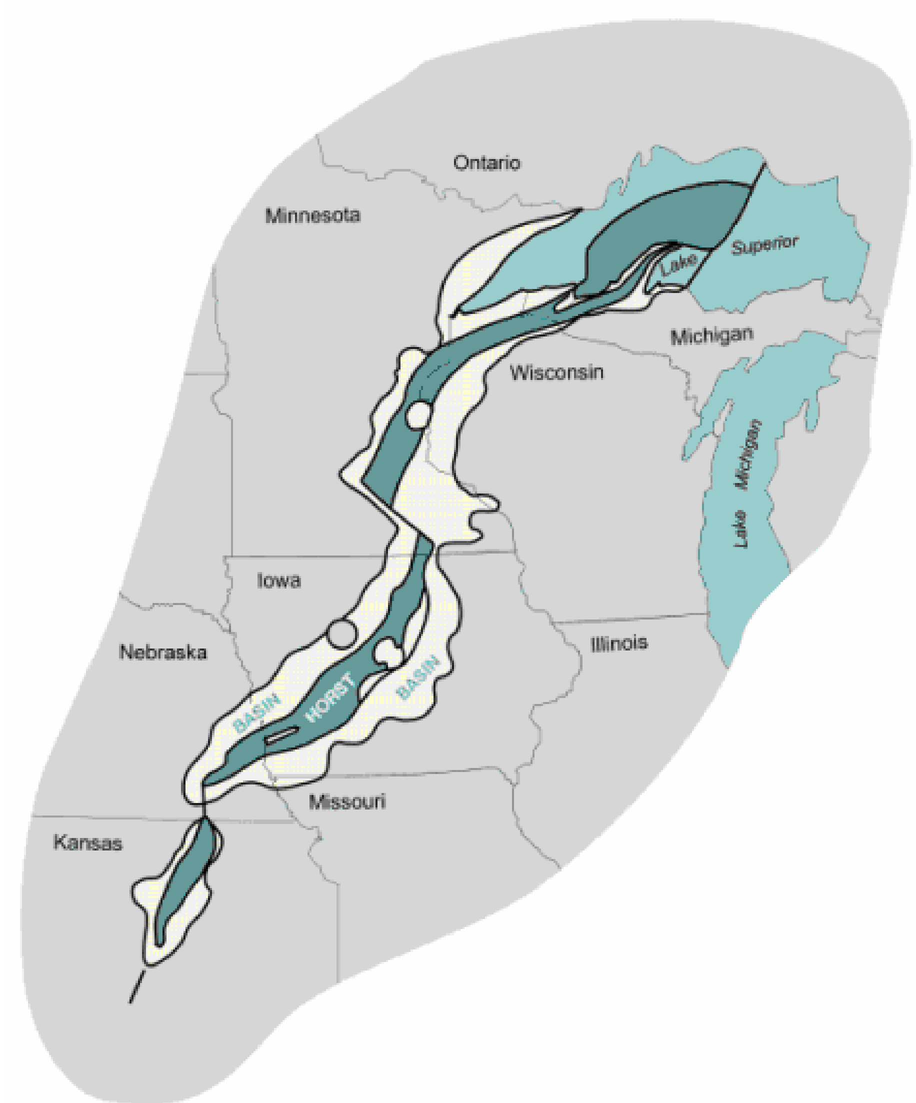
MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director



POTENTIAL CAPACITY FOR GEOLOGIC CARBON SEQUESTRATION IN THE MIDCONTINENT RIFT SYSTEM IN MINNESOTA

L. Harvey Thorleifson, Minnesota Geological Survey, Editor

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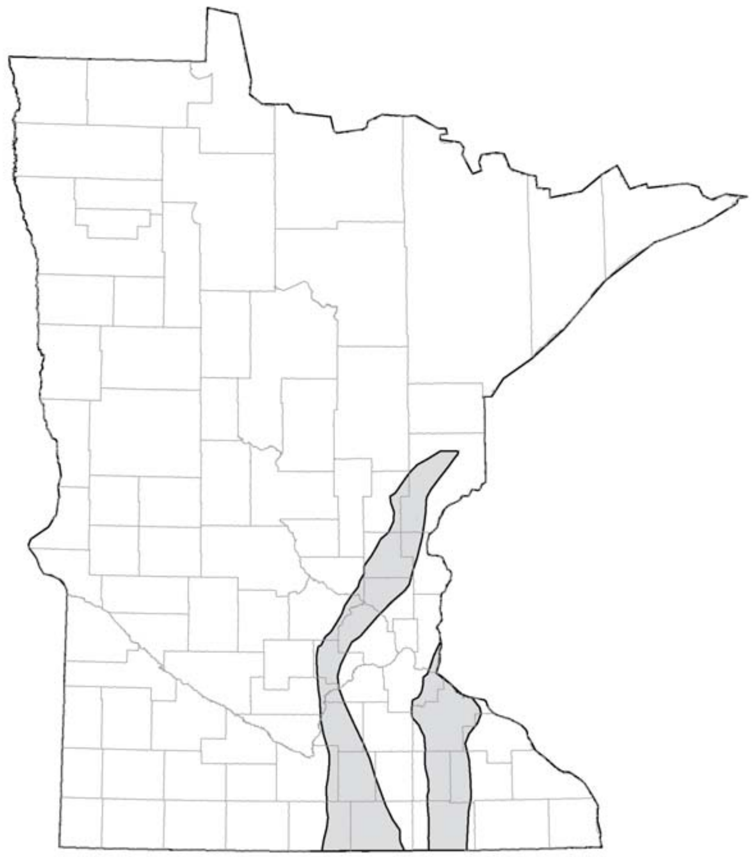
POTENTIAL CAPACITY FOR GEOLOGIC CARBON SEQUESTRATION IN THE MIDCONTINENT RIFT SYSTEM IN MINNESOTA: EXECUTIVE SUMMARY

Increasing concern about climate change has necessitated the assessment of ways to reduce greenhouse gas emissions, while concurrently increasing our preparedness for climate change and variability. For example, in 2007, the Minnesota Legislature set goals to reduce our emissions 15% by 2015, 30% by 2025, and 80% by 2050. These reductions can be achieved by reducing combustion of fossil fuels, and by reducing other activity that generates greenhouse gases. Changes in land use can induce increased storage of carbon in soil and vegetation, thus facilitating terrestrial sequestration of emissions from the full range of sources, including vehicle emissions. In the case of stationary sources of carbon dioxide (CO_2) emissions, however, such as the coal-fired electrical generating stations, ethanol plants, and other stationary sources that make up over one-third of Minnesota CO_2 emissions, the technology to capture CO_2 is available, pending developments in methods and costs. The likely fate of CO_2 captured from stationary sources would be storage by geologic sequestration, also known as carbon capture and storage, by injection into underground geologic formations where it can be stored for long periods of time to prevent its escape to the atmosphere. This method is in the early deployment phase worldwide, but estimates indicate it may permit 15 to 55% of the emissions reductions needed to avoid dangerous levels of climate change. In addition, analyses indicate that achieving these reductions will be less costly if geologic carbon sequestration is an option. Another geologic technique is mineral carbonation, in which CO_2 is reacted with material from mining, producing mineral products for disposal or use in construction. While Minnesota has favorable geology for this option, the method is not fully developed and the costs remain high.

With respect to the deep injection method, an option for Minnesota is export of CO_2 from stationary sources by pipeline to one or more potentially willing jurisdictions such as North Dakota or Illinois, where apparently suitable geologic repositories have been confirmed. It is possible, however, that saline formations in Minnesota could be confirmed as geologic CO_2 repositories, possibly enabling carbon storage without the requirement for negotiations with neighboring jurisdictions and export by pipeline. The only rocks in Minnesota that potentially have the required reservoir properties below about a kilometer depth, the depth required for efficient CO_2 storage, are sequences of sedimentary rocks associated with the Midcontinent Rift, a southwestward extension of the Lake Superior basin that extends to Kansas. Criteria for confirmation of potential include depth, porosity, permeability, presence of a seal, integrity relative to previous drilling or fractures, appropriate chemistry relative to lack of drinking water potential and chemical trapping mechanisms, and adequate data availability.

As part of efforts by Minnesota to take steps toward dealing with the climate change issue, therefore, this report summarizes current knowledge and knowledge gaps regarding the potential capacity for geologic carbon sequestration in the Midcontinent Rift System (MRS) in Minnesota, as required by 2007 state legislation, while also discussing the mineral carbonation option. By reviewing published, unpublished, and new data, the report reviews available information pertinent to the potential long-term storage of carbon in Minnesota geologic formations. To do so, the study assesses the potential for porous and permeable sandstone layers deeper than one kilometer below the surface that are capped by less permeable shale, with emphasis on formation properties that determine injectivity, storage capacity, and seal effectiveness. Included is discussion on characteristics of key sedimentary units within the Midcontinent Rift System in Minnesota, including (1) likely depth, temperature, and pressure; (2) physical properties, including the ability to contain and transmit fluids; (3) the type of rocks present; (4) structure and geometry, including folds and faults; and (5) hydrogeology, including water chemistry and water flow. In addition, computer modelling methods are discussed and applied to the Minnesota context to the extent that could readily be achieved. The study thus identifies the most promising formations and geographic areas in Minnesota for physical analysis of carbon sequestration potential.

The prospective rocks primarily are known with respect to their depth and thickness on the basis of geophysical surveys. These seismic, gravity and magnetic interpretations indicate that sedimentary basins associated with the Midcontinent Rift in Minnesota are to a large degree associated with depths and volumes that are compatible with sequestration of CO_2. The area where sedimentary rocks are more than 1 km thick, including both the most promising rocks, Bayfield Group sandstones, and overlying rocks that contribute to making up required depth, are presently thought to encompass two north-south belts on either side of the Twin Cities, running from Pine County and Washington County, south to Iowa (box). Available geophysical information thus indicates that there is sufficient sedimentary rock depth and thickness in the Midcontinent Rift System sedimentary basins in the region for further consideration of sequestration capacity to be warranted.



Estimated extent of sedimentary rocks thicker than 1 km in Minnesota, the depth required for potential carbon sequestration, based on 3D gravity modelling by Allen (1994), and scattered shallow drillhole intersections. Additional 3D gravity modelling, taking advantage of currently available methods and computing power, is needed to clarify and refine these estimated extents, prior to further geophysical surveys, drilling, and modelling meant to clarify the extent, thickness, and character of the rocks, to determine if potential is present

There is little in available geophysical information, however, that addresses porosity or permeability of these rocks. Although factors other than porosity can affect seismic velocity, the available velocity data from seismic refraction surveys do not look promising, as most values exceed 12,000 ft/sec, which are values higher than those typical of highly porous rock. Nonetheless, further work using new methods, such as velocity or waveform analysis of either existing or, if necessary, new seismic reflection data could be implemented to potentially better address porosity. Another approach might be to use magnetotelluric methods to look for conductive brines in the sedimentary section, which would indirectly indicate porosity, while additional 3D gravity modelling is needed to clarify extent and thickness, using currently available methods and computing power.

Thus while depth and thickness of the rocks are amply demonstrated, required information on porosity and permeability is inadequately established from geophysical surveys, and the same conclusion applies to a review, synthesis, and limited new analyses of their lithostratigraphy, depositional history, physical properties, and hydrogeology. Therefore, these rocks may not be sufficiently well characterized to permit a fully informed judgment on their suitability as a site for the sequestration of CO_2, but the limited available information indicates that the MRS has attributes that make it far less suitable for sequestration than other sites currently being considered across the country. On the positive side, the MRS contains the only sedimentary rocks in Minnesota that extend to depths required for sequestration, including sandstone bodies that at relatively shallow depths of 2500 ft (762m) or less are known to locally have moderate porosity and permeability. Shale and mudstone intervals are present, which appear to be of sufficiently low matrix permeability to serve as seals. An additional positive attribute is the lack of previous exploration, as reservoirs that have a history of exploration and production tend to have been penetrated by large numbers of often-undocumented drill holes that may not have been properly abandoned, presenting a significant and unquantifiable risk of leakage. These attributes thus suggest that the MRS can not yet be ruled out as a potential site for deep geologic sequestration of CO_2.

On the negative side, however, the known and inferred properties of the MRS in Minnesota and neighboring areas indicate that there is only a very small probability that it contains the geologic attributes necessary to serve as a site for deep geologic sequestration of CO_2. Geophysical logs of deep exploratory boreholes in Iowa and Wisconsin, petrographic analyses of sandstone in those states as well as Michigan and Minnesota, and the limited number of tests on samples from Minnesota cores as part of this project indicate that sandstone at the depth required for sequestration is relatively low in porosity and permeability. Permeability has been measured to be orders of magnitude too low for sequestration to be viable everywhere it has been tested in the MRS. Furthermore, the MRS is associated with a more complex tectonic history compared to other sites being investigated, and therefore features such as faults and fractures may play a larger role in site evaluation. For example, low permeability beds in the MRS that are necessary to serve as seals on top of potential CO_2 reservoirs are known to contain fractures with evidence of fluid flow. Fractures associated with faults are believed to serve as conduits for deep MRS groundwater to travel upward across such seals to overlying freshwater aquifers today. Identification and mapping of such features will be a more difficult task compared to the relatively simple structural settings being assessed elsewhere. Thus while much information is available for regions elsewhere in the US, such a body of geologic knowledge does not exist for the Midcontinent Rift. If it is determined that further research is warranted, a comprehensive investigation encompassing geophysical surveys, multiple deep and thoroughly analyzed exploratory boreholes, followed by stratigraphic, structural, tectonic and hydrogeologic interpretation will be necessary to bring the understanding of these rocks up to a level analogous to that presently available for where sequestration is being implemented. Early-phase characterization of the rift thus would require significantly more time and expense than was expended for initial assessments elsewhere.

Also part of the current study was numerical simulation initiated at the University of Minnesota Department of Geology and Geophysics, to obtain insights into current methods, to clarify needed information, and to take steps toward building the capacity that would be required for iterative simulation should subsequent steps proceed. Concurrently, this research contributes to broader knowledge relevant to topics such as groundwater as well as mineral and energy resources, and positions Minnesota to contribute to carbon sequestration research more broadly. Current numerical modelling is, however, in the initial stages required in a comprehensive CO_2 project since a wide range of geologic conditions as well as injection and storage scenarios have yet to be fully explored. Significantly more detailed studies, both in the field and via numerical modeling, will be needed for the analysis to play needed roles in eventually determining whether the MRS has characteristics favorable to CO_2 storage. A limited range of injection scenarios have been tested, however, varying solute injection rate as well as aquifer and caprock permeability and porosity between scenarios. Within the ranges of geologic parameters currently expected in the rift, the current model suggests that the following reservoir properties would be feasible for CO_2 storage if they were to be confirmed: aquifer permeability, 10^{-15} m^2 to 10^{-13} m^2; aquifer porosity, 4% to 20%; caprock permeability, 10^{-21} m^2 to10^{-18} m^2; and caprock porosity, 6% to 16%. Currently under way is an expansion of modeling capabilities to include multiphase behavior, as well as varying reservoir geometries and conditions. A subsequent phase of modeling could proceed as a three-year effort to improve the numerical multiphase fluid flow modeling environment. Initial work would be possible without the aid of field studies, as model geology could be improved by analysis of existing or new rock cores, while shallow wells that intersect saline brines could be sampled in order to support reactive transport modeling. Results from these improved models would then contribute to selection of sites for geophysical surveys, which in turn would support improved model iterations. Similarly, model iterations and scenarios would contribute to drillhole site selection, if called for, and again, direct data on rock composition and geometry together with brine composition from deep borehole sampling would again improve model iterations, continuing the cycle. Iterative field investigations and modeling would continue until required confidence levels concerning the feasibility of CO_2 storage are reached, at which time field tests of CO_2 injection and storage could be considered.

In summary, a spring 2007 bill passed by the 85th Minnesota Legislative Session as S.F. No. 2096, the omnibus environment, natural resources, energy and commerce appropriations, signed by Governor Pawlenty on May 8, 2007, provided for carbon sequestration studies, including funding to the Minnesota Geological Survey (MGS) for the purposes of geologic carbon sequestration assessment. A draft report therefore was prepared by staff of Minnesota Geological Survey and University of Minnesota Department of Geology and Geophysics, and a technical review meeting attended by local, state, and national authorities was held January 17, 2008. Appreciation is expressed to all participants in the technical review. On the basis of the contents of this report, along with broader considerations, the report authors present the following conclusions and recommendations.

Conclusions:

1. At the outset, it is stressed that currently available data indicate that there is a very low probability of success in confirming suitable geologic conditions for deep geologic sequestration of CO2 in Minnesota. At the same time, it is acknowledged that these same data are inadequate to rule out the most prospective rocks
2. Sedimentary rocks of adequate thickness are present in two north-south belts on either side of the Twin Cities, but limited data to date have indicated that their properties are not favorable for CO_2 storage
3. Minnesota may require, however, knowledge at a higher level of certainty than presently possible to indicate whether geologic carbon sequestration is a potential option for implementation within the State - for this, more geophysical surveys, drilling, and numerical modeling of CO2 storage will be required to permit a reasonably informed judgment.

Recommendations:

1. Concurrent with any further geologic analysis and assessment of other emission reduction options, effort presumably is required in CO_2 source characterization, analysis of pipeline systems, drinking water protection, arrangements for the activity, and community consultations, along with further analysis of the mineral carbonation option
2. Should it be established that a more a conclusive determination of in-state sequestration potential is needed, taking into consideration costs, a 3-year program including deep (~2 km) drilling will be required
3. A one-year pre-drilling phase costing about one million dollars would include geophysical surveys, further analysis of cores and water chemistry, including analysis of regional diagenesis, and numerical modeling of CO2 storage
4. Drilling in the second year should be conducted at the minimum expense required to satisfactorily answer the questions at hand, possibly as much as ten million dollars. Inexpensive coring methods should be explored, while it is recognized that oilfield methods, including comprehensive downhole logging, may well be needed. A third year would then be required for analysis of field data, including integration of the data by further numerical CO2 storage modeling, leading to reporting.

The key conclusion of the report is, therefore, that, unlike better known rocks in oil or coal producing regions, we have little information on the Rift. A major effort costing tens to hundreds of millions of dollars would therefore be required to test the Rift sedimentary rocks in Minnesota for required reservoir capacity and properties, and the probability that these requirements would not be confirmed, despite this effort, is high.

INTRODUCTION

L. Harvey Thorleifson, Minnesota Geological Survey, University of Minnesota

Minnesota, with a population of about five million, is a significant source of greenhouse gas emissions (e.g. Strait et al., 2007), and a state that is vulnerable to climate change, such as the impact that increased frequency or severity of drought would have on agriculture, water supply, wildlife, and lake levels. Minnesota therefore has an interest in reducing our own vulnerability, while concurrently contributing to needed world-wide solutions. As has been stressed, for example, in documents prepared for and by the Minnesota Climate Change Advisory Group, emissions reductions can have multiple benefits, including conservation, cost efficiency, and air quality enhancement, while also directly contributing to mitigation of climate change. Anthropogenic climate change seems already to have begun (Solomon et al., 2007), however, so adaptation to climate change accompanies mitigation in the climate change policy agenda. Mitigation of greenhouse gas emissions can be achieved through reduced fossil fuel combustion, while concurrently capturing and storing carbon in biomass, or in geologic repositories (e.g. Metz et al, 2007). It has become apparent that the best approach in the current circumstances is for all options to concurrently be assessed (e.g. Pacala and Socolow, 2004).

CLIMATE CHANGE

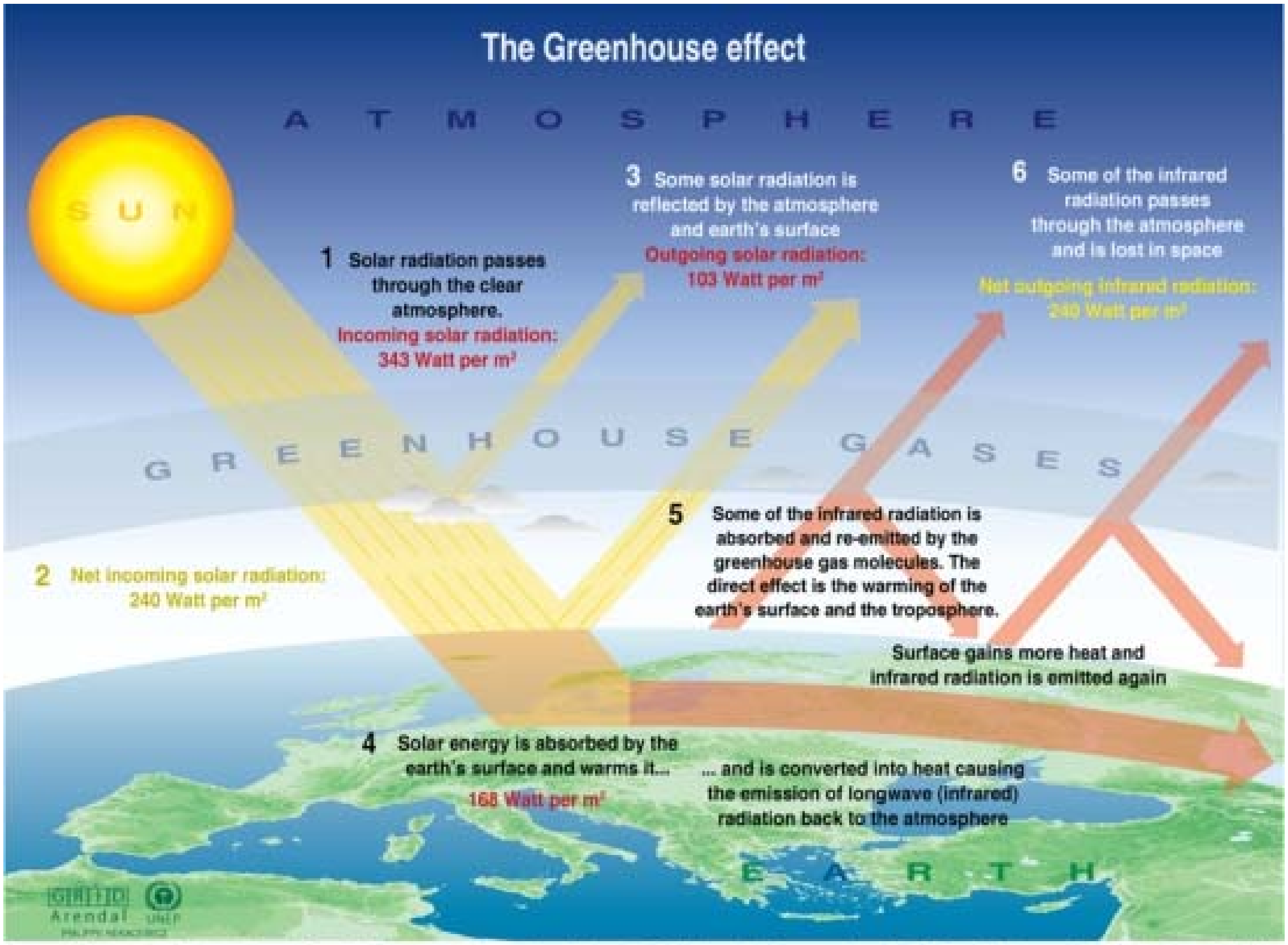
L. Harvey Thorleifson, Minnesota Geological Survey, University of Minnesota

Introduction

Human activity is changing the composition of the atmosphere, leading to current activity in monitoring and modelling of climate change (Figure 1). The US National Academies (National Academies, 2006), for example, summarized evidence for global warming, and the science required to better prepare for climate variability and change. Current discussions on climate change strategies such as carbon capture and storage are taking place within this national dialogue, largely within the scope of the US Climate Change Science Program (CCSP) and the US Climate Change Technology Program (CCTP), while deliberations on the international scene that are guiding consideration of topics such as carbon sequestration are largely centered on the Intergovernmental Panel on Climate Change (IPCC). In Minnesota, policy deliberations that the present report is meant to support are at present largely being facilitated by the Minnesota Climate Change Advisory Group (MCCAG).

Intergovernmental Panel on Climate Change (IPCC)

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), to provide to decision-makers an objective source of information about climate change (IPCC, 2004). IPCC indicates that it does not conduct research nor does it monitor climate, but rather it seeks to assess and synthesize scientific, technical and socio-economic literature, in order to produce reports of high scientific and technical standards that are neutral with respect to policy. According to IPCC, the findings of the first IPCC Assessment Report in 1990 were a contributor to the United Nations Framework Convention on Climate Change (UNFCCC), presented at the Rio de Janeiro Summit in 1992, thus providing the current policy framework for climate change issues. The UNFCCC made commitments to stabilizing greenhouse gas emissions at a level that would prevent dangerous anthropogenic interference with the climate system, with such a level to be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner. The IPCC Second Assessment Report of 1995 was part of the lead-up to the Kyoto Protocol in 1997, and the Third Assessment Report followed in 2001.



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

Figure 1. The greenhouse effect (IPCC)

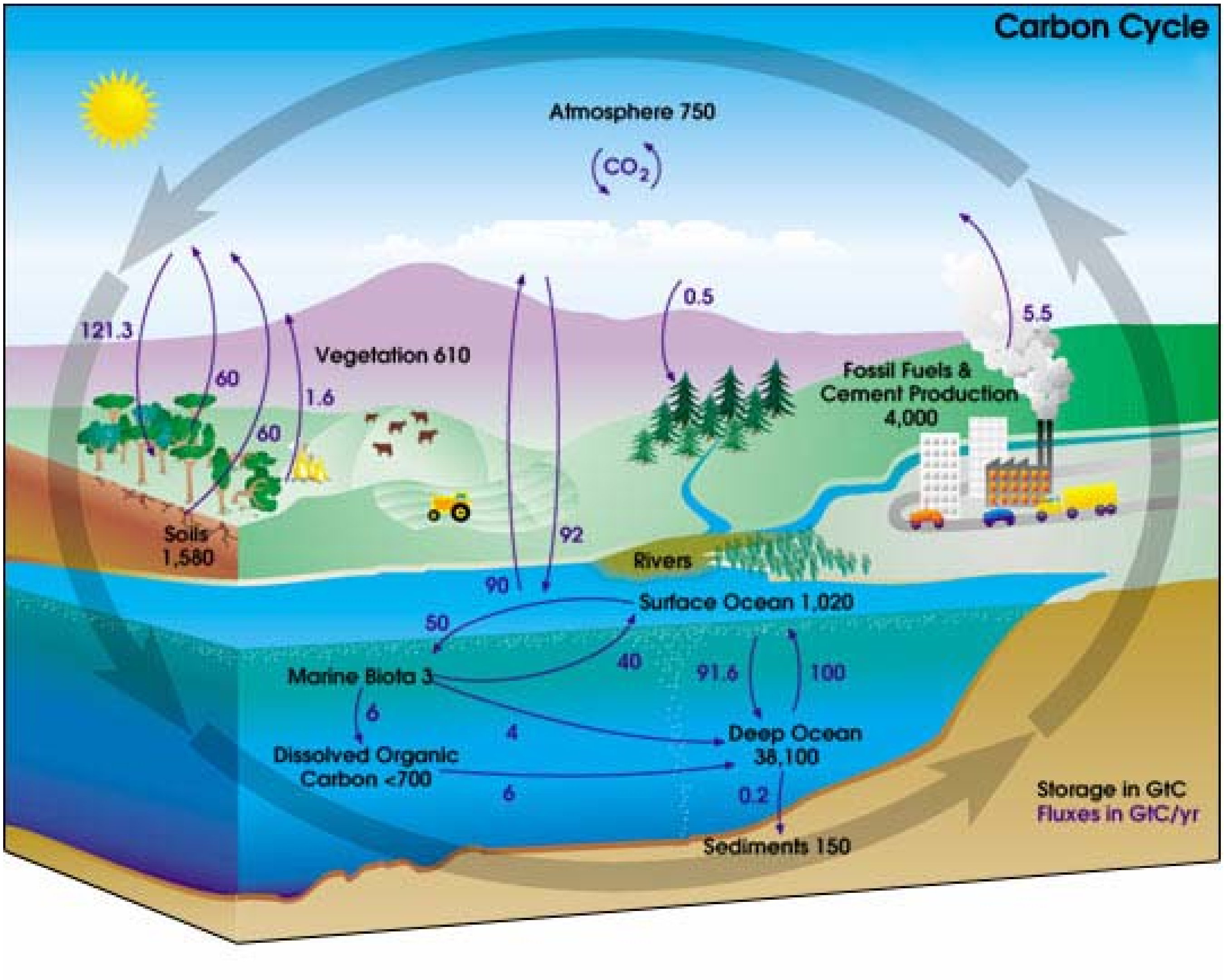


Figure 2. The global carbon cycle (IPCC)

IPCC Fourth Assessment

The IPCC Fourth Assessment, released 17 November 2007 (Solomon et al., 2007; Parry et al., 2007; Metz et al, 2007), again synthesized observed changes in climate and its effects, past climate change, effects of past climate change on natural systems and society, as well as natural and human-related causes of change, including carbon cycle (Figure 2) and other feedbacks. It also addressed scenarios for future climate change, including vulnerabilities and opportunities, as well as discussion on adaptation.

As part of this Fourth Assessment, IPCC Working Group I (Science; Solomon et al., 2007) assessed the current scientific knowledge of the natural and human drivers of climate change, observed changes in climate, the ability of science to attribute changes to different causes, and projections for future climate change regarding temperature, precipitation and sea level rise. Their summary indicated that greenhouse gas concentrations have markedly increased since 1750, that temperatures are increasing, that sea levels are rising, and that ice is melting. The report indicated that warming of the climate system is now unequivocal, that human activities have very likely caused most of the warming over the past 50 years, and that improved computer modeling has increased confidence in future climate projections. The report also concluded that temperatures will continue to increase, sea levels will continue to rise, and ice will continue to melt.

IPCC Fourth Assessment Working Group II (Impacts and Adaptation; Parry et al., 2007) assessed current scientific understanding of impacts of climate change on natural and human systems, their capacity to adapt, and their vulnerability. Their summary indicated that evidence from many parts of the world show that people, plants and animals are being affected by regional climate changes, particularly temperature increases, that warming caused by human activities has likely had a discernible influence on plants and animals, and that more detailed information is now available about how climate change will impact water resources, ecosystems, agriculture and forestry, health, coastlines, and regions of the world. The report indicated that these impacts will likely be both positive and negative across regions, although it is very likely that all regions will experience declines in benefits or increases in costs if global average temperatures warm more than two to three degrees Celsius, and that a mix of adaptation, preparing for and responding to climate change impacts, and mitigation action, reducing greenhouse gas emissions, can reduce the risks of climate change.

IPCC Fourth Assessment Working Group III (Mitigation; Metz et al, 2007) assessed greenhouse gas mitigation options in each sector of the global economy, addressing the economic and environmental costs and benefits of mitigation, the technical aspects of mitigation options, and potential cross-sectoral synergies and trade-offs. It also assessed the compatibility of near-term greenhouse gas mitigation activities with long-term climate stabilization pathways. Their summary indicated that global greenhouse gas emissions have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. With current climate change mitigation policies and related sustainable development practices, according to the report, global greenhouse gas emissions will continue to grow over the next few decades. The report found, however, that there is substantial economic potential for the mitigation of global greenhouse gas emissions across all sectors over the coming decades, where economic potential assumes that additional policies have been put into place to remove barriers and include social costs and benefits. In order to stabilize the concentration of greenhouse gases in the atmosphere, the report indicates that emissions would need to peak and decline thereafter. The lower the required stabilization level, the more quickly the peak and decline would need to occur. The report assumes that stabilization levels would be achieved by deployment of a portfolio of technologies that are currently available, and those that are assumed to be commercialized in coming decades. Macroeconomic costs for multi-gas mitigation, consistent with emissions trajectories towards stabilization between 445 and 710 ppm CO_2, were estimated on a global basis at between a 3% decrease in global gross domestic product (GDP) and a small increase in 2030 compared to the baseline, and between a 5.5% decrease and a 1% gain in 2050, assuming perfect implementation.

US Climate Change Programs

The US Climate Change Science Program (CCSP), according to its web site, integrates federal research on climate and global change, as sponsored by thirteen federal agencies and overseen by the Office of Science and Technology Policy, the Council on Environmental Quality, the National Economic Council and the Office of Management and Budget. This program and the preceding US Global Change Research Program (USGCRP) have funded research, presently at a level of $1.7 billion per year, in collaboration with other national and international science programs. The program has made a transition from a period of discovery and characterization beginning in 1990, to the current period of differentiation and strategy investigation under the President's Climate Change Research Initiative (CCRI), introduced in 2001. The concurrent Climate Change Technology Program (CCTP) includes the major role that the Department of Energy (DOE) is playing in carbon sequestration research, a topic allocated $78.2 million by DOE in fiscal year 2007, the largest allocation in their $306.8 million request among the National Climate Change Technology Initiative Priorities.

Minnesota Climate Change Advisory Group (MCCAG)

According to the Minnesota Climate Change Advisory Group (MCCAG) web site, members of the MCCAG were appointed by the Governor from the energy, manufacturing, agricultural, forestry, tourism, recreation, health care, non-governmental organization, academic, state government, and local government sectors in early 2007, to prepare recommended policy options for presentation to the Governor and the Legislature in February, 2008. This activity will facilitate fulfillment of the 2007 Next Generation Energy Act, signed into law by the Governor in May 2007, which includes a requirement for a comprehensive plan to reduce Minnesota’s emissions of greenhouse gases, by 15 percent before 2015, 30 percent by 2025, and 80 percent by 2050. The work of the MCCAG is being supported by the Center for Climate Strategies (referred to as CCS in committee documents), whose web site indicates that it is a Pennsylvania-based nonprofit service organization formed in 2004 that presently is working with sixteen US states to identify, design, and implement policies that address climate mitigation, clean energy, and economic development opportunities. The Center for Climate Strategies indicates that its objective is to enable state leaders to develop statewide climate action plans with comprehensive policy solutions, broad bipartisan stakeholder support, and successful implementation, through a process now replicated in several states, supported by specialized technical and policy assessments and planning related to climate, energy and economic issues. The MCCAG web site indicates that while federal activities have focused on climate research, development of new technologies, and voluntary programs to reduce emissions, more than twenty states have prepared state climate action plans to pursue multiple objectives, including improved air quality, reduced traffic congestion, more secure and reliable energy supplies, preservation of land, or improved waste management, in addition to reducing greenhouse gas emissions. MCCAG has drawn attention to states that are also addressing climate change on a regional basis, including the Western Governors Regional Greenhouse Gas Reduction Agreement, the West Coast Governors' Climate Change Initiative, and the Regional Greenhouse Gas Initiative in the northeast. This activity provided the context for more recent developments, such as the Midwest Regional Greenhouse Gas Reduction Accord, signed by Governor Pawlenty and other Midwest governors November 15, 2007. Five Technical Work Groups (TWGs) are supporting the efforts of the MCCAG, including an Energy Supply TWG. To guide the work of the MCCAG, the Center for Climate Strategies prepared a draft report on Minnesota’s current and possible future greenhouse gas emissions (Strait et al., 2007), thus supporting identification and analysis of policy options for mitigating greenhouse gas emissions. Minnesota’s anthropogenic greenhouse gas emissions were estimated for the period from 1990 to 2020. Activities in Minnesota were reported to account for approximately 151 million metric tons (MMt) of gross carbon dioxide equivalent (CO_2e) emissions in 2005, an amount equal to about 2.1% of total US gross greenhouse gas emissions, up from 115.7 MMt in 1990, an increase of 31% during a time when national emissions rose by 16%. This value was projected to reach 183.8 MMt in the year 2020. The largest source of Minnesota’s greenhouse gas emissions was reported to be electrical generation, accounting for 33% of Minnesota’s gross greenhouse gas emissions in 2005.

MITIGATION

L. Harvey Thorleifson, Minnesota Geological Survey, University of Minnesota

Climate change policy options include mitigation, which refers to reduction in greenhouse gas emissions, and adaptation, which refers to the enhancement of preparedness for climate change and variability. Pacala and Socolow (2004) advocated an idealized strategy for mitigation, with a goal of avoiding atmospheric CO_2 levels above 500 ppm, which would be less than a doubling of the pre-industrial level of 280 ppm. Their model specified maintenance of 2004 emissions levels for a half-century, followed thereafter by the reduction required for stabilization at 500 ppm. To achieve reductions from projected emissions levels, conceptual stabilization wedges were defined, consisting of a portfolio of available technologies whose role in averting emissions would each begin at a negligible level, and would then each take on a progressively larger role, thus together achieving what was referred to as a stabilization triangle of avoided carbon emissions required for stabilization (Figure 3). Technological options for reducing net CO_2 emissions to the atmosphere (Metz et al, 2005) include reducing energy consumption by increasing efficiency or shifting to less energy-intensive economic activities, switching to less carbon intensive fuels such as natural gas instead of coal, increasing the use of renewable energy sources or nuclear energy, or by sequestering CO_2 either by enhancing biological absorption capacity in forests and soils, or by carbon capture and storage (CCS) by physical or chemical means (Metz et al, 2005; Dooley et al., 2006; Friedmann, 2007; MIT, 2007). As was stressed in the IPCC Third Assessment and reiterated by Pacala and Socolow (2004), no single technology option will provide all of the emission reductions needed to achieve stabilization, so a portfolio of mitigation measures will be needed. Analyses to prioritize options are underway, however, and Electric Power Research Institute (EPRI, 2007), for example, cited CCS, seen in their report to be widely deployed after the year 2020, as having the largest potential among several options for emissions reduction in coming decades.

Terrestrial sequestration

According to the University of Minnesota Terrestrial Carbon Sequestration Program web site, terrestrial carbon sequestration is the capture and storage of atmospheric CO_2 in plants and soils. The site indicates that numerous land management practices that are well-known for conserving soils, water quality, and wildlife habitat, such as conservation tillage, use of perennial and cover crops, reforestation and afforestation, as well as wetland and grassland management, also sequester carbon. The program is based on the concept that determining optimal strategies for increasing carbon sequestration in Minnesota's landscape would promote increased sustainability of diverse ecosystems and, by adding a potentially valuable commercial product, sequestered carbon credits, could promote new economic opportunities in the state.

Geologic sequestration (carbon capture and storage; carbon capture and sequestration; CCS)

The CO_2 atmospheric emissions avoidance method know as carbon capture and storage (CCS) or geologic CO_2 sequestration consists of capturing CO_2 by separation from industrial and energy-related sources, for example by separating it from the flue gas stream of a fuel combustion system, compressing it to a high pressure, transporting it to a storage location, and storing it to achieve long-term isolation from the atmosphere, according to the IPCC report on Carbon Dioxide Capture and Storage (Metz at al., 2005), which assessed the method as an option in the portfolio of mitigation actions that will be required for stabilization of atmospheric greenhouse gas concentrations. The report encompassed scenarios for capture of CO_2 from large stationary sources, using capture systems ranging from post-combustion, pre-combustion, to oxyfuel combustion, with the concentration of CO_2 in the gas stream, the pressure of the gas stream, and the fuel type, whether solid or gas, being important factors in selecting the capture system. Compression would follow, while pipelines are preferred for transporting large amounts of CO_2 for distances up to around 1,000 km. Storage options discussed in the report are geological formations, the ocean, mineral carbonates, or use in industrial processes (Figure 4). In some regions,

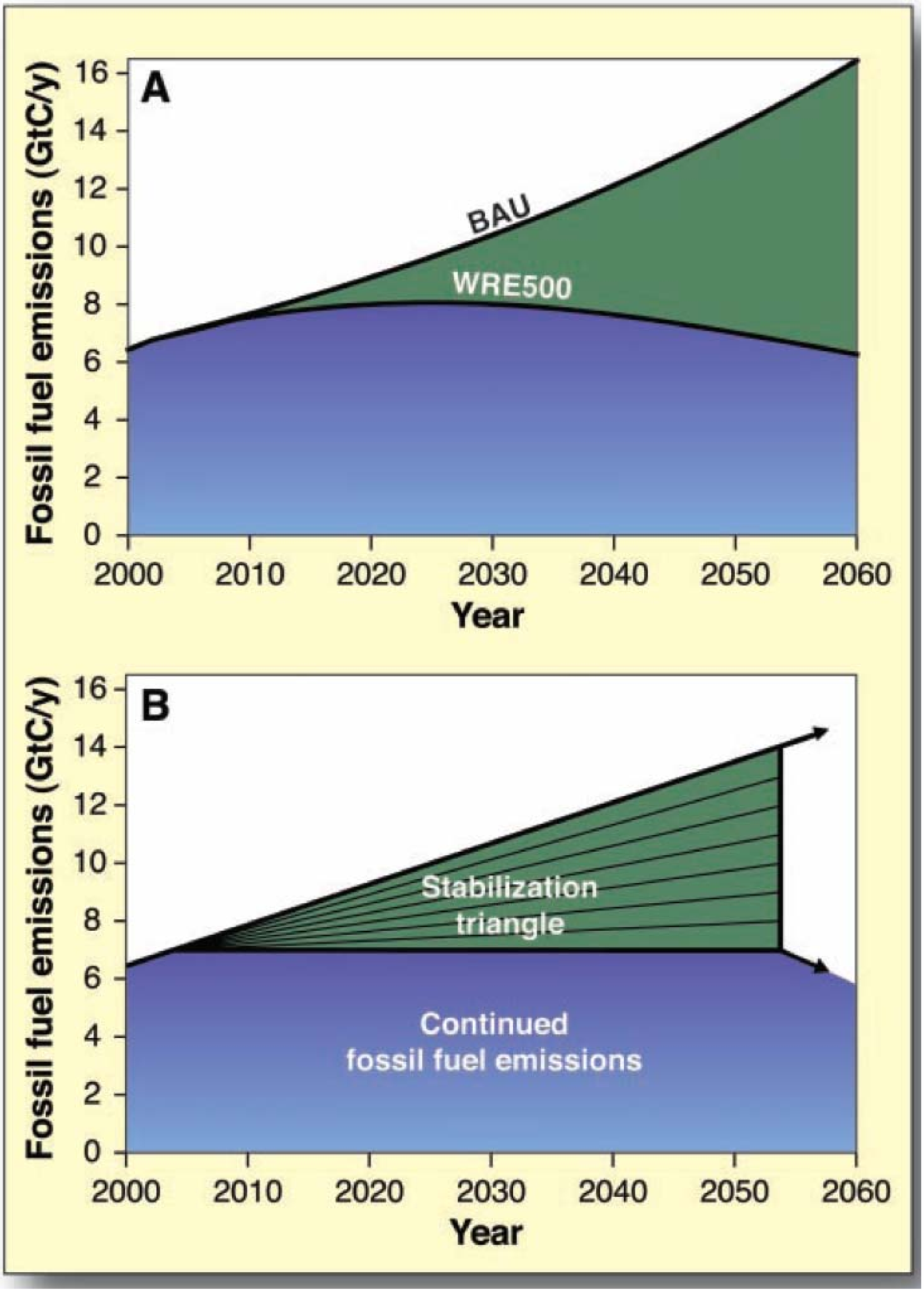


Figure 3. The model of Pacala and Socolow (2004), depicting business-as-usual (BAU) emissions projections and the emissions reduction scenario meant to achieve an atmospheric CO_2 concentration of 500 ppm by 2125 developed by Wigley, Richels, and Edmonds (1996; WRE500; A), and a schematic model for actions to achieve the WRE500 goal, through the use of several methods, each of growing prominence, forming wedges that together make up a stabilization triangle, thus realizing emission reduction objectives

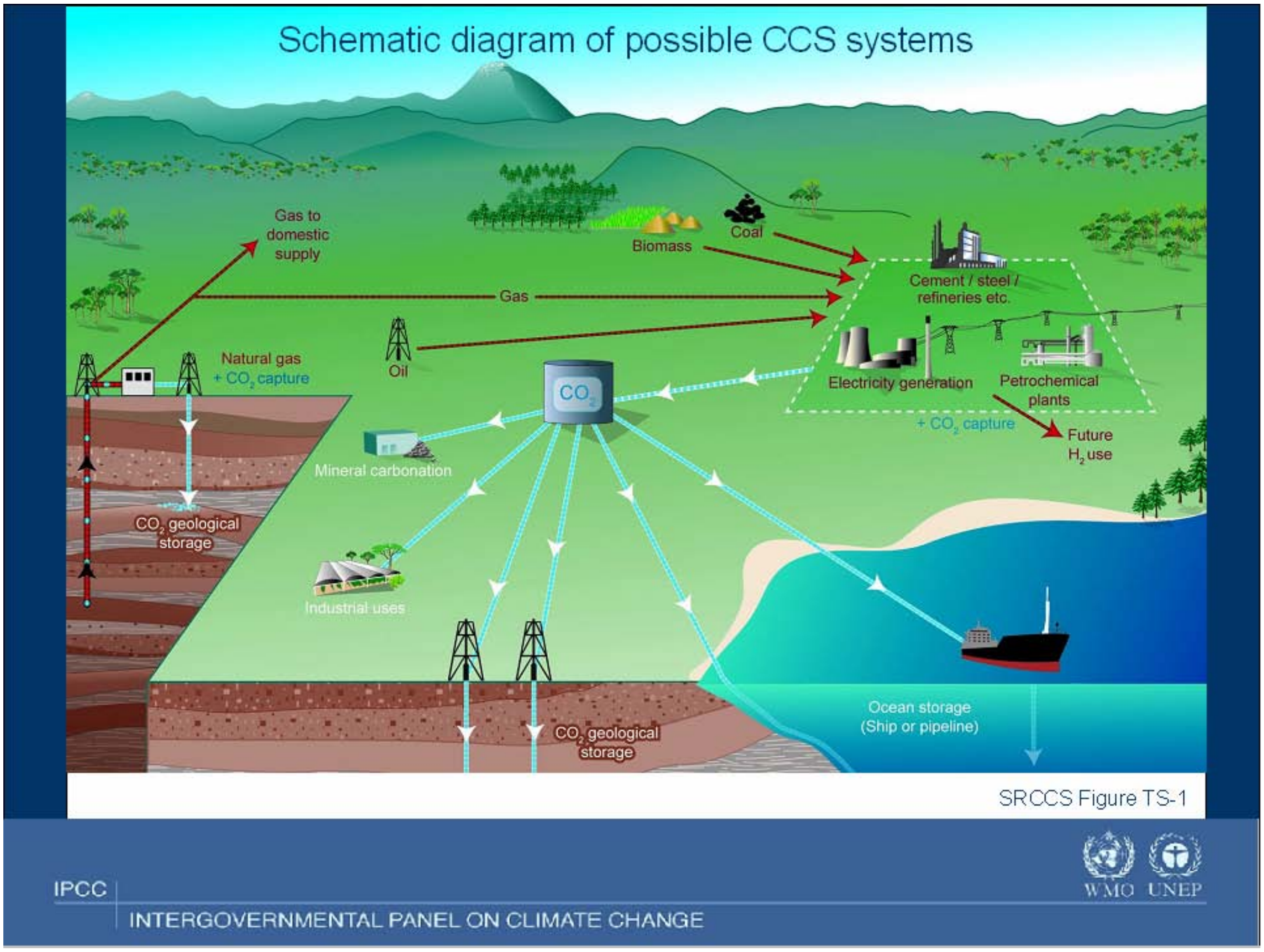


Figure 4. CCS systems, showing the carbon sources for which CCS might be relevant, and options for the transport and storage of CO_2 (Metz et al., 2005)Figure 3. The model of Pacala and Socolow (2004), depicting business-as-usual (BAU) emissions projections and the emissions reduction scenario meant to achieve an atmospheric CO_2 concentration of 500 ppm by 2125 developed by Wigley, Richels, and Edmonds (1996; WRE500; A), and a schematic model for actions to achieve the WRE500 goal, through the use of several methods, each of growing prominence, forming wedges that together make up a stabilization triangle, thus realizing emission reduction objectives

injection of CO_2 into oil and gas fields to enhance production of hydrocarbons helps to offset the cost. The net reduction of emissions to the atmosphere through CCS depends on the fraction of CO_2 captured, the increased CO_2 production resulting from loss in efficiency of power plants or industrial processes due to the additional energy required for capture, transport and storage, any leakage from transport, and the fraction of CO_2 retained in storage over the long term. Other important factors discussed in the report are the social and environmental consequences of implementation, safety of the technology, security of storage, as well as ease of monitoring and verification. It was stressed that complete CCS systems can be assembled from existing technologies that are mature or economically feasible under specific conditions, although it was added that the state of development of the overall system may be less than some of its components.

Options for by deep injection of CO_2 include depleted oil and gas formations, deep unmineable coal seams, and deep saline formations (Figure 5), and it appears that only saline formations have the required capacity for the long term (Schrag, 2007). In this method, the CO_2 occupies pore spaces in the rock like water in a sponge, in reservoirs consisting of porous rocks typically consisting of sandstone, limestone, or dolomites, overlain by impermeable rock such as shale that acts as a caprock or seal, with the CO_2 also being retained through dissolution or adsorption. Once a suitable geologic formation has been identified through an acceptable site characterization (Bachu, 2000; 2003; Bachu and Adams, 2003; Bachu and Shaw, 2003; Friedmann, 2007), CO_2 is ideally injected into that formation at a high pressure and to depths generally greater than 2625 feet (800 meters), where the pressurized CO_2 behaves as a liquid-like supercritical fluid, resulting in efficient utilization of underground storage space in the pores of the sedimentary rocks. Once injected, the liquid CO_2 tends to be buoyant and will flow upward, displacing water and other liquids and gases, until it encounters non-porous rock, which along with other trapping mechanisms then holds the CO_2 and prevents further upward migration.

This method takes advantage of a naturally occurring phenomenon, the trapping of gases in rocks, many of which have been holding gases such as CO_2 for millions of years. In addition, this is an established technology, as CO_2 has since the 1970s been injected into oil and gas fields to enhance recovery of oil and gas, mostly at over 50 projects in west Texas, presently at a rate of 30 $MMtCO_2$ per year of non-anthropogenic CO_2 injected annually (Metz et al., 2005). The well-drilling technology, injection technology, computer simulation of storage reservoir dynamics, and monitoring methods therefore can be adapted from existing applications. Also according to Metz et al. (2005), widespread existing industrial analogues, including seasonal underground natural gas storage projects around the world, acid gas injection projects, as well as deep injection of liquid wastes, such as subsurface disposal of oil-field brines, provide additional indications that CO_2 can be safely injected and stored at well-characterized and properly managed sites.

The principal carbon storage demonstration projects at present are the Weyburn project in Canada, where enhanced oil recovery (EOR) with provision for permanent storage is being supported by CO_2 derived from a coal gasification plant in North Dakota, the Sleipner West field in the North Sea off the coast of Norway, where CO_2 is compressed and injected via a single well into a 500 foot thick saline formation 2,000 feet below the seabed, and the In Salah gas field in Algeria, were one million tons of produced CO_2 is being injected annually at 5900 feet depth. In the short term, according to Metz et al. (2005), further CO_2 storage in depleted oil and gas reservoirs is very promising in some areas, because these structures are well known and significant infrastructure is already in place, although relatively few hydrocarbon reservoirs are currently depleted or near depletion, and CO_2 storage will have to be staged to fit the timing of reservoir availability. The overall global capacity to store CO_2 deep underground is large, however, with deep saline formations having by far the largest capacity for CO_2 storage, while being much more widespread than other options (Metz et al., 2005).

The IPCC report (Metz et al., 2005)went on to indicate that application of CCS to electricity production, under 2002 conditions, would increase electricity generation costs by about 0.01–0.05 US dollars per kilowatt hour (US$/kWh), depending on the fuel, the specific technology, the location, and the national circumstances. Inclusion of the benefits of EOR would reduce additional electricity production costs due to CCS by around

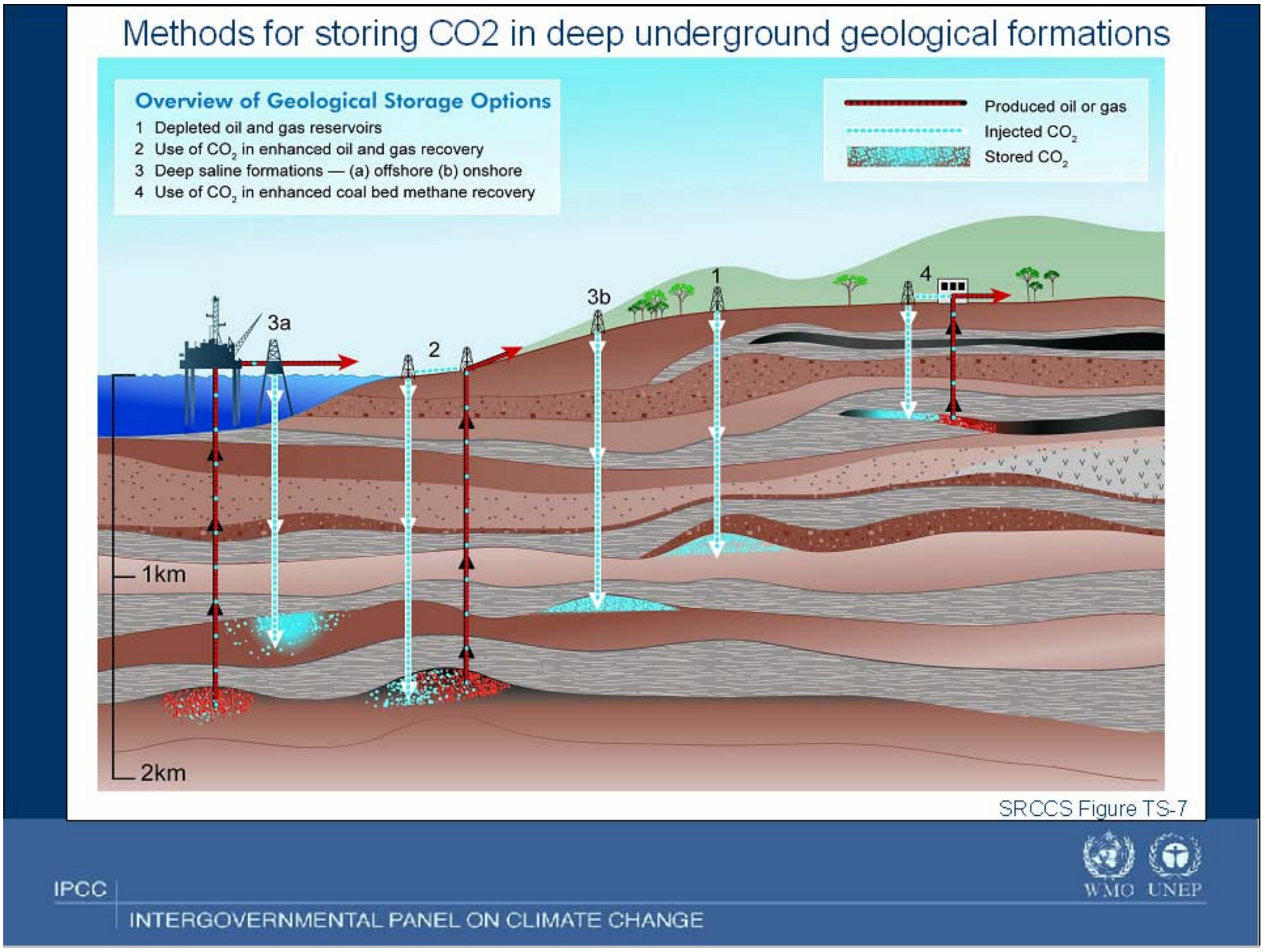


Figure 5. CCS systems, showing methods for storing CO_2 in deep underground geological formations (Metz et al., 2005)

0.01– 0.02 US$/kWh, while increases in market prices of fuels used for power generation would generally tend to increase the cost of CCS. In most CCS systems, the cost of capture, including compression, is the largest cost component. According to the report, Energy and economic models indicate that the CCS system's major contribution to climate change mitigation would come from deployment in the electricity sector. Most modelling as assessed in the report suggests that CCS systems begin to deploy at a significant level when CO_2 prices begin to reach approximately 25–30 US$/t$CO_2$. Available evidence suggested that, worldwide, it is likely that there is a technical potential of at least about 2,000 GtCO_2 (545 GtC) of storage capacity in geological formations. In most scenarios for stabilization of atmospheric greenhouse gas concentrations between 450 and 750 ppmv (parts per million by volume) CO_2, and in a least-cost portfolio of mitigation options, the economic potential of CCS would amount to 220– 2,200 GtCO_2 (60–600 GtC) cumulatively, which would mean that CCS would contribute 15–55% to the cumulative mitigation effort worldwide until 2100, averaged over a range of baseline scenarios. In most scenario studies, the report went on to state, the role of CCS in mitigation portfolios increases over the course of the century, and the inclusion of CCS in a mitigation portfolio was found to reduce the costs of stabilizing CO_2 concentrations by 30% or more.

Potential storage sites are likely to be distributed in many of the world's sedimentary basins, according to the report, located in the same regions as many of the world's emission sources and thus centers of population. With respect to the health, safety and environmental risks of CCS, the IPCC CCS report therefore indicated that the local risks associated with CO_2 pipeline transport would be similar to or lower than those posed by hydrocarbon pipelines already in operation. With appropriate site selection based on available subsurface information, a monitoring programme to detect problems, a regulatory system and appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological storage would be comparable to the risks of current activities such as natural gas storage, EOR and disposal of acid gas.

In terms of the risks of leakage, Metz et al. (2005) cited observations from engineered and natural analogues as well as models that suggest that the fraction of injected CO_2 retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years, and is likely to exceed 99% over 1,000 years. Monitoring systems would detect movement of CO_2 into shallower formations, and allow time to take corrective action to reduce potential impacts to human health and the environment. Potential risks to humans and ecosystems from geological storage could occur at leaking injection wells, abandoned wells, or leakage along faults or ineffective confining layers. Leakage of CO_2 could potentially degrade the quality of groundwater, damage some hydrocarbon or mineral resources, and have lethal effects on plants and sub-soil animals, while release of CO_2 back into the atmosphere could also create local health and safety concerns. Groundwater could be affected both by CO_2 leaking directly into an aquifer or by saline ground water entering an aquifer as a result of being displaced by injected CO_2. Avoiding or mitigating these impacts, according to the report, therefore will require careful site selection, effective regulatory oversight, an appropriate monitoring programme that provides early warning that the storage site is not functioning as anticipated, and implementation of remediation methods to stop or control CO_2 releases, thus making up a required program of monitoring, mitigation, and verification (MM&V).

In the field of legal and regulatory issues, some regulations for operations in the subsurface do exist that may be relevant or, in some cases, directly applicable to geological storage, but few jurisdictions have specifically developed legal or regulatory frameworks for long-term CO_2 storage (Metz et al., 2005; Keith et al., 2005; OECD/IEA, 2005; Wilson and de Figueiredo, 2006; Wilson et al., 2007; Bachu, 2007).

Friedmann et al. (2006) cited CCS capture costs of $25–60/t CO_2 and costs for transport and storage estimated at $0–15/t CO_2, with only about $0.1/t CO_2 going to geological characterization, to argue that public or private–public geologic assessments designed to clarify capacity and design considerations, while providing other tangible societal benefits such as fossil fuel and ground water assessments, should underpin early policy choices regarding CO_2 storage deployment, and should serve as a point of entry for policy makers and regulators.

In the US, the Department of Energy (DOE) is the lead federal agency on research and development of geologic sequestration technologies. The Department of Energy's Fossil Energy program is developing a portfolio of technologies meant to capture and permanently store greenhouse gases. As part of this portfolio, DOE and an industry alliance recently launched FutureGen, an initiative to complete the world's first near-zero emissions, coal-based power plant with sequestration by 2012. DOE is also sponsoring small-scale CO_2 pilot projects designed to learn more about how CO_2 behaves in the subsurface and answer practical technical questions on how to design and operate geologic sequestration projects. On the international scene, the Carbon Sequestration Leadership Forum (CSLF) is supporting development of cost-effective CCS technologies, making these technologies broadly available, and identifying wider issues relating to CCS.

To provide a useful visualization of the scale of CCS required to stabilize atmospheric CO_2 levels at a level less than double the pre-industrial level, Pacala and Socolow (2004) indicated that today, about 0.01 GtC/year of carbon as CO_2 is injected into geologic reservoirs to spur enhanced oil recovery, so a wedge of geologic storage in their model would require that CO_2 injection be scaled up by a factor of 100 over the next 50 years. Using seasonal storage of natural gas as a reference, roughly 4000 billion standard cubic feet (Bscf) are placed into and out of geologic storage, and a carbon flow of 1 GtC/year as methane or CO_2 is a flow of 69,000 Bscf/year (190 Bscf per day), so a wedge would be a flow to storage 15 and 20 times as large as the current flow. Norway's Sleipner project in the North Sea strips CO_2 from natural gas offshore and reinjects 0.3 million tons of carbon a year (MtC/year) into a non–fossil-fuel–bearing formation, so a stabilization wedge would be 3500 Sleipner-sized projects, or fewer, larger projects, over the next 50 years, according to Pacala and Socolow (2004).

As an example of recent literature on CCS feasibility, Gibbins et al. (2006) indicated that there could be significant implementation of CCS in UK fossil fuel power stations within one or two decades, perhaps ~45% by 2020 if incentives are put in place, and it was suggested that similar progress could be made anywhere that new fossil fuel power plants are being built within ~500 km of sedimentary basins.

The IPCC Fourth Assessment report on mitigation (Metz et al, 2007) has a chapter on energy supply by Sims et al. (2007) that includes an updated overview of the status of CCS. CCS is presented as one of the key sectoral mitigation technologies for the energy supply sector, which as a whole, according to the report, included improved supply and distribution efficiency, fuel switching from coal to gas, nuclear power, renewable heat and power such as hydropower, solar, wind, geothermal and bioenergy, combined heat and power, early applications of CCS such as storage of CO_2 removed from natural gas, CCS for gas, biomass and coal-fired electricity generating facilities, advanced nuclear power, as well as advanced renewable energy, including tidal and wave energy, concentrating solar, and solar photovoltaics. The report again stressed that no single technology can provide all of the mitigation potential in any sector.

In their review of the status of CCS, Sims et al. (2007) stressed that the principal uncertainties relate to proving the technologies, anticipating environmental impacts, and determining how governments should establish incentives by means such as regulation or carbon charges, thus setting a price on carbon emissions. They indicated that capture of CO_2 can best be applied to large carbon stationary point sources, including electric power-generation or cogeneration facilities burning coal, gas or biomass, major energy-using industries, synthetic fuel plants, natural gas fields, and chemical facilities for producing hydrogen, ammonia, cement or coke. They added that application of CCS for biomass-burning sources could result in net removal of CO_2 from the atmosphere. They noted that injection of CO_2 in suitable geological reservoirs is the most mature of the storage methods, with a number of commercial projects in operation, while ocean storage is still in the research phase and will not retain CO_2 permanently as the CO_2 will re-equilibrate with the atmosphere over the course of several centuries. It was noted that mineral carbonation requires a large amount of energy, and costs are high, so significant technological breakthroughs will be needed before deployment can be considered. They noted that estimates of the role CCS will play over the course of the century to reduce greenhouse gas (GHG) emissions vary, being seen by some as a transitional technology, with deployment from 2015 onwards, peaking after 2050 as existing heat and power plant stock is turned over, and declining thereafter as alternative energy sources are used. They acknowledged that other studies show more rapid deployment starting around the same time, with continuous expansion to the end of the century, while some studies suggest no significant use of CCS until 2050, while emissions reductions are achieved instead by energy efficiency and renewable energy. They noted that new power plants built today could be designed and located to be CCS-ready if rapid deployment is desired, and that all types of power plants can be made CCS-ready, although the costs and technical measures vary between different types of power plants. It was added that if CO_2 is injected into suitable saline formations or into oil and gas fields at depths below 800 m, various physical and geochemical trapping mechanisms can prevent the CO_2 from migrating to the surface. The report called for a common methodology for storage capacity estimates on the country- and region-level, given that estimates of the capacity of saline formations vary by an order of magnitude. There also was discussion of unconventional biological approaches to CCS or fuel production, such as biological removal of CO_2 from an exhaust stream by passing the stack emissions through an algae or bacteria-bearing solution in sunlight, or removal of CO_2 from air. They noted concerns surrounding geological storage, including the risk of seismic activity causing a rapid release of CO_2, and the impact of old and poorly sealed well bores on the storage integrity of depleted oil and gas fields, and they noted risks in CO_2 transportation, including rupture or leaking of pipelines, possibly leading to the accumulation of a dangerous level of CO_2 in the air. The Fourth Assessment review of the status of CCS concluded with discussion of costs for capture (5 to 115 US$/t$CO_2$), transport (1 to 8 US$/tCO_2), geological storage (0.5 to 8 US$/t$CO_2$), as well as monitoring and verification (0.1 to 0.3 US$/t$CO_2$), while an estimated cost for mineral carbonation was given as 50 to 100 US$/t$CO_2$. In addition, a recent DOE workshop report (Woodward, 2007), has outlined fundamental research priorities, many directed at the needs of CCS implementation.

By December 2007, the Minnesota Climate Change Advisory Group (MCCAG) facilitators had reported in their submissions to the committee, posted on the MCCAG web site, that over 300 possible state actions for mitigation of greenhouse gas emissions had been identified, including several options identified by Technical Working Groups (TWGs), from which 58 options had been selected for priority analysis. The Energy Supply TWG had indicated that for coal to play a significant role in Minnesota's future energy system, its overall environmental profile would need to improve, and come as close as possible to producing zero CO_2 emissions, while producing energy that is both affordable and reliable. In the field of energy supply, ten options were retained for analysis, including carbon capture and storage and/or reuse policies (referred to as CCS&R in committee documents), with a model for implementation starting in 2013. Late 2007 MCCAG deliberations reported in committee documents posted on the MCCAG web site included a CCS&R model that would reduce greenhouse gas emissions by 3.8 million metric tons per year of CO_2 equivalent (MMtCO_2e) by 2015, for a total from 2008 to 2025 of 49.5 MMtCO_2e, resulting in a net present value, 2008 – 2025, of $3,767 million, or a cost effectiveness of $76.1/t$Co_2$e, while early January 2008 values were revised to reduce these targets (Table 1). The preceding values for this reduction, however, were seen as facilitating achievement of about 5% of the Minnesota goal for reduction of emissions from projected levels by 2025. With respect to timing, the TWG indicated that by 2020, the Upper Midwest region should strive to have at least two coal-burning projects with carbon capture and storage through design, construction and into full operation. Additional Energy Supply TWG discussion acknowledged the need for legal and regulatory frameworks for geologic storage of CO_2, including new regulations addressing issues of ownership of and liability for CO_2 in storage, as well as permitting processes for underground storage, including guidance on pipelines, drilling, storage, measurement, monitoring and verification. Draft recommendations also cited the need to support comprehensive assessments of geologic reservoirs at state and federal levels to determine storage potential and feasibility, to evaluate the feasibility of CO_2 transport via pipeline, as well as assessment of advanced sequestration methods such as mineralization or carbon nanofibers, if Minnesota determines it has no in-state storage opportunities. The recommendations also encompass the need for tax incentives for carbon capture and storage, including when transported via pipeline for use in enhanced oil recovery operations.

Energy Supply
Technical Work Group

Summary List of Pending Priority Policy Options for Analysis

	Policy Option	GHG Reductions ($MMtCO_2e$)			Net Present Value 2008–2025 (Million $)	Cost-Effective-ness ($/$tCO_2e$)	Level of Support
		2015	2025	Total (2008–2025)			
ES-1	Generation Performance Standard	4	5	62	–$7,812	–$126	Pending
ES-3	Efficiency Improvements, Repowering and other Upgrades to Existing Plants	2	3	33	$554	$17	Pending
ES-4	Transmission System Upgrading, Including Reducing Transmission Line and Distribution System Loss	0	0	4	–$47	–$13	Pending
ES-5	Renewable and/or Environmental Portfolio Standard	8	16	133	–$1,675	–$13	Pending
ES-6	Nuclear Power Support and Incentives	0	8	48	$3,321	$70	Pending
ES-7	Advanced Fossil Fuel Technology Incentives, Support or Requirements	–2	–2	–22	$3,591	–$162	Pending
ES-8	Carbon Capture and Storage and/or Reuse Policies	1	1	18	$1,536	$84	Pending
ES-10	Voluntary GHG targets	*Not quantified*					Pending
ES-12	Distributed Renewable Energy Incentives and/or Barrier Removal	*Still being quantified*					Pending
ES-13	Technology-Based Approaches, Including Research and Development, Fuel Cells, Energy Storage, Distributed Renewable Energy Technologies, etc.	*Not quantified*					Pending
	Sector Total After Adjusting for Overlaps	**13.3**	**31.1**	**268**	**–$2,070**	**–$7.7**	
	Reductions From Recent Actions	**6.9**	**6.9**	**123**	**TBD**	**TBD**	
	Sector Total Plus Recent Actions	**23.2**	**37.0**	**381**	**TBD**	**TBD**	

Notes:

1. All option total are relative to the underlying assumption that electric expansion in MN proceeds with the recently legislated Conservation Improvement Program, Renewable Energy Standard and all planned additions including the Mesaba and Big Stone 2 stations.

2. During its September 27, 2007 meeting, the MCCAG agreed to move ES-2 (Improve the GHG Profile of Biofuels and Fossil Fuels [e.g., Low Carbon Fuel Standard, Biofuel Production]) to the TLU TWG which is now being addressed under TLU-3 (Low GHG Fuel Standard).

3. See Annex 3 for details of the calculation of sector total after adjusting for overlaps

Table 1. Minnesota Climate Change Advisory Group (MCCAG) Energy Supply Technical Work Group Summary List of Pending Priority Policy Options for Analysis, 10 January 2007

IMPLEMENTATION OF CARBON CAPTURE AND STORAGE IN THE US

L. Harvey Thorleifson, Minnesota Geological Survey, University of Minnesota

US Department of Energy (DOE) role

The US Department of Energy (DOE) has indicated on its web site that carbon sequestration is one of the most promising ways for reducing the buildup of greenhouse gases in the atmosphere, and that even under the most optimistic scenarios for energy efficiency gains and greater use of alternative fuels, sequestration will likely be essential if the world is to stabilize atmospheric concentrations of greenhouse gases at acceptable levels. The DOE Office of Fossil Energy, through research conducted at the National Energy Technology Laboratory (NETL), therefore is directing programs initiated in 1997 designed to demonstrate and deploy this method, largely through its Regional Partnerships program, and the FutureGen project, an initiative to build the world's first integrated sequestration and hydrogen production research power plant (DOE, 2007a; DOE, 2007b). The decision to site FutureGen in Illinois was announced in December 2007.

DOE has indicated (DOE, 2007a; DOE, 2007b) that if it is determined that carbon sequestration must be implemented in the US on a broad scale and in a relatively short timeframe of several years, it will take a concerted effort of federal and state agencies, working in cooperation with technology developers, regulators, and others, to put into place both the concepts and the necessary infrastructure to achieve meaningful carbon reductions. DOE therefore has established its Carbon Sequestration Regional Partnerships (Figure 6), to ensure that US agencies are prepared to implement this climate change mitigation option. This national network of public-private partnerships is determining the most suitable technologies, regulations, and infrastructure needed for carbon capture and storage in the varying settings across the nation.

These partnerships include a west coast group led by the California Energy Commission, a southwest group based at New Mexico Institute of Mining and Technology, the Big Sky Partnership headed by Montana State University, a group addressing the Illinois Basin based at Illinois State Geological Survey, a southeast partnership headed by Southern States Energy Board, and a Midwest group coordinated by the Battelle Memorial Institute in Columbus, Ohio. Minnesota is part of the Plains CO_2 Reduction Partnership (PCOR) region, led by the Energy and Environmental Research Center (EERC) at the University of North Dakota in Grand Forks.

The Regional Partnerships initiative is being implemented in three phases (Figure 7A), a characterization Phase from 2003 to 2005, in which opportunities for carbon sequestration were characterized, a validation phase from 2005 to 2009 in which small scale field tests are being implemented, and the deployment Phase from 2007 to 2017, in which large volume carbon storage tests will be conducted.

The characterization phase (DOE, 2007) began in 2003 with seven partnerships working to collect data on CO_2 sources as well as existing and potential carbon repositories known as sinks, to select methods appropriate to each region, to identify regulatory and infrastructure requirements, and to develop expertise to support and enable future carbon sequestration field tests and deployments. The Characterization Phase ended in 2005, with the networks having been established, with greater awareness and support for carbon sequestration as a greenhouse gas mitigation option within industry and the public, and with completion of a network of regional carbon sequestration atlases for the US referred to as NATCARB, which were used to identify the most promising sequestration opportunities.

The current validation phase of the regional partnerships is meant to confirm the most promising regional opportunities to deploy sequestration technologies, largely through 25 geologic and 11 terrestrial sequestration field tests. The phase builds on characterization phase accomplishments, while beginning field testing of

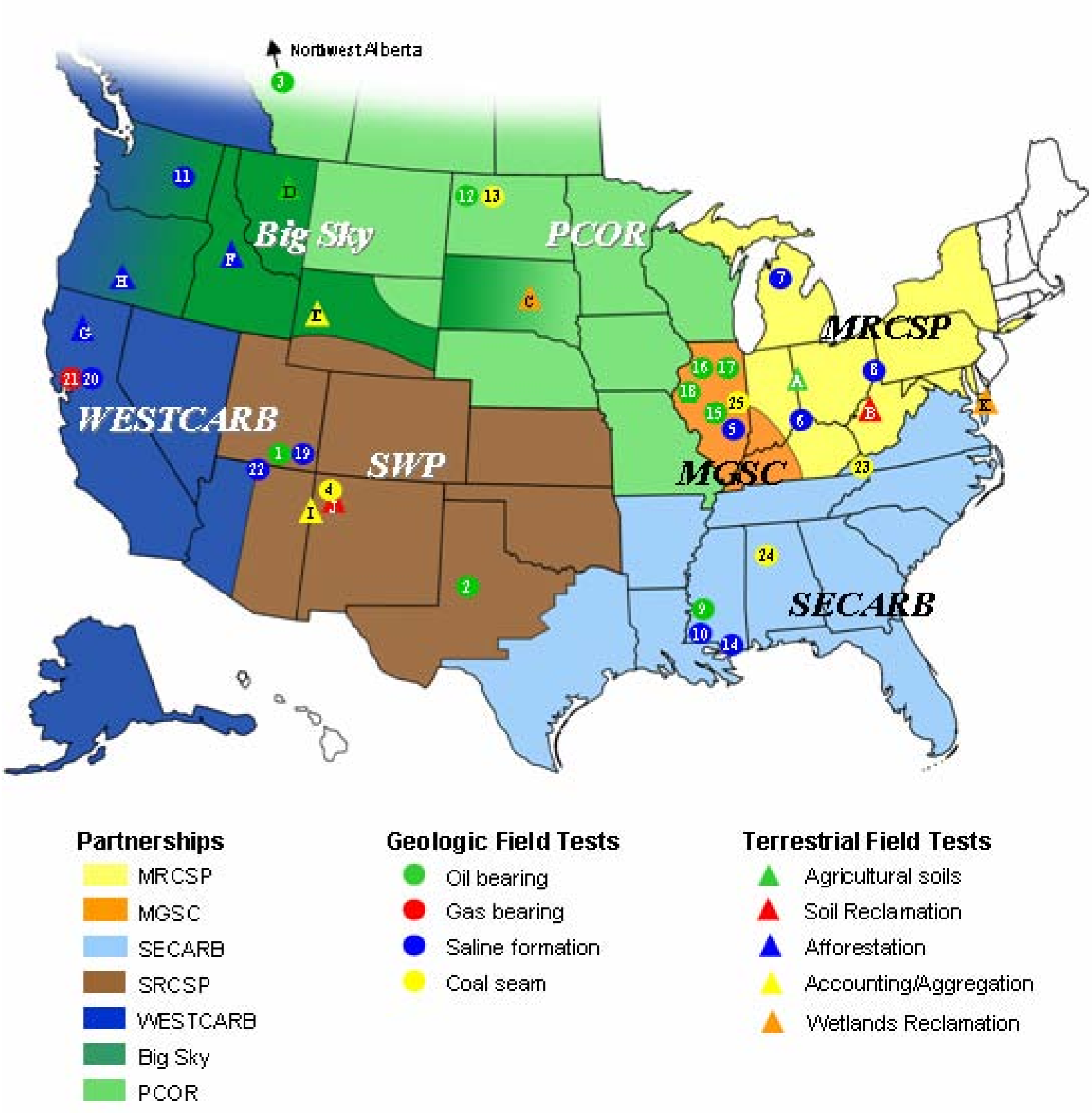


Figure 6. DOE Carbon Sequestration Regional Partnerships; MRCSP: Midwest Regional Carbon Sequestration Partnership, coordinated by the Battelle Memorial Institute, Columbus, OH; MGSC: Midwest (Illinois Basin) Geologic Sequestration Consortium which is evaluating sequestration options in the Illinois Basin of Illinois, western Indiana, and western Kentucky, led by the University of Illinois, Illinois State Geological Survey; SECARB: Southeast Regional Carbon Sequestration Partnership, headed by Southern States Energy Board, Norcross, GA; SRCSP: Southwest Regional Partnership for Carbon Sequestration which is involving the efforts of 21 partners in eight states coordinated by the Western Governors' Association and New Mexico Institute of Mining and Technology, Socorro, NM; WESTCARB: West Coast Regional Carbon Sequestration Partnership led by the California Energy Commission, Sacramento, CA; Big Sky Regional Carbon Sequestration Partnership, headed by Montana State University, Bozeman, MT; PCOR: Plains CO_2 Reduction Partnership, led by the Energy & Environmental Research Center at the University of North Dakota, Grand Forks, ND (DOE)

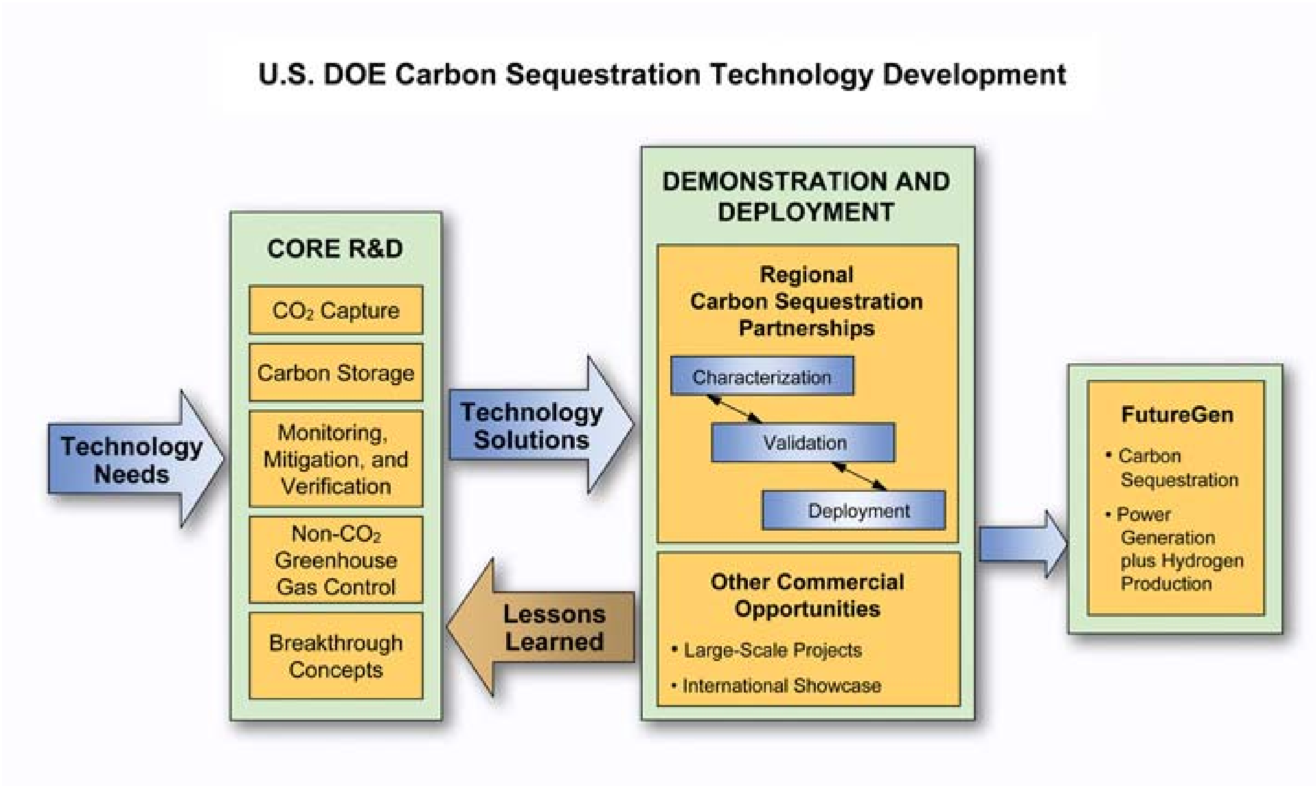


Figure 7A. Outline of the U.S. DOE Carbon Sequestration Technology Development program (DOE) sequestration technologies in areas designated as favorable for carbon storage, and also refining regional characterizations, continuing public outreach, and conducting regulatory analyses. The objective of the activity is to prove that the regional capacity and injectivity exists for commercialization, prior to the end of the phase in June 2009.

The deployment phase from 2007 until 2017 (Figure 7B) is intended to demonstrate at large scale, over several years, that CO_2 capture, transportation, injection, and storage can be achieved safely, permanently, and economically, while concurrently guiding the FutureGen Initiative. DOE has indicated that the geologic structures to be tested during these large-volume sequestration tests could become candidate sites for future near zero emissions power plants. The Deployment Phase tests will be implemented in three stages that will test key technologies during the demonstration and deployment. In the site selection and characterization stage, National Environmental Policy Act (NEPA) compliance, permitting, and infrastructure development will be the focus. In the second stage, CO_2 injection and monitoring operations will be conducted, and in the third stage, site closure, post injection monitoring, and analysis will be demonstrated. As of December 2007, DOE has announced major funding for four of the seven large-scale tests in this phase, including Plains region tests in North Dakota and Alberta.

Interstate Oil and Gas Compact Commission (IOGCC) role

The Interstate Oil and Gas Compact Commission (IOGCC) has been directing the 5-year efforts of a Task Force on Carbon Capture and Geologic Storage, funded by DOE, through a cooperative agreement with the New Mexico Institute of Mining and Technology. In September 2007, the task force released what it considered the first clear and comprehensive model legal and regulatory framework for the geologic storage of CO_2 that will accommodate the requirements of each US state or Canadian province (IOGCC, 2007), with the vision being a substantially consistent system for geologic storage of CO_2 regulated at the state and provincial level in conformance with national and international law and protocol. IOGCC indicates that it is a multi-state government agency established in 1935 that promotes the conservation and efficient recovery of domestic oil and natural gas resources while protecting health, safety, and the environment. The 2007 report concluded that states are the logical and best equipped entities to implement and administer regulations for the storage of CO_2, through public involvement in a transparent process. In addition to background information, the report includes a paper on property rights, an overview and explanation of the model statute, rules and regulations, a Model Statute for Geologic Storage of Carbon Dioxide, and Model General Rules and Regulations. The Task Force suggested that the most appropriate state regulatory entity to implement these rules and regulations would be the state oil and gas regulatory agency, as most of the proposed regulations were based on natural gas storage and oil and gas injection well rules, although it was recognized that some states, such as those without an oil and gas regulatory framework, might choose to designate another regulatory agency, such as an environmental agency or public utility commission, as the lead agency for the state. In addition, the report stressed the view that CO_2 is a safe and non-toxic product that that has beneficial uses following removal from a regulated emission stream, in contrast to contaminants and pollutants such as hydrogen sulfide, nitrogen oxide and sulfur oxide that in their view should remain regulated for health, safety, and other environmental concerns. The Task Force stressed that treatment of geologically stored CO_2 as waste using waste disposal frameworks rather than resource management frameworks would diminish significantly the potential to meaningfully mitigate the impact of CO_2 emissions on the global climate through geologic storage. The Task Force concluded that control of the necessary storage rights should be required as part of the initial storage site licensing to promote orderly development and maximized utilization of the storage reservoir. In the US, with the exception of federal lands, the acquisition of these storage rights, which are considered property rights, generally are functions of state law, according to the report. The Model General Rules and Regulations propose the required acquisition of these storage rights and contemplates use of state natural gas storage eminent domain powers or oil and gas unitization processes to gain control of the entire storage reservoir. The Task Force went on to propose a two-stage Closure Period and Post-Closure Period to deal with long-term monitoring and liability issues. The

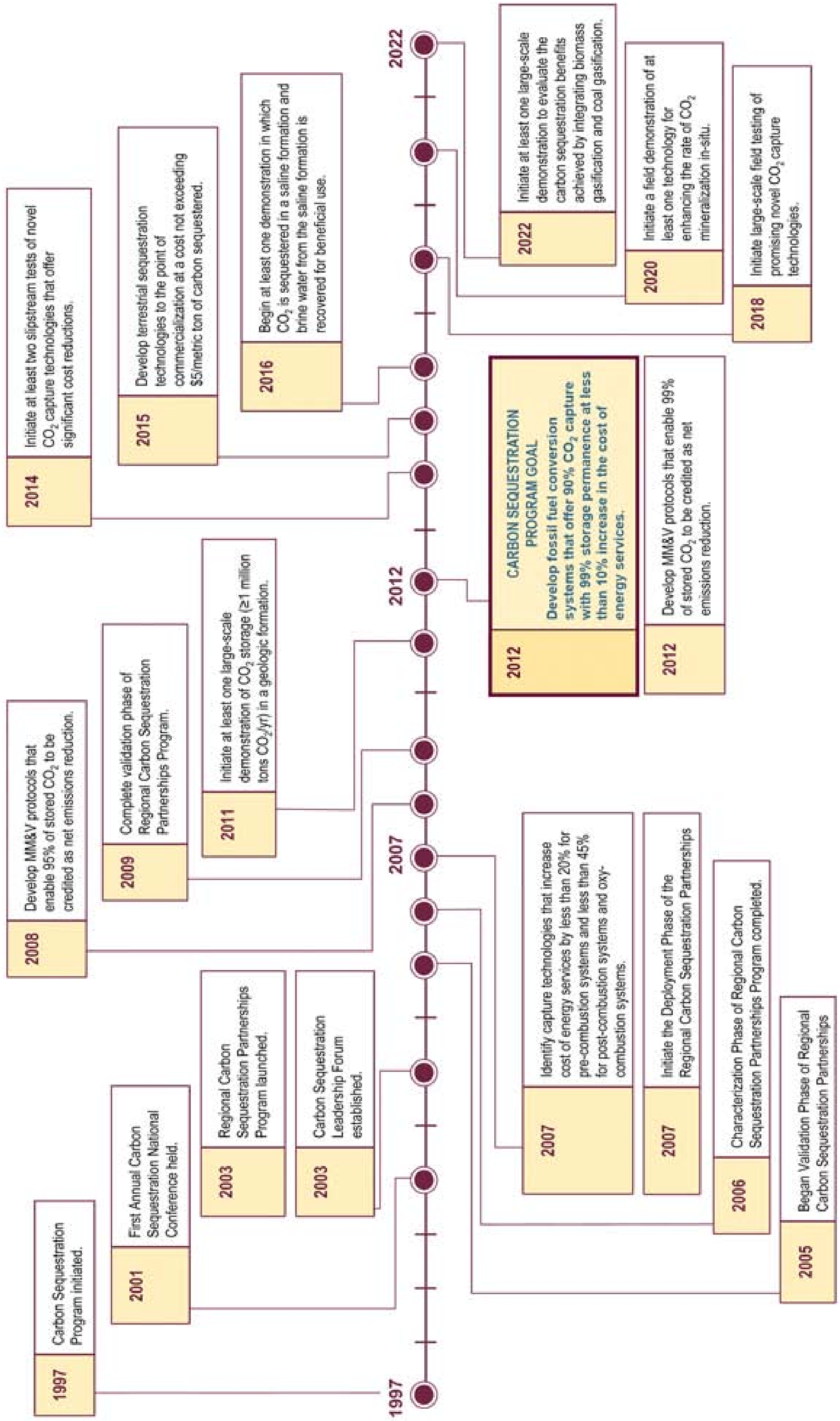


Figure 7B. U.S. DOE Carbon Sequestration Program Goals (DOE) operator of the storage site would be liable for a period of ten years after the injection site is plugged, unless otherwise designated by the state regulatory agency. At the end of the Closure Period, the liability for ensuring that the site remains a secure storage site during the Post-Closure Period would transfer to the state. A trust fund that is industry-funded and state-administered would provide the necessary oversight during the Post-Closure Period, according to the report. The trust would be funded by an injection fee assessed to the Carbon Storage Project operator and calculated on a per ton basis. Finally, the report discussed national-level regulation, and the role of the US Environmental Protection Agency. It was acknowledged that the EPA Underground Injection Control (UIC) program may be applicable at the discretion of a state program; it was the view of the task force that the current limitations of the UIC program make it applicable only to the operational phase of the storage project.

US Environmental Protection Agency (EPA) role

On October 11, 2007, EPA announced their intention to develop regulations for geologic sequestration of CO_2, to ensure a consistent and effective permit system under the Safe Drinking Water Act for commercial-scale geologic sequestration programs. EPA indicated that it is working with the Department of Energy as it carries out its carbon sequestration research and development program, and is also coordinating efforts to evaluate potential impacts on health, safety and the environment. Their release stated that the Safe Drinking Water Act established the Underground Injection Control (UIC) program to allow the safe injection of fluids into the subsurface in a manner that does not endanger current or future underground sources of drinking water, and that EPA plans to propose regulatory changes to the UIC program in the summer of 2008, and will invite the public and stakeholders to provide input throughout the rule development process. In 2007, EPA held workshops on Geological Setting and Area of Review Considerations for CO_2 Geologic Sequestration, a Technical Workshop on Well Construction and Mechanical Integrity Testing, and a Technical Workshop on Well Construction and Mechanical Integrity Testing, and a State Regulators Workshop on Geologic Sequestration of Carbon Dioxide.

CCS CAPACITY ASSESSMENTS IN ADJACENT REGIONS

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Consideration of steps to clarify potential capacity for geologic carbon sequestration in Minnesota will benefit by comparison to the procedures used, the geologic conditions prevailing, and the amount of existing data available in areas where capacity has already been confirmed. It also will be beneficial to consider how any actions by Minnesota will be coordinated with concurrent activity in neighboring states. Both points may be addressed by consideration of the activity of the two nearest DOE Regional Sequestration Partnerships, the Plains CO_2 Reduction (PCOR) Partnership, based at the Energy & Environmental Research Center (EERC) at the University of North Dakota in Grand Forks and mandated to examine with partners an area that includes Minnesota, and secondly the Midwest (Illinois Basin) Geologic Sequestration Consortium, based at the Illinois State Geological Survey.

Plains region

PCOR is a collaboration of over sixty-five US and Canadian groups that has confirmed capacity for geologic carbon sequestration in North Dakota and western Canada, and which is facilitating the coordination of terrestrial and geologic carbon sequestration activity over a region extending from Missouri to Alberta, including Minnesota (Figure 8). The PCOR web site stresses that while CO_2 sequestration is emerging as a major strategy for addressing climate change concerns, regional characteristics must be taken into account to ensure successful sequestration projects. Phase I of the PCOR Partnership program, from 2003 to 2005, focused on characterizing the major CO_2 sources and sites with potential for CO_2 sequestration in the PCOR Partnership region. Phase II from fall of 2005 to fall of 2009 features several sequestration field validation projects designed

Figure 8. Plains CO_2 Reduction Partnership (PCOR) region, extending across Minnesota, North Dakota, South Dakota, Nebraska, Iowa, Missouri, Wisconsin, Montana, Wyoming and three Canadian provinces (PCOR)

to develop the expertise and business models needed to implement full-scale CO_2 sequestration projects in the region. In the fall of 2007, the PCOR Partnership was selected for a ten-year, Phase III program focused on implementing a commercial-scale geologic carbon sequestration demonstration project in the region, with DOE funding at a level of $67 million.

During the two-year Phase I period of PCOR activity, over twenty topical reports were produced, along with additional databases and outreach material. In an overview released in May 2005 of the sequestration-related general geological characteristics of the Williston Basin, a sequence of sedimentary rocks centered in western North Dakota that is as much as 16,000 feet thick, Fischer et al., (2005a) indicated that the search for CO_2 sequestration capacity is equivalent to petroleum exploration, in which a source, a reservoir, and a trap are sought. The stratigraphy of the area was reported to be well studied, especially in those intervals that are oil-productive, and the potential for sequestering CO_2 in the Williston Basin was deemed significant, due to the presence of nearly 1100 active and depleted oil fields, as well as deep saline formations and coal seams. The oil fields were considered particularly attractive candidates for geological sequestration, as many of them already have in place key infrastructure elements necessary for CO_2 transport. The report also discussed widely-occurring Williston Basin deep saline formations, including the Madison carbonate, and Dakota sandstone. It was acknowledged that while general information on the structural geology, lithostratigraphy, hydrostratigraphy, and petroleum geology of the Williston Basin is readily available, additional characterization data for specific candidate sinks will be necessary before their utilization as CO_2 storage sites. In particular, the need for detailed maps of critical elements such as formation thickness, porosity, permeability, and water salinity will need to be developed, and the competency of regional traps will have to be further studied. The paper thus presented an overview of the geology and geohydrology of the Williston Basin with respect to CO_2 sequestration in petroleum reservoirs and deep saline formations, and a plan was laid out for outlines discussing basic geology and geohydrology of several formation that would follow the report. Formation outlines followed for the Mission Canyon Formation in May 2005 (Fischer et al., 2005b), and, in September 2005, outlines for the Inyan Kara Formation (Fischer et al., 2005f), the Newcastle Formation (Fischer et al., 2005g), and the Skull Creek Formation (Fischer et al., 2005c).

To clarify the potential for sequestration in PCOR-region coal seams, three reports were prepared on geologic CO_2 sequestration potential of the Wyodak-Anderson coal zone in the Powder River Basin of Montana and Wyoming (Nelson et al., 2005c), of the lignite coal in the US portion of the Williston Basin (Nelson et al., 2005b), as well as the Ardley Coal Zone in the Alberta Basin (Bachu, 2005). A separate report examined the sequestration potential of petroleum reservoirs in the Williston Basin (Smith et al., 2005). Two methods were used to estimate capacity, one based on oil pools undergoing enhanced oil recovery (EOR) and the other assuming that the reservoir pore space can be filled to capacity with CO_2. Oil fields were chosen based on their cumulative production totals and characteristics that would promote long-term storage of CO_2. The objective of this work was to develop a method that could be used to choose sites based not only on EOR potential, but also on the CO_2 volume that can be sequestered. It was acknowledged that, absent non-market-based incentives, CO_2 sequestration in many geologic sinks is not economically viable under current market systems, but enhanced oil recovery (EOR) could provide a bridge to conducting non-EOR-based geologic sequestration. It was foreseen that as production matures, those fields that have not yet undergone EOR or are considered depleted and abandoned would become prime candidates for CO_2 sequestration. Fields were also looked at as potential storage areas for non-EOR-related CO_2 sequestration, based largely on the pore volume of the reservoir that can be filled with CO_2, giving a maximum storage potential for each field. To assess the sequestration potential of saline formations in the region, two reports were produced, one in September 2005 on the Madison carbonate unit of the Northern Great Plains aquifer system (Fischer et al., 2005e), and one on saline portions of the Lower Cretaceous sandstone aquifer system in the PCOR Partnership Region (Fischer et al., 2005h).

These geologic assessments were synthesized in December 2005 as a report on geologic sequestration potential of the PCOR Partnership Region (Sorensen et al., 2005a). The report depicted PCOR region geology as containing vast geologic sinks that can be used to sequester CO_2 in thousands of oil reservoirs, three major coal fields, and two regional deep saline formations that had been evaluated using readily available data. It was stressed that the characterization data that were available for each sink varied widely, so the storage capacity estimates were considered to be preliminary, at the order-of magnitude level of accuracy. It thus was reported that over 240 billion tons of CO_2 could be sequestered in geologic formations in the region, while major stationary sources in the region produced over 500 million tonnes of CO_2 in 2000, and on this basis, the region's geologic sinks could theoretically sequester all of the CO_2 produced in the region for over 400 years. It was added, however, that one of the primary functions of the PCOR Partnership is to facilitate the implementation of geologic sequestration strategies, in part through the critical goal of identification and characterization of sinks with a value-added component. With that goal in mind, therefore, emphasis was placed on evaluation of oil and coal fields, and the synthesis indicated that over 3.4 billion barrels of incremental oil production might be recovered from oil fields in the region through the injection of CO_2, with a vast majority of the potential located in the Alberta and Williston Basins. Coal seams in the region were also shown to have potential for value-added CO_2 sequestration, with reconnaissance-level estimates of over 17 trillion cubic feet of natural gas potentially being produced as a result of the injection of CO_2 into those coal seams. It was thought that these significant gains in incremental oil and gas production, as well as continued high oil and natural gas prices, might provide the incentive needed for stakeholders to invest in the infrastructure and capture technologies needed to make large-scale CO_2 sequestration a reality. It was added that establishment of carbon credit markets would further improve the economics of CO_2-based enhanced hydrocarbon recovery projects, and would be essential to the implementation of sequestration projects that target brine formations, thus requiring proper accounting of injected CO_2. It was thought that since the most detailed characterizations of the deep subsurface have been conducted as part of hydrocarbon exploration and production activities, it is likely the first implementations of sequestration will be oil fields that are currently in production, depleted oil and gas fields, and other characterized structures that are known to have effective trapping mechanisms. It thus was thought that saline formations would be problematic regarding the required legal arrangements. It thus was thought necessary to identify localized areas within a saline formation with specific characteristics that allow for the secure long-term storage of CO_2, and concurrently the ability to quantify and verify the amount of CO_2 in a given reservoir within a carbon credit regime.

Two reports also dealt with the anticipated integrity of the reservoirs, one summarizing factors affecting the potential for CO_2 leakage from geologic sinks (Nelson et al., 2005a), and a second report on the influence of tectonics on the potential leakage of CO_2 from deep geological sequestration units in the Williston Basin (Fischer et al., 2005d). Two additional reports then facilitated application of the geologic assessments to sequestration scenarios for the PCOR Partnership region, one on identification of CO_2 sequestration strategies linking source and sink (Jensen et al., 2005a), and a report on deployment issues related to geological and terrestrial CO_2 sequestration in the region (Reilkoff et al., 2005).

The key finding of the PCOR Phase I final report that brought together the analysis to date (Steadman et al., 2006), from the point of view of geologic sequestration, was identification of three source – geologic sink combinations found to be promising to become market-driven, full-scale sequestration project opportunities, thus meriting field validation testing in Phase II. These projects included CO_2 potentially from the Dakota Gasification Company plant used for simultaneous sequestration and EOR in oil fields proximal to the existing CO_2 pipeline in western North Dakota, acid gas (65% CO_2, 35% H_2S) from sour gas plants in Alberta injected into a nearby oil field for simultaneous sequestration and EOR, as well as CO_2 injected into economically unmineable lignite seams in western North Dakota for both CO_2 sequestration and coalbed methane production.

The PCOR Phase I accomplishments thus included assessment and prioritization of opportunities for sequestration in the region, helping to resolve the technical, regulatory, and environmental barriers to the most promising sequestration opportunities, as well as informing policy makers and the public regarding CO_2 sources, sequestration strategies, and sequestration opportunities. The Phase I products included the described regional assessment of CO_2 sinks as well as an inventory of sources, development of the PCOR Partnership Decision Support System (DSS) which is a web-based geographic information system (GIS) system available to partners co-funding the activity, identification, ranking, and action plans for promising sequestration demonstration projects, key GIS products for CO_2 sources and sinks, infrastructure, and regulatory issues, as well as recommendations for monitoring and verification systems.

Also featured in the Phase 1 report (Steadman et al., 2006) were quantitative estimates for the total geologic CO_2 storage potential for the PCOR region in billions of tonnes, and capacity in years relative to the then current estimated total CO_2 emissions from stationary sources in the region of 502 million tonnes per year. On this basis, unmineable coals were at that time thought to offer storage potential of 7 billion tonnes or 14 years capacity in the ideal scenario of full capture from stationary sources, oil and gas fields offered capacity for 12 billion tonnes or 24 years, while the saline formations that had been examined offered capacity for 200 billion tonnes or 400 years capacity. An appendix in the report outlined the method used to derive these estimates.

PCOR Phase II goals and objectives, within the broader goal to validate technologies and identify locations in the partnership region that can support future full-scale geological and terrestrial sequestration opportunities, include continuing to assess regional carbon sequestration opportunities, developing field projects, evaluating the feasibility of selected commercial-scale carbon sequestration technologies, assessing sink capacity permanence, economics, risk, public acceptance, as well as societal and monetary co-benefits, along with providing outreach and educational materials for CO_2 sequestration stakeholders and the general public. It is anticipated by PCOR that the development of one terrestrial sequestration field trial and two or more geologic field trials will be completed in Phase II. Field projects will include injection of acid gas into a depleted oil reservoir in Alberta, for acid gas disposal, enhanced oil recovery, and carbon sequestration, injection of CO_2 into a deep carbonate reservoir in North Dakota for enhanced oil recovery and carbon sequestration, injection of CO_2 into a lignite coal seam for enhanced methane production and carbon sequestration, as well as restoration of prairie pothole wetlands for terrestrial carbon sequestration. On October 10, 2007, DOE awarded $67 million to PCOR, to launch Phase III of the activity, while PCOR partners will concurrently contribute $68 million to Phase III.

The findings of the PCOR activity were also summarized as the PCOR Partnership Atlas (Peck et al., 2005). A second edition of the atlas (Peck et al., 2007) included discussion of the Midcontinental Rift System that acknowledged that the PCOR Partnership region includes other areas besides the major petroleum-producing basins that are underlain by thick sequences of sedimentary rock, and one of the largest and most notable of these areas was stated to be the Midcontinental Rift System, which stretches from eastern Nebraska across central Iowa and south-central Minnesota to the western portion of Lake Superior. The atlas indicated that the sedimentary rocks of the Midcontinental Rift System may be viable locations for CO_2 sequestration, but because oil and gas have never been discovered in these rocks, very few deep wells have been drilled in the area; therefore, little is known about the characteristics of these rocks. It was further stated that continued regional characterization activities being conducted under Phase II of the PCOR Partnership, such as the activity presented in the current report, will result in a better understanding of the potential for the sedimentary rocks of the Midcontinental Rift System to sequester large volumes of CO_2.

Illinois Basin

On December 18, 2007, DOE announced an award of $66.7 Million for a large-scale carbon sequestration project that will demonstrate permanent storage of one million tons of CO_2 at a site in Illinois. This was the fourth recent award through the DOE Regional Carbon Sequestration Partnership Program, and was granted to the Midwest Geological Sequestration Consortium (MGSC), led by Illinois State Geological Survey. The DOE press release indicated that, subject to annual appropriations from Congress, this project including the partnership’s cost share is estimated to cost $84.3 million, and that the geologic repository will be the Mount

Simon Sandstone Formation approximately 5,500 feet below the surface. Injection rate will be about 1,000 tons of CO_2 per day for three years, followed by closure, monitoring, and modeling to determine the effectiveness of the storage reservoir. MGSC has partnered with Archer Daniels Midland (ADM) Company, and an ADM ethanol plant in Decatur, IL, will serve as the source of the CO_2 for the project. ADM will cost share the expense of the CO_2, which will come from the company's ethanol production operation. DOE will fund the dehydration, compression, short pipeline, and related facility costs to deliver the CO_2 to the wellhead. In addition, another December 18, 2007, press release indicated that Illinois had been selected as the site for the planned FutureGen project, a near-zero emissions coal-fueled power plant.

The confirmation of the Mount Simon Sandstone in this region (Figure 9) as an appropriate CO_2 repository, resulting in these developments, largely was reported in the MGSC Phase I final report (Finley, 2005). According to their web site, the MGSC Phase I activity had included data compilation, a review of capture and transportation options (Finley, 2004), a review of coalbed sinks and methane production, oil reservoir sinks and oil recovery, and deep saline reservoir sinks, including characterization of saline reservoirs, including the Mt. Simon Sandstone, Ironton-Galesville Sandstone, St. Peter Sandstone, and their overlying caps to determine their long-term suitability for CO_2 storage in the Illinois Basin. In addition, information was integrated on storage options, sources, transportation pathways, environmental and regulatory frameworks, as well as sequestration scenarios. The work concluded with compilation of results as reports, presentations, journal articles, and map products, education and outreach through educational workshops and web content, and an implementation plan for a technology validation field test of one or more geological CO_2 storage options within the Illinois Basin.

MGSC examined Illinois Basin coal resources, oil fields, and deep salt-water-bearing reservoirs potentially capable of storing CO_2 as a consortium of the state geological surveys of Illinois, Indiana, and Kentucky, joined by six private corporations, five professional business associations, one interstate compact, two university researchers, two Illinois state agencies, and two consultants. Assessing the options for capture, transportation, and storage of the CO_2 emissions within the region was a 12-task, 2-year process that assessed 3,600 million tonnes of storage capacity in coal seams, 140 to 440 million tonnes of capacity in mature oil reservoirs, 7,800 million tonnes of capacity in saline reservoirs deep beneath geological structures, and 30,000 to 35,000 million tonnes of capacity in saline reservoirs deeper than 4,000 feet. Options for capture, transportation, and geological storage were linked and integrated with the environmental and regulatory framework to define sequestration scenarios and potential outcomes for the region. Extensive use of GIS and visualization technology was made to convey results to project sponsors, other researchers, the business community, and the general public.

The screening criteria for geologic CO_2 sequestration used by the MGSC team examined the Illinois Basin saline aquifers, oil reservoirs and coal seams with respect to storage capacity per unit of reservoir volume, and a caprock that prohibits vertical migration of CO_2, along with enhanced hydrocarbon recovery opportunities, using both general criteria and geologic-formation-specific criteria. Geographic information system (GIS) software was used to integrate key criteria and identify areas with the greatest geologic sequestration potential. The conclusion of the screening was that pressure and temperature criteria are required for all formation types to determine CO_2 phase behavior, whether vapor, liquid, or critical fluid. CO_2 fluid properties, including density, coal adsorption, and solubility in water and oil also are required, while area, thickness, porosity, irreducible saturation, and flood efficiency of accessible pore volumes are required for estimating capacity. In oil reservoirs, immiscible or miscible CO_2 flooding conditions that determine CO_2 sequestered volume and EOR potential also need to be defined on a reservoir-by-reservoir basis, according to the MGSC team.

Saline formations were assessed using seven criteria regarding their potential for CO_2 sequestration sites in Illinois (Finley, 2005), including geologic structural closure, subsurface depth of the target reservoir, faults and earthquake hazards, paleotopography on the underlying Precambrian surface, lateral proximity of the target reservoir to its equivalent freshwater interval, reservoirs with adequate porosity and permeability for storage and injection of CO_2, as well as the quality and thickness of the reservoir seal.

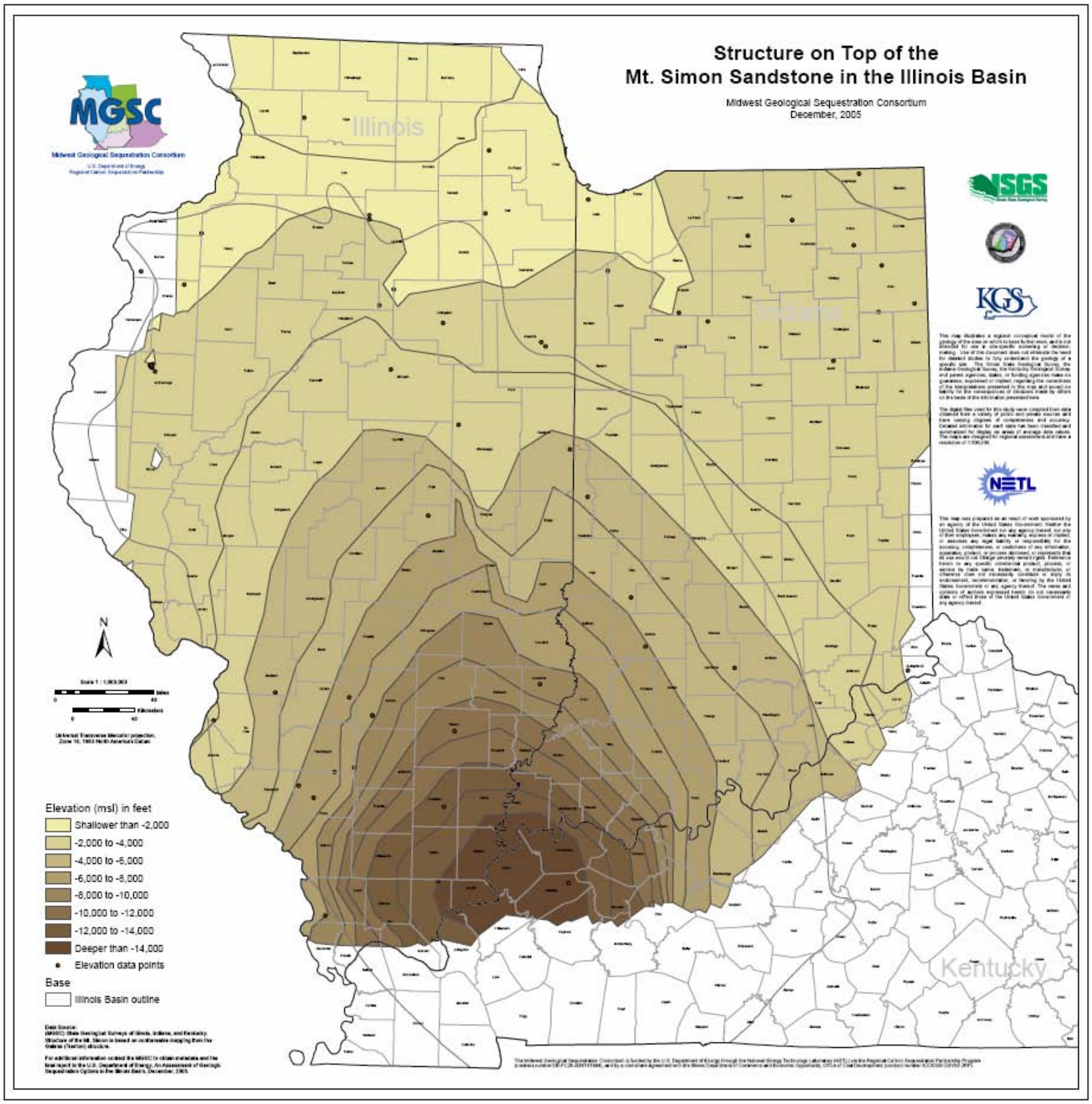


Figure 9. Structure on top of the Mt. Simon Sandstone in the Illinois Basin, showing the top to be above 2000 feet below mean sea level in the north, and deeper than 14,000 feet below mean sea level in the south (MGSC)

Three major saline reservoirs in the Illinois Basin were reviewed as potential CO_2 storage reservoirs in this manner (Finley, 2005): the Ordovician St. Peter Sandstone and the Cambrian Ironton-Galesville and Mt. Simon Sandstones. The St. Peter Sandstone is widespread, porous, and permeable with good lateral continuity. Seals above the St. Peter include several hundred feet of dense limestone and dolostone overlain by 150 to 250 feet of Maquoketa Shale. The Ironton and Galesville Sandstones are thin and are not present in the central and southern parts of the Basin, so consideration of them in the context of basin-wide sequestration potential was discontinued. There are perhaps no more than 20 penetrations of the Mt. Simon in the southern part of the Illinois Basin; thus, reservoir quality data are limited. Extrapolating studies of natural gas storage reservoirs in the Mt. Simon over the Illinois Basin, however, suggested a capacity of 5.9 billion tonnes in the Mt. Simon and 1.9 billion tonnes in the St. Peter in structural traps. It also was thought that an additional 28 to 33 billion tonnes could be trapped by dissolution below 4,000 ft, outside of structural traps and below deep natural gas storage, even in areas where no constraining geological structure is present.

The MGSC report demonstrated that the Mount Simon Sandstone beneath Illinois Basin, nearly a km thick in places and reaching a depth of over 4 km, is an ideal target for sequestration. The Eau Claire Formation, directly overlying the Mt. Simon, provides the primary seal that will prevent CO_2 migration into shallower formations. A factor in achieving this level of confidence was the fact that the Illinois Basin has the largest number of saline natural gas storage fields in the US. These gas storage fields provided important analogs that were used to analyze the potential for CO_2 sequestration, illustrating seal integrity, injection capability, storage capacity, and reservoir continuity. The long history over nearly fifty years of successful natural gas storage in the Mt. Simon and St. Peter formations in the Illinois Basin demonstrated that these two saline reservoirs could provide successful containment of CO_2 and that further detailed evaluation was warranted. The MGSC report (Finley, 2005) therefore provided a detailed account of the stratigraphy, depositional environments, groundwater flow, fractures, structural mechanics, faults, seismicity, water salinity, temperature, pressure, porosity, and other attributes of these strata.

Scenarios were then developed for water displacement by CO_2 injection, using two scenarios, closed system injection, and open system injection. In a closed system scenario, there is no pressure communication with surrounding geologic formations, and free-phase CO_2 storage capacity is available from the water and pore compressibility. With increasing pressure, the water contracts, and the pore volume expands, and additional storage capacity is through dissolution of CO_2 into reservoir water. During the injection, storage capacity of a closed system will decrease as distance from the project site increases, while after injection is complete, there is a relaxation in the pressure disturbance, and CO_2 is anticipated to become distributed more evenly. The great Mt. Simon thickness of 610 m (2,000 ft) available for injection would generate significant pore volume available for sequestration, and there would also be a slight increase in pore and bulk volume due to pore expansion due to injection pressures, according to the report. In an open system scenario, the reservoir is connected to the outcrop belt and pressure changes due to CO_2 injection in one area would affect the entire aquifer system, so in this scenario, compressibility is only important around well bores during injection and not the reservoir as a whole following injection. In the MGSC work, three simple piston-like displacement volumetric models were evaluated to estimate velocity and distance the water displaced from CO_2 injection moves.

This modelling allowed conclusions to be reached, such as the inference that injection of large volumes of CO_2 would have an inconsequential effect on the position of a distant freshwater-salt water interface, although a scenario of a large number of injection points was recognized to be a separate consideration. It was recognized, however, that a shift in the freshwater-salt water interface would affect the dynamics of the freshwater part of the flow system, so careful consideration would be needed in relation to long-term effects of CO_2 sequestration in deep saline aquifers on parts of the formation used as water supplies in large metropolitan areas at the margins of the Basin. It was noted, however, that before any possible interference with freshwater areas, water could be pumped to balance the water displaced by CO_2 storage.

In addition to other report components, such as analyses of coalbeds, oil reservoirs, faulting and structural reactivation, regulatory frameworks, pipeline systems, an analysis of CO_2 capture in ethanol plants, and outreach materials, the MGSC Phase 1 report (Finley, 2005) also included an analysis of the geochemistry of the Mt. Simon sandstone in the context of CO_2 sequestration. This preliminary geochemical modeling, based on data from a Mount Simon sandstone gas storage field in Illinois, served to establish a methodology, provide initial estimates of sequestration effectiveness, and show where additional information is needed to refine the calculations. The modelling assumed a requirement for a formation to be deeper than about 792 m (2,600 ft), and the water salinity in the formation to be more than ~ 10,000 mg/L, based on work by Gunter et al. (2000). These criteria were seen as the requirement to ensure that the formation will not be used as a source of drinking water, and that CO_2 will exist as a supercritical fluid after injection.

Physical multiphase flow in a heterogeneous medium was seen as displacing formation waters, formation of a buoyant CO_2 plume, lateral migration of the plume in response to the regional hydrologic gradient, as well as dispersion and diffusion in response to the porosity and permeability structure of the host formation. Concurrent chemical processes encompassed by the analysis included multiple, kinetically controlled geochemical reactions in heterogeneous media between supercritical CO_2 and formation water, as well as between intraplume formation water and the host formation framework. As a result, two processes were seen as contributing to geochemical sequestration in saline formations, solubility trapping in the form of dissolution of CO_2 in formation water to a degree dictated by pressure, temperature, and salinity, as well as more permanent sequestration due to precipitation.

The geochemical system consisting of supercritical CO_2, saline formation water, and heterogeneous geologic media was seen as a complex set of reactions and processes. It was stressed that currently available knowledge and procedures require several assumptions, some of which have a significant influence on inferences. The MGSC report carefully listed what were seen as the most critical assumptions, starting with uncertainty in the thermodynamics of reactions between supercritical CO_2 and aqueous carbon species, such that CO_2 fugacity being set equal to reservoir pressure could result in an overestimate of the amount of CO_2 that would dissolve in formation water. Secondly, activity coefficients of aqueous species in CO_2-saturated, saline water were seen as being less than well known. Third, it was noted that all geochemical calculations were made on the basis of 1 kg of solvent water, while the amount of rock volume involved in the reaction would be determined from porosity estimates, and all porosity was assumed to be filled with water. It was added, however, that supercritical CO_2 will occupy some fraction of the total pore space, and some porosity may not be in effective communication with intraplume formation water, so this uncertainty was seen as probably not affecting the calculations significantly.

The fourth key assumption in their view was that all simulations were run as equilibrium reactions, while the system in reality will be dynamic, and reactions will occur over time. It was thought that incorporating kinetic reaction rates would be possible, but of limited value until the dynamics of plume migration can be estimated, although literature cited in the report was taken to suggest that equilibrium calculations overestimate the volumes of phases involved on the basis of comparing results produced by equilibrium models versus kinetic models. It also was added that there is considerable uncertainty in how well reaction kinetics incorporated in currently available software represent actual conditions, although it was noted that this point could be addressed experimentally. Finally, it was noted that the model predicted dissolution and precipitation of a number of silicate phases, some of which have complex chemical compositions and crystal structure and thus might not react significantly over the time scale of CO2 injection and plume migration. No phases were suppressed in this study, and it was assumed that a solid phase of similar composition and volume, if not crystal structure, would react, but if this is not correct, it was added, the predicted changes in porosity would be affected.

CONTEXT FOR POSSIBLE IMPLEMENTATION OF CCS IN MINNESOTA

L. Harvey Thorleifson, Minnesota Geological Survey, University of Minnesota

Introduction

Several Minnesota-based public and private agencies are members of the PCOR partnership, while it is apparent that various Minnesota entities are engaged in analysis of carbon sequestration scenarios. These activities are taking place with awareness of considerations specific to the State of Minnesota, such as the nature of CO_2 stationary sources in Minnesota, existing pipeline infrastructure, population density, existing regulations, existing underground gas storage, and future energy supply scenarios. The authors of the present report became more involved in the carbon sequestration topic in early 2007, as several factors stimulated increasing attention to the topic. To help increase shared awareness of this accelerating activity at the time, a workshop cosponsored by Minnesota Department of Natural Resources and University of Minnesota was held at the University of Minnesota in March 2007, with the emphasis focused on the carbon sequestration potential of Minnesota regional geology, and hence the Midcontinent Rift.

Regional geology

From a broad point of view, the rocks underlying Minnesota can be considered as having a 'basement' of igneous and metamorphic rocks (Figure 10) that due to their formation or modification by temperature and pressure lack the porosity and permeability required to function as a reservoir. At surface, on the other hand, are sediments such as sand that are largely glacial in origin, and that serve as excellent aquifers, but lack any potential for CCS due to shallow depth and lack of a seal. Similarly, the limestones and sandstones of Paleozoic age that blanket all of southeastern Minnesota (Figure 11), everywhere southeast of St. Cloud, also have excellent reservoir properties that serve us well for water supply and gas storage, but which are too shallow for carbon sequestration potential. Between these layers, the upper of which is too shallow, and the lowest of which is insufficiently permeable, are the prospective rocks discussed in this report, which are the Midcontinent Rift sedimentary rocks of late Precambrian age (Figure 12).

Chandler et al. (1989) as well as Anderson and McKay (1989) reported that the Middle Proterozoic Midcontinent Rift System (MRS) of North America is a failed rift that formed in response to region-wide stresses about 1,100 million years ago. The MRS is buried beneath Paleozoic and Mesozoic sedimentary rocks and Quaternary sediments to the southwest of the Lake Superior basin. An extremely large volume of sediments was deposited within basins associated with the rift at several stages during its development. Although the uplift of a rift-axial horst resulted in the erosional removal of most of these clastic rocks from the central region of the MRS, thick sequences are preserved in a series of horst-bounding basins. Studies incorporating petrographic analysis, geophysical modeling, and other analytical procedures have led to the establishment of a preliminary stratigraphy for these clastic rocks and interpretations of basin geometries, according to the review by Anderson and McKay (1989).

With respect to the sedimentary rocks, Anderson (1997) indicated that the structural configuration, nature of the major lithologic packages, and geologic history of the MRS in Iowa were investigated by examining and interpreting the limited data from drill samples, including the M. G. Eischeid deep petroleum test, gravity and magnetic anomaly maps, and petroleum industry seismic reflection profiles. His investigations included petrographic examination of samples, mapping, and the production of a series of two-dimensional gravity profiles constrained by the seismic data. These studies confirmed the MRS to be characterized by a central horst dominated by mafic volcanic rocks, and thrust over thick sequences of clastic rocks that fill flanking basins. At upper crustal depths, the MRS was found to display a relatively symmetrical structure, with sedimentary basins on both flanks of the central horst similar in depth and configuration. The clastic rocks that fill these basins

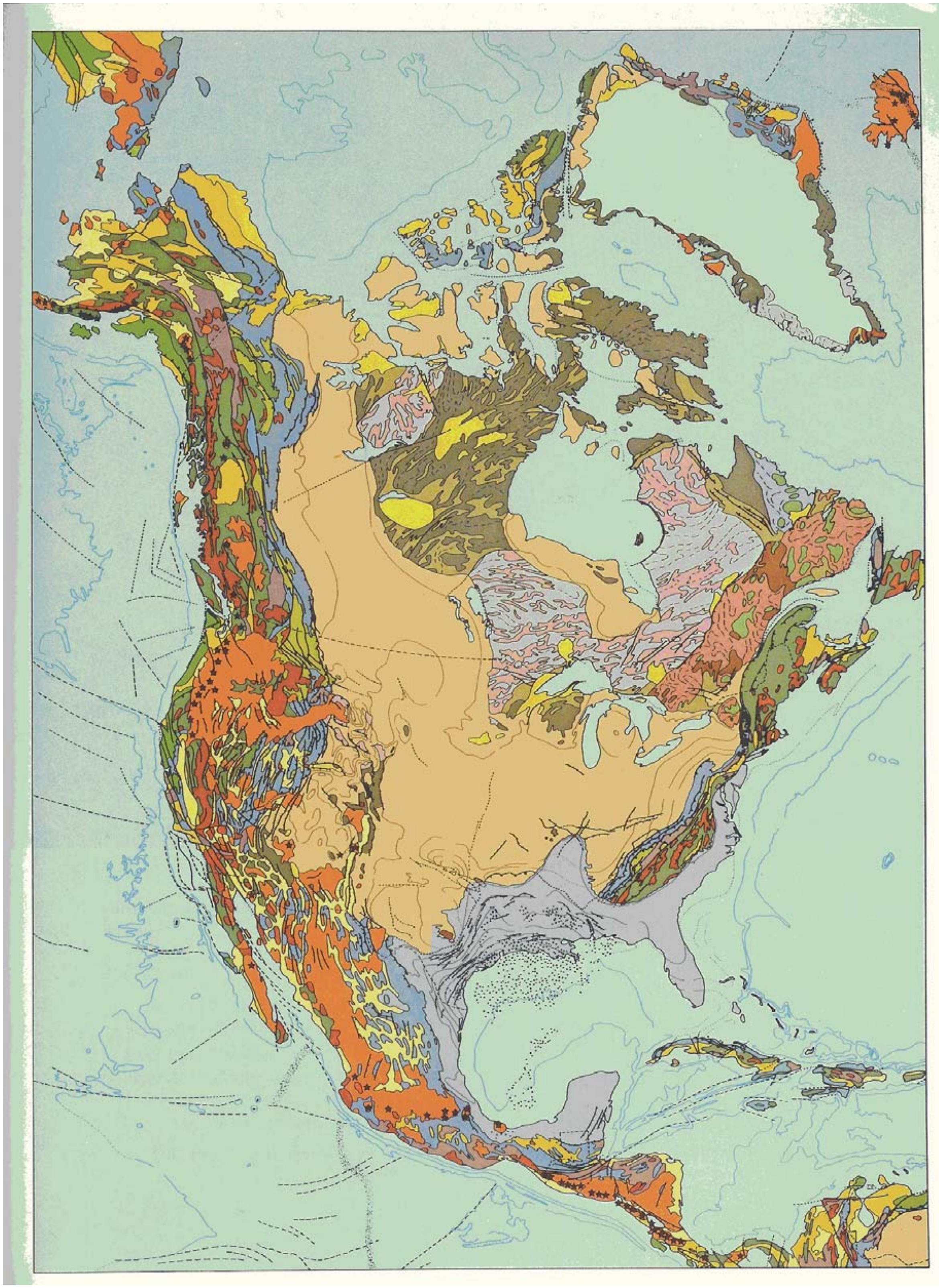


Figure 10. Bedrock geology of North America, showing regional extent of rocks shown in more detail in subsequent figures, such as the granites and other rocks of northern Minnesota, the young sedimentary rocks in southern Minnesota, and the exposures of Midcontinent Rift rocks on the south shore of Lake Superior (Hamblin and Howard, 1980)

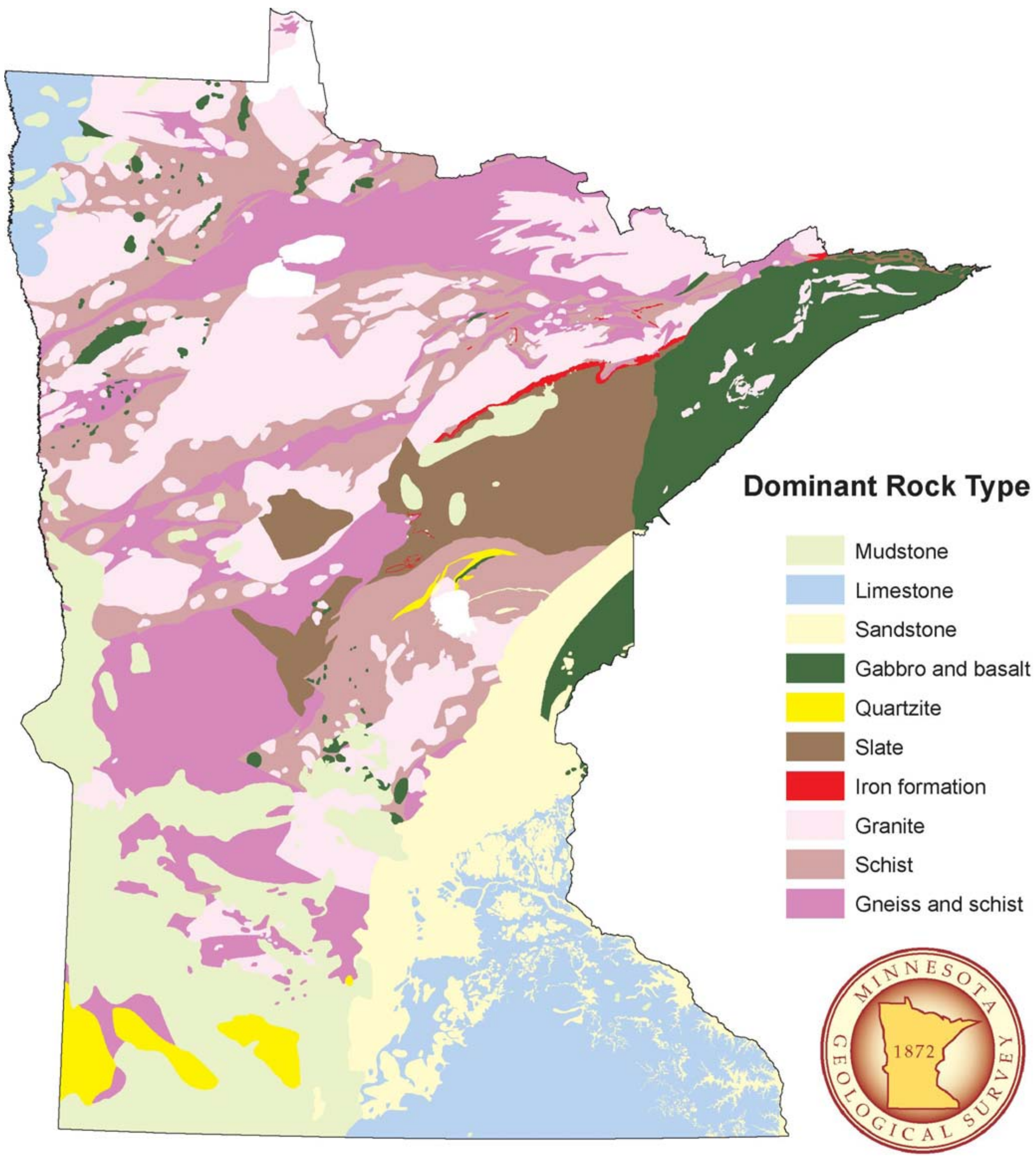


Figure 11. Bedrock geology of Minnesota, as dominant rock type, showing young sedimentary rocks, limestone and sandstone in the southeast and mudstone in the southwest, at depths too shallow for optimal carbon sequestration, granite and other rocks that lack required reservoir properties in northern and central Minnesota, and belts of sandstone and basalt just southwest of Duluth in east-central Minnesota, where these Midcontinent Rift rocks emerge from being covered by younger sedimentary rocks. The older Midcontinent Rift sandstone merges with younger sandstone to the south in this depiction that shows rock type without subdivision by age

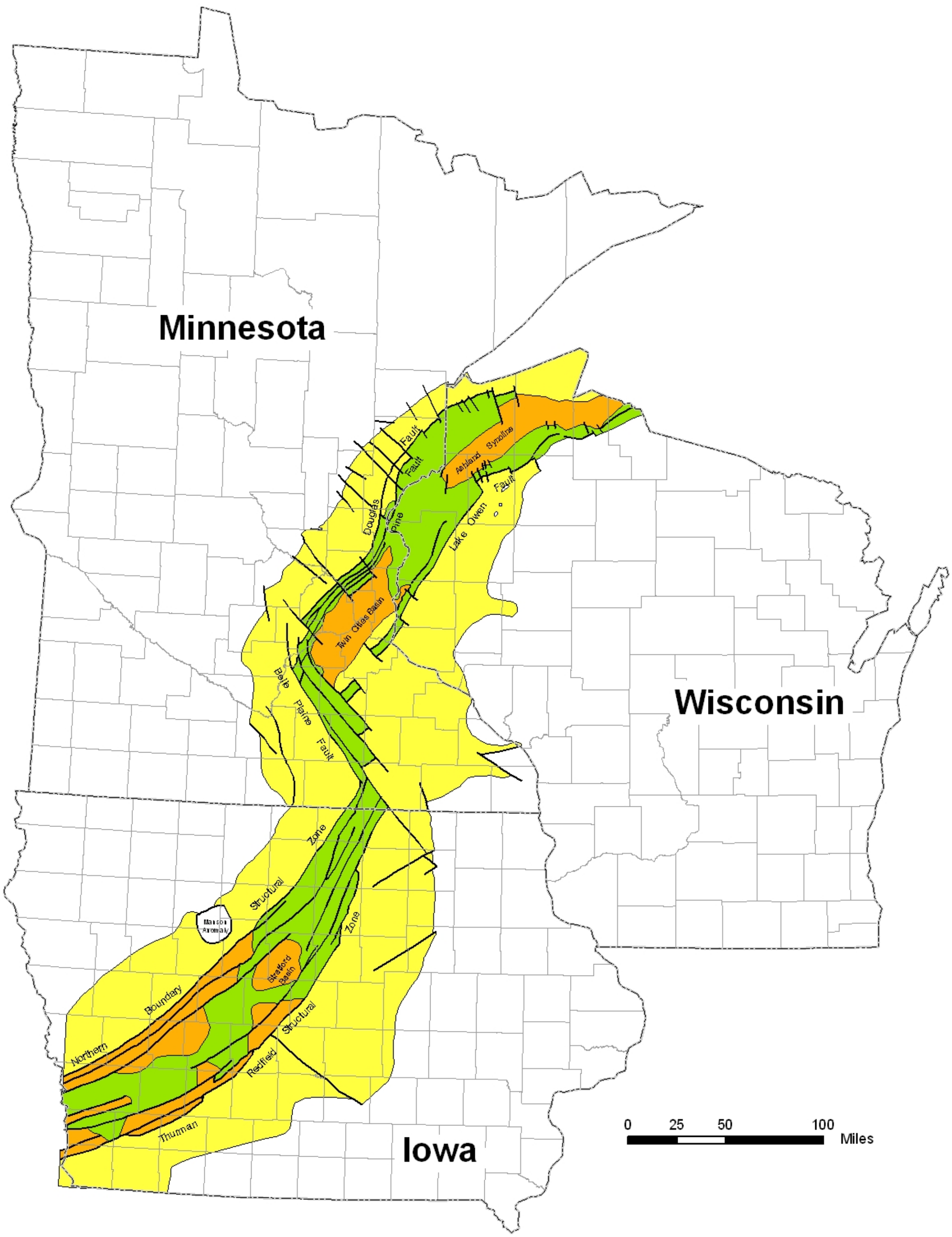


Figure 12. Extent of Midcontinent Rift rocks in Minnesota, Iowa, and Wisconsin, showing sandstone-dominated Bayfield Group and equivalent rocks in yellow, more gravel-rich Oronto Group and equivalent rocks in orange, and volcanic rocks in green (Chandler et al, 1989)

appeared to be dominated by two major sequences, the first apparently deposited shortly after the cessation of rift volcanism, and the second probably deposited during and shortly after the uplift of the horst.

March 2007 workshop

Concurrent with the discussions that led to the authorization and funding of the present study, a briefing for policy makers was held on Wednesday, 21 March 2007, at the University of Minnesota Humphrey Center, to discuss prospects for geologic CO_2 sequestration in the upper Midwest. At the meeting, over forty representatives of upper Midwest governmental, community, academic, and industry groups met to discuss prospects for geologic CO_2 sequestration in the region. It was recognized during planning of the meeting that the only prospective rocks at adequate depth in the immediate region are in the Midcontinent Rift. The goal of the meeting was to develop a shared understanding on prospects, opportunities and tradeoffs, to identify knowledge gaps, and to facilitate collaboration between stakeholders. The meeting was co-sponsored by the Minnesota Department of Natural Resources and the University of Minnesota-based Minnesota Geological Survey, Humphrey Institute of Public Affairs, College of Biological Sciences, Initiative for Renewable Energy and the Environment, and the Department of Mechanical Engineering. Meeting co-chairs Harvey Thorleifson and Elizabeth Wilson opened the meeting, and asked co-chair Marty Vadis, Minnesota Department of Natural Resources (DNR) Director of Lands and Minerals, to introduce Laurie Martinson, DNR deputy commissioner, who gave opening remarks on behalf of the State.

Brad Crabtree, of the Great Plains Institute (GPI), then described work done by the Coal Gasification Workgroup to build consensus on a long-term vision for low-carbon utilization of coal. It was anticipated at the time that in May 2007, GPI would release a 50-year regional energy roadmap including a chapter on the role of advanced coal technologies with geologic carbon capture and sequestration (CCS). Bill Grant of the Izaak Walton League then outlined the bill that was before the Minnesota Legislature at the time that ultimately provided funding for assessment of both geologic and terrestrial carbon sequestration in Minnesota, including the support that enabled the present report.

Elizabeth Wilson of the University of Minnesota Hubert Humphrey Institute then provided an overview of policy considerations for a carbon-managed energy system. She described how carbon capture and sequestration (CCS) is currently in commercial operation at several sites around the world, and is the focus of a major research effort by the US Department of Energy (DOE). Technology alone, she stated, will not be enough, as deployment will need to be embedded in a wider societal dialogue. States were described as having a key role in property rights and liability issues, as well as in managing potential risks to public safety, health and the environment. She then outlined how CCS could play an important role in decarbonizing our energy systems under a larger climate regime if legal and regulatory frameworks can be crafted that foster public acceptance and provide the stability and predictability necessary for companies to invest in these technologies. Finally, Wilson drew the attention of meeting participants to the Intergovernmental Panel on Climate Change report on Carbon dioxide Capture and Storage as an important reference.

Ed Steadman of the Energy & Environmental Research Center (EERC) at the University of North Dakota then described the work of the Plains CO_2 Reduction Partnership (PCOR), which he explained is one of seven regional partnerships under the US Department of Energy's Regional Carbon Sequestration Partnership Program. He outlined how PCOR has completed Phase I and Phase II research, including assessment and ranking of sequestration opportunities, outreach materials, and a PCOR Partnership Regional Atlas, and he indicated that PCOR is now preparing to conduct a number of CCS pilot projects in the Williston Basin under Phase III. Ed discussed the Midcontinent rift as part of his broad presentation, both in terms of its potential, and the lack of available information on the topic.

Ray Anderson of the Iowa Geologic Survey then gave a presentation on the geology of the Midcontinent Rift. He described how the billion-year-old rift can clearly be seen across the region as a gravity and magnetic anomaly, while rocks of the rift are only exposed in the Lake Superior Area. He indicated that the limited additional information available about rift formations comes from deep test borings done for petroleum exploration in Iowa and Wisconsin in the mid 1980s, along with a few shallower drillholes in Minnesota. He conveyed that available data indicate that the rift is composed of a central volcanic block, flanked by sedimentary basins up to 5 miles in thickness, while smaller sedimentary basins sit atop the volcanic block in several areas. Given that geologic sequestration requires porous rock formations at a depth of at least 2,500 feet or roughly a km, overlain by impermeable rock formations to trap the CO_2, Anderson stated that preliminary indications are that the Midcontinent Rift formations could possibly have the necessary characteristics, but that much more geologic assessment would be required.

A Policy/Technology breakout then addressed the challenge of timeframe, including short term siting and permitting decisions that must be made, while ensuring that these decisions make sense regionally over time. Included in the discussion were the need for interstate coordination on siting and regulation, the great cost of trying to characterize the Midcontinent Rift without the benefit of oil and gas industry data, determining who would pay, how decision making can best be guided by information on prospects for success, the need to evaluate trade-offs such as whether states like WI, MN and IA should produce power locally and export CO_2 via pipeline or import electricity on power lines from regions with CCS potential, the need for development of a regulatory framework including unitization rules and regulations, siting criteria guidelines, and the need to consider the public perception issue of acceptance for CCS and related infrastructure such as pipelines.

On the basis of this discussion, the Policy/Technology breakout recommended that we pursue coordinated policy and regulatory development among neighboring states to pursue early development of a carbon management infrastructure, while linking jurisdictions, power plants, coal resources, enhanced oil recovery (EOR) options, along with other sequestration options. This was described as being more advanced among Illinois Basin states, while such arrangements could be expanded more broadly. It was seen that once initial geological results are available, a comprehensive analysis of different energy futures would need to be conducted. This analysis would examine the policy, economic and environmental implications of a) importing electricity from out of state, b) producing electricity in-state but exporting produced CO_2 through pipelines, and c) producing electricity and sequestering CO_2 within the state. It was anticipated by the group that such an analysis will allow for the advantages and tradeoffs of different energy futures to be considered.

Concurrently, the Geology breakout affirmed that Rift formations are the only potentially porous rocks in MN and immediately adjacent areas that are deep enough to have geologic sequestration potential. The discussion also affirmed that very little is known about the detailed stratigraphy, porosity, permeability, geochemistry or hydrogeology of Midcontinent Rift formations in Minnesota at depths required for sequestration, as most cores extend to depths of less than 2,200 feet. It was anticipated that, based on information from other states, and limited information from relatively shallow depths in MN, rift formations at depths required for sequestration potentially could include both units with adequate permeability to store injected CO_2, and low permeability units to trap the injected CO_2, but the extent and configurations of potential reservoirs and caps is unknown, while preliminary data were recognized not to be promising. It was noted that rift formations are likely saline, as even some shallower aquifers in the Twin Cities area are saline. The level of characterization required for CCS in many respects was seen to be similar to the requirements for oil and gas exploration, although it was noted that specific tasks such as evaluation of seal integrity may require more rigorous characterization, and heterogeneity of fluvial rift formations will make characterization complex. Finally, it was thought that some seismic data previously collected by industry in the 1980s could potentially be reprocessed using current technology, if it can be acquired

The geology breakout therefore recommended that geologic assessment could be conducted in phases. It was seen that Phase One, at a cost of about $0.1M, could assemble existing information, and could include new modeling based on existing seismic data, in order to lay the groundwork for a more rigorous geologic assessment of the CCS potential in the Midcontinent Rift. This was the concept that was realized by the State funding that resulted in the present report. It was anticipated by the breakout discussion that an important purpose of a Phase I study would be to inform a decision on whether it is warranted to move on to a phase II study. A Phase Two was foreseen by the group as a geologic assessment based on new geophysical surveys and about 3 to 6 boreholes, at a cost of perhaps $5M to $10M, possibly through public funding or a public-private partnership. It was anticipated that the objective of Phase Two would be to determine whether CCS potential exists in the Midcontinent Rift, while if the results of a Phase Two were positive, Phase Three would expand the geological assessment to estimate the geologic storage capacity of the Rift, and begin characterizing the most promising sites.

A meeting summary, and the presentations, were posted on the Minnesota Geological Survey web site soon after the meeting.

Carbon dioxide stationary sources in Minnesota

A compilation of major CO_2 stationary point sources in Minnesota was compiled as part of the PCOR Phase I activity (Jensen et al., 2005b), including sources such as coal-fired power plants, natural gas-processing plants, ethanol plants, and refineries. For the PCOR region ranging from Missouri to Alberta, nearly 1400 significant point sources were identified, using US Environmental Protection Agency and Environment Canada databases. Across the region, about two-thirds of the CO_2 was seen to be emitted during electricity generation, followed by the manufacture of paper and wood products, petroleum and natural gas processing, chemicals and fuels production, ethanol production, petroleum refining, and cement/clinker production. The resulting database lists 169 point sources in Minnesota (Figure 13), including 7 agricultural processing facilities, 1 co-generation, 78 electrical generating, 17 ethanol plants, 13 industrial/institutional heat and power, 6 iron ore processing, 10 manufacturing, 6 municipal heat and power, 14 natural gas transmission, 6 paper and wood products, 2 petroleum refining, 4 sugar production, and 5 waste processing facilities (Figure 14). The largest source in the state, estimated at 18.0 million tons CO_2/yr at the time, is the Xcel Energy Sherburne County (Sherco) coal-fired electrical generating station near Becker, MN. Examples of sources at levels under 10 million tons CO_2/yr are the Minnesota Power Laskin Energy Center near Aurora MN, and the Minnesota Power Boswell Energy Center near Cohasset, MN. Remaining sources in the state each emit less than 4 million tons CO_2/yr.

Existing pipeline infrastructure

PCOR information resources also include a compilation of pipelines in Minnesota, with the most extensive system being for distribution of natural gas (Figures 15 and 16). In addition, two crude oil pipelines cross the state, and additional lines convey other liquids such as refined products.

Minnesota population density by County

Population density data by county based on the 2000 census are available from the Minnesota Department of Administration web site. These data show densities exceeding 70 per square mile in the Twin Cities region and in some southeastern Minnesota counties, with lesser densities in surrounding regions (Figure 17).

Minnesota regulatory context

Minnesota Department of Health (MDH) well management rules and laws, available on their web site, include the Minnesota rules chapter on wells and borings, Chapter 4725, which indicates that the use of wells or borings

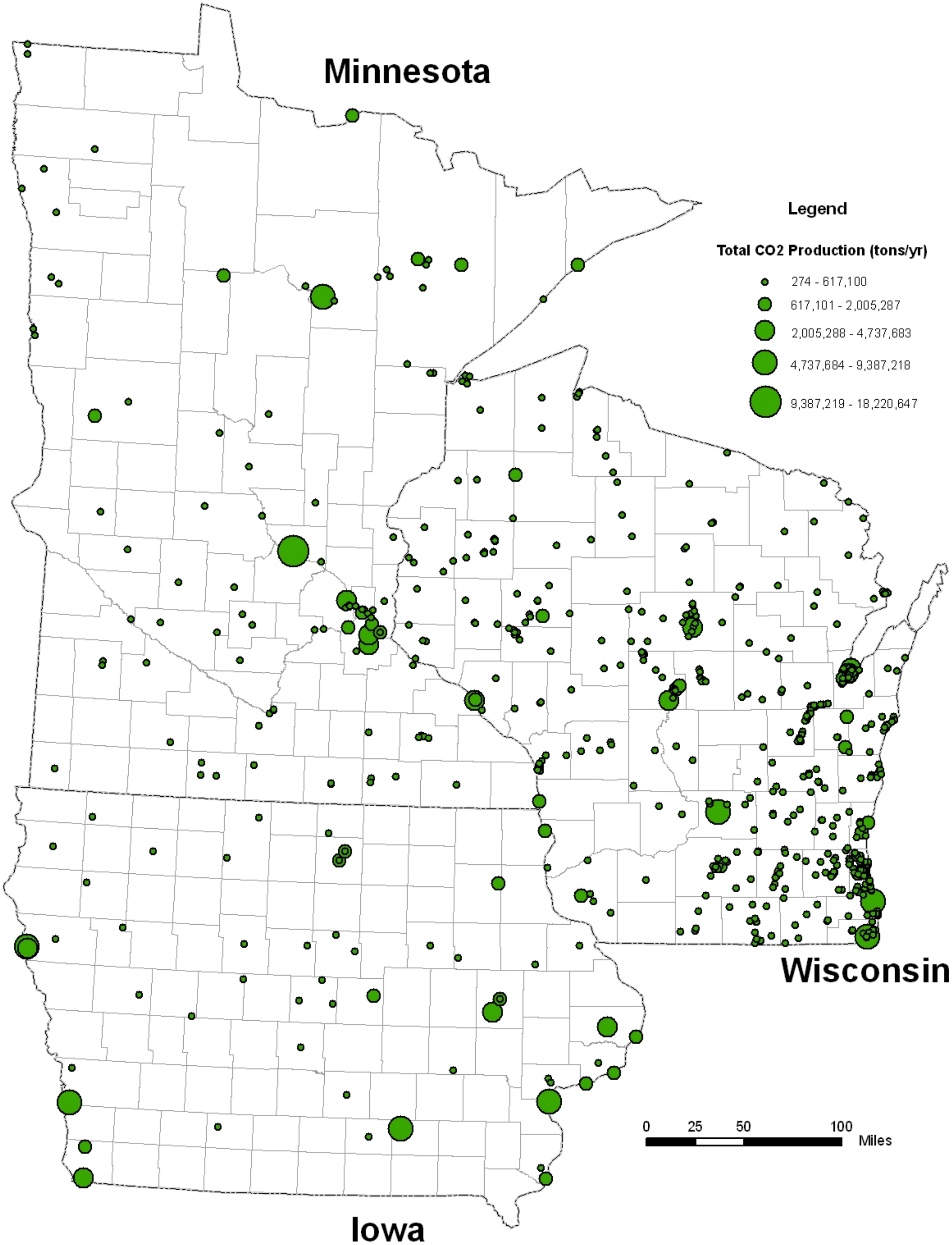


Figure 13. Stationary point sources of CO_2 in Minnesota, Iowa, and Wisconsin, showing estimated annual emissions (PCOR)

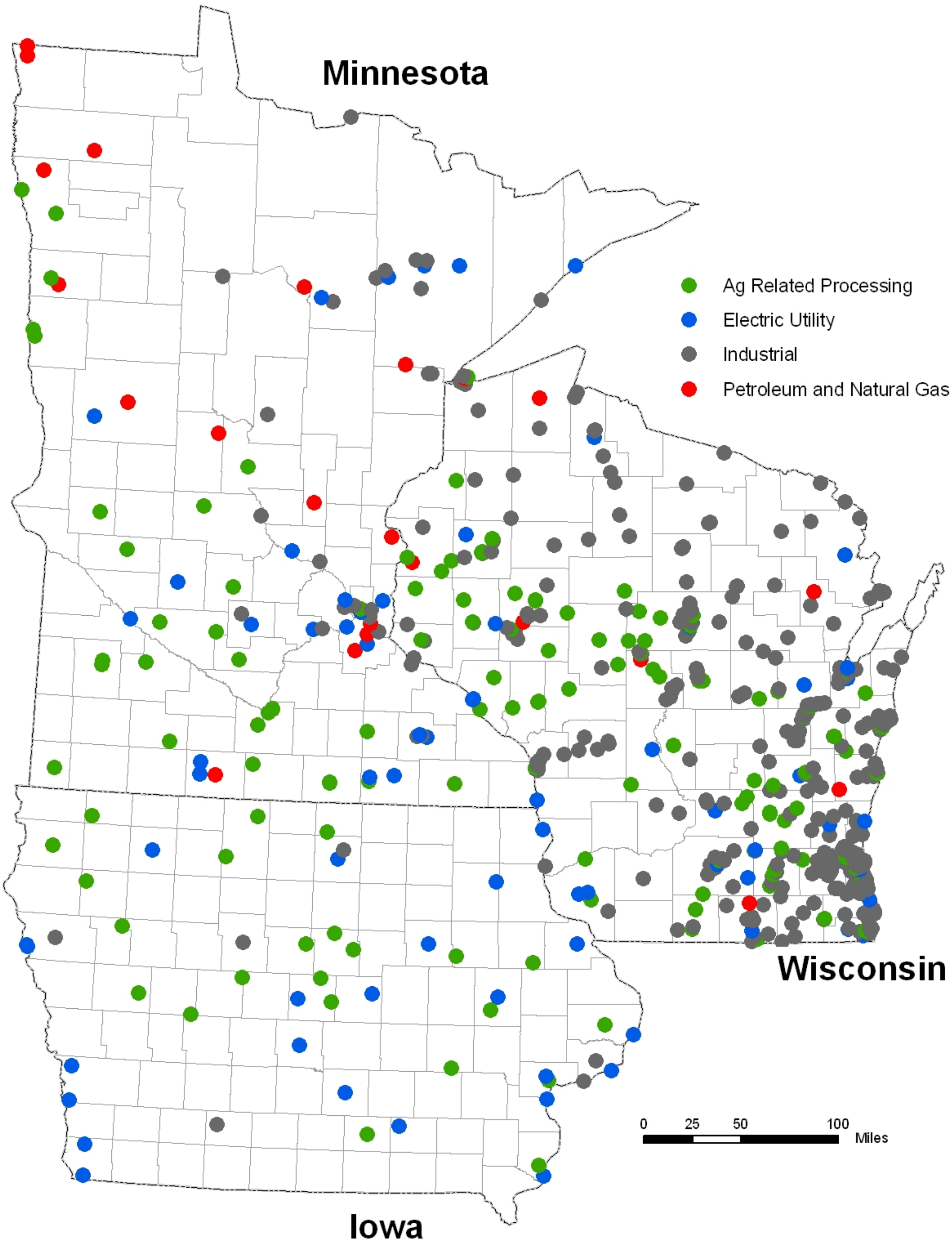


Figure 14. Stationary point sources of CO_2 in Minnesota, Iowa, and Wisconsin, showing major categories (PCOR)

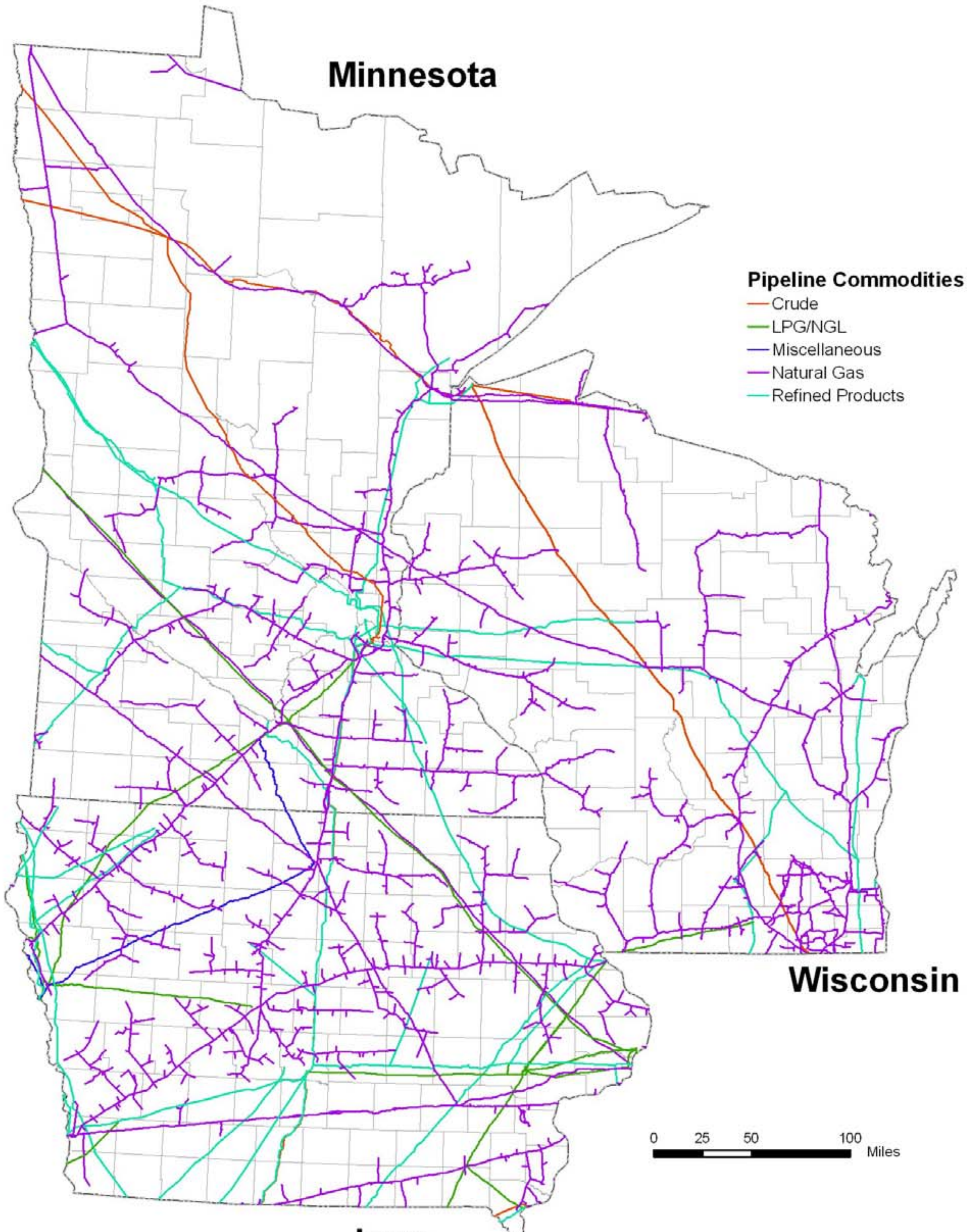


Figure 15. Pipelines in Minnesota, Iowa, and Wisconsin, showing major categories (PCOR)

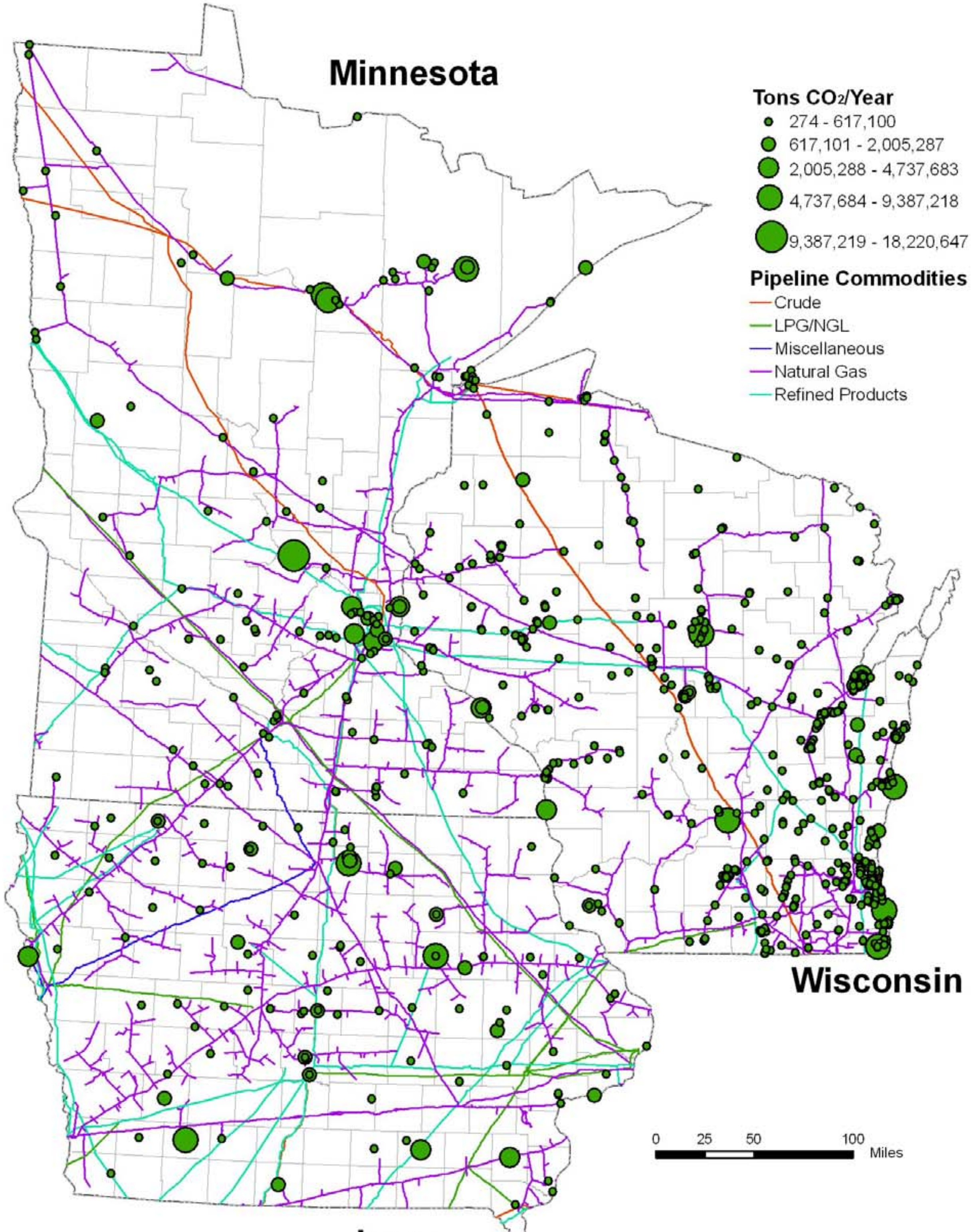


Figure 16. Pipelines in Minnesota, Iowa, and Wisconsin, and stationary point sources of CO_2 (PCOR)

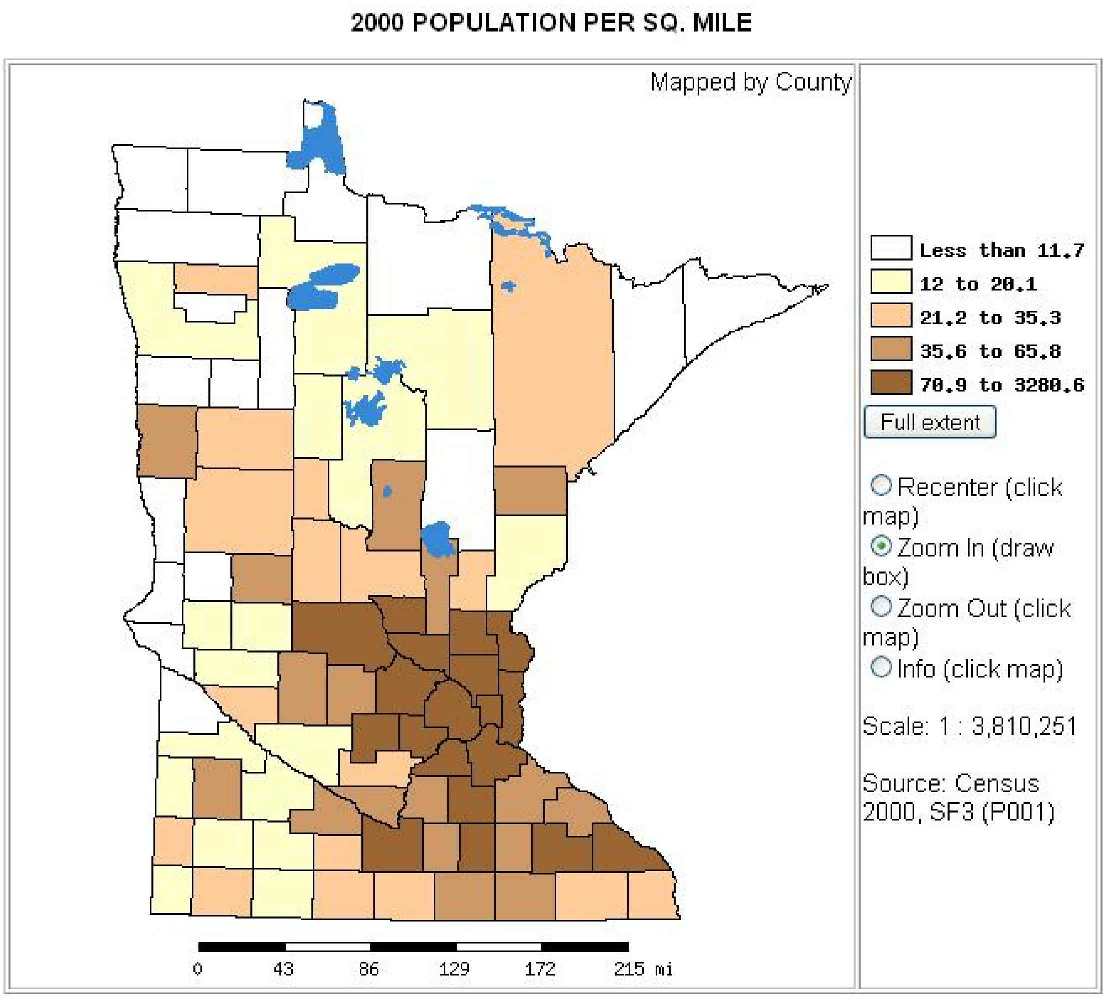


Figure 17. Minnesota population density by County (Minnesota Department of Administration)

for disposal is prohibited; a variance thus would be required to implement CCS. The rule states that a well or boring must not be used for disposal of surface water, groundwater, or any other liquid, gas, or chemical.

Existing underground gas storage

As has been seen from experience in Illinois, for example, underground gas storage facilities (Figure 18) provide much knowledge and experience that is relevant to contemplation of carbon sequestration. In Minnesota, a major underground gas storage facility (Figure 19) is managed by CenterPoint Energy near the town of Waterville, MN, midway between Mankato and Faribault, at the intersection of Waseca, Rice and LeSueur counties. CenterPoint Energy indicates in its literature that the facility is used to store natural gas during the summer and to withdraw gas during periods of high demand in the heating season. The gas is stored about 800 to 900 feet underground in the Mt. Simon sandstone, under an inverted bowl shaped formation of non-porous rock. The structure has over 70' in vertical dimensions, with gas storage under an area of 440 acres. The stored gas is held in place by the natural pressure (~300psi) of the water in the aquifer. Company literature indicates that the facility currently stores 5,000,000 MCF (1,000 ft3) of base gas injected during initial construction of the field, and not used during seasonal operation. In addition, the field holds 2,000,000 MCF of working gas, which can be cycled each year for storage and production. CenterPoint Energy reports that they normally cycle between 1.0 BCF and 1.6 BCF on an annual basis depending on the weather and need for supplemental production. The facility has a production capacity of approximately 50,000 MCF/Day, using 29 injection and withdrawal wells. The gas is withdrawn from the storage field, compressed, dried and delivered to the Northern Natural Pipeline system at Medford, MN. Northern Natural delivers the gas to CenterPoint Energy's distribution system. The storage facility development was begun in 1966 with the first gas being injected in 1968. It has been in continuous service since then. The Minnesota Department of Natural Resources regulates the storage of gas underground. The discharge of water at the facility is regulated by the Minnesota Pollution Control Agency. CenterPoint Energy has active permits for its operation from both of these agencies.

Current water resource utilization

The most prospective areas in the MRS for geologic sequestration lie beneath a sequence of Paleozoic bedrock units that include the most widely utilized aquifers in the state of Minnesota. These and other aquifer systems that overlie the MRS supply over 75 percent of the potable water supply for citizens in southeastern and east-central Minnesota, including the Twin Cities Metropolitan area. Protection of freshwater aquifers that overlie the proposed CO_2 storage sites therefore will be a paramount consideration in any evaluation of the potential for geologic sequestration. Deep geologic injection of CO_2 will displace saline groundwater from the targeted reservoirs, and site assessments must consider the potential for that saline water, or leaking CO_2, to migrate upward into freshwater aquifers. In some of the areas under consideration one or more of the lowermost Paleozoic aquifers may not currently be in use. However, those aquifers are likely hydrologically connected to other aquifers, or to places where they are in use. It is assumed that freshwater in even a portion of any Paleozoic aquifer would not be considered expendable for these purposes, and avoiding any impact on these aquifers would presumably be the intent of the evaluation and any development.

Energy supply scenarios

As an example of long-term planning of energy supply scenarios for Minnesota and the surrounding region, the Minneapolis-based Great Plains Institute released, in June 2007, an energy transition roadmap under the title 'Powering the Plains', available on their web site. Milestones were outlined under the themes energy efficiency, coal, wind energy, hydro, nuclear power, biomass, and hydrogen. With respect to coal milestones, stakeholders proposed for policy-makers' consideration that by 2015, the region should strive to have at least two Integrated Gasification Combined Cycle (IGCC) projects with CCS through design, construction and into full operation, including at least one project using sub-bituminous coal and another using lignite; by 2015, the region should

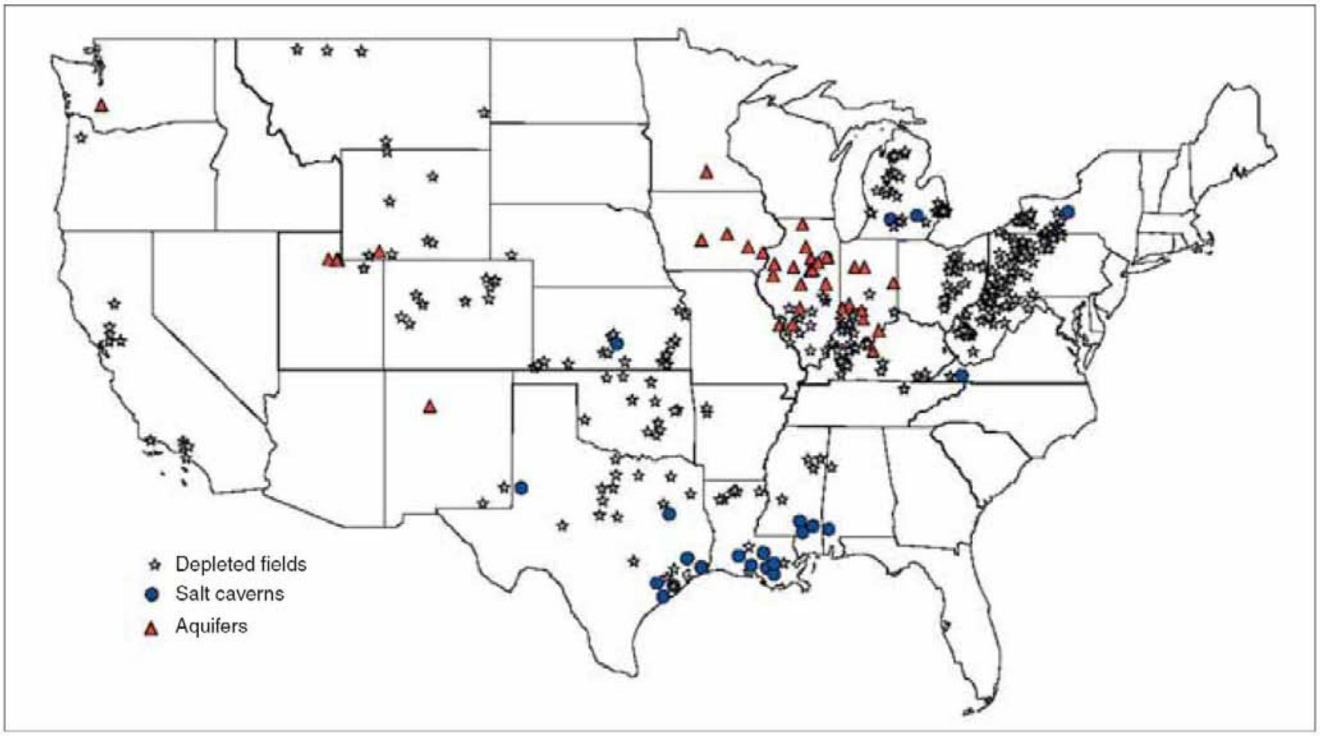


Figure 18. Underground gas storage facilities in the US (MGSC, after International Energy Agency)

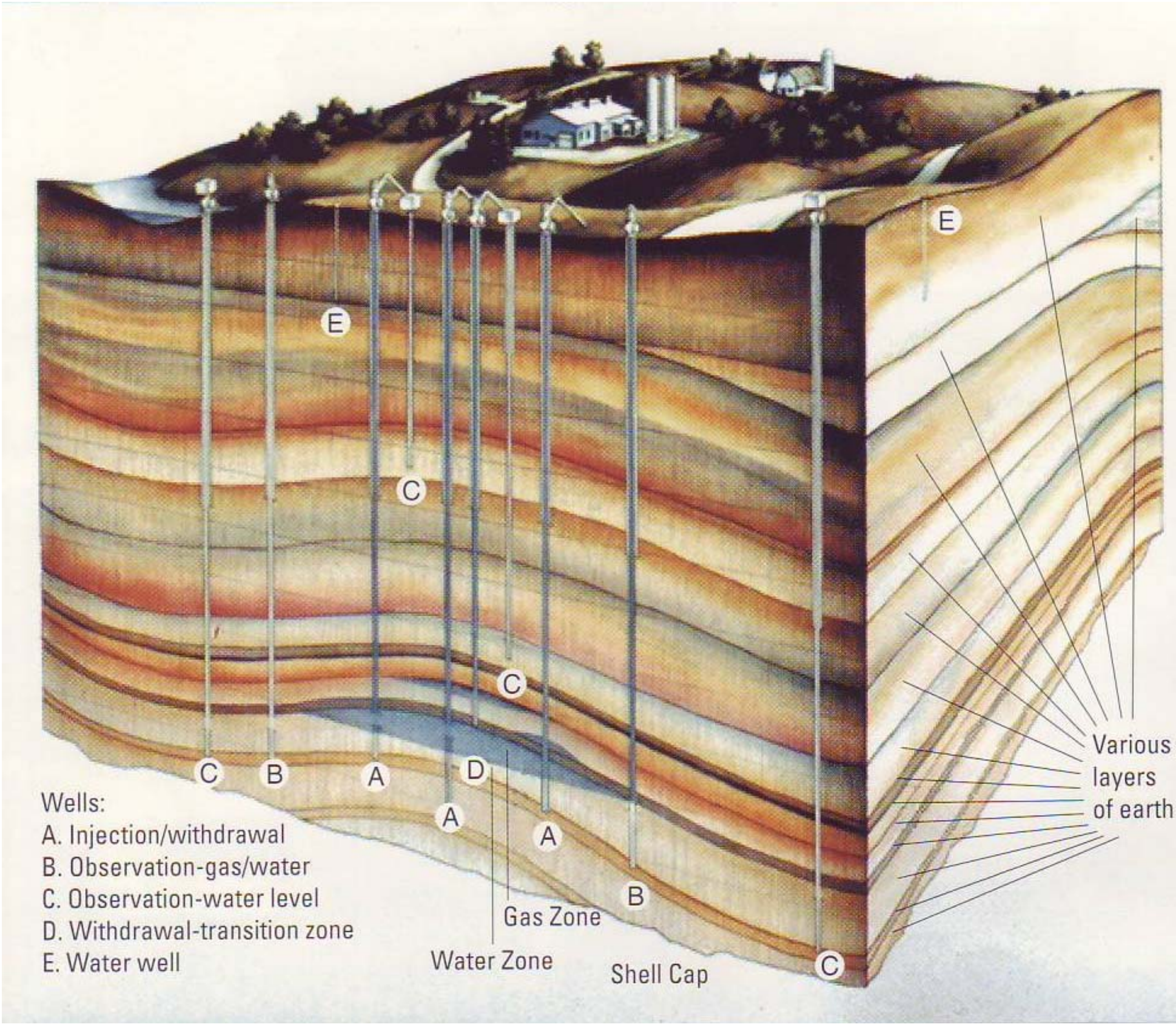


Figure 19. CenterPoint Energy underground gas storage facility, Waterville, MN (CenterPoint Energy)

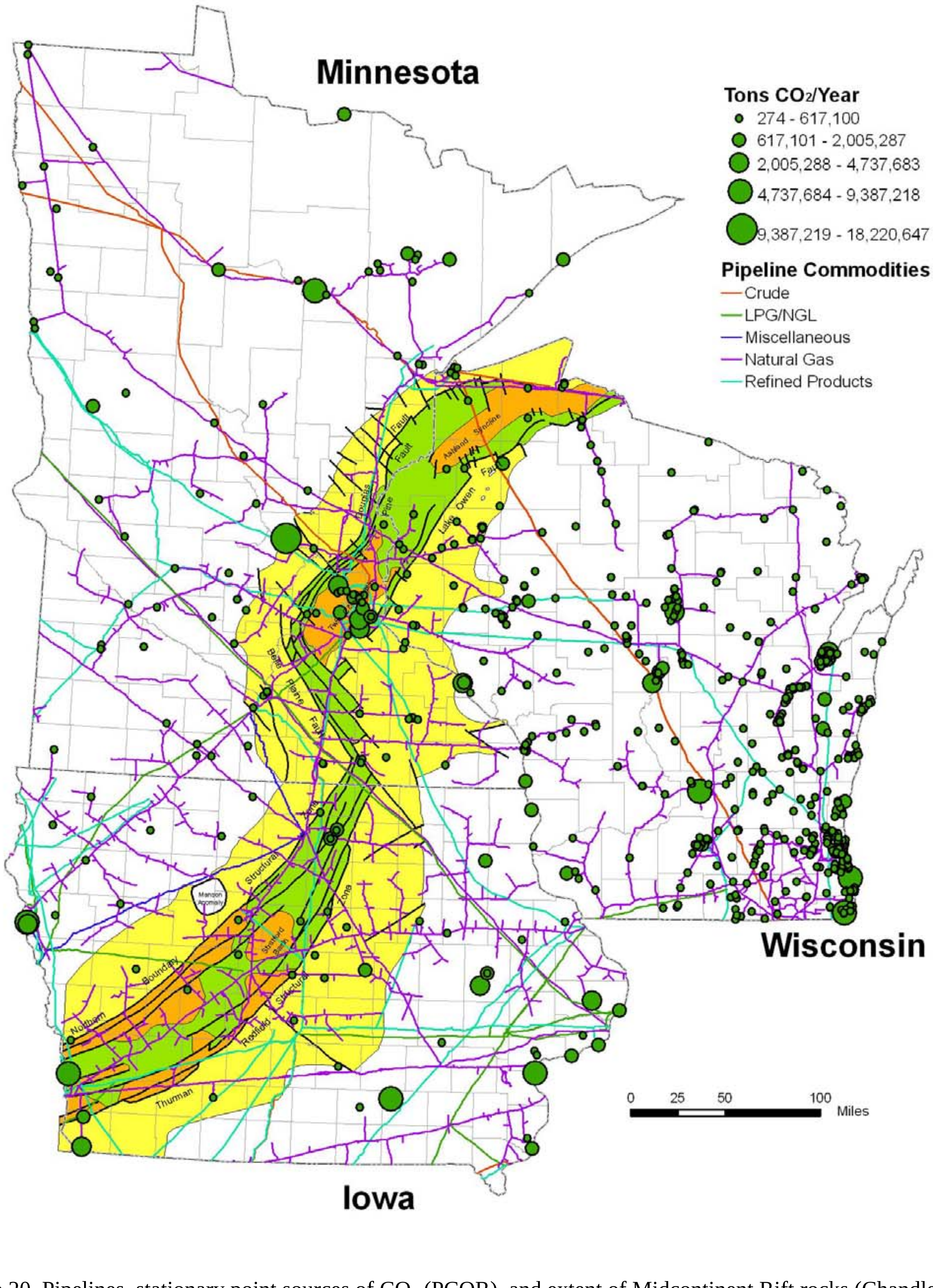
demonstrate commercial scale post-combustion capture of CO_2 at a pulverized coal plant; by 2020, the region will have operating at commercial scale multiple IGCC and/or pulverized coal combustion plants with CCS; and by 2055, the region will generate 80 percent of its coal-based electric power from plants that eliminate or capture CO_2 emissions. The report also recommended that in order to know whether or not the region is achieving its long-term vision for coal use, each jurisdiction should track the percentage of total CO_2 from coal use captured and permanently stored underground, and percent of new coal plant capacity installed with low-carbon technology and CCS, along with other measures.

Summary

Minnesota, with its population of about five million, and greenhouse gas emissions of approximately 151 million metric tons (MMt) of gross CO_2 equivalent (CO_2e) emissions in 2005 (Strait et al., 2007), has made a commitment to reduce emissions of greenhouse gases, by 15 percent before 2015, 30 percent by 2025, and 80 percent by 2050. Carbon capture and storage is one of the options being considered to pursue this objective. This will require export of CO_2 by pipeline, or confirmation of repositories within the State. Terrestrial sequestration is one option, while geologic options are possible deep injection, and possibly also mineral carbonation. Deep injection is only conceivable in the sedimentary rocks of the Midcontinent Rift. Any possible developments regarding this possibility will progress in the context of knowledge of our existing CO_2 point sources, existing pipeline infrastructure (Figure 20), population density, existing regulations, experience gained from successful underground gas storage in the State, and future energy supply scenarios.

MANDATE OF THE REPORT

In the spring of 2007, a bill passed by the 85th Minnesota Legislative Session as S.F. No. 2096, the omnibus environment, natural resources, energy and commerce appropriations, signed by Governor Pawlenty on May 8, 2007, provided for carbon sequestration studies by specifying in the summary of appropriations that $90,000 be provided to the Minnesota Geological Survey (MGS) for the purposes of geologic carbon sequestration assessment. The bill defines geologic carbon sequestration as injecting CO_2 into underground geologic formations where it can be stored for long periods of time to prevent its escape to the atmosphere. Section 36 of the Bill specifies that in Part A of the work, Minnesota Geological Survey shall conduct a study assessing the potential capacity for geologic carbon sequestration in the Midcontinent Rift system in Minnesota. The study is to assess the potential of porous and permeable sandstone layers deeper than one kilometer below the surface that are capped by less permeable shale and must identify potential risks to carbon storage, such as areas of low permeability in injection zones, low storage capacity, and potential seal failure. The study is to identify the most promising formations and geographic areas for physical analysis of carbon sequestration potential. The study must review geologic maps, published reports and surveys, and any relevant unpublished raw data with respect to attributes that are pertinent for the long-term sequestration of carbon in geologic formations, in particular, those that bear on formation injectivity, capacity, and seal effectiveness. The study must examine the following characteristics of key sedimentary units within the Midcontinent Rift system in Minnesota: (1) likely depth, temperature, and pressure; (2) physical properties, including the ability to contain and transmit fluids; (3) the type of rocks present; (4) structure and geometry, including folds and faults; and (5) hydrogeology, including water chemistry and water flow. In Part B of the work, the bill specifies that the commissioner of natural resources, in consultation with the Minnesota Geological Survey, shall contract for a study to estimate the properties of the Midcontinent Rift system in Minnesota, as described in paragraph (a), clauses (1) to (5), through the use of computer models developed for similar geologic formations located outside of Minnesota which have been studied in greater detail. The bill further specifies that MGS shall consult with the Minnesota Mineral Coordinating Committee, established in Minnesota Statutes, section 93.0015, in planning and implementing the study design, and that a Report to the commissioner of natural resources be submitted with the results of the study to the senate and house committees with jurisdiction over environmental and energy policies no later than February 1, 2008.



igure 20. Pipelines, stationary point sources of CO_2 (PCOR), and extent of Midcontinent Rift rocks (Chandler et al, 1989), showing Bayfield Group in yellow, Oronto Group in orange, and volcanic rocks in green

EXTENT AND THICKNESS OF DEEP SEDIMENTARY ROCKS IN THE UPPER MIDWEST: GEOPHYSICAL INFERENCES

Val W. Chandler, Minnesota Geological Survey, University of Minnesota

Introduction

Much of the Midcontinent Rift System is concealed beneath a cover of Pleistocene glacial materials and Phanerozoic rocks; therefore geologic studies of rift features rely to a significant extent on geophysical data. In addition to mapping rift features at or near the surface, geophysical data provides essentially the only tools to investigate the crustal structure of the rift. This section summarizes the structure of the rift in Minnesota and Wisconsin, as revealed by previous investigators, and uses a three-dimensional visualization scheme to evaluate and synthesize three independently-derived geophysical interpretations of rift structure. Similar to other sections of this report, emphasis will be on the sedimentary rocks of the rift, especially with regard to their thickness and basin geometry.

Previous Geophysical Studies

Gravity and Magnetic Surveys

Gravity and magnetic data have been the primary tools for investigating the Midcontinent Rift System. In fact, the discovery and regional significance of the rift was largely realized through gravity and magnetic investigations (Hinze and others, 1997; King and Zietz, 1961; Thiel, 1956, Woollard and Joesting, 1964). In recent years, high-quality gravity and magnetic data sets have become available, and these data have become important supplements for geologic mapping parts of the Midcontinent Rift System, as well as in adjacent Precambrian terranes (Chandler and others, 2007). Recent versions of the gravity and aeromagnetic data for the rift in Minnesota and Wisconsin are shown in Figures 21 and 22, respectively. The gravity data in Minnesota and Wisconsin are based on ground stations that are typically spaced 1 to 5 km apart (Chandler and Schaap, 1991; Daniels and Snyder, 2002), whereas the aeromagnetic data were acquired along flight lines that were spaced 400 to 1000 meters apart (Chandler, 1991). All of the aeromagnetic data and much of the gravity data shown in Minnesota were acquired with support from the Minnesota Legislature as recommended by the Legislative Commission on Minnesota Resources.

The Midcontinent Rift System extends from southeastern Michigan, westward through Lake Superior, and southward to Oklahoma (Hinze and others, 1997). In Minnesota and Wisconsin the rift is characterized by a prominent, northeast-striking belt of intense magnetic and gravity highs (Figures 1 and 2). These highs delineate blocks of predominantly mafic volcanic rocks and associated intrusions that, following their deposition in grabens or half-grabens, were uplifted along bounding faults to form the St. Croix horst (Allen and others, 1997; Chandler and others, 1989). The volcanic rocks are structurally flanked and locally overlain by the slightly younger sedimentary rocks of the Oronto and Bayfield groups. These sedimentary rocks have relatively low densities and are essentially non-magnetic, so they are characterized by strongly negative gravity anomalies and subdued magnetic signatures that flank the strongly positive signatures of the axial horst (Figures 1 and 2, respectively). In southeastern Minnesota, the axial block of volcanic rocks narrows and is deflected abruptly to the south-southeast along the Belle Plaine Fault zone (Allen and others, 1997).

Two-Dimensional Modeling of Gravity and Magnetic Data

Modeling of gravity and magnetic data has been frequently used to investigate the subsurface structure of the rift. To simplify interpretation, most of these studies have been conducted along profiles assuming two-dimensional (strike infinite) sources. Early studies along these lines included gravity modeling in southeastern

Minnesota by Craddock (1963), and magnetic modeling by King and Zietz (1971). Although informative, these earlier studies were usually not very well constrained by rock property data or by other geophysical data.

More recently, Chandler et al. (1989) used seismic reflection and seismic refraction data in conjunction with two-dimensional gravity and magnetic modeling along four profiles to study the Mid-Continent rift system between northwestern Wisconsin and central Iowa (three of these profiles are located on Figures 1 and 2). Mafic lavas in medial horsts were interpreted to be at least 10 km thick, and mafic roots extending to mid-crustal depths were defined from gravity modeling in northwestern Wisconsin, southeastern Minnesota, and central Iowa. A strong normally directed remanent magnetization was modeled for most lavas, although some lavas deep in the section of northwestern Wisconsin and central Iowa were modeled as magnetically reversed. The horsts were inferred to be bounded by faults that are vertical or dip moderately inward. Several of these faults were interpreted as having originated as growth faults in fault-bounded grabens, but these faults were thought to have been transposed into reverse faults by a late-stage compressional event. The medial horsts were shown to be flanked by several half-graben basins that contain as much as 5 km of sedimentary material inferred to be lithologically akin to the Oronto and Bayfield Groups of Michigan and Wisconsin. Several synclinal basins characterized by 2-4 km of sedimentary rocks were recognized atop the medial horsts. The authors pointed out that when viewed regionally, the four interpretive profiles show a marked asymmetry, with regard to the off-axis placement of the deep mafic roots and the positions of postulated growth faults. This asymmetry was thought to be consistent with the rift propagating as a series of northeast-striking, en echelon half grabens, separated by northwest-striking scissor faults or accommodation zones.

Allen et al. (1997) subsequently presented an integrated geophysical investigation of the Midcontinent Rift System in Minnesota, Wisconsin and western Lake Superior. Combining geologic, rock property, and seismic reflection data, he conducted two-dimensional gravity and magnetic modeling along a series of profiles in Minnesota and Wisconsin (Figures 1 and 2). In northwestern Wisconsin, over 6 km of Bayfield strata were interpreted to fill the basin east of the St. Croix Horst (informally named the Emerald basin). In Minnesota and Wisconsin, the great majority of the rift's volcanic rocks were found to be normally polarized and probably younger than the recorded ca. 1,098-Ma magnetic reversal, in contrast to western Lake Superior, where the lower half of the volcanic sequence was found to be reversely polarized and was probably erupted before ca. 1,098-Ma. Gravity modeling also suggested that the mass deficiency associated with crustal thickening along the rift is probably compensated by the positive effect of dense rift intrusions in the lower crust. It was suggested that the volume of magma trapped in the lower crust may be similar to that erupted into the rift basin.

Three-Dimensional Modeling of gravity data

Although two–dimensional (profile-based) modeling of geophysical data has been commonly applied to the Mid-Continent Rift System (see above), three-dimensional modeling has been comparatively rare, largely because of its complex and time-consuming nature. Anderson (1992) used seismic reflection interpretation and two-dimensional gravity modeling along a series of profiles to compile a three-dimensional visualization of rift structure in Iowa. Three-dimensional modeling of gravity data, used in conjunction with limited geologic control and seismic reflection profiles, has been used to investigate the upper crustal structure of the rift beneath eastern Lake Superior (Mariano and Hinze, 1994), western Lake Superior (Allen , 1994 and Allen and others, 1997), and Minnesota — Wisconsin (Allen, 1994). This study will focus on the Minnesota-Wisconsin modeling by Allen, and its implications regarding crustal structure of the rift in this area.

Allen (1994) developed his own gravity modeling software, where three-dimensional bodies were approximated by arrays of vertical line elements with assigned densities. For modeling in Minnesota and Wisconsin, Allen (1994) used rock-property data and the results from previous modeling to assign densities (gm/cc) of 2.40 for the Bayfield Group (Hinckley Sandstone and Fond du Lac Formation), 2.65 for the Oronto Group (Solor Church

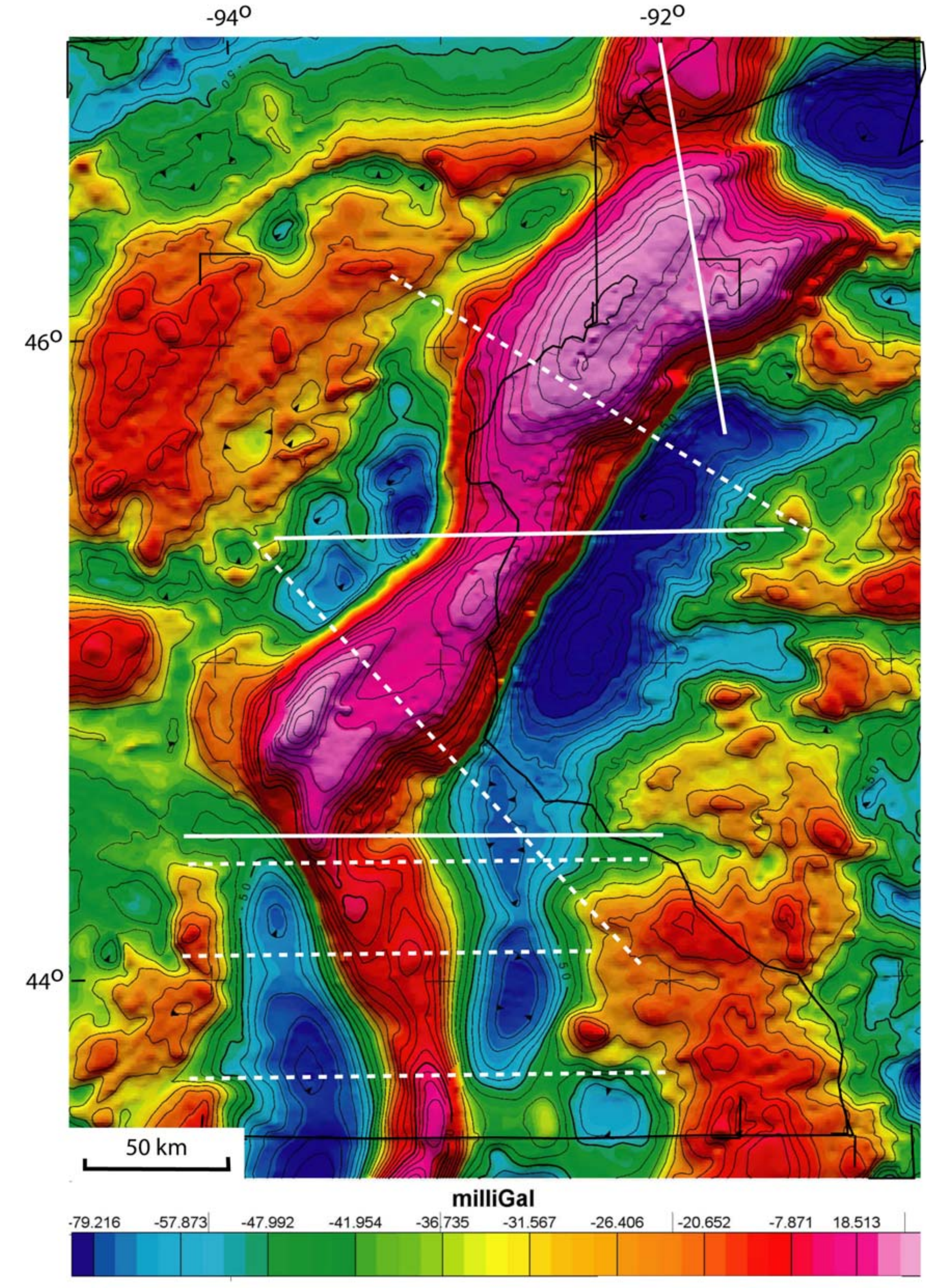


Figure 21. Bouguer gravity anomaly map of the Midcontinent Rift System in Minnesota and Wisconsin; color shaded relief presentation with false illumination from north at 45 degrees inclination. Solid white lines locate profiles where two dimensional gravity and magnetic model studies were conducted by Chandler et al. (1989) and by Allen (1994). Interpretation along these lines was constrained by nearly coincident seismic reflection data (Figure 26). Light dashed lines locate additional profiles with two-dimensional modeling by Allen (1994).

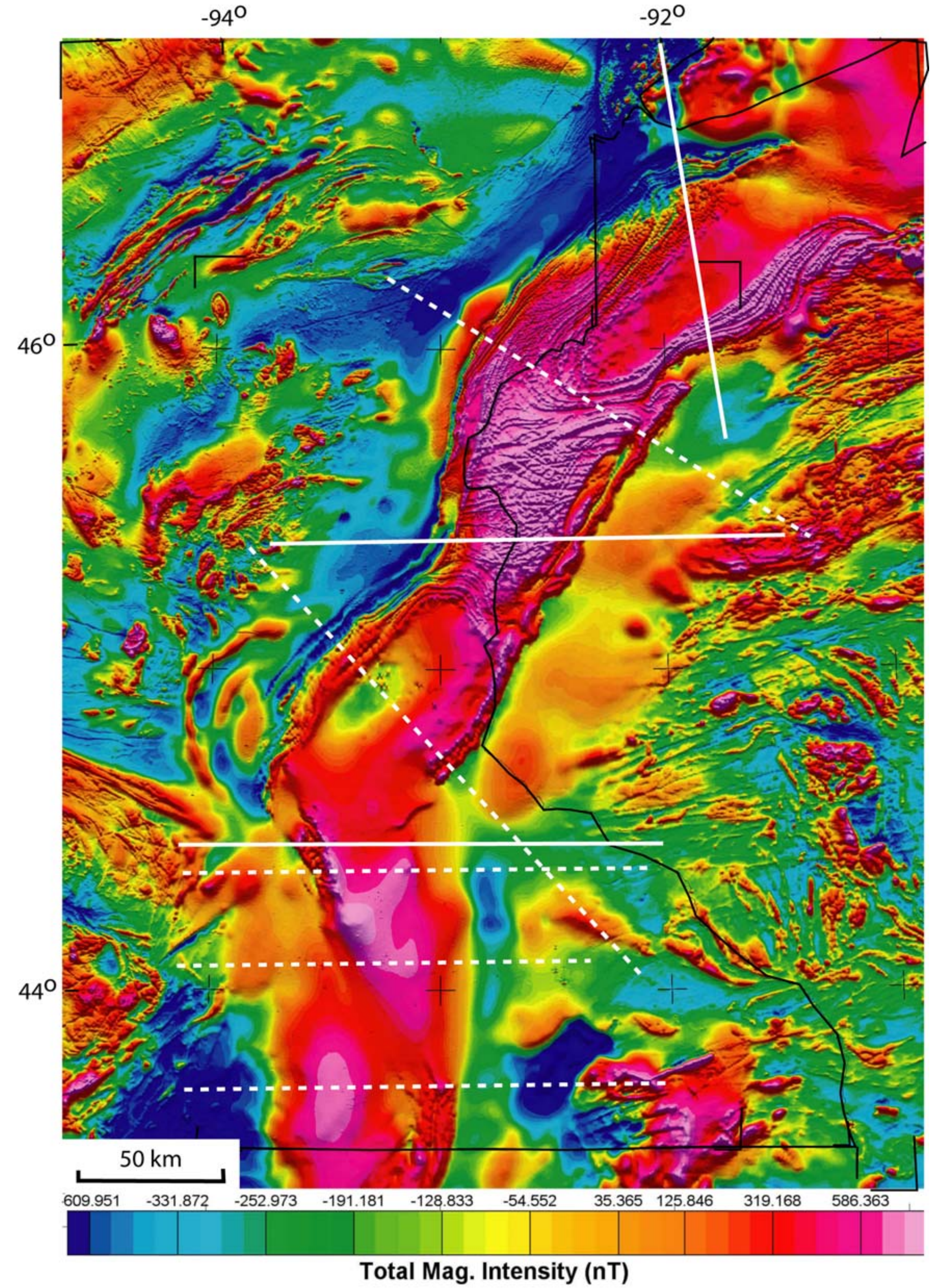


Figure 22. Aeromagnetic anomaly map of the Midcontinent Rift System in Minnesota and Wisconsin; color shaded relief presentation with false illumination from north at 45 degrees inclination. Solid white lines locate profiles where two dimensional gravity and magnetic model studies were conducted by Chandler et al. (1989) and by Allen (1994). Interpretation along these lines was constrained by nearly coincident seismic reflection data (Figure 26). Light dashed lines locate additional profiles with two-dimensional modeling by Allen (1994).

Formation), 2.95 for the rift volcanic rocks (Chengwatana Volcanic Group), and 2.75 for the pre-rift crustal rocks. Bodies representing these geologic units were translated into the modeling program, and their subsurface configurations were iteratively adjusted until a suitable match to the observed gravity signature was attained. Wherever possible, modeling was constrained at the surface by geologic control and in the subsurface by seismic reflection sections. The results of the modeling were presented by Allen (1994) as a series of maps showing the estimated thicknesses of the Bayfield Group, the Oronto Group and the volcanic sequence. The original model and grid files are no longer available (D. J. Allen, personal communication), so scanned images of the original grid maps were imported into ArcGIS, where they were registered and digitized into maps of thickness and depth. These were subsequently interpolated into raster files for display. Images of these reconstituted thickness maps are presented in Figures 23 (Bayfield Group), Figure 24 (Oronto Group), and Figure 25 (Volcanic rocks).

Allen's (1994) three-dimensional model of the rift in Minnesota and Wisconsin has some definite limitations, and the results shown in Figures 23-25 must be used with appropriate caution. The primary constraints to this modeling—geological control and seismic reflection profiles—are rather sparse in the southern part of the model (see Figure 26). In fact no seismic control and virtually no geologic control exists south of latitude 44° 30'. Consequently, determining considerations such as the relative proportions Oronto vs. Bayfield strata in a basin becomes quite ambiguous. Furthermore, the model anomaly data matches the observed data only to within +/- 5 milliGals (about 5% of maximum anomaly amplitude in the area), and does not closely match some of the high-gradient areas, such as along the edges of the St. Croix Horst (Allen, 1994). Nonetheless, the three-dimensional model by Allen (1994), does serve as a good starting point to visualize the rift in three dimensions, and it provides at least some rough estimates regarding the thicknesses and gross structure of the sedimentary basins associated with the rift.

The thickness map in Figure 23 indicates that Bayfield Group sequences in Minnesota and Wisconsin are distributed into two wedge-like basins that flank the axial horst of the rift (Saint Croix Horst). The eastern basin (Emerald basin) is interpreted to contain up to 6 km of Bayfield strata, with the greatest thicknesses in northwestern Wisconsin, along the faulted margins of the St. Croix horst. The Bayfield Group sequence in the eastern basin is inferred to thin to the southwest into Minnesota, where a maximum thicknesses of 3-4 km are interpreted (Figure 23). The western basin of Bayfield group rocks is interpreted to be somewhat smaller than its counterpart to the east, with maximum thicknesses of 3-4 km along the horst margin in east-central Minnesota and somewhat lesser values to the northeast and southwest (Figure 23).

The estimated thickness map in Figure 24 indicates that a thick sequence of Oronto Group strata underlies a large part of southeastern Minnesota. Maximum thicknesses of 4-5 km are interpreted for the Oronto Group in the vicinity of the "A" designation in Figure 24. In a structural context the Oronto strata would primarily lie atop the southwestern part of the St. Croix horst and beneath the southern part of the eastern basin. In this interpretation little or no Oronto Strata are inferred either beneath the western basin or the northern part of the eastern basin (compare Figures 23 and 24), although two-dimensional modeling by Allen (1994) , as well as earlier modeling by Chandler and others, (1989) implies that 1-2 km of Oronto Group strata may extend beneath these areas. A second basin of 1-2 km of Oronto strata is interpreted in northwestern Wisconsin (Figure 24), which correlates with the Ashland Syncline (Allen and other, 1997).

The estimated thickness map of the volcanic rocks (Figure 25) implies that volcanic rocks exceeds 15 km thickness beneath the southwestern and northeastern parts of the St. Croix Horst, and that they may have thicknesses exceeding 5 km beneath parts of the western and eastern basins. In addition, over 10 km of volcanic rocks are interpreted to occur along the Bell Plaine Fault zone. The apparent thinning of volcanic rocks in the vicinity the "A" designation in Figure 25 contradicts seismic reflection data in this area which implies a thick volcanic sequence (Allen, 1994, Chandler and others, 1989). This apparent thinning may actually reflect a decrease in density of the volcanic sequence due to the presence of either felsic volcanic rocks or interflow

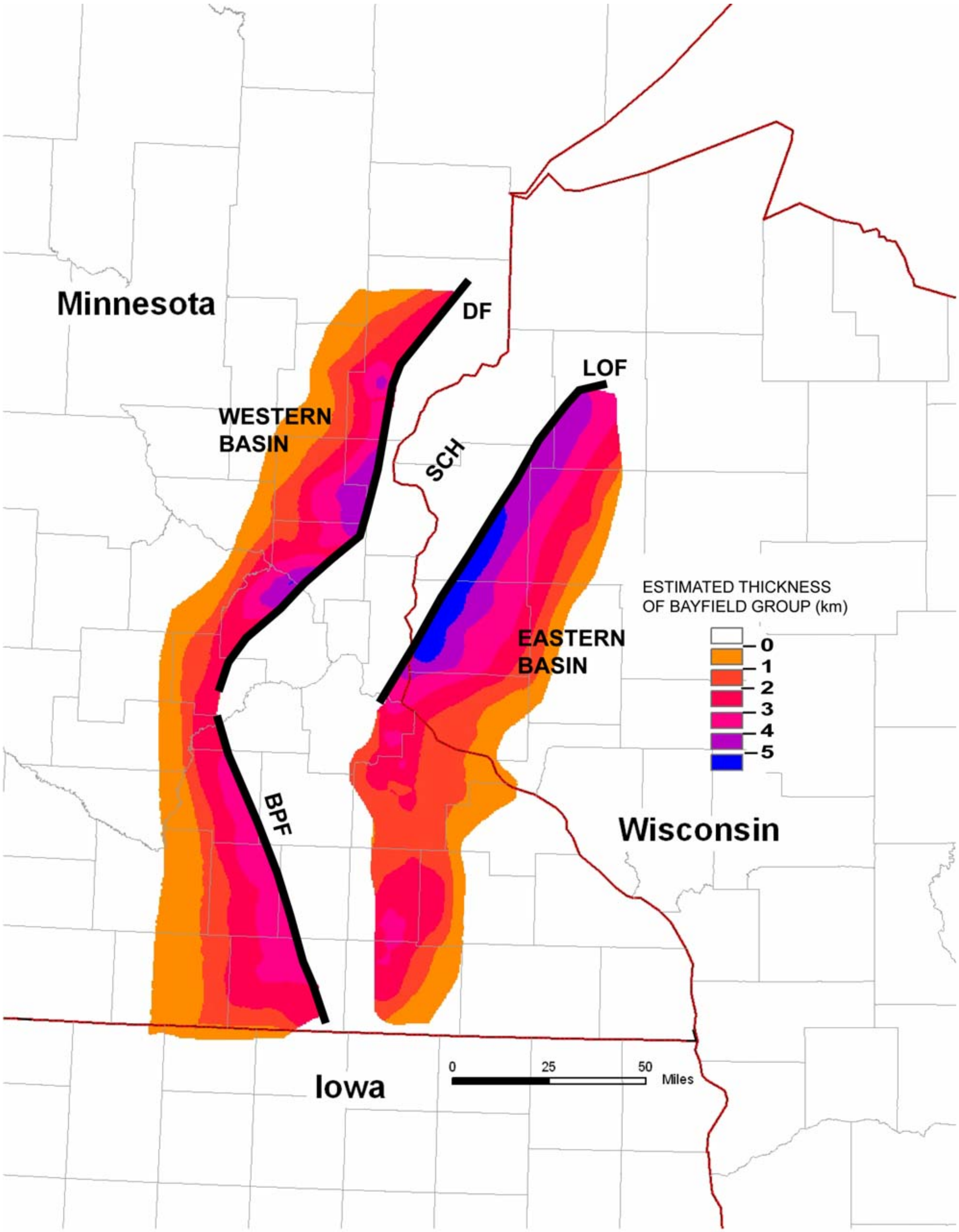


Figure 23. Estimated thickness map for Bayfield Group rocks in Minnesota and Wisconsin, based on three-dimensional gravity modeling by Allen (1994). Abbreviations: DF, Douglas Fault; LOF, Lake Owen Fault, SCH, St. Croix Horst, BPF, Belle Plaine Fault.

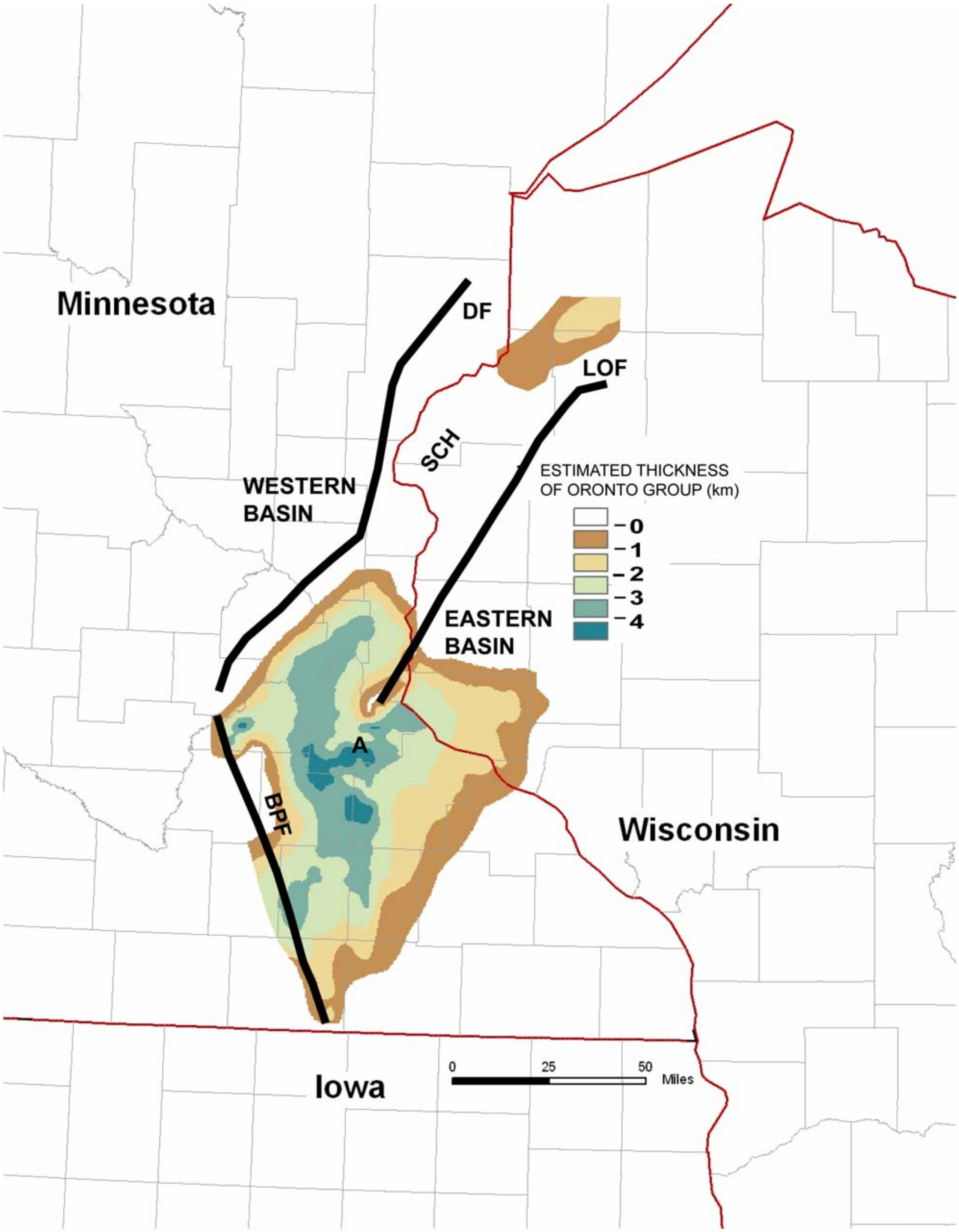


Figure 24. Estimated thickness map for Oronto Group rocks in Minnesota and Wisconsin, based on three-dimensional gravity modeling by Allen (1994). Abbreviations: DF, Douglas Fault; LOF, Lake Owen Fault, SCH, St. Croix Horst, BPF, Belle Plaine Fault. “A” designates an area that is discussed in the text.

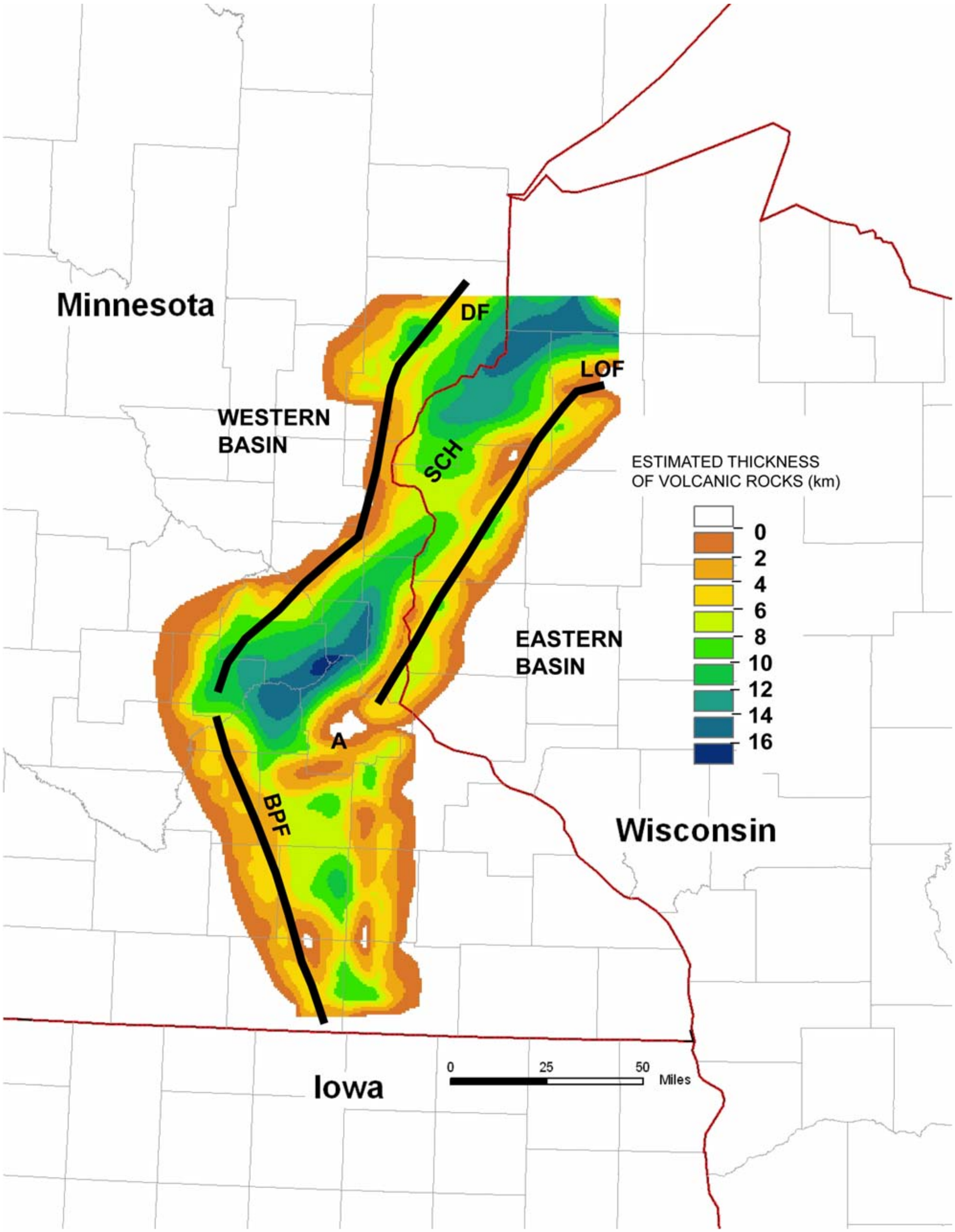


Figure 25. Estimated thickness map for Keweenawan volcanic rocks in Minnesota and Wisconsin, based on three-dimensional gravity modeling by Allen (1994). Abbreviations: DF, Douglas Fault; LOF, Lake Owen Fault, SCH, St. Croix Horst, BPF, Belle Plaine Fault. “A” designates an area that is discussed in the text.

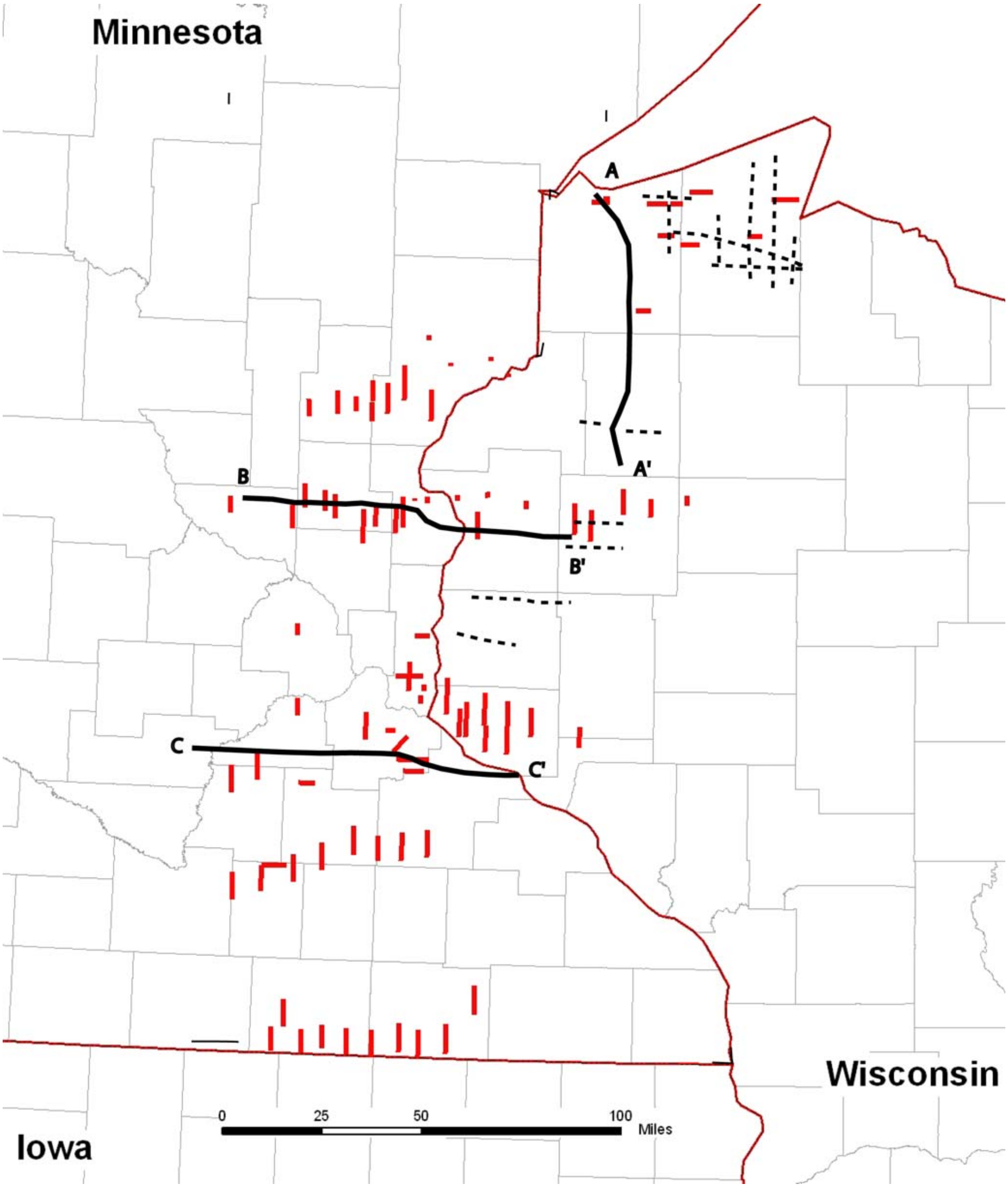


Figure 26. Seismic investigations of the Midcontinent Rift System in Minnesota and Wisconsin. Red lines designate seismic refraction profiles by Mooney et al. (1970). Heavy black lines designate seismic reflection profiles that were interpreted and incorporated into two dimensional gravity and magnetic models (Chandler et al., 1989; Allen, 1994; see Figures 21 and 22 for location of model profiles.

sedimentary rocks (Allen, 1994; Chandler and others, 1989). Thus, some of the strata interpreted to be part of Oronto Group Rocks in this area (designated "A" in Figure 4), may actually be part of the volcanic sequence (Allen, 1994).

The estimated thickness data presented by Allen (1994; Figures 23-25) can be used to roughly estimate the volumes and relative proportions of the individual rift sequences between 46°15' N and the Iowa border, which approximate the limits of the three-dimensional model study. Using the 3D Analyst module of ArcMap 9, the total volumes of Bayfield Group rocks is estimated to be approximately 29,700 km^3 (7,100 mi^3) for the eastern basin and 24,800 km^3 (6,000 mi^3) for the western basin. The volume of the Oronto Group rocks at the southwestern end of the St. Croix Horst is estimated to be about 27,000 km^3 (6,500 mi^3). The volcanic rocks have the largest volume estimate at 172,300 km^3 (41,500 mi^3). These volume estimates, imply that the entire rift sequence in Minnesota and Wisconsin may be roughly 68% mafic volcanic rocks, 11 % Oronto Group rocks and 22% Bayfield Group rocks. Compared to the rift in Iowa, the volumes derived here for rift-related sedimentary rocks are comparatively small; for example, on the basis of gravity modeling and seismic reflection sections, Anderson (1992) estimated volumes of 49,800 km3 (12,000 mi^3) and 96,700 km^3 (23,300 mi^3) for the red clastic basins lying west and east, respectively, of the horst.

Seismic Studies

Seismic investigations in Minnesota and Wisconsin have revealed further clues regarding the structure of the Midcontinent Rift System. Mooney and others (1970) conducted a series of seismic refraction profiles (Figure 26) to investigate rift structure down to depths of about 4.5 kilometers. These data were particularly helpful in determining the depths and geometries of the sedimentary basins in the rift. Mooney and others reported velocities of 8,900 -13,000 ft/ sec (2.7-3.4 km/sec) for the Bayfield Group rocks, 12,500-16,100 ft/sec (3.8-4.9 km/sec) for the Oronto Group, and 17,100-18,100 ft/sec (5.2-5.5 km/ sec) for the volcanic rocks.

Oil and gas exploration of the Midcontinent Rift System precipitated a series of proprietary seismic reflection programs in Minnesota and Wisconsin. Although no commercial oil and gas were found, the seismic reflection profiles were of potentially great scientific value. A formal agreement was reached with Petty-Ray/Geosource Inc. that allowed limited access and copying for three profiles in Minnesota and Wisconsin, which are designated A-A', B-B', and C-C' in Figure 26. These sections formed the core of the gravity and magnetic interpretations by Chandler and others (1989) and Allen (1994). Form line sections derived from the reflection profiles are shown in Figure 27. The volcanic rocks forming the core of the St. Croix Horst are characterized by strong and laterally continuous reflections that commonly exist down to the depth limits of the sections, which is approximately 15 km. These reflections provided an unprecedented view of structure within the horst and along some if the bounding faults. Unfortunately, much of the sedimentary strata of the rift appear to be either seismically transparent, or to be associated with generally poor signal quality. Allen (1994) was given very limited access to seismic reflection lines in Wisconsin that were acquired by Texaco and Amoco Production Company (Figure 23). In this arrangement the data were used to trace the base of the eastern sedimentary basin, but no copying was allowed.

Visualization and synthesis of current geophysical information

Among some of the more powerful tools to emerge recently in the geological sciences has been computer-based visualization of geographic and geologic information in three dimensions. With such capabilities, large and spatially extensive data sets can be readily observed and cross-evaluated, thereby leading to improved synthesis and geologic interpretation. One objective of this study was to use a three-dimensional visualization scheme, to bring together and cross-evaluate some independently derived geophysical interpretations of rift structure in Minnesota and Wisconsin. The geophysical interpretations for this cursory investigation were selected to meet three criteria: (1) it has to be readily available in digital form, (2) it should be spatially extensive, and (3) it has

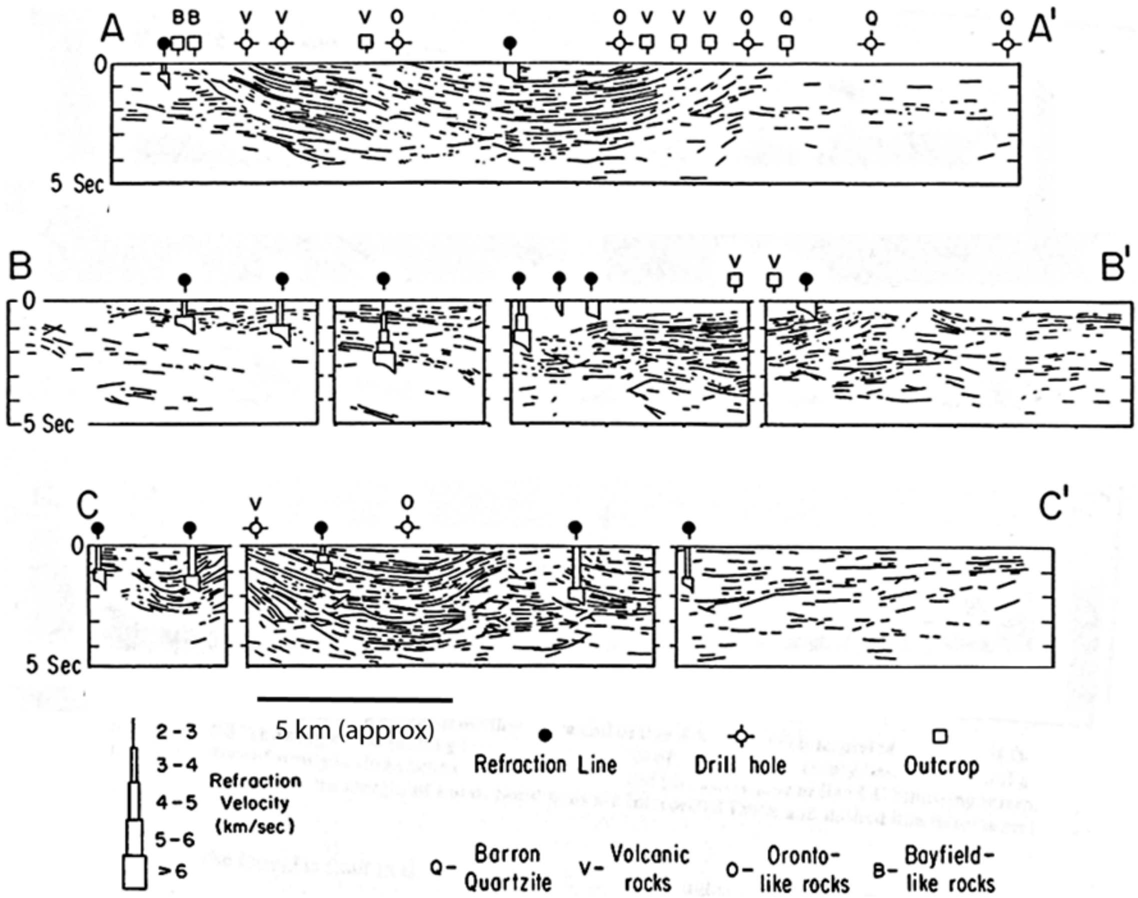


Figure 27. Form line summary of seismic reflections observed in seismic profiles A-A', B-B' and C-C' (see Figure 26). Nearby seismic refraction interpretations by Mooney and others (1970; see Figure 26) were converted to two way travel time, and superimposed on reflection section. Revised from Chandler et al. (1989).

to provide significant information on the thicknesses and structure of the sedimentary basins that are associated with the rift. Three interpretations that satisfy these criteria are the three-dimensional gravity model by Allen (1994), the combined seismic refraction interpretations by Mooney and others (1970, Figure 26), and a set of depth estimates that were derived from magnetic anomaly data during this investigation, using a computer-based inversion technique (Euler deconvolution). The three-dimensional visualizations were created with ArcGIS version 9.2 software, and the ArcScene and Arcglobe options of the 3-D Analyst module

Three-Dimensional Gravity Model

In spite of its caveats and limitations, the three-dimensional gravity model of the rift in Minnesota and Wisconsin by Allen (1994) is a logical starting point for three-dimensional visualization. To date, the model represents the most continuous and spatially extensive interpretation of the rift in Minnesota and Wisconsin, and as such, it serves as a reasonable three-dimensional hypothesis that can be readily tested against other geophysical information. Using the ArcGIS software, the thickness and depth grids for the Bayfield Group, the Oronto Group, and the volcanic sequence were divided into segments that were defined by structural overlap and the major bounding faults of the rift (Figures 23-25). These segments were subsequently stacked to their actual stratigraphic and structural positions in the rift, using a flat upper (zero) datum that represents the Precambrian unconformity. Thus re-constituted, the three-dimensional model is shown from several perspectives in Figure 28. This format of presentation accentuates the differing structural styles of basins that are associated with the rift; the Bayfield basins are characterized by a broad and gently dipping form that is wedge-like, whereas the Oronto Group basins have a more abrupt, trough-like character. In contrast, the volcanic basins are interpreted to have an abrupt and deep rooted character that is suggestive of grabens.

The use of a zero-datum that is flat and is assumed to approximate the Precambrian surface may complicate comparisons with other depth-based data. For example, the zero datum for the seismic refraction and magnetic interpretations that follow below use the ground surface as their datum. This difference in base-level is not significant in the northern parts of the study area, where Precambrian rocks lie at or near the ground surface, but in southeastern Minnesota, where Paleozoic rocks overlie the Precambrian surface, the difference can be up to about 0.5 km. Fortunately, the features of primary interest in these areas are typically on the order of a few kilometers below the surface, so the difference will not be very significant.

Seismic Refraction Data

The seismic refraction coverage of Mooney and others (1970) is commonly scattered with many large intervening gaps (Figure 26), but a few factors make it a favorable subject for three-dimensional visualization. Firstly, the interpretations of these data are a reasonably simple data set that can be readily digitized. Secondly, the refraction lines cover a large area of the rift, and they sample a representative suite of rift-related rocks. Finally, the refraction interpretations should serve as an independent cross-check for the three-dimensional gravity model of the rift by Allen (1994). Wherever possible, Allen constrained his interpretation with seismic reflection data, but, he apparently did not make use of Mooney’s refraction data. A database table summarizing the seismic refraction data therefore was attached to the digitized locations of the lines within ArcGIS. A three-dimensional visualization of all refraction interpretations is presented in Figure 29.

In general, the agreement between the seismic refraction interpretations and the three-dimensional gravity model was reasonably good, although some notable exceptions occur. A typical comparison between the two interpretations is shown in Figure 30, which shows a cut-away view of the eastern basin, as interpreted in Allen’s gravity model. Refraction lines 47 and 48 occur over Bayfield Group rocks, and the interpreted contact between 10,000-12,000 ft/sec material (green) and 16,000 ft/sec material (red) falls very close to the base of the Bayfield sequence. No Bayfield rocks were interpreted in Allen’s model to the west of line 48, but the persistence of a 10,000-12,000 ft/sec (green) layer in the upper parts of the line 49-52 interpretations imply that

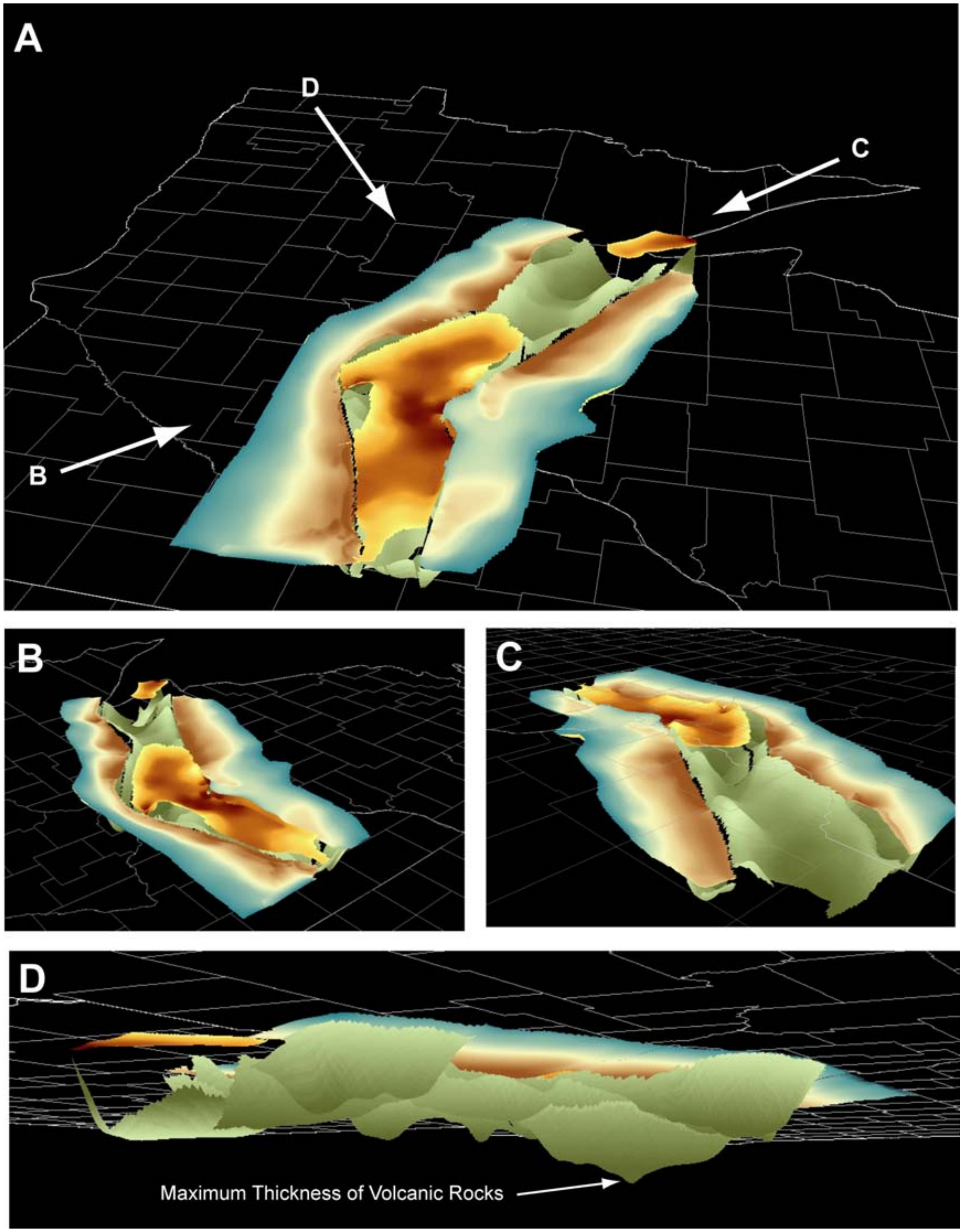


Figure 28. Three dimensional visualization of the gravity model derived by Allen (1994) for the Midcontinent Rift System in Minnesota and Wisconsin. The thicknesses of the main stratigraphic units of the rift sequence are individually color-coded as follows: Bayfield Group (eastern and western basins) - blue green (0) to dark brown (> 5 km), the Oronto Group - yellow (0) to dark brown (>4 km), and the volcanic sequence - light green (0) to dark green (~15 km). Individual units are transparent, but the colors representing thickness are rendered onto the bottoms of each respective unit. The zero-depth datum is flat, and is assumed to represent the Precambrian surface. Labeled arrows in part A represent the viewing directions for parts B, C and D of this figure. Similar to part A, the perspective in parts B and C are from above datum, whereas the perspective in part D is from below the datum. In part C the Oronto Group basin at the northern end of the model (Ashland Syncline) has been removed to better reveal the modeled base of the volcanic sequence.

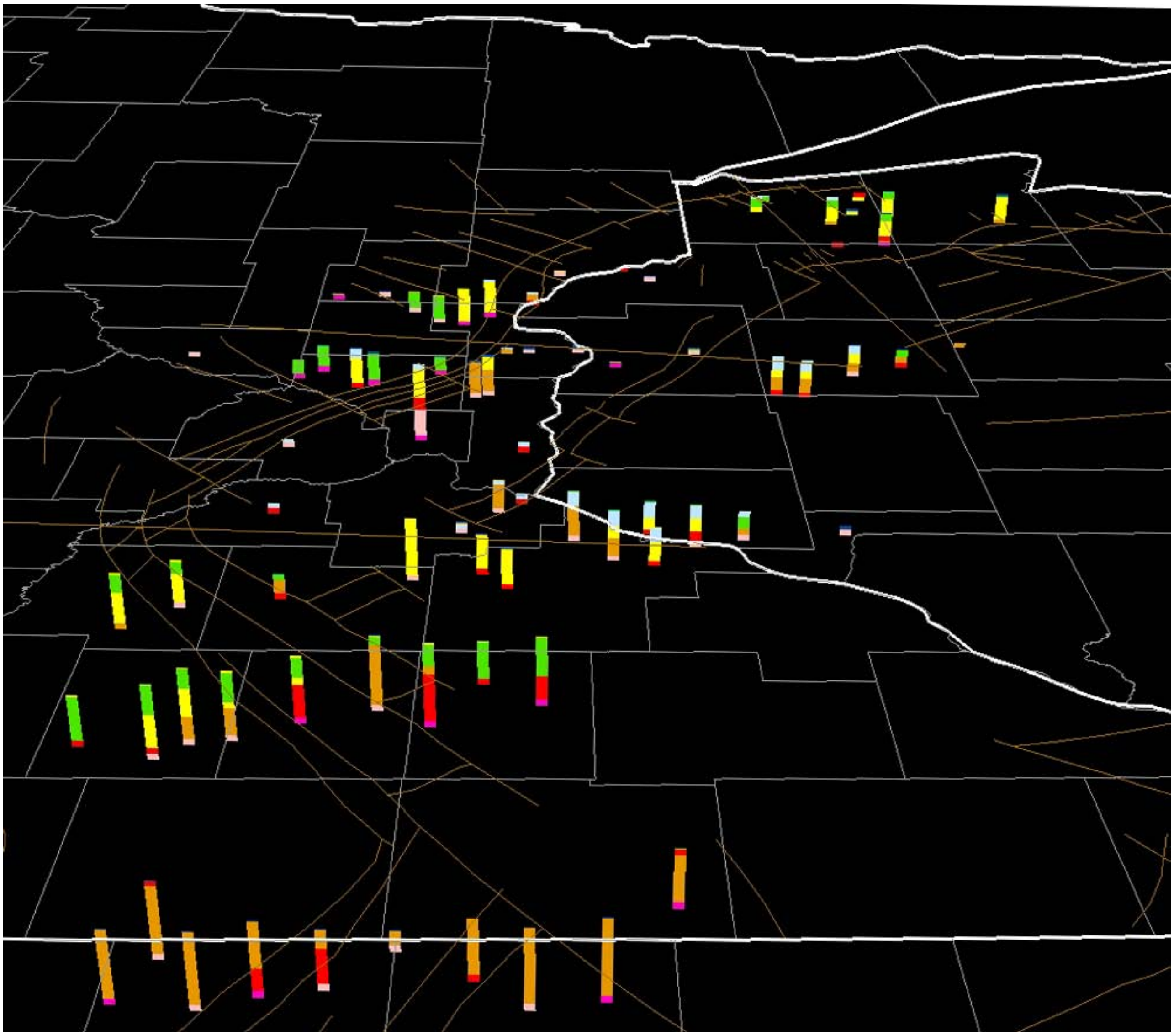


Figure 29. Seismic refraction interpretations of Mooney and others (1970). Seismic refraction interpretations are shown as a vertical column with the following color-coding for interpreted velocities: green = 10,000 to 12,000 feet/sec, yellow = 12,000 to 14,000 feet/sec, orange = 14,000 to 16,000 ft/ sec, red = 16,000 to 18,000 ft/sec, and pink = 18,000-20,000 feet/sec, magenta = >20,000 ft/sec. Depths of seismic refraction interpretations are relative to ground surface, which is assumed to approximate the zero-depth datum of the model. Geographic and geologic boundaries have been rendered to the zero depth datum of the model. Vertical exaggeration is about four times.

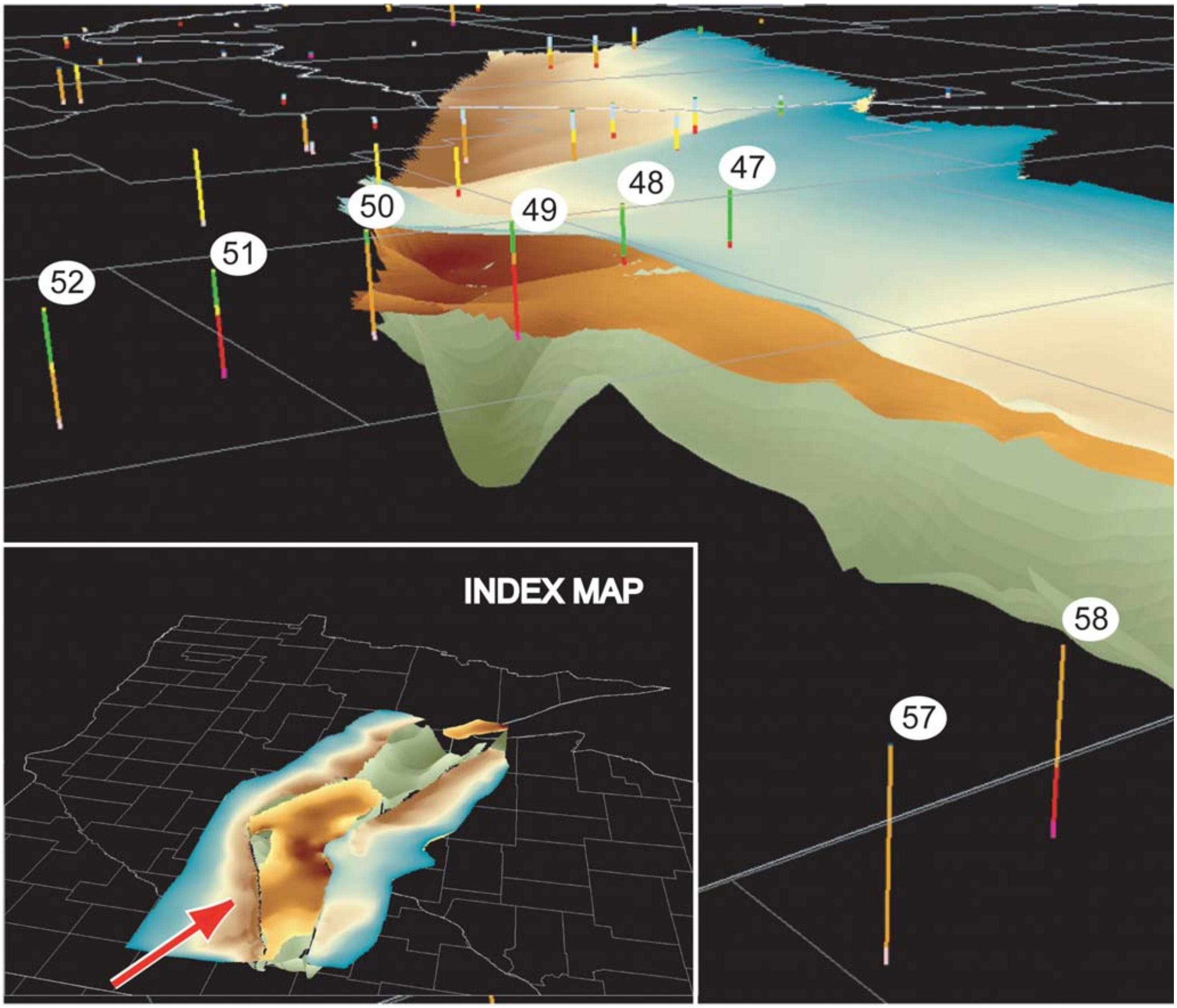


Figure 30. Seismic refraction interpretations of Mooney et al. (1970) superimposed on three-dimensional visualization of the eastern basin, based on the gravity model by Allen (1994). Color scheme on the gravity model is the same as given on Figure 28. Model image in index map is the same as that used in Figure 28 A, and arrow indicates viewing direction for the current figure. Bodies associated with the St. Croix Horst and the western basin have been removed to reveal the subsurface interpretation for the eastern basin. Seismic refraction interpretations shown as a vertical column with the following color-coding for interpreted velocities: green = 10,000 to 12,000 feet/sec, yellow = 12,000 to 14,000 feet/sec, orange = 14,000 to 16,000 ft/ sec, red = 16,000 to 18,000 ft/sec, and pink = 18,000-20,000 feet/sec., magenta = >20,000 ft/sec. Depths of seismic refraction interpretations are relative to ground surface, which is assumed to approximate the zero-depth datum of model. Numbers with selected seismic refraction interpretations are original line numbers from Mooney et al. (1970). Geographic boundaries have been rendered to the zero depth datum of the model. Vertical exaggeration is about two times.

the Bayfield rocks extend across the axial part of the rift. Indeed, follow-up modeling with somewhat more detail using two-dimensional methods includes a thin, discontinuous cover of Bayfield rocks across the axial part of the rift (Allen, 1994). The 14,000 -18,000 ft/sec material (orange and red) interpreted in the lower parts of lines 47-52 correspond closely with Oronto Group rocks in Allen's gravity model (Figure 30), although Mooney and others (1970) interpreted these velocities to represent mafic volcanic rocks of the rift sequence. However, replacing the thick, moderate density rocks of the Oronto Group with high-density volcanic rocks would make this part of the gravity model very difficult to match with observed gravity anomaly signatures, and the Oronto–based interpretation of the gravity model is favored. In fact, observations here call into question any refraction interpretation that implies 14,000-18,000 feet/sec materials are volcanic rocks. The results presented here indicate that the refraction interpretation of Mooney and others (1970) and the gravity model of Allen (1994) are in general agreement, and in areas where the two interpretations differ, improvements in overall interpretation are possible. The results also demonstrate the utility of three-dimensional visualization which allows rapid and efficient comparison of two independent interpretations.

Estimates of Depth to Magnetic Basement from Aeromagnetic Data

Among the most commonly derived estimates from aeromagnetic data are depths to the top of magnetic sources, or "magnetic basement". Such estimates are useful in mapping the thickness of non-magnetic sedimentary rocks that may cover the basement surface. The sedimentary rock basins associated with the Midcontinent Rift System are particularly well-suited for this type of application. In addition, some of the modern, automated procedures presently available for depth estimation can assist in geologic mapping by estimating the horizontal location of anomaly sources. One relatively new method that has become widely used is the Euler Method (Thompson, 1982, Reid and others, 1990; and Blakely, 1995). The Euler method, sometimes called "Euler Deconvolution", uses Euler's homogeneity equation—a differential equation that relates the gradient components of gravity or magnetic anomalies to the location of the source. The Euler method can be readily applied to gridded data (Reid and others, 1990) and it requires no *a priori* information regarding source magnetization (Reid and others, 1995). No particular geologic model is assumed for the Euler method, but most applications require selecting a structural index (SI) value, which is the power of the rate of field change, which varies with source-type. For example a SI=1 is consistent with a thin dike or sill (anomalies falls off as 1/r, where r is the distance to the source), whereas a SI=2 is consistent with a thin pipe or horizontal cylinder (anomalies fall of as $1/r^2$.

In this project we apply the Euler method on the Minnesota-Wisconsin aeromagnetic grid (Figure 22), using the Oasis montaj software of Geosoft. This program rigorously applies the Euler method in a moving-window that sweeps the entire data grid. Following Geosoft's recommendations for analyzing deep sources, the aeromagnetic data were smoothed by upward continuation to levels of 1 km and 2 km, and the respective grids were decimated to intervals of 500 and 1000 meters. Euler analysis was performed on each grid using a window size of 20 grid units. In order to eliminate some of the more spurious results, Euler solutions were rejected if their estimated vertical and horizontal uncertainties exceeded 7% and 50 meters, respectively. The zero-level datum for the depth estimates is the ground surface and solutions were rejected if they were above this datum by more than 20% of the respective level of continuation. Contact-type solutions were assumed to typify most anomaly sources in the region, and following Geosoft's recommendations, a SI of 0.50 was used for both analyses. The solutions from the 1 and 2 km level grids were combined into a common data set, and the 120,000-plus solutions are shown in a color/depth format in Figure 31. As with all inversion routines that generate thousands of solutions, some discretion must be used when interpreting the results. In general the best solutions tend to be spatially clustered, whereas less reliable solutions tend to be scattered and incoherent.

The Euler solutions tend to be shallow (Purple to deep blue) along the bounding faults of the St. Croix Horst, (Figure 31) which is generally consistent with geologic data. Similarly, shallow solutions also dominate the pre-Keweenawan rocks away from the rift, but clusters of somewhat deeper solutions in the west-central and extreme north-central parts of Figure 31 are associated with non-magnetic, pre-Keweenawan rocks. The eastern

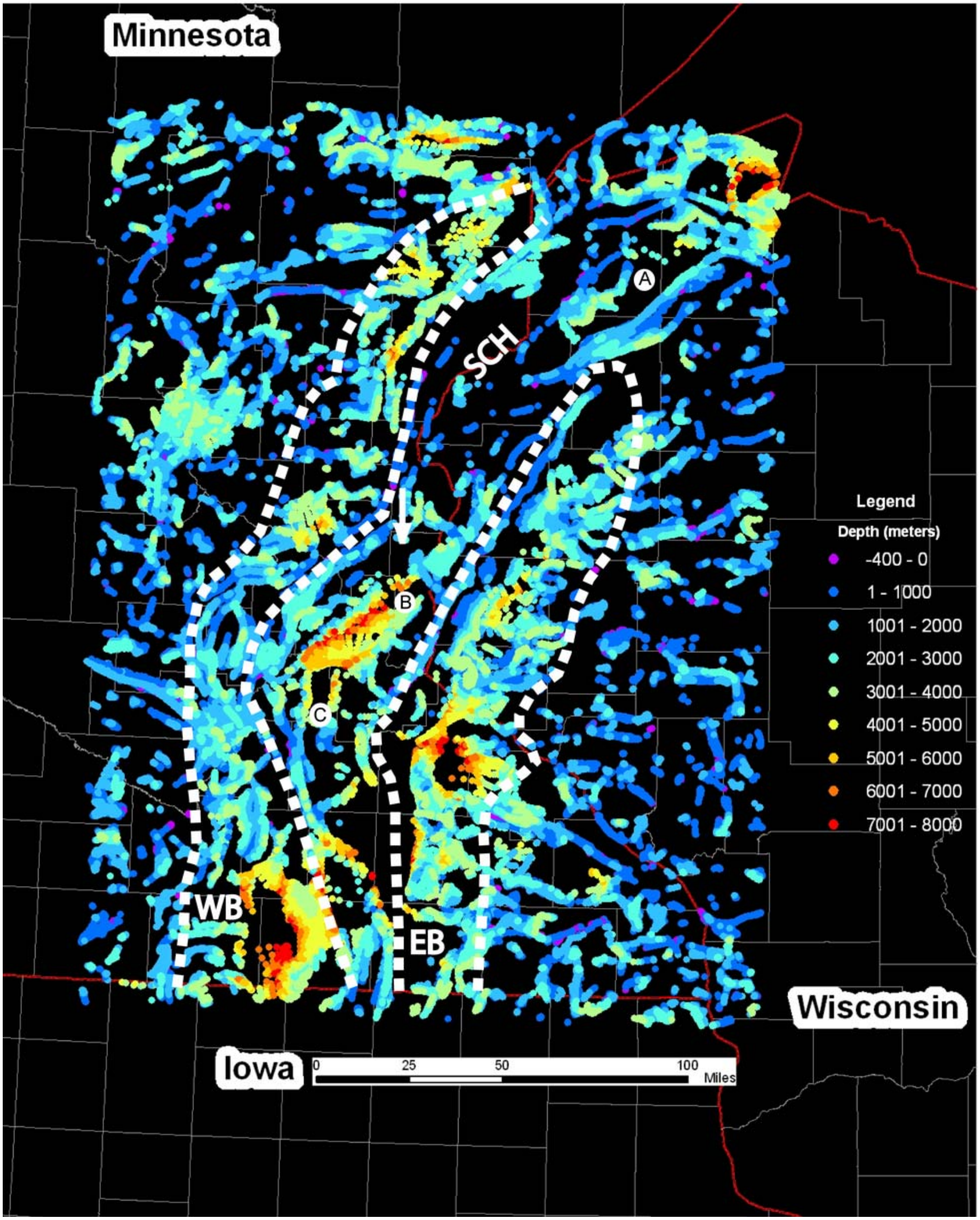


Figure 31. Euler solutions (SI = 0.5) for aeromagnetic data in Minnesota and Wisconsin. Solutions are based on analysis of aeromagnetic grids that were continued upward to levels of 1 and 2 km to emphasize deeper anomaly sources. Ideally the solutions locate the position of faults and contacts, and provide estimates of depth (see color legend). The eastern and western sedimentary basins of the rift (EB and WB, respectively) are outlined by a heavy dashed line. SCH=St. Croix Horst. Labels A, B, and C locate features that are discussed in text.

and western sedimentary basins of the rift are typically associated with depth estimates of 1-3 km, which is in general agreement with Allen's gravity model and Mooney's seismic refraction interpretations. However, depth estimates locally exceed 6 km in the southernmost part of the western basin and near the central part of the eastern basins in Figure 31, although solutions in these areas tend to cluster around 4-5 km. These deeper estimates differ somewhat from depths derived from seismic refraction data; for example refraction lines 57 and 58 (Figure 30), which are located near the deep spot in the western basin, indicate basin depths of no more than 3.9 km. The Euler Solutions from the Oronto Group basin in the Ashland Syncline (near area A in Figure 31) yield maximum depths of 2-4 km, whereas the basin at the southwestern end of the St. Croix (near area B in Figure 31) yield depth estimates that average 4-6 km, but locally exceed 8 km.

The structure of the southwestern part of the St. Croix Horst is further investigated using the three dimensional visualization shown in Figure 32. In this south-looking view the bases of the volcanic sequence and the Oronto Group from Allen's (1994) gravity model are shown, with the latter base cut partially away to reveal some of the deeper Euler solutions. Both the shallower and deeper Euler solutions form two linear patterns that extend southwesterly from near label A, bracketing the deeper part of the Oronto basin as defined by the gravity model. The overall pattern here implies that the deeper part of the Oronto basin is actually a graben, with its shoulders above and its deeper part below the sag-like basin modeled by Allen (1994). Interestingly the position of this inferred graben correlates with the deepest root of the volcanic sequence, as modeled by Allen (Figure 28c). A secondary graben may exist along two north-south trending lines of Euler solutions near label C in Figure 32, which also appears to correspond to a local deepening of the volcanic sequence. These results demonstrate the interpretive potential of the Euler method, especially when used with other geophysical data in a three dimensional visualization scheme.

Concluding Remarks

Seismic, gravity and magnetic interpretations indicate that the sedimentary basins that are associated with the rift in Minnesota and Wisconsin are associated with depths and volumes that are compatible with sequestration of carbon dioxide. Considering an approximate depth limit of 1 km for sequestration, we see that the 1 km depth contours on the thickness maps of the Bayfield and Oronto groups (Figures 23 and 24) encompass large parts of their respective basins. Furthermore, gravity and magnetic interpretations imply that some parts of these basins exceed 5 kilometers depth (Figures 23, 24, and Figure 31). In short, available geophysical information indicates that there are no depth or volume problems with regard to the sedimentary basins that are associated with the Midcontinent Rift System in Minnesota and Wisconsin. Furthermore, these basins lie either under or near areas of major CO_2 production (Figure 20).

Unfortunately, however, there is very little in the geophysical information that is presented here that properly addresses porosity or permeability of rift-related sedimentary rocks. Although factors other than porosity/permeability can affect seismic velocity, some rough inferences can be made by focusing on some empirical observations of sandstones. In the author's experience highly porous and permeable sandstones, such as the St. Peter Sandstone in the Twin Cities area, have seismic (P-wave) velocities around 9,000 ft/sec (2.7 km/sec). At the other extreme the Sioux Quartzite of southwestern Minnesota, which has virtually no porosity or permeability (due to extensive cementation), has seismic velocities around 15,000 ft/sec (4.6 km/sec). Comparing this to velocities of 8,900 -13,000 ft/ sec (2.7-3.4 km/sec) for the Bayfield Group rocks, and 12,500-16,100 ft/sec (3.8-4.9 km/sec) for the Oronto Group (Mooney and others, 1970), it can be inferred that that much of the sedimentary section, especially the Oronto Group may have low porosities. This is confirmed below in the discussion of the rift sedimentary rocks and their measured properties. Therefore, the best chance of finding a porous and permeable horizon is probably with the Bayfield Group rocks. Further evaluation of the Bayfield group will require new geophysical studies followed by test drilling. Velocity or waveform analysis of seismic reflection data might be one approach that would yield further information regarding rock properties (Kearey and others, 2002). Another approach might be to use magnetotelluric methods to look for conductive

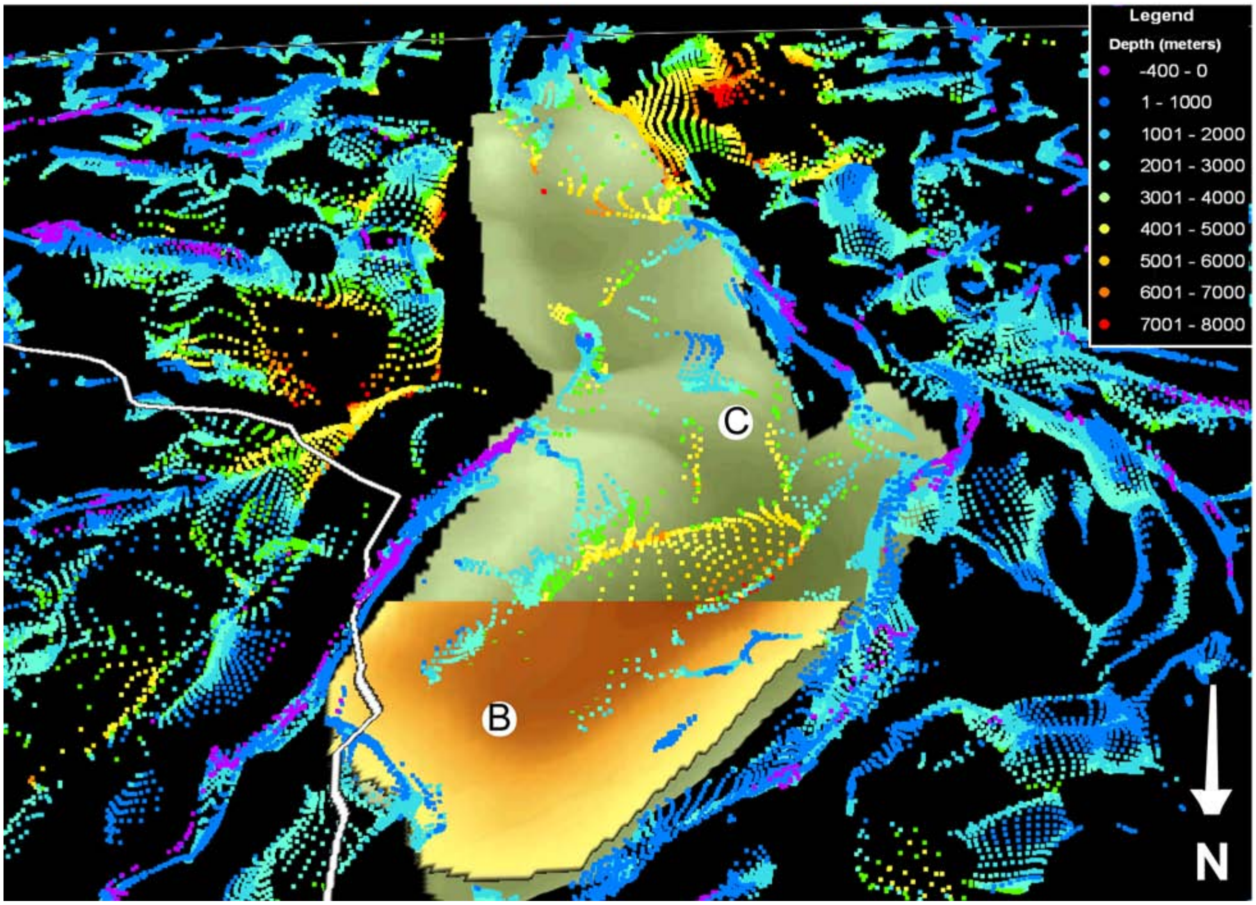


Figure 32. Three-dimensional visualization of Euler solutions (SI = 0.5) derived from aeromagnetic data. View is towards the south from above datum, and it shows the southwestern end of the St. Croix Horst and the extension of the rift along the Bell Plaine Fault zone into Iowa (very top of illustration). The base of the Oronto group and the volcanic sequence from the Allen (1994) gravity model are also shown, using the same coloring scheme as used in Figure 28. Base of Oronto sequence has been partially cut away to reveal deeper Euler solutions. See color legend for depth of Euler solutions. Labels B and C locate features that are described in text.

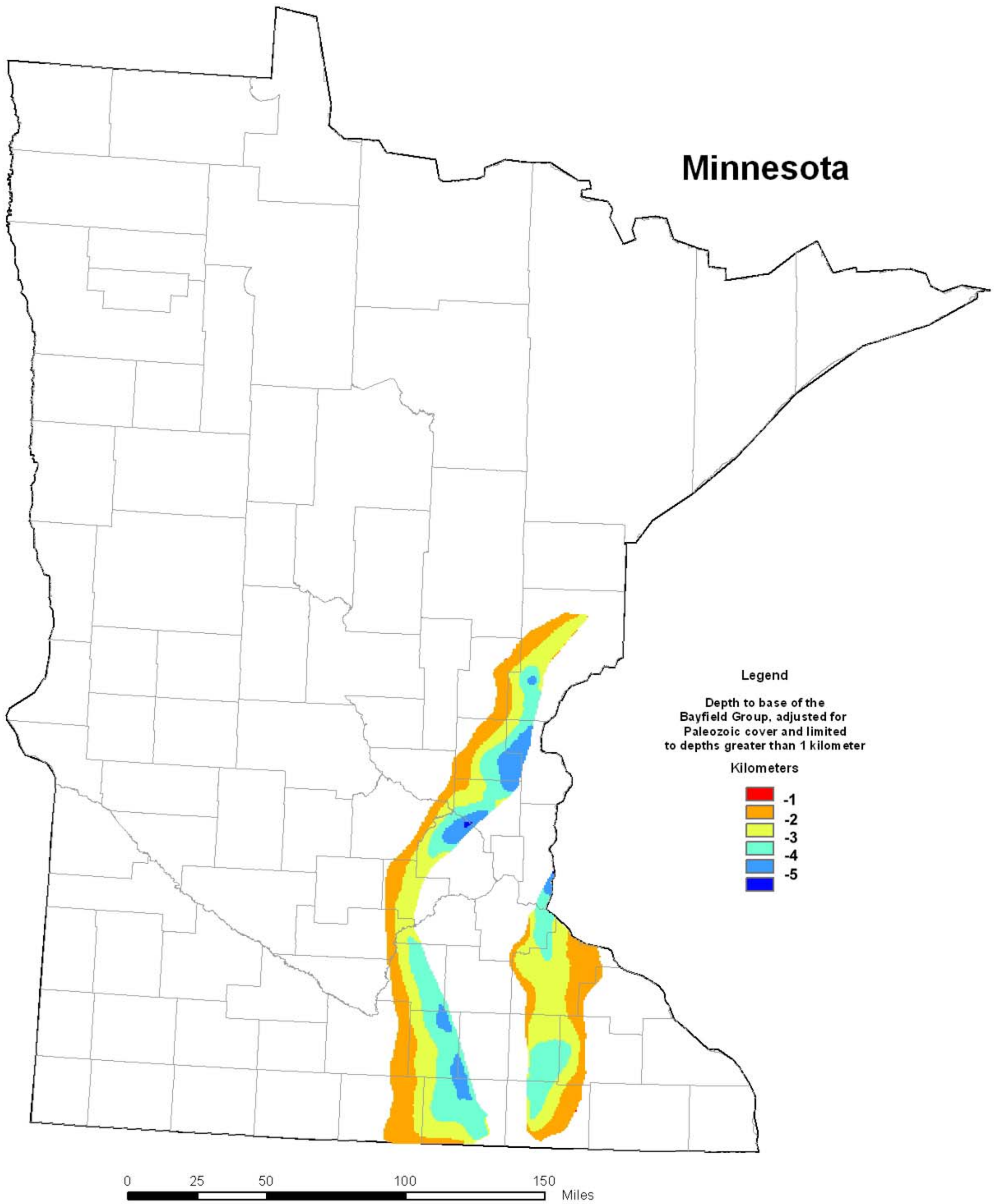


Figure 33. Estimated thickness of Bayfield Group rocks in Minnesota, trimmed to show only those areas where the inferred Bayfield sequence thickness (Figure 23), combined with the overlying Paleozoic rock thickness (Sims, 1990), exceeds one kilometer.

brines in the sedimentary section (Xiao and Unsworth, 2006), which would indirectly indicate porosity. However, either one of these approaches would be expensive, and some narrowing down of target areas will be necessary.

Some narrowing down of target areas for Bayfield Group rocks is possible with some simple criteria. We are only interested in Bayfield Group rocks that lie under 1 km or more of sedimentary rocks, and we are only interested in Bayfield Group rocks beneath Minnesota. Figure 33 shows a thickness map of the Bayfield Group that has been trimmed down with these criteria. As such the western and eastern basins represent 9,606 km^2 and 4,389 km^2, respectively, of area that may warrant further investigation. A logical approach would be purchase the rights to some of the proprietary seismic reflection data that is still available in these areas, and to re-process it for velocity information. A supplemental approach might be to conduct some magnetotelluric soundings in selected areas to investigate for the presence of brines that might be trapped within the Bayfield Sequence. An additional supplement would be to refine the three-dimensional gravity model of the rift using up-to-date modeling and visualization software. Such a three-pronged program could be implemented for $500,000 to $1,000,000 and the results could be used to optimize any test-drilling that might follow.

PREVIOUS STRATIGRAPHIC STUDY OF DEEP SEDIMENTARY ROCKS IN THE UPPER MIDWEST

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Introduction

The thick late Precambrian sedimentary rocks underlying southeastern Minnesota have been subjected to the sort of stratigraphic investigations that are meant to define a useful categorization and characterization, to the extent that has been permitted by access to the rocks. By far the best availability is along the south shore of Lake Superior, where these rocks are exposed at surface. To the southwest, were the rocks are covered by younger sedimentary rocks, stratigraphic study has progressed to the extent that has been permitted by availability of drillhole information and materials. This previous research is here reviewed, to provide background for the following update, synthesis, and re-evaluation of these rocks from the reservoir capacity perspective.

Previous stratigraphic investigations

For over 100 years it has been known, largely from inferences derived from the south shore of Lake Superior, that a considerable thickness of red sandstone and shale lies beneath the Paleozoic sedimentary rocks in southeastern Minnesota (Winchell and Peckham, 1874; Winchell, 1876; Winchell, 1885). With gradual acquisition of geophysical and drillhole data, it came to be recognized that these redbeds comprise a large proportion of the total sedimentary rock sequence in southeastern Minnesota. For example, in the vicinity of the Twin Cities, they were inferred to be at least 4,000 feet (1,220 meters) thick by Sims and Zietz (1967), whereas the overlying Paleozoic rocks are about 1,000 feet (305 meters) thick (Thiel and Schwartz, 1941). Over the years, many deep wells penetrated the Paleozoic cover, but the information that began to accumulate about these rocks thought to be of late Precambrian or Keweenawan age was sparse. As a result, although several excellent descriptions of well logs were obtained, literature until very recent decades simply referred to the rocks as hundreds of feet of undivided red sandstone or shale (Morey, 1977).

In the earliest effort to define the stratigraphy of the rocks, the red sandstones and shales where exposed in Minnesota near Duluth were referred to as the Fond du Lac Formation by Upham (1884), and also were referred to as the Red Clastic Series by Hall et al. (1911) where encountered in the subsurface beneath the Paleozoic cover. A 2000’ sequence at the top of the succession in Wisconsin and consisting of interbedded red feldspathic sandstone and micaceous shale was described and named the Bayfield Group by Thwaites (1912), in an area later examined by Hamblin (1958; 1961; 1965). Magnetic and drillhole information allowed Sims and Zietz (1967) to conclude that the redbeds along the south shore of Lake Superior extend beneath Paleozoic cover in a narrow belt across eastern Minnesota from Duluth to Iowa.

In Minnesota, detailed analysis of the rocks began with an investigation of the stratigraphy and petrology of the type Upper Keweenawan Fond du Lac Formation in the Duluth region by Morey (1967), based on examination of exposures along the St. Louis River. He inferred the unit to be more than 800 feet thick in the area, with only 300 feet exposed. He found that the formation consists predominantly of lenticular beds of red sandstone, siltstone and interbedded shale, with common conglomerate beds containing clasts of vein quartz, basalt, felsite, chert, and quartzite. Physically isolated exposures of quartz-pebble conglomerate previously assigned to the Lower Keweenawan were reassigned to the Fond du Lac Formation by Morey (1967) because the conglomerate was found to grade into sandstone and shale that are similar in lithology to Fond du Lac strata, and because heavy minerals identical to those found in the Fond du Lac sandstones were present in the occurrences. The sandstone of the Fond du Lac Formation was shown to be arkosic to subarkosic, consisting of 36 to 68 percent quartz, 5 to 29 percent feldspar, 1 to 10 percent rock fragments, 1 to 15 percent matrix material composed of quartz, illite, chlorite, and rare kaolinite and biotite, and 1 to 20 percent hematite, calcite, quartz and dolomite cement. Heavy minerals found by Morey (1967) in the Fond du Lac Formation included leucoxene aggregates, apatite, tourmaline, zircon, magnetite-ilmenite, and garnet. The siltstone and shale, although fine-grained, was found to be mineralogically equivalent to the sandstone. Analysis of cross-bedding and other sedimentary directional indicators allowed Morey (1967) to infer that the formation was derived from a terrane consisting of igneous, high-grade metamorphic, and sedimentary rocks that probably was situated to the west. Although the basal quartz-pebble conglomerate was found to have been deposited on an irregular surface during a transgressive sea in early Fond du Lac time, most of the formation was attributed to fluvial-deltaic processes, as indicated by observations interpreted as filled channels, intraformational fragments, mud cracks, ripple marks, rain imprints, and extensive large - and small-scale cross-bedding.

A major milestone in documentation of Minnesota geology was publication of the ‘Geology of Minnesota: a Centennial Volume’, edited by Sims and Morey (1972a). In their summary for the volume, Sims and Morey (1972b) described what they referred to as the Keweenawan Rocks in East-central Minnesota as lava flows and younger clastic sedimentary rocks that crop out locally in east-central Minnesota and extend in the subsurface through southeastern Minnesota. They noted that the lava flows are physically separated from those on the north shore of Lake Superior, and, lacking evidence for correlation of the two lava successions, those in east-central Minnesota were informally referred to as the Chengwatana volcanic group. Work by Craddock et al. (1963) was cited as the basis for inferring that the lava flows comprise part of a fault-bounded block named the St. Croix horst, which is flanked by and locally overlain by the younger clastic strata. The faults that bound the horst on the west and east were described as being are nearly vertical, with vertical displacements of at least 6,000’, and geophysical data were cited as the basis for suggesting that the lavas are more than 20,000 feet thick. It also was noted that ~6,000’ of dominantly basaltic lavas are exposed along several rivers in Pine County, south of Duluth, including moderately abundant interflow sedimentary rocks. In the Minneapolis-St. Paul area, the flows on top of the St. Croix horst were described as defining a broad basin which is filled with Keweenawan clastic strata, and it was pointed out that what had been known as the "Red clastic series" could then be divided into three formations: (1) Hinckley Sandstone, a buff sandstone containing 95 percent or more quartz; (2) Fond du Lac Formation, consisting of intercalated red shale and sandstone containing approximately 60 percent quartz, 30 percent orthoclase, microcline, and sodic plagioclase, and variable amounts of granitic and aphanitic rock fragments; and (3) Solor Church Formation, consisting of variable amounts of quartz, plagioclase of intermediate composition, and aphanitic mafic igneous rock fragments. The former two formations were described as being contiguous with units exposed at the surface in east-central Minnesota, while the Solor Church Formation was confined to the subsurface. The summary went on to state that, in the flanking basin on the west side of the horst, the Fond du Lac Formation disconformably overlies Solor Church Formation and is overlain gradationally by Hinckley Sandstone, while on top of the horst, the Solor Church Formation occupies an elliptical basin and is unconformably overlain by patches of generally thin Hinckley Sandstone. This regional geology was elaborated upon in the Centennial Volume by Craddock (1972a; 1972b), and the Hinckley Sandstone was discussed by Tryhorn and Morey (1972). In his review of Keweenawan geology of east-central and southeastern Minnesota, Craddock (1972b) presented a map of this geology that was described as a compilation of information derived from the work of Kirwin (1963), Craddock et al. (1963), Bath et al. (1964), Philbin and Gilbert (1966), Sims and Zietz (1967), Craddock et al., (1970) Mooney et al., (1970a; 1970b), and Morey (1972). The late Precambrian sandstones in the subsurface of southeastern Minnesota were described in greatest detail in the Centennial Volume by Morey (1972), and in a subsequent paper, Morey (1974) described cyclic sedimentation in the Solor Church Formation.

Drillhole intersections of the late Precambrian sedimentary rocks of southeastern Minnesota were then described in even greater detail by Morey (1977), who stressed that a search for reservoirs suitable for the underground storage of natural gas in 1965 and 1966 had resulted in the drilling of a number of test wells in southeastern Minnesota that had penetrated extensive thicknesses of Keweenawan sandstone and shale, providing core material that was the most complete subsurface record of these strata known to have been obtained. Morey (1977) demonstrated that the redbed sequence can be divided into several stratigraphically significant lithic units, at this point formally defined as a lithostratigraphic unit named the Solor Church Formation, for one of the intervals; and recorded and summarized in a single place the diverse data obtained during the drilling, while integrating these data with previously known data so as to provide a better insight into the rocks. Morey (1977) supported these conclusions with detailed descriptions of ~4,000’ (1,220 meters) of drill core from several localities that demonstrated the presence of at least three distinct lithic units that could be traced laterally. He therefore recommended that the name "Red Clastic Series" be abandoned and replaced by three Keweenawan formations recognized in the subsurface: (1) Hinckley Sandstone, a buff to tan rock containing 95 or more percent quartz; (2) Fond du Lac Formation, consisting of intercalated moderate red shale and reddish-brown sandstone containing quartz, orthoclase, microcline, sodic plagioclase and "granitic" rock fragments; and (3) Solor Church Formation, a newly named formation consisting of dark reddish-brown mudstone and pale reddish-brown sandstone, containing variable amounts of quartz, plagioclase of intermediate composition (oligoclase-andesine), and aphanitic rock fragments. The first two formations are named from surface exposures; however, the Solor Church Formation, so far as is known, is confined entirely to the subsurface. His stratigraphic analysis indicated that, in the flanking basins, the Solor Church Formation is overlain unconformably by the Fond du Lac Formation, which in turn is gradationally overlain by the Hinckley Sandstone. In contrast, the Solor Church Formation overlies basaltic rocks on top of the horst and in turn is unconformably overlain by the Hinckley Sandstone; at places a regolith separates the two formations. Morey (1977) added that either the Fond du Lac Formation was never deposited on top of the horst, or it was removed prior to the time of Hinckley deposition.

Understanding of the late Precambrian sedimentary rocks of eastern Minnesota as it stood in the early 1980s was summarized in an overview for the entire Lake Superior region by Ojakangas and Morey (1982), as well as a paper on Keweenawan sedimentary rocks of eastern Minnesota and northwestern Wisconsin by Morey and Ojakangas (1982). The latter paper described how Keweenawan sedimentary rocks associated with the Midcontinent Rift System form a thick, dominantly red-bed sequence of fluvial-lacustrine origin in eastern Minnesota and northwestern Wisconsin. The strata were described as being divisible into two major sequences on the basis of mineral composition and tectonic setting. The older sequence includes the Oronto Group in northwestern Wisconsin and the Solor Church Formation in southeastern Minnesota. Although these lithostratigraphic units were not seen as entirely correlative, they were regarded as having been derived largely from within the rift system. Both contain variable amounts of quartz, feldspar (plagioclase > K-feldspar), rock fragments (basalt > granite), and other labile constituents. The younger sequence includes the Bayfield Group in Wisconsin, and the Fond du Lac Formation and Hinckley Sandstone in Minnesota. These correlative lithostratigraphic units, derived largely from outside the rift system, contain abundant quartz, feldspar (K-feldspar > plagioclase), and rock fragments (granite > basalt). The Oronto Group and Solor Church Formations were deposited in part contemporaneously with basalt in several graben-like basins along the axis of the expanding rift system. Subsequently, relative uplift of the axial zone formed a series of half-graben-like basins along the flanks of the rift system, in which the Bayfield Group and its equivalents in Minnesota were deposited. The transition from Oronto-like to Bayfield-like rocks marks a transition from dominantly extensional to dominantly vertical tectonic processes. This relationship between tectonism and sedimentation was found to be useful in unraveling the stratigraphic history of the sedimentary rocks in those parts of the Midcontinent Rift System buried by Paleozoic and younger strata.

More recently, the character and context of these rocks have been described by Cannon and Nicholson (1992), who presented a revised stratigraphic nomenclature for the Keweenawan Supergroup based on work in Michigan, Ojakangas et al. (2001), who provided an overview of the Mesoproterozoic Midcontinent Rift System in the Lake Superior region, and by Ojakangas and Dickas (2001), who described the sedimentology of two deep boreholes in the upper Peninsula of Michigan.

Oil and gas potential

The 1995 United States Geological Survey National Oil and Gas Assessment (Palacas, 1995) indicated that the hypothetical Precambrian Midcontinent Rift System Play consists of possible oil and gas accumulations in structural and stratigraphic traps within the 800 mile long Midcontinent Rift System. Gravity and magnetic surveys were reported to indicate that this middle Proterozoic, 1.1 billion year-old rift extends from Kansas to Michigan. Broad, transverse-faulted medial volcanic horsts were described as being bounded by high-angle faults and flanked by asymmetric sedimentary basins up to 30,000’ thick, while basins up to 6500’ thick occur atop the horsts.

With respect to potential reservoirs, Palacas (1995) indicated that structural and stratigraphic traps may have formed by crustal extension and sedimentary facies distribution, while tectonic inversion late in rift development likely produced compressional and wrench structures. Primary targets, according to the report, would be fluvial, deltaic, and shoreline sandstones of the Nonesuch Formation and the underlying upper Copper Harbor Conglomerate, both with porosities up to 13%. Fractured shales occurring in the Nonesuch Formation were also cited, and sandstones with porosities up to 18% were reported by USGS to occur in the overlying Freda Sandstone. Nonesuch Formation shales up to 700’ thick were seen as a possible hydrocarbon source rock, as they contains up to 3% total organic carbon (TOC) by weight, and live oil seeps in the White Pine Copper Mine in Michigan confirm that liquid hydrocarbons have been generated. Kerogens were described as type II and type I, and moderately mature Tmax values of 435-440°C were noted. Although the organic matter was seen as oil prone, gas was considered the more likely target due to the typical degree of thermal maturity. In describing likely timing and migration of hydrocarbons, Palacas (1995) summarized available literature by indicating that, during extensional tectonism, the Nonesuch Formation and equivalents may have generated oil and gas, especially in the deeper portions of the basins, prior to compressional tectonism. In the shallower portions of flanking basins, a second phase of oil and gas generation probably occurred following deposition of Paleozoic sediments. In addition, hydrocarbons that might have accumulated during initial rifting may have re-migrated into structures formed during compression.

The review by Palacas (1995) included reference to work by Hatch and Morey (1985), who had examined the hydrocarbon source rock evaluation of the Solor Church Formation as sampled in the Lonsdale 65-1 well, in Rice County, Minnesota. Their work showed that: (1) the rocks are organic matter lean, as 24 of 25 samples had less than 0.8% organic carbon; (2) the organic matter is thermally post-mature, probably near the transition between the wet gas phase of catagenesis and metagenesis (dry gas zone); and (3) the rocks have minimal potential for producing additional hydrocarbons (genetic potential < 0.30 mg HC/g rock). Although no direct evidence was known to Hatch and Morey (1985) from which to determine maximum burial depths, the observed thermal maturity of the organic matter was regarded as requiring significantly greater burial depths, a higher geothermal gradient, or both. It thus was considered likely, at least on the Saint Croix horst, that thermal maturation of the organic matter in the Solor Church took place relatively early, and that any hydrocarbons generated during this early phase were probably lost prior to deposition of the overlying Middle Proterozoic Fond du Lac Formation.

Dual stages of tectonism would have produced a broad range of trapping conditions (Palacas, 1995), with varying styles of fault-related structures. Tectonic inversion may also have created structural features of varying scale that could contain giant accumulations of hydrocarbons. In Minnesota, seismic reflection was described as having documented large anticlinal features, while drag folds against reverse faulting were thought to offer multiple reservoir possibilities, and it was suggested that stratigraphic traps also likely occur. Probable seals were described as including shales of the Nonesuch Formation, as well as tight horizons in the overlying Freda Sandstone and Bayfield Group. Fault gouge may also account for some seals. Palacas (1995) pointed out that only five wells have penetrated the lower Keweenawan Supergroup rocks that have the highest potential for hydrocarbon reserves. No commercial oil or gas accumulations have been confirmed. Drilling in the 1980s at sites from Kansas to Michigan described as having been stimulated by increasing awareness of source rock potential and oil seeps, as well as improved knowledge of large reserves in other rift basins such as the North Sea, Gulf of Suez, and Pripyat Basin, as well other Precambrian terranes such as the Lena-Tunguska Petroleum Province of Eastern Siberia, the Sichuan Basin of southern China, and the Upper Proterozoic Huqf Group of Oman. USGS thus regarded the rift as a high risk play, as few wells have been drilled, potential source rocks are known to be or may be overmature, while reservoir porosities may be unfavorable. However, it seemed reasonable to Palacas (1995) to speculate that source rocks may have more favorable levels of thermal maturity if present at shallower depths of burial along the basin flanks, leading to possible drill tests from 3,000’ to as much as 25,000’.

This hydrocarbon potential was highlighted at a full-day Minnesota Minerals Coordinating Committee workshop held in St Paul in 2005, and subsequently, Minnesota and Iowa cooperated in promoting awareness of Midcontinent Rift oil and gas potential by hosting a display booth at the American Association of Petroleum Geologists’ national convention in 2006 and 2007. Research on the oil and gas potential of the Midcontinent Rift in the Minnesota and adjacent region is ongoing. For example, Hegarty et al. (2007) presented new analyses for the Amoco 1 Eischeid well in Carroll County, Iowa, described by them as the first significant well drilled along the flank of the Iowa horst, providing an opportunity to evaluate the stratigraphic and structural history of what they described as the enigmatic Mid-Continent rift system of the United States. Their new thermal history data obtained from cutting and core samples were used to conclude that three paleothermal events had affected the drilled section at the well, while three significant cooling events occurred sometime between 300 and 200, 70 and 50, and 35 and 10 Ma. They associated the first of these events with a high paleogeothermal gradient (35°C/km), demonstrably in their view to be greater than the present-day value (16°C/km). These new results were considered direct evidence of a significantly higher paleogeothermal gradient (and by inference, higher heat flow) during the Paleozoic. In addition, the results were taken to conclude that maximum maturity of the rich Precambrian source, the Nonesuch Shale and equivalents, was reached during the 300–200-Ma event and not 600–700 million years earlier as previously proposed. Their view was that previous work had been significantly influenced by the view that the craton was relatively stable or behaved uniformly throughout the Phanerozoic, with previous models imposing a Proterozoic time of generation and entrapment for any Precambrian source intervals. They thought that with recognition of significant Phanerozoic heating events, the opportunity for later generation would emerge, thus reducing the preservation time and increasing the probability of entrapment and preservation needed for exploration success in the region. They also concluded that these events mapped in the Mid-Continent rift system may be of great regional extent and correlative in time to other events along the North American plate margins, thus offering insights to new possible exploration targets within the rift, perhaps in their view indicative of deep-seated processes in the mantle beneath the North American craton during the Phanerozoic.

Iowa deep drilling

According to Anderson (1990a), in 1987, Amoco Production Company drilled the M. G. Eischeid #1 petroleum exploration well northeast of the town of Halbur in west-central Carroll County, Iowa. The Eischeid well was Amoco's first test of the petroleum potential of the Midcontinent Rift System (MRS). In this report that summarized published results of the drilling, the history of the MRS was reviewed by Anderson (1990b) and its structure is discussed by Anderson (1990c). Although petroleum was regarded in the report as being unusual in rocks as old as those of the MRS, small amounts of oil collected from MRS clastic rocks (sandstones, siltstones, and shales) in the Lake Superior area were noted.

The Eischeid well reached a total depth of 17,851 feet, far surpassing the 5305-foot depth of the previously deepest well in Iowa. The well penetrated 2802 feet of Phanerozoic sedimentary rocks, 14,898 feet of Proterozoic MRS clastic rocks, and 185 feet of Proterozoic igneous intrusive rocks. No liquid petroleum was reported during the drilling, according to the report, but minor occurrences of gaseous hydrocarbons were detected within the Proterozoic. The well was subsequently plugged and abandoned.

Drill cuttings were collected generally at 10-foot intervals; five cores totaling 72 feet in length were drilled; and a series of down-hole logs were produced. These data were released to the Iowa Department of Natural Resources Geological Survey Bureau (GSB) in the fall of 1989 for study and preparation of the 1990 report. Under the direction of the GSB, a series of investigations was initiated by geologists from the GSB, US Geological Survey, and from the academic community. These studies were primarily directed toward evaluating the petroleum potential of the MRS clastic rocks encountered in the drilling.

According to the report, Witzke (1990) studied the stratigraphy of the rocks encountered during the drilling of the Eischeid well. The Phanerozoic section was typical of the rock strata encountered in other wells in the area. Only the basal Phanerozoic unit, the Cambrian Mt. Simon Sandstone, produced any new interpretations. Based on new information from a related study (McKay, 1990) only 20 feet of Mt. Simon strata were identified in the Eischeid well. The underlying 813 feet of clastic sediments (initially thought to be a part of the Mt. Simon) were identified as pre-Mt. Simon.

The 14,898 feet of MRS clastic rocks, informally known as Red Clastics, is by far the thickest section of these rocks encountered in Iowa, and the thickest section penetrated by drilling anywhere along the trend of the MRS. Witzke subdivided the "Red Clastics" in the Eischeid well into two informal groups, the Upper "Red Clastic" Sequence and the Lower "Red Clastic" Sequence. The groups were further subdivided into informal formations and members, and the lithologic characteristics of each unit were described. One unit in the Lower "Red Clastic" Sequence, Unit C, was found to be dominated by dark gray to black organic-rich shales and siltstones that appeared to offer good source-rock potential.

Below the MRS clastic rocks, the Eischeid well penetrated 151 feet of relatively fresh gabbro. This unit was described by Van Schmus and others (1990), who interpreted it as a dike. They analyzed zircon crystals from the dike and used uranium-lead isotope concentrations to calculate an age of 1281 million years for the rock. This age indicated that the dike predated the formation of the MRS, and thus probably is an element of a suite of dikes that is widespread through North America, known collectively as the Mackenzie dike swarm.

Petrologic studies of thin-sections produced from Eischeid drill-cutting samples by Ludvigson and others (1990) and from core samples by Barnes (1990) were used to characterize the MRS clastic rock sequence. These studies led to the interpretation of the depositional environments of the rocks and identified the differences and similarities between the MRS clastic rocks in the Eischeid well and related units observed in their exposure area in the Lake Superior Basin.

The Proterozoic clastic rocks in the Eischeid well, especially in the Lower "Red Clastic" Sequence, were investigated by Palacas and others (1990) for their potential to produce hydrocarbons. They analyzed samples from 58 depth intervals for total organic carbon (TOC) content and selected samples for other parameters including maximum pyrolysis temperature (T_{max}), genetic potential, hydrogen index, and chloroform-extractable bitumens. They found that Unit C was the most organic unit, with TOC values ranging up to 1.4% and averaging 0.6%. These values are low, but many geologists consider 0.5% to be a minimum value for a rock unit to be considered a petroleum source rock. T_{max} values averaged 503° C indicating that the rocks in the Eischeid well were overmature with respect to hydrocarbon generation.

This advanced stage of thermal maturity was corroborated by several other researchers. Barker (1990) investigated fluid inclusions in calcite and quartz veins. He measured two-phase fluid inclusion homogenization temperatures of selected samples and identified two temperature populations, an earlier 200° C event and a later 140° C event. He verified the 200° C event peak by bitumen reflectance (vitrinite reflectance equivalent) measurements. Ludvigson and Spry (1990) conducted additional measurements of two-phase and other fluid inclusions in tectonic veins. They identified temperatures ranging from 125° to 178.6° C near the top of Unit C, and reported that many inclusions are filled by methane or CO_2 gas. They used coordinated fluid inclusion homogenization and stable isotopic (oxygen and carbon) data to suggest that petroleum may have migrated from the axis of the rift to its outer margin. Pollastro and Finn (1990) used clay geothermometry to calculate paleotemperatures for Unit C samples. They calculated a minimum paleotemperature of 175° to 180° C from samples near the top of Unit C, and used this information to estimate a minimum bottom hole (17,851 feet) paleotemperature of 192° to 197° C.

Palacas and others (1990) also calculated a genetic potential of 0.1 to 0.4 HG/g and hydrogen indices from 20 to 80 HC/g TOC for carbon-rich intervals of Unit C. They concluded that "at present, these shale beds have no potential of generating commercial petroleum...," but they suggested that significant amounts of hydrocarbons may have been generated in the geologic past.

Another important characteristic in evaluating the petroleum potential of the Eischeid "Red Clastic" rocks was their porosity. Schmoker and Palacas (1990) studied a variety of down-hole geophysical logs to calculate the porosity of sandstone units in the "Red Clastic" rocks. They calculated porosities ranging from 1 to 6% (averaging 2.3%) within the interval from 14,450 to 17,340 feet in the Eischeid well, with 14% of that section averaging 3.5% porosity or greater. However, Ludvigson and others (1990) and Barnes (1990) noted that optically observable porosity values were consistently below 3% below 3000’, less than 1.5% below a depth of 4000’, and no optically observable porosity was identified below 8000 feet. Anderson (1990d) suggested that the porosity identified by Schmoker and Palacas might be present as microporosity or as gas and/or liquid-filled inclusions.

Data and samples collected during the drilling of the Amoco M. G. Eischeid #1 deep petroleum test well facilitated the preliminary division of the "Red Clastic" sequence in Iowa into two informal groups, the groups into seven informal formations, and the formations into thirteen informal members. The "Red Clastic" rocks in Iowa are similar in many ways to the Oronto and Bayfield groups, MRS clastic rocks exposed in the northern Wisconsin area. They were thought by Anderson (1990a) appear to have similar depositional environments and probably nearly coeval. Some differences between the lithology and petrology of the Eischeid MRS strata and those observed in the Lake Superior region were attributed to their locations in different areas of the rift.

According to Anderson (1990a), the MRS clastic rocks encountered in the Eischeid well presently have almost no potential for producing hydrocarbons, but they were seen as apparently having generated significant volumes of petroleum at some time in the geologic past. It thus was seen as possible that similar rock sequences located at a greater distance from the axis of the rift may still contain economic volumes of petroleum, but it was acknowledged that a concerted exploration effort would be required to locate such resources.

Wisconsin deep drilling

Dickas and Mudrey (1999) edited a volume summarizing the Terra-Patrick #7-22 deep hydrocarbon test completed in Bayfield County, Wisconsin, in 1992. This well was the first test in Wisconsin of the hydrocarbon potential of the Midcontinent Rift System (MRS). The well was drilled to a depth of 4,966', penetrating 290' of Pleistocene sediments, overlying 4,676' of sandstone, shale, and conglomerate of the Oronto Group. No liquid petroleum was encountered, but very minor occurrences of natural gas were detected within carbonaceous shale of the Nonesuch Formation, the central formation of the Oronto Group of the Lake Superior Basin. The well was subsequently plugged and abandoned. The several ensuing studies at various agencies that were summarized by Dickas and Mudrey (1999) were directed toward a comprehension of the geology, hydrocarbon potential, structural development, and history of exploration, along the Midcontinent Rift trend of western and northwestern Wisconsin, with an emphasis on the region surrounding the Terra-Patrick #7-22 borehole.

According to Dickas and Mudrey (1999), the Oronto Group, a 14,000-ft clastic sequence composed of the Freda, Nonesuch, and Copper Harbor Formations, was the target of the Terra- Patrick #7-22 exploratory borehole. They stated that reflection seismology suggested that this target is a structural trap, interpreted to be south of and adjacent to the Douglas Fault, specifically a large, 6 to 10 mi long, east—west trending, 6,000-ft crest-to-trough anticline, cored with Lower Keweenawan basalt. This structural trap was believed to have been formed by drag stresses created by reverse faulting displacements. Potential reservoir strata were anticipated in three units: the upper part of the Copper Harbor Formation, a basal sandstone of the Nonesuch Formation, and throughout the Freda Formation. On the basis of wireline dipmeter survey analyses, the drilled sequence dips approximately 20° southeast, indicating the borehole was drilled on the southeast limb of the anticline. Borehole deviation at a drilling depth of 4,626 ft, near the bottom of the hole, was 16° from vertical. The borehole was finished in the Copper Harbor Formation.

In the volume edited by Dickas and Mudrey (1999), a paper by Dickas and Mudrey (1997) was reprinted, thus reiterating their description of the regional, segmented structure of the Superior Zone, that section of the Midcontinent Rift extending from southern Minnesota north and east into eastern Lake Superior. In their model, the Superior Zone was divided into a series of four half-grabens composed of rift-derived igneous and sedimentary rock stratigraphic packages separated by accommodation structures. Each half-graben was defined principally on the basis of major breaks in gravity and magnetic patterns, and opposing stratigraphic geometries as identified by reflection seismology interpretation.

The interpretation of geologic and geophysical information by Allen et al. (1997) also was reprinted in the volume, to provide an account of the structural heterogeneity of the Superior Zone. Dickas and Mudrey (1999) summarized this work by stating that two ridges of pre-rift basement rocks were identified by the pinch-out of rift volcanic strata and the lower section of the overlying sedimentary rock sequence. These accommodation structures were seen as controlling the termination of the Douglas and Isle Royale Faults, formerly considered by many investigators, according to Dickas and Mudrey (1999), to be continuous.

A detailed history of hydrocarbon leasing and reflection seismic field collection for the period 1983-92 was provided in the volume by Dickas (1999a). He described how, during this period, at least 2,671 mi of reflection seismology was collected by five contractors and more than 718,000 acres was leased by eight exploration companies. This search, unprecedented in a state historically considered void of hydrocarbons according to Dickas, produced a comprehensive geologic and geophysical data bank of great value in the interpretation of the Midcontinent Rift System in Wisconsin.

Dickas (1999b) also presented technical information about the Terra—Patrick borehole, which was spudded on March 9, 1992, and plugged and abandoned on April 1, 1992, after reaching a total depth of 4,966 ft. He reported that total drilling costs were $533,308, for an average cost of $107.39 per foot.

Daniels (1999) interpreted wireline data from the site, especially gamma ray and acoustic logs, and borehole drill cuttings, to define a series of electro-stratigraphic sequences encountered during the drilling, and correlated the units to the Oronto Group, which in the Lake Superior district, was subdivided into the Copper Harbor, Nonesuch, and Freda Formations, from oldest to youngest.

A second analysis of the drill cuttings by Burruss and Palacas (1999), addressed the potential of the Nonesuch Formation, thought to be lacustrine in origin, as a source rock for hydrocarbons, using pyrolysis assay techniques to conclude that although the Nonesuch is marginally mature with respect to hydrocarbon generation, regional variability of depositional environments would suggest that similar analyses elsewhere could produce more optimistic results.

Also in the volume edited by Dickas and Mudrey (1999), Uchytil et al. (1999) addressed regional hydrocarbon potential of the Nonesuch Formation, using core and outcrop samples collected along a 200-mi long trend extending from northwestern Wisconsin northeast to the Keweenaw Peninsula of Michigan. Lindblom (1999) contributed an evaluation of the suite of Terra-Patrick wireline logs, the field analysis of which was said to have been made difficult because charts employed for interpretation were devised for evaluation of quartz-bearing clastic rock, rather than the volcaniclastic strata encountered in the Terra-Patrick borehole. Lindblom (1999) verified this iron-rich sediment problem in his analysis of density and sonic porosity logs, and relationships between various wireline signatures and downhole lithologies.

Dickas and Mudrey (1999) summarized the report by stating that when the Terra-Patrick #7-22 borehole was abandoned on April 1, 1992, an eight and one-half year period of exploration for hydrocarbon in Middle Proterozoic rocks of the Midcontinent Rift trend of Wisconsin came to termination. They described how this period was extended beyond expectations by, in their view, initial lack of protective legislation, environmental concerns, and crude oil price fluctuation. Nevertheless, their view was that the combined and varied interests of industry, government, and academia in the Midcontinent Rift trend had yielded a valuable volume of geologic and geophysical data important in the analyses of Precambrian terranes in the central United States. They therefore concluded that the Terra-Patrick borehole was an economic failure, when measured by the discovery of only the minimal amount of natural gas that would be expected in penetrating any fine-grained, carbonaceous sedimentary rock. They cited, however, new concepts in the understanding of the Precambrian tectonic history of central North America, which they thought may prove valuable in the future discovery of hydrocarbon in the Middle Proterozoic strata of Wisconsin.

SEDIMENTARY ROCKS AND GROUNDWATER IN THE MIDCONTINENT RIFT SYSTEM OF MINNESOTA: ASSESSMENT OF POTENTIAL FOR DEEP GEOLOGIC SEQUESTRATION OF CARBON DIOXIDE

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Introduction

This section describes the attributes of Keweenawan sedimentary rocks and groundwater associated with the Midcontinent Rift System (MRS), focusing on properties in east-central and southeastern Minnesota that are pertinent to an evaluation of the potential for deep geologic sequestration of carbon dioxide. This section includes an overview of stratigraphic nomenclature, fundamental lithostratigraphy, facies attributes, depositional environment, mineralogy, texture, porosity, permeability, and groundwater chemistry. It is an evaluation of the potential for the presence in the MRS of relatively porous and permeable sandstone bodies at depths greater than 800 meters (~2600ft) that contain saline water, and are capped by relatively impermeable shale. Sequestration is generally believed to require sandstone reservoirs with porosity greater than about 5%, and permeability greater than about 5 millidarcies (md).

This section is largely a summary of existing published and unpublished reports and databases associated with studies of the MRS in Minnesota and nearby states over the past 40 years. The references cited, and additional background on the history of previous research outlined earlier in this report, provide more detailed information to the reader. In addition, about 50 new measurements of the porosity and permeability of samples from archived cores collected from Minnesota and Iowa are presented.

Compared to other Phase I studies to assess the potential for deep geologic sequestration of carbon dioxide elsewhere in North America (e.g. Finley, 2005; Steadman and others, 2005), information on the sedimentologic, stratigraphic, and groundwater properties of MRS sedimentary rocks in the subsurface is extremely limited. Only a dozen boreholes are known that penetrate MRS sedimentary rocks to depths greater than 2000 feet (610m) in Minnesota, and only a few of these wells are associated with boreholes logs, core, or other information useful for assessing the potential for sequestration. No holes deeper than 4000 feet (1220m) are known. Outcrops are scarce, and gravity and seismic surveys permit only a rudimentary depiction of bulk thickness of MRS sedimentary packages. These geophysical data lack the resolution necessary to construct an internal stratigraphic framework. Most of this section of the report is therefore based on a limited number of core samples and geophysical logs from depths shallower than necessary for sequestration, and from a few relatively deep exploration boreholes from Wisconsin, Michigan, and Iowa (Figure 34).

Lithostratigraphy

The oldest known sedimentary rocks clearly related to active rifting along the Midcontinent Rift System in Minnesota, aside from sandstones, now quartzites, that were deposited in the axial syncline before the initiation of volcanism, are immature conglomerates, lithofeldspathic sandstones, siltstones and shales that occur as interbeds within thick (1000’s of ft) packages dominated by volcanic flows. These interbedded volcanic and sedimentary successions are referred to as the North Shore Volcanic Group in northeastern Minnesota, and as Chengwatana Group to the south (Figures 35 and 36). Interflow sedimentary units are numerous, but volumetrically minor, and are typically thin, rarely exceeding 100 ft (30m) (Ojakangas and others, 2001).

Keweenawan sedimentary rocks that succeed the Chengwatana Group attain a thickness of over 16,000 ft (~5km) in some parts of east-central and southeastern Minnesota (Allen and others, 1997), where three formations are recognized (Figures 35 and 36). The Solor Church Formation consists of a red-brown succession of interbedded sandstone, siltstone, mudstone, shale, and intraclastic conglomerate (Morey, 1977). The sandstones and siltstones contain a considerable amount of lithic detritus. The Solor Church has traditionally been recognized only on top of the St Croix Horst and exceeds 10,000 ft (3049m) in thickness in some areas. The Solor Church is inferred, on the basis of seismic surveys, to also be present in the lower part of the MRS sedimentary succession in adjacent grabens (e.g. Figure 36; Allen and others, 1997). The Fond du Lac Formation consists of dark reddish-brown shale, mudstone, siltstone, and sandstone with greater percentages of quartz, and lesser proportions of lithic and potassium feldspar grains compared to the Solor Church Formation (Morey, 1977; Morey and Ojakangas, 1982). The Fond du Lac occupies grabens that flank the St Croix Horst (Figure 36), and based on geophysical evidence approaches 15,000 ft (4573m) in thickness (Allen and others, 1989). The Hinckley Sandstone is a tan to brown sandstone with a markedly greater mineralogical and textural maturity than the Solor Church and Fond du Lac Formations (Morey, 1977). The Hinckley is composed of greater than 95 percent moderately to well rounded quartz grains. A number of workers have suggested that the Hinckley Sandstone (or its presumed equivalents) is Paleozoic in age (e.g. Raasch, 1950; Ostrum, 1967; Boerboom and others, 2002), having attributes more closely related to the Cambrian and Ordovician quartzose sheet-sandstones that regionally cover the cratonic interior in Minnesota and adjacent states, than to the underlying strata associated with the Midcontinent Rift System. Regardless of its genesis and age, the Hinckley

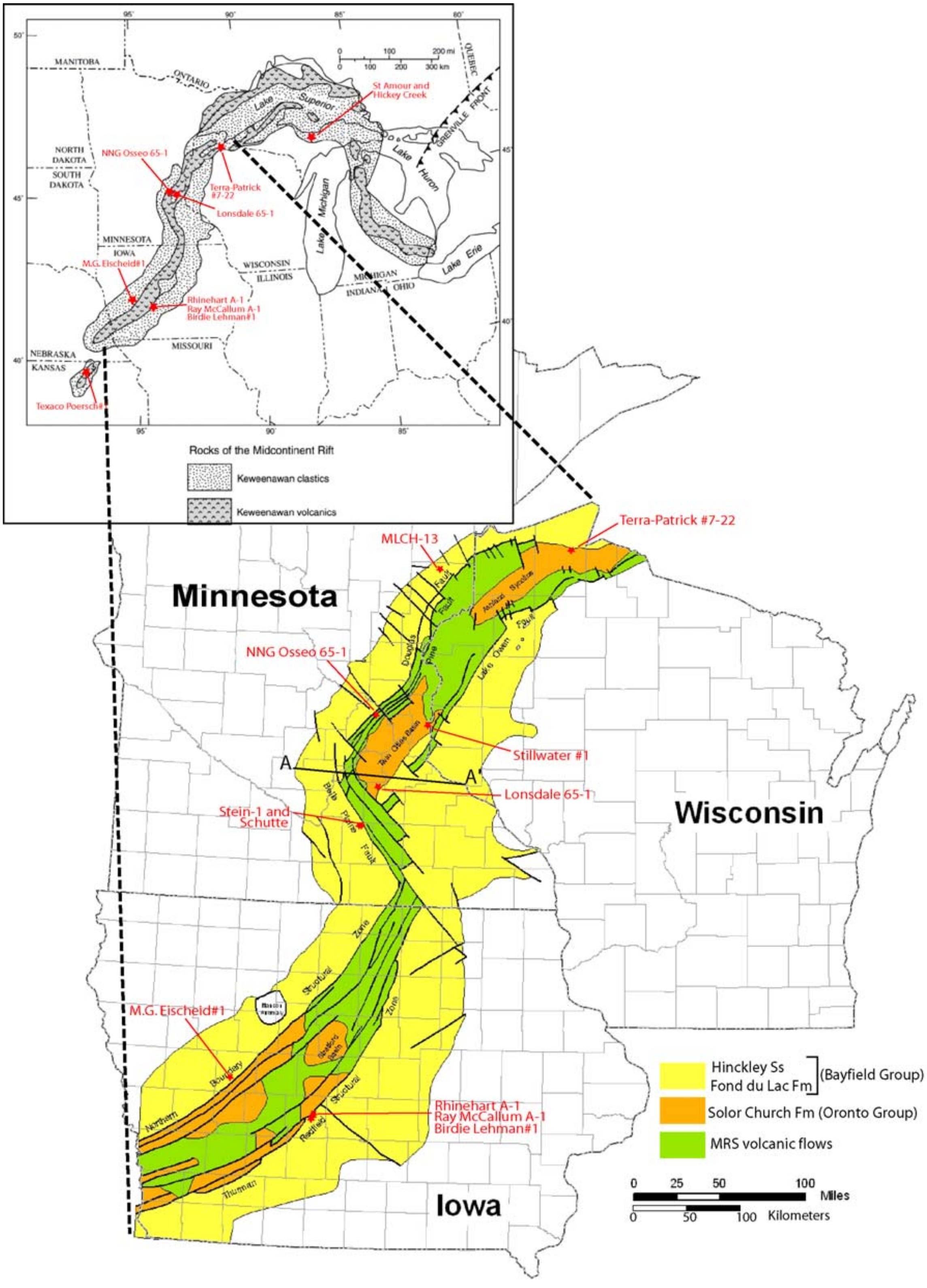

Figure 34. The Midcontinent Rift System (MRS), showing distribution of principal stratigraphic units, structural features and location of relatively deep drill holes referred to in this report. Inset shows regional extent of MRS, and location of the deepest (>2500'; 762m) drillholes with key rock property information described in this report. Line of cross-section for Figure 35 is shown as A-A'. Modified from Chandler et al. (1989) and Ojakangas and Dickas (2002).

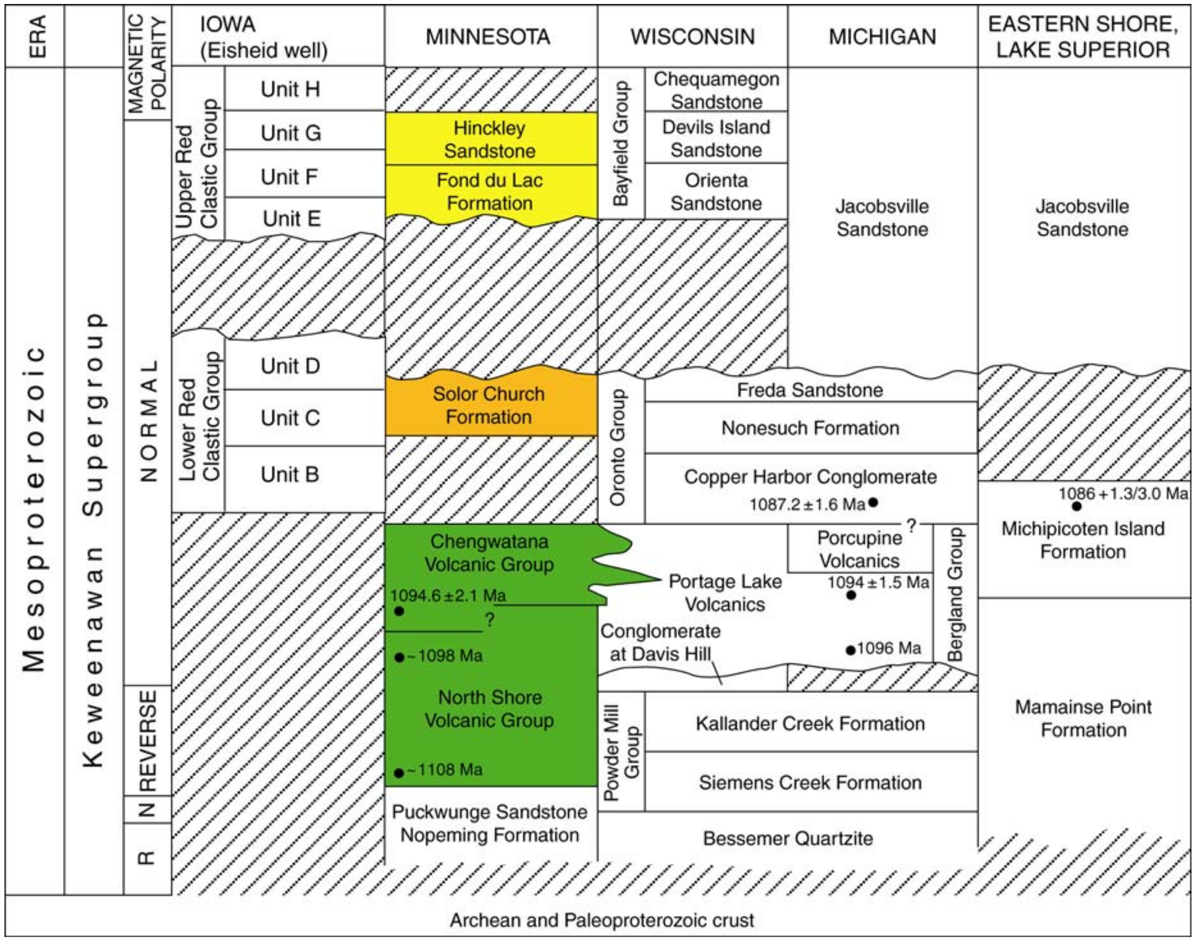

Figure 35. Comparative stratigraphy of the Keweenawan Supergroup in the Lake Superior region. Modified from Ojakangas and others (2001) and Anderson (1997).

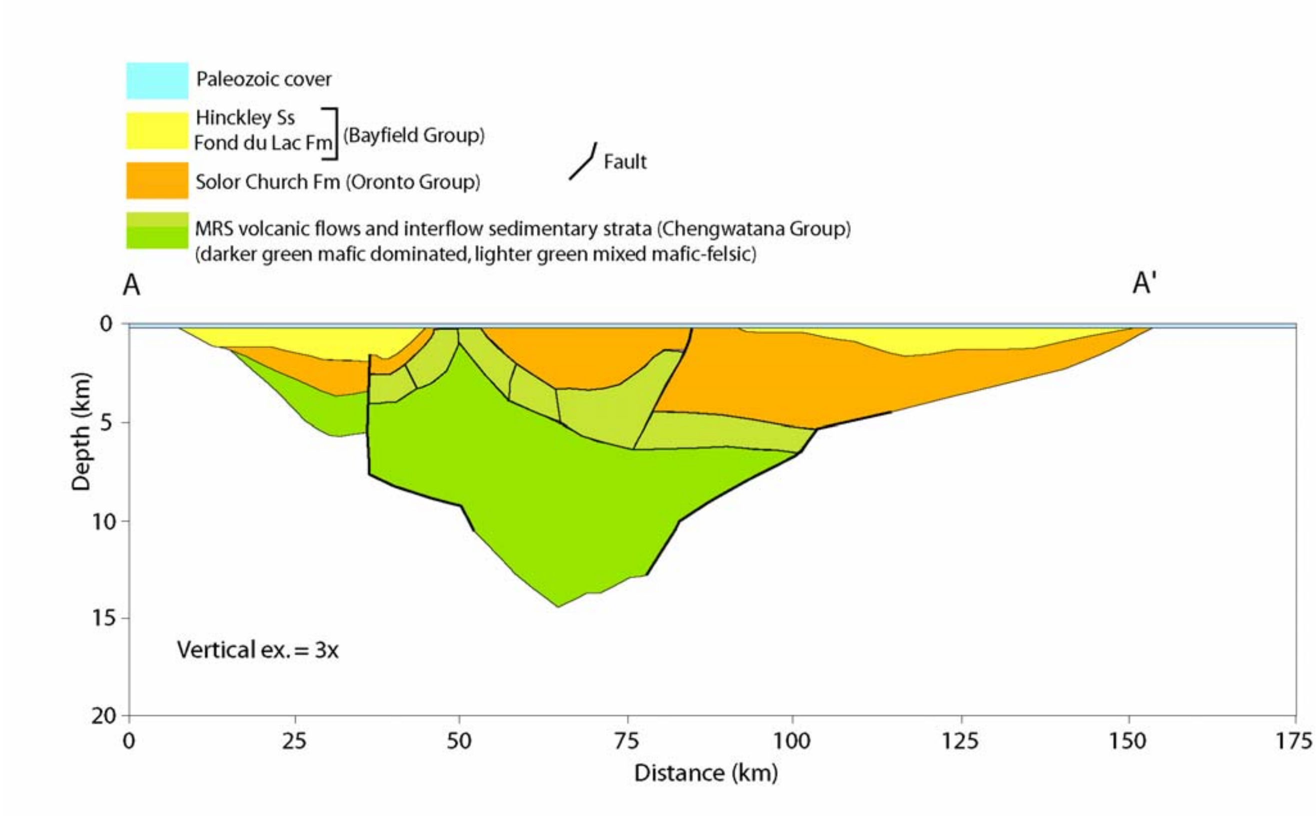

Figure 36. Cross-section of Midcontinent Rift System in southeastern Minnesota. Location of section line shown in Figure 34. Modified from Allen et al. (1997)

Sandstone is not known to be present at depths required for geologic sequestration of carbon dioxide, and so the Hinckley is not considered further in this section of the report.

The Minnesota Keweenawan sedimentary strata have been loosely correlated to sedimentary successions in other parts of the Midcontinent Rift system (Figure 35; Ojakangas and others, 2001). The Solor Church Formation is believed to be at least in part equivalent in age to the upper part of the Oronto Group in Wisconsin, and to part of the Lower Red Clastic Group in Iowa. The Fond du Lac Formation is correlated to the Orienta Sandstone of the Bayfield Group in Wisconsin, and to the lower part of the Upper Red Clastic Group in Iowa. These correlations are tentative, because MRS strata are poorly dated, contain no traceable marker beds, have few deep borehole penetrations, and in many places are associated with complex structural settings.

The geographic distribution and stratigraphic relationship of the Solor Church and Fond du Lac Formations are poorly known. A contact between the formations is not exposed in outcrop, nor penetrated by drill holes, and the two formations have never been confidently documented to occur in succession in any one place. Therefore, the interpretation that they represent an ascending succession separated by an unconformity is speculative, based largely on a poorly documented description of Fond du Lac Formation conglomerate that includes clasts derived from the Solor Church Formation (Morey, 1972). The limited core and outcrop information available is permissive of a significantly different interpretation whereby at least parts of these formations are equivalent in age. Additionally, the interpretation that the relative immature texture and mineralogy of the Solor Church Formation compared to the Fond du Lac Formation is evidence that the former is a temporally older unit is inconsistent with the Keweenawan MRS sedimentary succession described to the south in Iowa, where sandstone maturity decreases up section (Ludvigson and others, 1990). Because of these stratigraphic uncertainties, as well as other recently documented stratigraphic and structural complexities (e.g. Cannon, 2001), attempts to apply the traditional formation-level nomenclature in Minnesota has proven to be difficult. Therefore, although many of the descriptions in this report refer individually to the Solor Church and Fond du Lac formations, it should be noted that these two formation have not yet been proven to be mappable, and any described differences between the two may not correspond to a succession of two distinct sedimentary units.

The Solor Church Formation is described by Morey (1972) and Hatch and Morey (1985) as a red-brown, dense and well-indurated sequence of interbedded conglomerate, sandstone, siltstone and shale with a few beds of limestone in its upper part. About 50 percent of the formation is sandstone (Morey, 1972). Beds are typically less than 10 feet (~3m) thick, with some sandstone beds as thick as about 30 feet (~9m). Most conglomerates are intraformational, although clasts of basalt may be common near the base of the formation based on samples of borehole cuttings. The sandstones and siltstones are largely mineralogically and texturally immature arkoses, with appreciable amounts of feldspar and aphanitic rock fragments. Plagioclase feldspar exceeds potassium feldspar in abundance. Morey (1977) examined over 100 thin sections of sandstone from the Solor Church Formation and reported that 2% is quartz arenite, 31% subarkose, 20% arkose, 22% lithic arkose, 14% feldspathic lithic arenite, 10% lithic subarkose, and 1% lithic arenite. Sandstones are typically fine-grained or finer, poorly to moderately sorted, contain greater than 5% matrix material and pore-filling cement (clay, hematite, and calcite), and are angular to subrounded. Textural and mineralogical maturity increases upward in the formation.

The Solor Church Formation commonly contains intervals composed largely of shale and mudstone greater than 20 ft (~6m) thick, and some exceed 100 ft (~30m; Morey, 1977). The clay-sized fraction is predominantly composed of mixed-layer illite and montmorillonite and lesser amounts of illite. Hematite is common and calcite is locally very abundant. Chlorite and zeolites are moderately abundant in the lower part of the formation, which was interpreted by Morey (1977) to reflect incipient subgreenschist facies metamorphism. Most mudstone and shale is reddish-brown to gray-green, and has an organic carbon content as high as 1.77% (Hatch and Morey, 1985).

The Fond du Lac Formation is composed of greater than 50% sandstone (and subordinate interbeds of conglomerate), with the remainder siltstone, mudstone and shale (Morey, 1977). Sandstone beds, typically ranging from less than a foot (~30cm) to about 20 feet (~6m) thick, are fine- to coarse-grained, poorly sorted, and arkosic, and composed of 15-40% feldspar, with more potassium feldspar than plagioclase. The average framework grain mineralogy is 77% quartz, 15% feldspar and 8% rock fragments such as chert, quartzite, granitic, and aphanitic igneous rocks. Conglomeratic units contain granule to pebble-size clasts of quartz, basalt, and felsite. Matrix material in the sandstone constitutes 1-20% of the total rock, and consists of well-ordered illite and lesser kaolinite. Pore-filling cement constitutes 1-20% of the total rock and is mostly calcite and lesser hematite, the latter occurring as thin coatings on framework grains, as stain on clay minerals and rock fragments, and as interstitial void fillings (Morey, 1967; 1977).

Intervals dominated by mudstone and shale in the Fond du Lac Formation are as thick as 18 feet (5.5m; Morey, 1967). Such intervals are laminated or structureless, generally moderately to very dusky red, with mottles of green and yellow-brown. The clay-size fraction is predominantly illite and chlorite with lesser amounts of kaolinite and mixed-layer montmorillonite-illite (Morey, 1977).

Depositional History

The Solor Church and Fond du Lac Formations in Minnesota and their equivalents in nearby states are thought to be a record of “post-rift” deposition (Ojakangas and others, 2001), in reference to their deposition after major volcanic activity. The depositional environment of the MRS sedimentary successions within Minnesota (e.g. Morey, 1972; 1977; Morey and Ojakangas 1982; Ojakangas and Morey, 1982, Ojakangas and others 2001) is not well understood, particularly south of the outcrops in the east-central part of the state. The bulk of both the Solor Church and Fond Lac Formations have traditionally been interpreted to be a product of fluvial deposition. That interpretation is based largely on local documentation of lenticular, cross-stratified sandstone bodies and evidence for subaerial exposure in the limited outcrops of east-central Minnesota. and on the presence of fining upward cycles of sandstone-shale successions in outcrop and several cores (Morey 1977; Ojakangas and others, 2001). Carbonate beds and organic-rich mudstone and shale that compose a very small percentage of the Solor Church Formation were interpreted as the deposits of interchannel shallow lakes (Ojakangas and others, 2001). Others have suggested that chemical and organic attributes of possibly analogous facies elsewhere in the MRS are more indicative of marine than of lacustrine conditions (e.g. Pratt and others, 1991).

The previous interpretation that the bulk of the Solor Church and Fond du Lac formations were deposited in a fluvial environment can now be re-evaluated based on progress in sedimentologic research. Many of the facies attributes interpreted to indicate a dominantly fluvial depositional setting, such as the presence of fining-upward successions, are no longer regarded as strongly diagnostic of any specific environment. Reconnaissance examination of facies by the senior author of this section indicates while parts of both formations are most likely fluvial in origin, features such as hummocky cross-strata are common (e.g. Figure 37), and indicate that significant parts of both formations may have instead been deposited in a large lacustrine or marine setting. For example, the sedimentary features of all 1800+ ft (~550m) of the type section of the Solor Church are more consistent with deposition in a large body of standing water than with deposition in a fluvial system (Figure 37). Anderson (1997) proposed a model of deposition in an extensive body of standing water for some of the Lower Red Clastic Group strata in Iowa that are believed to be equivalent to part of the Solor Church.

Anderson (1997) provided the most comprehensive summary linking post-rift sedimentation to tectonism, based on his analysis of deep boreholes and geophysical surveys in Iowa, and a comparison to MRS features to the northeast, including Minnesota. He outlined a general sequence of events that apply across much of the MRS, and are consistent with the interpretations of Craddock (1972). In the model, initial extension led to crustal thinning, fracturing, formation of an axial graben, and deposition of voluminous flood basalts. As extension diminished and volcanism waned, the oldest post rift strata (Oronto Group and equivalents) were deposited in

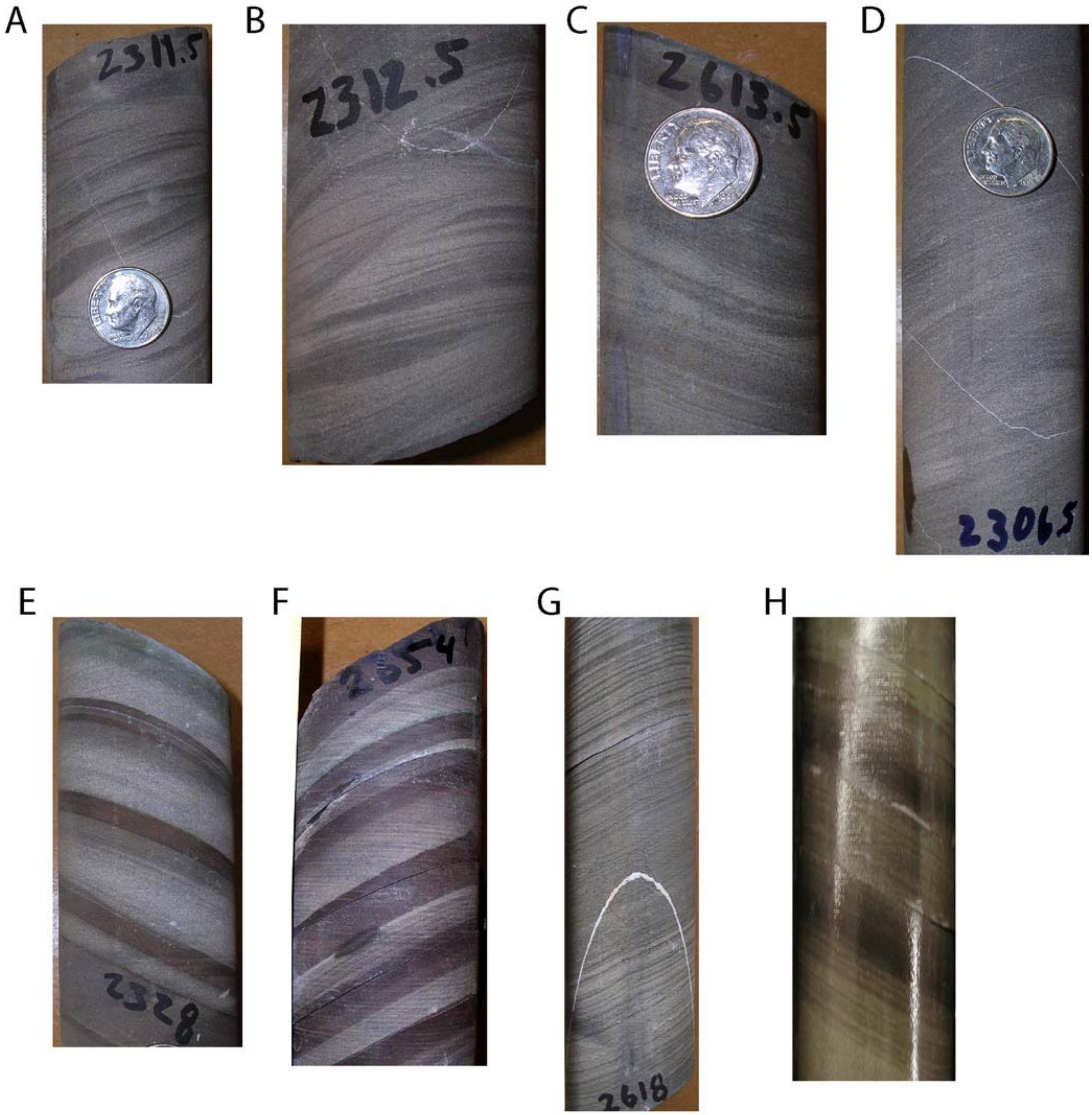

Figure 37. Common sedimentologic features in Solor Church Formation. **A)-D)** show hummocky to swaly cross-strata. **E)** Hummocky cross-strata with siltstone to mudstone caps (dark red/brown). **F)** Sandstone-mudstone couplets, some with normal grading. **G** and **H** show laminated sandstone, mudstone, and shale. Note that master bedding in all examples dips about 30 degrees. Core diameter is 1.6 inches (4.0 cm) in all photos. Examples are from 2300 to 2700 feet (701-823m) depth, Lonsdale 65-1 core (Minnesota drillhole unique number 235526).

the axial graben and flanking areas that continued to subside. Regional deformation switched to contraction, which reversed the direction of movement along graben-bounding fault zones, and initiated the uplift of the axial graben to form a horst (e.g. the Iowa and St Croix Horsts). Uplifted horsts contributed detritus that was mixed with contributions derived from outside the MRS and deposited in horst-flanking basins as part of the Bayfield Group and equivalents. In Minnesota and Wisconsin, an overall increase up section of sandstone maturity with a corresponding increase in constituents indicative of extrabasinal sources is interpreted as reflecting burial of MRS-related volcanics, and derivation of detritus from progressively more extensive source terrains as the rift filled and only slowly subsided (Ojakangas and others, 2001). The degree to which rift-related faulting and subsidence controlled the geographic extent of deposition and the distribution of facies is uncertain, largely because of the scarcity of outcrops, cores and deep boreholes south of the principal areas of exposure in east-central Minnesota. Ojakangas and others (2001) and Anderson (1997) suggested that parts of the Solor Church and Fond du Lac formations and their equivalents may have been deposited in basins that were considerably wider than the original rift grabens.

Reservoir and Seal Thicknesses, Porosity and Permeability

Intervals dominated by sandstone in the MRS are known to exceed 100 feet (~30m; e.g. Witzke 1990; Morey, 1977). They contain subordinate interbeds of mudstone, shale and siltstone that subdivide these intervals into individual sandstone units that typically range from a few feet to a maximum of about 30 feet (~9m) thick in Minnesota. The three-dimensional geometry of these sandstone bodies has never been documented, and cannot be reasonably predicted because of the uncertainties about the depositional setting for the MRS sedimentary succession.

Limited data from borehole geophysical logs, petrographic analyses, and plug tests of core samples (Table 1) appear to show a generally consistent trend whereby sandstone porosity at relatively shallow depths of 2500 feet (762m) or less varies from low to moderate, and at greater depths is low to very low (e.g. Figure 38). Porosity ranges from about 2 to 20% at depths of less than 2500 ft (762m) (Table 1). At greater depths, borehole geophysical logs (neutron, density and sonic) indicate that porosity is less than 10% for sandstone below about 2500 feet (762m) in deep exploration holes in Iowa and Wisconsin, and most commonly is below 3% (Table 1). The proportion of this porosity present within the clay matrix common to Keweenawan sandstone of the MRS is uncertain, although petrographic analyses indicate that it may be substantial (Ludvigson and others, 1990). Porosity values based on petrographic point counts of sandstone sampled from depths greater than 2500 feet (762m) in Iowa, Wisconsin, and Michigan are consistent with, or lower than, the values calculated from borehole geophysical logs, indicating a porosity of less than 5% and commonly averaging less than 1% (Ojakangas and Dickas, 2002; Ludvigson and others, 1990). Pore-filling cement and the fine siliciclastic matrix between framework grains that is characteristic of MRS sandstone (e.g. Figure 39) to a large degree accounts for these low porosity values. Values of porosity calculated from over 50 plug tests of samples from Minnesota and Iowa core (Table 1) are generally consistent with those calculated from thin section petrography, averaging 3.4 % for samples collected at depths greater than 2500 ft (762m).

A possible exception to characteristically low porosity at depths greater than about 2500 ft (762m) has been reported for MRS sedimentary rocks in Kansas. A 22 ft (7.6m) sandstone interval at about 11,055 ft (3370m) in the Texaco Poersch #1 exploration hole was interpreted on the basis of borehole geophysical logs to have a porosity of up to 15%, in contrast to the “negligible” (<2%) porosity interpreted for the thousands of feet of sandstone above and below it (Berendsen and others, 1988). However, the calculation of porosity for this relatively thin interval was not supported with analysis of rock material, nor was a clear evaluation for the potential that fractures or clay matrix accounted for the anomalously high porosity given.

Information on permeability of MRS sandstone is extremely scarce, consisting of a handful of unpublished records from relatively shallow site characterizations for natural gas storage, and about 50 plug tests of samples

Borehole name	St Amour (Amoco Product. #1-29 test) and Hickey Creek Hole	Terra-Patrick#7-22	Lonsdale 65-1 (unique no. 235526)	Schuette (unique no. 215681)	MLCH-13 (unique no. 251832)	NNG Osseo 65-1 (unique no. 207022)	Steinhouse-1 (unique no. 213185)	M.G. Eischeid#1	Birdie Lehman #1	Ray McCallum A-1	Rhinehart Farms A-1	Texaco Poersch #1
location	Upper Peninsula Michigan	NW Wisconsin	SE Minnesota	SE Minnesota	E-Central Minnesota	SE Minnesota	SE Minnesota	West-Central Iowa	Southwest Iowa	Southwest Iowa	Southwest Iowa	Northeast Kansas
Lithostrat. units	Jacobsville Ss over Oronto Group	Oronto Group	Solor Church Formation	Fond du Lac Formation	Fond du Lac Formation	Chengwatana Group Interflow sediments	Fond du Lac/Hinckley? Formation	Upper and Lower Red Clastic Groups	Upper Red Clastic Group	Upper Red Clastic Group	Upper Red Clastic Group	Rice Formation
P & K **1200'- 2500' depth**	P^c avg 14.2 P^c 2.1 to 27	P^b avg 7to 10	1294' P^a2.6 1823'P^a 3.9; Kv 10^{-4}	2349' 2 samples P^a 15.7 and 17.35 Kv 0.2 Kh 0.2	1803'-2390' 7 samples P^a avg 12.2 (3.3 to 17) Kv avg 10^{-2} (10^{-4} to 0.1) Kh avg 10^{-2} (10^{-2} to 10^{-3})	1449' P^a 5.1 Kh 10^{-4}	1976'-2078', 15 samples Kh avg 94.7 Kv avg 61.8 P^a avg 19.4					
P & K **2500'- 3000' depth**	P^c avg 0.6 P^c 0-3.3	P^b avg 7 to10	2503.5'-2773' 4 samples P^a 1.8 to 2.1 Kv <10^{-4} to 10^{-4} Kh <10^{-4}			2709'8" P^a 2.8 Kh 10^{-4}		P^c 6%	2930.5'-2960' 3 samples P^a avg 9.6 (8.9 to 10.5) K avg ~10^{-3} (10^{-3} to 10^{-4})			
P & K **3000'- 4500' depth**	P^c avg 0.6 P^c 0 to 3.3	P^b ~ 0 to10						P^c 1 to 2.5		3013.6' P^a 8.47 K 10^{-3}	3068.5'-3079.8 4 samples P^a avg 9.1 (6.3 to 11.6) K avg 10^{-2} (10^{-4} to 10^{-2})	
P & K **>4500 depth**	P^c avg 0.6 P^c 0 to 3.3	P^b avg ~3						4500'-~15,000' P^c 0 to 1 >11,450' P^b avg 2.3 P^b 1 to 6 8834.5'-15,106' 27 samples P^a avg 1.9 (0.3 to 3.8) K avg ~10^{-3} (26 samples <10^{-2}; 1 value 1.5)				~4500' to 11,296' P^b <2 with possible exception at 11,055' (see text)
Sources of data	Ojakangas and Dickas (2002)	Daniels (1999)	This study	This study	This study	This study	Unpublished Minnesota Gas Company Reports, stored at MGS	Ludvigson et al. (1990); Schmoker and Palacas (1990) This study	This study	This study	This study	Berendsen et al. (1988)

P= Sandstone Porosity, expressed as percent
K=Sandstone Permeability, in millidarcies (Kh=horizontal, Kv=vertical)
avg=average

Method of porosity measurement
a=laboratory tests of 1" diameter plugs
b=borehole geophysical logs
c= conventional point counts of thin sections
Permeability values all based on laboratory plug tests

Table 2. Compiled porosity and permeability of sandstone in boreholes and cores intersecting MRS sedimentary rocks. Plug samples tested as part of this study include samples selected as representative of the most porous appearing sandstone based on routine core inspection. As a frame of reference, injection and storage of carbon dioxide is believed to require, at depths greater than about 2600 ft, sandstone with a minimum porosity of about 5%, and a minimum permeability of about 5md.

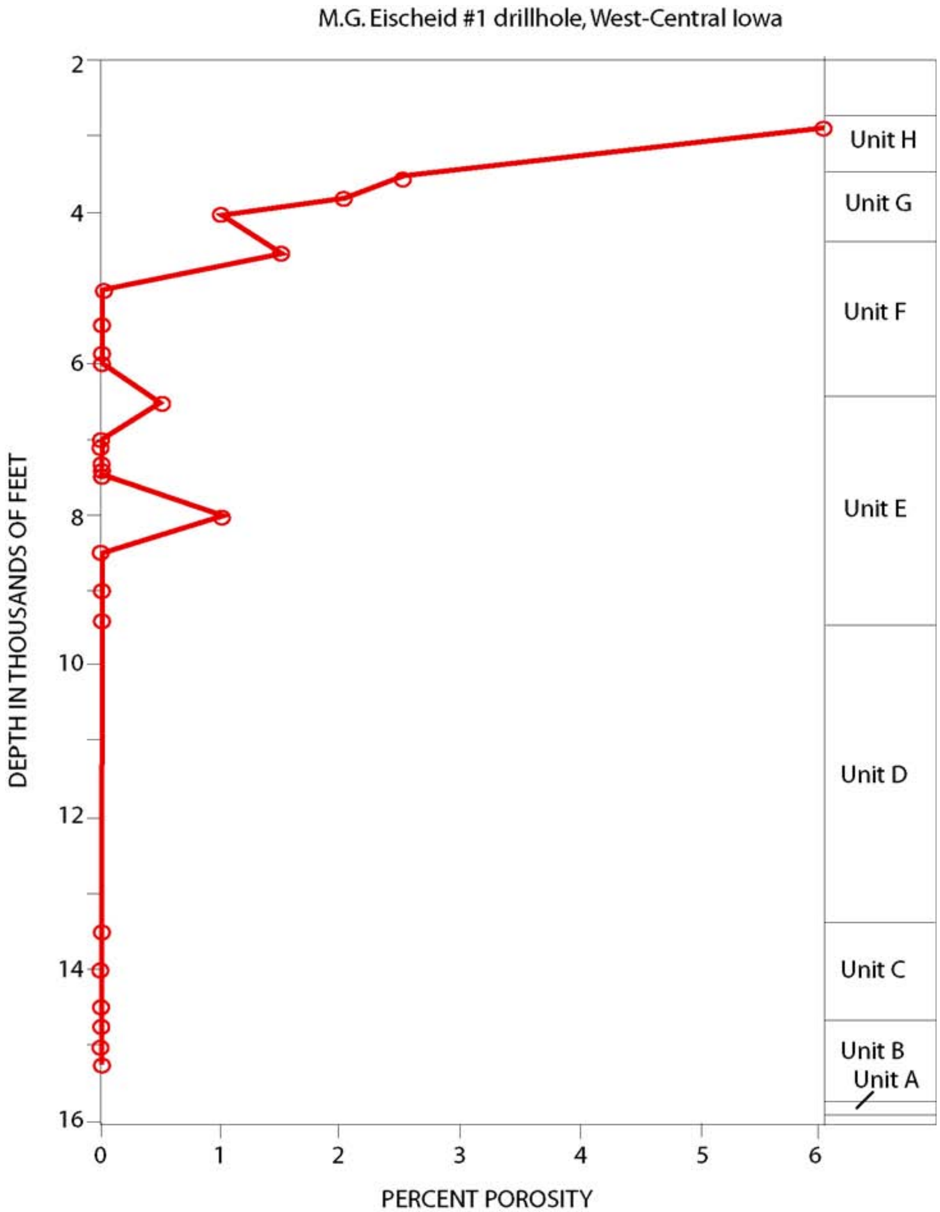

Figure 38. Percent porosity resolvable in petrographic analysis of sandstone chips in cuttings samples recovered from the M. G. Eischeid #1 drillhole, plotted against depth. The very low values below a depth of about 3000 ft are consistent with porosity versus depth relationships documented in other deep boreholes in the Midcontinent Rift System. Units A-F refer to informal lithostratigraphic units shown in Figure 35. Modified from Ludvigson et al. (1990).

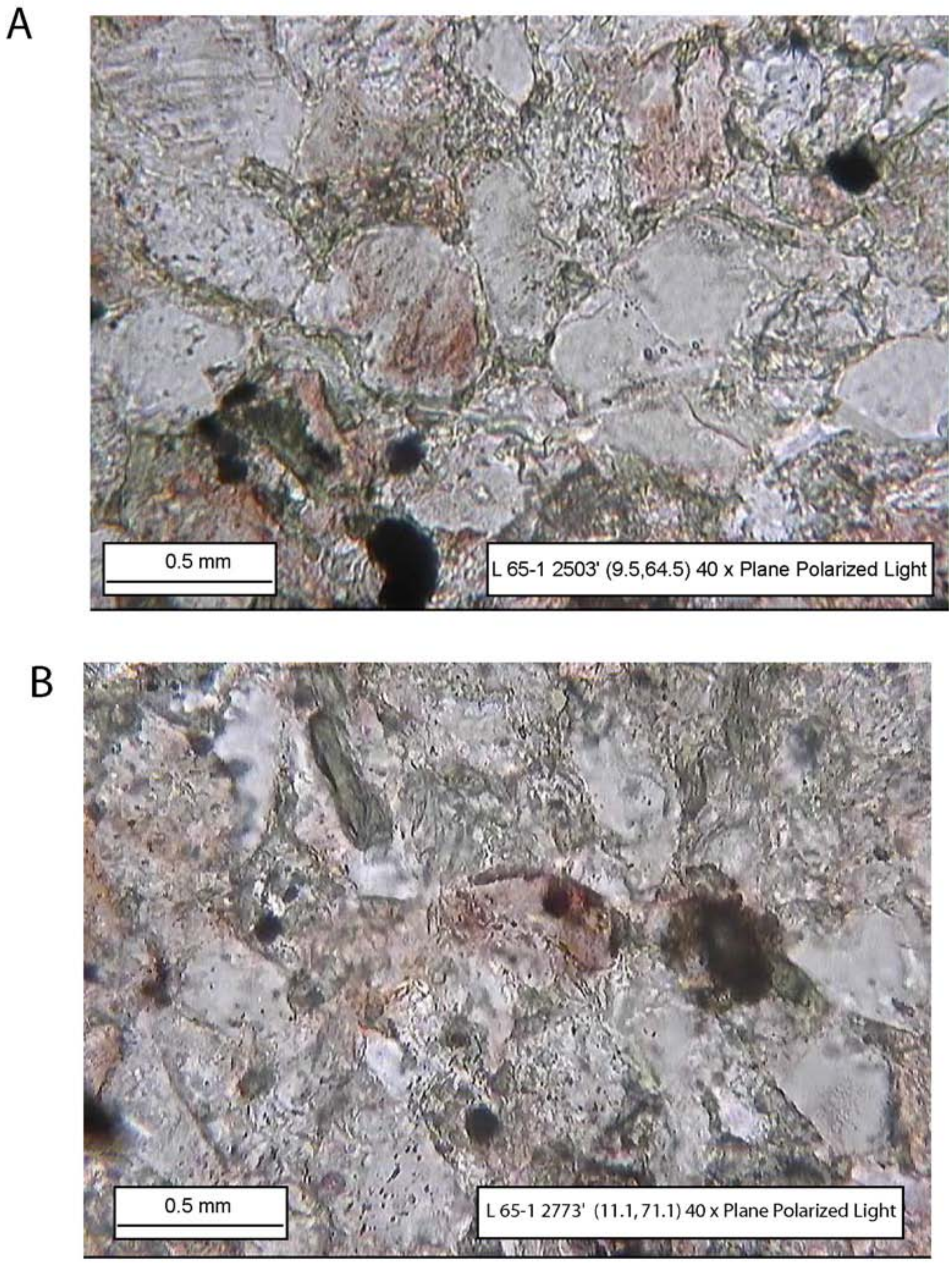

Figure 39. Photomicrographs of thin sections of Solor Church Formation sandstone. Representative examples showing spaces between framework grains filled with matrix and cement. **A**) In this view, the chlorite and other matrix filling the relatively small spaces between framework grains is readily apparent. Quartz grains range in size from 0.6 to 0.1 mm. Interstitial spaces range in size from about 0.2 to 0.08 mm. **B**) Interstitial spaces have an approximate size range of 0.6 to 0 .2 mm. These spaces are comparable in size to the quartz grains. They are filled with fine-grained material ranging in size from 0 .14 to 0.02 mm. This material was not identified, but is likely to be high in clay minerals. Opaque minerals are likely to be either iron oxides or iron sulfides. Lonsdale 65-1 core; **A)** 2503 ft. depth, **B)** 2773 ft. depth.

from Minnesota and Iowa cores compiled as part of this investigation (Table 1). The sandstone samples from Minnesota and Iowa that we submitted as part of this project all tested low to very low in permeability, averaging about 10^{-3} md. All but two samples (1.5 md, and 0.04 md) had permeability of less than 10^{-2} md. Some of these samples had a moderate porosity of between 10 and 20%, and therefore the low to very low permeability indicates that much of the porosity is in the form of poorly connected micropores in the clay matrix. One core in Minnesota contains sandstone at a depth of between 1976 ft (602m) and 2078 ft (633m) that has markedly greater permeability than those described above, with 15 samples having an average horizontal permeability of about 95 md (Table 1; Steinhouse-1; from unpublished Minnesota Gas Company records acquired by the Minnesota Geological Survey in 1980).

Intervals dominated by shale, mudstone and siltstone are known to exceed 100 ft (~30m; e.g. Morey, 1977, Witzke et al, 1990). A limited number of plug tests, and cursory core logging observations indicate that they have a low to very low matrix permeability, about 10^{-4} md or lower. The thickness of such intervals and their very low matrix permeability indicates that they could potentially serve as reservoir seals if they are not breached by fracture networks.

Sedimentary strata in the MRS are more indurated and brittle than overlying Paleozoic strata in southeastern Minnesota, and by comparison contain a markedly greater density of visible fractures in core. Moderate to abundant fractures (Figure 40) are common in sandstone, shale, and mudstone intervals (e.g. Morey, 1977), including horizontal, vertical, and oblique fractures. Fractures are most typically filled with calcite cement, but open fractures with iron-rich precipitates on faces are also common. Open fractures may be of greatest density near faults. A densely fractured, rubbly interval from 2129 ft to 2133 ft in the Lonsdale 65-1 core (Figure 34) separates beds below that dip approximately 30 degrees, from beds above that are subhorizontal. Secondary permeability generated by fractures is an important factor to consider in an evaluation of the ability of the fine siliciclastic intervals to serve as reservoir seals. Relationships between rock pigmentation and fractured intervals in Minnesota cores of Keweenawan strata indicates that fractures at one time served as pathways for reducing fluids (Morey, 1977). Furthermore, hydraulic connection between relatively deep and saline MRS groundwater and overlying freshwater aquifers (described below) suggests that shale and mudstone aquitards in the MRS are in many places breached by fractures that may be preferentially developed near faults.

Mafic and felsic volcanic rocks in the Chengwatana group have not been tested for porosity and permeability, but small samples of unfractured, nonvesicular material should be expected to have very low porosity and permeability. Cursory examination of approximately 1000 ft (~300m) of Chengwatana group core from southeastern Minnesota (NNG Osseo 65-1, unique number 207022), extending to a depth of 4000 ft (1220m) , reveals that vesicles and fractures in the volcanic flows are filled with secondary minerals. This observation is consistent with fracture analyses of MRS volcanic flows in Kansas (Texaco Poersch #1 drillhole) which were interpreted to be mostly “healed” on the basis of borehole geophysical signatures. Two core samples of Chengwatana Group interflow sandstone in southeastern Minnesota have relatively low porosity of about 3 to 5% and a very low permeability of 10^{-4} md (Table 1; NNG Osseo 65-1). Thus, the potential suitability for the Chengwatana Group rocks to serve as a seal, or alternatively as a reservoir, appears to depend largely on characteristics of open fracture networks, about which little is known.

Hydrogeology

Very little is known about the hydrogeologic conditions in the MRS at the depths required for deep geologic sequestration of carbon dioxide. The small number of boreholes that penetrate to such depths are not known to have been sampled for water chemistry, nor are they associated with any other kind of hydrologic analyses. Furthermore, the general scarcity of any kind of deep drillhole data precludes a meaningful interpretation of hydrostratigraphy beyond the limited porosity and permeability characteristics described previously.

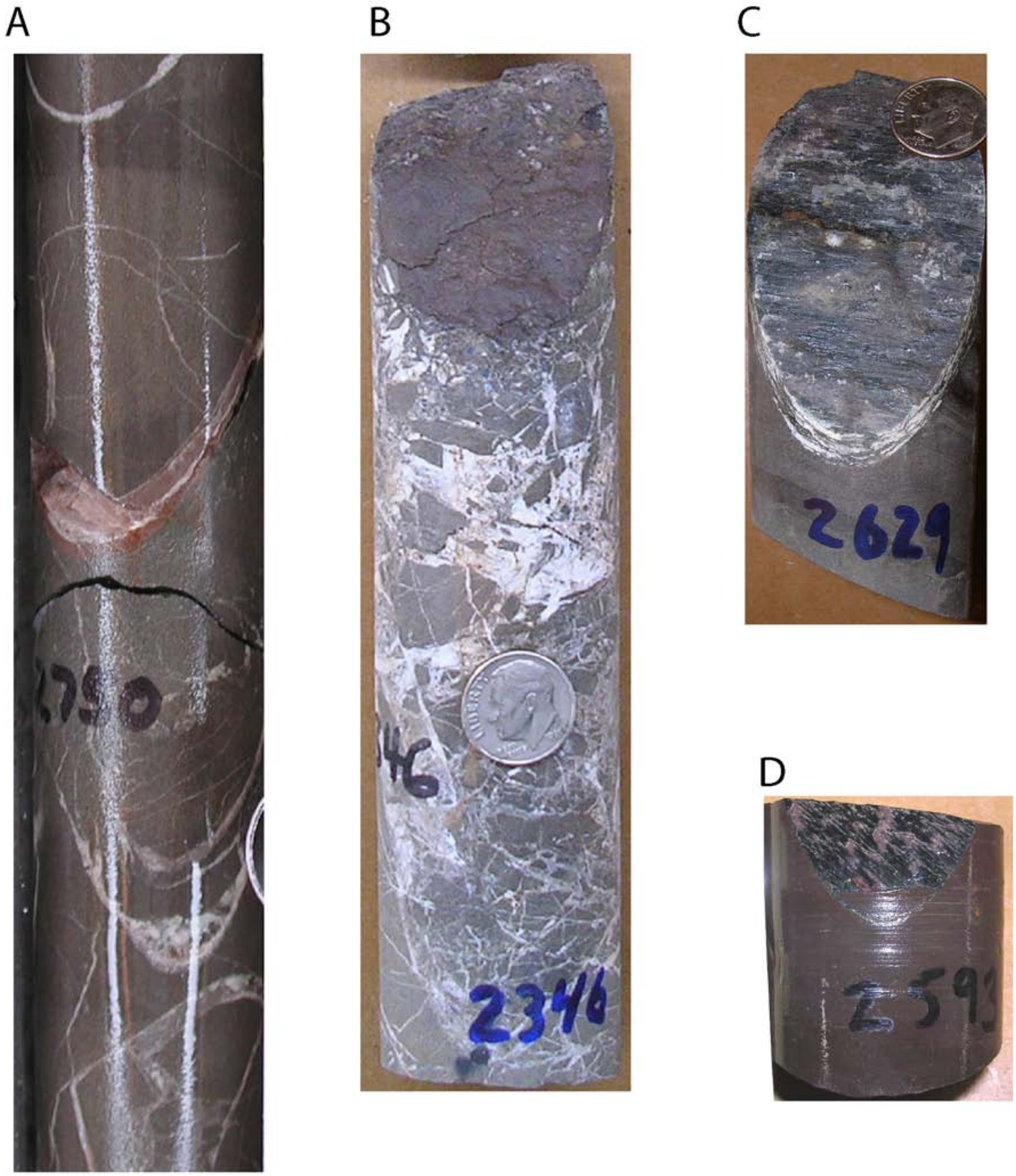

Figure 40. Representative examples of fractures in sandstone and shale of the Solor Church Formation. Calcite (white) commonly fills fractures. Other fractures are open, and commonly have striated surfaces and iron-rich precipitates (e.g. upper part of cores in **B**, **C**, and **D**). **A**, and **B** are largely sandstone, **C** is interbedded sandstone, siltstone and shale, and D is shale. Depths range from 2346 ft to 2750 ft (715-838m), Lonsdale 65-1 core (Minnesota drillhole unique number 235526). Diameter of core in all examples if 1.6 inches (4.0 cm).

Although deep groundwater in the MRS has not been directly sampled and tested, there is fragmentary evidence from relatively shallow conditions along the MRS that at some depth and in many places groundwater is saline, and relatively old compared to the near-surface groundwater systems that are utilized as water sources in Minnesota. In northeastern Minnesota, wells that penetrate the volcanic flows and interbedded siliciclastic strata of the North Shore Group are known to locally produce water with elevated calcium chloride levels (Tipping and Allen, 1997; Allen and others, 1997). Some springs emitted from surface exposures of bedrock on top of the MRS in east-central Minnesota produce water with chloride values of nearly 200 ppm (Shade, 2002). Deep oil exploration wells drilled over 80 years ago near the cities of Rochester (well unique number 220787) and Stillwater (unique number 208785) in southeastern Minnesota reported saline water in Keweenawan strata at depths between 1950 ft (595m) and 2450 ft (747m) (Hall and others, 1911; Minnesota Geological Survey County Well Index database). Elsewhere in southeastern Minnesota a small number of wells drilled into the basal Cambrian sandstone (Mt Simon Sandstone) overlying Proterozoic MRS rocks produced water too saline for domestic use, with concentrations locally exceeding 4000 ppm(e.g. Lively and others, 1992). A larger number have chloride levels elevated above the low regional background (Figure 41). Such wells have been documented in parts of several counties across east-central and southeastern Minnesota. There is evidence of several different geochemical types of saline waters, sodium chloride waters, high sulfate waters, mixed chloride and sulfate waters and high bicarbonate waters. Calcium sodium magnesium chloride brines are known from the older basement rocks adjacent to the MRS. Water from some of these wells is known to have relatively high radium concentrations and older radiocarbon ages than other wells open to the same aquifer elsewhere. Wells and springs with elevated chloride concentrations and associated anomalous chemical characteristics (negative redox potentials, elevated iron and other trace element levels, etc.) indicative of relatively old groundwater are believed to represent water that has a significant contribution from relatively great depth in the MRS. Many of the wells with anomalously saline water in southeastern Minnesota are in the vicinity of faults related to the MRS (Figure 41), and Lively and others (1992) suggest that secondary pores associated with the faults allow older, more saline water to flow upward into the Mt Simon Aquifer from the underlying Keweenawan rocks of the MRS. This interpretation implies that relatively deep groundwater in MRS strata is at least locally saline and has a hydrostatic head greater than that of the freshwater aquifers that overlie it. Furthermore, these conditions imply that the aquitards that confine deep MRS groundwater are in places hydraulically breached by secondary pores associated with faulting.

Summary

The MRS in Minnesota may not be sufficiently geologically characterized to permit a fully informed judgment on its suitability as a site for the sequestration of CO_2, but the limited available information summarized in this section indicates that the MRS has attributes that make it far less suitable for sequestration than other sites currently being considered across the country.

On the positive side, the MRS contains the only sedimentary rocks in Minnesota that extend to depths required for sequestration, including sandstone bodies that at relatively shallow depths of 2500 ft (762m) or less are known to locally have moderate porosity and permeability. Shale and mudstone intervals are present, which appear to be of sufficiently low matrix permeability to serve as seals. The unexplored nature of the MRS is a potential advantage for deep geologic CO_2 sequestration. Reservoirs which have historically produced energy or other types of resources are often riddled with undocumented exploration holes that were not properly abandoned. Such wells may be a significant and unquantifiable risk of leakage of the sequestered CO_2 to the surface. The MRS has not been subject to such exploratory drilling. These attributes suggest that the MRS should not be ruled out as a potential site for deep geologic sequestration of CO_2.

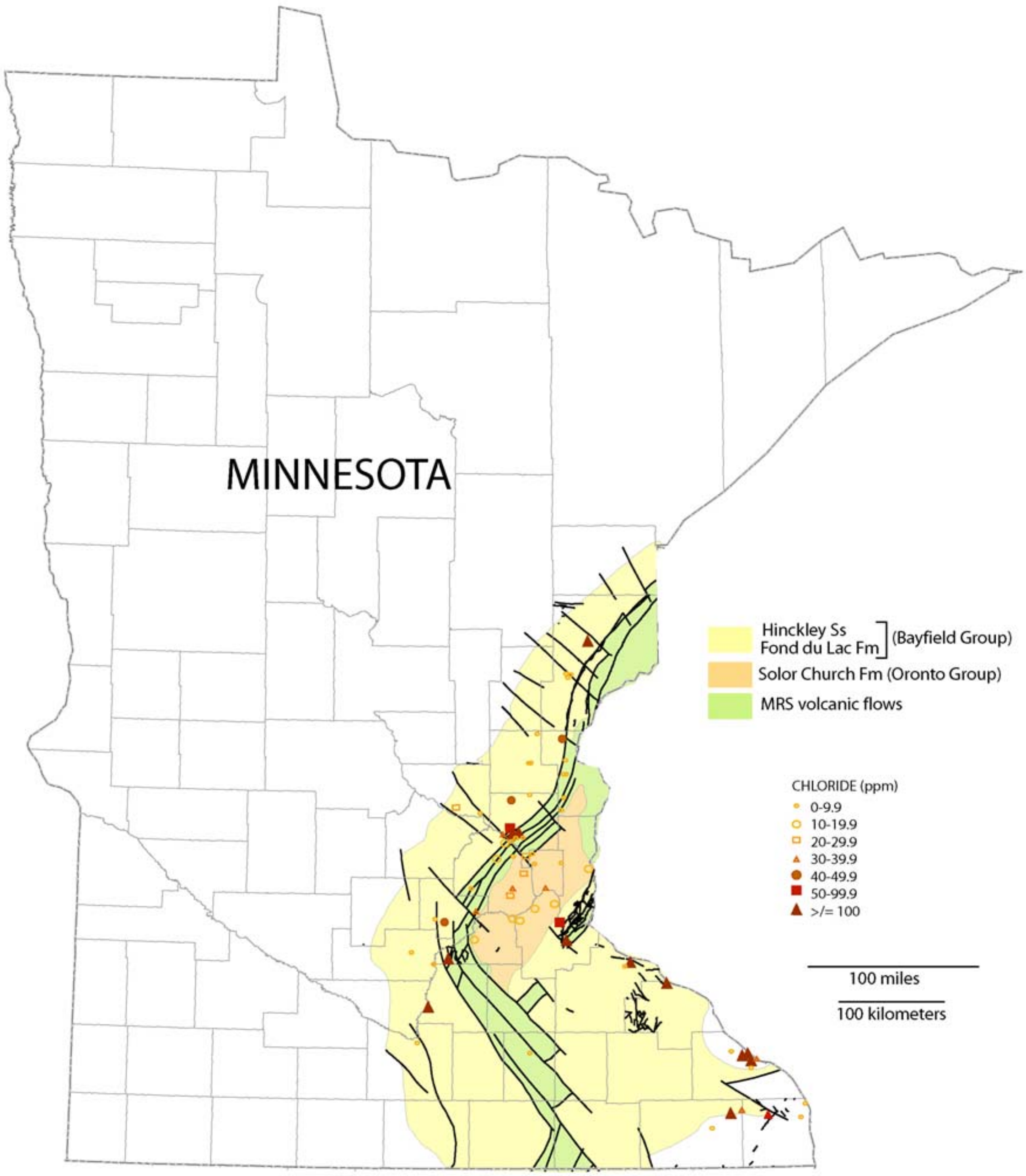

Figure 41. Areal distribution of chloride in the Mt Simon - Hinckley Aquifer, a basal Cambrian quartzose sandstone that overlies the rocks of the Midcontinent Rift System. Note that the highest chloride values commonly occur near MRS-related faults. Modified from Lively et al. (1992).

On the negative side, the known and inferred properties of the MRS in Minnesota and neighboring areas indicate that there is only a very small probability that it contains the geologic attributes necessary to serve as a site for deep geologic sequestration of CO_2. Geophysical logs of deep exploratory boreholes in Iowa and Wisconsin, petrographic analyses of sandstone in those states as well as Michigan and Minnesota, and the limited number of plug tests of samples from Minnesota cores as part of this project, indicate that sandstone at the depth required for sequestration is relatively low in porosity and permeability. Permeability has been measured to be orders of magnitude too low for sequestration to be viable everywhere it has been tested in the MRS. Furthermore, the MRS is associated with a longer, more pronounced, and complex tectonic history compared to other sites being investigated, and therefore features such as faults and fractures may play a larger role in site evaluation. For example, low permeability beds in the MRS that are necessary to serve as seals on top of potential CO_2 reservoirs are known to contain fractures with evidence of fluid flow. Fractures associated with faults are believed to serve as conduits for deep MRS groundwater to travel upward across such seals to overlying freshwater aquifers today. Identification and mapping of such features will likely be a markedly more difficult task compared to the relatively simple structural settings that are the target of sequestration sites elsewhere.

Targeted areas elsewhere were associated with comparatively large storehouses of information prior to consideration for deep geologic sequestration (e.g. , Finley, 2005; Steadman and others, 2005) and as a result were already known to contain sandstone bodies with adequate porosity and permeability, and shale of low permeability that served as seals. Depositional models, stratigraphic and structural frameworks, tectonic history, and hydrogeologic conditions were also relatively well understood. Furthermore, the presence of oil and gas reservoirs, including the successful use of sandstone bodies as storage sites for natural gas, demonstrated that geologic conditions in those areas were favorable for consideration of deep geologic sequestration.

Such a body of geologic knowledge does not exist for the MRS. If it is determined that further research is warranted, a comprehensive investigation will be necessary to bring the understanding of the MRS up to a level analogous to the understanding of potential sequestration sites in nearby Illinois and North Dakota prior to when the formal sequestration research programs even began in those areas. That investigation will need to include multiple deep exploratory boreholes with detailed logging and associated rock and groundwater analyses complemented with 3-D seismic data collected across a large area followed by stratigraphic, structural, tectonic and hydrogeologic interpretation. The early-phase characterization of the rift to assess its potential for sequestration will require significantly more time and expense than will be expended for the initial assessments made for other areas.

PRELIMINARY NUMERICAL MODELING OF CO_2 INJECTION AND STORAGE IN DEEP SALINE AQUIFERS: CURRENT RESEARCH, SCENARIOS, AND REQUIRED DATA

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Introduction - The Purpose of Numerical Modeling of CO_2 Injection and Storage

Numerical modeling is an essential element of the process of determining whether an aquifer is a good candidate for CO_2 injection, of the risk assessment associated with injection, and of injection itself.

CO_2 injection and storage in deep saline aquifers falls naturally in the geosciences, with its study encompassing the disciplines of hydrogeology (CO_2 and aquifer brine fluid flow, heat flow, and solute transport), geochemistry (reactions among injected CO_2, brine, and rock), geodynamics (subsurface pressure changes associated with injection, compression, and fracturing), as well as seismology and geophysics (both essential for gaining information about subsurface structures via seismic, electromagnetic, and gravity studies). Numerical modeling provides the framework for linking these different disciplines and determining how the various geologic conditions and processes within the CO_2 injection and storage problem affect the feasibility of the whole project.

Comprehensive experimental investigations of deep geologic processes are difficult, if not impossible, and expensive because of associated depths and the large, three-dimensional spatial extent requiring investigation. In addition, due to often complex feedback mechanisms that can act over long time spans, temporal effects of CO_2 injection would have to be studied in the field for up to thousands of years after (experimental) injection ceases (explained further in later sections). Clearly, such long durations of experimental investigation are impractical. Furthermore, detailed first-hand observation of deep aquifer behavior is typically impossible and remote observation techniques (e.g., equipment in deep wells, seismic/gravity/electromagnetic surveys) are expensive but provide essential (yet indirect) information of subsurface conditions. While the expense of some experimental studies is fully justifiable if a subsurface region appears promising for CO_2 injection and storage, viability of such experimental analysis cannot be determined without some initial study.

Numerical modeling of CO_2 injection and storage, while not without its own limitations that are predominantly caused by limited geologic information (as explained below), is a promising method for completing such initial – as well as subsequent – investigations. In fact, exploration of geologic parameters, numerical modeling based on those parameters, and field experiments complement each other. Each of these three approaches provides necessary background information for the next, more detailed level of study conducted by the other approaches. This iterative process of geologic exploration, numerical modeling, and field tests should then be continued until reasonable, predefined confidence levels regarding the feasibility of CO_2 injection and storage have been reached.

At the very start of a CO_2 injection and storage project, numerical modeling permits analysis of whether a particular deep saline aquifer (our proposed storage method, as explained later) holds promise for storage. From there, numerical models can be developed to test a variety of injection and storage scenarios for ranges of geologic parameters and their three-dimensional distribution. Storage aquifer and surrounding unit characteristics can be modified as desired and as information from drilling, seismic studies, and other methods becomes available. This approach permits ever improving approximations of how actual CO_2 may behave upon subsurface injection. Models can be developed to assess the risks (e.g., CO_2 leakage, induced seismicity, effects on other aquifers) associated with CO_2 injection, aiding risk minimization in actual projects. Finally, numerical models allow assessment of long term (hundreds to thousands of years) behavior of injected CO_2, far beyond what physical experiments permit. Thus, while numerical models can only be as good as the (always limited) three-dimensional subsurface geologic information provided as input from field measurements, they are ultimately a key method in determining complex, spatially expansive, and long-term subsurface processes and behaviors, such as the effects of CO_2 injection and storage in geologic formations.

Geologic storage of CO_2 generally refers to permanent CO_2 trapping in oil reservoirs, coal beds, or deep saline aquifers (see Figure 5). CO_2 injection into oil reservoirs helps maintain reservoir pressure thus improving oil recovery, and because such reservoirs trap oil, they readily store CO_2. CO_2 injected into coal beds bonds to coal, resulting in release of the methane that is typically bound to coal, which can be captured. Saline aquifers, described in detail in the next section, permit CO_2 trapping by a variety of mechanisms including dissolution of CO_2 into aquifer fluid and precipitation of carbon-containing minerals. Both oil reservoir and coal bed storage are profitable CO_2 reduction strategies, and oil reservoir CO_2 injection has been practiced for over 30 years (Kharaka et al., 2006). Injection of CO_2 in saline aquifers, however, is purely a reduction strategy. Then why consider saline aquifer storage? Of the three geologic storage scenarios, only deep saline aquifers are abundant and large enough to trap a significant fraction of global emissions from fossil fuel power plants (Plug and Bruining, 2007). Considering global CO_2 emissions through 2050, coal beds worldwide could store approximately 2% of emissions (40 to 150 billion tons, or Gtons), oil reservoirs could store approximately 42% of emissions (up to 920 Gtons), and saline aquifers could store approximately 500% of emissions (up to 10,000 Gtons; Plug and Bruining, 2007). Furthermore, saline aquifers are very prevalent worldwide, offering favorable proximity to large CO_2 sources; oil reservoirs and coal beds, by comparison, are sparsely distributed. Because of the significant advantages of geologic CO_2 storage via deep saline aquifers, the following discussion of numerical modeling of CO_2 injection and storage is primarily constrained to this method.

2 Currently Used Procedures for Numerical Modeling

Recent numerical modeling of CO_2 injection and storage has been accomplished using a variety of techniques; both individual, detailed aspects of the process (e.g., CO_2 leakage around abandoned wells or chemical reactions associated with CO_2 injection into a brine) and simplifications of entire injection scenarios are being modeled. In what follows, we describe a selection of recent literature regarding modeling of CO_2 injection and storage in deep saline aquifers, including much that is in progress.

2.1 Numerical modeling of multiphase fluid flow

We begin by describing the basic geologic structure of a potential CO_2 storage aquifer (Figures 42 to 44). An aquifer is a porous, permeable geologic unit containing water. Porosity is the fraction of aquifer space that is not rock; the more porous a rock, the more fluid (liquid or gas) the rock can hold. A porosity of 0.30 (i.e., 30%) indicates a very porous rock and one that would be excellent for CO_2 storage, if its permeability is high as well. Permeability is a measure of how readily a material allows fluid to pass through itself. Porous rocks do not necessarily have high permeabilities – for example, a rock with abundant but unconnected pores would have a low permeability and thus would not facilitate fluid flow through it. While higher porosities tend to result in higher permeabilities, this trend does not always hold true (e.g., Saar and Manga, 1999). As far as CO_2 injection, flow, and storage are concerned, a porosity of at least 0.04 (i.e., 4%) and a permeability of at least $10^{-13}m^2$ is currently considered reasonable for a CO_2 storage aquifer while permeabilities of $10^{-20}m^2$ or less permit essentially no fluid movement (e.g., Tsang et. al., 2007). It may be possible to store CO_2 in lower porosity and permeability formations than those mentioned above, however, significantly more fundamental (computer modeling and field testing) research regarding injection schemes, rock hydrofracturing methods, reactive CO_2 flow modeling, and other approaches must be conducted to test such hypotheses. A recent Department of Energy (DOE) Office of Science workshop report entitled "Basic Research Needs for Geosciences: Facilitating 21st Century Systems" (published in July 2007) illustrates some of the basic science and engineering research necessary to better understand CO_2 injection and storage in the subsurface. The proposed 3-year computer simulation program, with research conducted at the University of Minnesota, a public university, would allow such necessary fundamental research as well as applied research that is specific to CO_2 injection and storage in the Mid-Continental Rift System in Minnesota.

In a CO_2 storage scenario, one desires to permanently trap CO_2 in the subsurface. To accomplish this, storage aquifers must have virtually impermeable capping (or sealing) rocks above them. To complete the basic geology, the aquifer and caprock are encompassed by some surrounding material.

CO_2 storage in a deep saline aquifer (Figure 5) is inherently a multiphase problem and hence, multiphase modeling is a principal aspect of CO_2 storage modeling. 'Multiphase' indicates that the aquifer system has more than one fluid present, in this case the naturally occurring aquifer brine (highly salty water, greater than 10,000 ppm solutes, which is the EPA drinking water maximum; Xu et al., 2005), supercritical CO_2, and gaseous CO_2. A supercritical fluid is a fluid at sufficiently high temperature and pressure that it is neither a liquid nor a gas, though it behaves very similar to a liquid. The supercritical state of CO_2 is beneficial for storage because CO_2 in this state is considerably denser than gaseous CO_2, permitting storage of larger quantities of CO_2 in a relatively small volume. To achieve pressure and temperature conditions at which CO_2 is supercritical, depths of at least 800m (~2500 feet) are necessary; thus, deep aquifers are commonly proposed for CO_2 injection and storage. Furthermore, most drinking water supplies are relatively shallow while deep aquifers tend to have salinity far beyond drinking standards. Consequently, proposed CO_2 storage aquifers are typically deep and saline even though salinity is not required for storage. Salinity will, however, affect fluid-mineral reactions in these aquifers.

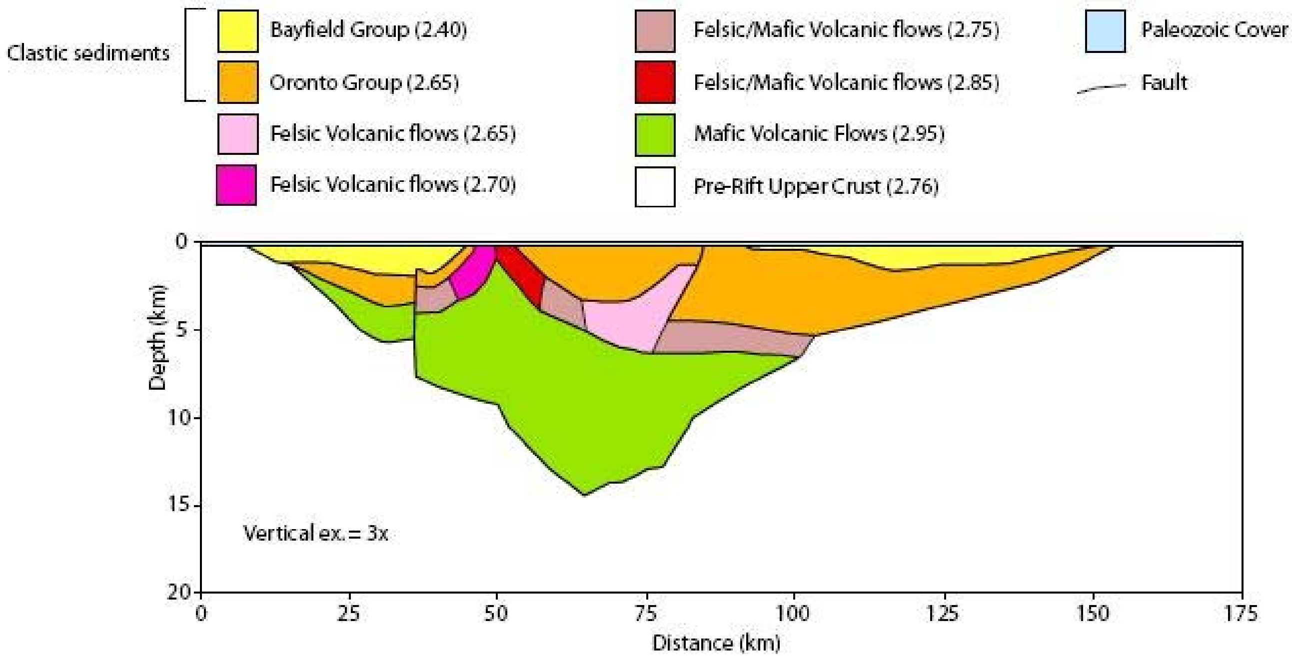

Figure 42. An approximate/generic cross section through the Mid Continental Rift System in Minnesota, based on the geophysical modelling of Allen et al., (1997). The geologic units of interest for CO_2 injection and storage are the Bayfield and Oronto groups. Numbers in parentheses are density in grams per cubic centimeter.

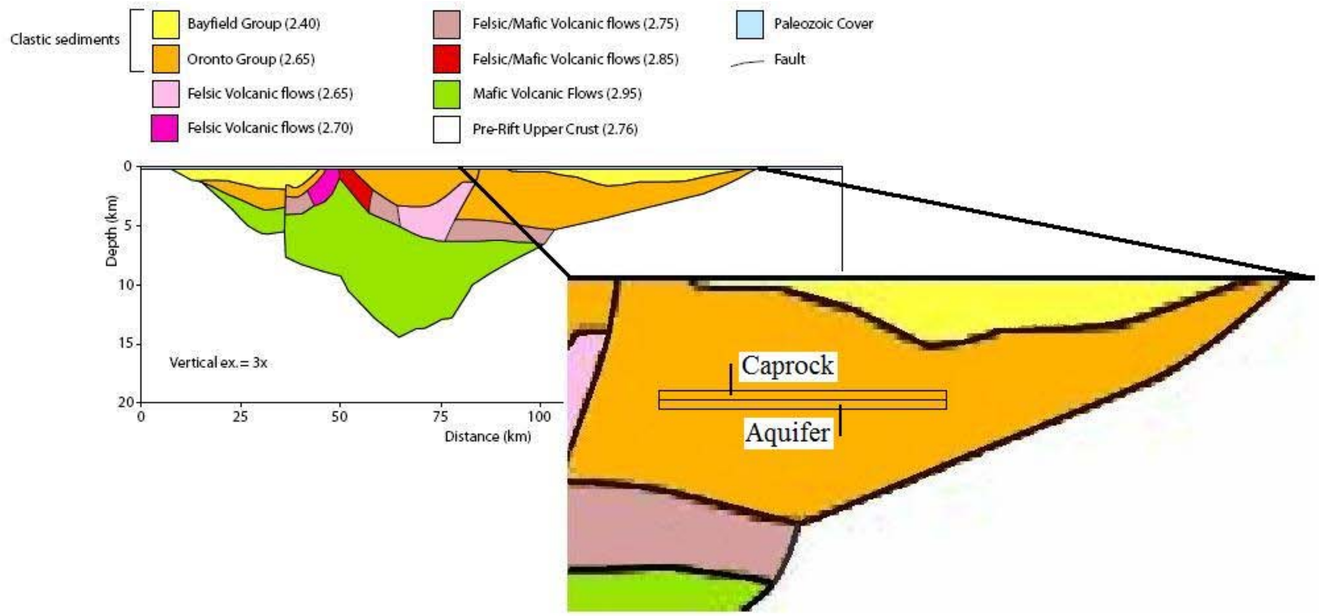

Figure 43. A conceptual model of the aquifer and caprock structure we use for the initial stage 1 and stage 2 modeling. Because of the lack of information, we assume a long, thin aquifer below a capping unit. The aquifer is within one of the sedimentary units of the Mid Continental Rift System of interest for CO_2 storage and is at a depth sufficient for storage.

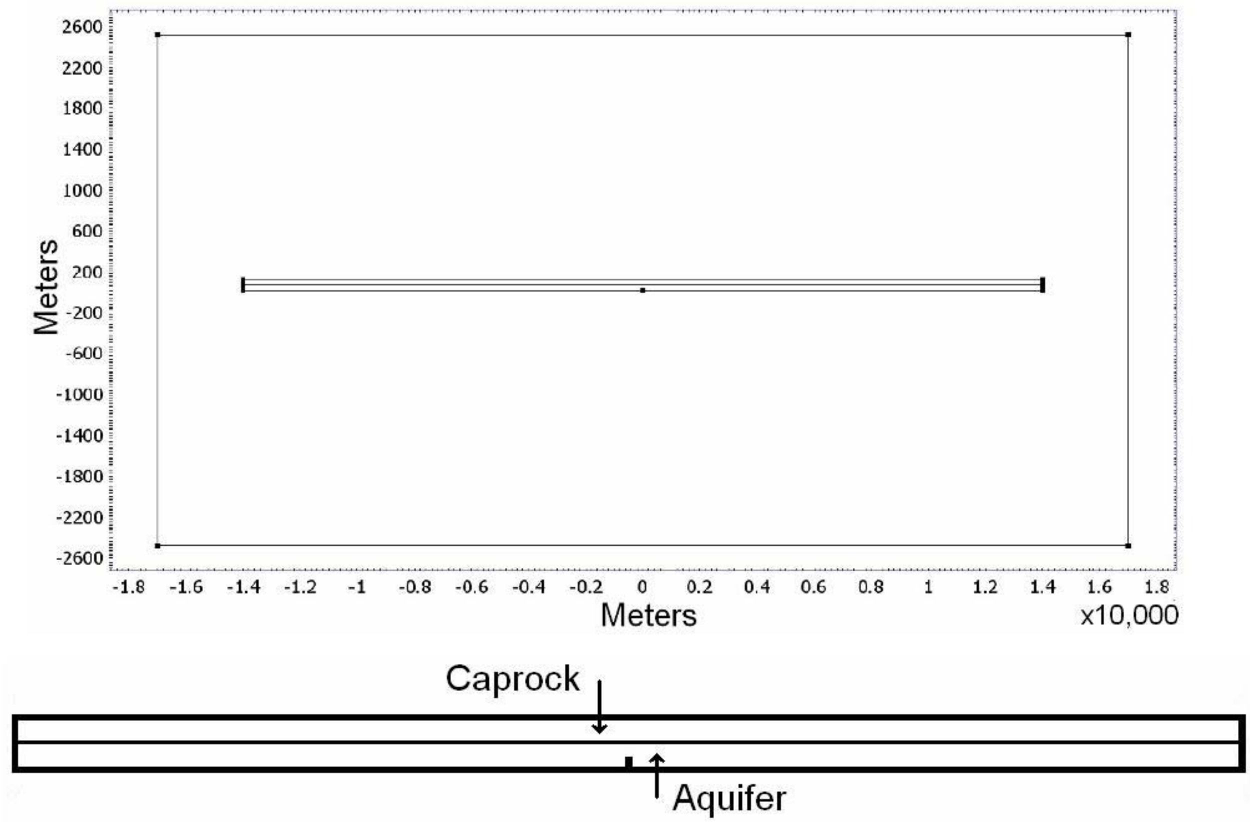

Figure 44. At top is the geologic structure used in the stage 1 numerical model. A long, thin aquifer is placed below a capping rock of similar shape and both are imbedded in a surrounding material. At bottom is an expanded view of the aquifer and caprock.

Finally, deep saline aquifers are prevalent worldwide and, therefore, could provide substantial CO_2 storage without directly interfering with drinking water supplies (that is, assuming no CO_2 leaks upwards from injection aquifers into overlaying fresh-water aquifers, which is discussed in Sections 2.3 and 2.4).

Modeling of multiphase fluid flow in a porous medium (i.e., material that contains a certain fraction of open space and the remainder is solid, such as most rock) is more complex than single phase flow modeling because in addition to the interactions between fluid and the rock matrix, fluid-fluid interactions must be simulated. While considerable fundamental research is required to improve our understanding of multiphase flow processes, particularly with respect to CO_2 injection and storage as mentioned previously, a large body of work is already available concerning the multiphase fluid flow aspects of CO_2 injection and storage in deep (saline) aquifers. We note some of the work in this section, and considerably more falls naturally into subsequent sections.

With sufficient simplifications – a homogeneous (aquifer composition is constant throughout space), isotropic (aquifer properties are the same in all directions), and perfectly horizontal aquifer; no capillary forces (described in detail in later sections); no deformation of geologic units following injection – the multiphase fluid flow behavior of CO_2 injection and storage can be modeled analytically (e.g., Okwen et al., 2007). Here, 'analytical' refers to the methodology of finding/developing exact mathematical solutions without requiring approximations; approximations are common with numerical modeling approaches. Analytical methods can provide upper bound estimates for post-injection pressure buildup and spread of injected material (e.g., Okwen et al., 2007). Furthermore, they can be used to estimate displacement of native brine (e.g., Zhou et al., 2007). However, because of the simplifying assumptions required to find analytical solutions, analytical models cannot capture all complex multiphase behavior. Real-world multiphase systems are prone to feed-back mechanisms where the outcome of such interactive processes is often considerably different from expectations at the outset or from results provided by necessarily simplified analytical models. Therefore, for the majority of real-world systems, numerical models are needed to approximate a range of possible outcome scenarios. <u>Hence, while inexact and strongly dependent on the quality of field-measured input parameters, numerical models can often provide upper and lower bounds as well as estimates of average behaviors and process outcomes. Such bounds and mean values help in the development of best/worst case scenarios and anticipated average system behavior.</u>

The vast majority of numerical models related to CO_2 storage have focused on the behavior of injected CO_2 as opposed to the native brine in a deep saline aquifer. However, the brine must also be considered as it is displaced by the injected CO_2. Birkholzer et al. (2007) are currently modeling brine flow using a radially symmetric geology and a 30-year, 1.5 million tons of CO_2 per year injection scheme that is followed by 70 years of non-injection fluid flow. This approach is similar to many other numerical modeling scenarios (e.g., White et al., 2005; Xu and Pruess, 2007). Displaced brine flows toward natural aquifer outlets and is accommodated by aquifer pore space provided by pore and brine compressibility, by caprock pore space, and by leaks in sealing units. Thus, aquifer, caprock, and fluid compressibility – none of which are included in simple models – as well as accurate approximations of caprock permeability and porosity are necessary to estimate brine flow. Birkholzer et al. (2007) found that lateral brine velocities induced by CO_2 injection are of similar magnitude to natural groundwater flow velocities, suggesting that brine displacement will not affect injection regions.

2.2 Modeling of physical CO_2 trapping

Immediately following CO_2 injection, CO_2 is trapped in deep saline aquifers primarily by stratigraphic trapping. Supercritical CO_2 is less dense than saline brines, so CO_2 floats above the brine. Because the caprock above an injection aquifer is impermeable, injected CO_2 pools against the bottom of the caprock; this is known as stratigraphic trapping. Numerous numerical models (e.g., Nordbotten et al., 2005; Xu et al., 2005; Huppert, 2007) capture this behavior. As time progresses, other physical trapping mechanisms become important.

For example, capillary forces, which can only be modeled numerically, contribute to permanent trapping of CO_2 in saline aquifers. In a system with multiple fluids, one fluid may improve or limit the ability of another fluid to move through a material. As such, the interface between fluids is not a sharp line. In the case of CO_2 injection into a brine, at the CO_2/brine interface, capillary forces draw CO_2 into the brine in shapes resembling fingers (a process thus known as fingering). While CO_2 injection maintains high pressures behind the CO_2 interface, these 'fingers' may move through an aquifer faster than the interface. But after injection ceases and pressures stabilize, capillary forces tend to trap and permanently store CO_2 at the interface (Szulczewski and Juanes, 2007). Including capillary forces in a numerical model can increase model computation time significantly; however, this process is included more frequently in CO_2 storage simulations (e.g., Szulczewski and Juanes, 2007).

In addition to permanently trapping CO_2 along the injection interface, capillary forces contribute to residual trapping. Following CO_2 injection, the shape of the CO_2 plume evolves as brine displaces CO_2 and injected CO_2 displaces brine. This behavior is particularly prominent in an aquifer with some angle to the horizontal (which most natural aquifers have) in which buoyancy forces move CO_2 up the inclined aquifer. When brine displaces CO_2, capillary forces trap a percentage of CO_2 in pore space; hence, this behavior is of interest in current numerical modeling of CO_2 storage (Hesse et al., 2007).

The percentage of CO_2 stored by residual trapping is debatable. A more substantial means by which CO_2 is trapped permanently in brine is solubility trapping – CO_2 dissolves into brine at a CO_2/brine interface and is thus stored in the aquifer. This type of trapping is considered permanent because deep saline aquifers tend to have lengthy residence times, that is, brine frequently stays in these units for long periods of time (several thousand years). Numerical models have found that more than 25% of injected CO_2 can be permanently trapped in this manner (e.g., Han and McPherson, 2007). Solubility trapping is relatively fast, making it the dominant and thus a very important form of permanent trapping immediately following injection. To note, the solubility of CO_2 in water – which is salinity-dependent – is much less than its solubility in oil. Therefore, CO_2 injected in a saline aquifer below an oil reservoir will rise (if not trapped in the aquifer) until it reaches the oil where it likely becomes permanently trapped. Numerical studies (Han and McPherson, 2007) are currently investigating the effectiveness of oil reservoirs as permanent CO_2 traps in this manner, though far fewer regions include such dual aquifer and oil reservoir systems than saline aquifers alone.

2.3 Reactive transport modeling

A primary aspect of modeling CO_2 storage in deep saline aquifers is the modeling of chemical reactions that occur following injection. CO_2 increases the acidity of water when in solution and as such, injection of CO_2 into native brine results in partial dissolution of the aquifer rock matrix. Matrix elements react with dissolved CO_2 and elements from the native brine, gradually precipitating minerals from the solution. Following injection, reactions and precipitation occur on timescales ranging from days to thousands of years resulting in a temporally complex modeling problem. Further, because CO_2 injection plumes grow with time, modeling reactions and associated transport of elements and minerals is also spatially complex. Finally, post-injection reactions are highly dependent upon initial chemistry thus requiring knowledge of pre-injection composition of the native brine, mineral composition of the aquifer's rock matrix , and caprock mineralogy in order to effectively model the temporal evolution of CO_2 storage systems.

Numerous aspects of the reactive transport problem have been simulated employing a variety of numerical modeling techniques. The following discusses some examples.

Transport of aqueous and gaseous species coupled with multiphase fluid and heat flow, together with capillary effects, has been modeled by Xu et. al. (2005) using the computer code TOUGHREACT (Xu and Pruess, 2001). They sought to examine mineral sequestration of injected CO_2 in a sandstone-shale system assuming a simple model geometry (essentially a cylindrical aquifer below a sealing unit). Their model extended for 100,000 years and determined that the majority of CO_2 stored as a mineral was in the form of dawsonite, a carbonate mineral similar to limestone.

White et. al. (2005) completed similar modeling using the code ChemTOUGH2 (White, 1995) with the geology of a section of the Colorado Plateau. Ideal geologic units for CO_2 storage are dome-shaped, as in such structures CO_2 rises and becomes trapped beneath the overlaying caprock. However, the work of White et. al. (2005) suggests that other structures can suffice for CO_2 storage. In addition to studying the impact of aquifer shape on storage, these authors analyzed the impact of mineral precipitation on aquifer permeability and porosity. If aquifer pores become plugged during injection, the amount of CO_2 that can be injected decreases substantially. White et. al. (2005) found that precipitation – primarily of the minerals calcite, dawsonite, and kaolinite – did not significantly alter aquifer permeability or porosity. One thousand simulated years after 30 years of CO_2 injection, their model showed that 21% of injected CO_2 was permanently sequestered as a mineral, 52% was stored as a gas or was dissolved in brine, and 17% leaked to the surface. After 1500 years, 70% of injected CO_2 was permanently stored as mineral components. These results apply to one model only, and more work needs to be completed concerning permanent storage in specific geologic settings; however, these results are encouraging as they suggest that long-term CO_2 storage is feasible under some geologic conditions.

As mentioned, the formation of aqueous complexes (i.e., here, carbon-containing minerals) in a saline aquifer following CO_2 injection allows for mineral trapping of CO_2. Xu and Pruess (2007) note that the presence of these complexes leads to increased CO_2 solubility, improving solubility trapping and increasing the density of the brine containing CO_2. Density variations in brine lead to mixing as heavier brine sinks, sometimes referred to as 'convective mixing' (Xu and Pruess, 2007). Further numerical modeling by Xu and Pruess (2007) using TOUGHREACT (Xu and Pruess, 2001) indicates that dissolution and precipitation in a CO_2 injection aquifer occur primarily at the CO_2/brine interface. High pH, which decreases solubility of aqueous carbonate species, contributes to precipitation at this interface. Thus, over large periods of time (several decades) permeability decreases at the interface, resulting in the formation of a barrier against CO_2 movement. Barrier formation seems to be beneficial because it is sufficiently slow that it does not reduce permeability during CO_2 injection but acts to contain CO_2 after injection ceases; however, more numerical modeling is needed to examine this behavior in detail over geologically relevant spatial and temporal scales.

Mineral precipitation provides for permanent CO_2 storage in deep saline aquifers, but it is not entirely beneficial as it can decrease the injectivity of a well and force well abandonment. Deep saline brines often contain high concentrations of sodium and chloride. Current models (e.g., Hurter et al., 2007) indicate that within days of injecting CO_2 into such brines, some water evaporates from brine into CO_2, increasing brine salinity. Halite (pure sodium chloride salt) then precipitates from the brine, plugging pore spaces and reducing permeability around injection wells. However, modeling by Pruess and Muller (2007) suggests that several hours of fresh water injection prior to CO_2 injection significantly reduces such halite precipitation, maintaining aquifer permeability and porosity near an injection well by providing a fresh water barrier between CO_2 and brine.

Reactive transport modeling, in addition to being important in analysis of storage potential, is essential on the risk assessment side of CO_2 storage modeling. For instance, the rocks of drinking water aquifers may contain elements such as lead that pose a health hazard if in solution. Thus, if injected CO_2 leaks into drinking water aquifers, it could increase water acidity and related aquifer host rock solubility, potentially causing dissolution of toxic elements or minerals. Current modeling (e.g., Birkholzer et al., 2007) is examining which aquifer host rock constituents could be mobilized following CO_2 injection and whether these materials might enter drinking water supplies. Further modeling needs to be completed concerning CO_2 leaks from deep injection sites and associated transport of hazardous elements from deep aquifers into drinking water supplies.

2.4 CO_2 leak assessment modeling

Methods of investigating deep geologic structures can sample only a small percentage of a potential CO_2 storage reservoir rendering CO_2 leak assessment a challenging problem. Reasonable estimates of the CO_2 storage viability of natural units in themselves may, however, be provided. Although the effects of human-made reservoir perforations, namely by deep wells, can be more difficult to quantify. While deep wells can potentially provide high-permeability CO_2 pathways to the ground surface, the effective integrity of abandoned wells, their casing materials, and their plugs are often poorly constrained. In regions with high concentrations of abandoned deep wells, such as oil fields, it is essential to model the effects of injected CO_2 on the integrity of well systems and the potential for CO_2 leakage around such wells. Numerical-analytical hybrid models (e.g., Gasda et al., 2007) have been developed to study well leakage; additional work is ongoing. To note, CO_2 storage projects in the Mid Continental Rift System are at a considerable advantage in this respect to many other storage projects in development worldwide because the rift is not punctured by numerous deep wells whereas most other sites are in (or near) explored oil fields.

Leakage modeling must also be concerned with pore-fluid pressure changes because injection into an aquifer alters the aquifer's rock matrix stress field, generally resulting in increased pore-fluid pressures. Pore-fluid pressure refers to the pressure exerted by the fluid in an aquifer's host rock on the rock matrix. Changes in pore-fluid pressure can induce fault slip (e.g., Saar and Manga, 2003) on pre-existing faults or fracture an aquifer or sealing unit rock (referred to as hydrofracturing), resulting in leakage if faults or fractures act as high permeability pathways for injected CO_2. Birkholzer et al. (2007) modeled pore-fluid pressure build-up in a deep saline aquifer following CO_2 injection. He noted that build-up is highly dependent on caprock permeability, aquifer and caprock compressibility, and fluid compressibility, with pressure build-up tending to extend beyond the extent of a CO_2 plume. Other recent modeling (e.g., Chiaramonte et al., 2007) seeks to determine CO_2 injection pressures required to induce fault slip or rock fracturing as well as estimate safe pressure ranges. To develop a useful pressure-inclusive CO_2 injection model, the pre-injection rock stress and pore-fluid pressure field of an aquifer and caprock need to be known from field measurements at aquifer depths.

While fracturing can cause CO_2 leakage, minor fracturing can improve the storage potential of an aquifer (e.g., Chiaramonte et al., 2007). If pore-fluid pressure variations following CO_2 injection cause minor aquifer fracturing, aquifer permeability might increase, improving transport of CO_2 away from an injection site and increasing storage potential.

2.5 Comprehensive modeling

As the previous discussion suggests, considerable modeling of the various elements of CO_2 injection and storage has been completed. Additionally, some work has integrated individual elements to create more comprehensive models with real-world geologic geometries. For example, Kim (2007) developed a fully coupled multiphase thermo-hydro-mechanical numerical model of CO_2 storage. This model accounts for CO_2 flow, heat transport, and ground deformation.

The work of Xu and Pruess (2007), for example, couples multiphase fluid flow with reactive transport permitting examination of CO_2 flow, formation of aqueous species, and mineral precipitation. However, their work uses very simple, radially symmetric injection aquifers and sealing units. Wang et al. (2007) modeled heat transport in addition to reactive transport and multiphase fluid flow, as have Xu et al. (2005). In the work of Wang et al., (2007), groundwater density and viscosity are dependent on chemical composition and chemical reactions are temperature dependent (to note, most models assume the simplified case of constant temperature). Further, precipitation of minerals from solution and dissolution of host rock affect aquifer porosity and permeability in addition to hydrodynamic dispersion (essentially the spreading of a solute), all of which are necessary for inclusive modeling scenarios.

Comprehensive numerical modeling of CO_2 injection and storage incorporates several geologic fields – hydrogeology (multiphase fluid, solute, and heat flow); geochemistry (chemical reactions); geodynamics (host rock stress and pore-fluid pressure build-up, hydrofracturing, and rock matrix deformation); and seismic and geophysical studies (to gain information about deep geologic structures) – resulting in a complex but interesting problem. Extensive modeling has been completed to date but much has yet to be done, particularly, combining individual fields into fully inclusive, thorough numerical models. Such models, for specific sites where field-measured model input data are available, would improve the previously mentioned upper and lower confidence bounds regarding the amount of possible CO_2 injection and storage as well as associated risks and costs.

3 Modeling Scenarios and Information Required

Due to the necessary integration of numerous geologic processes, modeling CO_2 injection and storage is complex and is made more so by the natural variability of geologic structures. As such, numerical modeling should begin with very simplified injection scenarios and geologic units, gradually evolving as information regarding geologic structures becomes more abundant and realistic and as different types of model parameters are added. At each stage in the modeling process, we gain additional information about the storage reservoir and injected fluid and, eventually, obtain a general sense of how CO_2 will behave following injection.

For much modeling, we restrain our geologic units to two dimensions for simplicity. The third dimension adds considerable complexity and computation time to models while without variation of parameters (e.g., aquifer or brine characteristics) in this dimension, no additional information can be gained from modeling the third dimension. Thus, except where noted, modeled geologic units extend vertically and in only one horizontal direction, i.e., they represent a vertically oriented, two-dimensional cross section through a potential injection region.

In the following, we provide the principal stages – with increasing complexity – involved in an ultimately comprehensive numerical modeling program for CO_2 injection and storage.

3.1 Stage one - CO_2 solute transport in porous media

Model with impermeable caprock: In the simplest case, the behavior of a solute (here CO_2) dissolved in water and injected into a pure water aquifer is investigated. The information required by the model is aquifer permeability and porosity, injection rate and duration, solute concentration, and aquifer geometry; each of these parameters can be varied as desired. The aquifer is assumed to be homogenous (porosity and permeability are constant throughout space), isotropic (permeability is direction independent), of constant thickness, and horizontal.

A solute rather than pure CO_2 is injected because solute flow behavior is much simpler. Recall that for deep saline aquifer storage, CO_2 exists as a supercritical fluid and, hence, requires a multiphase model. For initial modeling, the aquifer system is simplified by using a single fluid phase.

The geology consists of an aquifer alone – a long, thin unit in which water is allowed to flow through the sides but not the top or bottom. This is a reasonable first approximation for a CO_2 storage aquifer because any potential storage unit is capped (at the top) by an essentially impermeable rock, is large (several kilometers to several hundred kilometers in some direction), and discharges fluid far from CO_2 injection points. Furthermore, aquifers are typically relatively thin (tens of meters) compared to their horizontal spread. At this stage of detail, tilting the aquifer does not provide significant new information. Finally, were pure CO_2 injected, it would rise to the top of the aquifer, affirming the assumption of no-leakage through the bottom of the aquifer.

A solute, which is sufficiently dilute (1% CO_2, the remainder water) to permit solution of the solute transport equations, is injected in the center of the aquifer. The solute is weight-equivalent to pure CO_2 and is adjusted to equal in quantity the amount of CO_2 produced by a coal-fired power plant (of any desired size). Injection progresses for several years (e.g., 25 years), and the solute is tracked for many years thereafter (e.g., 75 years or even hundreds of years). From this model it is possible to determine the simplified transfer and dispersion (i.e., spreading) of injected material with time. Thus, with field-measured data for aquifer permeability, porosity, and geometry, one can develop a first, rough estimate as to whether an aquifer may be feasible for considerable, long-term CO_2 storage.

Model with caprock of finite permeability: To investigate CO_2 leakage following injection, the model geology is expanded to include a caprock above the injection aquifer and material surrounding the aquifer and caprock units. This model requires input data regarding the permeability, porosity, thickness, and extent of the aquifer, caprock, and surrounding material. Injection modeling then continues as in the previous case but with fluid flow permitted through the top and bottom of the aquifer (not, however, the top and bottom of the surrounding material) so that potential leakage can be observed. Caprock permeability and porosity are varied to evaluate their impact upon CO_2 leakage. Thus, in addition to CO_2 transport, this model imparts a sense of the possible extent of solute leakage. With data including caprock structure above an aquifer of interest, this model refines estimates of whether regional geology permits effective CO_2 storage. However, this model also requires significantly more field data from deep boreholes and other geologic and geophysical surveying techniques than the previous model.

3.2 Stage two - multiphase fluid flow in porous media

Injection of pure CO_2: Injecting a CO_2 solution rather than pure, supercritical CO_2 restricts the applicability of a numerical model, the primary limitations arising from low solute concentration and lack of multiphase behavior. Concerning the former, because we are injecting a solution, much more material is injected than in the case of pure CO_2. Regarding the latter, multiphase flow is different from, and more varied than, solute transport. Thus, the model evolves by replacing injection of a solute with pure, supercritical CO_2 injection.

As with all fluids, the density and viscosity of supercritical CO_2 depend on pressure and temperature. In addition to the information necessitated by the previous model, in the current case of multiphase modeling, the injection depth within the aquifer (which provides pore-fluid pressure) and the local geothermal gradient (the change in temperature with depth below ground surface, providing temperature at injection depths) are required – note that because of the latter, a borehole temperature-versus-depth measurement device is included in the modeling budget. Further, the aquifer's brine density and viscosity, parameters that depend on brine composition (as well as on pressure and temperature), are needed and determined using water samples taken from deep boreholes.

In a multiphase model, pure CO_2 is injected into a saline (i.e., salt-containing) aquifer – in quantities equal to those produced by fossil fuel power plants – and allowed to spread as in the solute models. At this stage, the brine (water plus salt) and CO_2 are assumed immiscible, i.e., they do not mix. This model provides an improved picture of aquifer storage capacity, the horizontal spread of CO_2 with time, and a caprock's ability to serve as a CO_2 barrier (*stratigraphic CO_2 trapping*). Additionally, local variations in caprock permeability can be included, simulating fractures or wells penetrating the caprock and causing CO_2 leaks.

Brine-CO_2 miscibility: Immiscibility of brine and CO_2 restricts the previous model's applicability because brine and CO_2 are in fact miscible. This CO_2 dissolution in brine is a primary means by which injected CO_2 is permanently stored in a saline aquifer (*solubility CO_2 trapping*). Thus, improved models allow brine-CO_2 miscibility, which depends on brine salinity. Relative permeability – the permeability experienced by one fluid as the other fluid facilitates or limits its movement through the aquifer matrix – now becomes important and is non-trivial. In addition to the information provided in preceding models, this modeling environment reveals the quantity of CO_2 stored by different trapping mechanisms as a function of time. *Stratigraphic trapping* tends to be the primary storage mechanism immediately following injection, but it may not be permanent as buoyancy forces may cause CO_2 leakage through a caprock with finite permeability. In contrast, *solubility trapping*, following *stratigraphic trapping*, provides permanent storage.

3.3 Stage three - reactive transport coupled to multiphase fluid flow

Three dimensional models: Once a multiphase model is developed, much of the behavior of injected CO_2 in a deep saline aquifer can be deduced and an aquifer's storage potential may be estimated. If additional information in the third dimension is available – for example, regarding aquifer/caprock porosity, permeability, host rock composition, or geometric variations; brine parameters; and/or geothermal/pressure gradients – the model can be expanded from two to three dimensions.

As discussed in the following paragraphs, numerical modeling is expanded to include reactive transport, rendering models more representative of the real world and providing new information relevant to an aquifer's CO_2 storage potential.

Reactive transport in the form of host-rock dissolution and mineral precipitation: Because CO_2 in solution increases water acidity, reaction modeling necessarily includes rock dissolution and, hence, requires pre-injection aquifer and caprock composition. Furthermore, brine composition is required because, as CO_2 and rock minerals move in and out of brine and as brine pH changes, composition-dependent reactions and mineral precipitation occur. Reactions arise within days of injection, yet significant *mineral trapping* of CO_2 can take hundreds to thousands of years (White et al., 2005). Thus, reactions such as rock dissolution, mineral precipitation, and associated transport of elements and minerals within brine are spatially and temporally variable, providing a challenging CO_2 storage simulation problem.

Using the final multiphase model from the previous section, multiphase flow is now coupled with reactive transport. Fluid flow proceeds similar to before, though permeability and porosity can now change as a result of host rock dissolution and mineral precipitation, altering flow patterns. To capture long-term reactions and precipitation, model runs need to represent several hundreds to thousands of years. This approach allows estimation of permanent CO_2 trapping via carbon-containing mineral precipitation (*mineral trapping* of CO_2). Further, this modeling stage allows evaluation of mineral precipitation in the vicinity of CO_2 injection wells. These numerical simulations may thus be employed to evaluate if brine and rock composition likely cause reactions that significantly decrease aquifer permeability near such wells and, hence, diminish the CO_2 injection and storage potential over time. Reaction models can also help refine assessments of a caprock's ability to serve as a CO_2 barrier. Specifically, they permit investigations of whether reactions following injection generate pathways for CO_2 through the rock or seal pre-existing pathways. With the development of reactive transport models, estimates of the CO_2 storage potential of deep saline aquifers can be significantly improved.

3.4 Stage four - additional model parameters

Hydrofracturing and capillary forces: A numerical model of reactive transport and multiphase fluid flow in porous media accounts for much of the post CO_2 injection behavior in a deep saline aquifer. As deep wells, seismic studies, and geophysical studies provide additional data concerning subsurface conditions, other parameters can be incorporated into models. For instance, with information on pre-injection host-rock stress and deformation, one can numerically investigate pore-fluid pressure changes and the possibility of resultant fracturing of a storage aquifer's host rock matrix. By simulating a variety of injection scenarios under a range of geologic conditions, modeling can help constrain fluid injection pressures that are unlikely to exceed such hydrofracturing thresholds. In addition, this type of so-called poroelasticity modeling allows estimation of aquifer matrix deformation (which occurs even without hydrofracturing) and associated possible land surface deformation, which is critical in evaluating if fluid injection could affect human-made structures on the land surface. Additionally, including capillary forces into numerical models refines estimates of CO_2 migration with time and an aquifer's CO_2 storage potential via *capillary trapping*.

Heat flow: Finally, just as density and viscosity of supercritical CO_2 and brine are temperature-dependent, chemical reactions, dissolution, and precipitation rates depend on temperature. Thus, permitting heat flow (which, to note, also affects pore-fluid pressures and host rock stresses) in numerical models improves their real world applicability and accuracy, particularly with respect to buoyancy-driven flow and associated CO_2 migration over time. Therefore, we include in the numerical modeling budget resources for measuring temperature-versus-depth within boreholes.

As the discussed complexity of multiphase fluid flow and reaction behavior in a host rock suggests, numerical modeling is essential to the process of determining a deep saline aquifer's potential for CO_2 injection and storage and associated risks. From the simplest solute flow model through comprehensive models that incorporate hydrogeology, geochemistry, geodynamics, seismology, heat flow, and geophysics, each stage of the modeling process adds to our understanding of the CO_2 injection and storage process. The following section provides some preliminary modeling results through the beginning of stage two, conducted by the Hydrogeology and Geofluids research group in the Department of Geology and Geophysics at the University of Minnesota -Twin Cities.

4 Some Preliminary Numerical Models

To date, we have developed a set of very preliminary models, encompassing stage one and the start of stage two as described in Section 3, to start exploring the potential for CO_2 injection and storage in the Midcontinent Rift System in Minnesota (Figure 42). As evident from the preceding section, developing a comprehensive CO_2 storage model for a given location requires considerable geologic and geochemical information. Unfortunately, relatively little geologic data exists for the Mid Continental Rift System through Minnesota and elsewhere. For the most basic numerical model, we require aquifer and caprock permeability, porosity, and thickness of the sedimentary units of interest for storage (the Bayfield/Oronto sandstone), all of which are most readily collected via deep wells. Few wells in Minnesota or elsewhere intersect these units at sufficient depths for CO_2 injection. The data used in the following models is derived from deep boreholes in Iowa (the Iowa Deep Drilling Project) and relatively shallow sections of the rift in Minnesota (data provided by the Minnesota Geological Survey) that we assume for now is applicable to deep sedimentary units in Minnesota. Eventually, several deep boreholes to potential storage aquifers depths as well as other geologic surveying techniques (seismic, electromagnetic, gravity, etc.) will be required to better constrain input parameters for numerical models. To encompass the range of likely values for aquifer and caprock permeabilities and porosities, we model CO_2 injection numerous times, systematically varying aquifer and caprock parameters each time (a modeling procedure called exploring parameter space). Aquifer permeability varies from 10^{-20} to $10^{-13} m^2$, aquifer porosity from 0.05 to 0.20 (i.e., 5 to 20%), caprock permeability from 10^{-21} to 10^{-18} m^2, and caprock porosity from 0.05 to 0.16 (i.e., 5 to 16%).

4.1 Stage one

We begin numerical modeling of CO_2 storage by building a two dimensional solute injection model - stage one in Section 3. The commercially available multiphysics modeling environment COMSOL is used. Figure 42 shows a generic cross section of the rift system in Minnesota which was provided by the Minnesota Geological Survey (MGS). Because no deep wells exist in Minnesota to provide geometric configurations of aquifer and caprock units, we use the cross section only to verify that the estimated rift structure is sufficiently deep for CO_2 storage and estimate depths for storage units. Due to lack of measured data, we assume a rectangular aquifer that is 50 meters thick and several kilometers long (Figures 43 and 44). These parameters are adjustable as desired once better-constrained estimates are provided. At this stage, the model consists of the injection aquifer alone;

fluid is allowed to flow through the sides but not the top or bottom of the unit. We inject a 1% CO_2 solute solution, with the solute weight approximately equivalent to supercritical CO_2 at a depth of 2500 m, in the center of the aquifer. The injection rate can be varied to approximate injection of all CO_2 produced by a large (e.g., 250MW to 1000MW) coal-fired power plant.

This model provides an extremely simplified CO_2 injection scheme from which we can upscale to a more realistic geometry immediately and when more detailed subsurface data is available. The model geology is expanded by placing a capping material, dimensionally equivalent to the aquifer, immediately above the aquifer. Then, the aquifer and caprock are encased in a surrounding material that extends vertically to the ground surface (with the aquifer at a depth of 2500m) and horizontally several kilometers beyond the aquifer/caprock (Figure 44). The extent of the surrounding material is chosen such that the upper and lower boundaries are far enough from the aquifer to assume no fluid flows across them while the left and right boundaries are sufficiently far to assume hydrostatic fluid pressure conditions (i.e., constant pre-injection fluid pressure conditions). The surrounding unit's permeability is 10^{-19} m^2 and the pore fraction is 0.04 (i.e., 4%), as provided by the MGS. Fluid flow is now permitted through the top and bottom of the aquifer to better approximate real-world conditions. Aquifer, caprock, and injection ranges are the same as the previous scenario.

This CO_2 injection model is developed to help us understand the spread of injected material with time and whether the capping unit could effectively seal the storage aquifer. Ultimately, this model provides the first, very preliminary, indications concerning the viability of the Mid Continental Rift's CO_2 storage potential. We inject a solution for one year, choosing a relatively short time period because, when employing a solute (and not a pure CO_2) injection model, we inject considerably more material per year than an actual, pure CO_2 storage project would. The large injection volumes result from the necessity (for very simple models only) to maintain a dilute solution, as described previously. Therefore, the amount injected is equivalent to what would be injected by an actual CO_2 project over a much longer time period. Approximately 30 scenarios were run (see Figure 45 for the visualization of a sample injection), varying injection rate and aquifer and caprock permeability and porosity (see Table 3 for a summary of results). Our modeling indicates that the matrix permeability of potential caprock in the rift is sufficiently low, 10^{-21} m^2 to10^{-18} m^2, to serve as an effective reservoir caprock (without consideration of fractures that would, however, increase caprock permeability). We also find that deep geologic sequestration would be possible in the strata of the rift if large sandstone bodies with porosities in the range 0.04 to 0.20 (i.e., 4% to 20%) and permeabilities in the range 10^{-15} m^2 to 10^{-13} m^2 (with uncertainty of approximately one order of magnitude) are eventually located in the rift at depths greater than 800 meters below a caprock with the above-described properties. The horizontal spread of solute modeled was generally less than ten kilometers from the injection point, a relatively small distance and interpreted in this initial study to indicate reasonable storage space for aquifers with the previously defined properties. Porosity of potential caprock units would need to be in the range 0.06 to 0.16 (i.e., 6% to 16%). Note that this range overlaps with that of aquifer porosity; our models indicate that porosity overlap is not problematic for CO_2 storage as long as caprock permeability is several orders of magnitude lower than aquifer permeability. Finally, our preliminary models indicate that a single injection well can support the injection of all the CO_2 produced by a 1000MW coal fired power plant, given a subsurface system with the above-described characteristics is found.

To summarize, <u>our results are very preliminary but suggest that potential CO_2 storage bodies will have to have a minimum of about 4% porosity and a permeability of 10^{-15} m^2 or higher for sequestration to be considered feasible, if a caprock with a maximum permeability of approximately 10^{-18} m^2 is present.</u> These results are in good agreement with ranges defined by the MGS using a compilation of current CO_2 storage studies worldwide.

Substantial field surveys, borehole drilling, and numerical studies are needed to determine whether the Mid Continental Rift System indeed exhibits favorable characteristics for CO_2 injection and storage. <u>Our current model is in the very initial stages of the type of modeling required in a comprehensive CO_2 project</u> because a wide range of geologic unit geometries and conditions as well as injection and storage scenarios have yet to be

Table 3. The results of the stage-1-type, CO_2 solute injection model runs with a total of 30 simulations conducted. An explanation of a sample run: under "pumping rate", range 10 m^3/s. For this run, aquifer and caprock permeability and porosity were given the values next to "value used when other parameters are varied" in their respective locations in the chart. Pumping rate was set to 10 m^3/s, which is equivalent to the amount of carbon produced by a 500MW coal-fired power plant (similarly, 5 m^3/s corresponds to a 250MW power plant, 15 m^3/s to a 750MW power plant, and 20 m^3/s to a 1000MW power plant). We then measured the maximum solute concentration in the aquifer (292 kg/m^3, column 3), the distance from the solute injection point to liquid in the aquifer with a solute concentration of 1 kg/m^3 (9101m, column 4), and whether CO_2 leaked through the caprock (no, column 5). The 1 kg/m^3 value used in column 4 is an arbitrary value chosen because it indicates a dilute solution and provides a simple measure of solute migration.

	porosity of aquifer			
		max concentration of solute in aquifer [units of kg/m^3]	distance in aquifer from injection well horizontally to liquid with a concentration of 1 kg/m^3 [units of m]	leakage through caprock?
value used when other parameters are varied:	0.1			
range:	0.02	150	14000	yes
	0.04	150	13139	no
	0.06	150	11588	no
	0.08	150	10214	no
	0.1	150	9075	no
	0.12	150	8150	no
	0.14	150	7391	no
	0.16	150	6749	no
	0.18	150	6225	no
	0.2	150	5761	no
	permeability of aquifer			
value used when other parameters are varied:	10^{-13} m^2			
range:	10^{-13}	150	9075	no
	10^{-14}	153	8927	no
	10^{-15}	186	7665	some
	10^{-16}	430	3656	some
	10^{-17}	1261	1167	yes
	10^{-18}	3472	360	yes
	10^{-19}	14080	170	yes
	10^{-20}	62970	123	yes
	porosity of caprock			
value used when other parameters are varied:	0.08			
range:	0.02	150	9160	yes
	0.04	150	9133	yes
	0.06	150	9101	some

	0.08	150	9075	no
	0.1	150	9031	no
	0.12	150	9024	no
	0.14	150	8997	no
	0.16	150	8963	no
	permeability of caprock			
value used when other parameters are varied:	10^{-18} m^2			
range:	10^{-18}	150	9075	no
	10^{-19}	158	8904	no
	10^{-20}	192	7820	no
	10^{-21}	317	5684	no
	pumping rate			
value used when other parameters are varied:	5 m^3/s			
range:	5	150	9075	no
	10	292	9101	no
	15	499	9134	no
	20	623	9150	some

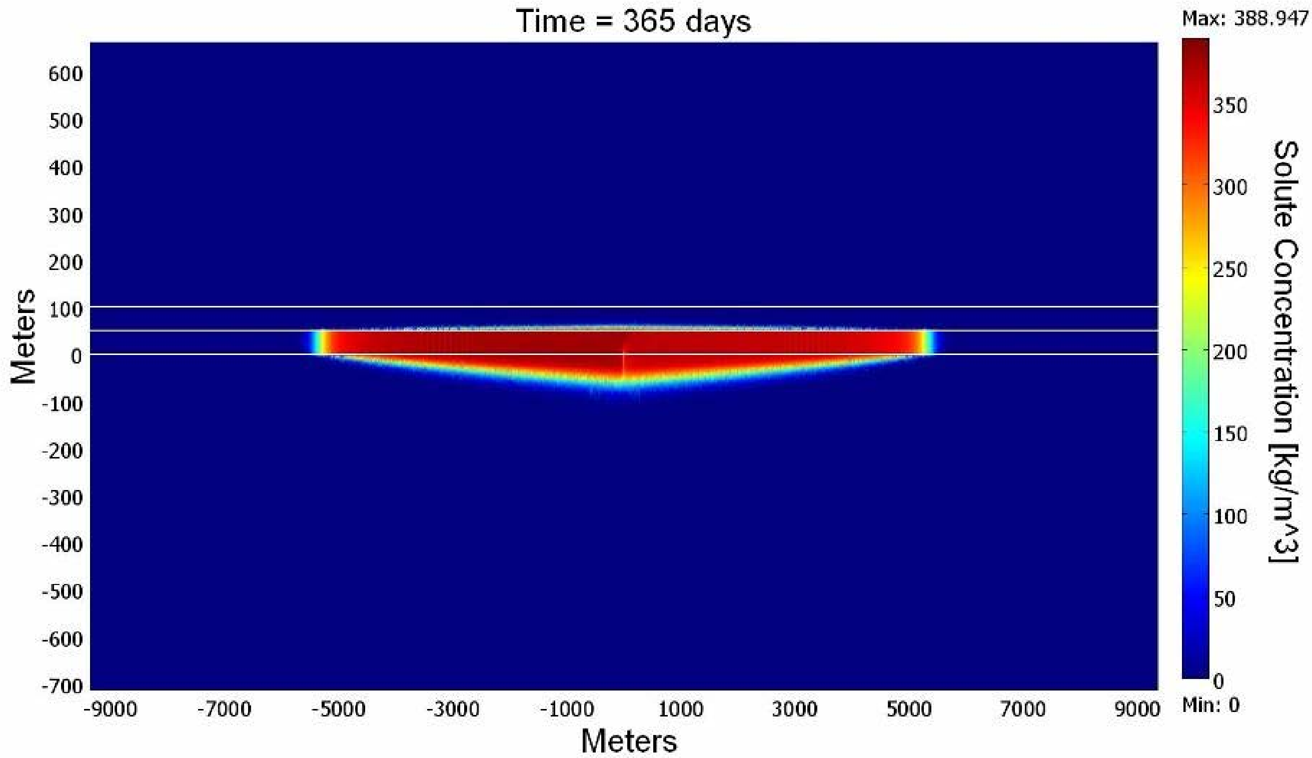

Figure 45. One year of dilute solution injection into the center of a 50m thick, several kilometer long fresh-water (for simplicity as actual injection would be in a brine) aquifer that is capped by a highly impermeable unit. The following model parameters were used: aquifer porosity = 0.10, aquifer permeability = 10^{-13} m^2, caprock porosity = 0.08, caprock permeability = 10^{-21} m^2, and injection rate = 5 m^3/s. Color indicates solute concentration. Notice that some solute leaks into the material below the aquifer. This would not be problematic in a real, pure CO_2 injection project because the CO_2 would be trapped in the subsurface as if it were in the aquifer. However, in a real scenario, it is unlikely that such leakage would occur because pure CO_2 rises above aquifer brine, causing injected CO_2 to pool against the bottom of sealing units (caprocks). Also visible are minor leaks into (but not through) the caprock.

fully explored. Therefore, these modeling results should be viewed as a means of guiding us toward significantly more detailed studies, both in the field and via numerical modeling, that are necessary to evaluate the potential of the rift for CO_2 injection and storage.

4.2 Stage two — initial study

The CO_2 solute injection model of the previous section, though a highly useful and informative exercise, cannot capture the multiphase aspects of pure CO_2 injection in a deep saline aquifer, as discussed in Section 3. Thus, we proceed to the second stage of numerical modeling (refer to Stage 2 in Section 3). We are in the process of developing a numerical framework to permit modeling of multiphase, miscible fluid transport in porous media (Figure 46). Currently we employ the computer code COMSOL to develop all numerical models. However, future numerical modeling will also employ TOUGH2 and TOUGHREACT to allow comparison of model results and to improve our ability to develop insightful numerical models for CO_2 storage in the rift system. Additionally, we are strongly interested in concurrent numerical and analytical modeling of geologic phenomena and, hence, are considering analytical models to further improve CO_2 storage modeling capabilities.

At this point in our stage-2-type scenario, we inject pure, supercritical CO_2 into a fresh-water (not yet brine) aquifer that is modeled as an open conduit (work is underway to convert this model to more representative porous medium fluid flow conditions where porosities and permeabilities can be assigned to geologic units as in the previous solute model). This results in a system with more than one fluid phase, i.e., a multiphase model, consisting of the CO_2 and water phases (dark red and blue, respectively, in Figure 46) that are considered immiscible for now. The model is symmetric about the right edge so that only the left half of the model needs to be simulated and visualized. This choice of symmetry permits relatively simple expansion of the model to three dimensions - the displayed geometry (Figure 46) would be rotated about the right edge to create a cylindrically-shaped aquifer (referred to as radial symmetry). CO_2 is injected into the model at the lower-right corner. The model clearly shows that the higher buoyancy of injected, supercritical CO_2 relative to fresh-water causes the CO_2 to rise and effectively pond underneath the caprock near the center of the aquifer (represented at the right edge since only the left half of the symmetric two-dimensional aquifer is shown).

As previously noted, a range of geologic parameters and injection schemes need to be simulated to evaluate the likely CO_2 behavior upon injection. And as discussed throughout this section on numerical modeling, many additional parameters and conditions – as illustrated by the different stages of modeling – need to eventually be included in simulations so that they become better representations of the natural system. Nevertheless, the current (very limited) model does provide some insights into conceivable CO_2 migration scenarios. Much more has to be done, however, both with respect to numerical modeling and field-measurement of geologic conditions and parameters that can be used as model input data.

5 Conclusion – Summary, Results and Recommendations

5.1 Summary

Of the three principal methods for geologic storage of CO_2 – storage in oil reservoirs, coal beds, and deep saline aquifers – deep saline aquifers offer the most promise for significant global reduction of CO_2 (Plug and Bruining, 2007). Considering global CO_2 emissions through 2050, coal beds worldwide could store approximately 2% of emissions (40 to 150 Gtons), oil reservoirs could store approximately 42% of emissions (up to 920 Gtons), and saline aquifers could store approximately 500% of emissions (up to 10,000 Gtons; Plug and Bruining, 2007). Furthermore, saline aquifers are very prevalent worldwide and offer favorable proximity to large CO_2 sources while oil reservoirs and coal beds are notably more sparsely located. This discussion of numerical modeling of CO_2 injection and storage is thus constrained to deep saline aquifers.

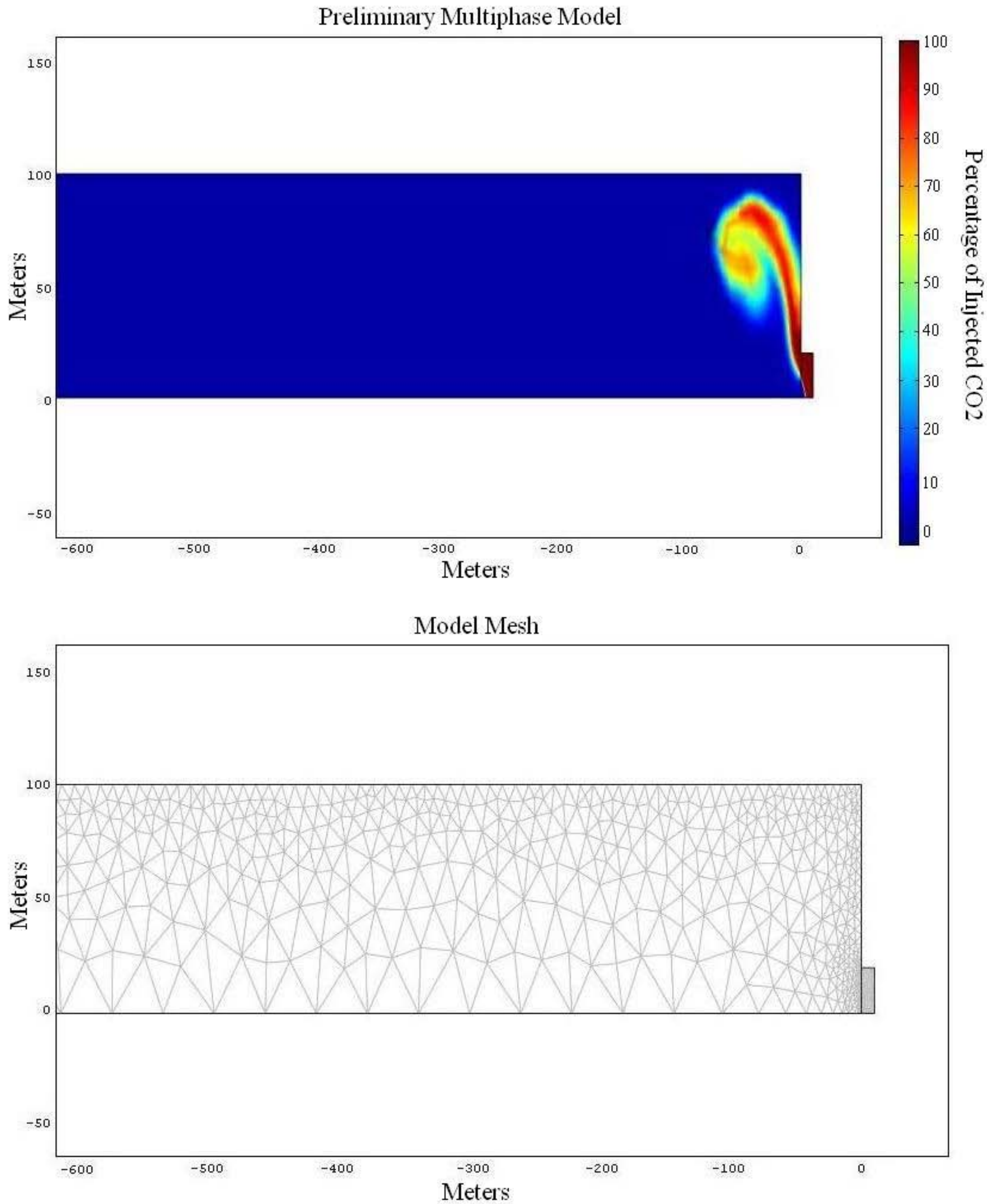

Figure 46. A preliminary multiphase (two phase) fluid flow model. The upper image is a sample CO_2 injection scenario while the lower image is the model mesh (the grid structure that the numerical code COMSOL uses to solve multiphase fluid flow scenarios). Only the left half of the model is pictured as the model is symmetric about the right edge. CO_2 is injected into the large rectangular unit from the small unit in the lower right. The color scale indicates the fraction of fluid that is CO_2 at any point – dark red is entirely the injected CO_2 while dark blue is entirely the fresh-water that was in the unit prior to CO_2 injection. The CO_2 and water are immiscible. This model shows that buoyant, supercritical CO_2 rises and ponds underneath the caprock. At this point, the fluids flow through an open conduit rather than porous media and, thus, permeability and porosity are not modeled. Work is in progress to simulate porous media flow in a multiphase system with brine and supercritical CO_2, more representative of fluid flow in deep saline aquifers.

Numerical modeling is essential to the process of determining a deep saline aquifer's potential for CO_2 injection and storage and analyzing associated risks. Experimental investigations of deep geologic processes are expensive and difficult, and often impossible, because of associated depths and the large spatial extent requiring investigation. First-hand observation of deep aquifer behavior is typically impossible and remote observation techniques are expensive but do provide useful (yet indirect and incomplete) information about subsurface structures and processes. In addition, temporal effects of CO_2 injection are not constrained to short time periods immediately following injection; thus, injection sites would have to be studied in the field for hundreds of years after experimental injection ceases. Clearly, such long durations of experimental investigation are impractical. While some experimental studies are fully justifiable if a deep aquifer appears promising for CO_2 storage, the viability of such experimental analysis cannot be determined without some initial study.

Numerical modeling of CO_2 injection and storage, while not without its own limitations that are primarily the result of incomplete geologic model input data, can be applied to complete such initial, as well as subsequent, investigations. <u>The true potential of numerical modeling is its ability to relatively easily examine numerous CO_2 injection and storage scenarios as well as ranges of geologic parameters to address necessarily incomplete three-dimensional subsurface data.</u> For example, geologic geometries can be varied, aquifer characteristics can be adjusted, and fracturing of sealing units might be induced to study CO_2 leakage, to name only a few scenarios and parameters. Such exploration of model parameter space counteracts the uncertainty caused by incomplete knowledge of subsurface conditions, thus ultimately improving our understanding of the feasibility, effects, benefits, and risks of geologic CO_2 storage.

Recent numerical modeling of CO_2 injection and storage has examined both individual, detailed aspects of the process as well as simplifications of entire injection scenarios. CO_2 storage in a deep saline aquifer is inherently a multiphase process – i.e., multiple fluids, including supercritical CO_2, gaseous CO_2, and aquifer brine exist in the storage system – and hence, multiphase modeling is a principle concern of this type of numerical modeling. Work at present includes investigation of multiphase fluid flow (e.g., Xu et al., 2005)) and brine displacement following CO_2 injection (Birkholzer et al., 2007). Ultimately, CO_2 storage projects seek permanent trapping of CO_2 in subsurface geologic features. A number of methods contribute to such storage – including *stratigraphic trapping* (Nordbotten et al., 2005), *solubility trapping* (Han and McPherson, 2007), *residual trapping* (Hesse et al., 2007), as well as precipitation of carbon-containing minerals, referred to as *mineral trapping* (White et al., 2005) – and modeling is ongoing to study each. Permanent CO_2 storage in saline aquifers can only be accomplished if leakage is minimal, and thus, various leakage assessment models (e.g., Chiaramonte et al., 2007; Birkholzer et al., 2007) have been established. Finally, several numerical exercises (e.g., Kim, 2007; Xu and Pruess, 2007) integrate individual elements of the CO_2 storage problem in order to develop more comprehensive models with real-world geologic geometries and conditions.

Due to the necessary integration of numerous geologic processes, CO_2 injection and storage is a complex subject to model and is made more so by the natural variability of geologic structures. As such, numerical modeling should begin with very simplified injection scenarios and geologic units, gradually evolving as information regarding geologic structures become more abundant and realistic and as different types of model parameters are added. Each stage of the modeling process contributes additional information about the storage reservoir and injected fluid, eventually providing a general sense of how CO_2 may behave following injection.

Modeling begins with the injection of a dilute CO_2 solution into a simple, two dimensional aquifer geometry, at this stage avoiding the complexities of multiphase behavior and three dimensional modeling. Such basic models reveal the impact of pumping rate as well as aquifer and caprock permeability and porosity on the migration and potential leakage of injected CO_2 solute with time. Subsequent models are expanded to allow pure, supercritical CO_2 injection and examination of multiphase fluid flow, refining estimates of aquifer viability for CO_2 injection and storage. When data from field-based measurements become available, dissolution of the aquifer host-rock matrix, chemical reactions, mineral precipitation, and transport of associated aqueous species can be modeled. Further, inclusion of reactive transport considerably improves model estimates of an aquifer's CO_2 storage capacity and analysis of risks associated with injection. As numerical models are used to target field-based measurements and field-based measurements yield improved information concerning geologic conditions, numerical models can be further improved via refinements of model input parameters such as geologic structure, rock and brine composition, and pore-fluid pressure and host-rock stress fields.

5.2 Results and recommendations

Our preliminary numerical model is in the very initial stages of the type of modeling that needs to be completed in a comprehensive CO_2 project since a wide range of geologic conditions as well as injection and storage scenarios have yet to be fully explored. The stage-1-type model (see Section 3) completed thus far is very simplistic. Significantly more detailed studies – both in the field and via numerical modeling are needed to determine whether the MRS has characteristics favorable to CO_2 storage.

The model currently developed injects a dilute CO_2 solution into a deep fresh-water (not yet brine) aquifer for one year. A range of injection scenarios have been tested, varying solute injection rate as well as aquifer and caprock permeability and porosity between scenarios. Little leakage through caprock was observed, and injected material generally migrates less than ten kilometers (a relatively small distance) from the injection well. Within the ranges of geologic parameters we expect to encounter in the rift system, the stage-1-type model suggests that the following subsets would be feasible for CO_2 storage if indeed encountered in the subsurface: aquifer permeability, 10^{-15} m^2 to 10^{-13} m^2; aquifer porosity, 4% to 20%; caprock permeability, 10^{-21} m^2 to10^{-18} m^2; and caprock porosity, 6% to 16%. Currently under way is an expansion of modeling capabilities to include multiphase behavior in addition to potentially existing, but less favorable, aquifer geometries and conditions.

A second phase numerical modeling program could proceed as follows. With additional time (three years), significant improvements could be made to a numerical multiphase fluid flow modeling environment. Initial work would be possible without the aid of simplified field studies to gain information about the potential CO_2 storage units in the continental rift system. Model geology could be improved by analysis of existing rock cores from the Iowa Deep Drilling Project as well as shallow cores that intersect rift system sedimentary units from locations around Minnesota. Shallow wells in the state and near the rift that intersect saline brines could be sampled in order to begin reactive transport modeling, further improving CO_2 storage models.

After an initial modeling study, results from such improved models could then be used to suggest sites in Minnesota to complete geophysical (seismic, electromagnetic, and gravity) field studies, if funding is available. Geophysical data would assist in the development of geologic unit geometries that can then be used to better constrain the next generation of numerical models. If, following this additional modeling, the rift seems to offer viable sites for CO_2 storage, deep boreholes that intersect geologic units of interest would be required, with the recent modeling aiding borehole site selection. Direct information on host-rock composition and geometric structure together with brine composition from deep borehole sampling could then be applied to numerical models. This 3-year iterative process of geologic investigations in the field and numerical modeling continues until reasonable, predefined confidence levels concerning the feasibility of CO_2 injection and storage are reached. If studies suggest acceptable storage potential, field tests of actual CO_2 injection and storage may begin.

MINERAL CARBONATION

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Minnesota may be uniquely positioned to utilize the mineral carbonation method of geologic carbon sequestration, given the presence of vast tonnages of appropriate rock material in the Duluth region, some of which could be mined for copper, nickel, and platinum group elements, pending the outcome of current permitting procedures. Should these deposits go into production, a slurry of minerals suitable for mineral carbonation of CO_2 would be produced as a waste product from the mines.

The principal constraint to mineral carbonation at present appears to be cost, given estimates such as those given by Sims et al. (2007) that indicate costs for deep geological storage of 0.5 to 8 US$/t$CO_2$, compared to current estimates of 50 to 100 US$/t$CO_2$ for mineral carbonation. Nevertheless, there could be developments in the method, and there could be circumstances in which a particularly favorable mineral carbonation opportunity could coincide with constraints to other aspects of the sequestration procedure, such as considerations regarding transportation, thus possibly making mineral carbonation a conceivable option.

In this method, according to Mazzotti (2005), captured CO_2 is reacted with metal-oxide bearing materials, thus forming stable solids that would provide permanent, secure storage on a geological time scale. Moreover, it was suggested, magnesium and calcium silicate deposits are so vast in their availability that CO_2 resulting from combustion of all known fossil fuels resources could be sequestered. Mazzotti (2005) indicated that to fix a tonne of CO_2 requires about 1.6 to 3.7 tonnes of rock, and that, from a thermodynamic viewpoint, inorganic carbonates represent a lower energy state than CO_2 so the reaction theoretically would yield energy. The kinetics of natural mineral carbonation are slow, however, so it was indicated that all currently implemented processes require energy intensive preparation of the solid reactants to achieve affordable conversion rates and/or additives that must be regenerated and recycled using external energy sources. The resulting carbonated solids therefore, according to the report, must be stored at an environmentally suitable location, such as refilling of an open pit mine. It was indicated that the technology is still in the development stage and is not yet ready for implementation, although the best case studied is the wet carbonation of the natural silicate olivine, costing 50 to 100 US$/t$CO_2$ stored, translating into a 30-50% energy penalty on the original power plant. When accounting for the 10-40% energy penalty in the capture plant as well, a full CCS system with mineral carbonation would need 60-180% more energy than a power plant with equivalent output without CCS (Mazzotti, 2005).

Large volumes of olivine-bearing rock occur in Minnesota (Southwick et al., 1987; Chalokwu and Grant, 1990; Miller et al., 2002), including occurrences in areas in the Duluth region currently being assessed for metallic mineral potential. As an example, a deposit drilled by Minnesota Geological Survey consisted of 45% olivine and serpentine, with secondary oxides (Southwick et al., 1986).

It thus is apparent that it is conceivable that a possible future mining project in the Duluth region could produce crushed waste rock that would be favorable for sequestering CO_2, if circumstances warranted the encouragement of this option, and if costs are reduced through technological innovation.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

At the outset, it is stressed that currently available data indicate that there is a very low probability of success in confirming suitable geologic conditions for deep geologic sequestration of CO_2 in Minnesota. At the same time, it is acknowledged that these same data are inadequate to rule out the most prospective rocks. While bearing these crucial points in mind, it can be reported that it is clear that the most prospective rocks are Midcontinent Rift sedimentary rock sequences that are confidently thought to have the required thickness in two north-south belts on either side of the Twin Cities, extending from as far north as Pine County, and continuing to the Iowa border. It is added that further three-dimensional gravity modelling is needed to clarify the extent of these rocks, given that the best available model dates to the methods of nearly two decades ago. It is added, however, that the limited data available to date have indicated that the properties of these rocks are not favorable for deep geologic sequestration, although a geologic rationale that required reservoir properties could possibly exist in a portion of the area can be constructed. It also is recognized that Minnesota may require knowledge at a higher level of certainty than presently possible to indicate whether geologic carbon sequestration is a potential option for implementation within the State. For this, drilling would be required to permit a fully informed judgment, if future policy development deems the costs justified. Should this proceed, a year of pre-drilling activity would be required, in which geophysical, geological, and modelling investigations would be conducted to support site selection. Subsequently, a post-drilling year would be required for analyses, modelling, and reporting. This three-year activity should only go ahead, in the view of the report authors, in the context of broader policy, social, engineering, and economic analyses and consultations, led by appropriate authorities. On this basis, the following recommendations are offered.

Recommendations

In order to take forward preparedness for Minnesota to achieve greenhouse gas emission objectives, further analysis of the potential for geologic carbon sequestration should be initiated concurrently with assessment of other emission reduction options. In addition, this activity would presumably be accompanied by concurrent activity in CO_2 source characterization, analysis of pipeline systems, drinking water protection, arrangements for the activity, and community consultations, along with further analysis of the mineral carbonation option. Should further policy development call for more a conclusive determination of in-state sequestration potential, taking into consideration costs for all stages, drilling will be required. A one-year pre-drilling phase costing about one million dollars would need to include geophysical modelling and surveys, further analysis of cores and water chemistry, including analysis of regional diagenesis, and numerical CO_2 storage modeling. Drilling in the second year should be conducted at the minimum expense required to satisfactorily answer the questions at hand, possibly costing as much as ten million dollars. Inexpensive coring methods should be explored, however, although it is recognized that oilfield methods, including comprehensive downhole logging, may well be needed. A third year would then be required for analysis of field data, including integration of the data by further numerical CO_2 storage modeling, leading to reporting.

To expand on these requirements leading up to any drilling that is called for, it again is noted that any further progress in the field of sequestration potential will require geophysical surveys based on existing data, and likely also on the basis of new field work. An early priority is to construct a new three-dimensional gravity model using up-to-date modeling and visualization software, to clarify the extent of the prospective rocks. In addition, velocity or waveform analysis of seismic reflection data is one approach that could yield further information regarding rock properties, and efforts to obtain existing data are recommended. Magnetotelluric methods could furthermore be used to test for conductive brines in the sedimentary section which would indirectly indicate porosity. To minimize costs, thorough efforts to select the most prospective areas would be undertaken. Such a three-pronged program could be implemented for less than one million dollars, and the results would be used to guide selection for drilling, if called for.

In the field of sedimentary geology, a key priority is to understand the causes of the low permeability observed in these rocks to date, through a regional assessment of diagenesis. The results of this analysis would be used along with the geophysics to guide drillhole site selection. In addition, further analysis of water chemistry would allow a better understanding of the degree of reservoir integrity to be expected in the prospective rocks, while also clarifying required efforts to protect drinking water during all phases of the activity. This activity that could go ahead in 2008 and early 2009 would cost less than $100,000.

An optimal, 3-year program of follow-up will also require iterative computer simulations of CO_2 injection and storage, and the University of Minnesota Department of Geology and Geophysics is well positioned to further develop this capability, under the leadership of Martin O. Saar, Assistant Professor and Gibson Chair of Hydrogeology and Geofluids. These computer simulations of CO_2 injection and storage are necessary, as they allow testing and evaluation of a range of geologic formation and CO_2 injection scenarios. Knowledge of subsurface formation conditions is always imperfect, and complex feedback mechanisms among processes need to be tested over long time periods of simulated time, up to tens or thousands of years. The input data will come from geological and geophysical observations and interpretations, and progress in these inputs will coincide with progressively improved forecasting capabilities. In addition, modeling will help with selection of geophysical survey locations and drill sites, if needed. This three-year program of modelling that would optimally support a program that would include drilling would cost on the order of $300,000.

Consultations are underway to clarify the most cost effective drilling method that could be applied, as early as late 2009. About four drillholes each to about 2 km depth would be required to obtain the confidence that presumably would be desired should drilling go ahead. Costs for drilling, as soon as 2009/2010, therefore would possibly be as much as $10 million. Further consideration of methods, in consultation with knowledgeable parties such as members of the DOE Regional Partnerships program, should presumably go ahead concurrently with, and in contact with, analysis of the nature of CO_2 sources in the region, as well as transportation and other considerations. In a third year, as early as 2010/2011, costs would be for analysis, modelling, and reporting only.

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