Preliminary Assessment of the Potential for Carbon Dioxide Sequestration in Geological Settings in Nevada

Topical Report

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Abstract

In this report we present a preliminary assessment of the potential for CO_2 disposal by sequestration in geological settings in Nevada using analysis with geographic information systems (GIS). The key assumptions made are that for CO_2 disposal in saline aquifers it is wisest to (1) avoid underground disposal in areas of fractured bedrock and restrict the assessment to parts of alluvial basins that are thick enough to provide a seal against leakage and have sufficient pressure to keep the CO_2 in a condensed phase; (2) stay away from active faults whose fracture zones may allow leakage of CO_2 from underground injection sites; (3) avoid areas that in the foreseeable future have a reasonably high probability of being explored and developed for mineral, geothermal, or water resources; (4) avoid current urban areas and areas that are likely to experience significant population growth during the 21st century; and (5) avoid restricted lands, such as parks and military reservations. The data sets used in the GIS analysis are made available in the electronic version of this report, so that others may reevaluate the approach with different assumptions and data sets.

There appears to be little potential for conventional enhanced oil recovery CO_2 sequestration in Nevada, partly because Nevada's oil fields do not have much associated natural gas. From this we infer that the natural gas has escaped, and so would CO_2 likely escape from these fields if CO_2 were injected into them. Furthermore, Nevada's oil fields are small when compared to fields in other parts of the country, and are at a considerably higher temperature than is ideal for maintaining a dense underground CO_2 phase.

Mined caverns and salt formations in southern Nevada, northwestern Arizona, and southwestern Utah offer some potential for CO_2 storage. Salt deposits in northwestern Arizona offer the highest potential for CO_2 storage, as these deposits are both well described and under investigation for natural gas storage.

Finally, the chemical reaction of CO_2 with mafic and ultramafic rocks has the potential to capture CO_2 in synthetic minerals. These minerals could, in turn, be used to isolate municipal and industrial wastes. Enough of these rocks are exposed in Arizona, California, Nevada, Oregon, and Washington to meet the expected needs for CO_2 sequestration in the region. Reaction of CO_2 with mafic or ultramafic rocks would be a long-term solution requiring considerably more research to design, perfect, and demonstrate the cost-effectiveness of the chemical reactors and associated facilities.

Table of Contents

List of Figures

List of Tables

1 Introduction

A recent report by the U.S. Government (U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 2004) stated:

> "Carbon is important as the basis for the food and fiber that sustain and shelter human populations, as the primary energy source that fuels economies, and as a major contributor to the planetary greenhouse effect and potential climate change. Carbon dioxide (CO_2) is the largest single forcing agent of climate change, and methane (CH_4) is also a significant contributor.
>
> "Atmospheric concentrations of CO_2 and CH_4 have been increasing for about two centuries as a result of human activities and are now higher than they have been for over 400,000 years. Since 1750, CO_2 concentrations in the atmosphere have increased by 30% and CH_4 concentrations in the atmosphere have increased by 150%.
>
> "Approximately three-quarters of present-day anthropogenic CO_2 emissions are due to fossil fuel combustion (plus a small amount from cement production). Land-use change accounts for the rest. The strengths of CH_4 emission sources are uncertain due to the high variability in space and time of biospheric sources. Future atmospheric concentrations of these greenhouse gases will depend on trends and variability in natural and human-caused emissions and the capacity of terrestrial and marine sinks to absorb and retain carbon.
>
> "Decisionmakers searching for options to stabilize or mitigate concentrations of greenhouse gases in the atmosphere are faced with two broad approaches for controlling atmospheric carbon concentrations: 1) reduction of carbon emissions at their source—such as through reducing fossil fuel use and cement production or changing land use and management (e.g., reducing deforestation); and/or 2) enhanced sequestration of carbon—either through enhancement of biospheric carbon storage or through engineering solutions to capture carbon and store it in repositories such as the deep ocean or geologic formations.
>
> "Enhancing carbon sequestration is of current interest as a near-term policy option to slow the rise in atmospheric CO_2 and provide more time to develop a wider range of viable mitigation and adaptation options. However, uncertainties remain about how much additional carbon storage can be achieved, the efficacy and longevity of carbon sequestration approaches, whether they will lead to unintended environmental consequences, and just how vulnerable or resilient the global carbon cycle is to such manipulations."

1.1 Background on the Need to Address CO_2

Large amounts of carbon dioxide (CO_2) are generated from the burning of fossil fuels (coal, natural gas, oil, and products, such as gasoline, derived from them), wood, and other biomass. Worldwide, humans put approximately 6.5 gigatons (6.5 billion metric tons) of carbon into the atmosphere each year from the burning of fossil fuels (Service, 2004). Some handy conversions regarding carbon and CO_2 are listed in Table 1. The U.S. alone burns approximately one gigaton of coal per year (U.S. Energy Information Administration, 2004) and has vast resources of coal. Service (2004), in interviewing Massachusetts Institute of Technology economist Howard Herzog, stated:

> "Generating electricity with coal and storing the carbon underground still costs only about 14% as much as solar-powered electricity. And unlike most renewable energy, companies can adopt it more easily on a large scale and can retrofit existing power plants and chemical plants. That's particularly important for dealing with the vast amounts of coal that are likely to be burned as countries such as China and India modernize their economies. 'Coal is not going to go away,' Herzog says. 'People need energy, and you can't make energy transitions easily.' Sequestration, he adds, 'gives us time to develop 22nd century energy sources.' That could give researchers a window in which to develop and install the technologies needed to power the hydrogen economy."

Table 1. Carbon and CO_2

Carbon, C (12.0111 grams per mole)
Oxygen, O (15.9994 grams per mole)

Burning carbon:
C [in wood, grass, and fossil fuels – natural gas, petroleum (and its products – gasoline, diesel, and heating oil), and coal] + **O_2** [from the atmosphere] = **CO_2** [into the atmosphere]

With this reaction, one ton of C yields 3.664 tons of CO_2;
1 gigaton of C yields 3.664 gigatons of CO_2.

1 gigaton = 10^9 tons = 1 billion tons

1 gigaton (metric) of water (with a density of 1.0 g/cm^3) occupies a volume of 1 km^3.

Typical density of liquid or supercritical CO_2 at pressure and temperature in the subsurface = 0.5 to 0.75 g/cm^3

One gigaton of liquid or supercritical CO_2 at a density of 0.75 g/cm^3 occupies a volume of 1.33 km^3.

1 ton of CO_2 as a gas at a temperature of 0°C and 1 atmosphere of pressure occupies a volume of 467 m^3.

1 barrel = 42 gallons = 158.76 liters = 0.15756 m^3

1 km^3 = 1 billion m^3 = 6.35 billion barrels

Although no coal is produced in Nevada, coal is the primary source of energy for generation of electricity in Nevada. Thus, burning of coal is the major industrial contributor of CO_2 to the atmosphere from Nevada. Other contributors in Nevada include power plants, homes, businesses, and other facilities that burn natural gas, heating fuel, diesel fuel, and petroleum; cement and lime plants (that heat carbonate rocks, particularly limestone, to drive off CO_2 and produce reactive lime); and aircraft, trains, trucks, and automobiles.

According to the U.S. Energy Information Administration (2004), in 2002 Nevada's coal-fired power plants, which had a capacity of generating 2,658 megawatts of electricity, released 16.6 million metric tons of CO_2 while producing 16.4 million megawatt hours. In the same year Nevada's gas-fired power plants, which had a capacity of generating 1,485 megawatts, released 5.8 million metric tons of CO_2 while producing 12.2 million megawatt hours. Total CO_2 emissions from Nevada power plants in 2002 were 22.4 million metric tons, corresponding to 6.1 million tons of carbon (Table 1).

Despite efforts to limit the burning of carbon, the world economy will almost assuredly continue to use these fuels for heat, generating electricity, and transportation for several decades to come. Concerns about the impacts of CO_2 on global climate and related aspects of weather and ecological and agricultural change have stimulated investigations of ways to sequester CO_2—that is, keep it from either getting into or otherwise removing it from the atmosphere.

1.2 General Logic for Near-Term and Long-Term Solutions

Near-term options for disposal of CO_2 in geological settings involve proven technologies—enhanced oil recovery (EOR) and injection into saline aquifers (Bartlett, 2003; Friedmann, 2003; White and others, 2004). Use of CO_2 in EOR projects has been demonstrated for many years in the Permian Basin of western Texas (Dutton and others, 2005) and elsewhere, but these projects did not attempt to keep the CO_2 in the ground permanently and leakage to the surface does occur (Klusman, 2003). In order to stabilize atmospheric concentrations, leakage of less than 0.01% per year for geological sequestration may be needed (S.M. Benson, personal commun., 2003). A large-scale demonstration project for both EOR and CO_2 sequestration is underway at the Weyburn oil field in Saskatchewan (Friedmann, 2003; White and others, 2004; Service, 2004); CO_2 is piped to the oil field from a plant in Beulah, North Dakota, which uses coal to produce a hydrogen-rich gas.

Demonstration projects are also underway to evaluate CO_2 injection into saline aquifers. A project in the Frio Formation in Texas shows promise for demonstrating disposal in permeable sandstones in states along the Gulf of Mexico (Bartlett, 2003; http://www.beg.utexas.edu/environqlty/co2seq/publications.htm). At the Sleipner West natural gas field in the North Sea, the producing company is injecting co-produced CO_2 into saline aquifers as a means of avoiding a Norwegian tax on CO_2 emissions (Bartlett, 2003; Friedmann, 2003). In a reconnaissance evaluation of possible sites for CO_2 sequestration in saline aquifers in the United States, Hovorka and others (2000) noted little potential in basin-fill sediments and carbonate aquifers in the Basin and Range province of Arizona, California, and Nevada, a conclusion reinforced by this report.

Less proven technologies for CO_2 sequestration include isolation in coal seams, thereby enhancing the recovery of coalbed methane, and oil shales, thereby enhancing oil recovery (Friedmann, 2003; Pinsker, 2003) and chemical reaction with rocks (Goff and Lackner, 1998; Friedmann, 2003; Reed, 2003; Cipolli and others, 2004). Nevada contains little coal or oil shale, but there are abundant exposures of rocks that could be used in chemical reactions.

2 Executive Summary

In 2003, the State of California, in collaboration with the U.S. Department of Energy and the States of Alaska, Arizona, Oregon, and Washington, asked the State of Nevada to participate in a regional analysis of CO_2 sequestration potential, through both terrestrial and geological approaches. The terrestrial approaches involve growing more biomass (particularly trees), and the geological options include proven technologies, such as using CO_2 to enhance recovery from oil fields and disposal of CO_2 in saline aquifers, and more unconventional approaches. As the state with the least amount of annual precipitation, Nevada has little potential for growing substantially more biomass, relative to states along the Pacific Ocean. The Nevada Bureau of Mines and Geology (NBMG) agreed to conduct a preliminary assessment of the potential for geological sequestration in Nevada. This report presents the methodology and results of this assessment.

The NBMG agreed to evaluate the potential for sequestration of carbon dioxide in geological settings in Nevada using geographic information systems (GIS) to combine the following sets of data:

- surface outcropping of bedrock versus alluvium (with the initial assumption that, because of repeated tectonic deformation during the last several hundred million years, including substantial crustal extension during the last 40 million years, areas of bedrock are unlikely to offer significant potential sites for sequestration);
- interpreted geophysical data (largely gravity) suggesting at least 1,000 meters of Quaternary and Tertiary cover over bedrock;
- presence of favorable geological formations (e.g., permeable sands and gravels into which CO_2 could be injected or thick halite beds that could be solution mined to create caverns for storage; thickness and continuity of aquitards to prevent escape of CO_2);
- nearness to extractable geological resources (e.g., mineral, petroleum, natural gas, geothermal, and water resources);
- depth to water table and depth to non-potable water deeper than 800 meters, if known;
- nearness to active faults;
- nearness to large generators of CO_2 (power plants);
- nearness to urban areas and corridors for urban growth;
- nearness to existing transportation routes;
- lands that are potentially off limits (e.g., military reservations, National Parks, National Recreation Areas); and
- other data as appropriate.

There does not appear to be much potential in Nevada for CO_2 sequestration through disposal in saline aquifers. Among the potential deep parts of alluvial basins, few remain after eliminating areas of potential potable water, geothermal resources, and mineral resources. Within the remaining areas, little is known about porosities, permeabilities, or salinities of aquifers at depths greater than 1 km.

There also does not appear to be much potential in Nevada for conventional approaches to CO_2 sequestration through enhanced oil recovery, in part because the oil fields in Nevada tend not to have much associated natural gas, implying that gas originally associated with the fields has escaped. Injected CO_2 would likely leak to the surface as well. In addition, the oil fields in Nevada are small relative to fields in many other parts of the United States, and some of the Nevada fields are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground.

There is some potential for disposal of CO_2 in mined caverns in salt formations in basins in southern Nevada, northwestern Arizona, and southwestern Utah. The highest potential for this approach is likely to be in northwestern Arizona, where thick salt deposits are well described and are being investigated for storage of natural gas.

Chemical reaction of CO_2 with mafic rocks (basalt, gabbro) and ultramafic rocks (serpentinite, dunite, peridotite) has the potential to capture CO_2 in synthetic minerals, which, in turn, could be used to isolate municipal and industrial wastes. Enough of these rocks are exposed in Arizona, California, Nevada, Oregon, and Washington to meet the expected needs for CO_2 sequestration in the region. Ultramafic rocks are more favorable than mafic rocks both volumetrically and thermodynamically. Reaction of CO_2 with mafic or ultramafic rocks would be a long-term solution requiring considerable research to design, perfect, and demonstrate the cost-effectiveness of the chemical reactors and associated facilities.

For Nevada to be considered a potential site for significant amounts of CO_2 sequestration in geological settings, considerably more work would need to be done to (a) assess the thicknesses and volumes of salt formations in southern Nevada, (b) demonstrate a cost-effective process for chemical reaction with ultramafic or mafic rocks, and (c) assess the volumes of ultramafic and mafic rocks that are located in optimal areas. Although Nevada occurrences of ultramafic and mafic rocks have the advantage of being remote, considerably larger areas of ultramafic rocks are known in California, Oregon, and Washington, and enormous volumes of basalt occur in eastern Oregon and Washington.

3 Experimental

3.1 General Aspects of the Geology of Nevada

The general geology of Nevada is summarized in Table 2 (modified from Price, 2004, and references therein). Of particular importance to CO_2 sequestration are repeated tectonic events during the Paleozoic, Mesozoic, and Cenozoic eras that have fractured the rocks to such an extent that natural gas generally has escaped to the surface. Ongoing crustal extension is responsible for the current basin-and-range topography in Nevada. Essentially every mountain range is bounded on one or both sides by a fault that has been active in Quaternary time.

Nevada's energy and mineral production (Fig. 1) is closely linked to its tectonic history. Deep circulation of meteoric water along faults helps make geothermal resources abundant. Igneous activity during the Jurassic, Cretaceous, and Tertiary Periods is responsible for the formation of many of the metallic ore deposits scattered throughout the state. Exploration for oil and gas has occurred throughout much of the state (Garside and others, 1988), but oil has been produced commercially from only two localities, Railroad Valley in Nye County and Pine Valley in Eureka County. Minor amounts of natural gas have been produced from some wells, but the amounts are too small to justify building gas pipelines to markets in urban areas. In many cases, oil has also migrated to the surface to form seeps at springs.

We have constructed a conceptual model of oil and potential CO_2 reservoirs and seals in Nevada (Fig. 2). In general, oil occurs in two broad types of reservoirs in Nevada: fractured and permeable Paleozoic sedimentary rocks (mostly limestones but locally also sandstones) and fractured Tertiary ash-flow tuffs. Ideal reservoirs for CO_2 sequestration would be permeable (but unfractured) sandstones. Such sandstones may occur in the Paleozoic section and in the Tertiary valley-fill sequences in the basins. Seals for the oil reservoirs include Paleozoic marine shales, Tertiary lacustrine shales, and the non-welded, clay- or zeolite-altered upper zones of ash-flow tuffs. These rocks could also form seals for CO_2 reservoirs. The best seals appear to be above the Paleozoic-Tertiary unconformity. Some Paleozoic shales may be adequate seals, but these would have to be thoroughly tested if they were to provide the primary deterrent to escape of CO_2 from a potential reservoir.

Table 2. Geologic time scale with major events in Nevada history (modified from Price, 2004)

Million years before present	Era / Period	Events
	CENOZOIC	
	Quaternary	Modern earthquakes, mountain building, basaltic and rhyolitic volcanism, and geothermal activity are expressions of Basin and Range extension that began in the Tertiary Period. The crust is being pulled apart in Nevada, causing valleys to drop relative to mountains, and right-lateral strike-slip faults in western Nevada accommodate approximately 20% of the motion between the Pacific and North American plates. Prior to 10,000 years ago, ice ages caused glaciers to form in the higher mountains and large lakes to develop in valleys.
1.8		
	Tertiary	Basin and Range extension began about 30 to 40 million years ago. Igneous activity during the Tertiary Period was caused not only by extension but also by subduction (descent of oceanic crust into the Earth's mantle) of oceanic plates beneath the North American Plate and, in northern Nevada, by motion of the crust over the Yellowstone hot spot in the mantle. Numerous Nevada ore deposits, including most major gold and silver deposits and the copper ores near Battle Mountain, formed during this time. Gypsum deposits formed from evaporating lakes in southern Nevada. Tertiary basalts are abundant in several parts of the state.
65		
	MESOZOIC	
	Cretaceous	The Cretaceous Period and Mesozoic Era ended abruptly with the extinction of dinosaurs and many marine species. Numerous granitic igneous intrusions, scattered throughout Nevada, originated from subduction along the west coast of North America. Much of the granite in the Sierra Nevada formed at this time. The igneous activity caused many metallic mineral deposits to form, including the copper-gold-silver-lead-zinc ores near Ely in White Pine County, copper-molybdenum ores north of Tonopah in Nye County, and tungsten ores in several mining districts. In southern and eastern Nevada, sheets of rocks were folded and thrust from the west to the east during the Sevier Orogeny (mountain building), which began in Middle Jurassic time and ended at or beyond the end of the Cretaceous Period.
144		
	Jurassic	A subduction zone to the west caused igneous intrusions (including the gabbroic complex near Lovelock), volcanism, and associated ore deposits (e.g., copper deposits near Yerington). Sandstones, including those in the Valley of Fire, were deposited in southeastern Nevada, and sedimentary gypsum deposits formed in northwestern Nevada.
208		
	Triassic	The general geography of Nevada during the Triassic Period was similar to that during the Jurassic Period—igneous activity in the west and deposition of sedimentary rocks in continental to shallow marine environments to the east. Explosive volcanism produced thick ash-flow tuffs in west-central Nevada. Economically important limestone, gypsum, and silica-sand deposits formed in southern Nevada. The Sonoma Orogeny, which began during Late Permian time and ended in Early Triassic time, moved rocks from the west to the east along the Golconda Thrust in central Nevada. The large marine reptiles at Berlin-Ichthyosaur State Park lived during the Triassic Period.
251		
	PALEOZOIC	
	Permian	Volcanism to the west and deposition of thick limestones to the east were characteristics of much of the Paleozoic Era in the Great Basin. Some marine gypsum deposits formed in southern Nevada.
290		
	Pennsylvanian	The Antler highland, which formed earlier, was eroded and shed sediments into the basins to the east. Carbonate rocks were deposited in eastern and southern Nevada.
320		
	Mississippian	During the Antler Orogeny, from Late Devonian to Early Mississippian time, rocks were folded and thrust from the west to the east. Rocks thrust from the east include fragments of oceanic crust, including some basalts, serpentinites, and deep-water sedimentary rocks. The Roberts Mountains Thrust, below which many of the gold deposits in north-central Nevada occur, formed at this time. Conglomerate, sandstone, siltstone, and shale were deposited in the thick basin of sediments derived from the Antler highland, and carbonate rocks were deposited further east.
360		
	Devonian	Limestone was deposited in eastern Nevada, and shale, chert, and economically important barite were deposited in northeastern and central parts of the state. No record of middle to lower Paleozoic rocks exists in the western part of the state. The quiet, shallow-marine tectonic setting that persisted earlier in the Paleozoic Era began to change, as small land masses from the Pacific Ocean collided with western North America.
418		
	Silurian	Carbonate rocks (dolomite and limestone) in the eastern part of the state and silica-rich rocks (shale, sandstone, and chert) in the central part of the state record similar deposition to that during the rest of the middle to early Paleozoic Era.
438		
	Ordovician	Marine deposition during the Ordovician Period was similar to that during the rest of the early Paleozoic Era, with the exception of basalts (metamorphosed to greenstones) locally interbedded with sedimentary rocks found today in the central part of the state. Some sedimentary barite deposits and copper-zinc-silver ores formed in sea-floor sediments during this time.
490		
	Cambrian	Middle and Upper Cambrian deposition resembled that during much of the Paleozoic Era, with carbonate rocks to the east and shale plus sandstone to the west. Lower Cambrian and uppermost Precambrian rocks are characterized by quartzite and metamorphosed siltstone throughout much of Nevada.
543		
	PRECAMBRIAN	The oldest rocks in Nevada (at least 2,500 million years old in the East Humboldt Range in northeastern Nevada and at least 1,700 million years old in southern Nevada) are metamorphic rocks. Precambrian rocks also include granites (about 1,450 million years old) and younger sedimentary rocks. Beginning approximately 750 million years ago, Antarctica and Australia may have rifted away from western North America, setting the stage for the development of a western continental margin that is similar to the Atlantic coast of today. A shallow marine, tectonically quiet setting persisted in eastern Nevada for the next 700 million years.

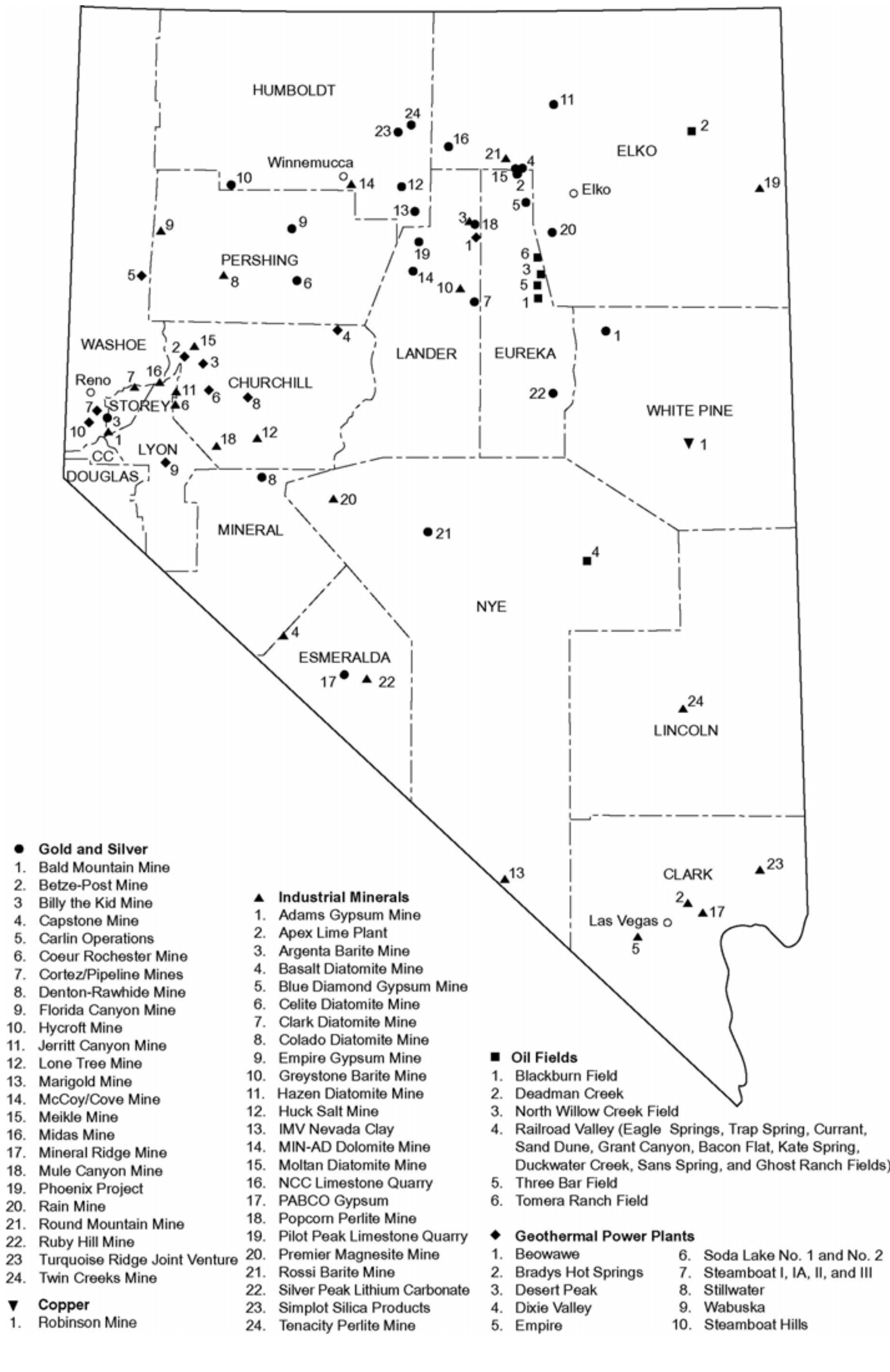

Figure 1. The location of oil fields, major mines, and geothermal power plants in operation in Nevada in 2004

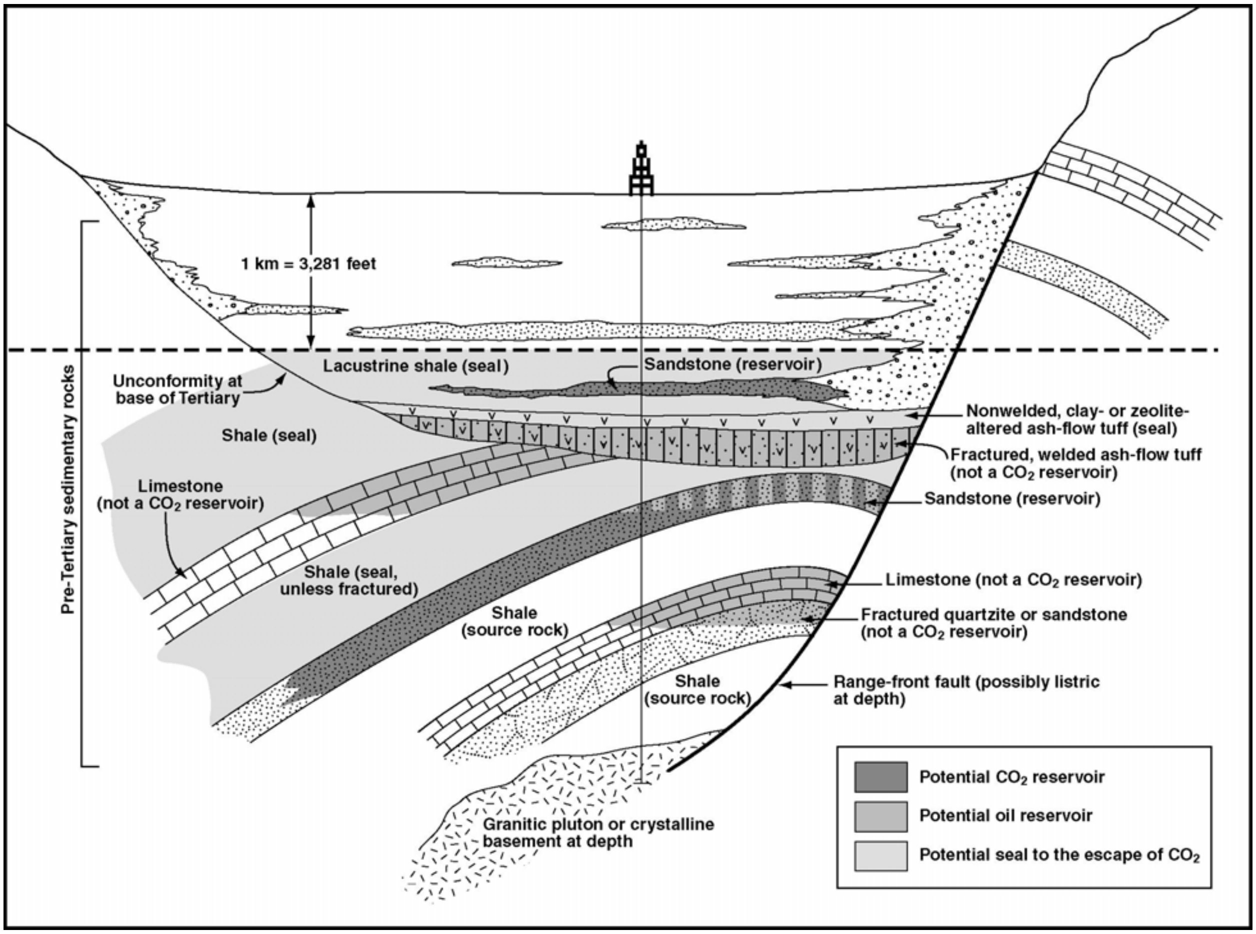

Figure 2. Cross-sectional conceptual model of potential CO_2 reservoirs and seals in Nevada

3.2 Factors and Maps Considered in the Assessment

In this section, we describe the assumptions, factors, and maps considered in assessing areas for possible CO_2 sequestration in saline brine formations in Nevada, and we discuss the potential for CO_2 sequestration through enhanced oil recovery. Details of the analysis methodology using a geographic information system (GIS) are provided in the appendix. Copies of all GIS layers used in the analysis are supplied in the compact disc accompanying this report, so that users may choose other assumptions and approaches in reanalyzing the data. We use a simple, binary approach; that is, in considering each factor, an area is either favorable or not favorable for CO_2 sequestration. In the final analysis, we combine the areas in the GIS to determine remaining areas for possible consideration.

3.2.1 Restriction of Consideration to the Deeper Parts of Alluvial Basins

Areas of bedrock outcrop (Fig. 3) are eliminated from consideration for CO_2 sequestration, because Basin and Range extensional deformation, coupled with earlier fracturing associated with crustal shortening (Table 2), has so thoroughly fractured the bedrock that it is unlikely to contain seals that are adequate to prevent escape of CO_2.

The pressure needed to keep CO_2 in a liquid or dense supercritical state depends on temperature (Fig. 4). The pressure at the critical point is 7.4 megapascals (1,070 pounds per square inch), which corresponds to a depth of 753 m, if one assumes hydrostatic pressure (pressure of a column of water with a density of 1.0 g/cm^3). A minimum depth depth of 800 m for consideration of CO_2 sequestration has been assumed in other studies (eg., Downey and Clinkenbeard, 2005). As illustrated on Figure 4, if temperatures are higher than typical geothermal gradients (25 to 30°C/km) would predict at that depth, the supercritical CO_2 fluid density would be lower, and less CO_2 could be accommodated in the formation than in the preferred case for sequestration. Temperatures in some oil fields in Nevada are considerably higher than would be predicted from typical geothermal gradients (Fig. 4), and abundant hot springs throughout the state attest to shallow, hot rocks in many locations. Given the absence of reliable data on temperature gradients in many areas, we have used a somewhat more conservative figure of 1,000 meters as a minimum depth for consideration of CO_2 sequestration in Nevada.

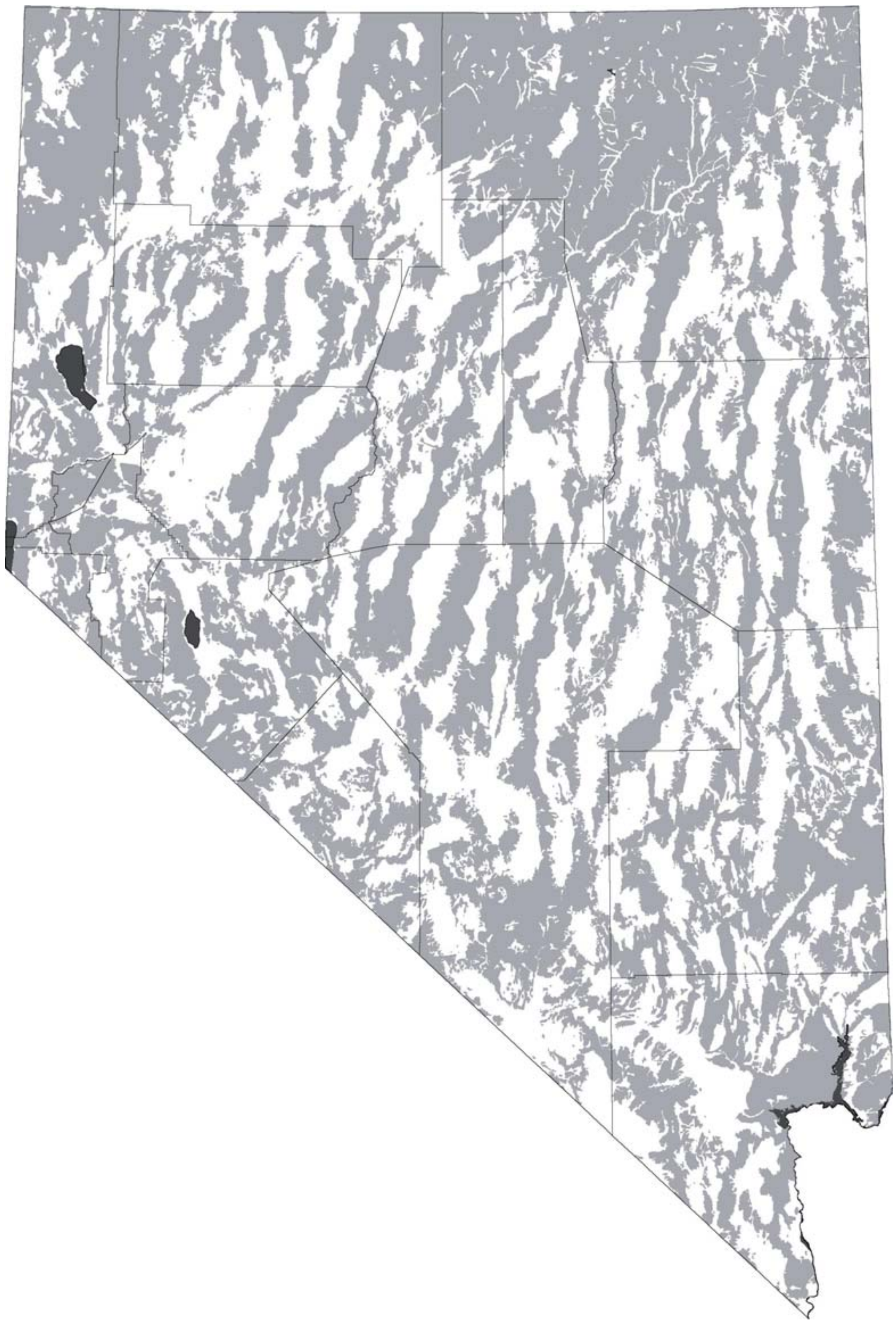

Figure 3. Map showing the distribution of bedrock (gray, representing consolidated rocks of Tertiary and older age) versus Quaternary-Tertiary alluvial deposits (white) in Nevada. Areas of Quaternary glacial drift, which are generally thin and occur mostly in mountains, are included with the bedrock. Major lakes are shown in black.

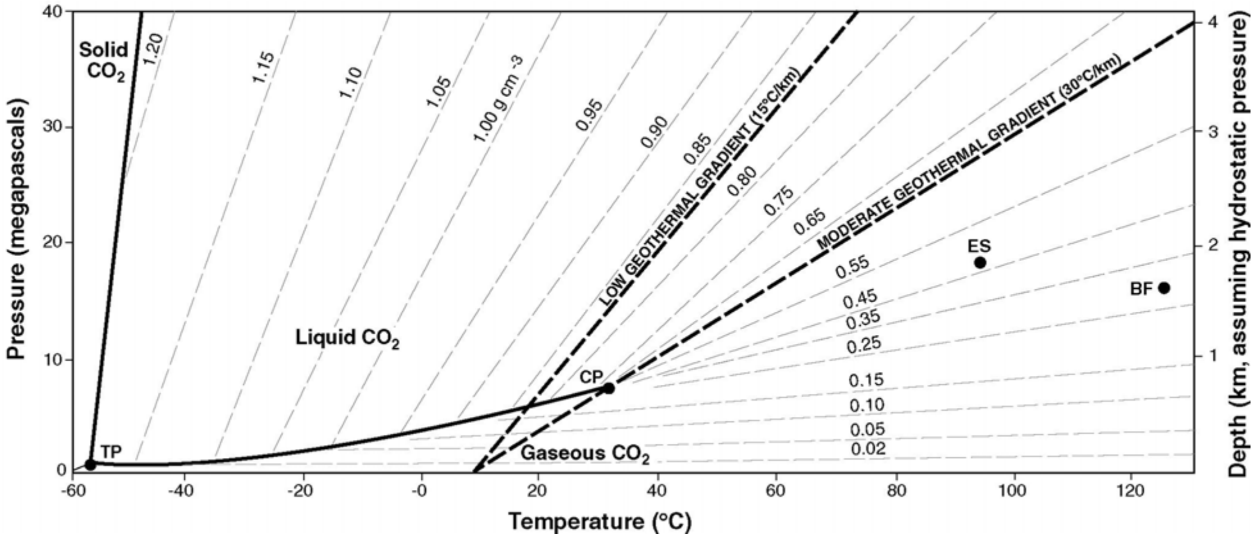

Figure 4. Phase relations, with lines of equal density, for CO_2 (modified from Roedder, 1984). TP = triple point (-56.6°C, 0.5 megapascals), at which solid, liquid, and gaseous CO_2 coexist. CP = critical point (31.0°C, 7.38 megapascals), above which the distinction between gas and liquid cannot be made with increasing pressure or temperature. ES = bottom-hole temperature (93°C at 1,830 m) in the Eagle Springs oil field (Shevenell and Garside, 2005, and http://www.nbmg.unr.edu/geothermal/gthome.htm). BF = reservoir temperature (120-130°C at about 1,625 m) in the Bacon Flat-Grant Canyon oil fields (Hulen and others, 1994).

The United States Geological Survey (USGS) has interpreted publicly available gravity data, calibrated with known depths from exploration drilling, to infer areas that have at least one km of valley fill (Fig. 5). We exclude from consideration any areas that are not considered in this USGS analysis to have at least one km of valley filling sediments and/or volcanic rocks.

The NBMG is the official repository for information about wells drilled for oil and gas and geothermal exploration and development in Nevada. Using the conceptual model of potential CO_2 reservoirs and seals (Fig. 2), we extracted important geologic data from the well records (Table 3). These data are summarized in NBMG Open-File Report 04-1 (Hess, 2004a). These data may be helpful in a more detailed analysis of the potential for CO_2 sequestration at a later time, and they are useful in assessing the potential for CO_2 sequestration using EOR.

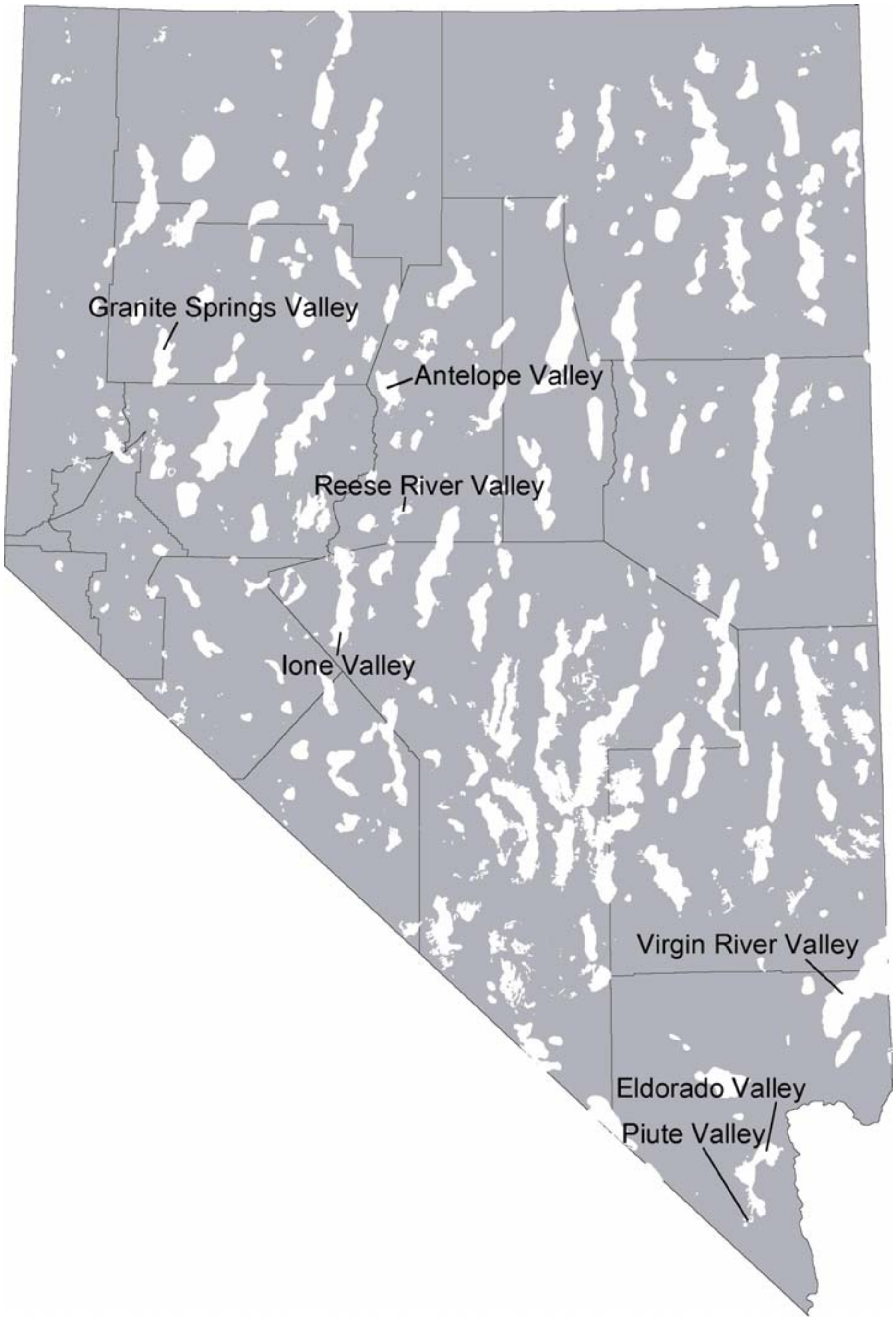

Figure 5. Map showing where valley-filling alluvium and volcanic rocks exceed 1 km in thickness (white areas, modified from Dohrenwend and others, 1996)

Table 3. Information recorded from records of deep wells drilled in Nevada (Hess, 2004)

DEFINITIONS

CO_2 reservoir rock ≡ sandstone, conglomerate, sand, or gravel

Seal rock ≡ shale, mudstone, claystone, mud, clay, halite, gypsum, salt, or nonwelded (possibly clay- or zeolite-altered) ash-flow tuff

NEITHER A CO_2 RESERVOIR ROCK NOR SEAL ≡
limestone, dolomite, fractured volcanic rock, fractured sandstone, quartzite, metamorphic rocks, or granite or other igneous rocks

Data collected from well records, if available, in wells within areas not otherwise excluded for consideration of CO_2

1. Total depth of well.
2. Are there potential CO_2 reservoir rocks in the well below 1 km (3281 ft) depth? If no, go to next well.
3. Is there a potential seal below 1 km and above that reservoir rock? If no, go to next well.
4. Depth to base of Cenozoic/Tertiary volcanic rocks and alluvium.
5. Depth to base of deepest reservoir rock in pre-Tertiary sedimentary package.
6. How fresh is the water in this deepest reservoir rock? (Total dissolved solids – TDS?)
7. How porous is this deepest reservoir rock? % of porosity?
8. How permeable is this deepest reservoir rock? K in millidarcy?
9. Thickness of the thickest single pre-Tertiary reservoir rock.
10. How fresh is the water in this thickest pre-Tertiary reservoir rock?
11. How porous is this thickest pre-Tertiary reservoir rock?
12. How permeable is this thickest pre-Tertiary reservoir rock?
13. Total thickness of all pre-Tertiary reservoir rocks.
14. Thickness of the thickest single pre-Tertiary seal rock above the deepest reservoir rocks.
15. Total thickness of all pre-Tertiary seal rocks above the deepest reservoir rocks.
16. Depth to base of deepest reservoir rock in Tertiary sedimentary package below 1 km.
17. How fresh is the water in this deepest reservoir rock in Tertiary package?
18. How porous is this deepest reservoir rock in Tertiary package?
19. How permeable is this deepest reservoir rock in Tertiary package?
20. Thickness of the thickest single Tertiary reservoir rock below 1 km.
21. How fresh is the water in this thickest single Tertiary reservoir?
22. How porous is this thickest single Tertiary reservoir?
23. How permeable is this thickest single Tertiary reservoir?
24. Total thickness of all Tertiary reservoir rocks below 1 km.
25. Thickness of thickest single Tertiary seal rock below 1 km.
26. Total thickness of all Tertiary seal rocks below 1 km.
27. Total thickness of all Tertiary seal rocks below 1 km and above shallowest reservoir rock.
28. Thickness of halite beds below 1 km.

FACTORS THAT CAN NOW BE DERIVED FROM THESE NUMBERS

A. Total thickness of potential reservoir rocks = #13 + #24
B. Total thickness of potential seal rocks above the deepest reservoir rock and below 1 km = #15 + #26
C. Reservoir rock to seal rock ratio = #A/#B, ~ sand/shale ratio

3.2.2 Proximity of Active Faults to Potential CO_2 Sequestration Sites

We use the Quaternary fault database of the USGS (http://qfaults.cr.usgs.gov/) and the database prepared by Craig M. dePolo (NBMG work in progress) for locations of faults (Fig. 6). The former database has been checked by NBMG earthquake experts. There are two broad types of Quaternary faults in the Basin and Range Province in Nevada – strike-slip faults and normal faults. Some faults have moved with oblique slip (a combination of normal and strike slip). Faults commonly have zones of fracturing, which could allow CO_2 to escape. In fact, it is likely that CO_2 would escape along these faults, because many Nevada petroleum seeps and hot springs occur along faults. We therefore exclude from consideration areas that are close to faults. For normal faults, we exclude an area 1.93 km wide on the hanging wall (down-dip side) of the fault. The 1.93 km figure corresponds to the surface projection of a 60-degree dipping fault to a vertical depth of 3 km plus an additional 200 meters into the hanging wall to account for a zone of fault gouge, breccia, and fractures (Fig. 7A). In the GIS analysis, we actually use a 1.93-km zone on both sides, because the footwall is already excluded as bedrock or as areas of alluvial cover less than one kilometer in thickness. For strike-slip faults, we exclude an area 500 meters on either side of the fault (Fig. 7B). We feel that this is a reasonable minimum number, corresponding to the typical 1-km width of breccia and gouge along the San Andreas fault in California but somewhat less than the 2-km-wide zone of fault splays along well mapped strike-slip faults in Nevada. Before any site in Nevada would be used for CO_2 sequestration in saline brines or EOR, the geological framework of the site would need to be investigated in detail to locate the three-dimensional distribution of fault splays, gouge, and breccias.

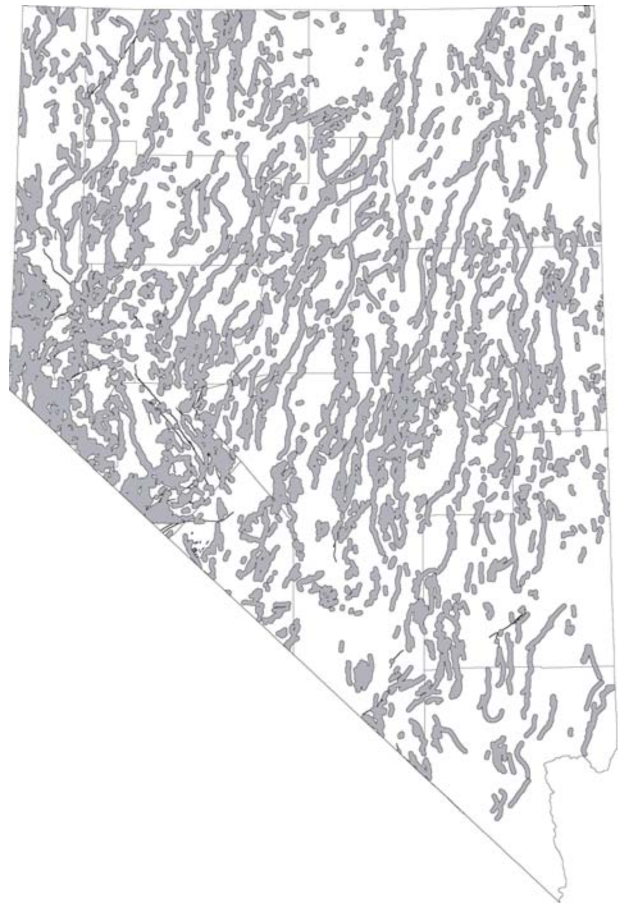

Figure 6. Distribution of Quaternary faults in Nevada with buffered zones next to faults

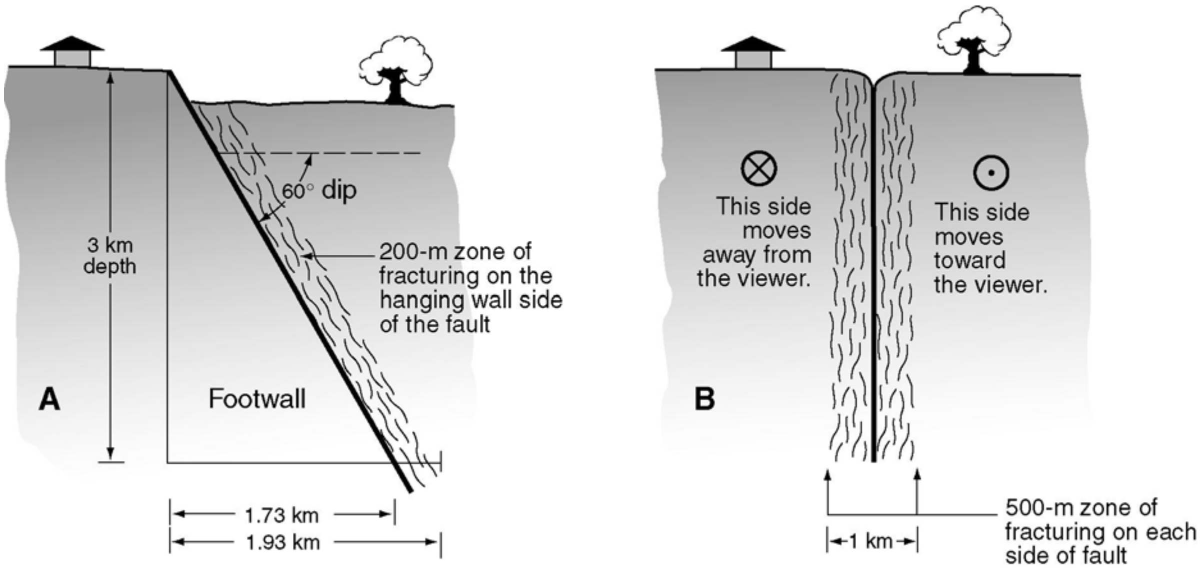

Figure 7. Cross sections of active faults typically found in Nevada. A. Normal fault B. Strike-slip fault.

We use the probabilistic seismic hazard analysis by the USGS to report the expected peak acceleration (expressed as a percentage of the acceleration due to gravity, %g) with 2% probability of exceedance in 50 years (http://eqhazmaps.usgs.gov/html/us2002.html) for the state, including those areas that may be potential CO_2 sequestration sites (Fig. 8). We did not eliminate any areas based on these values of seismic intensity and ground motion. Should sites be chosen, the engineers designing the facility should take into consideration these values and any (deterministic) values based on credible scenarios on nearby faults. Furthermore, should CO_2 pipelines be built across faults in Nevada, care must be taken to design them to accommodate the maximum likely slip resulting from earthquakes on specific faults.

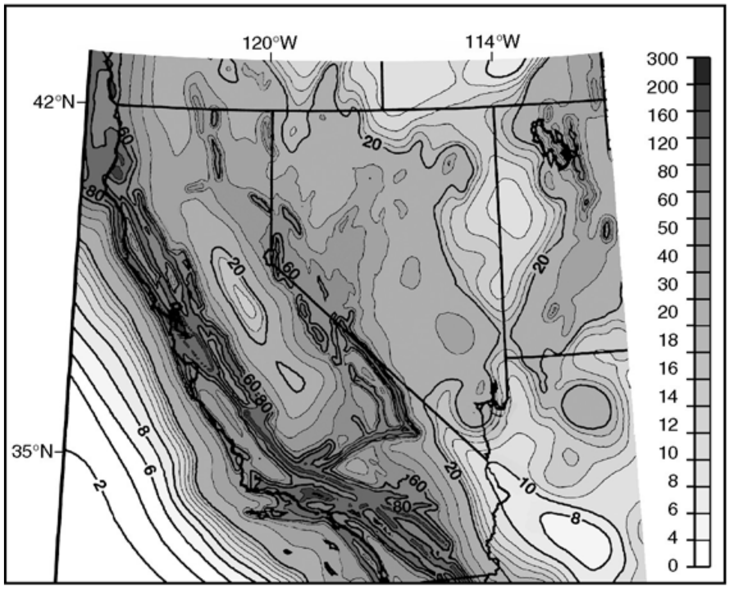

Figure 8. Map showing expected peak acceleration (as percentage of the acceleration due to gravity) with 2% probability of exceedance in 50 years from the USGS probabilistic seismic hazard analysis (http://eqhazmaps.usgs.gov/2002April03/CNU/CNUpga2500v4.gif)

3.2.3 Proximity to Extractable Geological Resources

3.2.3.1 Mineral Resources

Nevada is a major producer of non-fuel mineral resources, generally ranking second or third among the 50 states in recent years in terms of total dollar value of annual production. Nevada production is the reason why we are in the midst of the biggest gold-mining boom in American history (Fig. 9). Gold and silver dominate the mining activity, but many other commodities are currently being mined [barite, copper, magnesite, lithium, the specialty clays, sepiolite and saponite, other clays, construction aggregate (sand, gravel, and crushed stone), lime, diatomite, gypsum, raw materials for cement, silica (industrial sand), dimension stone, semiprecious gemstones, perlite, salt, kalinite (potassium alum), zeolites, and mercury as a by-product of gold and silver processing]. In the past, Nevada has been a major producer of antimony, arsenic, fluorite, iron, lead, manganese, molybdenum, tungsten, and zinc, and resources exist of a number of additional metals, industrial minerals, and uranium. For some of these commodities, Nevada will undoubtedly be a producer again in the future.

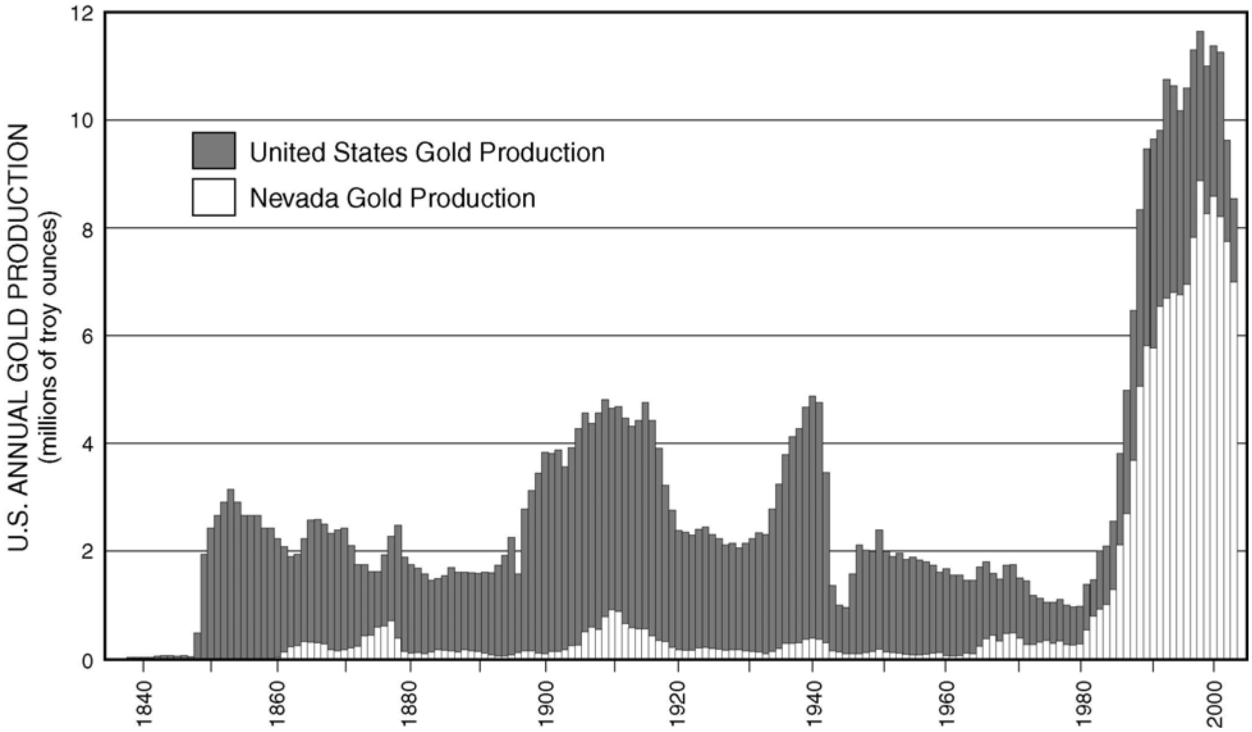

Figure 9. U.S. and Nevada gold production from 1835 through 2004 (Price and Meeuwig, 2005)

Hess (2001) identified over 100,000 point locations of mine shafts, prospect pits, adits, open-pit mines, quarries, sand-and-gravel borrow pits, and other excavations in Nevada (Fig. 10). Although this database was not directly used in the analysis of mineral resources, it illustrates the broad geographic distribution of mineral resources in Nevada.

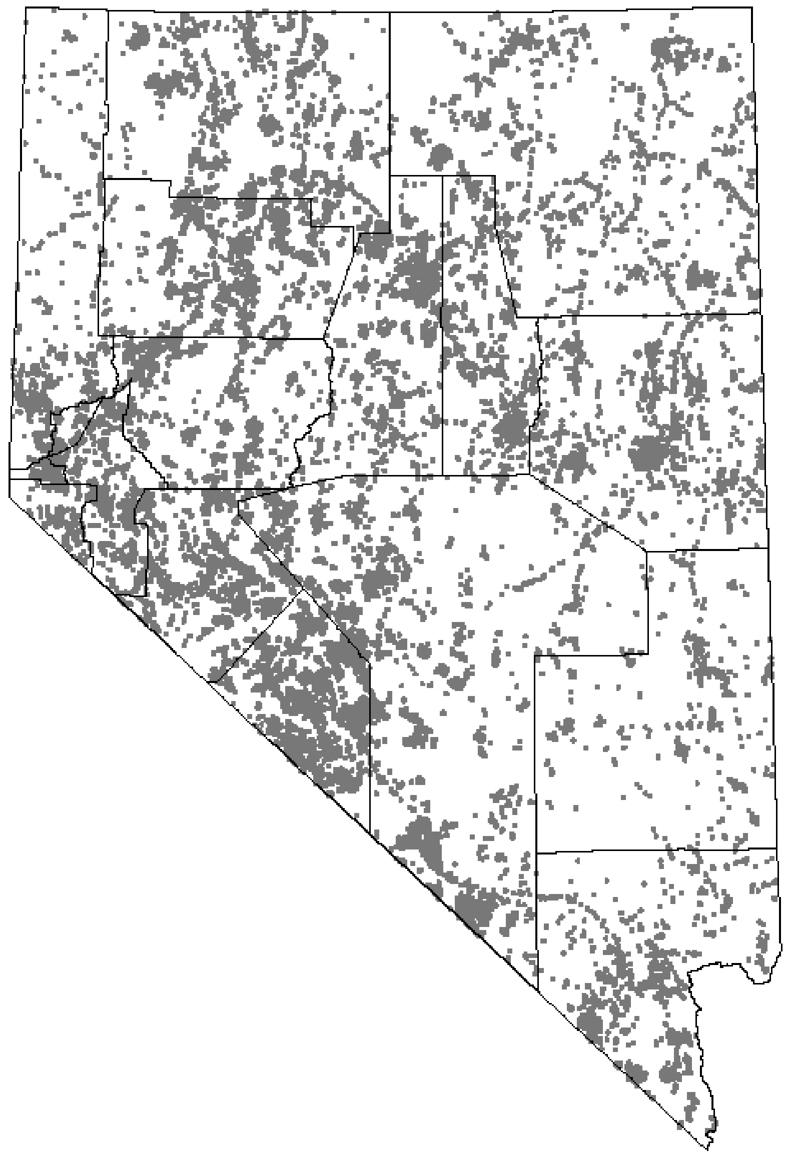

Figure 10. Locations of mine shafts, prospect pits, adits, open-pit mines, quarries, sand-and-gravel borrow pits, and other mineral-resource excavations in Nevada (from Hess, 2001)

We exclude from consideration for potential CO_2 sequestration any areas that are likely to experience mineral production in the future, with the exception of sand and gravel resources, which are mined from shallow (generally less than 100 m deep) quarries and blasting is rarely needed to break the rock. Most of the other mineral commodities are mined from underground workings or large open pits. Deep exploratory drilling, the opening of mine workings themselves, and ground shaking from blasting could adversely affect the integrity of a CO_2 sequestration reservoir.

There are several approaches that could be taken to evaluate areas of potential mineral-resource development. The USGS (Cox and others, 1996a, b, and c) used various geological and GIS approaches to identify tracts of land that they consider permissive for several types of metal deposits, including epithermal deposits (Fig. 11), pluton-related deposits (Fig. 12), and deposit types not directly related to plutonic activity (Fig. 13). When combined, the three USGS maps would eliminate from consideration nearly all of the state (Fig. 14).

Figure 11. Tracts permissive for epithermal deposits (dark areas, Cox and others, 1996b).

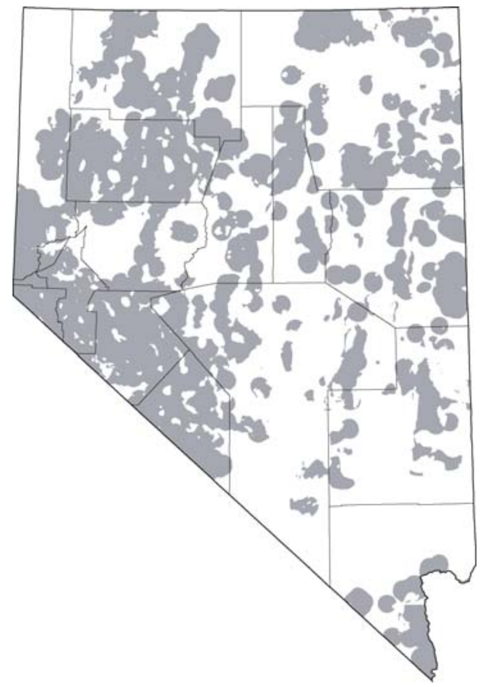

Figure 12. Tracts permissive for pluton-related deposits (dark areas, Cox and others, 1996a).

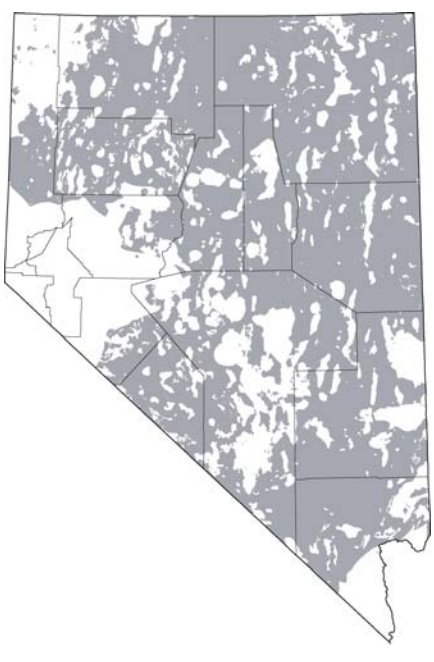

Figure 13. Tracts permissive for deposit types not directly related to plutonic activity (dark areas, Cox and others, 1996c).

Figure 14. Combined tracts permissive for metal-bearing mineral resources (dark areas, derived by combining dark areas from Figs. 11, 12, and 13).

Another approach to evaluating areas of potential mineral-resource development is to use locations of existing mines and prospects. Tingley (1998) outlined mining districts (Fig. 15) using similarities in geological environments and, to a lesser extent, commodities produced. To test how well this map captures known mineral deposits, we compared the mining district outlines with two databases on mineral occurrences in Nevada – (1) the combined Mineral Resource Data System (MRDS) database of the USGS and the Mineral Industry Location System (MILS) database of the former U.S. Bureau of Mines and (2) an NBMG database on gold and silver resources in Nevada (updated from Davis and Tingley, in review). The latter database includes known deposits, mostly with well defined resources, many of which have yet to go into production.

Many MRDS/MILS data points lie outside the mining district outlines (Fig. 16), because these locations often represent single mines for which a district designation was not warranted. Ninety-five percent of the MRDS/MILS data points lie within a buffer of 5 km around the mining district outlines; 99% are within a 12-km buffer; and 100% are within 42 km of the mining district outlines. Most, but not all, of the locations from the NBMG database on gold and silver resources in Nevada fall within the outlines of the mining districts (Fig. 17).

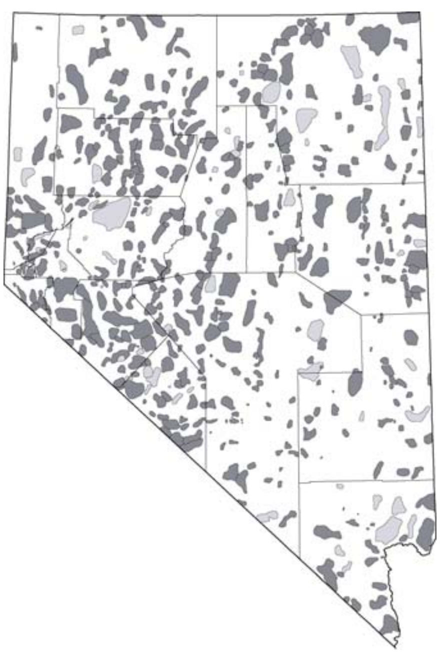

Figure 15. Locations of mining districts (Tingley 1998). Metal-mining districts are shown with dark shading; districts that produced only industrial minerals are shown with light shading.

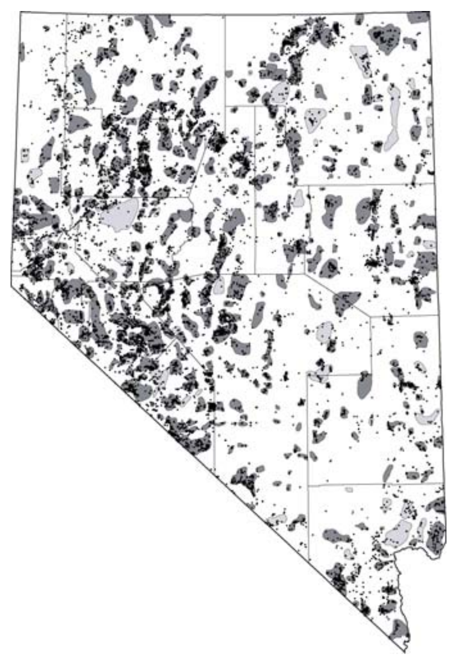

Figure 16. Locations of points (individual mines) in the combined MRDS/MILS database (Source: USGS and U.S. Bureau Mines) superimposed on the outlines of mining districts (Fig. 15).

We compared the MRDS/MILS data points with the NBMG database. With few exceptions, the bulk of the deposits in the NBMG database fall within 5 km of a MRDS/MILS location (Fig. 18). A combination of these maps provides us with our best estimate of the areas likely to experience mineral-resource development; these are areas to be excluded from consideration for CO_2 disposal (Fig. 19). We chose to include features from three databases:

(1) a 5-km buffer around the MRDS/MILS locations,
(2) a 5-km buffer around the NBMG database of known gold and silver resources, and
(3) outlines of mining districts.

We chose not to add a buffer around the mining districts because the 5-km buffer around the other locations largely covers those outlines and because many of the outlines for industrial minerals reasonably cover the area that is likely to experience production.

Figure 17. Locations of points (individual gold and silver deposits) in the NBMG database on gold and silver resources superimposed on the outlines of mining districts (Fig. 15).

Figure 18. Locations of points (individual gold and silver deposits) in the NBMG database on gold and silver resources superimposed on the 5-km buffers around locations (individual mines) in the combined MRDS/MILS database.

Although we can use this approach to predict the most likely areas for metallic mineral-resource exploration, it is not possible to predict where everyone may choose to explore in the future. As an example, the Carlin trend, a belt of gold deposits in north-central Nevada, which accounts for 12% of all the gold ever mined in the United States and a bit more than 1% of all the gold ever mined in the world (Price and Meeuwig, 2005), had little activity before the discovery of the Carlin deposit in 1961. Since then, many Carlin-type gold deposits have been discovered along the Carlin trend and the subparallel Battle Mountain-Eureka trend, areas which before 1961 would have been beyond the 5-km buffers of known deposits.

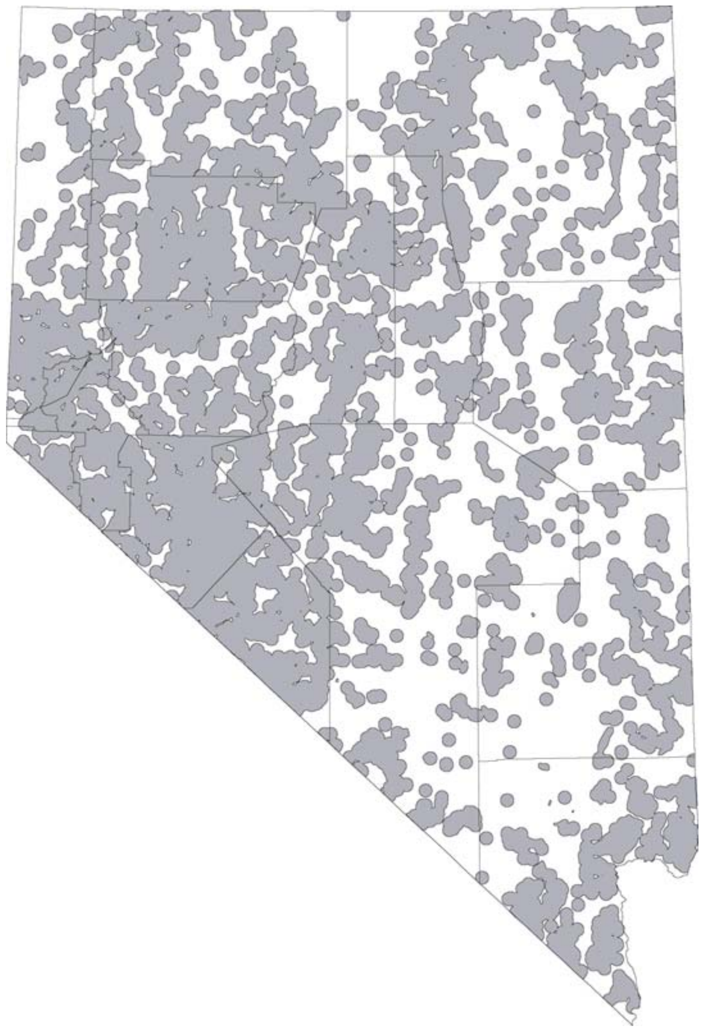

Figure 19. Areas likely to experience mineral-resource development, with the exception of sand and gravel in Nevada (dark areas). This map combines a 5-km buffer around the MRDS/MILS locations with a 5-km buffer around the NBMG database of known gold and silver resources, and outlines of mining districts. Note that a broader area is indicated by the USGS in their analysis of tracts permissive for metal-bearing mineral resources (Fig. 14).

3.2.3.2 Petroleum and the Potential for CO_2 Sequestration through Enhanced Oil Recovery

Significant production of oil in Nevada has come only from Railroad and Pine Valleys (Fig. 20). There is, however, considerable excitement about the potential for oil and gas discovery in deep zones below thrust faults. We do not attempt to eliminate any areas of potential oil and gas discovery from consideration for CO_2 sequestration (unless those areas are eliminated for other reasons), because such areas may be ideal for use of CO_2 in enhanced oil recovery. Before any enhanced oil recovery using CO_2 would be undertaken, however, care must be taken to ensure that the reservoirs would not leak beyond the limits required for effective long-term sequestration. We suspect that the reservoirs would, in general, be leaky, because the active extensional tectonic environment in Nevada has probably limited natural gas accumulations.

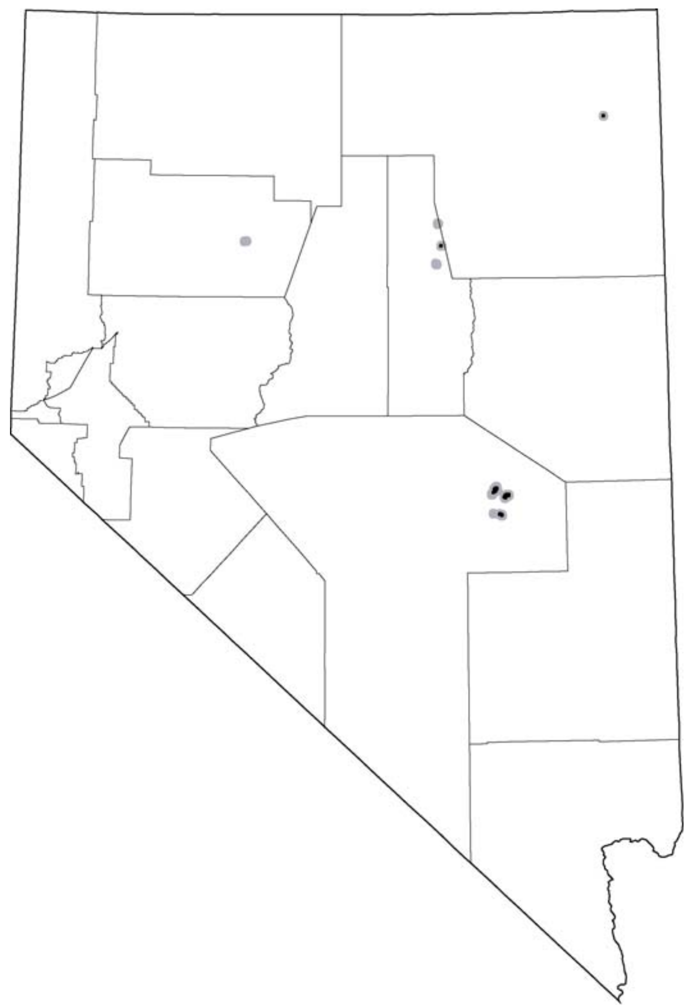

Figure 20. Gray shading indicates areas of reported oil production in Nevada. Black dots indicate oil production wells with greater than 1 km of Quaternary-Tertiary valley fill.

There is some potential for use of CO_2 in enhanced oil recovery in Nevada, but the ability for the Nevada oil reservoirs to trap and retain the CO_2 is questionable. Some of the oil fields are hot, and the amount of CO_2 sequestered would therefore be less than in an equal volume of reservoir rock at the same depth in a cooler area (Fig. 4). The fields are also small, relative to many fields in the United States. Only two Nevada fields have produced over 10 million barrels, and cumulative production from all 15 fields is only 48 million barrels (Davis, 2004). To put this in perspective, one gigaton of CO_2 at a density of 0.75 g/cm^3 would occupy a volume of 8.5 billion barrels. That is, much larger oil fields than those discovered thus far in Nevada will be needed for significant CO_2 sequestration. Some of the fields (particularly in Pine Valley) are shallower than the minimum depth of 800 m for liquid or supercritical CO_2. The potential for CO_2 sequestration through enhanced oil recovery in Nevada is also likely to be further limited because of leakage. These oil fields tend not to have much associated natural gas, implying that gas that was probably associated with the fields has largely escaped. We do know that gas was associated with these oil fields, because small amounts of gas have been reported in some of the fields, and one well in Huntington Valley (Jiggs No. 10-1 of Wexpro Co.) discovered significant quantities of gas but was too far from market to be economic. Injected CO_2 would likely leak to the surface as well, although the time scale for such leakage is not known. The timing of oil and gas generation in Nevada is not well known, and it almost assuredly occurred at different times at different places, given the repeated history of thrusting and intrusion (Table 2). The fact that some source rocks near the producing oil fields in Nevada are immature and the hot temperatures of some of the fields imply that oil and gas may be generated today, in which case leakage of natural gas has likely been fairly rapid.

In addition, the larger fields in Railroad Valley, one of which (the Kate Spring Field) does have a small amount of natural gas (Davis, 2004), are distant from any natural gas pipelines and major industrial sources of CO_2. A relatively close source could arise in the future, however, if the 1,600-megawatt coal-fired power plant proposed in White Pine County (Public Utilities Commission of Nevada, 2005) comes on line as expected by 2010 or shortly thereafter.

3.2.3.3 Geothermal Resources

Nevada is a significant producer of electrical energy from geothermal resources (worth on the order of $100 million per year; Hess, 2004b). Geothermal resources are also used in Nevada for space heating and other industrial purposes, notably for drying garlic and onions. Hot springs and wells (with water warmer than 37°C) and warm springs (with water warmer than 20°C and 10°C above the average annual surface temperature) occur throughout the state (Shevenell and Garside, 2005), but most of the commercial geothermal developments have been in the northern part of the state (Fig. 1). Known geothermal areas are likely to be problematic for CO_2 sequestration because densities of the supercritical CO_2 will be lower than is optimal for economical sequestration (Fig. 4).

The Great Basin Center for Geothermal Energy at the University of Nevada, Reno has analyzed the potential for geothermal development in Nevada, largely using regional heat flow and state of stress as deduced from geodetic observations (Fig. 21, Coolbaugh and others, 2005, in press). Primarily using locations of known hot and warm springs and wells, Trexler and others (1983) outlined broad areas in Nevada as having potential for geothermal resource development (Fig. 22a). Blackwell and Richards (2004a and 2004b) used a combination of data from bottom-hole temperatures and heat-flow measurements of various petroleum and geothermal exploration wells to estimate temperatures at 4 km below the surface. As an additional comparison, areas with temperatures greater than 150°C at 4 km are considered by Blackwell and Richards (2004b) to have the most potential (Fig. 22b).

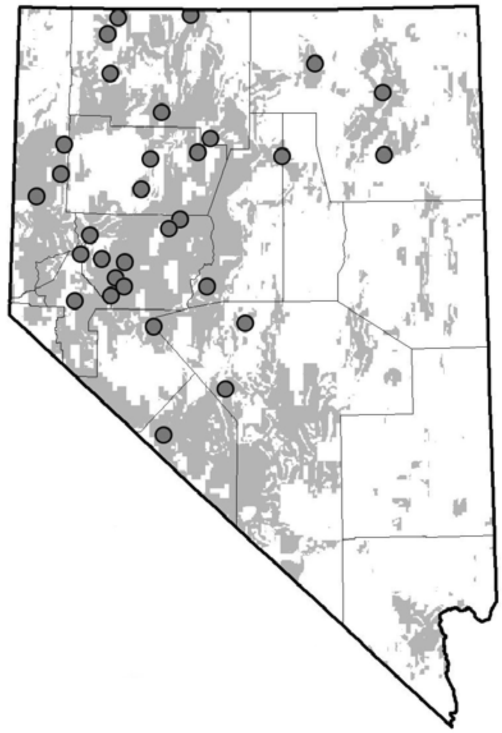

Figure 21. Simplified geothermal potential map of Nevada, adapted from Coolbaugh and others (in press). Gray areas have a higher than average probability of hosting high-temperature (greater than or equal to 150°C) geothermal resources compared to the rest of the Great Basin. Circles are known geothermal systems with estimated reservoir temperatures greater than or equal to 150°C.

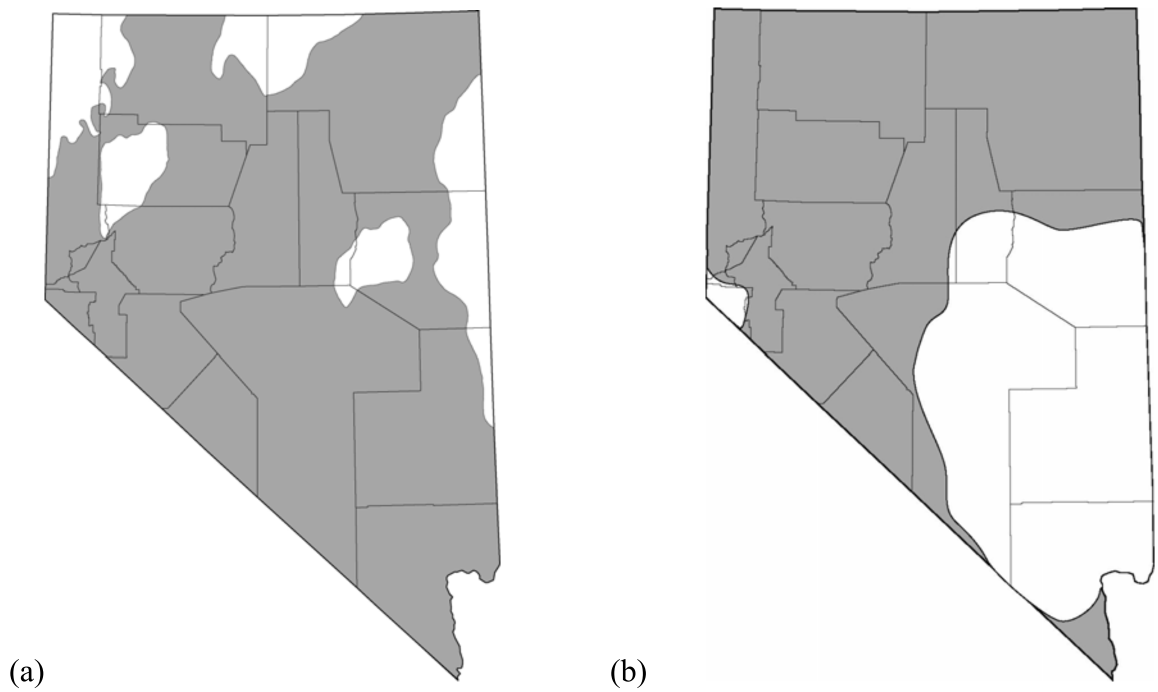

Figure 22. (a) Areas of potential for geothermal development (gray) according to Trexler and others (1983). (b) Areas of potential for geothermal development (gray) according to Blackwell and Richards (2004b), using their areas with temperatures in excess of 150°C at 4 km depth.

In comparing the locations of known geothermal anomalies (hot and warm springs, hot and warm wells, and holes with measured moderate and high heat flow from Shevenell and Garside (2005) with Figures 21 and 22, we note that a buffer of 20 km from these geothermal anomalies includes nearly all the high and moderate potential areas shown on Figures 21 and 22a. We have therefore chosen a buffer of 20 km from these known geothermal anomalies for the areas to exclude from consideration for CO_2 sequestration on the basis of potential geothermal resources (Fig. 23). Although a more sophisticated approach may have been to elongate the buffer zones along faults that control the geothermal systems, we know too little about the controlling faults to do this throughout the state (Faulds and others, 2004).

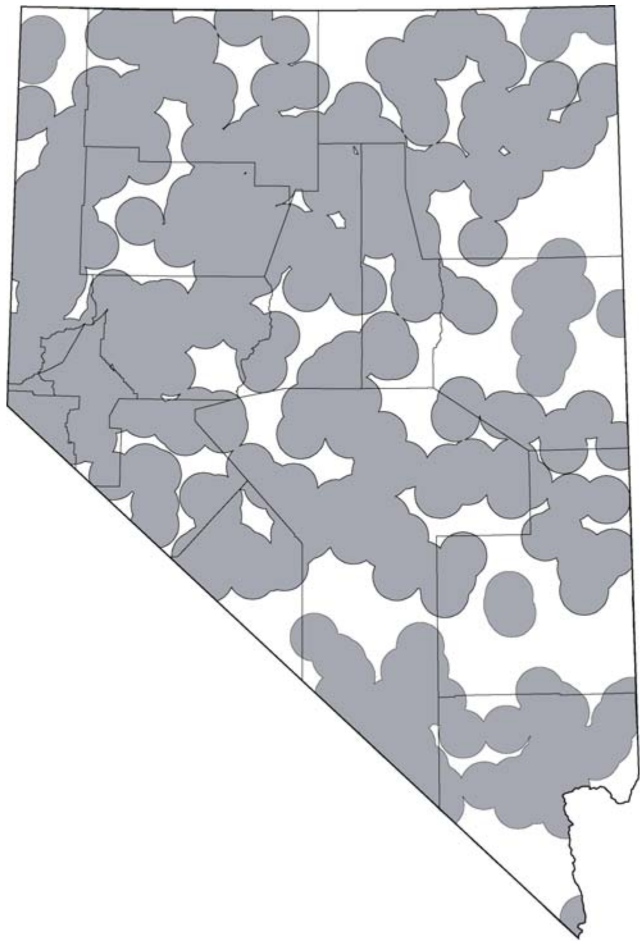

Figure 23. Areas excluded from consideration for CO_2 sequestration on the basis of potential geothermal resources. This map uses a buffer of 20 km from the locations of known hot and warm springs, hot and warm wells, and moderate to high heat flow wells shown on NBMG Map 141 (Shevenell and Garside, 2005).

3.2.3.4 Water

Nevada is the driest state in the nation in terms of average annual precipitation. Water is a precious resource for many reasons—industrial and urban sustainability and growth, ecological health, agriculture, recreation, and other cultural values. Sustaining adequate water resources is vital for Nevada's future. One of the principal aquifers in the state is the Deep Carbonate Aquifer of eastern Nevada (Thomas and others, 1986; Fig. 24). It is broadly defined to include the entire package of Paleozoic carbonate rocks stretching from the northeastern part of the state south-southwestward into California, with a general drop in the elevation of the potentiometric surface in that direction. The aquifer is recharged primarily through rain and snowmelt in the high mountains. The carbonate rocks underlie many of the valleys as well. For example, the water co-produced with petroleum in carbonate rocks in Railroad Valley is dominantly fresh water and is considered a resource for future use. This aquifer feeds important springs and wetlands in the region. We eliminate areas potentially underlain by the Deep Carbonate Aquifer from consideration for CO_2 sequestration.

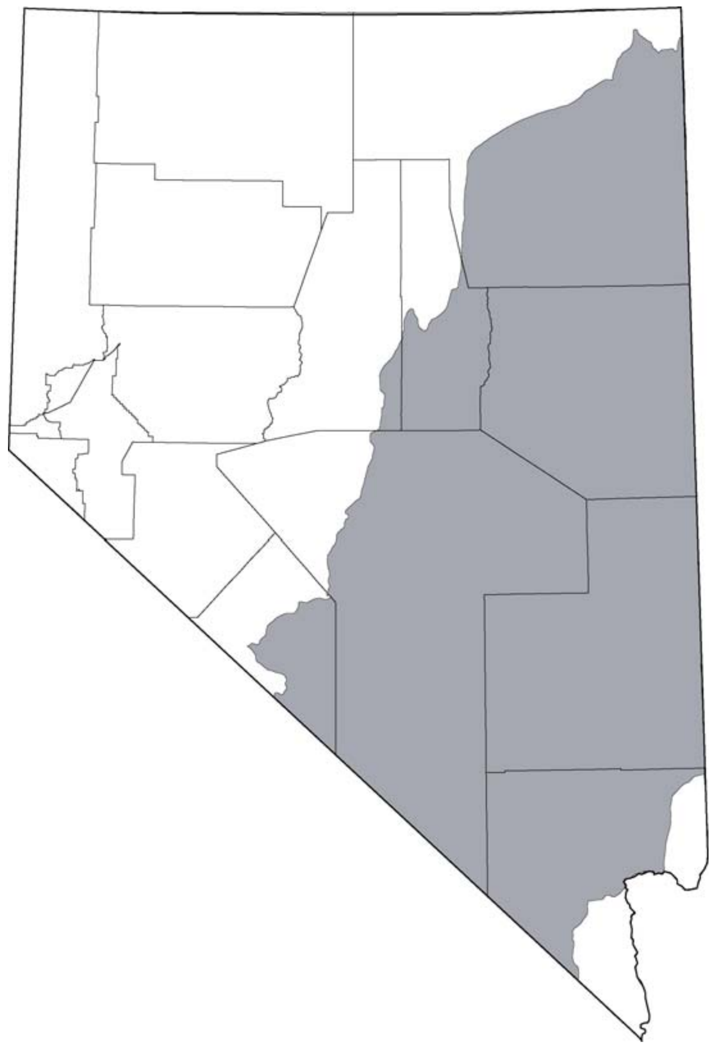

Figure 24. Distribution of the Deep Carbonate Aquifer, the principal deep aquifer in eastern and southern Nevada

By eliminating all areas potentially underlain by the Deep Carbonate Aquifer, we are also eliminating the possibility of using deep (> 1 km) saline aquifers that may occur above the Deep Carbonate Aquifer in the Tertiary basins of eastern and southern Nevada. We anticipate that such situations are rare, because the Deep Carbonate Aquifer, itself recharged by rain and snowmelt high in the mountains, tends to recharge the overlying Tertiary aquifers, as in Las Vegas Valley. There are two major reasons for eliminating these areas: (1) drilling through any deep saline aquifers in search of potable water in the Deep Carbonate Aquifer could hinder the integrity of a CO_2 sequestration site; and (2) depending on the density of the brine-CO_2 fluid and the relative heads of the brine and the deeper aquifer, the brine could sink into and contaminate the Deep Carbonate Aquifer.

There are other areas of significant potable groundwater resources outside the Deep Carbonate Aquifer. For example, some large gold-mining operations in northern Nevada pump substantial quantities (tens to hundreds of thousands of liters per minute) of high-quality water from alluvial and bedrock aquifers. Before any project to dispose of CO_2 in saline aquifers were to be undertaken, the local hydrogeology would need to be investigated in detail to understand impacts on useable water resources.

3.2.4 Proximity to Urban Areas and Areas of Future Urban Growth

We do not feel that it would be wise to build a CO_2 sequestration facility near urban areas. We have therefore eliminated from consideration areas that are currently densely populated or may be developed during the 21st century (Fig. 25). We eliminate from consideration a 30-km buffer around current urban areas (as mapped from 2000 data of the U.S. Census Bureau), a 10-km buffer around current towns not classified as urban areas, and a 10-km buffer along major highways connecting urban areas (specifically, U.S. Highway 395, I-15, I-80, U.S. Highway 50 from Lake Tahoe to Fallon, U.S. Highway 95 from Indian Springs to Laughlin, U.S. Highway 93 from Apex to Hoover Dam, and Nevada Route 160, which goes through Pahrump). These buffers are reasonable given the remarkable urban growth in Nevada during the 20th century. For example, Las Vegas was not an urban area at the beginning of the 20th century, but by the beginning of the 21st century, nearly the entire 20x30-km valley had been converted to urban and suburban development.

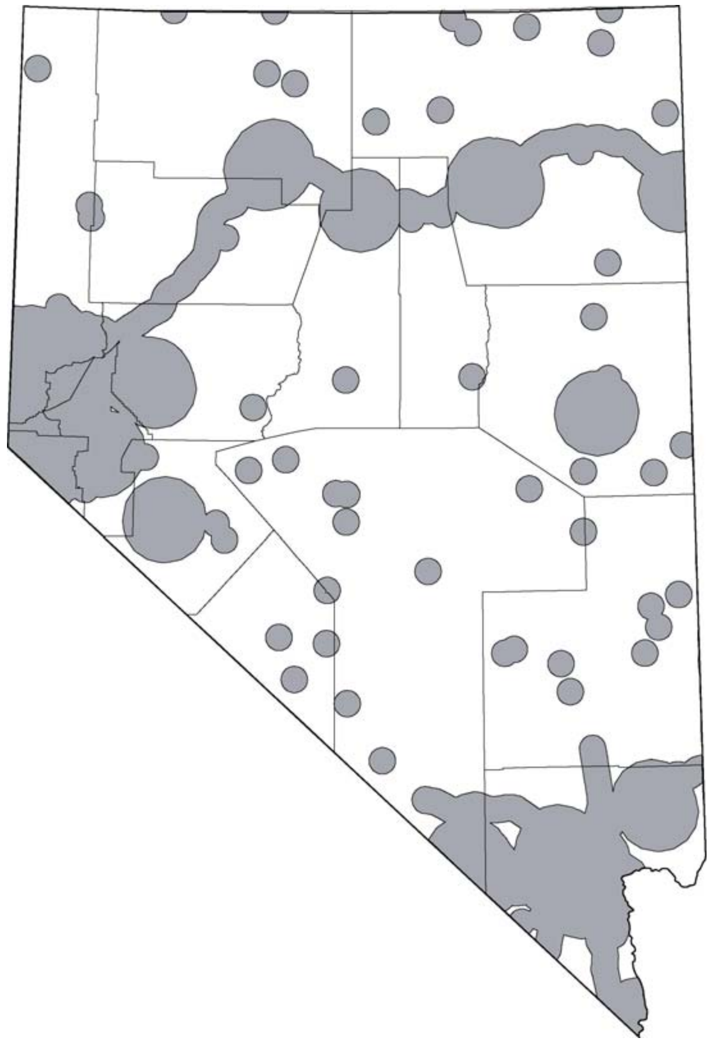

Figure 25. Areas of current high population density and areas likely to be developed during the 21st century. The gray areas include a 30-km buffer around major current population centers and a 10-km buffer around highways along which significant development has been taking place.

3.2.5 Restricted Lands

Approximately 86% of Nevada is managed by the federal government, largely by the Bureau of Land Management (BLM), the U.S. Forest Service, the National Park Service, the Department of Defense, and the Department of Energy. Nevada contains many areas in which a CO_2 sequestration facility could not be permitted, in part because of the difficulty of building a pipeline into the facility. These include National, Regional, and State Parks; National Recreation Areas; Wilderness Areas (but not Wilderness Study Areas); Military Reservations; and the Nevada Test Site. These areas have been eliminated from consideration (Fig. 26), because it is unlikely that permission for building a CO_2 sequestration facility would be granted by the controlling agencies. We did not consider the possibility of directional drilling into these restricted lands, nor did we consider the possibility that Congress could act to allow CO_2

sequestration in these areas as a general benefit to the public. Permission might be granted in some other reserved lands, such as BLM Areas of Critical Environmental Concern, National Conservation Areas, Indian Reservations, and National Wildlife Refuges. Should further consideration be given to specific areas, care should be taken to avoid areas that may be converted to a restricted status.

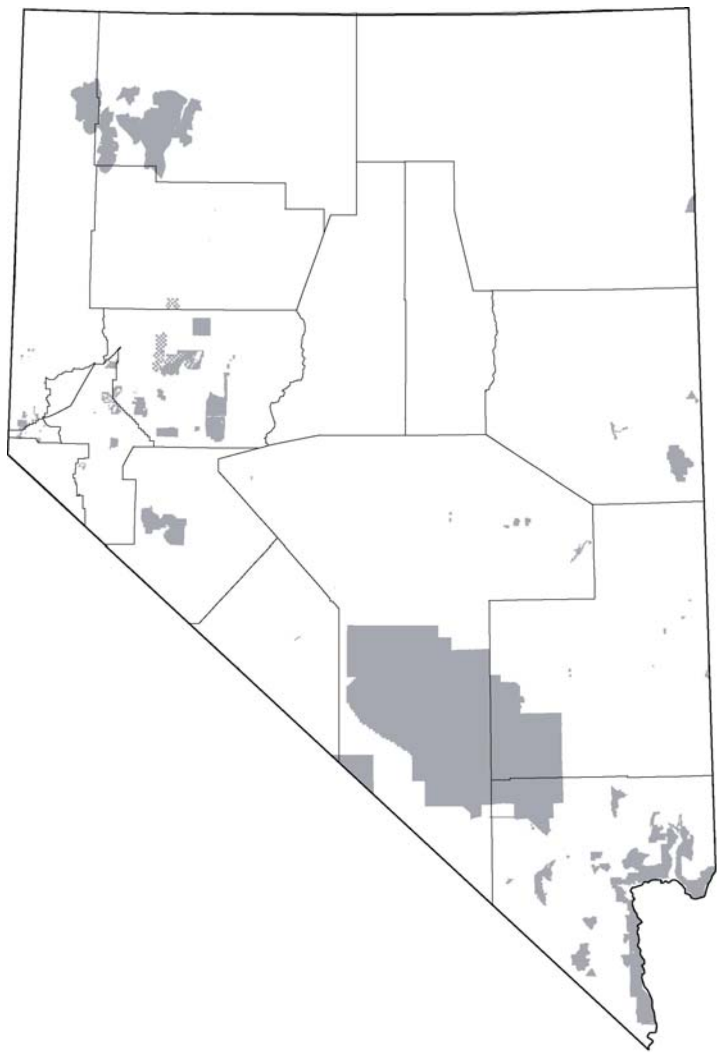

Figure 26. National, Regional, and State Parks, National Recreation Areas, Wilderness Areas, Military Reservations, and the Nevada Test Site

3.2.6 Other Data Considered

3.2.6.1 CO_2 Generators

Ideally, a sequestration site will be located close to the site of CO_2 generation. The largest generators of CO_2 are generally power plants, refineries, and lime and cement plants (Fig. 27). In Nevada, large coal-fired power plants are located near Battle Mountain (Valmy plant, Humboldt

County), Laughlin (Mohave plant, Clark County), and Moapa (Reid Gardner plant, Clark County). New coal-fired power plants have been proposed in the Gerlach area in northern Washoe County in the northwestern part of the state (Sempra Energy's Granite Fox project), in White Pine County in the eastern part of the state (White Pine Energy Associates), and in Boulder Valley in Eureka County in the northern part of the state (Newmont Mining Company), and Sierra Pacific Power has proposed expanding the Valmy operation.

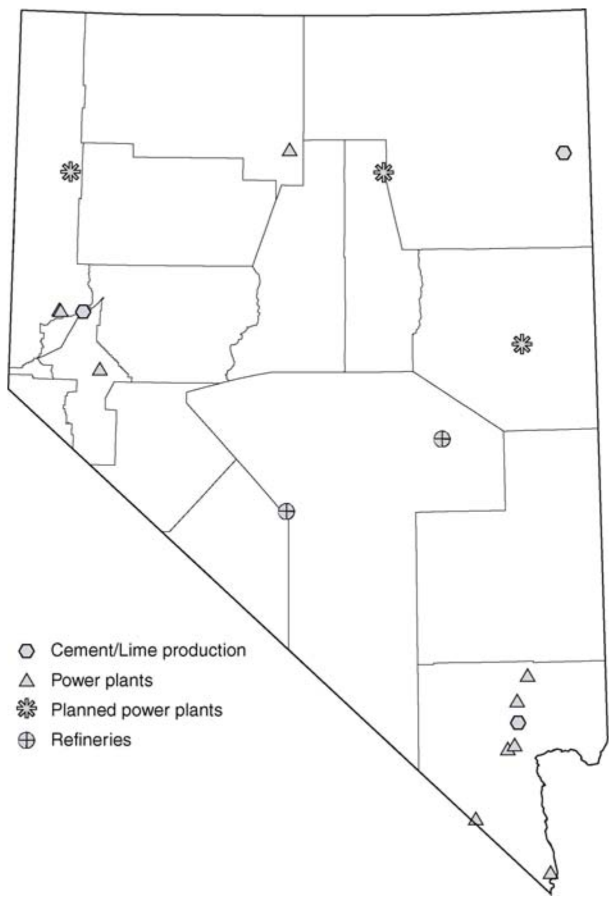

Figure 27. Location of major generators of CO_2 in Nevada [coal- and natural gas-fired power plants (triangles); proposed coal-fired power plants (stars); cement and lime plants (hexagons); and refineries (circles with crosses)]

Nevada also has several natural gas-fired (and oil-fired) power plants; among the largest are the Clark Station in Las Vegas Valley in Clark County, the Fort Churchill plant in Lyon County, the El Dorado plant southwest of Boulder City in Clark County, and the Tracy plant near Reno-Sparks in Washoe County. Additional gas-fired plants came into service in 2003 and 2004 at Apex, North Las Vegas, and Primm in Clark County, and others have been proposed to the Public Utilities Commission of Nevada (http://www.puc.state.nv.us/) to meet the demands of the region's increasing population. Natural gas is also burned in the production of wallboard from gypsum in Clark and Washoe Counties.

The only significant, albeit small, oil refinery in Nevada is in Railroad Valley. Much of Nevada's petroleum is trucked or railed to the Salt Lake City area for refining. A small refinery near Tonopah in Nye County is no longer in operation.

The only major operating cement plant in Nevada (with production over 500,000 short tons per year) is at Fernley in Lyon County. Another plant near Logandale in Clark County produced intermittently in recent years, and development is underway to start a new plant near Interstate 80 in Pershing County (Castor, 2004). Major lime plants operate in the Toano Range near West Wendover in Elko County, and at Apex, near Las Vegas in Clark County. Small amounts of lime are also produced at a plant in Henderson near Las Vegas (Castor, 2004). The major existing CO_2-generating facilities are located on Figure 27.

3.2.6.2 Transportation Infrastructure

Constructing a CO_2 pipeline would be facilitated if it follows current pipelines and transportation routes, along which rights of way may be easier to obtain than in remote areas. Figure 28 has locations of current major gas and petroleum-product (gasoline, jet fuel, diesel fuel) pipelines, electrical transmission lines, highways, and railroads. Major storage facilities for petroleum products in Nevada are currently in and near urban areas and on military bases.

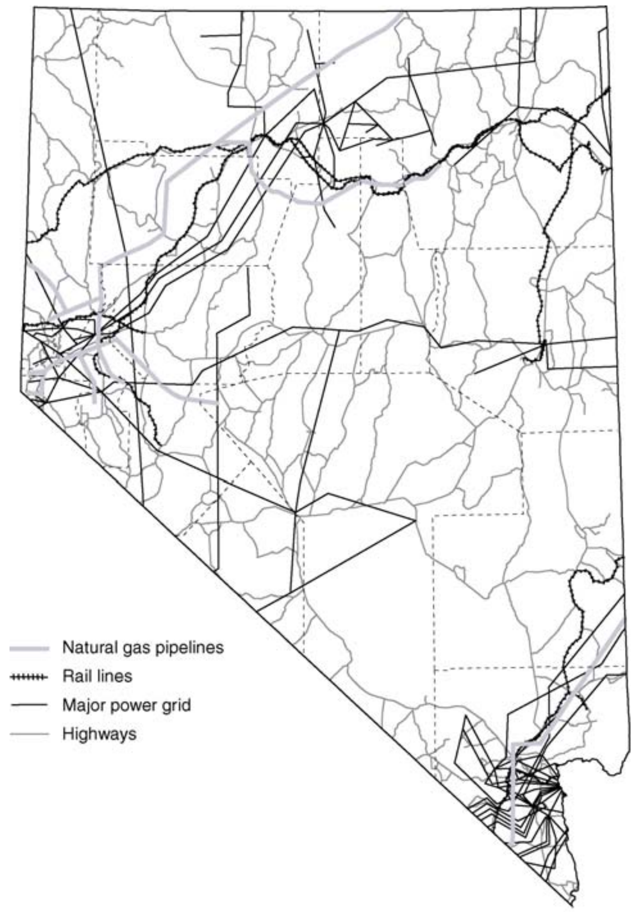

Figure 28. Major pipelines for petroleum products and natural gas, electrical transmission lines, highways, and railroads

4 Results and Discussion

The binary (yes-no) approach of GIS analysis used in this report (Appendix) to assess the potential for CO_2 disposal in saline aquifers boils down to the following key assumptions or criteria: (1) avoid underground disposal in areas of fractured bedrock and restrict the assessment to parts of alluvial basins that are thick enough to provide a seal against leakage and have enough pressure to keep the CO_2 in a condensed phase; (2) stay away from active faults whose fracture zones may allow leakage of CO_2 from underground injection sites; (3) avoid areas that in the foreseeable future have a reasonably high probability of being explored and developed for mineral, geothermal, and water resources; (4) avoid current urban areas and areas that are likely to experience significant population growth during the 21st century; and (5) avoid restricted lands, such as parks and military reservations. After combining the relevant GIS data sets, a few areas that meet all the criteria remain (Fig. 29).

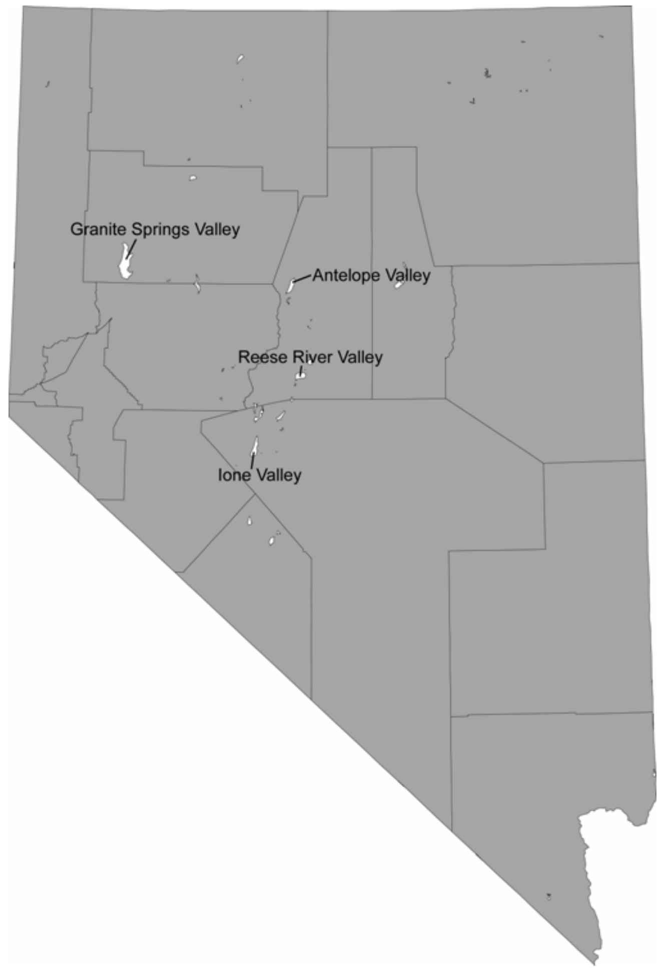

Figure 29. Areas that have the potential for CO_2 waste disposal through geological sequestration in possibly saline aquifers in Nevada. This map is a combination of maps in Figures 3 (eliminating areas in which consolidated rocks of Tertiary age and older crop out), 5 (eliminating areas with less than 1 km of valley fill), 6 (eliminating areas close to Quaternary faults), 19 (eliminating areas likely to experience mineral-resource development), 23 (eliminating areas that are likely to be developed for geothermal resources), 24 (eliminating areas potentially underlain by the Deep Carbonate Aquifer), Population (eliminating current and likely future urban areas), and 26 (eliminating areas in which permission is not likely to be granted).

The valleys with the largest areas of potential for CO_2 sequestration by injection into saline aquifers are Granite Springs Valley in Pershing County, Antelope and Reese River Valleys in Lander County, and Ione Valley in Nye County. Each contains 30 km^2 or more area. The NBMG has no records of deep (>1,000 m) wells in any of these areas. The type of information listed in Table 3 would be needed to more fully evaluate the potential for CO_2 sequestration in these areas. In particular, information is needed on the porosity, permeability, thickness, and salinity of deep aquifers in these areas. Although no data are available in the immediate areas shown to be potentially favorable for CO_2 sequestration on Figure 29, we can hypothesize the existence of favorable aquifers on the basis of nearby wells and the expectation that most deep alluvial basins will contain some permeable sandy aquifers and clay-rich seals.

A further complication is that some of the areas shown as thick basins are likely filled with thick accumulations of Tertiary volcanic rocks rather than mostly sediments. Because the differences in density between sediments and volcanic rocks, particularly tuffs, is small, the zones shown on Figure 5, interpreted from gravity data, actually show combined thickness of basin-filling sediments and volcanic rocks. For example, the upper part of a well near the thickest part of Antelope Valley (Arco Exploration's Antelope Valley No. 1 well, a wildcat drilled in late 1984 and early 1985 in Lander County) contains basin-filling sands, gravels, silt, and clay, but from 212 to 890 m, the well penetrated mostly tuff and clay-rich tuffaceous sediments. All four areas with 30 km^2 or greater area in Figure 29 are likely to contain significant accumulations of Tertiary volcanic rocks; that is, the basin-filling sediments may not be as thick as desired.

The total area identified with potential for CO_2 disposal in Figure 29 is 524 km^2. If further investigation indicated that thick, permeable sandstones with saline water do indeed exist in these areas, it is possible that significant amounts of CO_2 could be sequestered. Assuming a porosity of 10% in the subsurface sandstone formation, 1 gigaton of CO_2 at a density of 0.75 g/cm^3 would require a volume of 13.3 km^3. Assuming the sandstone thickness to be 100 m, this would require a surface area of 133 km^2. One gigaton of CO_2 is a reasonable expectation for a full-scale CO_2 sequestration project associated with a large power plant. A 2,000+-megawatt plant that burned 5 million metric tons of carbon per year for 50 years would produce 0.9 gigaton of CO_2. Clearly, more data would be needed on the subsurface geology in these areas remaining after the GIS analysis before proceeding with a CO_2 sequestration project.

The largest of the areas identified with potential for CO_2 sequestration in Figure 29 is Granite Springs Valley. Although little is known about the subsurface geology in this valley, based on regional comparisons, it is possible that the area has potential for geothermal development, and the subsurface temperatures may be too high for cost-effective sequestration. Richards and Blackwell (2002a) rated the Trinity Mountains, immediately east of Granite Springs Valley, as one of the top 15 areas for geothermal development in Nevada, based in part on estimated heat loss (Richards and Blackwell, 2002b). Should further investigation of Granite Springs Valley be warranted, particular care should be taken to evaluate its geothermal potential.

5 Alternative Approaches to CO_2 Sequestration in Geological Settings

Although enhanced oil recovery and deep disposal in non-potable aquifers are two proven technologies for CO_2 sequestration, opportunities for these approaches appear to be limited in Nevada. There are, however, alternative approaches. We explore two such alternatives here. Storage of CO_2 in mined caverns in salt formations would take advantage of existing technologies for storage of natural gas in these formations. Chemical reaction with mafic and ultramafic rocks is an unproven technology that has much promise for long-term, permanent disposal of CO_2 without the leakage concerns associated with underground injection.

5.1 Storage in Mined Caverns in Salt Formations

One possible approach to CO_2 sequestration is to develop repositories in thick salt deposits. Caverns within salt are excavated through dissolution of salt with fresh water (i.e. solution mining). This process produces significant quantities of brine, which can be reinjected into saline aquifers proximal to the salt deposit. In some cases, solution mining is used to produce industrial salt. For example, Morton Salt operates a solution mine in thick salt deposits near Phoenix, Arizona (Rauzi, 2002). Volatile materials, such as liquefied petroleum gas (LPG), have been safely stored in salt-solution caverns in many parts of the country. Two LPG facilities presently exist in Arizona and several others are currently or have recently been under investigation (e.g., Federal Energy Regulatory Commission, 1982).

The Basin and Range province hosts several unusually thick Cenozoic salt deposits, including some of the thickest in the world (Fig. 30; Peirce, 1976; Faulds and others, 1997). Most of the salt resides in Cenozoic basins produced by basin-and-range extension. Halite deposits are particularly thick in some of these basins and may have significant economic potential for storage of natural gas (Rauzi, 2002).

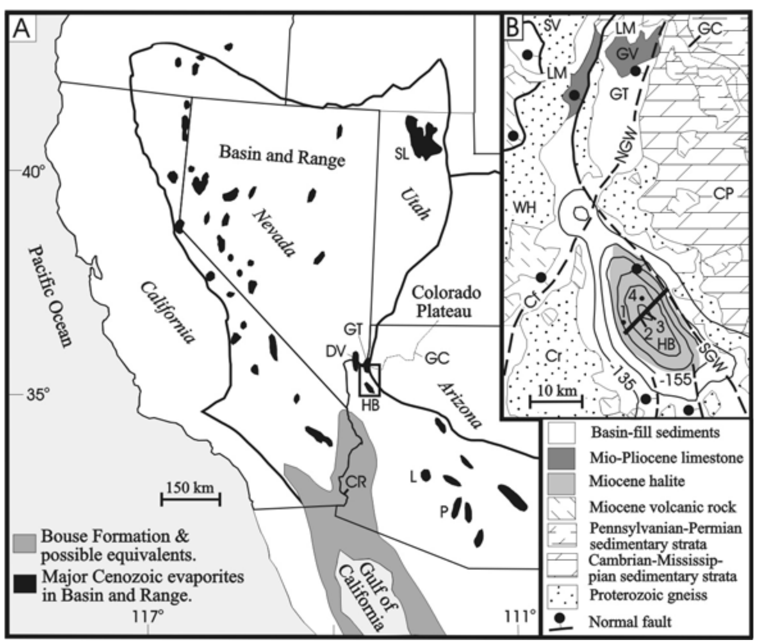

Figure 30. (a) Major Cenozoic evaporite deposits in the Basin and Range (from Faulds and others, 1997). (b) Generalized geologic map of the Hualapai basin area showing Bouguer gravity contours (10 mgal intervals; from Davis and Conradi 1981) and location of drill holes and cross section (Fig. 31). Cf, Cerbat Range fault; CP; Colorado Plateau; Cr, Cerbat Range; CR, Colorado River; DV, Detrital and southern part of Virgin River depression; GC, Grand Canyon; GT, Grand Wash trough; GV, Grapevine Mesa; HB, Hualapai basin; L, Luke basin; LM, Lake Mead; NGW, northern Grand Wash fault; P, Picacho basin; SGW, southern Grand Wash fault; SL, Great Salt Lake; SV, South Virgin Mountains; WH, White Hills.

The basins containing the thick salt deposits owe their origin to a relatively complex history of tectonism and drainage evolution. Large-magnitude crustal extension in middle Tertiary time gave way to more widely distributed east-westerly extension and block faulting in the late Miocene (typically ~10 Ma in much of the province). Localized deep basins developed in the hanging walls of steeply dipping northerly striking normal faults. Basin-and-range block faulting that accompanied deposition of post mid-Miocene basin fill locally produced steep basin margins and prominent escarpments (Dickinson, 1991), which served to accentuate development of some regional depressions or sinks. In the western Great Basin, northwest-striking right-lateral faults contributed to development of some basins.

By late Miocene time, a reduction in extensional strain rates promoted widespread aggradation (building up) of sediments within composite basins. Basin-fill sedimentation ultimately buried a rugged mid-Tertiary paleogeography of corrugated tilt blocks (Dickinson, 1991). Facies patterns in late Tertiary basin fill are congruent with modern topography and reflect construction of alluvial fans derived from flanking ranges. The alluvial fans interfinger with and give way to floodplain, lacustrine, and continental playa environments toward the basin floors.

Reduced strain rates and regional aggradation in late Tertiary time facilitated the evolution of regional drainage systems that ultimately integrated large networks of basins. In eastern parts of the Basin and Range, major drainages emanated from the relative highlands of the Colorado Plateau, and vast quantities of fresh water began flowing into regional sinks in late Tertiary time. Many basins also became regional sinks for groundwater flow systems. Prior to development of through-going drainage systems to the Gulf of California in Pliocene time (~3 to 5 Ma), thick nonmarine evaporite deposits (halite, anhydrite, and gypsum) accumulated in these sinks. Evaporite deposition was focused in the younger basins associated with high-angle basin-and-range faulting, either within the lower parts of the sinks or in satellite basins proximal to major river systems. The thickest known salt deposit of this vintage is the 2.5-km-thick Red Lake salt in the Hualapai basin of northwest Arizona just south of Lake Mead (Fig. 31; Faulds and others, 1997).

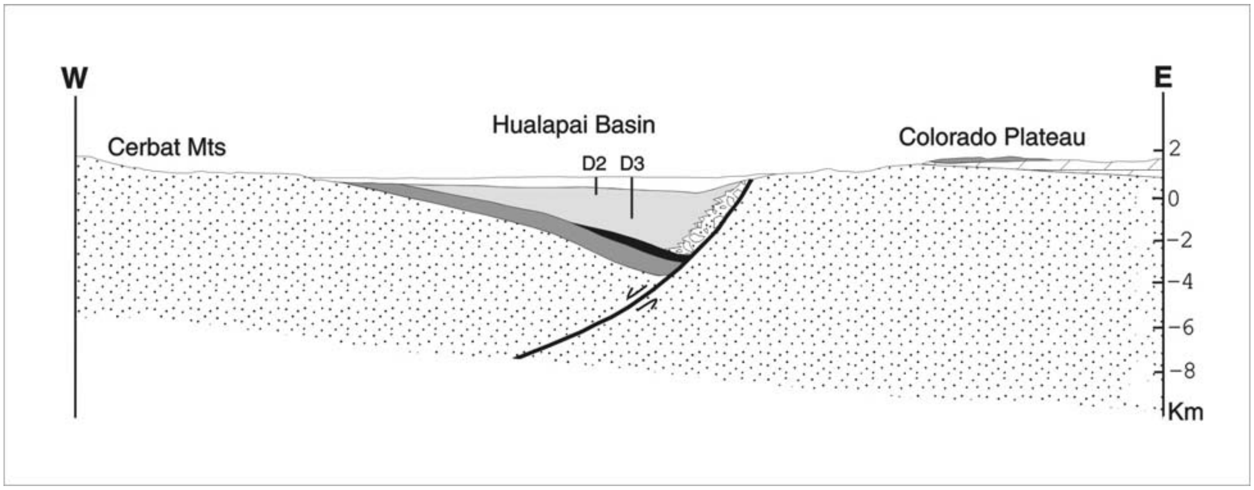

Figure 31. 1:1 cross section showing the Red Lake salt deposit in the Hualapai basin, northwest Arizona (view is toward the north; from Faulds and others, 1997). Unit patterns: stippled, Proterozoic gneiss; cross-hatched, Paleozoic sedimentary strata; dark gray, Miocene volcanic rocks; black, Miocene sedimentary rocks; light gray, late Miocene-early Pliocene salt deposit; gravel pattern along fault, alluvial fan deposits; white, early Pliocene to recent silt and sand deposits, with minor anhydrite and gypsum at base.

Because the geologic setting of southern Nevada is similar to that of northwest Arizona, several northerly trending basins within southern Nevada probably host thick salt deposits. These include the Virgin River depression and Eldorado and Piute basins (Fig. 5). Mannion (1974) documented ~500 m of late Tertiary salt in the southern part of the Virgin River depression, specifically in the Overton Arm area of Lake Mead. In addition, high TDS (total dissolved solids) characterizes wells in the northern part of Eldorado Valley and the deeper levels (~300 m) of some wells in the Mesquite area (M. Johnson, Virgin Valley Water District, personal commun., 2004). Maximum basin depth and thickness of basin-fill sediments generally ranges from ~2 to 6 km in Nevada (e.g., Bohannon and others., 1993; Langenheim and Schmidt, 1996; Langenheim and others, 2001). However, the eastern part of the Virgin River depression exceeds 8 km in depth in the northwest corner of Arizona (Langenheim and others, 2001). Although thick salt has not been documented in the northern and eastern parts of the Virgin River depression, it is important to note that the deeper parts of this basin have not been penetrated by drill holes. Considering the location of the Virgin River depression at both the mouth of the Virgin River Canyon and near the confluence of the Virgin and Colorado Rivers, as well as the presence of thick salt in the shallower southern part of the basin (Mannion, 1974), it is likely that thick evaporite deposits reside in the deep eastern part of the basin. Most of the potential salt-bearing basins in southern Nevada are relatively quiet tectonically, with little activity on range-bounding faults over the past several million years. One exception to this is the northern part of the Eldorado basin, where the Black Hills fault shows evidence of rupturing in a sizeable earthquake in the past 10,000 years (Fossett and Taylor, 2003).

Considering the rapid population growth and related recent construction of natural gas power plants near Las Vegas, presence of the coal-fired Mohave Generating Station (MGS) at Laughlin, relative tectonic quiescence, and proximity of thick salt deposits, the southern Nevada region may be a favorable location for a CO_2 sequestration project. This may be particularly relevant for the MGS, a 1,580-megawatt coal-fired power plant located approximately 120 km southwest of the Grand Canyon and only 65 km southwest of the 2.5-km-thick Red Lake salt deposit. The MGS began operations in 1971 and is one of the largest sources of air pollution in the West (emitting up to 40,000 short tons of sulfur dioxide, SO_2, per year), contributing significantly to visibility impairment at the Grand Canyon (U.S. Environmental Protection Agency, 1999). In fact, once controls are installed at the Centralia Power Plant in Washington State, as scheduled in the next few years, the MGS will be the largest source of SO_2 in the West. The MGS is operated by Southern California Edison, the majority owner of the plant. The Los Angeles Department of Water and Power, Nevada Power Company, and Salt River Project also own interests in the plant. This facility is the only coal-fired, base-loaded power plant in the United States that receives coal through a slurry pipeline, which originates 440 km to the east at Black Mesa in northern Arizona. Carbon dioxide emissions from the MGS could possibly be contained within a solution cavern within the nearby Red Lake salt deposit. However, the MGS may shut down in the near future due to the costs of necessary pollution control retrofits and repairs to the coal-slurry pipeline that transports coal from northeastern Arizona, in which case the MGS may no longer be a major source of CO_2 (Edwards, 2005).

The volume of caverns needed to hold the CO_2 exhaust from a major power plant is substantial. Using the factors in Table 1, a plant that burns 250 million metric tons of carbon in coal over its lifetime (approximately a 2,000-megawatt plant operating for 50 years) would need 1.2 km^3 of underground storage space. For such an operation, only sedimentary basins with thick, extensive salt formations would be practical.

5.2 Chemical Reaction with Mafic and Ultramafic Rocks

The principal means by which CO_2 is naturally sequestered in rocks is through the alteration of calcium- and magnesium-rich rocks, ultimately forming carbonates (rocks composed primarily of calcite, $CaCO_3$, the major mineral in limestone, and dolomite, $CaMg(CO_3)_2$). The Earth contains abundant calcium and magnesium in basalts (volcanic rocks commonly erupted at ocean ridges on the seafloor, in volcanic islands, such as Hawaii, and in certain continental areas, such as the Columbia River Plateau east of the Cascade Range in Oregon and Washington) and gabbros (intrusive equivalents of basalts). These rocks are termed mafic to describe their high magnesium and iron (ferrous) contents.

One approach to permanent CO_2 sequestration would be to speed up the natural process. Minerals in these rocks can react with CO_2 to produce various carbonates, silica, and alumina as reaction products. As indicated in Table 4, in terms of volume of material required for the reactions and volume of materials produced, rocks with high concentrations of the mineral forsterite (Mg_2SiO_4), the magnesium end member of the olivine group, would be most favored. One gigaton of carbon, approximately the amount of coal burned annually in the United States, would require reaction with 5.86 gigatons of forsterite (approximately 1.82 km^3 of dunite, a rock composed mostly of Mg-rich olivine) and would produce 9.52 gigatons of product composed of 7.02 gigatons of magnesite plus 2.50 gigatons of quartz. Assuming 20% porosity in the waste product, this would be 2.92 km^3 of magnesite product and 1.18 km^3 of quartz product, for a total of 4.10 km^3 of waste product. Reaction of CO_2 with other minerals would require considerably more volume of reactant and would produce considerably more waste product than reaction with Mg_2SiO_4, although reaction with serpentinite, a rock composed mostly of serpentine minerals, such as antigorite, $Mg_6Si_4O_{10}(OH)_8$, is nearly as favorable volumetrically as reaction with olivine (Table 4). Coincidentally, the reaction of CO_2 with Mg_2SiO_4 is also favorable thermodynamically; heat generated from the reaction could be used to provide energy needed to pulverize the rock, thereby speeding up the kinetics of the reaction.

Goff and Lackner (1998) describe the potential use of ultramafic rocks for CO_2 sequestration. These are particularly Mg-rich igneous rocks, including dunite, serpentinite, and peridotite, a rock composed mostly of olivine and pyroxenes, minerals composed primarily of $(Mg,Fe,Ca)SiO_3$. They describe a scenario in which the ultramafic rocks would be reacted with hydrochloric acid to facilitate reactions with CO_2. Unfortunately, although ultramafic rocks are abundant in California, Oregon, and Washington, Nevada contains only small amounts of these types of rocks near the surface. Nevada does, however, have abundant basalt and other mafic rocks (Fig. 32). The volume requirements for reactions with basalts are considerably less favorable than for reactions with ultramafic rocks, such that any use of basalts in Nevada would have to deal with large volumes of waste products. For example, using the hypothetical basalt composition in Table 4, 5.2 km^3 of basalt would need to be mined to react with one gigaton of carbon, and 8.5 km^3 of waste would be generated from the reaction, more than enough to refill the hole from which the basalt would be mined.

A hypothetical scenario for permanent CO_2 sequestration would be to site a CO_2-generating power plant near a large amount of ultramafic rock or basalt, which would be mined and used in chemical reactors. The waste products from the reactions could be used to isolate municipal and other waste materials, which would refill the holes dug in the mining operations. Because of the volume considerations (Table 4), additional landfills would be required, or artificial hills would be constructed near where the ultramafic rock or basalt had been mined. Ideally, such an industrial ecology facility would be located close to railroads (to bring coal from Wyoming and other sources and waste from cities) or perhaps ports (to bring coal from Alaska and possibly oil or natural gas from any location), electrical transmission lines, and cities that use the electricity and generate the municipal waste.

The locations of large outcrops of mafic rocks in Nevada are plotted with locations of current railroads, piplelines, electrical transmission lines, and major CO_2 generators in Figure 32. Should such a scenario be pursued, volumes of mafic rocks would need to be assessed. It is likely that sufficient volumes of basalt and ultramafic rocks occur in the western states to meet the CO_2 sequestration needs of the region (Goff and Lackner, 1998). In Nevada, Tertiary basalts crop out in many parts of the state, and a large gabbroic complex occurs near Lovelock in northern Churchill and southern Pershing Counties. Serpentinite, presumably altered pieces of dunite- or peridotite-rich oceanic crust thrust onto the North American continent during Paleozoic and Mesozoic mountain-building events (Stewart, 1980), occurs in small bodies in Mineral, northwestern Nye, and eastern Humboldt Counties.

Table 4. Theoretical weights and volumes of reactants and products in reactions between CO_2 and various rocks and minerals (data from Weast, 1971, Roberts and others, 1974, and Robie and Hemingway, 1995).

Mineral reactant	Ratio of weights of mineral reactant to C	Volume of mineral reactant (m^3/t of C)	Ratio of weights of solid products to C	Volume of solid products (m^3/t of C) assuming 20% porosity in products
1. Mg_2SiO_4 (forsterite)	5.86	1.82	9.52	4.10
2. Fe_2SiO_4 (fayalite)	8.48	1.93	12.15	4.24
3. $Mg_6Si_4O_{10}(OH)_8$ (antigorite)	7.69	2.98	10.36	4.49
4. $MgSiO_3$ (enstatite)	8.36	2.62	12.02	5.28
5. $FeSiO_3$ (ferrosilite)	10.98	2.75	14.65	5.42
6. $CaSiO_3$ (wollastonite)	9.67	3.32	13.34	6.20
7. $CaAl_2Si_2O_8$ (anorthite)	23.16	8.39	26.83	11.22
8. $NaAlSi_3O_8$ (albite)	43.66	16.67	47.33	21.18
9. Hypothetical basalt	16.32	5.21	19.98	8.50

1. Mg_2SiO_4 (forsterite in olivine) + $2CO_2$ (gas, captured from power plant) = $2MgCO_3$ (magnesite) + SiO_2 (quartz or other silica compound)
2. Fe_2SiO_4 (fayalite in olivine) + $2CO_2$ (gas) = $2FeCO_3$ (siderite) + SiO_2 (quartz)
3. $Mg_6Si_4O_{10}(OH)_8$ (antigorite) + $6CO_2$ (gas) = $6MgCO_3$ (magnesite) + $4SiO_2$ (quartz) + 4H2O (water)
4. $MgSiO_3$ (enstatite in pyroxenes) + CO_2 (gas) = $MgCO_3$ (magnesite) + SiO_2 (quartz)
5. $FeSiO_3$ (ferrosilite in pyroxenes) + CO_2 (gas) = $FeCO_3$ (siderite) + SiO_2 (quartz)
6. $CaSiO_3$ (wollastonite in pyroxenes) + CO_2 (gas) = $CaCO_3$ (calcite) + SiO_2 (quartz)
7. $CaAl_2Si_2O_8$ (anorthite in plagioclase) + CO_2 (gas) = $CaCO_3$ (calcite) + Al_2O_3 (alumina or corundum) + $2SiO_2$ (quartz)
8. $2NaAlSi_3O_8$ (albite in plagioclase) + CO_2 (gas) = Na_2CO_3 (sodium carbonate) + Al_2O_3 (alumina or corundum) + $6SiO_2$ (quartz)
9. The composition of this hypothetical basalt is calculated with the following assumptions:

Hypothetical Basalt	Mole Fraction	Chemical composition	Weight %
Mg_2SiO_4 (in olivine)	0.15	SiO_2	48.6
Fe_2SiO_4 (in olivine)	0.05	Al_2O_3	19.2
$CaSiO_3$ (in pyroxenes)	0.07	MgO	11.5
$MgSiO_3$ (in pyroxenes)	0.23	FeO	7.8
$FeSiO_3$ (in pyroxenes)	0.10	CaO	11.2
$CaAl_2Si_2O_8$ (in plagioclase)	0.30	Na_2O	1.7
$NaAlSi_3O_8$ (in plagioclase)	0.10	TOTAL	100.0
TOTAL	1.00		

With the exception of reaction 8, all reactions are thermodynamically favorable (with respect to calculated negative Gibbs free energies of reaction at 25°C).

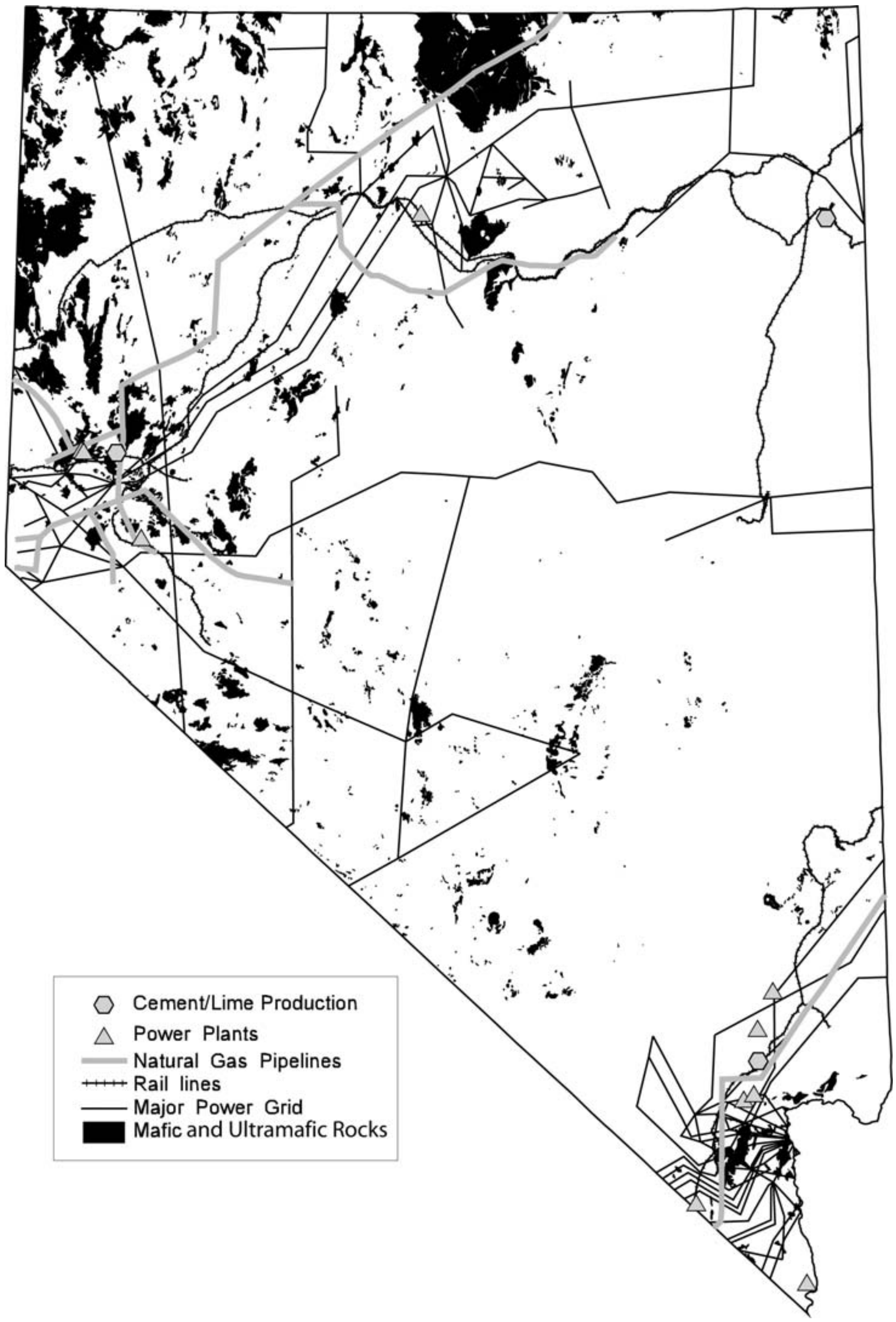

Figure 32. Distribution of mafic (magnesium- and iron-rich) rocks (black), major power plants (gray triangles), cement and lime plants (gray hexagons), major electric power transmission lines, pipelines, and rail lines in Nevada.

Using the factors in Table 4, a large coal-fired power plant (burning 5 million metric tons of carbon in coal per year and generating on the order of 2,000 megawatts) would need to mine approximately 14.9 million m^3 of serpentinite or 26.1 million m^3 of basalt per year and would generate approximately 22.5 or 42.5 million m^3, respectively, of solid waste per year. Over a 50-year life, the solid waste would amount to approximately 1.1 or 2.1 km^3, depending on whether serpentinite or basalt, respectively, were used for the chemical reactions. These numbers are comparable to the sizes of large-scale copper and gold mines in Nevada (e.g., the Robinson and Yerington copper mines and the Carlin and Betze-Post gold mines) and other parts of the western United States.

Depending on the chemical reactor design (using supercritical, liquid, or gaseous CO_2 versus an aqueous solution as described by Goff and Lackner, 1998), considerable water may be needed for the process. Interestingly, reaction of CO_2 with serpentinite, which is more abundant in California than in Nevada, would produce approximately one ton of water for each ton of carbon sequestered, thereby perhaps eliminating the need to consume existing water resources. A further advantage of serpentinite is that it is locally considered a nuisance, because of commonly contained asbestos, which would be destroyed upon reaction with CO_2. Commercial-scale sequestration by reaction with rocks, although highly attractive as a means of permanently disposing of the CO_2, is likely to be far in the future, because the chemical reactors and overall power generation-mining-waste disposal systems would need to be designed, perfected, and demonstrated to be cost-effective.

6 Conclusions

We have presented an approach to a preliminary assessment of the potential for CO_2 disposal by sequestration in geological settings in Nevada using GIS analysis. The key assumptions made are that for CO_2 disposal in saline aquifers it is wisest to (1) avoid areas of fractured bedrock and restrict the assessment to parts of alluvial basins that are deep enough to provide a thick, relatively impermeable seal against leakage and have sufficient pressure to keep the CO_2 in a condensed phase; (2) stay away from active faults whose fracture zones may allow leakage of CO_2 from underground injection sites; (3) avoid areas that in the foreseeable future have a reasonably high probability of being explored and developed for mineral, geothermal, and water resources; (4) avoid current urban areas and areas that are likely to experience significant population growth during the 21st century; and (5) avoid restricted lands, such as parks and military reservations. The data sets used in the GIS analysis are readily available through references provided in this report or are made available in the electronic version of this report, so that others may reevaluate the approach with different assumptions and data sets.

There does not appear to be much potential in Nevada for CO_2 sequestration through disposal in saline aquifers. Among the potential deep parts of alluvial basins, few remain after eliminating areas of potential potable water, geothermal resources, and mineral resources. Within the remaining areas, little is known about porosities, permeabilities, or salinities of aquifers at depths greater than 1 km.

There also does not appear to be much potential in Nevada for conventional approaches to CO_2 sequestration through enhanced oil recovery, in part because the oil fields in Nevada tend not to have much associated natural gas, implying that gas that was associated with the fields has escaped. Injected CO_2 would likely leak to the surface as well, although the time scale may be quite long. In addition, the oil fields in Nevada are small relative to fields in many other parts of the United States, and some of the Nevada fields are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground.

There is some potential for disposal of CO_2 in mined caverns in salt formations in basins in southern Nevada, northwestern Arizona, and southwestern Utah. The highest potential for this approach is likely to be in northwestern Arizona, where thick salt deposits are well described and are being studied for storage of natural gas.

Chemical reaction of CO_2 with mafic rocks (basalt, gabbro) and ultramafic rocks (serpentinite, dunite, peridotite) has the potential to capture CO_2 in synthetic minerals, which, in turn, could be used to isolate municipal and industrial wastes. Enough of these rocks are exposed in Arizona, California, Idaho, Nevada, Oregon, and Washington to meet the expected needs for CO_2 sequestration in the region. Ultramafic rocksare more favorable than mafic rocks both volumetrically and thermodynamically. Chemical reaction with mafic or ultramafic rocks would be a long-term solution requiring considerable research to design, perfect, and demonstrate the cost-effectiveness of the chemical reactors and associated facilities.

For Nevada to be considered a potential site for significant amounts of CO_2 sequestration in geological settings, considerably more work would need to be done to (a) assess the thicknesses and volumes of salt formations in southern Nevada, (b) demonstrate a cost-effective process for chemical reaction with ultramafic or mafic rocks, and (c) assess the volumes of ultramafic and mafic rocks that are located in optimal areas. Although Nevada occurrences of ultramafic and mafic rocks have the advantage of being remote, considerably larger areas of ultramafic rocks are known in California, Oregon, and Washington, and enormous volumes of basalt occur in eastern Oregon and Washington.

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Appendix: Geographic Information System Analysis

The GIS data sets used in this assessment are included in the compact disk (CD) version of this report. Included on the CD are metadata files for each data set. Further descriptions of the metadata and the assumptions made in deciding how to use each data set are given in this section. Should further consideration be given to CO_2 sequestration in Nevada, others may wish to reevaluate our approach, make different assumptions, or use different data sets.

A. Software and Projection Information

All coverages in this project are in UTM, zone 11, meters, NAD 27 projection. Original data coverages that were not in this projection were projected using the projection wizard in Arcview 3.3. Coverages that extended beyond the Nevada State line were clipped to exclude areas outside of the State prior to final modeling. Arcview 3.3 and ARCGIS 9.0 were used for data development, editing, analysis, and modeling. All data layers are designed to be used at a scale of 1:1,000,000 or smaller. Minor edits were performed on some preliminary coverages to remove line work errors and close polygons.

B. The Binary Model

We used a binary model for the GIS analysis. A binary model is, simply put, a series or stack of data layers that are attributed in such a way as to show where data of interest, per layer, are and where they are not. Typically, values used include zero or one, yes or no, or a unique number per map layer if the feature is present and no value or a null value where it is not present. In this approach, for any data layer being considered, an area is either acceptable for subsurface CO_2 sequestration or eliminated from consideration. We considered other approaches, such as assigning different weights to different layers and applying distance-probability distributions (e.g., to handle nearness to urban areas or known mineral deposits), but for this preliminary assessment of CO_2 sequestration, we considered the binary model to be the most justifiable and easiest to understand.

In our binary model, we assign a “no” value to areas of bedrock and to shallow parts of alluvial basins that are not thick enough to provide a seal against leakage or have sufficient pressure to keep the CO_2 in a condensed phase. We assign a “no” value to areas close to active faults where CO_2 may easily leak from underground injection sites and to areas that in the foreseeable future have a reasonably high probability of being explored and developed for mineral, geothermal, and water resources. We also assign a “no” value to current urban areas and areas that are likely to experience significant population growth during the 21st century, as well as to restricted lands, such as parks and military reservations. In the final GIS analysis, areas assigned an attribute of “no” in any of these GIS layers are combined spatially (unioned) to create the overall area eliminated from further consideration. The remaining area, which was assigned “yes” on every GIS layer, remains as having potential for CO_2 sequestration by disposal in deep brine aquifers.

In this preliminary assessment of the potential for CO_2 disposal by sequestration in geological settings, we use the entire state as the spatial extent. There are two near-term opportunities for CO_2 sequestration in Nevada: EOR and injection into saline aquifers. There are limited opportunities for EOR in oil fields with past production (see section on Petroleum above), and these are not considered in the GIS analysis. The GIS binary model is restricted to areas that may be amenable to injection into saline aquifers. Alternative approaches for geological sequestration are discussed separately from the GIS binary model.

The primary question asked of the binary model is “where should consideration be given to CO_2 disposal in saline aquifers?” Another way of asking the question is “what areas should be eliminated from consideration for CO_2 disposal in saline aquifers?”

C. Primary Map Layers (Coverages) for the Binary Model

C.1 Nevada State and County Boundaries

The digital 1:1,000,000-scale Nevada State and County boundary coverage, 2nd edition, 1998, produced by the Nevada Bureau of Mines and Geology was extensively used for graphic presentation of data results, primarily on plot maps and graphics used in this report, and as the layer that all of the data sets were clipped to for the special extent of the binary model.

C.2 Geology

We used the digital version of the Stewart and Carlson (1978) Geologic Map of Nevada (Raines and others, 2003) to produce a map that indicates areas of valley fill versus bedrock in Nevada. The original paper map was printed as a single sheet at a scale of 1:500,000, then reprinted as two sheets in 1991. The database by Raines and others (2003), which is reproduced in this report, supercedes earlier published digital versions (Turner and others, 1991, Raines and others, 1996). This database can be queried in many ways to produce a variety of maps. This database is not meant to be used or displayed at any scale larger than 1:500,000 (for example, 1:100,000). Attributes that were selected from the Stewart and Carlson map that indicated areas of valley fill included alluvium, lake deposit, landslide, and playa. These selected attributes were exported into a shape file called “Val_fill” and became the model layer for areas of valley fill. With the exception of alluvium, lake deposit, landslide, playa and water features, all other units were selected and exported as the shape file “Bedrock.” This shape file became the model layer for areas of bedrock (Fig. 3). In the binary model, areas of bedrock were not considered for CO_2 sequestration.

C.3 Areas with Greater than One Kilometer of Valley Fill

The U.S. Geological Survey has interpreted gravity data in terms of thickness of valley fill, including alluvium and some Tertiary volcanic rocks (Dohrenwend and others, 1996). We use the 1-km contour in Plate 8 of Dohrenwend and others (1996) to locate deep basins in Nevada, which we define as equal to or more than 1 km in depth. The NBMG Open-File Report from which this coverage came is a large compilation of various data sets that were designed to expand the knowledge base on mineral deposits in Nevada with the end goal of presenting a series of mineral deposit permissive maps for Nevada. The gravity dataset is one of the preliminary coverages that was developed to complete the permissive maps. Because of limitations such as data availability, uneven distribution of data, and model grid size, the overall accuracy of this data set is believed to be plus/minus 250 m (Dohrenwend and others, 1996). The shape file (Depth_1k.shp) was used to generate Figure 5. In the binary model, only areas greater than 1 km of valley fill were considered for CO_2 sequestration.

The coverage developed in the preceeding step was used to produce a layer showing areas of shallow valley fill. This was done by combining the greater then 1 km of valley fill map with the alluvial cover map, developed earlier in this process from the Stewart and Carlson (1978) Geologic Map of Nevada (Raines and others, 2003). The areas of valley fill that fell outside of the area of greater then 1 km depth were selected and exported to a new shape file (Vf_Shallow.shp). The map layer showing areas with less then 1 km versus greater than or equal to one kilometer of valley fill was then utilized in the model (Fig. 5).

C.4 Faults

Locations of faults that have moved during the Quaternary Period (the last 1.6 million years) were taken from the USGS Quaternary Fault (USGS_QF) database (U.S. Geological Survey, 2004) and NBMG Quaternary Fault (NBMG-QF) database (dePolo, 1999). We used NBMG-QF to identify strike-slip faults that were not attributed as such in the USGS-QF database. This was accomplished by selecting those faults that were within 500 m of identified strike-slip faults within the NBMG-QF database. Faults that fell within 500 m but were attributed as normal faults in the USGS-QF data were not included on the list of strike-slip faults. The strike-slip faults so identified in the USGS-QF database plus those already attributed as strike-slip in the original USGS-QF database, plus those faults shown as strike-slip in the NBMG-QF database were plotted with a 500-m buffer. All other faults from both quaternary fault data sets were plotted with a 1,930-m (1.93-km) buffer. All the buffer maps were then merged into one coverage to create a map layer showing the distribution of areas potentially affected by Quaternary faults in Nevada. A graphic plot of these data showing the buffer areas around the faults combined with the actual location of the faults shown as lines was produced (Fig. 6). In the binary model, areas within these buffers near faults are excluded from consideration for CO_2 sequestration.

C.5 Mineral Resources

The mineral resources layer is a compilation of four data sets. The first data set (Mining_Districts) is the “Mining Districts of Nevada” 2nd edition by Tingley (1998). This is a digital polygon coverage of mining districts in Nevada.

The second data set (NV_MRDS) is the USGS Mineral Resource Data System (MRDS) database from “Nevada Abandoned Mines Database Compilation Update” by Hess (2001). A subset of MRDS data contained in this report was used as a point coverage indicating sites that have had some type of mineral exploration, development, or production. The original MRDS database was created and is still maintained by the USGS. Sand and gravel locations were removed before these data were used.

The third data set (MILS2000) is the Mineral Inventory Lands System (MILS) database from Hess (2001). A subset of MILS data contained in this report was used as a point coverage indicating sites that have had some type of mineral exploration, development, or production. The original MILS data base was created by the U.S. Bureau of Mines and is no longer being updated. Sand and gravel locations were removed before these data were used.

The fourth data set (Map_120_e) is the “Gold and silver resources in Nevada” database by Davis and Tingley (in review). This map shows locations of deposits with a noted or implied gold and/or silver resource or reserve discovered since 1930. Base-metal and industrial-mineral deposits that contain a significant amount of gold or silver are also shown. This point coverage was used to show locations of known precious metal resources. Significant pre-1930 gold and silver deposits are captured in the second and third data sets.

The second, third, and fourth data sets, all point coverages, were plotted with a 5-km buffer, which takes into account potential location inaccuracies, necessary space to develop a large surface or subsurface mine, and the potential for additional discoveries associated with the known resource. Five kilometers is also within the effective distance of large hydrothermal systems responsible for the formation of most ore deposits in Nevada. Once the point coverages were buffered, all three were combined with the mining district coverage using the union command. Internal polygons were dissolved by aggregating all areas that fell within a buffer or mining district area into single polygons. Portions of those polygons that fell outside of Nevada were clipped to the Nevada State boundary. This became the mineral resource coverage for the model (Fig. 19). In the binary model, areas within the 5-km buffer of known deposits or within a defined mining district were excluded from consideration for CO_2 sequestration.

C.6 Geothermal Resources

The geothermal resource layer is based on the identified geothermal springs and wells found on the Nevada geothermal resources map of Shevenell and Garside (2005). The well and spring locations are available for download as an Excel spreadsheet file. This file was generated into a point shape file and projected to UTM, zone 11, meters, NAD 27 projection. A 20-km buffer was then created around all of the geothermal sites. Twenty kilometers was chosen because this buffer map visually correlated well with previously published resource potential outlined by Trexler and others (1983), and it included most of the moderate to high potential areas suggested by Blackwell and Richards (2004a and 2004b) and Coolbaugh and others (2005, in press). Areas within the 20-km buffer (Fig. 23) were excluded from consideration for CO_2 sequestration in the binary model.

C.7 Deep Carbonate Aquifer

We used the approximate extent of the carbonate-rock province (Deep Carbonate Aquifer) in eastern Nevada as outlined by Thomas and others (1986) in their study of groundwater levels in the Great Basin region of Nevada, Utah, and adjacent states. A shape file was created showing the area identified as being underlain by carbonate rocks and then utilized in the binary model (Fig. 24), wherein areas underlain by the Deep Carbonate Aquifer are excluded from consideration for CO_2 sequestration in saline aquifers.

C.8 Areas of Population

The areas of population layer was developed from three data sets. The first data set, consisting of roads in Nevada, 1998 edition (Roads_10k_buffer.shp), was digitized by the Nevada Bureau of Mines and Geology from 1:500,000-scale source materials. The coverage contains interstate highways, U.S. highways, state highways, and some minor roads. From this coverage, major highways such as Interstates 80 and 15 and sections of United States and State highways near urban areas were selected (see section on Proximity to Urban Areas and Areas of Future Urban Growth). These features were exported to a shape file. A 10-km buffer was created around the selected highways. This selection was made because ongoing rapid growth in Nevada's urban areas tends to follow the major transportation corridors outward from existing communities.

The second data set, showing urban areas as of 2000 (Nv_urban_utm27.shp), was developed by the U.S. Census Bureau. The Nevada data were downloaded as a polygon shape file from the ESRI Web Site (http://www.esri.com/data/download/census2000_tigerline/index.html). All urban areas identified in Nevada where selected and a 30-km buffer was produced around the urban polygons. This was done to include areas of possible future development during the 21st century.

The third data set (Cities.shp) includes digitized point locations for the center of 101 communities in Nevada. This includes many smaller communities not included in the urban areas coverage. A 10-km buffer was developed around these communities.

All three of the above coverages were combined using the union command to form the urban area coverage (People.shp) for use in the model. This combined coverage includes the Las Vegas and Reno-Carson City urban areas, major towns along Interstate 15 and 80, and the communities of Yerington, Ely, Austin, Eureka, and other small Nevada towns (Fig. 25). In the binary model, these areas are excluded from consideration for CO_2 sequestration.

C.9 Restricted Lands

The restricted lands layer was developed from two data sets. The first data set is the "Nevada Lands Status Coverage" developed by the U.S. Bureau of Land Management (2003a). This was designed to display the distribution of land ownership throughout Nevada. It was originally captured for the Bureau of Land Management by the University of Utah, for use with the U.S. Fish and Wildlife GAP Program. The data were updated using the Geographic Coordinate Data Base (GCDB) in 2003. From this data set we selected areas identified as being managed by Department of Defense, Department of Energy (Nevada Test Site), National Park Service, Nevada State lands, and regional parks. These select areas were then exported to a shape file.

The second data set is the "Wilderness Lands of Nevada" developed by the U.S. Bureau of Land Management (2003b). These data represent designated wilderness areas in Nevada administered by the U.S. Department of the Interior - Bureau of Land Management. Late in 2004 the President signed a new law passed by Congress to designate additional land in Lincoln County as wilderness. It is not included in this data set and has not been included in the project analysis. The wilderness lands data set was combined with the shape file created in the step above and used as the restricted lands coverage for the model (Fig. 26). These restricted lands were excluded from consideration in the binary model.

D. Construction of Model Shape File

All the map layers developed above were merged together using a union command. When supplied with two input shape files (map layers), the union command merges the data so that all the attribute data that are present in the coverages remain spatially intact in the new output shape file. Where the various polygons overlap and the boundaries stay the same, the data are attributed from both data sets to the existing polygon. Where the polygon boundaries do not overlap or only partially overlap, new polygons covering only the area of difference are created in the output shape file and attributed with the data from the specific coverage for that particular area. The first two shape files to be unioned were bedrock and shallow valley fill. These two shape files were then unioned with the Quaternary faults layer followed by the mineral resource layer. This combined file of four layers was then unioned with the carbonate rocks layer and the areas of population layer. This combined layer was then unioned with the restricted lands layer and the geothermal resources layer. This combined shape file was then unioned to the final layer, the one kilometer or greater basin fill coverage.

Typical Boolean operators for query statements include AND, OR, and NOT. Other operators that can be used in query expressions include equals (=), great than (>), less than (<), not equal to (<>), greater than or equal to (>=), and less than or equal to (<=). The final areas identified for potential CO2 sequestration were identified by applying the following compound query: areas **not equal** to BEDROCK and **not equal** to SHALLOW VALLEY FILL and **not equal** to QUATERNARY FAULTS and **not equal** to MINERAL RESOURCES and **not equal** to CARBONATE ROCKS and **not equal** to POPULATION and **not equal** to RESTRICTED LANDS and **not equal** to GEOTHERMAL RESOURCES and **equal** to ONE KILOMETER OR GREATER OF VALLEY FILL.

The above query selected 98 polygons out of a database total of 37,690 polygons (Fig. 29). These 106 polygons collectively have an area of 524 km^2 or less than 0.2 % of the total area of the state's 285,987 km^2. Only four of the 98 polygons are 30 square kilometers or greater in area.

E. Other Coverages

E.1 Oil and Gas Well Database

The Nevada Oil and Gas Well Database (Hess, 2004a) was updated and used to generate a shape file for checking some basin depth information.

E.2 Nevada Abandoned Mines Database Compilation Update.

The Nevada Abandoned Mines Database Compilation Update (file name NV_PTS) contains the digitized locations of mine shaft, prospect, mine tunnel and cave, quarry, and gravel-sand-clay or borrow pit locations from all Nevada 7.5-minute U.S. Geological Survey topographic quadrangles plus sites identified by the Nevada Division of Minerals as hazardous mine site locations. Each location has an associated record that identifies the map name; symbol type; mining district name determined from Tingley (1998), if within a district; Division of Minerals serial number (for their sites only); land management code, which identifies the site as being on federally managed or private land (location data merged from digital land status coverage supplied by BLM); and UTM (zone 11, NAD27) location coordinates.

This coverage was used during the model definition phase as a possible alternate or additional additive layer indicating areas of potential mineral resources. There are over 100,000 points identified in this data set. Attempts at building this layer into the model, either as a density grid, point coverage, or buffered point coverage, was not practical due to a lack of associated attribute information such as size of workings, production, commodity, reserve, or resource information. We decided not to utilize this data set in the final model. It was, however, used to produce Figure 10, indicating areas of past mineral development and exploration.

E.3 Tracts Permissive for Ore Deposits

The U.S. Geological Survey's analysis of Nevada's metal-bearing mineral resources (Cox and others, 1996a, b, and c) was tested for potential model layers. Specifically, we compared their maps of tracts permissive for three broad types of deposits: epithermal deposits (Fig. 11), pluton-related deposits (Fig. 12), and deposit types not directly related to plutonic activity (Fig. 13).

E.4 Geothermal Resource Maps

We examined the maps of potential geothermal resources by Trexler and others (1983), which was digitally converted by the Idaho National Engineering & Environmental Laboratory (2003), Blackwell and Richards (2004a and 2004b), and Coolbaugh and others (2005, in press). The former map (Fig. 22a) shows the regions favorable for the discovery of thermal water at shallow depth (<1000 m) of sufficient temperature for direct heat applications. This map was reproduced in the Geothermal section of The Nevada Mineral Industry 2003 (Hess, 2004a). Trexler and others (1983) cautioned that although only small areas of this region may be underlain by such thermal water; the region represents that part of the state that deserves further exploration. Local sources of thermal water may be discovered in areas of Nevada not identified in this coverage. Existing data do not document the presence or lack of usable thermal water at shallow depths. The original published map also included data on geothermal well and spring temperatures and known geothermal resource area (KGRA) boundaries that were not included in the digital conversion data set. The Blackwell and Richards (2004a and 2004b) maps (Fig. 22b) rely primarily on bottom-hole temperatures and heat-flow measurements in wells, and the Coolbaugh and others (in press) maps (Fig. 21) is created by combining several GIS layers in a manner that attempts to optimize areas favorable for discovery of geothermal reservoirs capable of being exploited for power generation.

E.5 Power Grid, Power Plant, Pipeline, and Cement and Lime Plant Data

The power grid, power generation, and pipeline data were put together from parts of various data sets supplied by Sierra Pacific Power Company, the Federal Energy Information Administration, the Nevada Public Utilities Commission, and the Western Governors' Association. These data can be used to identify potential sites within proximity to existing electrical generation or transmission facilities and to generate page size graphics. The cement and limestone production coverage (Cement.shp) was developed from information in the Nevada Mineral Industry 2003 (Castor, 2004) publication. Major CO_2 generators are plotted on Figures 27 and 32, and pipelines and electrical transmission lines are plotted on Figures 28 and 32.

E.6 Railroads and Highways

The railroad coverage was developed and provided by the Nevada Department of Transportation (NDOT). This coverage is an advance draft version; it is part of a larger digital conversion project which is still in the review process and has not been released. The original line coverage with which NDOT started was from the USGS transportation-rail digital line graphs (DLG) for Nevada. NDOT provided additional data and locational update edits from USGS 1:24,000-scale topographic maps in the form of digital raster graphic (DRG) files, USGS digital orthophoto quads (DOQ), and other historical maps georeferenced to the DRGs or DOQs. The NDOT coverage includes active rail lines as well as historic, dismantled, planned, and proposed rail routes. For this project, only active rail lines were utilized in Figures 28 and 32.

Highways (Roads_10k_buffer.shp) were digitized by the NB M G from 1:500,000 scale source materials (1998 version, which is still valid today). These are plotted on Figure 28.

E.7 Mafic and Ultramafic Rocks

Map layers were developed to show areas with potential for chemical reaction of CO_2 with minerals in mafic and ultramafic rocks. We used the digital version of the Stewart and Carlson (1978) Geologic Map of Nevada (Raines and others, 2003) to identify areas associated with mafic rocks. Attributes that were selected from the Stewart and Carlson map included Qtb (Quaternary basalt flows), Tb (Tertiary basalt flows), Tba (Tertiary andesite and basalt flows), Tbg (Tertiary Banbury Formation), Tob (Tertiary older basaltic rocks), Jgb (middle Jurassic gabbroic complex), and Pzsp (serpentinite). These selected units were exported into a shape file (mafic.shp) and became a layer for areas of mafic rocks. Although this layer was not used in the binary analysis, it was used, along with locations of major sources of CO_2 (electric power generation plants and cement and lime plants), major electrical transmission lines, major gas pipelines, and active rail lines, to create Figure 32.