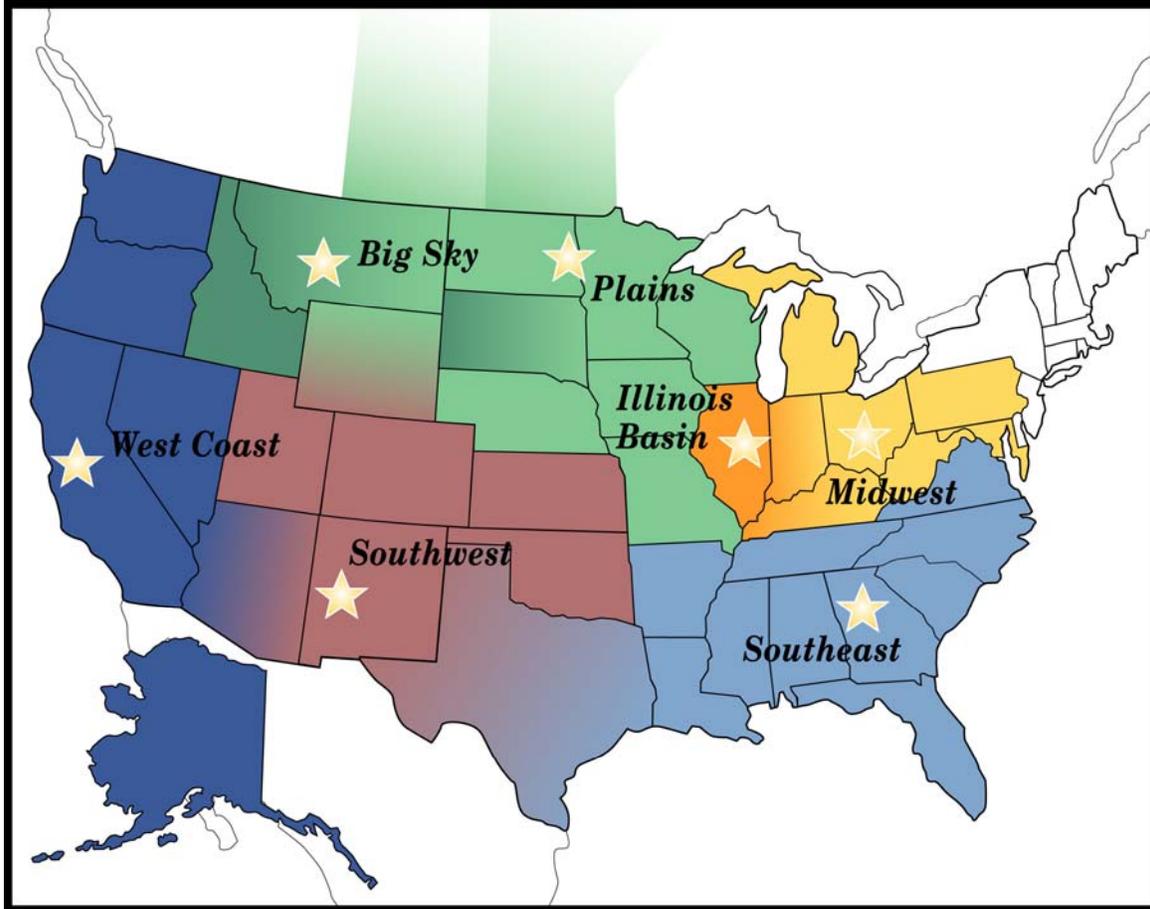


## 1.0 EXECUTIVE SUMMARY

### 1.1 INTRODUCTION

The U.S. Department of Energy's Carbon Sequestration (CS) program directly supports the President's Global Climate Change Initiative designed to reduce the carbon intensity of the U.S. economy 18 percent by 2012 (Bush, 2002). CS complements energy efficiency and low-carbon fuel greenhouse gas reduction efforts by capturing and storing greenhouse gases, primarily carbon dioxide (CO<sub>2</sub>), which is the predominant greenhouse gas associated with global warming based on volume emitted to the atmosphere. The impact of the CS program will be to reduce the 201 tons of greenhouse gas emissions per million dollars of gross domestic product (GDP) in 2002 to 166 tons per million dollars GDP by 2012 (Scott Klara, National Energy Technology Laboratory, written communication, 2003). To place this goal in context, this reduction would be equivalent to taking an estimated 70 million cars off the road assuming 5 tons of CO<sub>2</sub> emissions per year for newer model cars.

In August 2003, the U.S. Department of Energy (DOE) and its National Energy Technology Laboratory (NETL) established seven regional partnerships in five geographic areas across the U.S. to become the centerpiece of the CS program (fig. 1.1). These partnerships form a nationwide network for the purpose of evaluating the most suitable carbon sequestration methods for specific areas of the country. The partnerships are comprised of 154 government and non-government organizations in 40 states, three Indian Nations, and two Canadian provinces. (More information is available at [http://www.netl.doe.gov/technologies/carbon\\_seq/partnerships/partnerships.html](http://www.netl.doe.gov/technologies/carbon_seq/partnerships/partnerships.html))



**Figure 1.1:** Seven regional partnerships formed by U.S. DOE and NETL in August 2003 for the evaluation of CO<sub>2</sub> sequestration methods (modified from Scott Klara presentation to NETL May 2004). The yellow stars designate the location of each partnership lead: West Coast, California Energy Commission; Southwest, New Mexico Institute of Mining and Technology; Big Sky, Montana State University; Plains, University of North Dakota, Energy and Environmental Research Center; Illinois Basin, University of Illinois, Illinois State Geological Survey; Midwest, Battelle Memorial Institute; Southeast, Southern States Energy Board.

The partnerships are tasked with (1) identifying all suitable sources and sinks for their specific regions, (2) creating action plans for regulatory, liability, environmental, and outreach issues, (3) establishing monitoring and verification protocols, (4) validating sequestration technology and availability of infrastructure, and (5) determining the benefits of sequestration within their respective regions.

DOE is utilizing a two-phased approach for the project - Phase 1 for planning and Phase II as a proof-of-concept or deployment phase. Phase I consisted of seven partnership projects of 18- to 24-month duration beginning in

late 2003. DOE funded each project with about \$1.5 million with an overall 40 percent cost share requirement from the partnerships. During this phase, the partnerships evaluated various sequestration technologies that have emerged over the past few years. They also initiated study of the kinds of regulations and infrastructure that might be required for wide-scale use of carbon sequestration.

Phase II is budgeted for about \$1.5 to \$2.5 million per year per partnership for a period of four years with a minimum 20 percent cost share requirement from all partners. During this phase, dozens of sequestration pilot projects recommended for small-scale validation testing under Phase I will be deployed across the country beginning in early 2006. Each of these projects will continue to focus on regulatory and infrastructure requirements, such as environmental permitting.

## **1.2 SOUTHWEST PARTNERSHIP REGION**

The Southwest Regional Partnership's (SWP) primary goal is to determine an optimum strategy for minimizing greenhouse gas intensity in the southwestern portion of the U.S. (fig. 1.1, brown-shaded area). The SWP is led by the New Mexico Institute of Mining and Technology (NMT) and comprises a large, diverse group of expert organizations and individuals specializing in carbon sequestration science and engineering, as well as public policy and outreach. These partners include 21 state government agencies and universities, five major electric utility industries, several oil, gas and coal companies, three federal agencies, the Navajo Nation, and several non-government organizations (table 1.1).

**Table 1.1:** Partners in the Southwest Regional Partnership

<b>State Partners</b>	<b>Industry Partners</b>
<p><b>Arizona Universities &amp; Government</b> Arizona Geological Survey Arizona State University</p> <p><b>Colorado Universities &amp; Government</b> Colorado Geological Survey</p> <p><b>New Mexico Universities &amp; Government</b> New Mexico Oil Conservation Division New Mexico Bureau of Geology New Mexico Environmental Department New Mexico Institute of Mining and Technology New Mexico State University Dine College (Navajo Nation)</p> <p><b>Oklahoma Universities &amp; Government</b> Oklahoma Geological Survey University of Oklahoma Oklahoma State University Sarkey's Energy Center</p> <p><b>Utah Universities &amp; Government</b> Utah Geological Survey University of Utah Utah State University Utah AGRC Utah Division of Air Quality Utah Energy Office Utah Division of Oil, Gas &amp; Mining</p>	<p><b>Power Utilities</b> PacifiCorp Public Service Co. of New Mexico (PNM) Intermountain Power Agency Tucson Electric Power Oklahoma Gas &amp; Electric</p> <p><b>Energy Providers (Oil, Gas, Coal)</b> Yates Petroleum, ChevronTexaco Marathon, Occidental Permian ConocoPhillips, Burlington</p> <p><b>Gas Infrastructure (CO<sub>2</sub> Pipelines)</b> Kinder Morgan</p> <p><b>U.S. Federal Government Partners</b> Los Alamos National Laboratory Sandia National Laboratory U.S. Department of Agriculture</p> <p><b>Various Additional Partners</b> Navajo Nation New Mexico Oil and Gas Association Gas Technology Institute Electric Power Research Institute Interstate Oil &amp; Gas Compact Commission Center for Environmental Economic Develop Advanced Resources International Western Governors Association Petroleum Recovery Research Center Waste-Management Education &amp; Research</p>

In the absence of action, annual CO<sub>2</sub> emissions in the SWP region are expected to rise from 500 million tons per year (2001) to nearly 750 million tons per year by 2012 (McPherson, 2003). The region can offset much of this growth through various sequestration technologies. The region contains the principal CO<sub>2</sub> pipeline infrastructure in the country; it has the potential to offset natural CO<sub>2</sub> production from reservoirs with flue gas CO<sub>2</sub> sequestration from the numerous large coal-fired plants, and diverse terrestrial, geologic, and mineralization options are available in the region.

The SWP has developed the framework necessary for assessing optimum sequestration strategies for the Southwest Region. Primarily, the approach includes (1) dissemination of existing regulatory/permitting requirements, (2) educating the public about possible sequestration methodologies and assessing the public's knowledge and acceptance, and (3) evaluation and ranking of the most appropriate sequestration technologies for capture and storage of CO<sub>2</sub> in the Southwest Region. In addition, the Partnership has identified the potential gaps in monitoring and verification approaches needed to validate long-term storage efforts.

Figure 1.2 shows an approximate boundary for the Southwest Region and indicates major CO<sub>2</sub> emissions sources, existing CO<sub>2</sub> pipelines, and prospective geologic sequestration targets (major sedimentary basins). The Environmental Protection Agency (EPA) has funded comprehensive reviews of greenhouse gas (GHG) emissions from four of the states comprising the SWP region (U.S. Environmental Protection Agency, 2004c). The EPA-funded reviews show that 95-99 percent of all CO<sub>2</sub> emissions in the region are from fossil fuel combustion. In 2000, more than 320 million tons of emissions came from the nearly 70 power plants located within the region; about 25 percent of the CO<sub>2</sub> emissions were from the transport sector.

The economic aspects of carbon emissions in the region also play a critical role. Figure 1.3 illustrates the trends in GHG intensity (metric tonnes carbon equivalent per million gross state product (GSP) dollars) for the Southwest Partnership Region (McPherson, 2003). The national average in 2002 was 185 carbon equivalent per GSP. The Southwest Region is above average because it consumes a large amount of fossil fuels, often for the export of electricity generated in the region. Between 1993 and 2000, the regional average GHG intensity declined 22 percent, largely because of rapid economic growth.

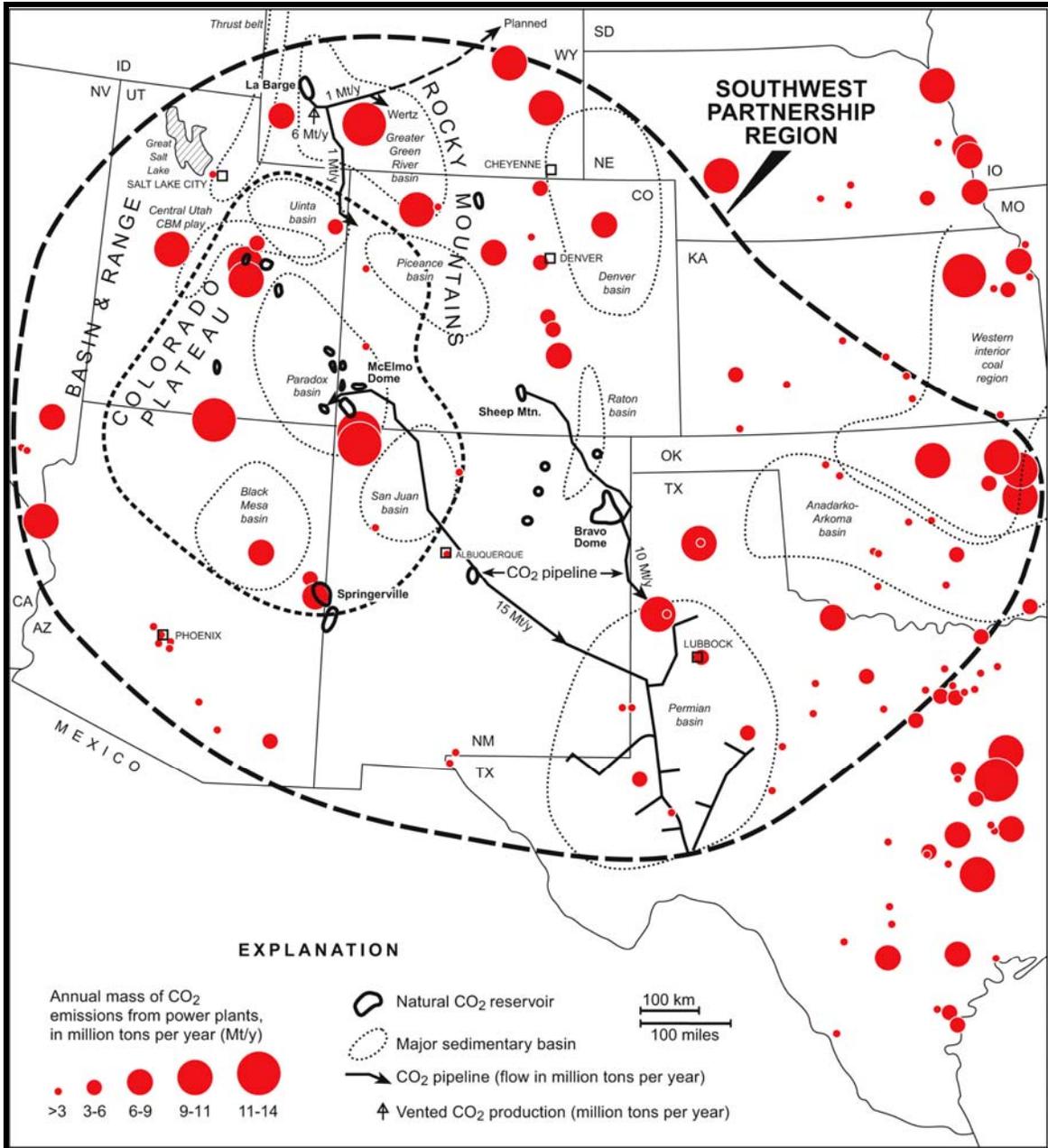
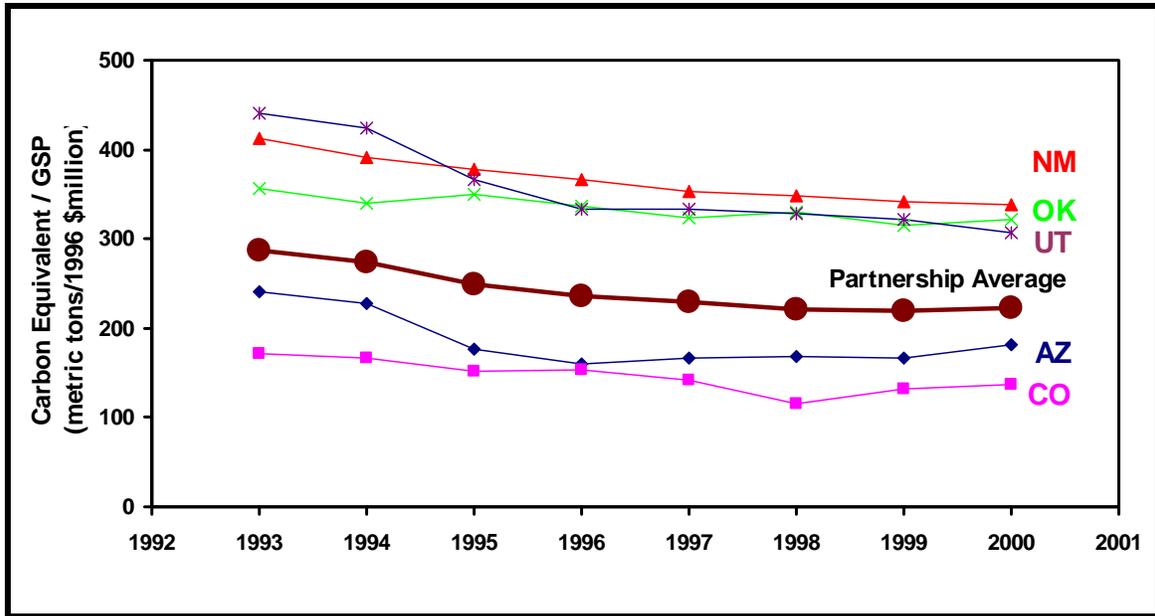


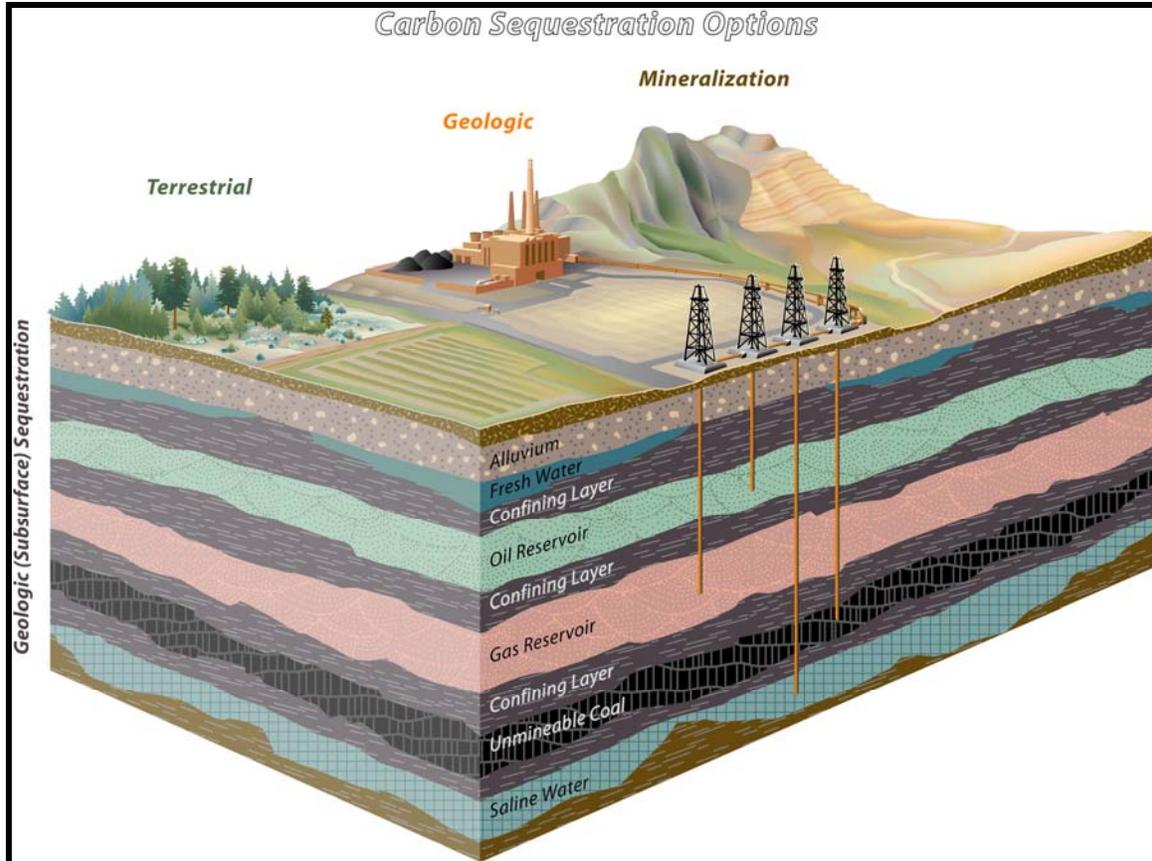
Figure 1.2: Map of the Southwest Region (Allis and others, 2003).



**Figure 1.3:** Trends in greenhouse gas intensity in the Southwest Region (Brian McPherson, NMT, written communication, 2003; modified after Allis and others, 2003). New Mexico (NM), Oklahoma (OK), Utah (UT), Arizona (AZ), and Colorado (CO), Gross State Product (GSP).

### 1.3 SEQUESTRATION THEMES

Carbon sequestration options assessed for the Southwest Region fall into three broad categories - geologic, terrestrial, and mineralization engineering (fig. 1.4). Geologic storage options in the region include deep unmineable coal beds, natural gas and CO<sub>2</sub> fields, depleted and marginal oil fields, and deep saline aquifers. One option that the Partnership has examined is the viability of supplanting the CO<sub>2</sub> currently produced from natural CO<sub>2</sub> reservoirs (used for improved oil recovery and enhanced coalbed methane applications) with anthropogenic power plant CO<sub>2</sub>. In some parts of the Southwest Region it is important to evaluate the tradeoffs associated with using saline aquifers as CO<sub>2</sub> sequestration reservoirs when they might ultimately be needed as a source of potable, post-desalination water for human consumption in this rapidly growing region.



**Figure 1.4:** Sequestration themes evaluated for the Southwest Region (modified from Brian McPherson, NMT, written communication, 2003).

Terrestrial sequestration (TS) can play an important role in mitigating climate change. This option involves the transfer of carbon from the atmosphere to soil and vegetation via natural processes such as photosynthesis, humification, and aggregation. Although carbon dynamics have been explored at small scales, integrating TS into regional GHG management has received little attention. Exploiting terrestrial sinks is an attractive policy alternative (results can be achieved quickly, technologies are compatible with existing land management practices, delivery infrastructure is in place), but achieving the potential requires thorough economic, social, and biological analysis. Ownership includes both private and public lands managed by federal and state agencies, suggesting outreach must be broad-based, flexible, and integrated with existing programs. Land cover varies considerably, from deciduous forest to desert and coniferous forests, creating a unique potential to capture and store carbon, dictating

application of robust land management principles. Although terrestrial CO<sub>2</sub> sequestration appears to be a viable alternative in several parts of the Southwest Region, the Partnership recognizes that the rate of CO<sub>2</sub> emissions caused by drought-related forest fires and wind dispersal of cropland soil may increase under a range of dryer-than-usual climate futures.

CO<sub>2</sub> mineralization is a novel concept for binding CO<sub>2</sub> in a solid form, which eliminates the need for long-term monitoring and any concerns over the long-term fate of the CO<sub>2</sub>. Carbon dioxide mineralization is an ongoing natural process, but an engineered process that can be implemented at a meaningful rate and scale remains an active research challenge. Although not fully realized as an operational approach, two mineralization processes are actively being investigated. One process involves extracting divalent cations from silicates using ultramafic and mafic igneous rocks (e.g., as occur in the Four Corners area of the Southwest Region). The other process involves extracting divalent cations from brines, which could be extracted either from the deep basins of the region or from the produced waters associated with the production of oil and gas. The Partnership's approach for the assessment of the CO<sub>2</sub> mineralization option focuses on characterizing the location and volumes of potential subsurface mineralization storage sites provided by ultramafic and mafic rocks and brines. The Partnership used available publications and databases detailing size and characteristics of the resources to estimate potential carbon storage capacity and potential value-added byproducts (which include mineral carbonates for silicate mineralization and potable water for brine mineralization).

Environmental and social consequences are associated with each of these options. Quantifying the consequences is challenging because complex interrelationships link the economy, energy production, population growth, greenhouse gas emissions, and the environment. The SWP developed a dynamic simulation model to quantitatively compare alternative sequestration technologies relative to their associated environmental risks, monitoring and verification requirements, life-cycle cost, and applicable regulatory and permitting constraints. The resultant decision model provides: (1) scenario development

where policy makers and regulators explore a range of “what if” scenarios, (2) constituency development wherein industry representatives and other partners can examine the scenario results as a test of their viability, and (3) outreach and education where the model can be taken directly to the public and used to improve their understanding of CO<sub>2</sub>/energy cycle issues and complexity, explain the decision process, and be directly engaged in evaluating proposed sequestration options. (Refer to the SWP website for further details [http://southwestcarbonpartnership.org/.](http://southwestcarbonpartnership.org/))

## **1.4 CARBON STORAGE IN COLORADO**

The Colorado Geological Survey (CGS) participated in Phase I of the Southwest Regional Partnership on Carbon Sequestration Project where the primary objective was to characterize the CO<sub>2</sub> environment throughout the southwestern region of the U.S. For the State of Colorado, this task consisted of the following three subtasks: (1) assemble CO<sub>2</sub> source data, (2) assemble CO<sub>2</sub> sink data, and (3) estimate carbon storage capacity. These results were incorporated into a geographical information system for public-access and regional-based analysis. The summary that follows briefly discusses the methodology, data sources, and findings for each of these subtasks.

### **1.4.1 CO<sub>2</sub> Source Data**

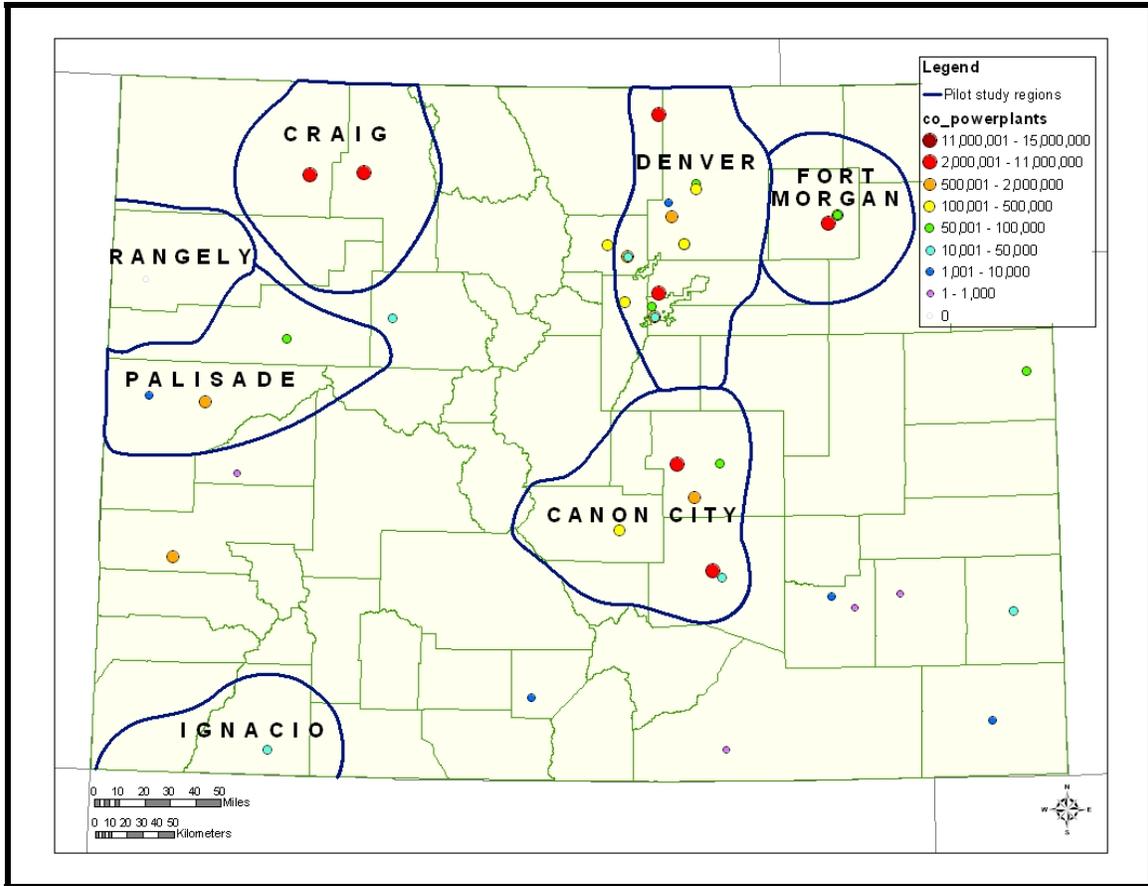
In 2000, CO<sub>2</sub> emissions were more than 92 million short tons (MT) in Colorado and are projected to increase by 2.4 percent per year through 2025 (U.S. Environmental Protection Agency, 2004a). Nearly 76 percent of these emissions result from activities in the utility and transportation sectors. Power generation in the state relies primarily on coal and as a result, 42 MT of CO<sub>2</sub> or 46 percent of the total emissions in Colorado are emitted from power plants in the utility sector (U.S. Environmental Protection Agency, 2004a). With the application of the appropriate technology, these stationary point sources afford the possibility of capture and separation of CO<sub>2</sub> for transport and storage at nearby “sinks”.

The sequestration capacity calculations summarized below assume an anthropogenically-sourced CO<sub>2</sub> that has been “purified” for enhanced recovery use and/or longer-term storage. However, the combustion of fossil fuel produces a contaminated flue gas that is approximately 80 percent N<sub>2</sub> and only 20 percent CO<sub>2</sub> by volume. There is an investment required to capture, separate, transport, and sequester the CO<sub>2</sub>. Depending on the technology selected, the average cost of carbon capture and storage is approximately \$55 per metric tonne for avoided CO<sub>2</sub>. The high degree of variability in these costs (\$23 to \$84 per metric tonne avoided CO<sub>2</sub>) dramatically highlights the need for site-specific analysis in the selection of an appropriate technology for fully integrated carbon capture and storage projects.

The primary source of the CO<sub>2</sub> emission data for this project was the *Emissions & Generation Resource Integrated Database (eGRID)*, which is maintained by the Office of Atmospheric Programs at the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency, 2004c).

#### **1.4.2 CO<sub>2</sub> Sink Potential**

Although CO<sub>2</sub> sink potential is widely distributed across the state, data collection focused on seven primary Pilot Study Regions (fig. 1.5).



**Figure 1.5:** General outline of source areas identified for Colorado.

These study regions were defined based on the maximum diversity in potential sequestration options within close proximity to CO<sub>2</sub> sources; that is, within a 30 to 40 mile radial distance of one or more power plants. The sequestration options evaluated for Colorado include oil and gas reservoirs, underground gas storage facilities, natural CO<sub>2</sub> fields, coalbed reservoirs, deep saline aquifers, and advanced mineralization processes. Table 1.2 summarizes the CO<sub>2</sub> emissions for 2000 and the potential CO<sub>2</sub> sequestration capacity for each of the sequestration options in each of the pilot study regions. The emissions are not for the entire state; they represent the aggregate totals estimated for the individual pilot study regions (refer to table 2.1 in Section 2.0).

**Table 1.2:** CO<sub>2</sub> sequestration capacities in million short tons estimated for Colorado

Pilot Study Regions	2000 Emissions	Geologic			Mineralization		Total Capacity
		Oil & Gas	CBM	Saline Aquifers	Silicates	Produced Waters	
Cañon City	9.4	0	493	122,118	2,200	0	124,811
Craig	14.4	123	11,059	46,209	30,000	0	87,391
Denver	14.1	557	602	129,138	0	<0.001	130,297
Fort Morgan	4.9	164	0	43,770	0	<0.001	43,934
Ignacio	31.5	186	2,809	92,142	0	0	95,137
Palisade	0.8	116	1,798	132,330	200	<0.001	134,444
Rangely	3.4	740	1,037	102,579	0	0	104,356
<b>Total</b>	<b>78.5</b>	<b>1,886</b>	<b>17,798</b>	<b>668,286</b>	<b>32,400</b>	<b>0</b>	<b>720,370</b>

Utilizing both geologic and mineralization options, the preliminary forecast for CO<sub>2</sub> sequestration within the seven primary source areas is more than 720 billion tons (720 gigatons or GT). These areas have the potential of providing several hundred years of carbon storage based on 2000 emission levels. The highest CO<sub>2</sub> sequestration capacity potential for Colorado lies within the Denver Basin and Cañon City Embayment east of the Rocky Mountains, and within the Piceance and Sand Wash basins in northwestern Colorado.

The Denver and Rangely study regions provide the greatest potential for carbon storage utilizing oil and gas reservoirs; their combined carbon storage is estimated at 1.3 GT or nearly 70 percent of the total oil and gas sink potential for Colorado. The Craig study region is estimated to provide more than 11 GT of carbon storage due to the vast coal resources in the area. When combined with the coal resources of the Ignacio and Palisade study regions, the carbon storage potential for these three regions exceeds 15 GT or approximately 88 percent of the total coalbed methane (CBM) storage potential for Colorado. The Cañon City, Denver, and Palisade study regions have very similar carbon storage capacities estimated for the deep saline aquifers that occur in these areas. With more than 120 GT each, the carbon storage for these three regions represents more than half of the saline aquifer potential for Colorado. The Craig study

region provides the greatest mineralization potential through carbonation of silicate minerals. Preliminary estimates exceed 32 GT in storage capacity if mineralization engineering technology were commercially available.

### ***Oil and Gas Reservoirs***

There are approximately 1,400 oil and gas fields in Colorado; about 223 of these fields constitute large-volume producers; that is, cumulative production exceeds 1 million barrels (MMBbls) of oil and/or 10 billion cubic feet (Bcf) of gas. More than half of these large-volume producing fields (122) are located within 30 miles of a large CO<sub>2</sub> point source consisting of one or more coal-burning power plants. All of these 122 large-volume fields produce from oil and gas reservoirs that are deep enough to maintain CO<sub>2</sub> at supercritical conditions; that is, average reservoir depth exceeds 3,000 feet, which is sufficient to maintain CO<sub>2</sub> at a pressure and temperature of 1,000 psi and 90 °F, respectively. At this pressure and temperature, the density of CO<sub>2</sub> exceeds that of gas, oil, or water, which facilitates its containment in the subsurface.

A minimum level of data has been compiled on all oil and gas fields in Colorado, consisting primarily of location, geologic age, production, discovery date, and depth. Where data are available in the public domain, additional reservoir properties such as porosity, permeability, gas and oil composition, and fluid properties have also been compiled, particularly for those reservoirs within the seven pilot study regions. Data sources consisted of the Colorado Oil and Gas Conservation Commission (COGCC), PI/Dwights, U.S. Department of Energy, and state geological survey publications.

The estimate of CO<sub>2</sub> sequestration capacity for oil and gas reservoirs in the seven source areas is 1,886 MT with nearly 70 percent of that capacity contained in the Denver and Rangely source areas (table 1.2). This estimate is based on cumulative production through December 2004. Estimating CO<sub>2</sub> storage capacity for oil and gas reservoirs was accomplished by calculating the equivalent mass of CO<sub>2</sub> that is required to replace the reservoir volume voided by production. This CO<sub>2</sub> capacity calculation for Colorado should be considered

conservatively low due to the significant underestimation of water production from oil and gas reservoirs for the state.

Recent work by Advanced Resources International (ARI) suggests that 510 to 580 MMBbls of oil may be economically recovered from potential future enhanced oil recovery projects using CO<sub>2</sub> flooding (CO<sub>2</sub>-EOR) in 12 of Colorado's major oil reservoirs (U.S. Department of Energy, 2006). These EOR projects would not only provide suitable longer-term sequestration opportunities but would also result in increased production to offset costs.

### ***Underground Gas Storage***

In 2004, Colorado had nine underground gas storage (UGS) facilities in operation, providing a total working gas storage capacity of 45.3 Bcf (American Gas Association, 2004). Most of these are located in the Denver and Piceance basins. In addition to working gas volumes, UGS facilities require base gas that in Colorado ranges from 17 to 163 percent of working gas.

Current UGS facilities in Colorado have nearly 48 Bcf committed in base gas representing a significant portion of total project investment. Some of these facilities may be suitable to base gas reductions via CO<sub>2</sub> replacement. Up to 4.4 MT of CO<sub>2</sub> would be required to offset the current base gas levels in Colorado, assuming complete replacement of existing base gas volumes. If this replacement is linked with a 30 percent increase working gas, the current 45.3 Bcf could potentially be increased to 58.9 Bcf.

### ***Natural CO<sub>2</sub> Fields***

Large, naturally-occurring, geologic deposits of carbon dioxide are found in three of Colorado's sedimentary basins – the Paradox, Raton, and North Park (fig. 1.2). The resources of the Paradox and Raton basins provide low-cost sources of high-pressure CO<sub>2</sub>, primarily for EOR projects in the Permian Basin of New Mexico and Texas. In this basin alone, approximately 50 projects produce an incremental 145 MMBbls of oil per day, more than 80 percent of the North

American enhanced oil produced from CO<sub>2</sub> floods in 2004 (Cappa and others, 2005).

An extensive CO<sub>2</sub> pipeline and re-injection infrastructure system exists throughout the Permian Basin, making it attractive for expanding or starting new projects. High-pressure pipelines supply CO<sub>2</sub> from natural source fields at Bravo Dome in northern New Mexico, and McElmo Dome and Sheep Mountain in southern Colorado. Shell's completion of the pipeline out of McElmo Dome in 1983 significantly increased the value of the naturally occurring CO<sub>2</sub> reserves in Colorado. In addition to EOR applications, CO<sub>2</sub> is used in welding, the manufacture of dry ice, and the food and beverage industry.

Colorado's production of natural CO<sub>2</sub> has averaged 300 Bcf per year since the mid-1980s. Representing an annual equivalent of 18 MT, economic sources of anthropogenic CO<sub>2</sub> would have considerable commodity value and would have the potential to offset depletion of existing natural deposits.

### ***Coalbed Reservoirs***

Deep unmineable coal for Colorado is defined as coal-bearing formations occurring between 2,000 and 7,500 feet of depth. Coal parameters such as rank, gas content, ash and moisture content were compiled from U.S. Bureau of Mines data, Gas Research Institute reports, and state geological survey publications. The vast majority of coals in the state are bituminous in rank, which makes them suitable for enhanced coalbed methane recovery and carbon sequestration. The estimate of CO<sub>2</sub> sequestration capacity for coalbed methane reservoirs in the seven pilot study regions is almost 18 MT with nearly 80 percent of that capacity associated with the Iles-Williams Fork-Fort Union coals of the Sand Wash Basin (Craig Pilot Study Region) and the Fruitland coals of the San Juan Basin (Ignacio Pilot Study Region) (table 1.2). This estimate of capacity was made by applying a carbon dioxide/methane (CO<sub>2</sub>/CH<sub>4</sub>) replacement ratio based on coal rank and a replacement efficiency of 65 percent. In reality, the physics are far more complicated than this and require a reservoir simulator to calculate more accurately.

### ***Deep Saline Aquifers***

The criteria used to select water-bearing formations suitable for CO<sub>2</sub> sequestration in deep saline aquifers included lithology consisting primarily of sandstone or other rock types with sufficient porosity and permeability, depth exceeding 3,000 feet (to maintain supercritical conditions and to minimize the possibility that the formation would be developed for future water resources), salinity exceeding 1,000 ppm (again, to minimize the possibility that the formation would be developed for potable water sometime in the future), and the presence of an overlying formation that would function as a top seal to prevent vertical migration of injected CO<sub>2</sub>. Most of the formations evaluated have had some associated oil or gas production. This implies the existence of a long-term structural or stratigraphic trapping mechanism that may decrease the possibility of migration of injected CO<sub>2</sub> to the surface or other unintended geological units. Data sources consisted of Colorado Oil Gas Conservation Commission (COGCC), Colorado Division of Water Resources (CDWR), and publications from the Rocky Mountain Association of Geologists (RMAG), Texas Bureau of Economic Geology (TBEG), U.S. Geological Survey (USGS), and state geological surveys.

The amount of carbon that a given formation may sequester was calculated using a volumetric method. The capacity was adjusted assuming that the efficiency of the storage process would vary between one and four percent. (The values for saline aquifers summarized in table 1.2 reflect an efficiency factor of four percent.) Thus, the estimates should be considered conservative. The calculation makes no distinction between CO<sub>2</sub> that is stored as an immiscible phase within a specified brine formation, CO<sub>2</sub> that is stored as a dissolved phase in the brine, and CO<sub>2</sub> that is precipitated as minerals. However, displacement of brine in the pore volume by immiscible CO<sub>2</sub> is the fundamental mechanism implicit in the calculations. The estimate of CO<sub>2</sub> sequestration capacity for deep saline aquifers in the seven pilot study regions is 668,286 MT with about 57 percent of that capacity contained in the Cañon City, Denver, and Palisade source areas (table 1.2). This capacity estimate is limited to only that portion of

these areally extensive aquifers that lie within a 30 mile radius of the primary CO<sub>2</sub> sources. In most cases, the carbon storage capacity of these vast deep saline aquifers will be much greater when not screened for distance. However, further study is required to develop a better understanding of the distribution of trap mechanisms needed to contain injected CO<sub>2</sub>.

### ***Mineralization***

The primary goal of the mineral carbonation process is to sequester large amounts of carbon dioxide through carbonation of silicate minerals. Although there are numerous naturally occurring silicate minerals in the earth's crust, research for mineral CO<sub>2</sub> sequestration has focused primarily on olivine, serpentine, and wollastonite; silicate minerals that are rich in magnesium or calcium. In Colorado, these minerals are prevalent in mafic and ultramafic rocks such as serpentinite, peridotite, dunite, gabbro, and to a lesser extent, basalt and alkalic igneous rocks. In the industrial sector, waste materials such as coal fly ash or municipal solid waste incinerator bottom ash, asbestos waste, and metal slag are potential alternative feedstocks. Mineral silicates are a promising option for CO<sub>2</sub> sequestration in Colorado. Given current technology, silicate ore contained within the Cañon City, Craig, and Palisade source areas could sequester a total of 32,400 MT of CO<sub>2</sub> assuming 15 to 20 percent efficiency and subtracting CO<sub>2</sub> emitted during the sequestration process (table 1.2). Continued research and technological advances are needed before this process becomes a cost-effective and leading contender in the pool of technologies available for CO<sub>2</sub> sequestration.

Waters produced in association with oil and gas extraction are also a potential source of cations, particularly calcium, for mineral carbonation. However, preliminary calculations indicate that the water needed to sequester CO<sub>2</sub> emissions in a given region far exceeds current produced water volumes, and sequestration via this method is not likely to be practical. Even assuming 100 percent efficiency, the volume of water produced in Colorado could only sequester about 25,000 short tons of CO<sub>2</sub> (table 1.2).

### 1.4.3 Public-Access GIS Database

All characterization data gathered during completion of the initial task of the Phase I project has been compiled in a combination of Microsoft Excel™ spreadsheets and Access™ databases. A complete set of ESRI ArcMap™ shapefiles with attribute tables and metadata have also been assembled. This geographical information system (GIS) database for Colorado has been provided to Utah's Automated Geographic Reference Center (AGRC) for public access and use in further analysis by the SWP utilizing the dynamic simulation model. The GIS database for Colorado is also included on the CD with this report as well as being available via the CGS website <http://geosurvey.state.co.us>.

### 1.5 CGS PROJECT TEAM

The Colorado Geological Survey (CGS) comprises a diverse group of expert geoscientists and GIS specialists. The project team assembled for Phase I of the Southwest Regional Partnership on Carbon Sequestration Project is summarized in table 1.3 along with each team member's primary area of responsibility.

**Table 1.3:** Colorado Geological Survey project team

<b>Team Member</b>	<b>Area of Responsibility</b>
James Cappa	Colorado Point of Contact for SWP SWP Executive Steering Committee
Genevieve Young	CGS Principal Investigator and Project Manager Oil, Gas, and Coalbed Sink Characterization
Vanessa Lintz	Source and Sink Characterization; GIS
Beth Widmann	Mineralization Potential; Database Design
David Bird	Deep Saline Aquifers
Chris Martin	Coalbed Reservoir Characterization
Rachel Garrison	Oil and Gas Database
Jennifer McHarge	Oil and Gas Database
Larry Scott	Graphical Design

## 1.6 ABOUT THIS REPORT

This report has been prepared so that the Executive Summary may stand alone as a broad summary of the efforts conducted by CGS during participation in Phase I of the Southwest Regional Partnership on Carbon Sequestration Project. For those seeking greater detail, the chapters that follow the Executive Summary are intended to provide additional information on the source and sink characterization efforts completed by CGS. Authorship of these chapters is summarized in table 1.4.

**Table 1.4:** Chapter authors

Author	Chapter
Genevieve Young	1.0 Executive Summary
Vanessa Lintz	2.0 Carbon Dioxide Sources in Colorado
Genevieve Young	3.0 Oil and Gas Sinks in Colorado
Genevieve Young	4.0 Coalbed Methane Sinks in Colorado
David Bird	5.0 Deep Saline Aquifer Sinks in Colorado
Beth Widmann	6.0 Mineralization in Colorado
Genevieve Young	7.0 Carbon Capture and Storage Costs
Genevieve Young	8.0 Summary and Conclusions

Data summarized in the appendices are available on the CGS website <http://geosurvey.state.co.us/> and included on this CD. The Microsoft Access database **CoPrD** that generated the production reports in appendix 4 is also included on this CD and can be accessed via the CGS website.