognate strength in social science disciplines. Faculty in the Department of Earth and Planetary Science will continue to work on the natural carbon cycle and paleoclimate dynamics as these constitute core research areas for them. A promising new collaboration between Sageman and faculty in Civil and Environmental Engineering is focused on the fracture mechanics of shales and will be relevant to shale gas exploration and production efforts. This project may help to develop more significant industry partnerships between Northwestern and the energy firms for which Sageman has done geological consulting work in the past.

**Cited Publication**