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EDITORIAL

Introduction to the special issue on site characterization for geological storage of CO_2

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Concentrations of carbon dioxide (CO_2) in the atmosphere have been rising rapidly as a result of human activities since the Industrial Revolution. From about 280 ppm before the start of this period in history, these values have increased to about 379 ppm in 2005, which is by far higher than the natural range of CO_2 determined from ice cores over the last 650,000 years (IPCC 2007). The primary source of this increase is the use of carbon-rich fossil fuels such as coal, oil, and natural gas for energy production. It is widely accepted today that these changes in atmospheric CO_2 concentrations are a major contributor to global warming by trapping heat radiating from the earth's surface, by the so-called greenhouse effect (NAP 2001; IPCC 2007).

Several technological options have been proposed to stabilize atmospheric concentrations of CO_2 (Pacala and Socolow 2004). One suggested remedy is to separate and capture CO_2 from power plants burning fossil fuels and from other stationary industrial sources and to inject the produced CO_2 into deep subsurface formations for long-term storage and sequestration (IPCC 2005). The most promising targets for geologic sequestration of the CO_2 would be deep saline formations as well as depleted or near-depleted oil and gas reservoirs. Saline formations offer the largest CO_2 storage capacity and are widely distributed worldwide. Hydrocarbon reservoirs, on the other hand, are not so common, but have the advantage of having caprocks with proven "sealing" capacity (buoyant fluids remained trapped in place over geologic times), and the injected CO_2 may enhance oil or gas production. The scale at which CO_2 would have to be sequestered is large. Considering Norway's North Sea Sleipner project, which is the world's first industrial-scale CO_2 geologic storage operation with an annual injection of about one million tonnes of CO_2 since 1996 (e.g., Torp and Gale 2003), Pacala and Socolow (2004) estimate that 3,500 Sleipner-sized capture and storage (CCS) projects, would be needed worldwide over the next 50 years to help stabilize atmospheric CO_2 concentrations.

While geologic sequestration is a promising method for CO_2 mitigation, continued research and development efforts are important to advance the state of the art in many areas so that CCS can be effectively and safely deployed on a global scale (e.g., Litynsky et al. 2006). One challenging research area is the optimization of the methodology to assess the suitability of potential geologic sequestration sites. Careful site characterization is necessary to demonstrate that storage in geologic formations is both feasible, i.e., that the formations have a large enough storage capacity and good injectivity, and effective, i.e., that the formations provide safe long-term containment, without adverse impacts to human health or the environment (Bachu 2000). The importance and objective of site characterization are reiterated in the special report on carbon dioxide capture and storage issued by the intergovernmental panel on climate change (IPCC 2005), which stated that "site characterization, selection and performance prediction are crucial for successful geological storage. Before selecting a site, the geological setting must be characterized to determine if the overlying cap rock will provide an

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effective seal, if there is a sufficient voluminous and permeable storage formation and whether any abandoned or active wells will compromise the integrity of the seal."

This special issue of *Environmental Geology* is focused on the selection and characterization of potential CO_2 storage sites. It includes 11 research papers addressing a wide range of related scientific aspects of this topic, with emphasis on framework and strategies, improved process understanding, innovative measurement methods, and new screening and characterization tools. The papers were selected from a set of about 90 that were presented at the International Symposium on Site Characterization for CO_2 Geological Storage (CO2SC) that was held in March 2006 at the Lawrence Berkeley National Laboratory in Berkeley, CA, USA. More than 150 participants from 13 countries, namely Germany, Denmark, Spain, France, Great Britain, Italy, Japan, The Netherlands, Norway, Australia, India, Canada, and the United States, were in attendance. The 11 papers were reviewed by two or more technical referees.

The first three papers in this special issue comprise site characterization case studies selected from a pool of more than 25 articles on potential future storage projects. These papers provide a good overview of strategies and methodologies to be used for careful selection and assessment of suitable storage sites. Gibson-Poole et al. (2007) describe the evaluation of a potential storage site in the offshore Gippsland basin in southern Australia. A framework is presented that evaluates the three most important attributes of a suitable geologic formation, i.e., capacity, injectivity, and long-term containment, via a comprehensive program of geophysical, geologic, hydrologic, geomechanical, and geochemical investigations, complemented by multi-phase flow numerical simulations. Meyer et al. (2007) conduct a stepwise screening and ranking of several candidate sites for on-shore storage of CO_2 from a large coal-fired power plant in northeastern Germany. After this pre-feasibility effort, the most promising candidate site is selected for further study of its structural integrity and long-term safety; this effort is still ongoing. Ambrose et al. (2007) address the question to which extent structural and depositional factors control geologic facies variability in subsurface formations considered for CO_2 storage. Based on experience with oil and gas reservoirs, the authors suggest that facies variability and corresponding permeability heterogeneity may have important implications for CO_2 injectivity and migration pathways. Examples are given for the Texas Gulf Coast region, which is the main oil-producing region in the United States and, not coincidentally, also an important potential area for CO_2 sequestration.

The next set of papers deals with the Frio Brine pilot test a small-scale CO_2 injection conducted specifically for detailed geo-scientific studies on CO_2 storage in a brine aquifer near Houston, Texas, USA. Doughty et al. (2007) argue that, in addition to traditional characterization techniques conducted prior to injection, the monitoring of the CO_2 plume during the early injection phase provides valuable site information that is otherwise not available, such as a detailed understanding of the migration patterns influenced by buoyancy, multi-phase effects, and geologic heterogeneity. The authors discuss a numerical model designed to integrate the comprehensive set of pre-injection data available from the Frio Brine pilot test and demonstrate the merit of improving this model as new data is obtained during this early injection phase. Daley et al. (2007) describe, for the same pilot test, the use of time-lapse seismic surveys providing in-situ estimates of the spatial distribution of the injected CO_2. Results demonstrate that even relatively small CO_2 plumes (about 1,600 tonnes) are detectable in saline aquifers by high-resolution tomographic imaging.

Several papers in the CO2SC symposium dealt with the possibility of CO_2 leaking from the storage formations. Potential leakage paths include permeable faults, caprock imperfections and unsecured abandoned wells. Two of these papers were selected for this special issue. Chiaramonte et al. (2007) conduct a geomechanical characterization and evaluation of caprock integrity at a pilot test site in Wyoming, USA, with the objective of predicting the potential risk of CO_2 leakage along reservoir-bounding faults. The concern is that CO_2 injection may lead to increased pore pressure and changes in effective stresses in the reservoir, which could fracture the overlying seal or cause reactivation of pre-existing faults. Pruess (2007) focuses on the complex flow behavior of CO_2–brine mixtures upon leakage from a storage formation, along a permeable fault and an open wellbore, respectively. Numerical simulations for idealized scenarios show a potential for self-enhancement of CO_2 migration, but demonstrate equally effective self-limiting features due to strong adiabatic cooling effects stemming from pressure decrease. The possibility of strong eruptive discharge of CO_2 at the land surface is discussed, but considered highly unlikely, though further studies are recommended.

The following two papers describe screening and ranking methods for a quick and reliable selection of candidate storage sites out of a large number of proposed locations. Such methods are useful in the early stages of site selection, when geologic data are sparse, and not enough resources are available to allow for in-depth evaluation of all the alternatives. Oldenburg (2007) introduces a computer-aided screening and ranking framework that evaluates potential geologic storage sites on the basis of health, safety, and environmental risk arising from CO_2 leakage. Applications to three California sites demonstrate the usefulness of this approach. Núñez López et al. (2007) present a multi-stage methodology for the efficient screening of mature oil fields, where CO_2 storage can be combined with the benefit of enhancing oil production. The main screening criteria in this approach are the potential for improving oil recovery and the field's capacity for CO_2 storage. The method is applied to identify optimal candidate sites in the Texas Gulf Coast region, with a specific example given for the Galveston area.

The next paper selected for the issue deals with the fundamental hydrological processes involved in CO_2 geological storage. Bachu and Bennion (2007) describe results from laboratory experiments measuring the displacement characteristics of CO_2–brine systems under in-situ pressure and temperature conditions. The authors present a synthesis and interpretation of relative permeability, capillary pressure, and interfacial tension data for sandstone, carbonate and shale formations in Alberta, Canada. Such information is very valuable and much needed input for evaluating and predicting CO_2 injectivity, migration, and containment in deep saline formations.

The final paper in this special issue provides a summary comparison of hydrologic topics related to CO_2 geologic storage on one hand, and the deep-well disposal of liquid wastes on the other. Liquid waste disposal in the deep subsurface has been practiced in the United States for more than 50 years, and has been carefully regulated and well documented since the 1980s. Tsang et al. (2007) review the similarities and differences between CO_2 geologic storage and liquid waste disposal, and evaluate aspects of carbon geologic sequestration that can benefit from the extensive experience gained from liquid waste disposal projects.

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