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Nevada Bureau of Mines and Geology

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ABSTRACT

This report follows the preliminary assessment of the potential for carbon dioxide (CO_2) sequestration in geological settings in Nevada (Price et al. 2005) by more thoroughly evaluating the potentials for reaction of CO_2 with naturally occurring minerals and for use of CO_2 in enhanced oil recovery (EOR). The results of these two evaluations have been published by the Nevada Bureau of Mines and Geology (Sturmer et al. 2007 for the mineral-reaction work; LaPointe et al. 2007 for the EOR work). This contract report combines those two reports.

One option for decreasing the amount of greenhouse gas that is added to the atmosphere from the burning of fossil fuels is to capture CO_2 and react it with certain minerals found in rocks. Part 1 of this report investigates the potential for such carbon sequestration using rocks in Nevada. There are sufficiently large volumes of basalt (a rock rich in the oxides of magnesium, iron, and calcium) in Nevada to consider reaction of those rocks with CO_2 from coal-fired power plants.

Reaction with minerals has theoretical advantages over many other schemes for carbon sequestration in that it would be essentially permanent disposal (that is, no leakage as could possibly occur from geological storage in deep saline aquifers, oil fields, or other geological environments, and there would be no threat of loss of CO_2 from wildfires, as with terrestrial sequestration in trees or other biomass). Nonetheless, the technology for mineral reaction is unproven. Considerably more research would be needed before a commercial operation could be seriously considered.

When and if commercial viability is demonstrated, those areas most likely to be of interest in Nevada would be ones with large volumes of basalt or chemically similar rock near railroads and major power lines. Those areas would most likely be northwestern Washoe County; southern Washoe and parts of Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties.

Part 2 of this report covers the potential for EOR as a means of CO_2 sequestration. Critical factors in Nevada include depth, temperature, and cumulative production. Most Nevada oil reservoirs are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground. Furthermore, none of the Nevada oil fields is large enough to accommodate all the CO_2 from a large coal-fired power plant. The cumulative volume of oil and associated water

production from all Nevada oil fields is about two orders of magnitude less than what would be needed to sequester a significant amount of CO_2 from a power plant. Therefore, there is not much potential in Nevada for CO_2 sequestration through EOR.

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*** Appendices are available on line at www.nbmg.unr.edu/dox/r52/r52append.htm.**

PART 1

Assessment of the Potential for Carbon Dioxide Sequestration by Reactions with Rocks in Nevada

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EXECUTIVE SUMMARY

One option for decreasing the amount of greenhouse gas that is added to the atmosphere from the burning of fossil fuels is to capture carbon dioxide (CO_2) and react it with certain minerals found in rocks. This report investigates the potential for such carbon sequestration using rocks in Nevada. There are sufficiently large volumes of basalt (a rock rich in the oxides of magnesium, iron, and calcium) in Nevada to consider reaction of those rocks with CO_2 from coal-fired power plants.

Reaction with minerals has theoretical advantages over many other schemes for carbon sequestration in that it would be essentially permanent disposal (that is, no leakage as could possibly occur from geological storage in deep saline aquifers, oil fields, or other geological environments, and there would be no threat of loss of CO_2 from wildfires, as with terrestrial sequestration in trees or other biomass). Nonetheless, the technology for mineral reaction is unproven. Considerably more research would be needed before a commercial operation could be seriously considered.

Whereas there is plenty of basalt in Nevada to meet the CO_2 sequestration demands for several large power plants, there are insufficient quantities of other rock types (serpentinite, iron and manganese ores, wollastonite, and brucite) considered to be of significance for sequestering CO_2 from a large power plant. However, in-situ reaction of CO_2 with basalt is impractical, because the large volume increases that would result from the creation of carbonates of magnesium, iron, and calcium would plug pore spaces. Basalt would therefore have to be mined. It may make more sense to locate a coal-fired power plant close to the source of basalt than to transport mined basalt to an existing plant that may be located close to a source of coal. Solid waste products from burning the coal and other waste materials brought in by rail could be disposed along with the carbonates created from reacting CO_2 with the basalt, partly in the holes dug to mine the basalt.

When and if commercial viability is demonstrated, those areas most likely to be of interest in Nevada would be ones with large volumes of basalt or chemically similar rock near railroads and major power lines. Those areas would most likely be northwestern Washoe County; southern Washoe and parts of Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties.

INTRODUCTION

Large amounts of carbon dioxide (CO_2) are generated from the burning of fossil fuels (coal, natural gas, oil, and derivative products, such as gasoline), wood, and other biomass. Worldwide, humans put approximately 6.5 gigatons of carbon (6.5 billion metric tons—some pertinent conversions regarding carbon and CO_2 are listed in Table 1) into the atmosphere each year from the burning of fossil fuels (Service, 2004). Some of that carbon returns to the Earth's oceans and land, but in recent years, the atmosphere has gained approximately 3.2 gigatons of carbon per year (Intergovernmental Panel on Climate Change, 2001). Because CO_2 is a greenhouse gas (it reflects heat radiated from the Earth, thereby contributing to global warming), and although other factors, both natural and anthropogenic, may be contributing to global climate change, considerable effort (see, for example, Deutch et al. 2007; Friedmann, 2007) has focused on investigating whether CO_2 can be captured (particularly from power plants and cement manufacturers) and sequestered (disposed of effectively and permanently, such that it does not reenter the atmosphere).

The United States alone burns approximately one gigaton of coal per year (Energy Information Administration, 2006a) and has vast resources of coal. In recent years, China has exceeded the U.S. in annual coal production and consumption (Energy Information Administration, 2004). The U.S., Russia, China, and India, in descending order, lead the world in recoverable reserves of coal (Energy Information Administration, 2006b), which are likely large enough to continue as a major energy source for electricity throughout the 21st century. In recent decades, coal has been the major source of energy for electricity in Nevada, with production from a few major power plants (e.g., Figure 1).

The primary sources of energy consumed in the United States and Nevada are fossil fuels. In 2006, collectively fossil fuels accounted for 85% (and coal accounted for 23%) of the energy consumed in the United States; nuclear energy (8%) and renewable sources, including hydroelectric, geothermal, solar, wind, and biomass (collectively 7%) made up the rest (Energy Information Administration, 2006c). In Nevada in 2004, the latest year for which state statistics are available from the Energy Information Administration (2006c), 93% of energy consumption came from fossil fuels (27% from coal), 2% came from hydroelectric power, and 4% came from geothermal power. Nevada's largest coal-fired power plant, the Mohave Generating Station in far southern Nevada, shut down at the end of 2005 because it was unable to meet current pollution-control standards. Most of the deficit from the loss of this plant was made up by more electrical production from burning natural gas.

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 join the West Coast Regional Carbon Sequestration Partnership (WESTCARB) and 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. Some unconventional approaches are also being evaluated. 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) reported its findings from a preliminary assessment of the potential for geological sequestration in Nevada (Price et al. 2005). This report follows up with a more detailed evaluation of one of the unconventional approaches—sequestration through reaction with minerals and rocks.

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.

The concentration of CO_2 in the Earth's atmosphere is currently approximately 370 parts per million by volume (ppmv), which is equal to approximately 560 parts per million by weight (ppmw). The bulk of the remainder of the Earth's atmosphere is nitrogen (N_2, 78.1% by volume or 75.5% by weight), oxygen (O_2, 20.9% by volume or 23.1% by weight), and argon (Ar, 0.93% by volume or 1.3% by wieght). The total amount of carbon in the Earth's atmosphere is approximately 730 gigatons (Intergovernmental Panel on Climate Change, 2001).

Theoretical Considerations Regarding Reactions with Rocks and Minerals—

Recent research has explored the feasibility and practicality of carbon dioxide sequestration by reaction with common minerals, also known as mineral carbonation (Lackner et al. 1995, 1997a,b,c; Butt and Lackner, 1997, Goff and Lackner, 1998; O'Conner et al. 2002; Voormeij et al. 2004; Mazzotti et al. 2005). Most studies have investigated the conversion of magnesium-iron-calcium silicates (olivine and pyroxenes) to carbonates of magnesium, iron, and calcium, but it is similarly possible to sequester carbon dioxide by reaction with iron oxide ore, manganese oxide ore, or other minerals to form iron and manganese carbonate minerals stable under atmospheric conditions. The reactions most applicable for minerals and rocks in Nevada are listed in Table 2.

Table 2. Theoretical weights and volumes of reactants and products in reactions between CO_2 and various rocks and minerals (data from Weast, 1971, Roberts et al. 1974, and Robie and Hemingway, 1995; modified from Price et al. 2005).

Mineral reactant	Ratio of weights of mineral reactant to C	Volume of mineral reactant (m^3/ton of C)	Ratio of weights of solid products to C	Volume of solid products (m^3/ton of C) assuming 20% porosity	Ratio of volumes of solid products to solid reactants	Heat generated (- Enthalpy of reaction) (kJ mol-^{1} CO_2)	Free energy of reaction (kJ mol-^{1} CO_2)*
1. Mg_2SiO_4 (forsterite)	5.86	1.82	9.52	4.09	2.24	88.65	-36.45
2. Fe_2SiO_4 (fayalite)	8.48	1.93	12.15	4.24	2.19	78.65	-27.00
3. $MgSiO_3$ (enstatite)	8.36	2.62	12.02	5.27	2.01	84.90	-33.10
4. $FeSiO_3$ (orthoferrosilite)	10.98	2.75	14.65	5.42	1.97	77.90	-26.70
5. $CaSiO_3$ (wollastonite)	9.67	3.32	13.34	6.20	1.87	89.80	-41.40
6. $CaAl_2Si_2O_8$ (anorthite)	23.16	8.39	26.83	11.22	1.34	77.00	-21.10
7. $NaAlSi_3O_8$ (albite)	43.66	16.67	47.33	21.18	1.27	5.60	52.20
8. $Mg_6Si_4O_{10}(OH)_8$ (antigorite)	7.69	2.98	10.35	4.49	1.51	64.13	-19.90
9. $Mg(OH)_2$ (brucite)	4.86	2.02	7.02	2.92	1.44	81.10	-38.70
10. MnO (manganosite)	5.91	1.10	9.57	3.23	2.93	114.20	-61.80
11. MnO_2 (pyrolusite)	7.24	1.43	9.57	3.23	2.26	-20.60	40.30
12. Fe_2O_3 (hematite)	6.65	1.26	9.65	3.06	2.42	-50.70	83.80
13. Fe_3O_4 (magnetite)	6.43	1.24	9.65	3.06	2.47	-9.50	49.17
14. Fe (iron)	4.65	0.59	9.65	3.06	5.18	362.40	-288.40
15. Hypothetical basalt	16.32	5.21	19.98	8.50	1.63	74.49	-21.11

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. $MgSiO_3$ (enstatite in pyroxenes) + CO_2 (gas) = $MgCO_3$ (magnesite) + SiO_2 (quartz)
4. $FeSiO_3$ (ferrosilite in pyroxenes) + CO_2 (gas) = $FeCO_3$ (siderite) + SiO_2 (quartz)
5. $CaSiO_3$ (wollastonite in pyroxenes) + CO_2 (gas) = $CaCO_3$ (calcite) + SiO_2 (quartz)
6. $CaAl_2Si_2O_8$ (anorthite in plagioclase) + CO_2 (gas) = $CaCO_3$ (calcite) + Al_2O_3 (alumina or corundum) + $2SiO_2$ (quartz)

9. $Mg(OH)_2$ (brucite) + CO_2 (gas) = $MgCO_3$ (magnesite) + 4H2O (water)
10. MnO (manganosite) + CO_2 (gas) = $MnCO_3$ (rhodochrosite)
11. MnO_2 (pyrolusite) + CO_2 (gas) = $MnCO_3$ (rhodochrosite) + $0.5O_2$ (gas)
12. Fe_2O_3 (hematite) + $2CO_2$ (gas) = $2FeCO_3$ (siderite) + $0.5O_2$ (gas)
13. Fe_3O_4 (magnetite) + $3CO_2$ (gas) = $3FeCO_3$ (siderite) + $0.5O_2$ (gas)
14. Fe (iron) + CO_2 (gas) + $0.5O_2$ (gas) = $FeCO_3$ (siderite)

* With the exception of reactions 7, 11, 12, and 13, all reactions are thermodynamically favorable (with respect to calculated negative Gibbs free energies of reaction at 25°C and 10^5 pascals).

15. The composition of this hypothetical basalt is calculated with the following assumptions:

Hypothetical Basalt	Mole fraction of minerals	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		

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 and their intrusive equivalents, gabbros. Basalts are 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. These rocks are termed mafic to describe their high magnesium and iron (ferrous) contents. Dissolved calcium in the oceans, and that trapped in limestone and dolomite, owes its origin primarily to the weathering and hydrothermal alteration of these mafic rocks, although dissolution of other common, feldspar-, amphibole-, and pyroxene-rich igneous rocks (granites, andesites, etc.) and carbonates undoubtedly contributes to the calcium budget of the ocean.

One approach to permanent CO_2 sequestration would be to speed up the natural process of mineral carbonation. Minerals in these rocks can react with CO_2 to produce various carbonates, silica, and alumina as reaction products. As indicated in Table 2, 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. These are ultramafic rocks, particularly Mg-rich igneous rocks, including dunite (a rock composed primarily of forsterite) and peridotite (a rock composed mostly of olivine and pyroxenes, minerals composed primarily of $(Mg,Fe,Ca)SiO_3$). Serpentinite, another ultramafic rock, is a rock composed mostly of serpentine minerals, such as antigorite, $Mg_6Si_4O_{10}(OH)_8$, which is nearly as favorable volumetrically as reaction with olivine (Table 2).

Coincidentally, the reaction of CO_2 with Mg_2SiO_4 or $Mg_6Si_4O_{10}(OH)_8$ is favorable thermodynamically and exothermic; heat generated from the reaction could provide energy needed to pulverize the rock, thereby speeding up the kinetics of the reaction. Mazzotti et al. (2005) discussed the status of engineering research on mineral carbonation, including problems of slow reaction kinetics. The reactions with several other minerals in Table 2 are also thermodynamically favorable. The exceptions include albite, the sodium end member of the plagioclase feldspar solid solution, and the oxides for which iron or manganese would have to be reduced to the divalent state (pyrolusite, hematite, and magnetite).

Goff and Lackner (1998) described the potential use of ultramafic rocks for CO_2 sequestration. They proposed a process 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. Nevad1a does, however, have abundant basalt and other mafic rocks (Figure 2).

The amount of CO_2 generated during the lifetime of a coal-fired power plant can be immense. 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 burn a quarter of a gigaton of carbon during a 50-year lifespan. We use this figure of 0.25 gigaton of carbon for comparison throughout the report. For example, using the hypothetical basalt composition in Table 2, 1.3 km^3 of basalt would need to be mined to react with 0.25 gigaton of carbon, and 2.1 km^3 of waste would be generated from the reaction, approximately 1.6 times the amount needed to refill the hole from which the basalt would be mined. For dunite and serpentinite, the volumes of reactant rocks would need to be 0.45 and 0.75 km^3, respectively, and the amount of waste would be 1.0 and 1.1 km^3, respectively. These volumes 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.

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 2), additional landfills would be required, or artificial hills would be constructed near the mining sites of the ultramafic rock or basalt. 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.

As outlined by Mazzotte et al. (2005), considerable engineering and environmental research would be necessary to determine whether this hypothetical approach to carbon sequestration (mineral carbonation involving mining of ultramafic or mafic rocks) is practical. Major issues to be resolved, if possible, include overcoming slow reaction kinetics (and the related energy costs of mining and comminution), taking advantage of the energy savings from the exothermic reactions, health concerns if dealing with rocks containing asbestos (as is the case with many serpentinites), and environmental concerns (ecological disturbance, reclamation involving volumes of waste materials that are larger than what was taken from the ground, impacts on groundwater and surface water, etc.) and social concerns (traffic, safety, noise, increased employment, demands on local infrastructure, sustainability, etc.) associated with surface mining operations.

Large outcrops of mafic rocks in Nevada are plotted with current railroads, piplelines, electrical transmission lines, and major CO_2 generators in Figure 2. In this report, we assess the volumes of mafic and ultramafic rocks in Nevada. Recognizing that approximately 87% of the state is managed by federal agencies, we have not evaluated these outcrops in terms of land ownership.

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 or significantly reducing 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.

McGrail et al. (2006) investigated in-situ reaction of CO_2 with basalt. This would involve pumping CO_2 into the ground, as with conventional approaches to geological sequestration. We believe that any attempt to achieve substantial permanent sequestration through in-situ mineral carbonation is impractical, because the large volume increase resulting from the chemical reactions (Table 2) would plug available pore space. For the example of the hypothetical basalt in Table 2, the ratio of volumes of solid products to reactants would be at least 1.31 (assuming no change in intergranular porosity) and perhaps as much as 1.63 (assuming a porosity of 20% within the product phases). That is, for the reaction to proceed to completion, with all the key reactants consumed, the in-situ basalt would need to have an initial porosity of 31%, well more than is likely to be found in nature. Whether significant volumes of CO_2 could be stored in a liquid phase within the pore spaces or open fractures in subsurface basalts is a separate question that would require thorough understanding of the hydrogeology (including the seals necessary to prevent escape of CO_2 under pressure). In this report, we restrict our consideration to above-ground reaction with rocks and minerals.

MAFIC AND ULTRAMAFIC ROCKS IN NEVADA

Sufficient volumes of basalt and ultramafic rocks likely 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. Small bodies of 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), occur in Mineral, northwestern Nye, and eastern Humboldt Counties.

The mafic and ultramafic rocks exposed in Nevada range in age from Paleozoic to Recent, but the overwhelming majority are post-Early Miocene (Figure 3, Table 3). The magmas

Table 3. Major exposures of mafic and ultramafic rocks in Nevada.

Rock Type	Age	Geologic Setting
Basalt, serpentinite, and dunite	Paleozoic	Oceanic lithosphere
Gabbro and basalt	Mesozoic	Lopolith
Basalt	Cenozoic	Basin-and-range extension

from which these rocks crystallized were formed in the lithospheric mantle and have undergone minor geochemical modification in the crust. The following contains a brief discussion of the tectonic setting of Nevada and the older ultramafic and mafic rocks, followed by geochemical and isotopic heterogeneities in Tertiary and Quaternary basalts. For a more thorough discussion the reader is directed to Dickinson (2001, 2004), DeCelles (2004), et al. cited below.

The oldest lithosphere in Nevada is a promontory of the Archean Wyoming province in northeastern Nevada (Lush et al. 1988). During the Proterozoic, several terranes were accreted to the Archean Wyoming province, including the Mojave (~2.0 billion years ago, or Ga), Yavapai (1.76 Ga) and Mazatzal (1.63 Ga) (Ball and Farmer, 1991; Magnani et al. 2004; Dubendorfer et al. 2006). Initial Proterozoic rifting began locally, and is recorded in deep epicratonal basins in Montana, Idaho (Belt basin), California (Death Valley), and Arizona (Unkar and Chuar). Renewed rifting began ~750-800 million years ago (Ma) with the breakup of Rodinia (Stewart and Suczek, 1977; Stewart, 1991). What is now western North America rifted away from a number of possible land masses, including Antarctica, Australia, China, and Siberia, although Siberia and/or Australia seem to be most likely (Moores, 1991; Dalziel, 1992, 1997; Karlstrom et al. 1999; Sears and Price, 2000, 2003; Stewart et al. 2001; Li et al. 2002).

Subsidence and cooling of the crust began nearly 150 Ma after initial rifting, allowing for deposition of a thick passive margin sequence. Initial deposition in Nevada included a terrigenous detrital sequence in the latest Proterozoic – Lower Cambrian and deeper water carbonate and shale in the Cambrian (Stewart and Szucek, 1977; Stewart, 1991). These rocks crop out in eastern and southern Nevada, and generally thicken to the west (Stewart, 1991). Passive margin deposition continued into the Devonian, when sedimentation was largely disrupted by a series of orogenic events, including the Antler and Sonoma orogenies. During the Devonian to Late Pennsylvanian Antler orogeny, the Roberts Mountains allochthon (composed of generally deep-ocean sediments, some basalts, and rare ultramafic rocks) was thrust eastward above the miogeoclinal sequence (generally shallower ocean sediments). The Sonoma orogeny occurred as another terrane-accretion event in the Late Permian – Early Triassic. Whereas these orogenies have been thought of as discrete events (Nilson and Stewart, 1980; Speed and Sleep, 1982), recent work by Trexler et al. (2004) has documented as many as seven tilting events in Pennsylvanian-Permian time, indicating that contractional deformation was more continuous than discrete during the mid to late Paleozoic. The long period of contraction resulted in stacking of thrust sheets and produced thick crust through much of Nevada, comparable to parts of the contemporary Andes.

Arc-related Sierra Nevada volcanism began in the Late Triassic, with episodes of back-arc spreading occurring intermittently during the Mesozoic and into the Cenozoic (Dickinson, 2002). Major pulses of magmatism occurred during the Middle Jurassic and Middle to Late Cretaceous (Moore, 2000; Ducea, 2001), concurrent with back-arc contraction in an arcuate belt between the Nevada-Idaho border and southeast California. The Laramide orogeny began in the Late Cretaceous. During this time magmatism and contractional deformation migrated eastward to the longitude of Colorado (Christiansen and Yeats, 1991), or ~1000 km east of the subduction zone. This volcanic/orogenic migration has been attributed to the flattening of the Farallon plate slab in the Late Cretaceous (Dickinson and Snyder, 1978).

Over-thickened crust began to locally extend rapidly after the end of the Laramide orogeny, eventually forming a belt of metamorphic core complexes that extends from British Columbia to Mexico (Armstrong, 1972; Coney, 1980; Davis et al. 1980; Wernicke, 1981; Miller et al. 1983; Bartley and Wernicke, 1984; Reynolds and Spencer, 1985; Davis and Lister, 1988; Wernicke, 1992). The plate boundary in southern California began to switch from subduction to a dextral strike-slip transform about 30 Ma, although it did not fully organize into the San Andreas fault as we know it until about 17 or 18 Ma, when basin-and-range extension (with steeply dipping normal faults forming along the edges of many current mountain ranges and adjoining sediment-filled basins) began in Nevada (Atwater 1970, Dickinson, 1997; Atwater and Stock, 1998).

Beginning in the Eocene two volcanic fronts began to migrate towards southern Nevada; one moving southward from Idaho and the other moving west-northwest to northward from New Mexico and Arizona (Christiansen and Yeats, 1991; Faulds et al. 2001). The southward migrating front stalled in central Nevada during late Oligocene-early Miocene time and produced multiple calderas that resulted in the widespread deposition of ash-flow tuffs in Nevada, eastern California, and Utah (Axen et al. 1993). The northward-migrating volcanic front abated just south of Las Vegas ~13 Ma, though no caldera-forming eruptions appear to have been associated with the stall (Christiansen and Yeats, 1991; Faulds et al. 2001). The Las Vegas amagmatic zone lies between the two stalled fronts, between latitudes 36°N and 37°N (Eaton, 1982).

Two types of volcanism dominated after ~18 Ma: dominantly andesitic calc-alkaline volcanism and bimodal (basalt-rhyolite) volcanism. The andesitic volcanism is consistent with derivation from an arc system, whereas the bimodal volcanism is interpreted as related to extension (Christiansen and Yeats, 1991; John et al. 1999; Garside et al. 2000). Large volume basaltic volcanism occurred in Washington and Oregon during the initial stages of the bimodal volcanism (~18-15 Ma) although these events may not be directly related to basin-and-range extension (Dickinson, 1997). Arc volcanism began to shut off as the Mendocino triple junction propagated northward, with andesitic volcanism ending at the latitude of Reno around 7 Ma. Arc volcanism continues locally in northeastern California, with Mount Shasta and the Lassen volcanic fields as prominent features. Locally basaltic and volumetrically less rhyolitic volcanism has occurred in the Quaternary in Nevada (Scott, 1969; Scott and Trask, 1971; Naumann et al. 1991; Rash, 1995; Yogodzinski et al. 1996; Smith et al. 2002; Smith and Keenan, 2005).

Most of the mafic to ultramafic rocks exposed in Nevada are extension-related and were erupted during the past ~18 Ma. The main exceptions are Paleozoic serpentinite and oceanic basalt and a Mesozoic mafic lopolith. The serpentinite is part of the mélange obducted onto North America during Paleozoic-Mesozoic orogenies. Basaltic Pennsylvanian and Eocene dikes crop out in the Independence Mountains in Elko County (Phinisey, 1995), but these occurrences are volumetrically minor. Minor mafic rocks also crop out in Mesozoic metamorphic rocks in western Nevada (Proffett and Dilles, 1984).

The only ultramafic rocks exposed in Nevada are small scattered lenses of Paleozoic serpentinite in the Candelaria area of Mineral and Esmeralda Counties and in northern Nye County (Page, 1959; Stewart and Carlson, 1978; Kleinhampl and Ziony, 1985) and exposures of ultramafic rocks in the Twin Creeks Mine in Humboldt County (Thoreson et al. 2000). These minor occurrences are most likely related to Paleozoic-Mesozoic accretion of Paleozoic crust and upper mantle.

Geochemistry

Throughout Nevada the geochemical and isotopic compositions of basalts vary both temporally and spatially. The temporal variation may be related to the change in type of plate boundary to the west (Farmer et al. 1989; Glazner and Ussler, 1989; Fitton et al. 1991), late Cenozoic asthenospheric upwelling (Fitton et al. 1991), lithospheric delamination (Humphreys, 1995; Ducea and Saleeby, 1998), and/or relative crustal thinning (Glazner and Ussler, 1989). Spatial variations in geochemical and isotopic data probably are due to a combination of crustal (Brandon, 1989; Fitton et al. 1991; Kempton et al. 1991) and mantle lithosphere (Hedge and Noble, 1971; Mark et al. 1975; Leeman, 1982; Menzies, 1989; Fitton et al. 1991; Kempton et al. 1991; Rogers et al. 1995) heterogeneities.

Initial Cenozoic volcanism in Nevada was dominantly intermediate to felsic in composition, though volcanism was more bimodal (felsic plus mafic, without significant intermediate compositions) but primarily basaltic beginning about 18 Ma. This may have been due to the end of subduction and the coalescence of the proto-San Andreas fault off the coast of California at that time (Dickinson, 1997). The northern Nevada rift formed 17–14 Ma; it is a 500 km-long, 4–7 km-wide zone of basaltic dikes that extends from the Nevada-Oregon border to southern Nevada, and is coeval and geochemically similar to the Columbia River flood basalts (Zoback, 1978; Zoback and Thompson, 1978; Hildebrand and Kucks, 1988; Blakely and Jachens, 1991; Zoback et al. 1994; John et al. 2000b; Wallace and John, 2000; Leavitt et al. 2000; Ponce and Glen, 2002; Grauch et al. 2003). Glazner and Ussler (1989) pointed out that at least some of the basaltic volcanism does not directly correlate with basin-and-range extension, because many syn-extensional volcanic rocks are intermediate to silicic in composition. They suggested that the change to dominantly basaltic volcanism is related to crustal thinning due to extension. As the crust thins, magma generated in the mantle will move through the crust faster, and the amount of magma-crustal interaction will decrease.

It appears that variations in major oxide, trace element, and isotopic compositions of basalts could not have possibly been due to crustal interaction alone and must be due, at least in part, to heterogeneities in the lithospheric mantle (Ormerod, 1988; Ormerod et al. 1988; Lum et al. 1989; Menzies, 1989; Rogers et al. 1995). Lum et al. (1989) compared two end member basalts to see if the differences in the basalts could have been due to crustal interaction alone and concluded that there must be heterogeneities in the lithosphere.

Menzies (1989) used seismic tomography, heat flow, and xenolith thermobarometry to map out lithospheric mantle domains in the western United States (Figure 4). He separated the mantle lithosphere into four domains, two domains of enriched mantle, one depleted mid-ocean ridge basalt mantle domain, and one domain similar to mantle underlying ocean island basalts. One of the enriched mantle domains is restricted to sub-Archean areas in Wyoming, Utah, and northeastern Nevada. The depleted mid-ocean ridge mantle domain (DMM in Figure 4) is below Proterozoic/Phanerozoic crust but not Archean crust. The other enriched mantle domain (EM2) is widespread beneath Proterozoic crust, and it seems to replace depleted mid-ocean ridge mantle in some areas. Formation of the enriched mantle domain may be related to subduction or recycling processes. The ocean island basalt mantle (OIB) area occurs in an area of upwelling beneath the southern Basin and Range, and it partially replaces older mantle. Depleted mid-ocean ridge mantle may represent a sub-Proterozoic lithosphere that existed prior to the subduction-related creation of more enriched mantle. Spatial arrangement of lithospheric mantle domains is representative of the tectonic history that led to their formation. Archean crustal production, and stabilization led to the enriched mantle domain. In the Proterozoic, subduction may have led to the enriched mantle domain. Cenozoic asthenospheric upwelling has led to the ocean-island basalt domain (Menzies, 1989).

Geochemical data (major oxide, minor element and some trace element analyses) were assembled for approximately 450 Nevada rocks (Appendix 1, which is available on line at www.nbmg.unr.edu/dox/r52/r52append.htm). Most of the analyses were found in the NAVDAT (http://navdat.kgs.ku.edu) and PETROS (http://www.ngdc.gov/mgg/geology/petros.html) databases. These databases contain published and unpublished geochemical data from the 1800s through 1980 (PETROS) and since 1980 (NAVDAT). More geochemical data were found in papers and unpublished theses that had yet to be incorporated into the NAVDAT database. For areas where data were scarce, we collected a few samples and analyzed them for major oxide compositions (Table 4). In most other cases, the rocks selected from the geochemical databases had $SiO_2 < 55\%$ by weight.

A helpful way of comparing chemical compositions of igneous rocks is through calculations of normative mineralogy, hypothetical minerals that would form if magma of a given chemical composition crystallized slowly at low pressure (Iddings, 1909). Cross, Iddings, Pirsson, and Washington (CIPW) norms were calculated for 200+ basalt analyses. Calculations were completed using the CIPW, meso- and kata-norm calculator from the Saskatchewan isotope laboratory (http://sil.usask.ca/software.htm). Preferred samples are those with normative olivine greater than 10%, especially with dominantly normative forsterite. A large percentage of forsterite is preferred, because the greater the amount of normative forsterite (e.g., the more mafic), the less waste product produced by the reaction with carbon dioxide (Table 2). The rocks that are highest in normative forsterite are generally dunites, serpentinites, and basalts that are particularly Mg rich. Igenous rocks with high concentrations of Fe and Ca, as well as Mg (basalts), are also favorable, but less so than those with particularly high concentrations of Mg. If and when specific rocks are evaluated for mineral carbonation reactions, careful petrographic work would need to be undertaken to determine actual mineralogy, not relying on the calculated norms.

Of approximately 450 samples for Nevada, 100 had CIPW olivine norms greater than 10% (Appendix 2, which is available on line at www.nbmg.unr.edu/dox/r52/r52.append.htm). Most of these analyses were from the basalt fields of eastern Nye County, southern Mineral County, northern Esmeralda County, eastern Clark County, southern Pershing County, and southern Washoe County (Figures 5 and 6).

Table 4. Major element analyses of selected mafic rock samples from western Nevada.

Major Oxides* (%)	M05-1	M05-2	M05-3	M05-6	M05-7	M05-8
SiO_2	51.3	49.8	58.3	53.7	58.4	55.3
TiO_2	0.96	1.20	1.45	0.85	0.72	1.20
Al_2O_3	19.2	18.2	15.8	16.4	18.2	17.1
Fe_2O_3	9.73	9.92	7.94	8.47	6.58	7.59
MnO	0.15	0.15	0.19	0.15	0.12	0.12
MgO	5.44	5.62	1.16	7.21	2.15	4.02
CaO	9.88	8.30	3.83	10.0	6.01	6.52
Na_2O	2.53	3.40	4.86	2.05	3.98	3.69
K_2O	0.51	1.17	3.62	0.77	2.02	3.00
P_2O_5	0.22	0.40	0.78	0.13	0.30	0.73
LOI	0.92	0.97	1.54	0.14	0.65	0.12
Total	100.8	99.1	99.4	99.9	99.1	99.4

* Analyses of major oxides by x-ray fluorescence at the Nevada Bureau of Mines and Geology (Paul Lechler, Chief Chemist). LOI = loss on ignition.

Sample	Location	UTM (NAD 1983)
M05-1	Western Smoke Creek Desert, Washoe County	11 T 278784/ UTM 4505319
M05-2	Hwy 447, northern Washoe County	11 T 286832/ UTM 4522013
M05-3	Sheldon Antelope Range, northwestern Humboldt County	11 T 286943/ UTM 4634886
M05-6	US 95, north of Winnemucca, Humboldt County	11 T 439450/ UTM 4543640
M05-7	US 95, southeast of Hawthorne, Mineral County	11 S 373409/ UTM 4268302
M05-8	Near Belleville, Mineral County	11 S 395609/ UTM 4229341

Procedure for Evaluating Mafic Volcanic Fields

Basalt outcrops are located in every county in Nevada (Figure 3), but many of these outcrops contain much less than the 1 km^3 necessary to supply a power plant for 50 years. Because a large volume of basalt is needed for carbon dioxide sequestration, we chose to focus this study on the largest basalt fields in Nevada (Figure 3) and disregard areas with only thin basalts exposed (Figure 7). In order to calculate the thickness of basalts in these areas, we combined existing maps and LANDSAT images to estimate aerial extent, and existing geologic maps, air photos, topographic maps, and field observations to estimate thickness and thickness variations (see below).

Basalt fields that met the volume requirement were then combined with geochemical and selected geospatial data in order to determine which field(s) may be favorable for future development. The geochemical data are fairly sparse and are only meant to be used as a broad characterization of the basalts in each field. The geospatial data includes proximity of the basalt fields to existing roads, railroads, and power lines, all of which affect the cost and/or placement of future power plant(s) that could use basalt to sequester carbon dioxide.

Procedure for Assessing Mafic Rock Volume

The first step was to constrain the aerial extent of basalt in the selected fields using the 1:500,000-scale digital state geologic map (Stewart and Carlson, 1978) and 92/93 LANDSAT images (available at http://keck.library.unr.edu/data/landsat/pathrow.html). The state geologic map was converted from a NAD 1927 projection to NAD 1983 projection so that 1:24,000-scale digital orthophotoquads (DOQs) could also be overlaid on the geologic map. The geologic map was set on 60% transparency and laid over the DOQs in ARCMAP 9.1. Mafic and ultramafic areas of interest were then redigitized in ARCMAP 9.1 based on the state geologic map but modified by the color contrasts seen on the LANDSAT images.

Thicknesses were estimated using a combination of existing data, air photos, topographic maps, and field photos. Several control points were chosen for each study area. True dip was taken from existing geologic maps, if available. Estimates for the dip and percentage of basalt at a control point were taken from the air photos and geologic maps, and an apparent thickness was calculated from a topographic map using elevation differences between top and bottom of the basalt flows. Field reconnaissance photography was also done to help estimate basalt thickness. Photos were taken (usually at distance) in order to find estimates of percent basalt and basalt dip at a control point and then combined with data from a topographic map to calculate thickness. Geologic maps were used to help convert apparent dip from photographic angles to true dip (using the relationship $\tan(\delta) = \tan(\delta')\cdot\cos(\gamma)$, where δ = true dip, δ' = apparent dip, and γ = angle of divergence between the direction of the true dip and the apparent dip). At each measurement point, true thickness of mafic rock, t, was estimated using the following formula:
$t = f\cdot a\cdot\cos(\delta)$, where
f = fraction of thickness that is mafic rock (as opposed to, for example, interbedded tuff);
a = apparent thickness measured from topographic elevations; and
δ = true dip of the mafic rocks.

Using the thickness control points, we then contoured the areas containing mafic rocks with a 30-m contour interval, with the exception of the Humboldt lopolith (100-m contour interval). The digitized lines and points were converted into polygons in ARC Catalog, and the newly created shape file with basalt thickness polygons was brought back into ARCMAP 9.1. In order to calculate the volume, the area of each polygon was multiplied by the basalt thickness for that polygon and converted from m^3 to km^3. The thickness values given for each polygon are the average of the bounding thickness contours. When there is only one bounding contour (thickest sections), the thickness used is a preexisting maximum thickness estimate (if one exists) or 15 m greater than the highest contour (if a maximum thickness estimate does not exist).

Our volume estimates are minimum numbers for three major reasons. First, we have not made an attempt to project basalts under alluvial cover. Although it is certain that basalts occur beneath valley-filling alluvium, we have limited our volume calculations to areas of known basalt outcrops in the highlands, as outlined by Stewart and Carlson (1978). Second, for the Humboldt lopolith, we have calculated thicknesses of the mafic units only above the valley floors. That is, volume below the elevations of the valley floors is not considered, with the rationale that deeper mining would be more costly than mining in the hills because of the need to pump groundwater during the mining operation. Third, our volume estimates are minimum numbers for steeply dipping basalts, because we use true thickness, rather than vertical depth, to multiply by surface area. Our volume estimates should be divided by the cosine of the dip to provide more accurate estimates; however, for the purpose of this study (in which an error of a factor of two or three is acceptable), the dip of the basalt only introduces a large underestimation when it exceeds 60° (for which the cosine is 0.5). With the exceptions of steeply dipping basalts that occur locally in the area of southern Washoe, Storey, Lyon, and Churchill Counties, most of the basalts in the areas studied for this report are gently dipping or nearly horizontal.

Because this procedure does not involve actually measuring sections, it probably has a fair amount of error associated with it, such that thickness estimates are probably good to one significant figure. This error will propagate through to the volume calculation so that the volumes are only accurate to one significant figure. That is acceptable for the purposes of this report, but the field should be studied in greater detail to generate more accurate volume estimates if and when basalt is going to be used to sequester CO_2 in Nevada,.

Description of Selected Mafic Rock Fields

Nine mafic rock fields in Nevada were studied, and all meet the volume requirement for carbon dioxide sequestration (Table 5). Polygon volume data can be found in Appendix 3, which is available on line at www.nbmg.unr.edu/dox/r52/r52append.htm. Each field is briefly described below.

Table 5. Estimated volumes of mafic rocks for the studied fields.

Field	Estimated Volume (km^3)	Volume requirement met?
Northwestern Washoe County	139	Yes
Owyhee Plateau	177	Yes
Battle Mountain area	29	Yes
Southern Washoe/Storey/ Lyon/Churchill/Pershing Counties	176	Yes
Humboldt lopolith	31	Yes
Southwestern Mineral/ Northwestern Esmeralda Counties	41	Yes
Reveille/Pancake Ranges*	9	Yes
San Antonio Mountains	13	Yes
Southern Clark County	3+	Not necessarily

* Estimate from Yogodzinski et al. (1996).

Northwestern Washoe County

The area studied in northwestern Washoe County extends from west of the Smoke Creek desert on the south to southern Long Valley on the north, and includes portions of the Hays Canyon Range, Granite Range, Buffalo Hills (Figure 8), Buffalo Meadows, and Poodle Hills (Figure 9). Rocks in this area were grouped into the Canyon Assemblage by Bonham and Papke (1969). The geomorphology in the area is dominated by flat-lying plateaus to gently dipping fault blocks bounded by basin-and-range normal faults. Cenozoic and Quaternary rocks comprise ~90% of all outcrops. Lithologies are dominantly volcanic, mostly basalt with lesser andesite, dacite, rhyolite, and intercalated tuffaceous sediments (Bonham and Papke, 1969).

Mafic rocks are exposed throughout much of northern Washoe County, especially in the Hays Canyon and Granite Ranges, and in the Buffalo and Poodle Hills. The most common type of basalt in the area is reddish-brown to black weathered, dark-gray fresh, augite-plagioclase-olivine aphyric basalt (Bonham and Papke, 1969). Relatively little published geochemical data exist from this area. Our samples from this area (M05-1 and M05-2, Table 2) were hypersthene-normative and did not contain normative olivine. However, based on rock descriptions and hand samples, olivine is present in most of these basalts.

Basalt thickness is extremely variable from ~30 m near the Oregon border to ~300 m at Poodle Mountain and in the Hays Canyon Range (Bonham and Papke, 1969). Individual flows are commonly 3-7 m thick. Because the basalt in this area covers such a large area, the thickness required for 1 km^3 is minimal. Based on the estimated thicknesses (Appendix 3) the volume of basalt in this area is ~139 km^3.

Owyhee Plateau

These basalts are located in northeastern Humboldt and northwestern Elko Counties, as well as extending north into Oregon and Idaho (Figure 10). This 17–11 Ma basalt plateau (Shoemaker and Hart, 2004) is a center of volcanism on the Yellowstone hotspot track. On the state geologic map, the basalts in this area are part of the Banbury Volcanics (Stewart and Carlson, 1978), though the basalts were renamed the Big Island Formation by Coats (1985). The Big Island Formation includes ~100 m of boulder gravel, covered by ~6 m of rhyolitic tuff, and ~60 m of tholeiitic olivine basalt. Above the plateau surface are scattered small shield volcanoes and cinder cones, none of which is more than ~90 m above the plateau (Coats, 1985). Basalts are fairly uniform in phenocryst assemblage, geochemistry, and age throughout the plateau (Coats, 1985). CIPW norm values reported by Coats (1985) range from 0 to 14.7 % normative olivine, although all but one analysis had greater than 5% normative olivine. This field is the most voluminous mafic field, with an estimated 177 km^3 of mafic rock.

Battle Mountain Area

A thick section of northern Nevada rift basalts occupies the southern Sheep Creek and northern Shoshone Ranges (Argenta Rim) of northern Lander and Eureka Counties (Figure 11). The basalts range in age from 15.85 Ma to 14.7 Ma (John et al. 2000a) and have an estimated volume of 29 km^3. The northern Nevada rift related rocks have been divided into five units, including (from oldest to youngest) the Mule Canyon sequence (basalt and andesite), the andesite of Horse Heaven, porphyritic dacite, trachydacite, and olivine basalt (John et al. 2000a). If deep surface mining were considered, additional volumes of basalt presumably could be mined from feeder dikes for the basalt flows exposed in this area. One possible area to consider initially would be the Mule Canyon gold mine, where a basalt-andesite volcanic center, including dikes and flows of basalt, was mined (John et al. 2000a, 2003), and sufficient mafic rock may be available for pilot testing of mineral carbonation.

Southern Washoe/Storey/Lyon/Churchill Counties

Mafic rocks crop out throughout southern Washoe, Storey, Lyon, Churchill, and parts of Pershing Counties (Figures 12-17). Basalts in this area are post-~12-18 Ma. The most voluminous basalt package is the 16-12 Ma Pyramid sequence (Bonham and Papke, 1969; Garside et al. 2000; Faulds et al. 2003a, b; Henry et al. 2004; Drakos, 2007). More recent lava flows, including the Lousetown (11-6 Ma, John et al. 1999; Schwartz, 2001) and McClellan Peak (1.5-1.44 Ma, Silberman and McKee, 1972; Morton et al. 1980; John et al. 1999; Schwartz, 2001) Basalts, are thinner and less widespread than the Pyramid sequence basalts. Basalt caps most of the ranges and locally is up to 1 km thick. The mafic rock in this field has a volume of 176 km^3, though the outcrops are spread over a large area.

Humboldt Mafic Lopolith, Churchill and Pershing Counties

The Jurassic Humboldt igneous complex is exposed in the West Humboldt and Stillwater Ranges, the Clan Alpine Mountains, the Carson Sink area, and ranges bordering Dixie Valley (Figure 18). The plutonic sequence includes, from the bottom, olivine gabbro (35 % olivine), melatroctolite (10 % olivine), hornblende gabbro (10 % olivine), microgabbro and diorite, and more felsic intrusions (Speed, 1962). Published ages for the complex include 165±5 Ma and 145±5 Ma, which are K-Ar ages on hornblende and biotite from a gabbro in the West Humboldt Range (Willden and Speed, 1974) and 157±4 Ma, K-Ar on hornblende from diorite in the Stillwater Range (Dilek and Moores, 1995). However, these ages may be anomalously young as the entire complex has been hydrothermally altered (Vanko and Bishop, 1982). The sequence is probably Middle Jurassic (Dilek and Moores, 1995; Johnson and Barton, 2000b).

The olivine gabbro-hornblende gabbro section of the plutonic complex is only exposed locally. The microgabbro-diorite unit is the most extensively exposed plutonic unit. A 100-m-wide basaltic dike swarm intrudes the microgabbro at Cottonwood Canyon and farther south (Dilek and Moores, 1991). Basaltic lavas related to the plutonic complex are exposed at the top of the extrusive segment of the igneous complex. The estimated volume of this unit is 31 km^3, more than an order of magnitude smaller than the ~1,300 km^3 estimate of Willden and Speed (1974). We believe that our volume estimate is considerably smaller because we only include mafic units within the complex and because we only include material above the elevation of the valley floors.

Southwestern Mineral/Northwestern Esmeralda Counties

Late Tertiary (post 5 Ma) basalts are exposed throughout southwestern Mineral and northwestern Esmeralda Counties (Figure 19), especially prevalent east of Aurora, between Candelaria and Teel's Marsh, along the border with California, and in the Garfield, Anchorite, and Volcanic Hills (Ross, 1961; Albers and Stewart, 1972; Brem, 1978; Ormerod, 1988). Thicknesses of basalt approach ~300 m (Ross, 1961), and the estimated volume is 41 km^3. The mafic rocks here are usually dark-gray to gray-black fresh, vesicular, and aphyric with small phenocrysts of olivine, hypersthene, and/or augite. Mafic rocks in this area are generally highly potassic, and as such are classified as trachybasalts, trachyandesites, and quartz latites (Figures 20 and 21; Ross, 1961).

Reveille/Pancake Ranges, Eastern Nye County

Some of the youngest basalts in Nevada are in the Lunar Crater volcanic field (LCVF) in the southern Pancake Range. This is at the northern end of NNE-trending zone of Pliocene-Holocene (?) mafic volcanism that extends from Death Valley to the southern Pancake Range (Vaniman et al. 1982; Farmer et al. 1989; Yogodzinski et al. 1996; Smith et al. 2002; Smith and Keenan, 2005). While volcanism at the LCVF is the youngest in eastern Nye County, older basalts to the south in the Reveille Range are more voluminous (Figure 22). Yogodzinski et al. (1996) estimate that ~9 km^3 of Pliocene basalt occurs in the Reveille Range. Basaltic volcanism reached a peak during the Pliocene, becoming more localized and sporadic during the Quaternary (Yogodzinski et al. 1996).

Mafic volcanism began ~14 Ma in the Reveille Range and continued until ~3 Ma (Rash, 1995; Yogodzinski et al. 1996). The initial mafic volcanism was basaltic and is exposed in the northwest Reveille Range with an estimated volume of ~0.05 km^3 and a thickness of up to 30 m where exposed (Rash, 1995). The next episode of basaltic volcanism (episode 1 of Naumann et al. 1991) occurred between 5.9 and 5.1 Ma. These are porphyritic olivine basalts (hawaiites) with plagioclase megacrysts. They erupted from 52 vents with an estimated volume of 8 km^3 (Naumann et al. 1991; Rash, 1995; Yogodzinski et al. 1996). Following the eruption of 4.24-4.39 Ma trachytes (Naumann et al. 1991) a second package (episode 2) of basalts was erupted between 4.24(?) and 3.00 Ma. These are porphyritic plagioclase-clinopyroxene-olivine basalts (mostly basanites with lesser hawaiites). They erupted from 14 vents with an estimated volume of 1 km^3 (Naumann et al. 1991; Rash, 1995; Yogodzinski et al. 1996). Because published volume estimates are based on detailed study of the mafic field, those estimates are used for this report.

More recent mafic volcanism has occurred in the Quaternary-Holocene (?) in the southern Pancake Range at the LCVF, which contains numerous cinder cones and lava flows (Figures 23 and 24; Scott, 1969; Scott and Trask, 1971; Smith et al. 2002, Smith and Keenan, 2005). These flows cover ~250 km^2 but are fairly thin. Many of the flows contain mafic and ultramafic xenoliths of olivine ± pyroxene ± plagioclase (Scott, 1969; Scott and Trask, 1971). Because the mafic rocks in the Pancake Range are thin, they are not included in the volume estimate for the field.

Based on geochemical and isotopic data, Yogodzinski et al. (1996) found that these basalts were derived from asthenospheric melts. The episode 2 basalts have $^{87}Sr/^{86}Sr$ of 0.7035 and ε_{Nd} of +4.2, but the episode 1 basalts have more variable $^{87}Sr/^{86}Sr$ (up to 0.7060) and ε_{Nd} (+0.8 to +4.5). Additional variations in Sr/Nd and Pb/La require that the episode 1 basalts have a crustal component, probably carbonate wall-rock. Because basanites only were erupted during episode 2, these eruption episodes were probably caused by separate melting events (Yogodzinski et al. 1996).

San Antonio Mountains, western Nye County

Most of the San Antonio Mountains and Thunder Mountain in the Monitor Range consist of basalt (Figure 25). Basaltic volcanism in this area came at the end of volcanic activity in the Tonopah area, and the basalt caps much of the San Antonio Mountains. Red Mountain, which is north of Tonopah, was one source of the basalt. Another volcanic center occupies the northern end of the San Antonio Mountains at the San Antone mining district (Kleinhampl and Ziony, 1985). Estimated basalt volume is 13 km^3.

Southern Clark County

Basaltic rocks are exposed in Clark County between Las Vegas and Searchlight (Figure 26). Those considered for this study are in the McCollough Range (Figure 27) and Eldorado Mountains. More basalt is exposed in the Black, River, and South Virgin Mountains, but because these ranges are in the Lake Mead National Recreation Area, they were not considered for this study. The volcanic units in this area were divided into three main members by Anderson (1971); those are 1) the Patsy Mine Volcanics, 2) the tuff of Bridge Spring, and 3) the Mount Davis Volcanics. Faulds et al. (2001) show eight episodes of volcanism in the Lake Mead area, including 1) mafic to intermediate 21-18.5 Ma “Pre-Patsy Mine Volcanics”, 2) 18.5 Ma Peach Springs Tuff (Glazner et al. 1986; Nielson et al. 1990), 3) 18.5-15.2 Ma basaltic andesite to rhyolite of the Patsy Mine Volcanics (Anderson, 1971; Anderson et al. 1972; Faulds et al. 1995;

Faulds, 1996), 4) 15.2 Ma tuff of Bridge Spring (Anderson et al. 1972; Morikawa, 1994; Faulds et al. 1995) and the 15.0 tuff of Mount Davis (Faulds 1995; Faulds et al. 2002), 5) 15-~12 Ma basalt to basaltic andesite of the Mount Davis Volcanics (Anderson et al. 1972; Faulds, 1995), 6) local 11.9-8.7 Ma tholiitic basalt fields, including Malpais Flattop Mesa in the northern Black Mountains, 7) local 10.6-8.0 Ma basaltic andesites, including those at Callville Mesa, and 8) 6.0-4.5 Ma alkalic Fortification Hill basalts (Feuerbach et al. 1993).

Whereas basalt is present in southern Clark County, the overwhelming majority of the volcanic rocks are andesites, basaltic andesites, and dacites (Anderson, 1977; 1978). The Tertiary volcanic section in this area is on the order of ~5 km thick, but basalt only comprises 10-150 m of the section (Anderson, 1977; Faulds et al. 2001). The final stage of volcanism is basaltic, but that is confined to eastern Clark County (in the Lake Mead National Recreation Area) and northwestern Arizona (Faulds et al. 2001). Structural complexity (especially in the Eldorado Mountains) makes obtaining an accurate "above valley-fill" basalt volume estimate exceedingly difficult. Additionally, much of this area is part of the newly formed McCollough Mountains Wilderness Area and would therefore be off limits for mining. Nonetheless, a range of basalt volumes was calculated by multiplying the area of volcanic rocks (Figure 26) by the basalt thicknesses. The basalt volume ranges between 3.4 and 50.6 km^3, though the majority of this is not exposed at or near the surface. More work would need to be done to determine the amount of basalt outside the wilderness area.

OTHER NEVADA MINERAL RESOURCES THAT COULD BE AMENABLE TO SEQUESTRATION OF CO_2

We have made a literature survey of iron and manganese deposits in an effort to determine the extent of remaining reserves of iron and manganese ore in Nevada that might be amenable for use in carbon sequestration by mineral carbonation. Significant deposits of iron and manganese in Nevada with sufficient reserves to use in carbon dioxide sequestration are summarized in Table 6 showing their names, location, land status, predominant mineralogy, past production, and estimated remaining reserves.

A location map of iron and manganese deposits and other minerals amenable to mineral carbonation in Nevada is shown in Figure 28 illustrating proximity to railways, highways, and existing power plants. Other considerations of iron and manganese deposits besides reserve tonnage are:

- proximity of the deposits to rail transport or to existing or future coal-fired power plants
- amenability of the mineralogy of the deposits to carbonate formation
- land status (public or private)
- depth and geometry of the deposits (cost of extraction)

Significant Iron Deposits of Nevada

Total tonnage of resources remaining in Nevada iron deposits was estimated in 1964 at between 0.5 billion and 1.0 billion metric (approximately the same as long) tons of material grading more than 40% iron (Reeves, 1964). Nevada's iron production dropped off sharply in the 1960s and

Table 6. Significant deposits of iron, manganese, and other minerals in Nevada with sufficient reserves to be considered for use in carbon dioxide sequestration.

Site Name	District Name	County Northing	UTM Easting	UTM (NAD 27)	Latitude (NAD 27)	Longitude	Ore Minerals	Land Status	Past Production	Estimated Remaining Reserves
IRON DEPOSITS										
Buena Vista Hills, Churchill & Pershing Counties										
Buena Vista Mine	Mineral Basin	Churchill	4425400	400000	39-58-29N	118-10-16W	magnetite, hematite	patented and BLM-administered land	Collectively, the mines of the Buena Vista Hills produced over 4 million tons of iron ore averaging over 50% Fe over a production history that peaked in the 1950s and dwindled in the 1980s.	Collectively the Buena Vista Hills mines contain an estimated 1.5 million tons grading 50–60% Fe plus a significant tonnage of lower grade material.
Segerstrom-Heizer Mine	Mineral Basin	Pershing	4432890	402220	40-02-32N	118-08-51W	magnetite, hematite, pyrite, marcasite	patented and BLM-administered land		
Thomas Mine	Mineral Basin	Pershing	4438100	398680	40-05-20N	118-11-19W	magnetite, hematite	patented and BLM-administered land		
American Ore Co. Mine	Mineral Basin	Pershing	4433225	403040	40-02-49N	118-08-12W	magnetite	patented and BLM-administered land		
American Ore Co. Mine (North)	Mineral Basin	Pershing	4437570	399060	40-05-11N	118-11-17W	magnetite	patented and BLM-administered land		
American Ore Co. Mine (South)	Mineral Basin	Pershing	4431650	401550	40-01-52N	118-09-14W	magnetite	patented and BLM-administered land		
Cortez Mountains, Eureka County										
Barth Mine (West Mine)	Safford	Eureka	4492025	561832	40-34-43N	116-16-10W	Hematite, magnetite, specular hematite	patented and BLM-administered land	Collectively the Cortez Mountains area mines produced about two million tons of iron ore. The main periods of production were 1903–1918 and 1950s–1960s, with sporadic production into the 1980s.	Collectively the Cortez Mountains area mines and prospects contain an estimated 3.5 million tons of material grading about 50% Fe plus a significant tonnage of lower grade material.
Unnamed Iron Deposit	Safford	Eureka	4496500	565813	40-37-07N	116-13-19W	magnetite, hematite	patented and BLM-administered land		
Modarelli (Amarilla) Iron Mine	Modarelli-Frenchie Creek	Eureka	4468474	562640	40-21-59N	116-15-44W	martite, magnetite	BLM-administered land		
Sheep Creek Prospect	Modarelli-Frenchie Creek district	Eureka	4461505	558779	40-18-14N	116-18-30W	magnetite, hematite	BLM-administered land		
Big Pole Creek	Modarelli-Frenchie Creek	Eureka	4465880	558320	40-20-36N	116-18-48W	magnetite, hematite	BLM-administered land		
Jackson Prospect	Modarelli-Frenchie Creek	Eureka	4468342	557688	40-21-56N	116-19-14W	hematite, magnetite	BLM-administered land		
Imperial Prospect	Modarelli-Frenchie Creek	Eureka	4467959	559979	40-21-43N	116-17-37W	magnetite, hematite	BLM-administered land		
Frenchie Creek Prospect	Modarelli-Frenchie Creek	Eureka	4467345	560338	40-21-23N	116-17-22W	magnetite, hematite	BLM-administered land		
Frenchie Canyon Prospect	Modarelli-Frenchie Creek	Eureka	4466719	559187	40-21-03N	116-18-11W	hematite, magnetite	BLM-administered land		
Jackson Mountains, Humboldt County										
Iron King (DeLong) Mine	Jackson Mountains District; Jackson Creek	Humboldt	4573700	381000	41-18-36N	118-25-22W	magnetite, hematite	patented and BLM-administered land	Collectively the three main Jackson Mountains mines produced probably less than a million tons of iron ore, mainly in the 1950s.	Collectively the three main Jackson Mountains mines contain an estimated 750,000 tons of material grading between 15–40% Fe.
Black Jack (Humboldt) Mine	Jackson Mountains District; Jackson Creek	Humboldt	4572800	380300	41-17-29N	118-26-22W	magnetite, hematite	patented and BLM-administered land		
Redbird Mine	Jackson Mountains District; Jackson Creek	Humboldt	4573120	381000	41-18-10N	118-25-17W	magnetite	patented and BLM-administered land		

continued

Table 6 (continued). Significant deposits of iron, manganese, and other minerals in Nevada with sufficient reserves to be considered for use in carbon dioxide sequestration.

Site Name	District Name	County	UTM Northing	UTM Easting	Latitude (NAD 27)	longitude (NAD 27)	Ore Minerals	Land Status	Past Production	Estimated Remaining Reserves
IRON DEPOSITS (continued)										
Dayton area, Lyon & Storey Counties										
Dayton Iron Deposit (Rosetta Mine)	Red Mountain	Lyon	4360095	288936	39-21-25N	119-25-41W	magnetite, pyrite	patented and BLM-administered land	The Dayton iron deposits have not produced any appeciable amount of iron.	The Dayton iron deposits contain an estimated 7.5 million short tons of ore grading from >40% Fe to >50% Fe, plus 100 million tons of lower grade material.
Iron Blossom Prospect	Red Mountain	Lyon	4358363	285276	39-20-60N	119-29-31W	magnetite	patented and BLM-administered land		
Gabbs area, northwest Nye County										
Phelps Stokes (Iron Mountain) Mine	Gabbs	Nye	4304600	428000	38-53-34N	117-49-30W	magnetite, hematite, pyrite, pyrrhotite	patented and BLM-administered land	The Phelps-Stokes Mine produced about a half million tons of iron ore from 1949 through the 1950s with sporadic small production into the 1970s.	There is an estimated 500,000 tons of material grading between 50% Fe remaining in the mine area.
Yerington Area, Douglas & Lyon Counties										
Minnesota Mine	Buckskin	Douglas	4326600	298000	39-04-08N	119-20-03W	magnetite, pyrite	patented and BLM-administered land	The Minnesota Mine produced nearly 4 million tons of iron ore, mainly in the 1950s and 1960s.	There is an estimated 2–3 million tons of ore grading about 50% Fe remaining in the mine area.
Pumpkin Hollow deposit (Lyon Prospect)	Yerington	Lyon	4311400	321000	39-04-01N	119-20-05W	magnetite, chalcopyrite	patented and BLM-administered land	The Pumpkin Hollow deposit remains unmined.	Up to 440 million short tons of ore grading 24% to 40% Fe.
TOTAL									Total production of iron ore from Nevada iron mines is about 12 million tons of ore grading over 50% Fe.	A conservative estimate of Nevada's total remaining iron-bearing resource is about 558 million tons of material grading up to 50% Fe, with a possibility of as much as 1.5 billion tons of material of grade varying between 15% and 50% Fe.
MANGANESE DEPOSITS										
Las Vegas Area, Clark County										
Three Kids Deposit (Manganese Inc. Mine)	Las Vegas	Clark	3995000	688000	36-05-29N	114-54-43W	manganite, pyrolusite	patented and BLM-administered land	More than 2.2 millon tons of manganese ore was mined from the Three Kids deposit, mainly from the 1950s through the 1960s.	There are about 3.3 million tons grading 5% to 18% Mn plus more lower grade material remaining in the Three Kids Mine area.
Boulder City Deposit	Las Vegas	Clark	3980000	699350	35-56-45N	114-47-24W	manganite, pyrolusite	patented and BLM-administered land	No production was reported from the Boulder City manganese deposit.	The Boulder City deposit contains approximately one million tons of material grading 7.5% Mn or 15 million tons with an average grade of 3% Mn.
TOTAL										A conservative estimate of Nevada's total remaining manganese-bearing resource is about 4.3 million tons of higher grade material grading between 5% and 18% Mn, plus about 20 million tons of lower grade manganese-bearing material with an average grade of up to 3% Mn.
WOLLASTONITE DEPOSITS										
Gilbert Wollastonite Deposit	Gilbert	Esmeralda	4222000	441000	38-08-45N	117-40-23W	wollastonite	BLM-administered land	No wollastonite has been produced.	The Gilbert wollastonite deposit is estimated to contain a resource of about two million tons of material containing 50–70% wollastonite.
BRUCITE DEPOSITS										
Gabbs Brucite Deposit	Gabbs	Nye	4302100	422500	38-51-58N	117-53-36W	brucite	patented and BLM-administered land	About 3 million tons of brucite ore was mined from the Gabbs brucite deposit beginning in the late 1930s and continuing into the 1980s. The high-grade brucite ore was mostly mined out in the early days, but mining of magnesite continues today.	The Gabbs Brucite deposit contains an estimated 200,000 tons of remaining brucite ore.

dwindled to near zero by the 1980s leaving most of these reserves unmined. That estimate was made, however, before reports of the reserves of the Pumpkin Hollow (Lyon) iron skarn deposit were public. Inclusion of this additional deposit would increase the total estimated amount of unmined iron ore in Nevada to approximately 1.5 billion metric tons.

There are six known areas of Nevada that host significant iron deposits with total endowment (past production plus reserves and resources) in excess of a million metric tons of iron ore:

- The Buena Vista Hills, located on the Pershing –Churchill County line in west-central Nevada (Reeves and Kral, 1958; Nylen, 1998; Johnson and Barton, 2000a, 2000b).
- The Cortez Mountains of Eureka County (Shawe et al. 1962; Roberts et al. 1967).
- The Jackson Mountains of Humboldt County (Shawe et al. 1962)
- The Dayton area near the Lyon-Storey County line (Roylance, 1965; 1966; Reeves et al. 1958).
- The Gabbs area in northwest Nye County (Reeves et al. 1958).
- The Yerington area in Lyon and Douglas Counties (Reeves et al. 1958; Dilles et al. 2000a, 2000b; Matlock and Ohlin, 1996).

Buena Vista Hills

Although iron was discovered in the Buena Vista Hills in 1898, there was no appreciable production from the deposits before World War II. Iron ore was mined from several deposits in the Buena Vista Hills beginning in 1952 and was shipped to Japan for use in post-World War II reconstruction. The area had produced more than 560,000 long metric tons of ore by the end of 1952. The grade of the ore shipped at this time was about 57% Fe or higher. Production continued throughout the 1950s at a rate of 2,500 to 3,000 metric tons of iron ore per day. Production dwindled throughout the 1960s (Reeves and Kral, 1958; Johnson, 1977), and ended completely by the early 1980s. The mines of the district were estimated to have produced a total of more than 4 million metric tons of iron ore with an average grade of over 50 weight percent iron (Moore, 1969, 1971; Johnson and Barton, 2000b).

There were four main producing iron mines in the Buena Vista Hills area: the Buena Vista Mine, the Segerstrom-Heizer Mine, the Thomas Mine, and the American Ore Company Mine (Stoker-Marker, Parker Brothers). Remaining reserves from the combined mines were estimated to be several hundred thousand metric tons plus an additional million tons of inferred material, all grading from 50% to more than 60% Fe. There may be a considerable tonnage of material in these deposits of too low a grade for iron ore, but which would be amenable for use in mineral carbonation.

Most of the Buena Vista Hills iron mine area is underlain by a large composite intrusion of Mesozoic (Jurassic) age and basaltic composition, which intruded and metamorphosed Upper Paleozoic to mid-Mesozoic volcanic and sedimentary rocks. The intrusive rock in the mined areas is a diorite that has undergone intense sodium-rich hydrothermal alteration forming a medium- to coarse-grained rock consisting almost entirely of scapolite and hornblende (Johnson and Barton, 2000a, 2000b). This scapolitized diorite is the main host rock for the iron deposits. The deposits occur as steeply dipping irregular replacement bodies in brecciated areas at fault intersections and as stratabound orebodies. The mineralogy of the deposits is predominantly magnetite with partial minor replacement by hematite (Reeves and Kral, 1958). Minor gangue minerals constitute a small fraction of the ore material and include calcite, apatite, chlorite, scapolite, and hornblende.

An order-of-magnitude, liberal estimate of the amount of magnetite available in the Buena Vista Hills is 1.4 million metric tons of Fe_3O_4 (equivalent to two million metric tons of ore grading 50% Fe) or 2.7×10^5 m^3 (2.7×10^{-4} km^3) of magnetite.

Cortez Mountains

Major deposits in the Cortez Mountains include those at the Barth Mine and Modarelli Mine, and the Frenchie Creek prospects. The Barth iron mine is located on formerly Southern Pacific Railroad land 10 km west of Palisade, on the Humboldt River, southwest of Elko in Eureka County. The Barth deposit is a replacement of Mesozoic-age andesitic volcanic rocks by magnetite subsequently replaced by hematite. Quartz monzonite intrudes similar rock about 550 m west of the Barth pit. The ore mineralogy of the deposit is predominantly hematite with some magnetite (Shawe et al. 1962; Cornwall, 1965).

The deposit was recognized in the 1860s, and mined in the 1900s. From 1903 to 1918, 761,000 metric tons of iron ore were mined from the Barth deposit and shipped by rail to Salt Lake City for use as smelter flux ore (Nylen, 1998). Exploration in the 1950s discovered that the iron deposit was approximately 370 by 90 m and up to 75 m thick, and extended to the north underneath alluvium in the river bed. The Humboldt River channel was diverted and the mine was reopened in 1961, producing approximately 600,000 metric tons of ore grading 63-64% Fe by 1964 (Shawe et al. 1962). The Barth Mine continued minor production of iron ore through 1988 (Nevada Bureau of Mines and Geology, 1981, 1982, 1983, 1984, 1987, 1988, and 1989).

The Modarelli Mine deposit, about 40 km south of the Barth deposit, was discovered in 1903 and mined sporadically throughout the 1950s into the 1960s (Nylen, 1998). By 1961 the mine had shipped nearly 400,000 metric tons of iron ore concentrate grading 58% Fe. The deposit was wedge-shaped with dimensions of approximately 430 by 300 by 270 m. It consisted of a replacement of Mesozoic rhyodacitic volcanic rocks by magnetite, in turn partially replaced by hematite. The deposit was developed both by an open cut and by underground workings on eight levels. The southeast half of the deposit was described as consisting of ore with the rest of lower grade material, so one can assume considerable tonnage (perhaps half a million metric tons) of iron-rich material grading less than 58% Fe remaining as a resource in the Modarelli Mine area (Shawe et al. 1962).

In the same general area are the Frenchie Creek prospects, a series of about nine sub-ore grade lenses or pods of iron oxides replacing rhyodacitic tuff along a northeast-striking shear zone. These range from a few tens of m in diameter up to a 120-by-120-m pod, grading 34% to 53% Fe. Iron is in the form of magnetite and hematite in varying proportions (Shawe et al. 1962). Exact tonnage of these lenses and pods is unknown, but collectively they could constitute up to a few million metric tons of iron-rich material amenable to mineral carbonation.

An order-of-magnitude, liberal estimate of the amount of hematite available in the Cortez Mountains is 1.5 x 10^6 metric tons of Fe_2O_3 (approximately equal to past production) or 2.9 x 10^5 m^3 (2.9 x 10^{-4} km^3) of hematite.

Jackson Mountains

The Jackson Mountains in west-central Humboldt County host three sizeable deposits of iron ore: the Iron King (DeLong), Red Bird, and Black Jack Mines, which were developed together beginning in the 1950s. Combined total production for the Jackson Mountains deposits was more than 780,000 metric tons of massive magnetite ore with few impurities, grading more than 50% Fe (Shawe et al. 1962). The amount of ore remaining in the deposits is unknown but may be estimated to be at least equivalent to the amount produced, probably at a somewhat lower grade (15% to 40% Fe). The orebodies are lenticular replacements of metavolcanic rocks within a north-striking shear zone near a contact with intrusive diorite. An order-of-magnitude, liberal estimate of the amount of magnetite available in the Cortez Mountains is 1.0 million metric tons of Fe_3O_4 (equivalent to two million metric tons of ore grading 50% Fe) or 1.9 x 10^5 m^3 (1.9 x 10^{-4} km^3) of magnetite.

Dayton Area

The Dayton iron deposits are about 35 km southeast of Reno, 19 km northwest of Dayton, and 3 km northwest of U.S. Highway 50 on a pediment along the southeast base of the Flowery Range. There are two exposures of iron oxide about 300 m apart, which are connected at depth forming the main Dayton deposit, with several smaller satellitic magnetite bodies (Roylance, 1965, 1966). The Dayton iron deposit was first discovered and patented between 1903 and 1908, and was further explored in the 1940s by the U.S. Bureau of Mines (USBM), which did trenching and drilling of the area to delineate the areal extent of the deposit. Utah Construction and Mining Company bought the property in 1951 and explored it with 11,000 m of rotary drilling through 1961 (Roylance, 1965, 1966).

The Dayton deposit is composed predominantly of magnetite partially oxidized to hematite to a depth of about 30 m. The southern part of the deposit is exposed at the surface, whereas the northern half is overlain by 1.5 to 9 m of colluvium. The mineralized zone covers an area at least 610 m long by 460 m wide, extends to a depth of 180 m, and is exposed at the surface. Reserve tonnages are estimated at 6.8 million metric tons of iron ore grading more than 40% Fe, much of it more than 50% Fe. The total resource of lower grade iron-bearing material could be as much as 100 million metric tons.

Regionally metamorphosed Mesozoic carbonate sediments and mafic volcanic rocks were intruded by Jurassic diorite to granodiorite. Magnetite ore formed mainly at the contact between carbonate sedimentary rocks and the granodiorite. Ore-forming fluids are thought to have accompanied the intrusion of the granodiorite. A later quartz monzonite intrusion is post-mineral in age, possibly Cretaceous. The entire package was tightly folded in an anticline overturned to the northeast, and subsequently faulted into segments (NBMG mining district files available at www.nbmg.unr.edu/scans/3870/38700001.pdf, www.nbmg.unr.edu/scans/3870/38700003.pdf, www.nbmg.unr.edu/scans/3870/38700005.pdf, www.nbmg.unr.edu/scans/3870/38700007.pdf, and www.nbmg.unr.edu/scans/3870/38700010.pdf. An order-of-magnitude estimate of the amount of magnetite available in the Dayton area is 60 million metric tons of Fe_3O_4 (equivalent to 110 million metric tons of ore grading 40% Fe) or 1.2×10^7 m^3 (1.2×10^{-2} km^3) of magnetite.

West-Central Nevada

Approximately 20 iron deposits and prospects in west-central Nevada have had variable amounts of production, but of these, only three contained more than a few thousand metric tons of iron ore: 1) the Phelps-Stokes Mine near Gabbs, 2) the Minnesota Mine northwest of Yerington, and 3) the Pumpkin Hollow deposit (Lyon prospect) southeast of Yerington.

Gabbs Area

The Phelps Stokes Mine in northwestern Nye County near Gabbs was discovered in 1902 and was mined mainly between 1949 and 1954, producing more than 400,000 metric tons of iron ore grading up to 55% Fe during that time period. It was sporadically active during the 1960s and 1970s (Cornwall, 1965). The mineralogy of the deposit is primarily magnetite with some hematite. The deposit formed as a replacement of Triassic Luning Formation dolomite, probably associated with the intrusion of Tertiary dikes (Reeves et al. 1958). Remaining reserves are not published but are conservatively estimated to be about equal to the amount mined – approximately one-half million metric tons of material grading up to 50% Fe. This equates to 3.5×10^5 metric tons of Fe_3O_4 or 6.7×10^4 m^3 (6.7×10^{-5} km^3) of magnetite.

Yerington Area

The Minnesota Mine is located in the Buckskin Mountains in the extreme northeast corner of Douglas County, a few kilometers northwest of Yerington. It is a skarn (contact metamorphic hydrothermal) deposit, and was first worked in the early 1900s as a copper mine. Although sporadic iron ore production began in the 1940s, Standard Slag Company began large-scale production of iron ore from the mine in 1952. By 1969, the Minnesota Mine had produced more than 3.7 million metric tons of iron ore averaging about 50% Fe in grade, mainly for shipment to Japan during reconstruction. There may be as much as two to three million metric tons of iron ore remaining in the deposit. The iron skarn deposit formed in Triassic and Jurassic metasedimentary (dolomite) and metavolcanic rocks intruded by granodiorite and pyrite-bearing quartz monzonite porphyry. Magnetite is the predominant ore mineral present in the deposit, with lesser disseminated chalcopyrite and minor molybdenite (Reeves et al. 1958).

Pumpkin Hollow Deposit

The Pumpkin Hollow deposit (Lyon prospect) is reportedly the largest iron skarn deposit in Nevada. It is located in the Wassuk Range about 8 km southeast of Yerington in Lyon County. The estimated aggregate tonnage of the several Pumpkin Hollow orebodies is at least 250 million metric tons of ore grading from 24% to 40% iron and containing up to a few percent copper and up to 0.7 parts per million gold by weight (0.02 troy ounces of gold per short ton of ore), but the deposit may be as large as 400 million metric tons (Sherlock et al. 1996; Nevada Bureau of

Mines and Geology, 2000, 2001). Smaller reserves have been reported for the higher-grade copper-gold portion of the deposit. The Pumpkin Hollow deposit is similar to many other Nevada iron skarns in its geology, but is much larger and remains totally unmined. The deposit does not crop out at the surface and is covered by 90 to 400 m of alluvium. It was first located in 1960 by an aeromagnetic survey, followed by extensive ground geophysical surveys and drilling in the early 1960s to delineate the size and extent of the orebodies (Smith, 1984; NBMG mining district files available at www.nbmg.unr.edu/scans/5430/54300039.pdf and www.nbmg.unr.edu/scans/5430/54300043.pdf).

The Pumpkin Hollow deposit was formed when Upper Triassic to Jurassic carbonate and siliceous sedimentary rocks were intruded by Jurassic plutonic rocks ranging in composition from quartz monzonite to granite porphyry. The mineralizing intrusion is part of the northern Yerington batholith associated with the Yerington porphyry copper deposit. Contact metasomatic replacement mineralization occurred in the metasedimentary rocks adjacent to the igneous contact. The orebodies are irregularly shaped masses greater than 300 m long, 150 m wide, and 520 m thick vertically. Metallic minerals include magnetite, pyrite, chalcopyrite, and pyhrrotite. Gangue minerals are silica, calcite, actinolite, tremolite, garnet, epidote, chlorite, and talc (Ohlin et al. 1995; NBMG Yerington mining district file, available on line through http://www.nbmg.unr.edu/mdfiles/mdfiles.htm).

An order-of-magnitude, liberal estimate of the amount of magnetite available in the Yerington area is 250 million metric tons of Fe_3O_4 (equivalent to 450 million metric tons of ore grading 40% Fe) or 4.8×10^7 m^3 (4.8×10^{-2} km^3) of magnetite.

Significant Manganese Deposits of Nevada

The Three Kids Mine area of southern Clark County, located just southeast of Las Vegas, is the only significant manganese resource in Nevada with the potential for use in mineral carbonation. The manganese ore at the Three Kids Mine occurs as a bedded deposit concordant with layering of the enclosing sedimentary rocks, formed by the replacement of volcanic tuff and volcaniclastic sediments. Tabular beds of manganese oxide minerals pyrolusite (MnO_2), psilomelane ($Ba(Mn^{2+}, Mn^{4+})_5O_{10}\ H_2O$), and manganite ($Mn^{3+}O\ (OH)$) are found in a persistent zone about 30 m above the base of the sedimentary sequence of gypsum and other sedimentary rocks (Hewett and Weber, 1931; Hunt et al. 1942; Hewett et al. 1963; Longwell et al. 1965).

The Three Kids deposit was estimated to contain at least 500,000 metric tons of manganese ore grading 30% Mn, with the possibility of an additional half million tons of the same when it was first explored in the 1930s. In 1942, after detailed mapping and sampling work, Hunt et al. (1942) estimated the reserves of the Three Kids deposit at about 5.0 million metric tons of material averaging 10% Mn, of which about a 0.9 million metric tons averaged 20% Mn. Total Nevada production of manganese ore to 1964 was about 800,000 metric tons of ore and concentrates grading mostly over 35% Mn. Most of the production was from the Three Kids Mine, where more than 2.0 million metric tons of 18% Mn ore was processed to yield more than 540,000 metric tons of concentrate grading 45% Mn. Total resource tonnage remaining in the deposit could be estimated at about 3.0 million metric tons of ore averaging between 5% and 18% Mn, plus an unknown additional tonnage at lower grades. In addition, the nearby Boulder

City deposit # 7 was estimated in 1964 to contain resources of one million metric tons of material grading 7.5 % Mn or 15 metric million tons averaging 3% Mn (McKelvey and Wiese, 1949; Trengove, 1959).

An order-of-magnitude, liberal estimate of the amount of manganese available in the Three Kids deposit area is one million metric tons of Mn. Apart from psilomelane, the ore minerals in this area contain relatively oxidized ions, making the reactions with CO_2 thermodynamically unfavorable. If the estimated amount of Mn occurred as the reduced mineral, manganosite, it would occupy a volume of approximately 2.4×10^5 m^3 (2.4×10^{-4} km^3).
A significant amount of manganese-bearing ore in Nevada also remains in the mines of the Pioche District in Lincoln County (Bell, 1911; Gemmill, 1968; Tschanz. and Pampeyan, 1970; Westgate and Knopf, 1932). The mineralogy of the Pioche ore, however, is predominantly manganoan siderite, a carbonate mineral which would not be amenable to carbon dioxide sequestration because it has no capacity to combine with additional CO_2.

Other Minerals Amenable to Carbonation

There are sizeable deposits in Nevada of other industrial minerals that might prove to be compatible with carbon dioxide sequestration by mineral carbonation. Notable among these are wollastonite ($CaSiO_3$) and brucite ($Mg(OH)_2$).

Gilbert Wollastonite Deposit

Reaction of CO_2 with wollastonite is thermodynamically attractive (Table 2). There is at least one area in Nevada that hosts a resource of wollastonite large enough to possibly have potential for use in CO_2 sequestration. The Gilbert wollastonite deposit is located in the Gilbert mining district in Esmeralda County, about 48 km north of Tonopah. The Anaconda Company first identified the wollastonite in the 1970s during gold exploration. Mapping and drilling in the 1980s identified at least three wollastonite zones in a skarn, and an unsuccessful attempt was made in 1994–1995 to develop, process, and market wollastonite from the property (Nevada Bureau of Mines and Geology, 1990; 1991; 1995; 2001; 2003). Recent reports indicate that the Gilbert deposit contains a resource of more than 1.8 million metric tons grading more than 50% wollastonite with zones averaging over 70% wollastonite. Mineralization extends to depths as much as 150 m, and overburden in the area is reported to be negligible. Slightly more than doubling the known resource to estimate total potential of the deposits in the area results in two million metric tons of wollastonite (a volume of 6.9×10^5 m^3 (6.9×10^{-4} km^3).

The Pinson Mine property in the Potosi mining district of Humboldt County hosts scattered veins and small lenses of wollastonite, but no significant tonnage of wollastonite material has been reported (Willden, 1964).

Gabbs Brucite Deposit

Brucite ($Mg(OH)_2$) is one of the minerals that have been mined at Premier Chemical Company's Gabbs magnesite mine (formerly Basic Refractories) near Gabbs in Nye County. There is an abandoned brucite pit on the mine property which still contains an estimated resource of 180,000 metric tons or more of brucite ore (Adam Knight, mine manager, personal commun., 2006). This is the only known brucite deposit of any size in the state. Most of the material currently mined from the property consists of magnesite (magnesium carbonate), which is not amenable to mineral carbonation. If the ore were pure brucite, it would occupy a volume of approximately 8.3 x 10^4 m^3 (8.3 x 10^{-5} km^3).

DISCUSSION

There is plenty of mafic rock (mostly basalt) in Nevada to meet the CO_2 sequestration demands for several large power plants (Table 7). However, it is clear from the estimated volumes (Table 7) that Nevada lacks sufficient quantities of other rock types for sequestering CO_2 from a large power plant. Even the locality with the largest amount of material (magnetite from the Yerington area) has only 15% of what would be needed for a large power plant. Furthermore, the oxidized iron and manganese ores found in Nevada are not thermodynamically favorable for the reactions (endothermic and positive free energies of reaction for magnetite, hematite, and pyrolusite in Table 2). Although wollastonite or brucite would be thermodynamically favorable, the amounts available from known deposits are three to four orders of magnitude smaller than what would be needed.

Table 7. Estimated volumes of potential rock and mineral reactants available in Nevada, compared with what is needed for a large power plant.

Rock type	Volume required for power plant that burns 0.25 gigaton of C (km^3)	Locality	Volume of rock or mineral (km^3)
Basalt	1.3	Northwestern Washoe Co.	139
		Southern Washoe area	176
		Humboldt lopolith	31
		Owyhee Plateau	177
		Battle Mountain area	29
		Southwestern Mineral area	41
		San Antonio Mountains	13
		Reveille/Pancake Ranges	9
		Southern Clark County	3+
Magnetite	0.31	Buena Vista Hills	0.00027
		Jackson Mountains	0.00019
		Dayton area	0.012
		Gabbs area	0.000067
		Yerington area	0.048
Hematite	0.32	Cortez Mountains	0.00029
Manganosite*	0.28	Three Kids Mine area	0.00024
Wollastonite	0.83	Gilbert deposit	0.00069
Brucite	0.51	Gabbs	0.000083

* The actual Mn ore minerals are thermodynamically less favorable for reaction with CO_2 than manganosite, which has not been reported in this area.

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. Mazzotti et al. (2005) discussed industrial and environmental hurdles to a commercial enterprise, including standard issues involved with mining. Unfortunately, judging from rates of chemical weathering of these rocks and some experiments (e.g., Carroll and Knauss, 2006), the kinetics of the reactions are generally slow (Intergovernmental Panel on Climate Change, 2005; Mazzotti et al. 2005).

Mazzotti et al. (2005) noted that several industrial waste products, including various ashes from coal-fired power plants and municipal solid-waste incinerators, stainless steel slag, and waste cement, may be attractive for reactions with CO_2, as they contain high concentrations of CaO and MgO. In addition, scrap iron could be ideal, because its reaction with CO_2 to form iron carbonate is thermodynamically highly favorable (Table 2). These waste products could be incorporated into an industrial complex that included a coal-fired power plant located near a substantial source of basalt. The resultant carbonate minerals could be used to isolate other municipal and industrial waste products, much of it refilling the holes dug in the ground to mine the basalt. Substantial new mounds would be created as well, because of the large volume increases from the chemical reactions.

Although the need for sites for CO_2 sequestration may ultimately be so great that industrial sites could be chosen in remote areas, in an initial screening, the most favorable sites are likely proximal to both a major electric power transmission line and to a railroad. Coal would be transported to the site by rail, and the power plant would be located near the source of material to react with the CO_2 waste. The rail lines would also be used to bring other waste materials to the site, either for additional reaction with CO_2 or for burial with the iron, magnesium, and calcium carbonate reaction products. The major mafic rock localities, railroads, and major power grid in Nevada are shown on Figure 2. There do appear to be possible sites that are close to railroads and the major power grid in the following six areas: northwestern Washoe County; southern Washoe, Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties. The basalts on the Owyhee Plateau in northern Elko and Humboldt Counties are several tens of kilometers farther from railroads than the other sites. Locations with sufficient amounts of basalt in two other areas (the San Antonio Mountains in Nye County; and the Reveille and Pancake Ranges in Nye County) are far from existing railroads.

CONCLUSIONS AND RECOMMENDATIONS

There are sufficiently large volumes of basalt near railroads and major power lines in Nevada to consider reaction of those rocks with CO_2 from coal-fired power plants as a possible means of disposing of the CO_2. Reaction with minerals has theoretical advantages over many other schemes for carbon sequestration in that it would be essentially permanent disposal. That is, there would be no leakage as possible from geological storage in deep saline aquifers, oil fields, or other geological environments, and there would be no threat of loss of CO_2 from wildfires, as with terrestrial sequestration in trees or other biomass. Nonetheless, the technology for mineral reaction is unproven. Considerably more research would be needed before a commercial operation could be seriously considered. When and if commercial viability is demonstrated, those areas of greatest interest in Nevada would contain large volumes of mafic rock near railroads and major power lines. Those areas would most likely be northwestern Washoe County; southern Washoe, Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties.

PART 2

Assessment of the Potential for Carbon Dioxide Sequestration with Enhanced Oil Recovery in Nevada

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ABSTRACT

This report follows the preliminary assessment of the potential for carbon dioxide sequestration in geological settings in Nevada (Price et al. 2005) by compiling data on the 15 oil fields that have had historical production. Critical factors in assessing the potential for enhanced oil recovery as a means of carbon dioxide sequestration in Nevada include depth, temperature, and cumulative production. Most Nevada oil reservoirs are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground. Furthermore, none of the Nevada oil fields is large enough to accommodate all the CO_2 from a large coal-fired power plant. The cumulative volume of oil and associated water production from all Nevada oil fields is about two orders of magnitude less than what would be needed to sequester a significant amount of CO_2 from a power plant. Therefore, there is not much potential in Nevada for CO_2 sequestration through enhanced oil recovery.

INTRODUCTION

In recent years, the prospect of using carbon dioxide (CO_2) injection as an enhanced oil recovery (EOR) technique has gathered much interest, not only as a way of improving oil recovery, but also as a method of sequestering CO_2 generated by coal-burning power plants. In a typical oil field, less than 15 percent of the oil present in the reservoir is recovered during the primary recovery phase, when the initial natural pressure of the reservoir or gravity helps drive oil into the wellbore, where it is generally pumped to the surface. Secondary recovery techniques may extend the oil field's productive life and increase recovery to 20 to 40 percent by injection of water or gas to displace oil and drive it to a production wellbore. With much of the easily produced oil already recovered from U.S. oil fields, some producers have attempted tertiary or EOR techniques that offer the possibility of converting up to 60 percent or more of the reservoir's original oil reserves to production.

Gas injection is the most commonly used EOR technique, accounting for nearly 50 percent of EOR production in the United States. Large volumes of gas such as CO_2, natural gas, or nitrogen are injected into a mature oil reservoir, where the gas pushes additional oil to a production wellbore. The gas also dissolves in the oil, lowering its viscosity and improving its flow rate. CO_2 injection has been used successfully to enhance oil recovery throughout the Permian Basin of West Texas and eastern New Mexico, and is now being pursued to a limited extent in many other states.

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 join the West Coast Regional Carbon Sequestration Partnership (WESTCARB) and 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 in EOR and disposal of CO_2 in saline aquifers. Some unconventional approaches are also being evaluated. The Nevada Bureau of Mines and Geology (NBMG) reported its findings from a preliminary assessment of the potential for geological sequestration in Nevada (Price et al. 2005). This report follows up with detailed information on Nevada oil fields.

DATA COMPILED

To aid in the evaluation of Nevada oil fields as potential targets for CO_2 EOR, we researched available literature on 15 commercially productive oilfields in Nevada for information pertinent to the suitability of these oil fields for sequestration of CO_2. Nevada's commercially productive oil fields are Bacon Flat, Currant, Duckwater Creek, Eagle Springs, Ghost Ranch, Grant Canyon, Kate Spring, Sand Dune, Sans Spring, and Trap Spring in Railroad Valley, Nye County; Blackburn, North Willow Creek, Three Bar, and Tomera Ranch in Pine Valley, Eureka County; and Deadman Creek in Toano Draw, Elko County. Their locations and relative approximate sizes are shown in Figure 29. Additional fields have been explored and identified within Nevada, but as yet, none of these has had significant commercial production of petroleum, so they were not included in this compilation. Nearly all Nevada oil production has come from fields in Railroad Valley (89.27%) and Pine Valley (10.73%; Davis, 2007).

Because Nevada's 15 commercially producing oil fields are either one-reservoir fields or consist of communicating reservoirs, the field and reservoir level data are essentially the same and are combined on a single data spreadsheet for the 15 oil fields, shown here as Table 8. The data presented in Table 8 are included in a geographic information system (GIS) coverage which accompanies the electronic version of this open-file report. Table 9 is an annotated list of the data field labels and a description of the data contained in each of the fields on Table 8. Field locations in Table 8 and on Figure 29 are based on the point locations of the discovery wells for each field as shown on the petroleum data map of Garside and Hess (2007). The oil field GIS coverage was generated in a shape file format, in UTM zone 11 projection, North American Datum (NAD) 1927. This is the same projection and NAD as the UTM coordinates listed in Table 8. The GIS coverage that accompanies the map of Garside and Hess (2007), available at http://www.nbmg.unr.edu/dox/zip/m162d.zip, includes locations of all oil and gas exploration and production wells in the state.

Table 8. Data compiled for each commercially productive oil field in Nevada. See Table 2 for descriptions of the data fields.

Oil field name	Discovery well name	NV permit number	Discovery well API number	Location	County
OILFIELDNA	DISCO_WELL	PERMIT	API	LOCATION	COUNTY
Eagle Springs	Eagle Springs Unit No. 1-35	4	27-023-05011	Railroad Valley	Nye
Kate Spring	Kate Spring No. 1	436	27-023-05365	Railroad Valley	Nye
Trap Spring	Trap Spring No. 1	180	27-023-05220	Railroad Valley	Nye
Currant	Currant No. 1	241	27-023-05265	Railroad Valley	Nye
Bacon Flat	Bacon Flat No. 1	316	27-023-05305	Railroad Valley	Nye
Blackburn	Blackburn No. 3	324	27-011-05210	Pine Valley	Eureka
Grant Canyon	Grant Canyon No. 1	353	27-023-05318	Railroad Valley	Nye
Tomera Ranch	Foreland-Southern Pacific Land Co. No. 1-5	492	27-011-05235	Pine Valley	Eureka
North Willow Creek	Foreland-Southern Pacific Land Co. No. 1-27	503	27-011-05239	Pine Valley	Eureka
Three Bar	Three Bar Federal No. 25-A	556	27-011-05246	Pine Valley	Eureka
Duckwater Creek	Duckwater Creek No. 19-11	542	27-023-05413	Railroad Valley	Nye
Sans Spring	Federal No. 5-14	635	27-023-05466	Railroad Valley	Nye
Ghost Ranch	Ghost Ranch Springs No. 58-35	789	27-023-05544	Railroad Valley	Nye
Deadman Creek	Deadman Creek No. 44-13 (formerly SP No. 3-13)	342	27-007-05228	Toano Draw	Elko
Sand Dune	Sand Dune Federal No. 88-35	816	27-023-05561	Railroad Valley	Nye

Table 8 (continued).

Oil field name	Township	Range	Sections	Quarter section	Depth to top of field
OILFIELDNA	T	R	S	QTRSEC	DEPTHTOTOP
Eagle Springs	9N	57E	35	SE/4 NE/4 NW/4	5780 feet (1,762 meter)
Kate Spring	08N	57E	2	NW/SW	4450 feet (1,356 meters)
Trap Spring	9N	56E	27	SE/SE	3210 feet (978 meters)
Currant	10N	57E	26	SW/SE	6850 feet (2088 meters)
Bacon Flat	07N	57E	17	C /SW	4960 feet (1512 meters)
Blackburn	27N	52E	8	C NE/4 SW/4 SW/4	5776 feet (1761meters)
Grant Canyon	07N	57E	21	C E/2 SW/4 NW/4 Sec. 21, T 7N, R 57E	4374 feet (1333 meters)
Tomera Ranch	30N 31N	52E 53E	5; 33	SE/NE/NE	1150 feet (351meters)
North Willow Creek	29N	52E	27	NW/SE	6290 feet (1917 meters)
Three Bar	28N	51E	25	C NE/4	5720 feet (1743 meters)
Duckwater Creek	09N	057E	19	NW/NW	5680 feet (1731meters)
Sans Spring	07N	056E	14	SW/NW	5640 feet (1710 meters)
Ghost Ranch	08N, 09N	057E, 057E	02; 34, 35	NE/NW 02; SE/SW 35	4350 feet (1326 meters)
Deadman Creek	39N	65E	13	SE/SE	8165 feet (2489 meters)
Sand Dune	09N	057E	35	SE/SE/SE	5970 feet (1820 meters)

Table 8 (continued).

Oil field name	Depth of producing zone in discovery well	Average depth of production zone in all producing wells	Average depth of production zone in all producing wells (meters)	Cumulative production through 2006 (barrels)
OILFIELDNA	PRODDEPTH	AVDEPTHPRO		CUMPROD2006
Eagle Springs	5,780-7,360 feet	6508 feet	1984	5,218,259
Kate Spring	4450-4820 feet	4598 feet	1401	2,256,573
Trap Spring	3210-4950 feet	4005 feet	1221	13,753,356
Currant	6850-7080 feet	7059 feet	2152	1,523
Bacon Flat	4960-5350 feet	5163 feet	1574	997,509
Blackburn	5776-7140 feet	6902 feet	2104	5,183,966
Grant Canyon	4374-4426 feet	3979 feet	1213	20,938,790
Tomera Ranch	1150-1950 feet	1670 feet	509	36,472
North Willow Creek	6290-6470 feet	6093 feet	1857	50,529
Three Bar	5720-7070 feet	5448 feet	1661	23,837
Duckwater Creek	5680-5830 feet	5755 feet	1754	18,310
Sans Spring	5640-5770 feet	5766 feet	1757	265,457
Ghost Ranch	4350-4620 feet	4474 feet	1364	502,023
Deadman Creek	8165-8850 feet	8508 feet	2593	367
Sand Dune	5970-6200 feet	6178 feet	1883	116,626

Table 8 (continued).

Oil field name	Zone status (currently producing, shut-in, or abandoned wells) 2006 data	Number of producing wells (2006)	Number of inactive wells (2006)	Depth to base of fresh water
OILFIELDNA	ZONESTATUS06	NUMPRODWEL	NUMINACTWE	DEPTHFRESH
Eagle Springs	15 producers, 6 shut-in, 1 injection	15	5	not known
Kate Spring	4 producers, 2 shut-in	4	2	not known
Trap Spring	33 producers, 10 shut-in, 1 P&A	33	11	not known
Currant	1 past producer, now shut-in	0	1	not known
Bacon Flat	1 active producer, 2 shut-in	1	2	not known
Blackburn	5 producers, 2 shut-in	5	2	not known
Grant Canyon	2 producers, 4 shut-in	2	4	not known
Tomera Ranch	2 shut-in, 1 P&A, 1 injection	2	1	not known
North Willow Creek	1 producer, 1 shut-in, 1 P&A	1	2	not known
Three Bar	2 shut-in, 1 P&A	2	1	not known
Duckwater Creek	1 producer	1	0	not known
Sans Spring	1 producer, 2 shut-in, 1 abandon	1	3	not known
Ghost Ranch	4 producers; 1 shut-in	4	1	not known
Deadman Creek	1 P&A	0	1	not known
Sand Dune	1 producer	1	0	not known

Table 8 (continued).

Oil field name	Host rost age/formation/rock type	Average thickness of reservoir rock units in producing wells
OILFIELDNA	HOSTROCK	AVEUNITTHI
Eagle Springs	Oligocene Garrett Ranch Group; Eocene Sheep Pass Formation lacustrine carbonates; Pennsylvanian Ely Limestone carbonate (minor production)	1500 feet
Kate Spring	Neogene Horse Camp Formation breccia and Devonian Guilmette Formation (carbonate, dolomite)	413 feet of Pennsylvanian carbonate breccia; 560 feet of Devonian dolomite & limestone
Trap Spring	Oligocene Tuff of Pritchards Station, ash flow tuff (ignimbrite)	2490 feet
Currant	Eocene Sheep Pass Formation calcareous shale and shaly limestone	439 feet
Bacon Flat	Devonian Guilmette Formation carbonate, dolomite; possibly also Sheep Pass Fm	73 feet
Blackburn	Devonian Telegraph Canyon Formation dolostone; Mississippian Chainman Shale and Dale Canyon Formation shale, sandstone & siltstone; Oligocene Indian Well Formation tuff and tuffaceous sandstone	1275 feet
Grant Canyon	Devonian Simonson and Guilmette Formation vuggy brecciated dolomite	448 feet
Tomera Ranch	Oligocene Indian Well Formation chert and tuffaceous sandstone	189 feet
North Willow Creek	Mississippian Chainman Shale	604 feet
Three Bar	Miocene Humboldt Formation sandstone and volcanic rock; Oligocene Indian Well Formation, and Cretaceous Newark Formation sandstone and carbonate	6000 feet
Duckwater Creek	Oligocene Garrett Ranch Group volcaniclastic rocks and ignimbrites	3125 feet
Sans Spring	Oligocene Garrett Ranch Group volcaniclastic rocks and ignimbrites	933 feet
Ghost Ranch	Late Tertiary landslide breccia blocks of Devonian Guilmette Formation limestone and dolomite	265 feet
Deadman Creek	Miocene Humboldt Formation	685 feet
Sand Dune	Permian and Pennsylvanian limestones	465 feet

Table 8 (continued).

Oil field name	Field area (from literature)	Porosity	Permeability
OILFIELDNA	FIELDAREA	POROSITY	PERMEABILI
Eagle Springs	640 acres	volcanics - 13.5%; Sheep Pass - 16%	volcanics - 10 md; Sheep Pass - 4 md
Kate Spring	Tertiary - 60 acres, Devonian - 200 acres	average 10-12%, up to 17 % in Devonian rock	2000-4100 md possible
Trap Spring	2440 acres	overall, <3%, but 5-15 % matrix porosity in isolated vesicles	highly variable
Currant	40 acres	5.80%	up to 24.6 md
Bacon Flat	80 acres	< 4 %	very high- interconnected fractures, vugs & caverns
Blackburn	400 acres	8%	high - open fractures
Grant Canyon	320-400 acres	< 4 %	very high- interconnected fractures, vugs & caverns
Tomera Ranch	80 acres	up to 24 % but average 6-15 %	<2 md
North Willow Creek	<120 acres	15 - 26% in discovery hole	.05 - 78 md in discovery hole (7.35 md)
Three Bar	<120 acres	unknown	unknown
Duckwater Creek	~40 acres	< 2%	highly variable
Sans Spring	160 acres	18%	1688 md
Ghost Ranch	1500 acres	huge	huge permeabilities
Deadman Creek	~40 acres	unknown	unknown
Sand Dune	~40 acres	10%	0.39 - 1.3 md

Table 8 (continued).

Oil field name	Initial pressure	Initial temperature	Formation water salinity
OILFIELDNA	INITPRE	INITIALTEM	FMSALINITY
Eagle Springs	3000 psi at 6400 feet	200°F (93℃) at 6400 feet	24,298 ppm Cl; 7476-27,912 ppm TDS in oil field waters of 6 wells
Kate Spring	unknown	150°F (66℃)	TDS 239 ppm; 914-2,952 ppm TDS in oil field waters of 5 wells
Trap Spring	1645 psi at 1000 feet	100°-120°F (38-49 ℃)	3000-6000 ppm TDS; 2633-3378 ppm TDS in oil field waters of 3 wells
Currant	2944 psig	194°F (90℃)	2264 mg/l TDS
Bacon Flat	2273 psig	250°F (121℃)	4380 ppm TDS; 4662-4943 ppm TDS in oil field waters of 3 wells
Blackburn	3233 psig at 7196 feet	250°F (121℃)	1984-3684 ppm TDS in oil field waters of 3 wells.
Grant Canyon	1,885 psig at 4,400 feet; 1,735 psig at 4,000 feet	239°F (115℃)	4382-4487 ppm TDS in oil field waters of 5 wells
Tomera Ranch	unknown	120°F (49℃)	543-580 mg/l TDS
North Willow Creek	2,798.5 psi	180°-185°F (82-85℃)	7000 ppm to 9000 ppm salt water chlorides in re-entry well
Three Bar	unknown	unknown	530-939 ppm chlorides
Duckwater Creek	unknown	140°F, (60℃) estimated	10,200 ppm TDS
Sans Spring	2410 psig	200°F (93℃)	10,000-17,000 ppm TDS
Ghost Ranch	2179 psig	unknown	TDS concentration 17,500 to 21,000 mg/L.
Deadman Creek	unknown	154°F (68℃)	11,260 to 52,917 ppm TDS
Sand Dune	2866 psig	149°F (65℃)	unknown

Table 8 (continued).

Oil field name	Seal type	Seal thickness	Trap type
OILFIELDNA	SEALTYPE	SEALTHICK	TRAPTYPE
Eagle Springs	Indurated valley fill (Horse Camp Formation) and altered basal volcaniclastic-rich valley fill sediments	169-2680 feet	paleotopographic & stratigraphic, structural-stratigraphic; erosional unconformity pinch-outs
Kate Spring	Indurated clay-rich Tertiary valley fill above unconformity	4371-4738 feet	structural/unconformity; clay-rich valley fill trap
Trap Spring	Alluvial valley fill, argillized clay-rich non-welded tuff layer, unfractured clays, and devitrified ash	271-4854 feet	fault block, structural-stratigraphic
Currant	altered basal volcaniclastic-rich valley-fill sediments; Tertiary volcanic rocks	2995 feet	structural-stratigraphic
Bacon Flat	altered Tertiary basal volcaniclastic-rich valley fill sediments	153-5355 feet	structural; structural-stratigraphic; valley fill trap
Blackburn	pre-Tertiary unconformity; altered Tertiary basal volcaniclastic-rich valley fill sediments	1200-2768 feet	structural
Grant Canyon	altered Tertiary basal volcaniclastic-rich valley fill sediments	910-4020 feet	structural; structural-stratigraphic; valley fill trap
Tomera Ranch	valley fill clays	800-1850 feet	structural fault block; structural-stratigraphic
North Willow Creek	range-bounding fault of the Pinon Range and Devonian Woodruff Fm.	1500 -3000 feet	structural fault block
Three Bar	Tertiary valley fill and volcanic rocks	3000-5000 feet	probably structural
Duckwater Creek	Tertiary valley fill and volcanic rocks	5500 feet	structural - fault block
Sans Spring	Tertiary valley fill and volcanic rocks	5000 feet	fault-bounded structure; structural-stratigraphic
Ghost Ranch	altered basal volcaniclastic-rich valley fill sediments	unknown	Structural high with four-way closure
Deadman Creek	Ash member, Humboldt Formation	2365 feet	unknown
Sand Dune	Tertiary valley fill and volcanic rocks	5900 feet	unknown

Table 8 (continued).

Oil field name	Stimulation (history of secondary and tertiary recovery efforts)	Logs available (discovery hole)
OILFIELDNA	STIMULATIO	LOGS
Eagle Springs	2,000 gallon (7,571 liter) mud acid wash	Lithologic 0 - 10,358 feet; IES 1,018 - 10,358 feet; GR/N 30 - 10,358 feet; ML 1,500 - 10,354 feet; DM 3,460 - 8,205 feet; Section Gauge 1,016 - 10,356 feet.
Kate Spring	Worked over after 1521 BO produced; plugged original perfs; perforated and acidized 4500-1625 feet (1372-1410m)	FIL 4,864-7,495 feet; DM 4,864-7,495 feet; DLL/ML 4,864-7,487 feet; BHCS 4,864-7,497 feet; CBL 3,490-4,814 feet; Directional 4,864-7,495 feet; CN/FDC 4,864-7,495 feet; GR 3,400-7,495 feet; lithologic 60-7500 feet.
Trap Spring	A few attempts to acidize or fracture have been mostly unsuccessful.	Lithologic 1,000 - 6,137 feet; DIL 1,008 - 5,982 feet; CNL/FDC 1,008 - 5,990 feet; BHCS 1,008 - 5,970 feet; FIL 4,000 - 5,600 feet
Currant	none	Lithologic 60-7,800 feet, 6,720-7,115 feet; FIL 2,200-7,790 feet; DIL 427-7,789 feet; GR 6,800-7,118 feet; BHCS 429-7,791 feet; CNL/FDC 428-7,793 feet; DM 436-7,793 feet
Bacon Flat	acidized with 1000 gallons (3,785 liters) 15 % HCl	Lithologic 515-5,441 feet; DI 519-5,451 feet; BHCS 519-5,433 feet; CNL/FDC 3,404-5,439 feet; DM 612-5,450 feet; Dip log 3,414-5,419 feet; CBL 3,350-5,394 feet
Blackburn	Devonian - none, Mississippian & Oligocene - sand/oil fracture treatment	Lithologic 80-7,950 feet; FDL 4,800-7,867 feet; CBL 5,200-7,900 feet; TS 58-7,909 feet; Cal 1,548-5,550 feet; CNL/FDC/DI 95-7,954 feet; BHCS 95-7,943 feet; FIL/GR 4,800-7,956 feet; DM 1,608-7,956 feet; DLL 5,800-7,523 feet
Grant Canyon	none	Lithologic 400 - 4,040 feet; DLL/ML 392 - 3,949 feet; BHCS 392 - 3,957 feet; DI 3,931- 4,297 feet; LSS 3,931- 4,300 feet; FIL 3,931- 4,300 feet; CNL/FDC 392 - 4,300 feet; DM 3,931- 4,300 feet; Temp/press/gradient 3,900 - 4,150 feet
Tomera Ranch	none	Lithologic 1007 - 5786 feet; DLL 980 - 5774 feet; FDC/N 1018 - 5772 feet; BHCS 988 - 5755 feet; DM 1000 - 5570 feet; DM/computed 1000 - 5570 feet; CBL 1000 - 4567 feet
North Willow Creek	none	CBL 4200 - 6393 feet; FDC/N 980 - 7672 feet; BHCS 950 - 7666 feet; ML 5600 - 7662 feet; DLL 950 - 7650 feet; DM 980 - 7672 feet; Perf. Rec. 6200 - 6393 feet; lithologic 0 - 7678 feet
Three Bar	unknown	Lithologic 57-7217 feet; GR 950-7217 feet; DI 950-7213 feet; DM 950-7216 feet; EM 950-7201 feet; FDC/N 950-7217 feet; S 950-7203 feet; CBL 750-7213 feet
Duckwater Creek	none	DI/GR, 716-5754; BHCS/GR, 716-5750; DM, 3737-5754
Sans Spring	none	lithologic 900-8,463 feet ; CBL-5,000-6,087; DM 4,000-8,459 feet; DI 4,000-8,460 feet; BHCS 4,000-8,462 feet; FDC/N 4,000-8,464 feet; Drift survey 4,000-8,459 feet; Water Flow 5,690-5,910 feet
Ghost Ranch	unknown	lithologic log 515 feet-4570 feet; BHCS/GR 512 feet-4530 feet; Directional Plot 512 feet-4580 feet; DLL 512 feet-4562 feet; FDL/N 3550 feet-4530 feet
Deadman Creek	unknown	Lithologic 90 - 10,930 feet; DM 916 - 10,918 feet; CBL 7,818 - 8,745 feet; BHCS 897 - 10,926 feet; DI 898 - 10,926 feet; FIL 1,500 - 10,923 feet; FDC/N 898-8,638; DM 898 - 8,639 feet; DL 898 - 10,923 feet; GR 898-8,607 feet.
Sand Dune	unknown	Lithologic log 642 feet-6411 feet; BHCSGR 642 feet-6366 feet; Directional 636 feet-6400 feet; DMGRCal 3000 feet-6400 feet; IESGR 642 feet-6398 feet; MLGRCal 2400 feet-6407 feet; NGRCal 2400 feet-6407 feet

Table 8 (continued).

Oil field name	Location of logs	Samples available (discovery hole)	Reservoir fluid (oil, gas, water)
OILFIELDNA	LOGLOC	SAMPLES	RESFLUID
Eagle Springs	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 140 - 10,345 feet; Core 4,710 - 9,960 feet.	oil, gas, water
Kate Spring	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 60 - 7,500 feet	oil, water, gas
Trap Spring	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 1,800 - 6,100 feet; Core 4,375 - 4,444 feet	oil, water
Currant	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 430-7,800 feet	oil
Bacon Flat	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 520-5,450 feet	oil, water
Blackburn	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 1,600 - 7,930 feet	oil, water
Grant Canyon	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 390 - 4,040 feet	oil, water
Tomera Ranch	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 900 - 5786 feet	oil, gas, water
North Willow Creek	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 3000 - 7678 feet	oil, water (none initially), some gas initially
Three Bar	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 57 - 7,217 feet	oil, water
Duckwater Creek	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 718-5835 feet	oil, water
Sans Spring	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 900-8,463 feet	oil, water
Ghost Ranch	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings: 500 feet - 4570 feet	oil, small amount of gas, (no) water
Deadman Creek	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 0 - 10,930 feet. Core analysis is available at NBMG for 9440-9475 feet.	oil, gas, water
Sand Dune	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings: 642-6411 feet	oil, water

Table 8 (continued).

Fracture intensity	Main reference, number 1	Main reference, number 2	Main reference, numbers 3+
FRACINTENS	REF1	REF2	REF3
fractured	Bortz (1994a and b)	Bortz and Murray (1979)	Nevada Petroleum Society (1989)
fractured carbonate	Herring (1994a and b)	Nevada Petroleum Society (1989)	
unknown	French (1994b and c)	French and Freeman (1979)	Duey (1979)
unknown	Duey (1994a and b)		
high concentration of interconnected fractures, vugs, and caverns	Johnson and Schalla (1994a)	Hulen and others (1994)	Johnson (1994); MCCutcheon and Zogg (1994)
strong	Flanigan (1994)		
intense; high concentration of interconnected fractures, vugs, and caverns	Johnson and Schalla (1994b)	Hulen and others (1994)	Read and Zogg (1988); Johnson (1994); McCutcheon and Zogg (1994)
strong	Hansen and others (1994a)	Ransom (1994b)	
unknown	Hansen and others (1994b)	Ransom (1994a)	
fractured limestone	Schalla and Grabb (1994)		
unknown	French (1994a)	French and Kozlowski (1994)	Hess and others (2004)
unknown	Grabb (1994a and b)	Hess and others (2004)	
intense fracturing of dolomite	Montgomery and others (1999)	Hansen and Schaftenaar (2005)	
unknown	Frerichs and Pekarek (1994)	Hess and others (2004)	
unknown	Nevadd Bureau of Mines and Geology oil well files		

Table 8 (continued).

Oil field name	Current operator	Approximate UTM northing	Approximate UTM easting	Cumulative water production through 2006 (barrels)
OILFIELDNA	OPERATOR	APROX_UTMN	APROX_UTME	H2OCUMPROD
Eagle Springs	Meritage Energy Company	4273342	627676	5,121,534
Kate Spring	Western General Incorporated	4270858	627193	6,255,046
Trap Spring	Apache Incorporated	4273931	617249	32,908,982
Currant	Makoil, Inc.	4283509	627560	0
Bacon Flat	Equitable Res. Energy Co., Balcron Oil Div.	4257863	622670	729,680
Blackburn	Amoco Production Co.	4453568	573279	33,116,941
Grant Canyon	Makoil, Inc.	4256785	624173	4,856,303
Tomera Ranch	Foreland Corp.	4485300	574050	498,612
North Willow Creek	Deerfield Production Corporation	4468420	576920	3,210
Three Bar	The Gary-Williams Company	4459310	571050	5,958
Duckwater Creek	Makoil, Inc.	4276600	620800	66,225
Sans Spring	Double D Nevada, LLC	4258450	617700	3,716,058
Ghost Ranch	Eagle Springs Production LLC	4272120	627980	2,619,324
Deadman Creek	Foreland Corp.	4570112	703709	0
Sand Dune	Meritage Energy Company	4272050	627800	298,659

Table 9. Data field labels and description of the data contained in each of the fields on Table 1 and in the accompanying GIS coverage of Nevada's commercially producing oil fields.

OILFIELDNA	Name of the oil field
DISCO_WELL	Name of the discovery well for the oil field
PERMIT	Nevada permit number for the discovery well for the oil field
API	API number of the discovery well for the oil field
LOCATION	General location of the oil field
COUNTY	County in which the oil field is located
T	Township in which the oil field is located
R	Range in which the oil field is located
S	Section(s) in which the oil field is located
QTRSEC	Quarter section in which the discovery well for the oil field is located
DEPTHTOTOP	Depth to top of the oilfield in the discovery well for the oil field
PRODDEPTH	Range of depth of the producing zone in the discovery well for the oil field
AVDEPTHPRO	Average depth of the production zone in all producing wells for the oil field
CUMPROD2006	Cumulative production of the oil field through 2006 (in barrels)
ZONESTATUS06	Zone status of all wells in the oil field as of the end of 2006: currently producing, shut-in, or abandoned (P&A)
NUMPRODWEL	Number of producing wells in the oil field at the end of 2006
NUMINACTWE	Number of inactive wells in the oil field at the end of 2006
DEPTHFRESH	Depth to base of fresh water in oil field wells (not known)
HOSTROCK	Host rock (reservoir) ages, name of formations, and rock types for oil fields
AVEUNITTHI	Average thickness of reservoir rock units in producing wells for each field (this may not be the average potential thickness of reservoir rocks in the surrounding area.)
FIELDAREA	Field area as reported in or inferred from literature. A minimum value of 40 acres was used for small fields with no area reported.
POROSITY	Porosity of reservoir rocks
PERMEABILI	Permeability of reservoir rocks
INITPRE	Initial pressure at TD in discovery well
INITIALTEM	Initial temperature at TD in discovery well
FMSALINITY	Formation water salinity
SEALTYPE	Type of seal for reservoir
SEALTHICK	Seal thickness if known or thickness of formation that acts as the seal to the reservoir
TRAPTYPE	Type of trap; structural, stratigraphic, lithologic, other
STIMULATIO	Stimulation, history of secondary and tertiary recovery efforts
LOGS	Logs available for the discovery hole in each oil field
SAMPLES	Samples available for discovery hole in each oil field
LOGLOC	Location of logs and samples for discovery hole and other producing wells of the oil field
RESFLUID	Reservoir fluid (oil, gas, water)
FRACINTENS	Intensity or presence of fracturing of reservoir rock
REF1	Main reference, number 1
REF2	Main reference, number 2
REF3	Main reference, numbers 3+
OPERATOR	Current or most recent operator for the oilfield
APROX_UTMN	Approximate UTM northing of the discovery well for the oilfield
APROX_UTME	Approximate UTM easting of the discovery well for the oilfield
H2OCUMPROD	Cumulative water production of the oil field through 2006

Sources of data for Table 1 include well, core, sample, and log repositories of the Nevada Bureau of Mines and Geology and the U.S. Geological Survey. The Nevada Bureau of Mines and Geology Information Office archives the most complete records and samples. Companies drilling oil and gas wells are required by Nevada state law to give the state copies of logs and two sets of cuttings for each oil and gas well drilled. The logs and sample sets are kept confidential for six months. The Information Office is also the repository for other well cuttings (from geothermal and some other wells) and core. All cuttings, core, and well logs described in the accompanying database of producing Nevada oil fields are housed at NBMG and available for examination. The collection is electronically indexed and may be examined during NBMG business hours. There are also logs for 115 Nevada oil and gas exploration wells available from the USGS as part of the Basin and Range Carbonate Aquifer System Study. They are available online at http://nevada.usgs.gov/barcass/geo_logs/nye_county.htm

DISCUSSION

Critical factors in assessing the potential for enhanced oil recovery as a means of CO_2 sequestration in Nevada include depth of oil production (with a minimum depth of 800 m, so that the CO_2 stays in a liquid state under hydrostatic pressure), temperature (so that the density of CO_2 is preferably greater than 0.6 g/cm^3), volume of pore space available (as estimated from the resource potential or, for fields with declining production, cumulative production), permeability of the oil reservoir, and thickness of the seal that kept the oil in place. These factors, along with others, are listed in Table 1. With one exception (the Tomera Ranch field in Pine Valley), the Nevada oil fields meet the minimum depth criterion. Most fields, however, are so hot that densities of the CO_2 would likely to be less than 0.6 g/cm^3 within the reservoirs (Figure 30). Exceptions, where CO_2 may be denser, include two insignificant producers (Duckwater Creek in Railroad Valley and Deadman Creek in Toano Draw) and one major producer (Trap Spring field in Railroad Valley).

Davis (2007) provided the most recent update on Nevada oil production. Nevada's total oil production in 2006 was 425,705 barrels (0.023% of total U.S. production), from nine fields located in Railroad Valley, Nye County, and from two fields in Pine Valley, Eureka County. Nevada's four other past-producer oil fields were shut in throughout 2006. Nevada ranked 26 out of the 31 oil producing states in the country in 2006 oil production. Nevada's 67 productive oil wells yielded between 3 and 166 barrels of oil and up to 2,503 barrels of water per day. Nevada's cumulative oil production from 1954 through 2006 from all commercial oil fields totaled just less than 50 million barrels, and annual production has steadily declined since 1992 (Figure 31). Cumulative production for each oil field during this time period is shown in Table 1, and cumulative production for each field is shown in Figure 32. Each of the major Nevada oil fields – ones that have produced over 1 million barrels (Grant Canyon, Trap Spring, Eagle Spring, and Kate Spring in Railroad Valley and Blackburn in Pine Valley) – experienced substantial declines in production since peaking in the 1990s or earlier (Figure 33). For more detailed information on Nevada's petroleum resources, please refer to Garside and Hess (2007); their petroleum data map shows current and past oil production and exploration wells in Nevada, as well as "seeps" or surface shows of oil, gas or solid bitumen.

Price et al. (2005) concluded that there does not appear to be much potential in Nevada for 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 most Nevada fields are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground. A large coal-fired power plant that burned 250 million tons of carbon over its lifetime would generate 0.916 gigaton of CO_2, which would occupy a volume of 7.7 billion barrels at a CO_2 density of 0.75 g/cm^3 (typical of areas with low geothermal gradients) or 19 billion barrels at a density of 0.30 g/cm^3. The lower density of CO_2 is applicable for the largest oil fields in Nevada, which are hot (Figure 30; 120 to 130°C at 1,625 m in the Bacon Flat-Grant Canyon oil fields; Hulen et al. 1994). Cumulative oil production from Nevada, through 2006, is slightly less than 50 million barrels, and cumulative water production has been approximately 90 million barrels. The cumulative volume of oil and water production from all Nevada oil fields, approximately 140 million barrels, is about two orders of magnitude less than what would be needed to sequester a significant amount of CO_2 from a power plant. Therefore the conclusion still stands: there is not much potential in Nevada for CO_2 sequestration through enhanced oil recovery.

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Figure 1. The Valmy coal-fired power plant in Humboldt County, Nevada.

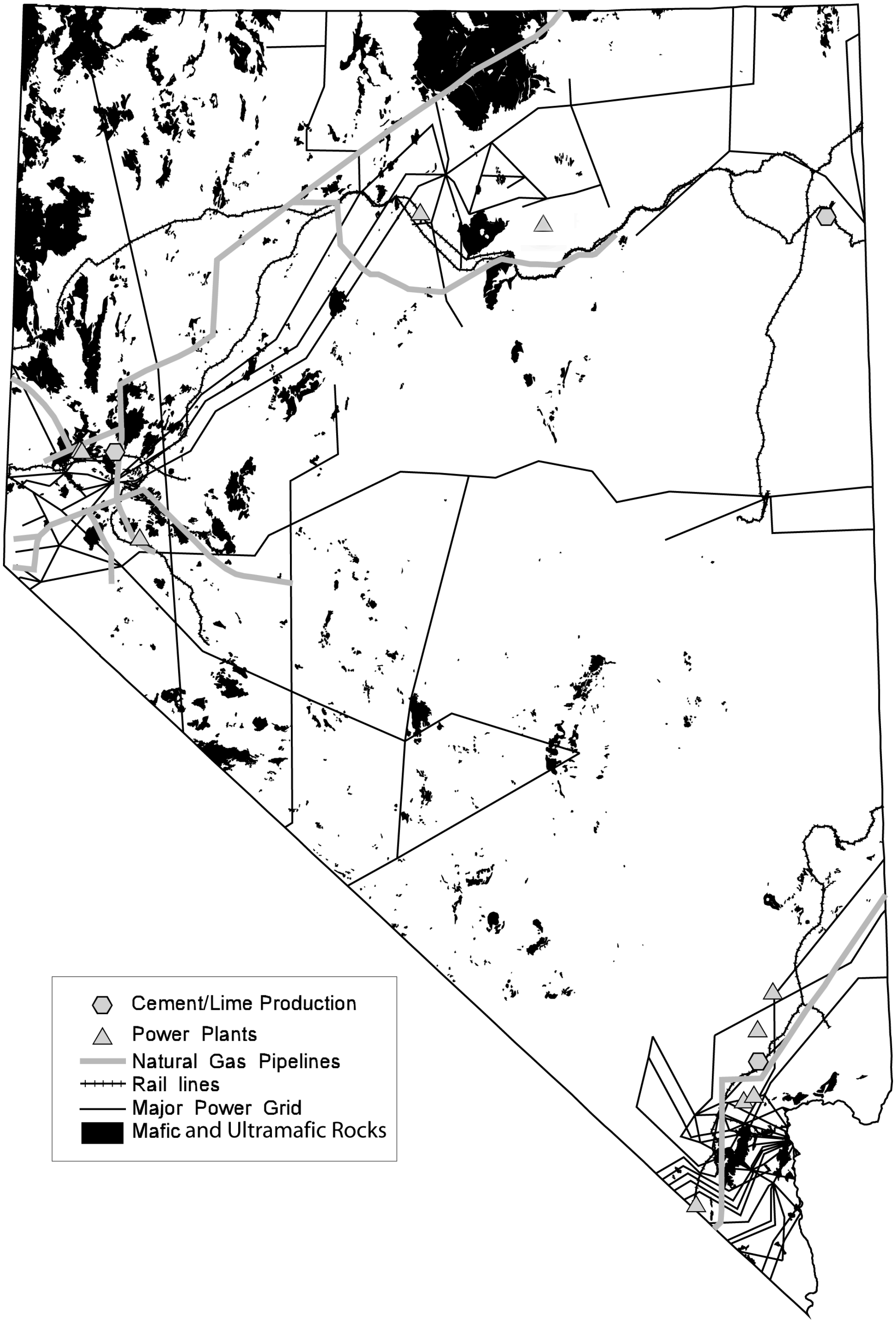

Figure 2. Distribution of mafic (magnesium- and iron-rich) and ultramafic rocks (black), major power plants (gray triangles), cement and lime plants (gray hexagons), major electric power transmission lines, pipelines, and rail lines in Nevada. Outcrop extents are taken from Stewart and Carlson (1978).

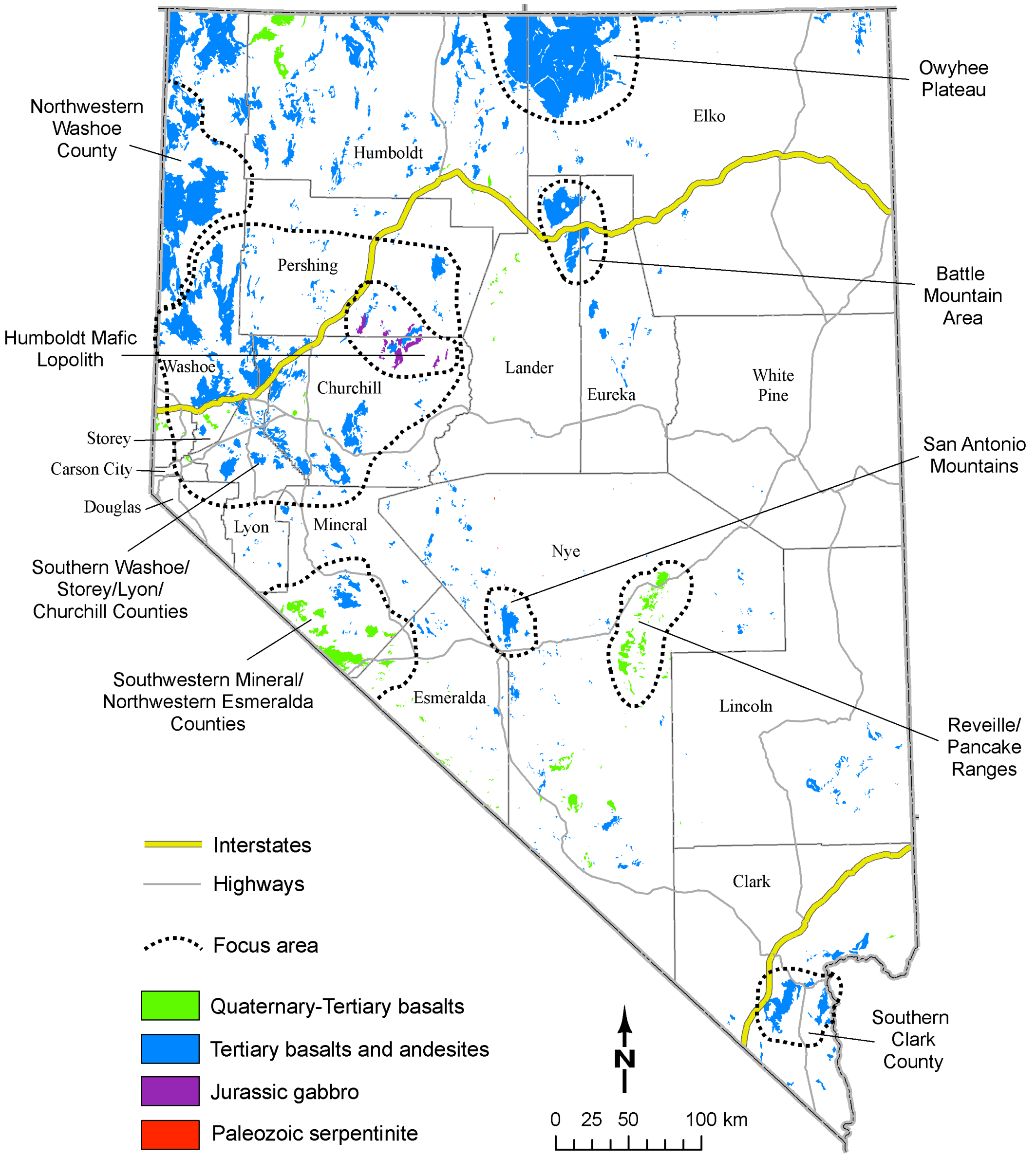

Figure 3. Mafic and ultramafic rocks in Nevada outlining the nine focus areas for this study. Outcrop extents are taken from Stewart and Carlson (1978).

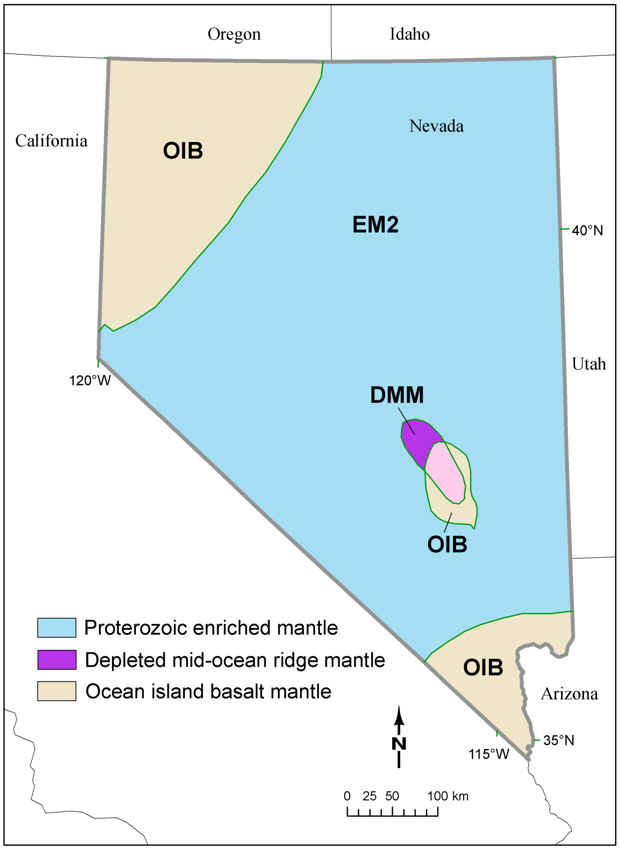

Figure 4. Lithospheric mantle domains in Nevada, based on seismic tomography, heat flow, and xenolith thermobarometry. Locally domains are overprinted. DMM = depleted mid-ocean ridge basalt mantle; EM2 = enriched mantle domain; OIB = ocean island basalt mantle. The sub-Archean lithospheric mantle domain does not appear on this map, because the area of exposed Archean rocks in Nevada is too small to be portrayed. Modified from Menzies (1989).

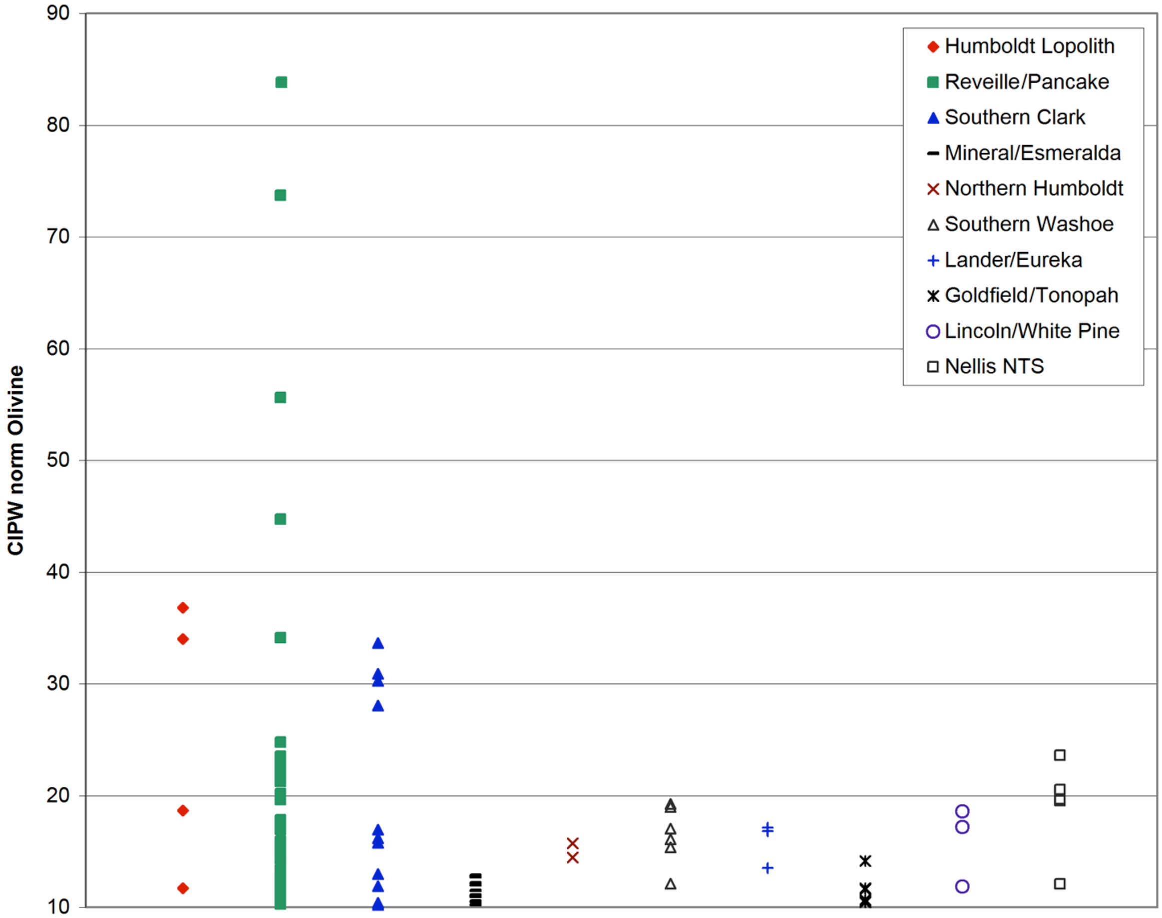

Figure 5. CIPW normative olivine values for some mafic rocks in Nevada (with olivine greater than 10%).

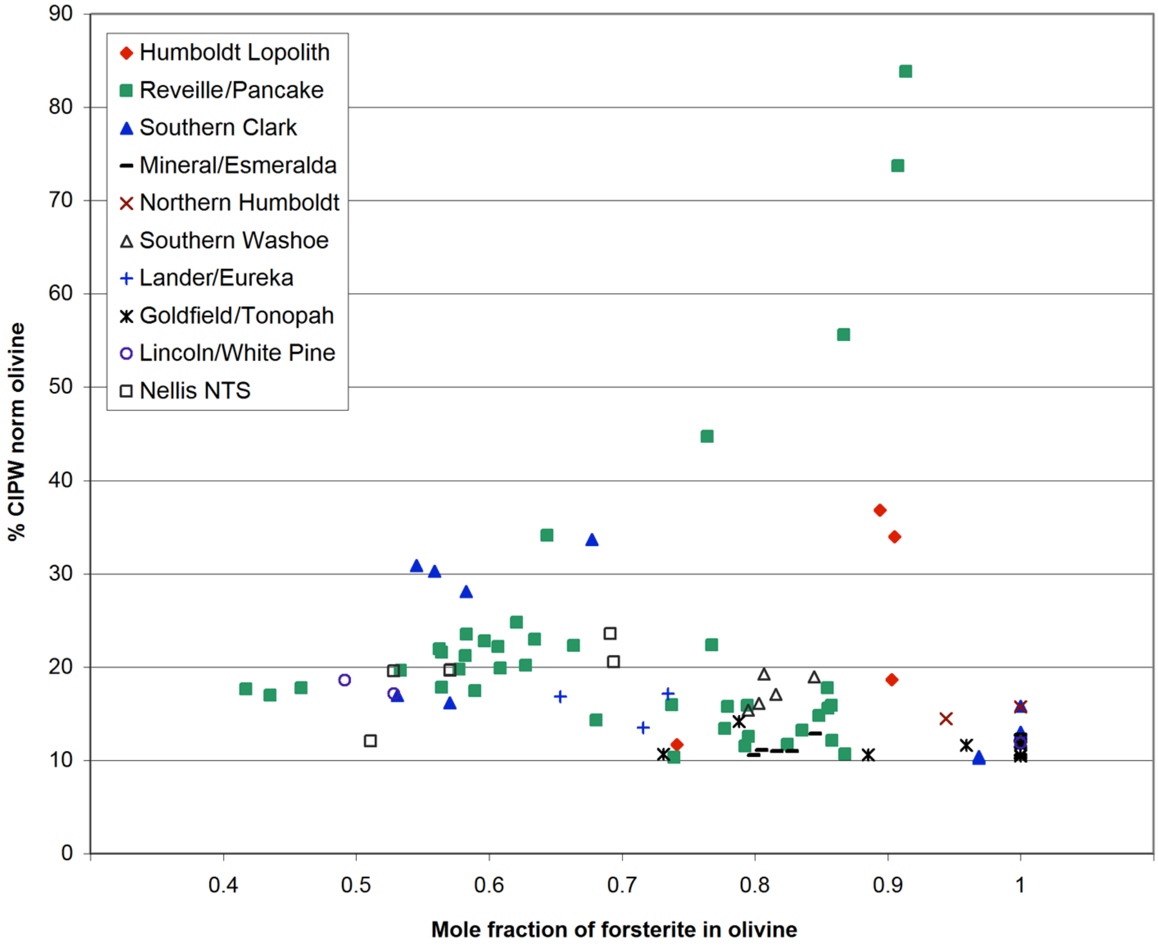

Figure 6. Normative forsterite vs. normative olivine for some mafic rocks in Nevada with normative olivine greater than 10%.

Figure 7. Example of thin (only a few m thick) basalts, not considered in this study, from the Sheldon National Wildlife Refuge in northern Washoe County. Thicker basalts may occur at depth.

Figure 8. Thick (hundreds of meters) sequence of basalt flows in the Buffalo Hills, Washoe County (looking to the northwest).

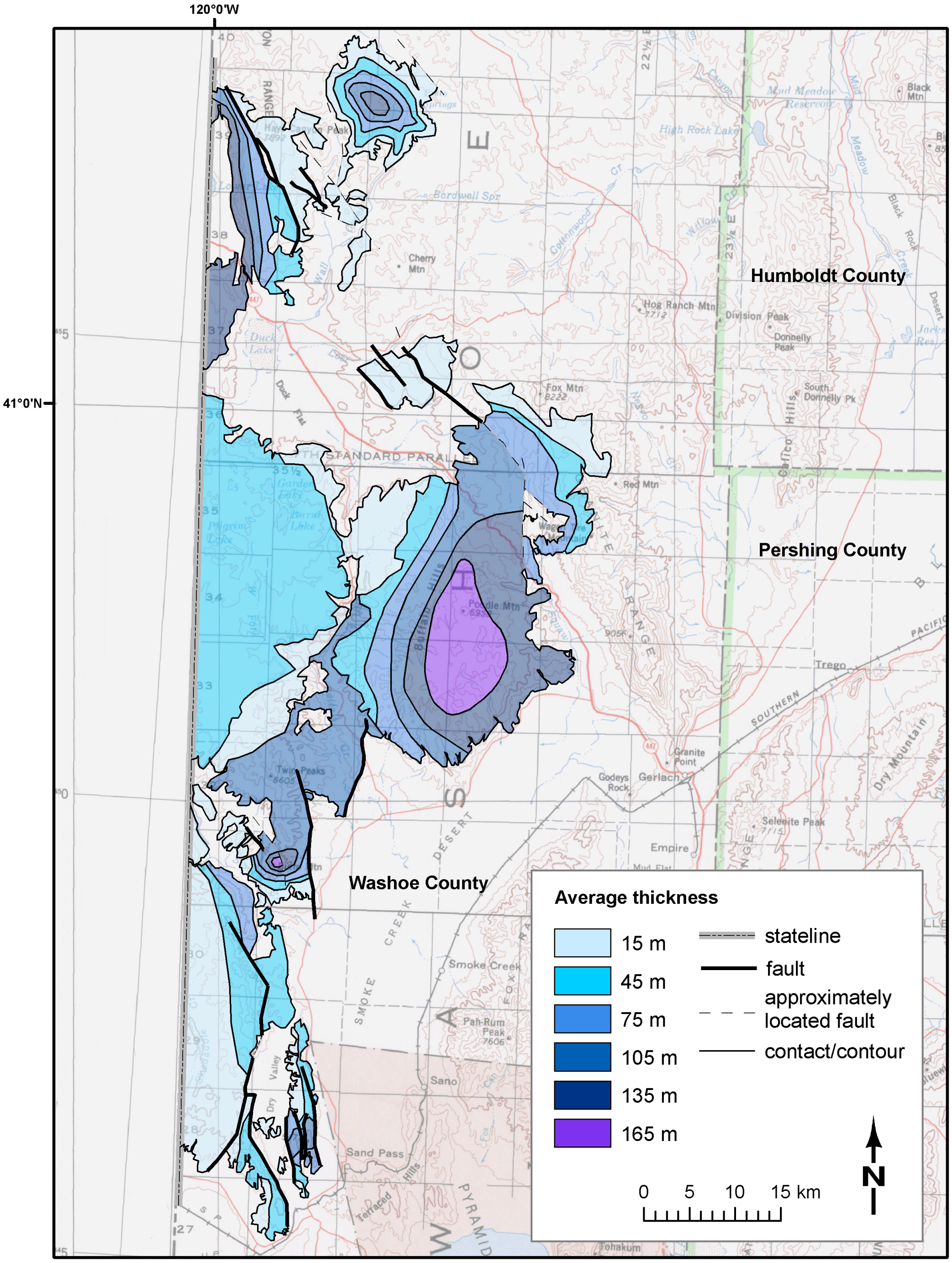

Figure 9. Mafic rock isopach map of northwestern Washoe County.

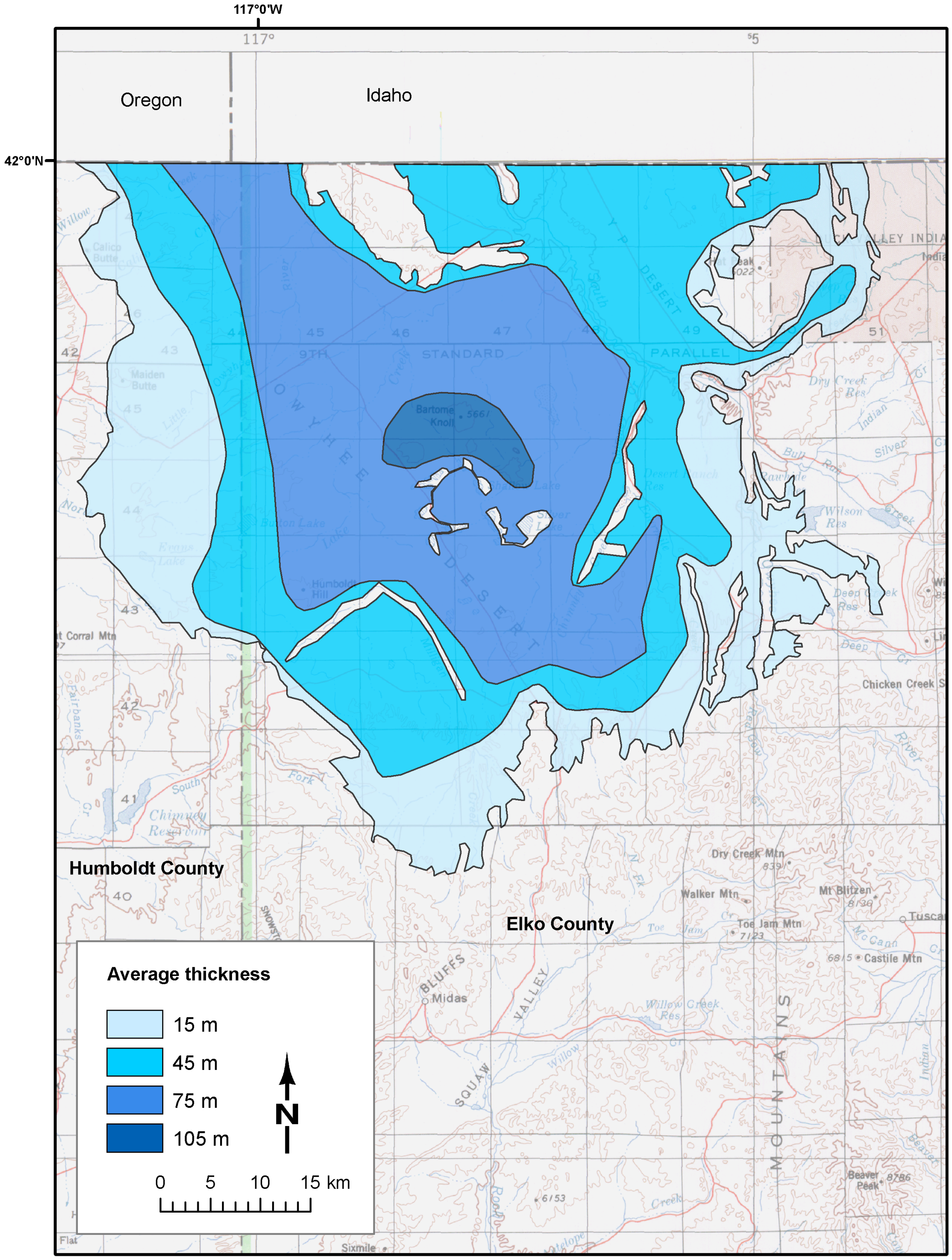

Figure 10. Mafic rock isopach map of the Owyhee plateau area, Humboldt and Elko Counties.

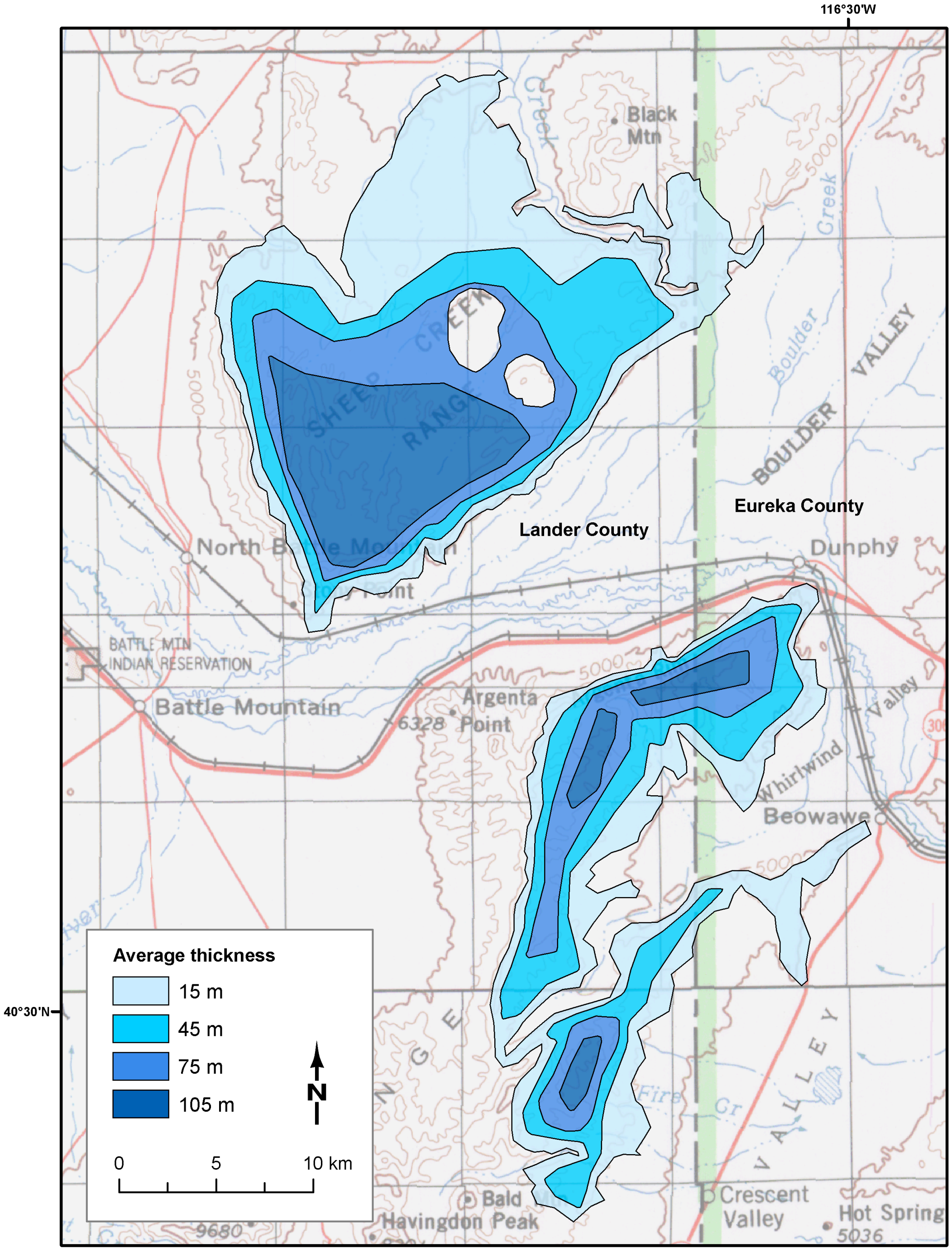

Figure 11. Mafic rock isopach map of the Battle Mountain area, Lander and Eureka Counties.

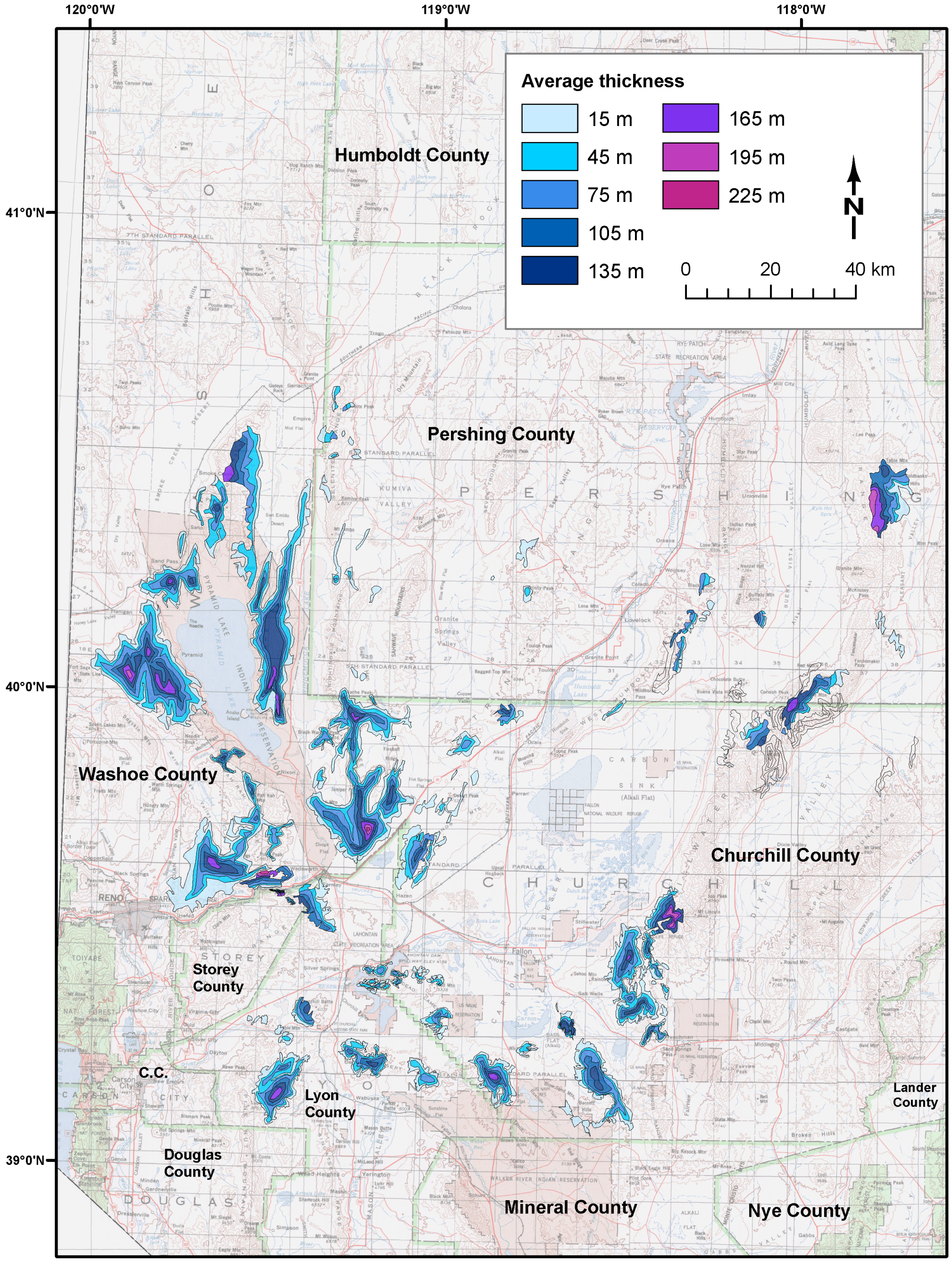

Figure 12. Cenozoic mafic rock isopach map of western Nevada, including southern Washoe, Storey, Lyon, Churchill, and Pershing Counties. Zoomed-in views are presented in Figures 13, 14, 15, and 17.

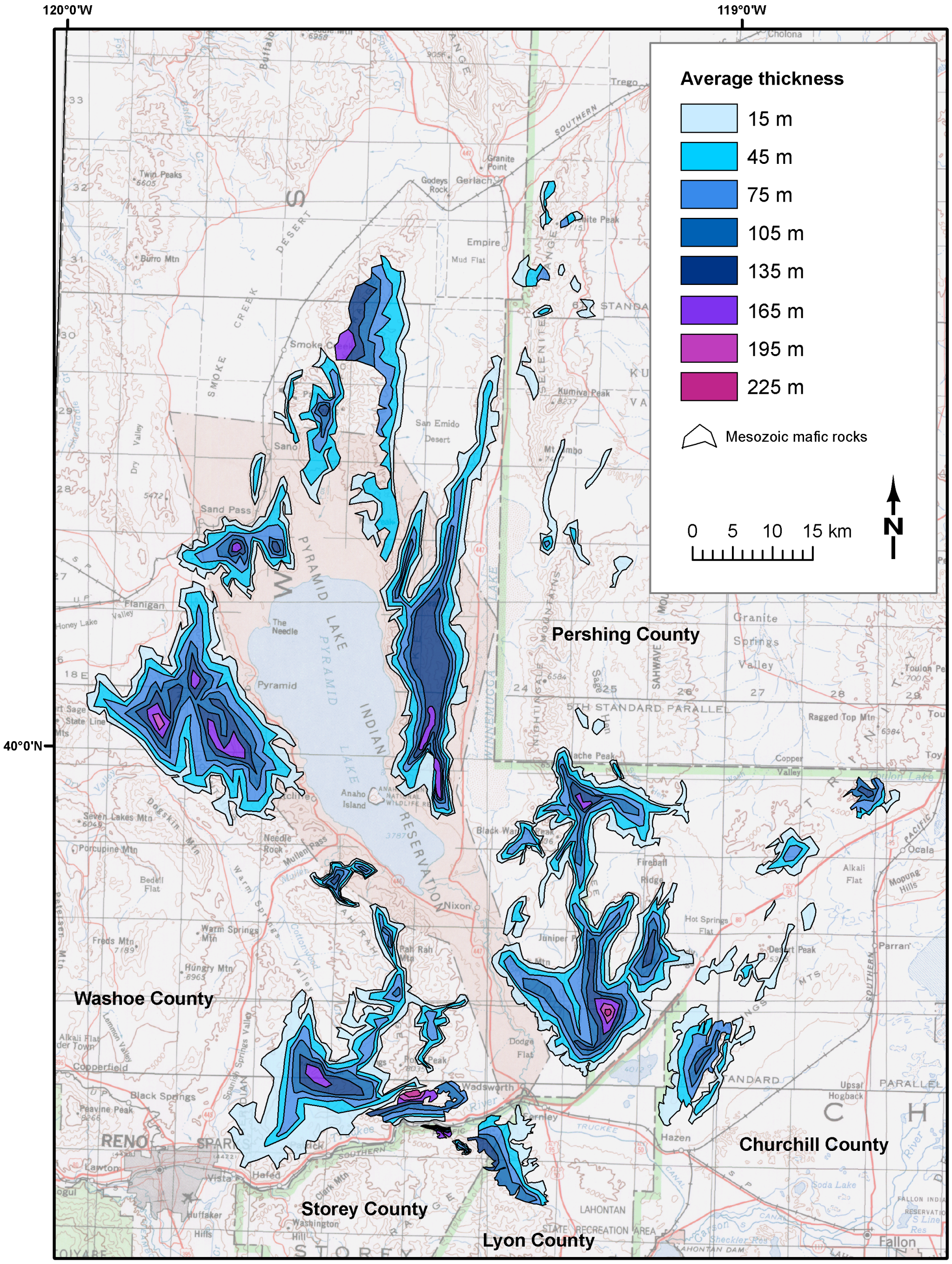

Figure 13. Cenozoic mafic rock isopach map of southern Washoe, Storey, northern Lyon, northwestern Churchill, and southwestern Pershing Counties.

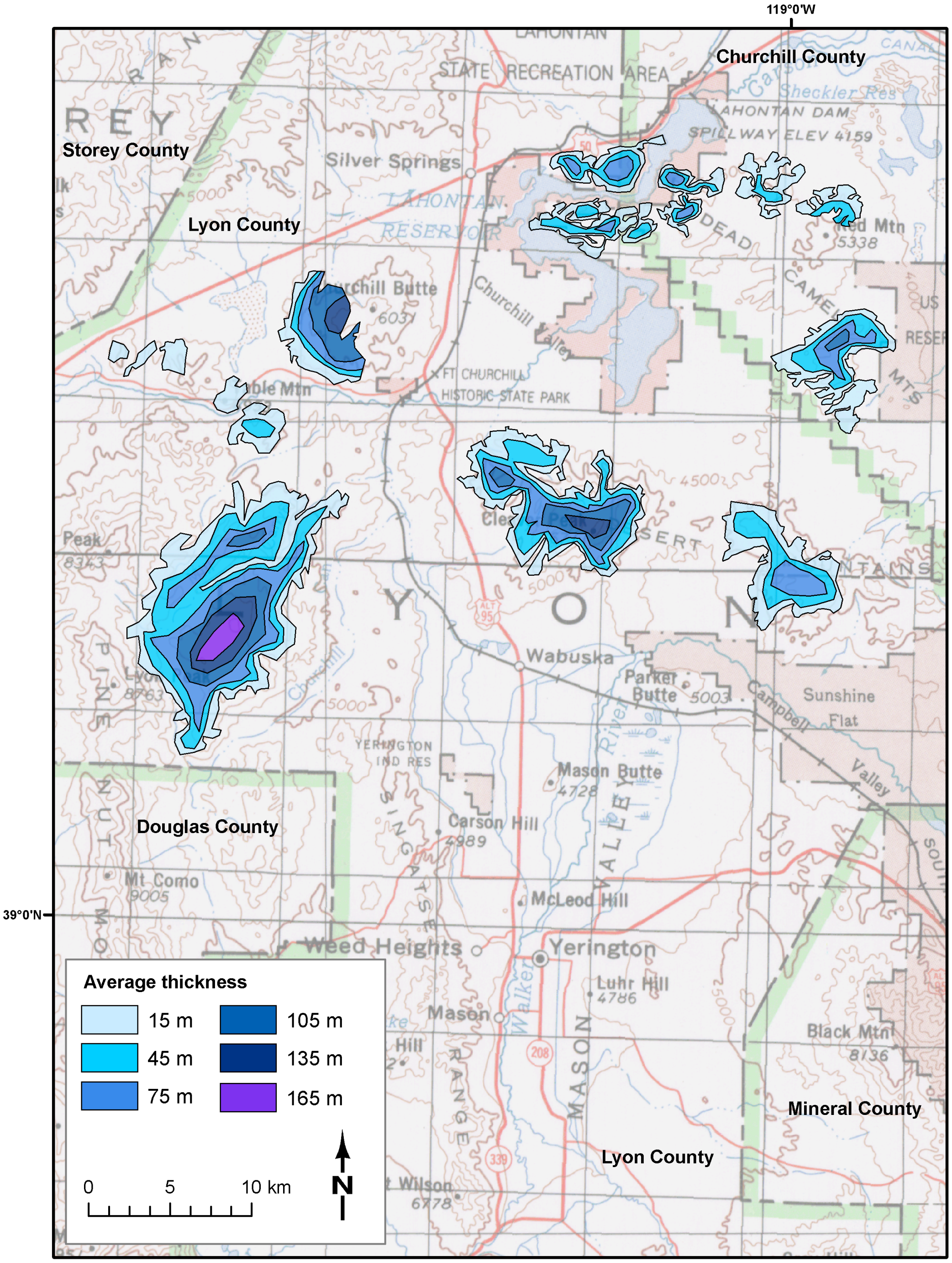

Figure 14. Cenozoic mafic rock isopach map of central Lyon and western Churchill Counties.

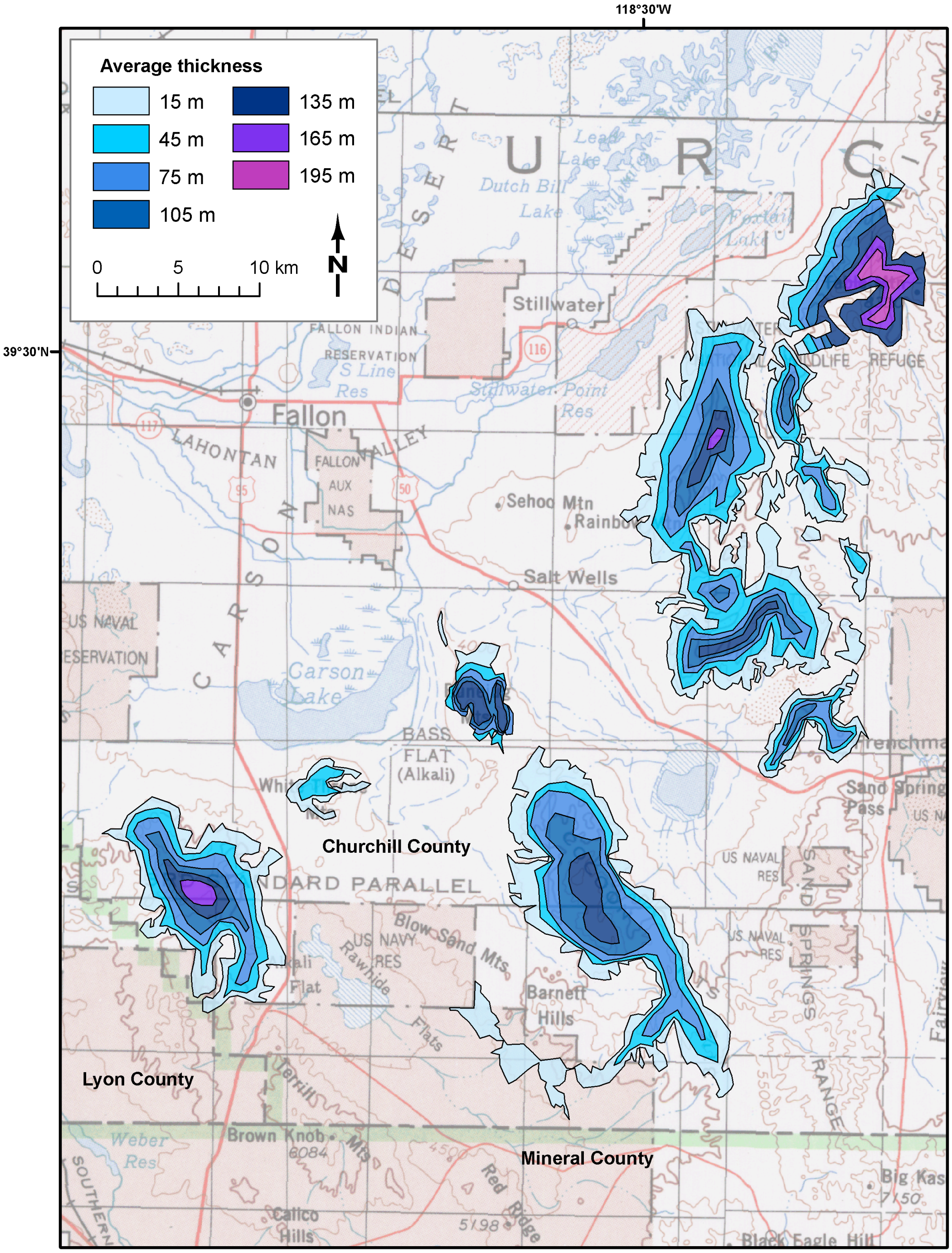

Figure 15. Cenozoic mafic rock isopach map of southwestern and central Churchill Counties.

Figure 16. Thick sequence of basalt flows east of Sand Mountain in Churchill County (looking to the northeast).

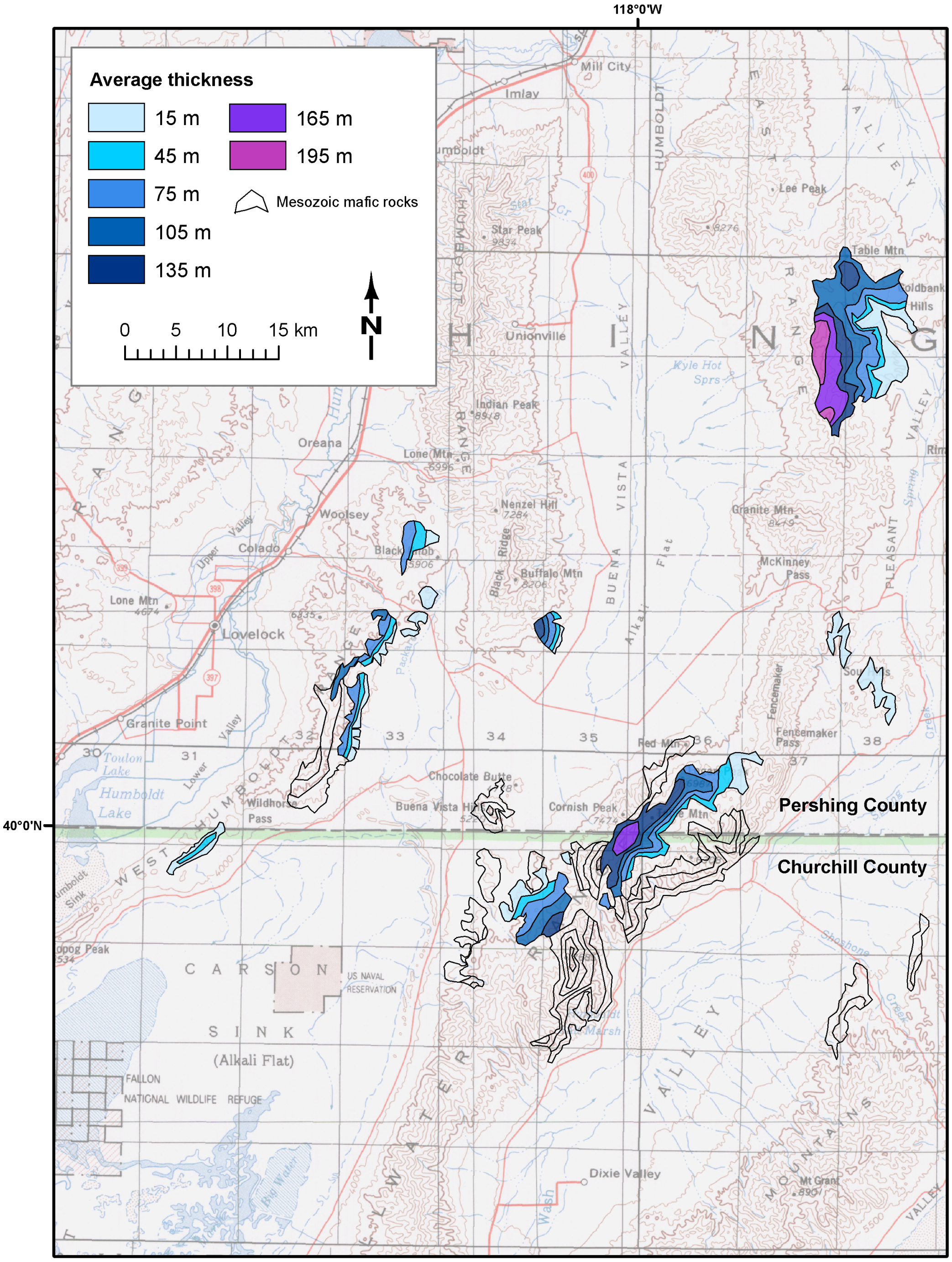

Figure 17. Cenozoic mafic rock isopach map of southern Pershing and northern Churchill Counties.

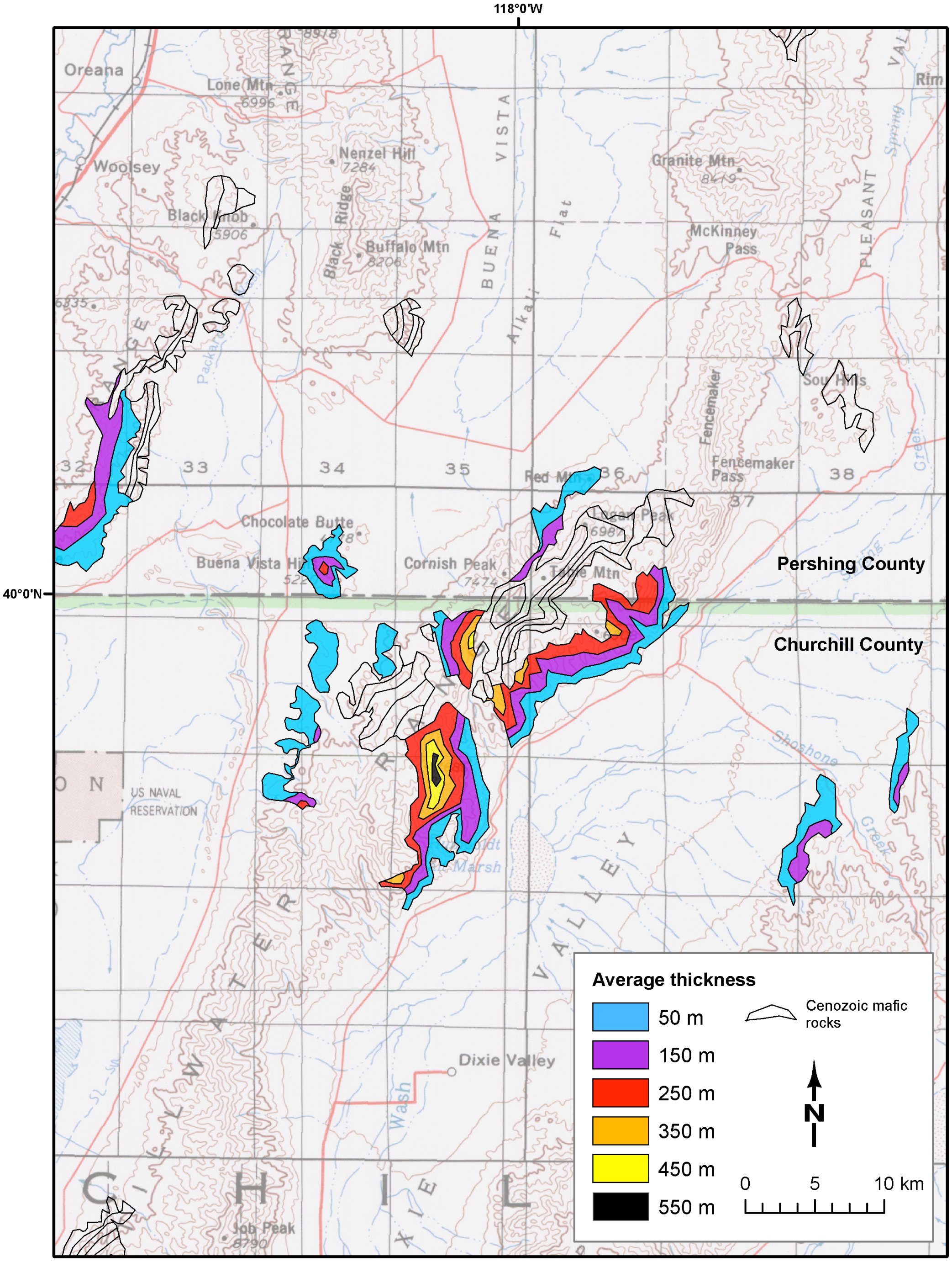

Figure 18. Mafic rock isopach map of the Humboldt lopolith, Churchill and Pershing Counties.

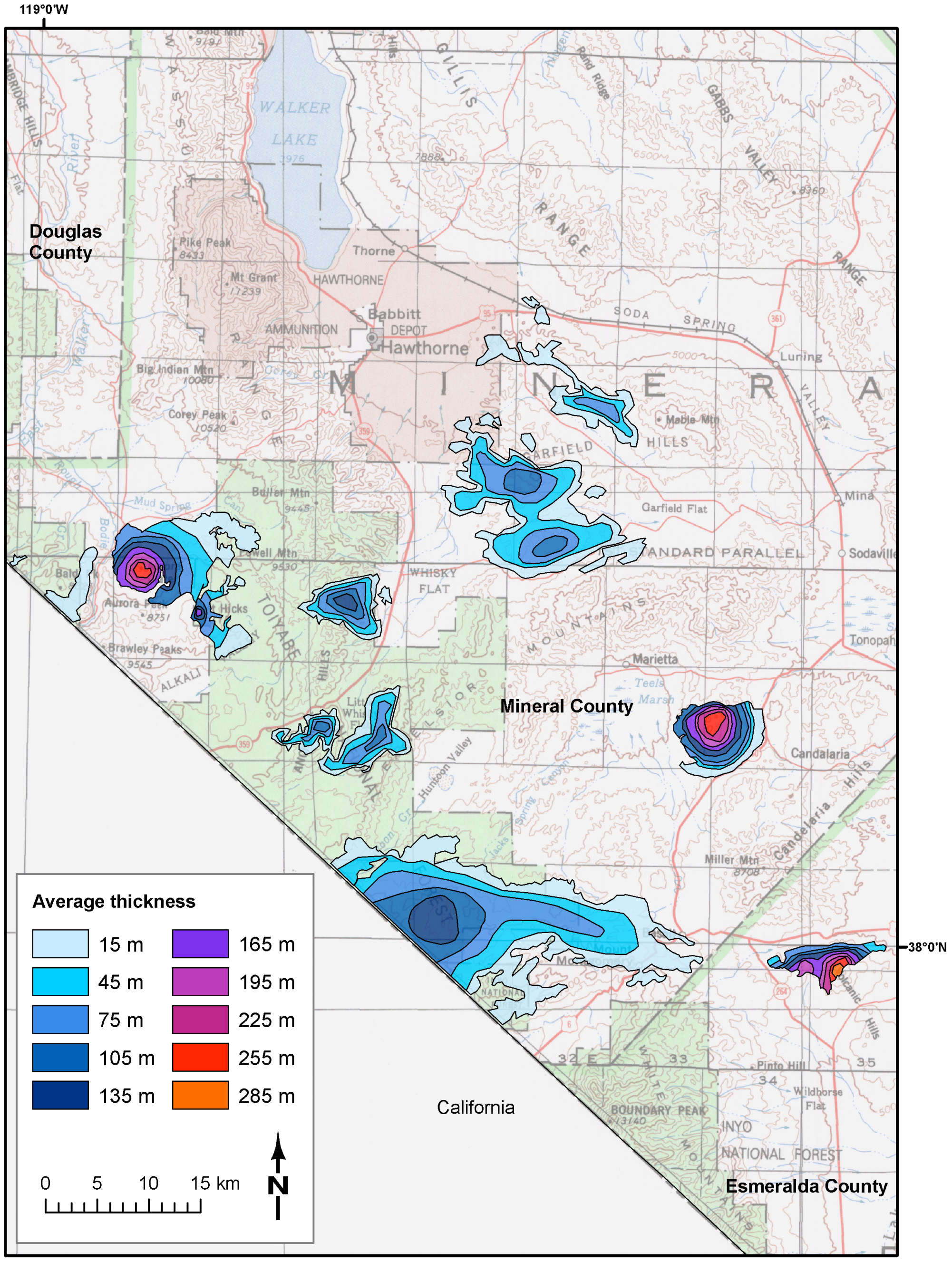

Figure 19. Mafic rock isopach map of southwestern Mineral and northwestern Esmeralda Counties.

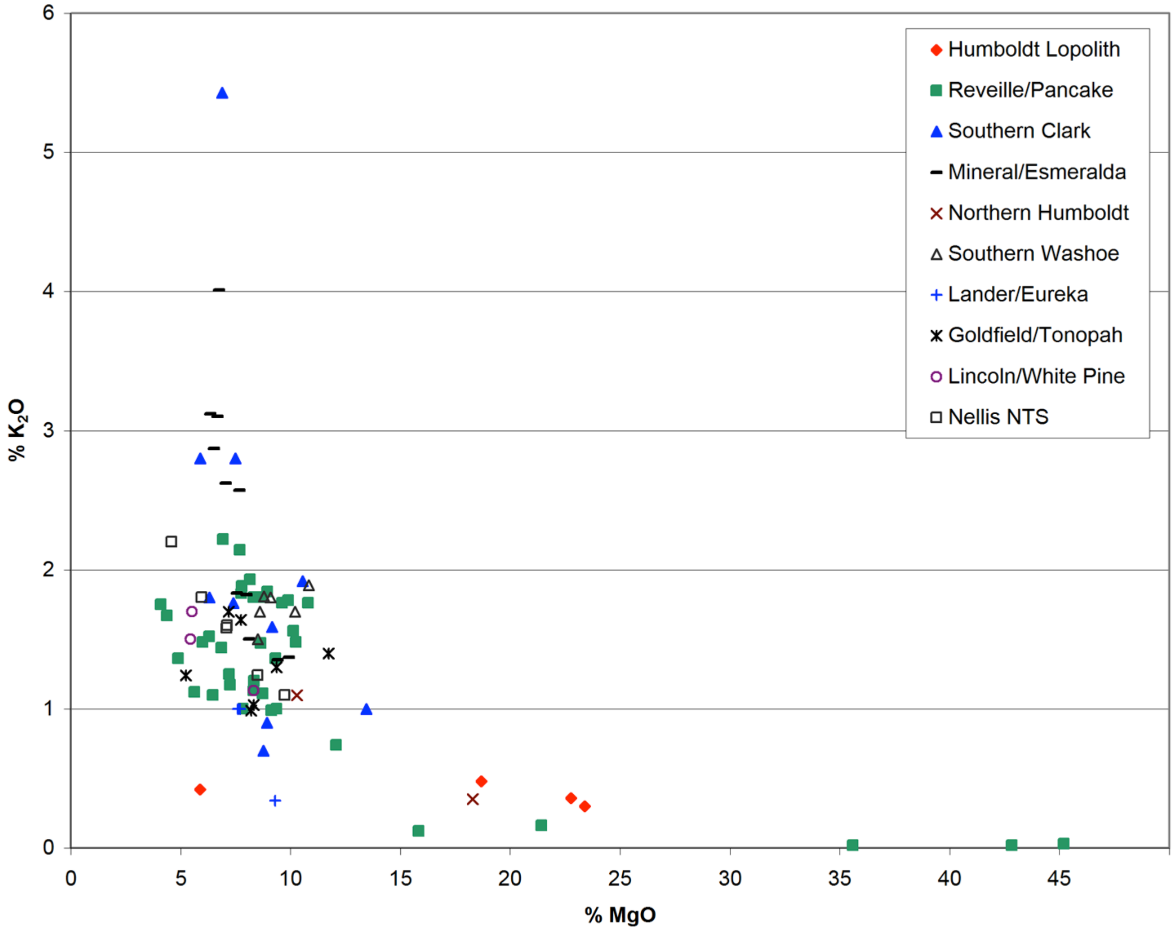

Figure 20. MgO versus K_2O for mafic rocks with CIPW normative olivine greater than 10%. Note that Mineral County mafic rocks have some of the highest K_2O values.

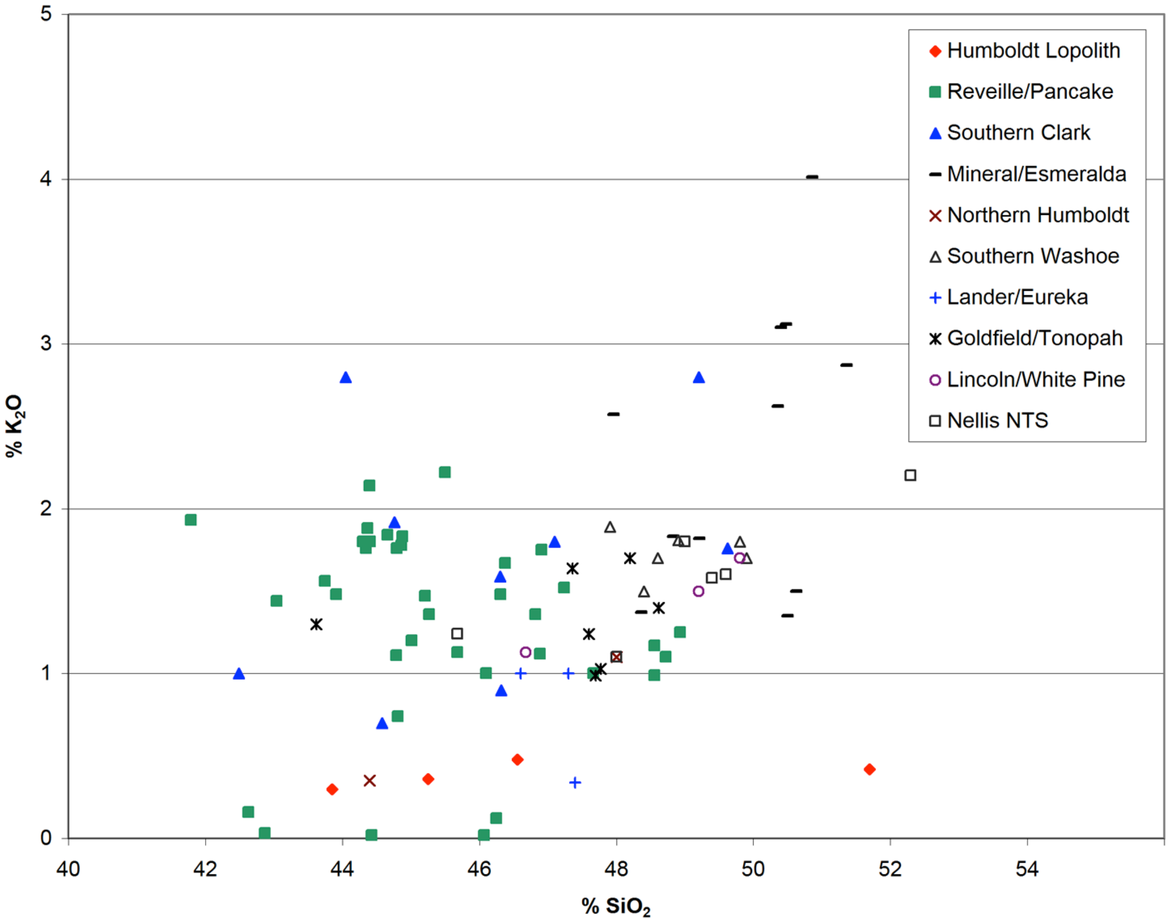

Figure 21. SiO_2 versus K_2O for mafic rocks with CIPW normative olivine greater than 10%.

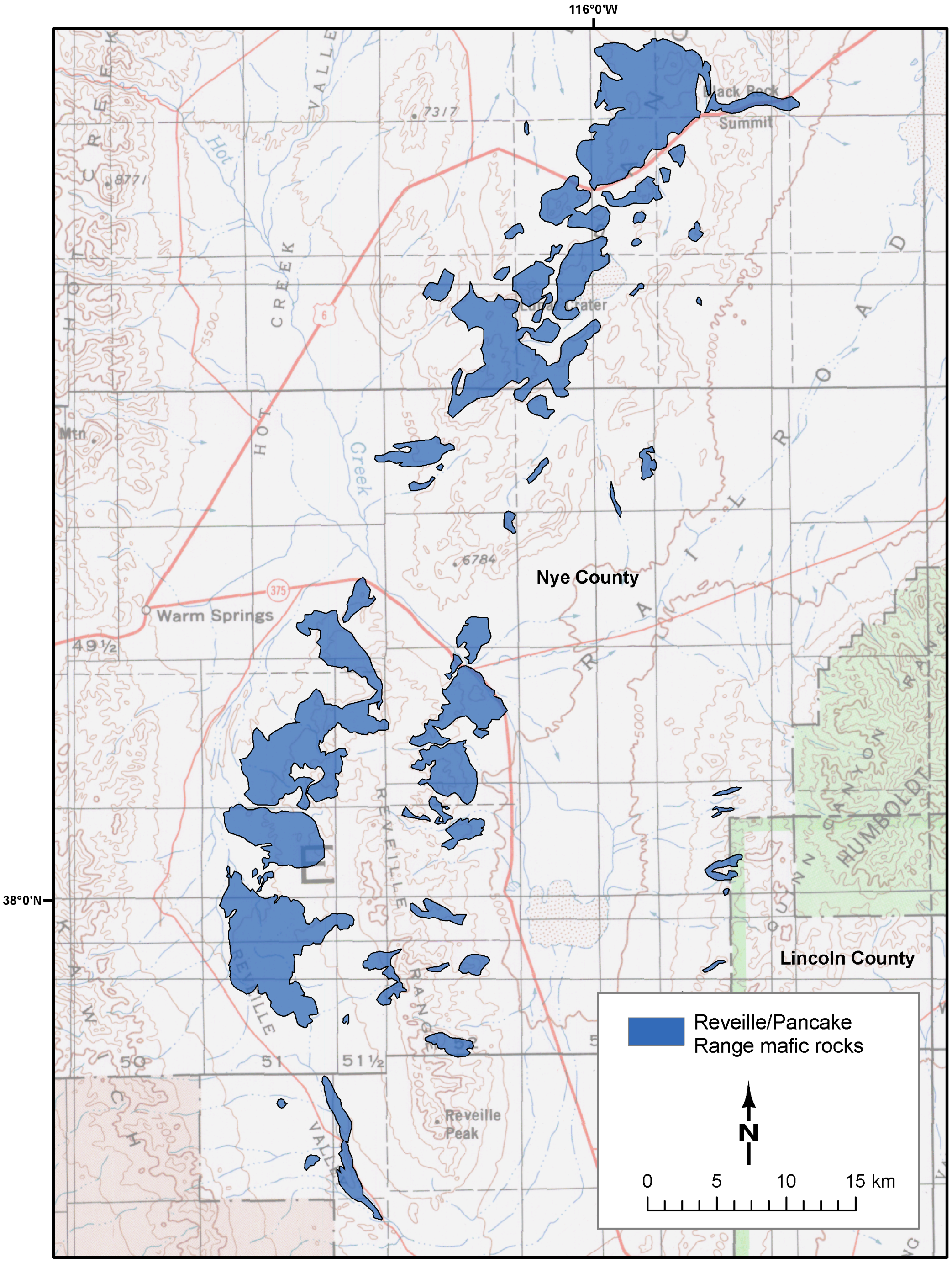

Figure 22. Mafic rock outcrops in the Reveille and southern Pancake Ranges, Nye County.

Figure 23. Easy Chair Crater, one of the Quaternary basalt cinder cones in the Lunar Crater field, Nye County (looking to the east).

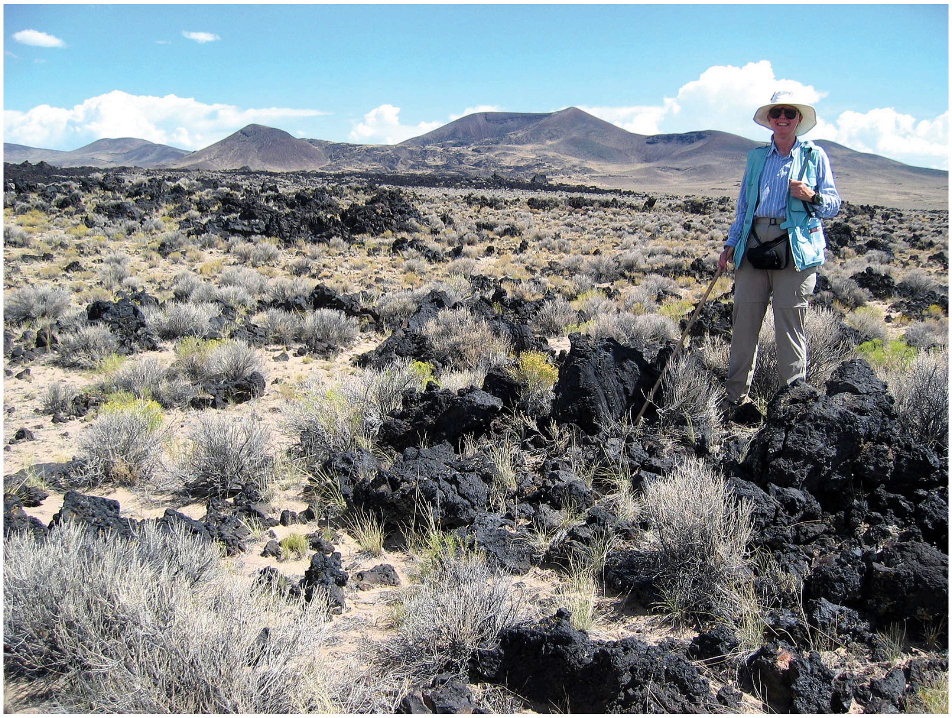

Figure 24. Edge of the Black Rock lava flow, with one of the Quaternary basalt cinder cones of the Lunar Crater field in the background (looking to the northeast).

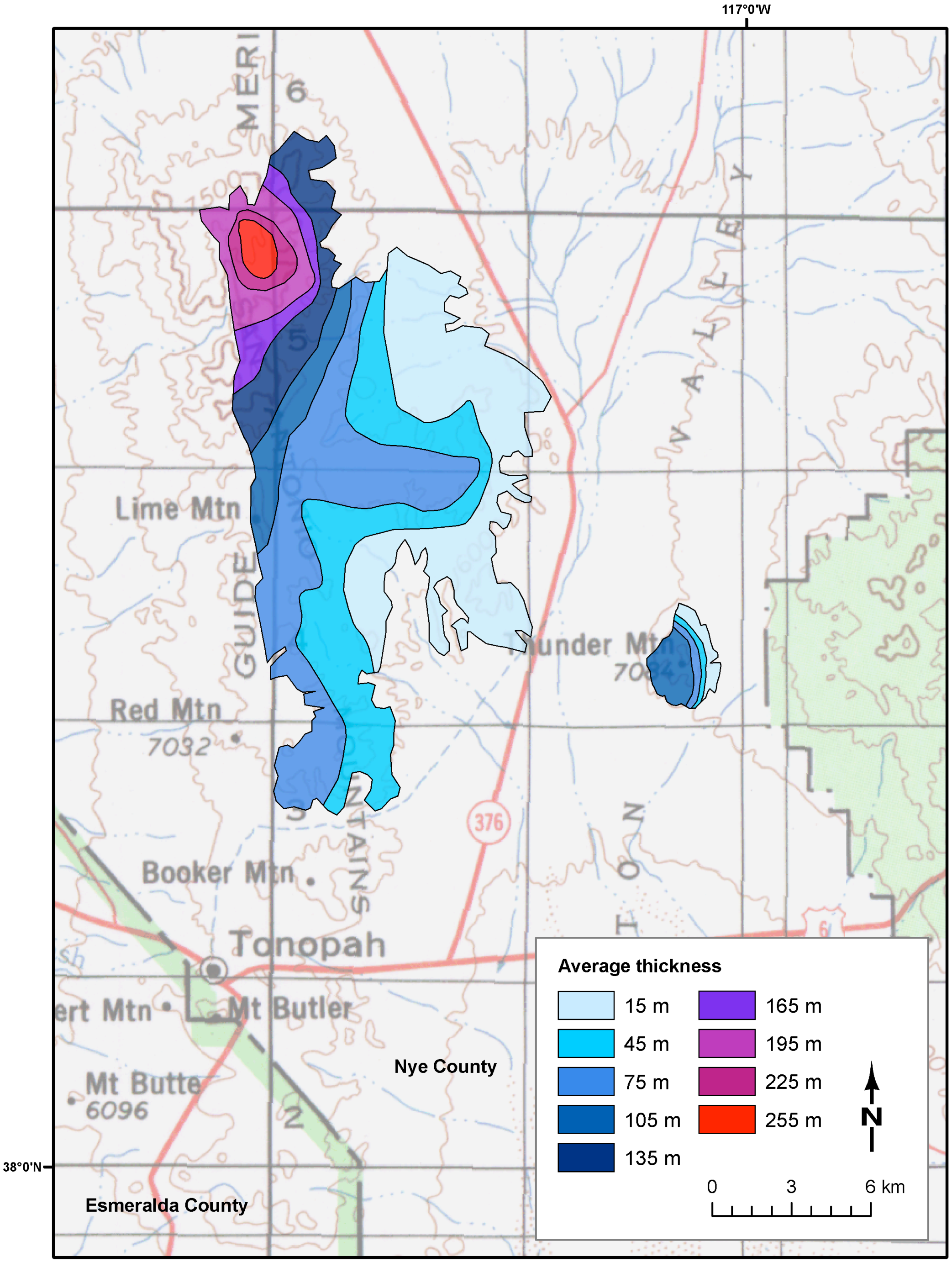

Figure 25. Mafic rock isopach map of the San Antonio Range, Nye County.

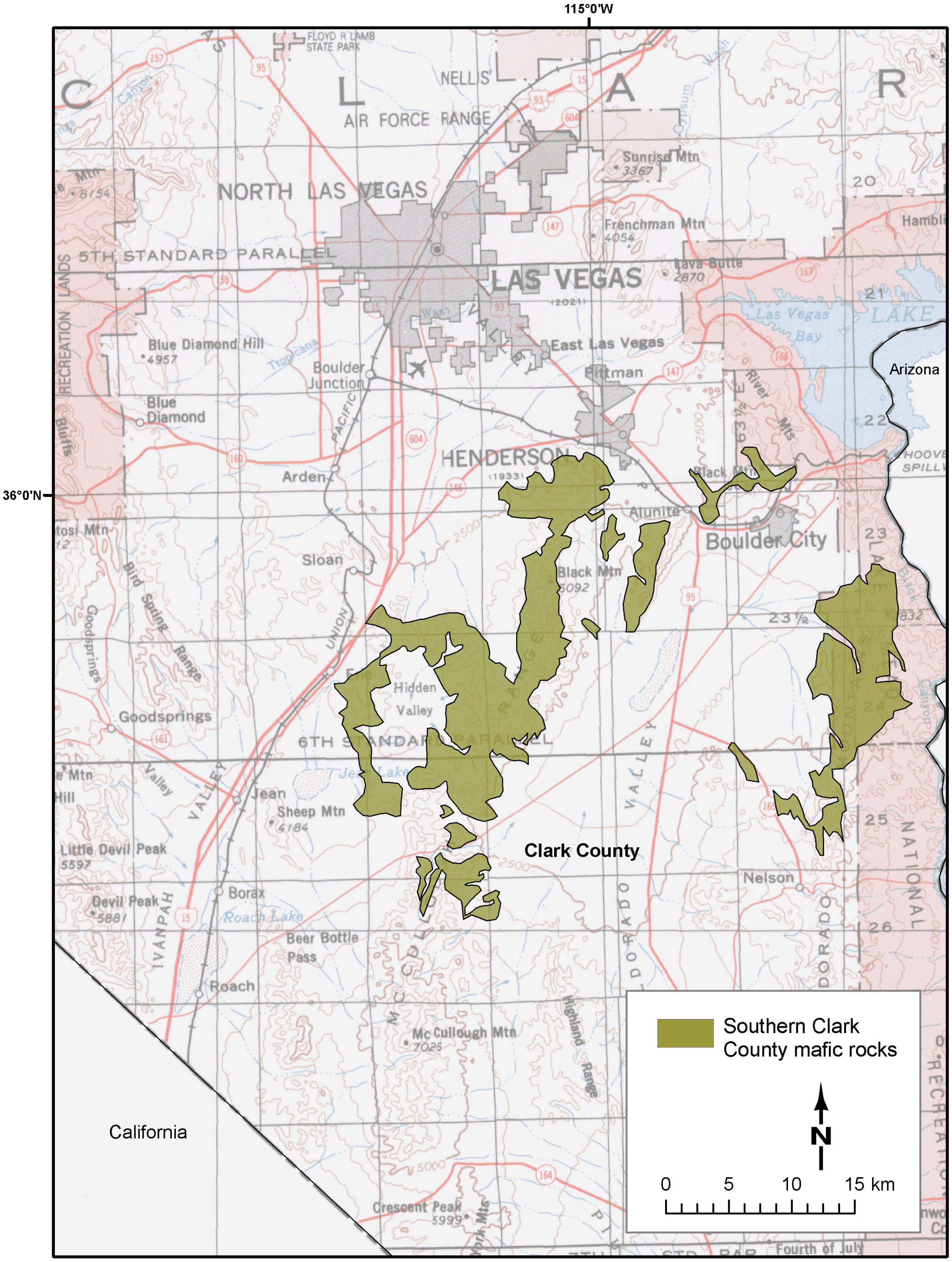

Figure 26. Mafic rock outcrops in southern Clark County.

Figure 27. Basalt flows capping the McCullough Range south of Las Vegas (looking to the northwest).

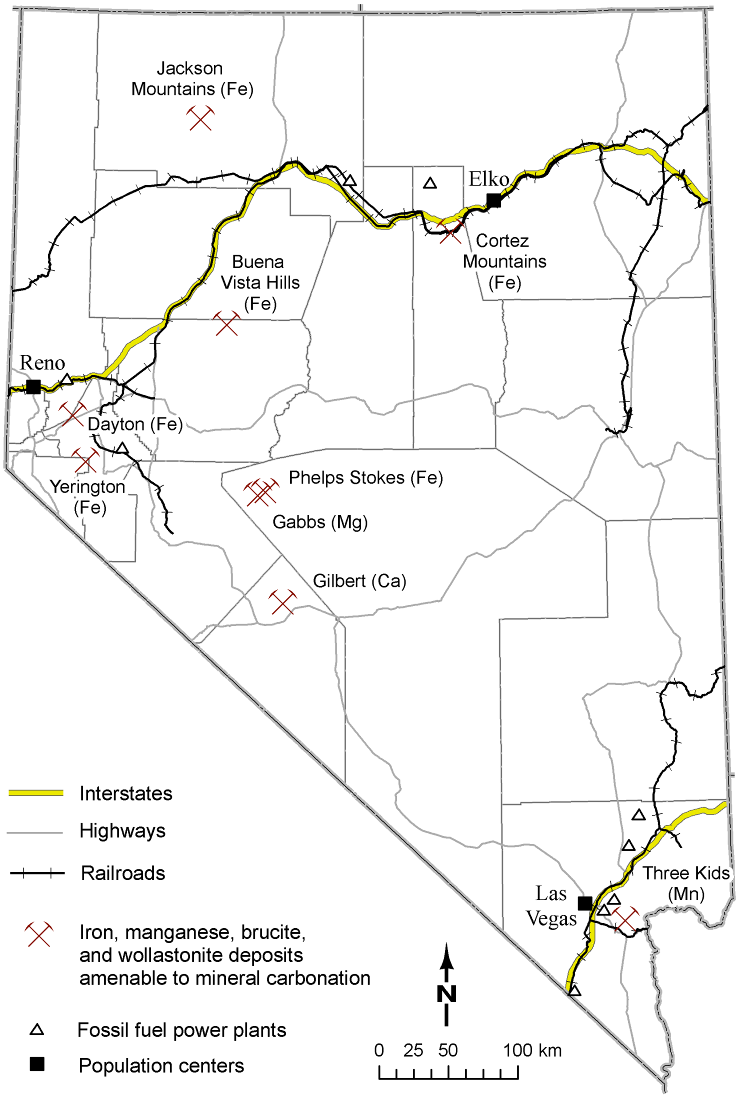

Figure 28. Location map of iron, manganese, and other mineral deposits amenable to mineral carbonation in Nevada, showing proximity to railways, highways, and existing power plants. Deposits include iron in the Buena Vista Hills, in the Cortez Mountains, near Dayton, in the Jackson Mountains, at the Phelps-Stokes Mine, and near Yerington; manganese at the Three Kids Mine; brucite near Gabbs; and wollastonite at the Gilbert deposit.

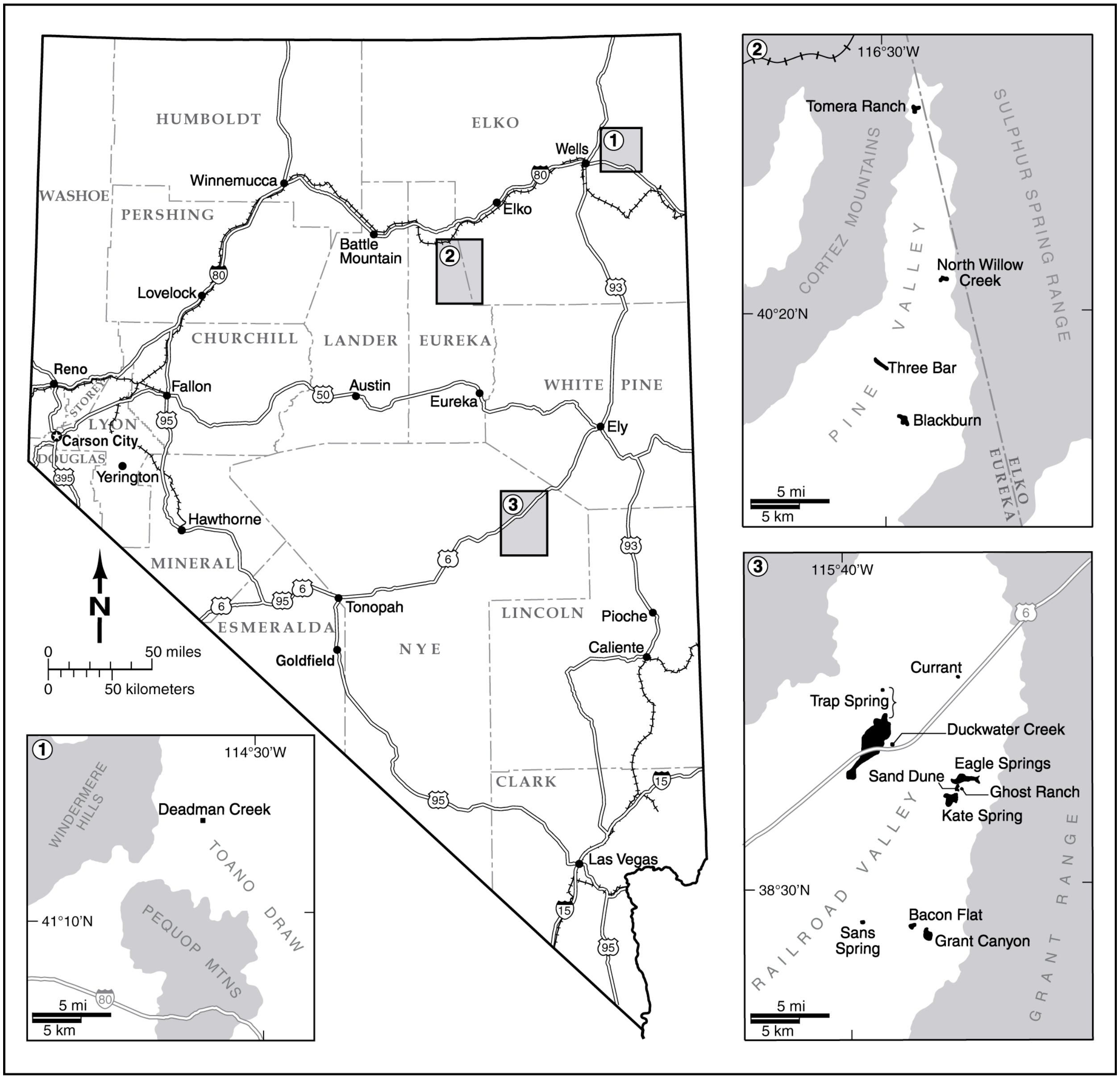

Figure 29. Location and relative sizes of oil fields from which production has been recorded in Nevada.

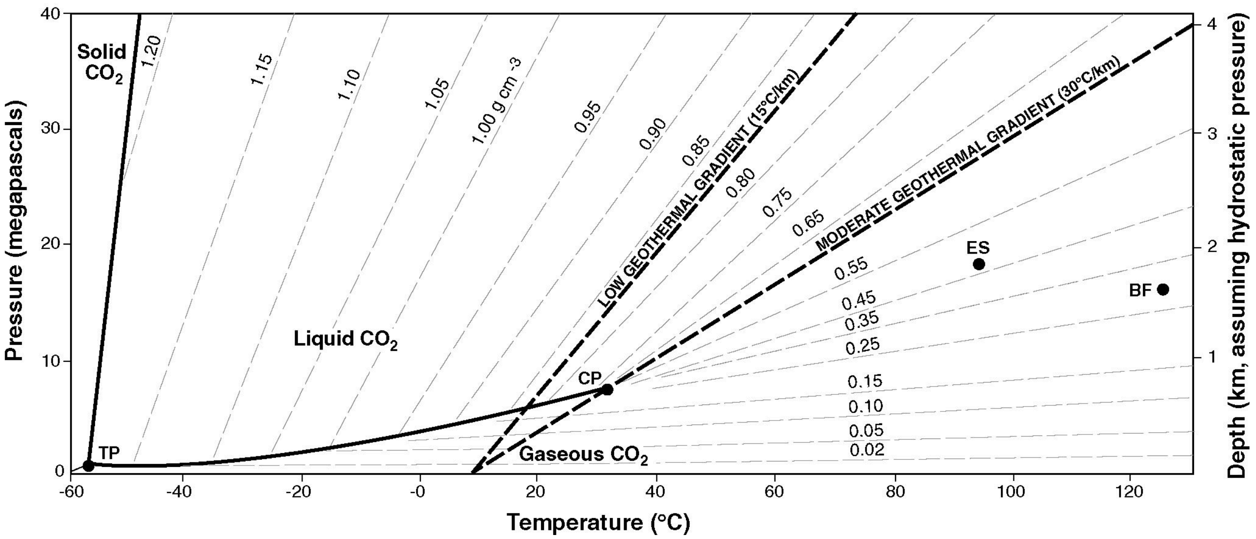

Figure 30. Phase relations, with lines of equal density, for CO_2 (modified from Roedder, 1984). TP = triple point (-56.6°C, 0.5 megapascals), at which solid, liquid, and gaseous CO_2 coexist. CP = critical point (31.0°C, 7.38 megapascals), above which the distinction between gas and liquid cannot be 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 et al. 1994).

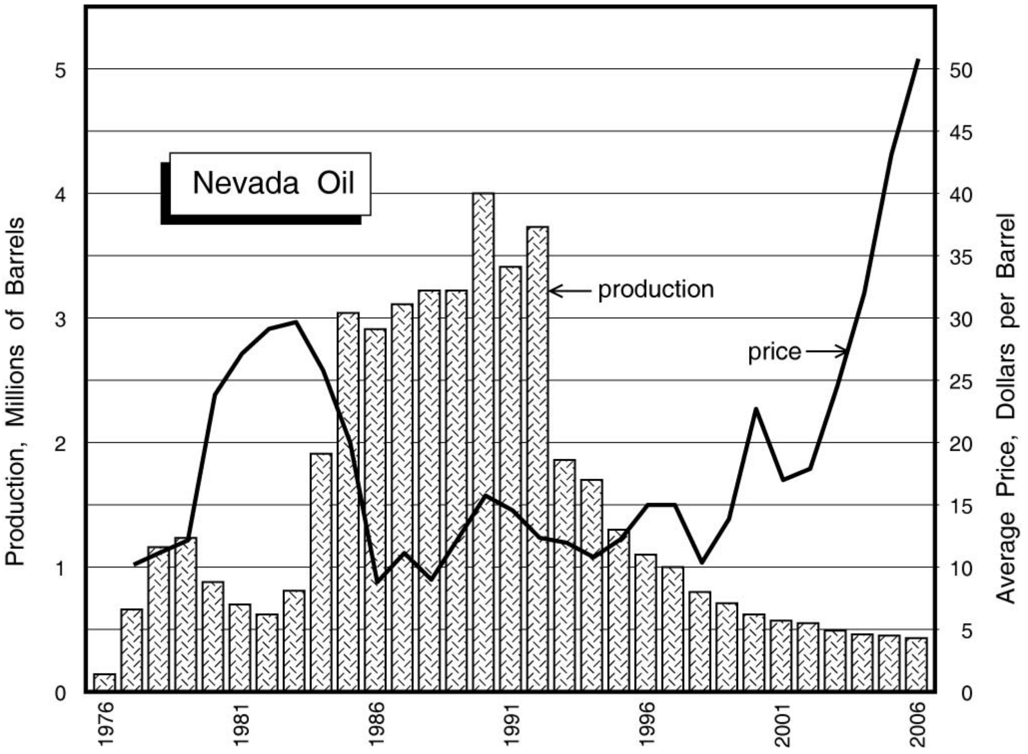

Figure 31. Production and price history for Nevada oil, 1976-2006 (from Price and Meeuwig, 2007).

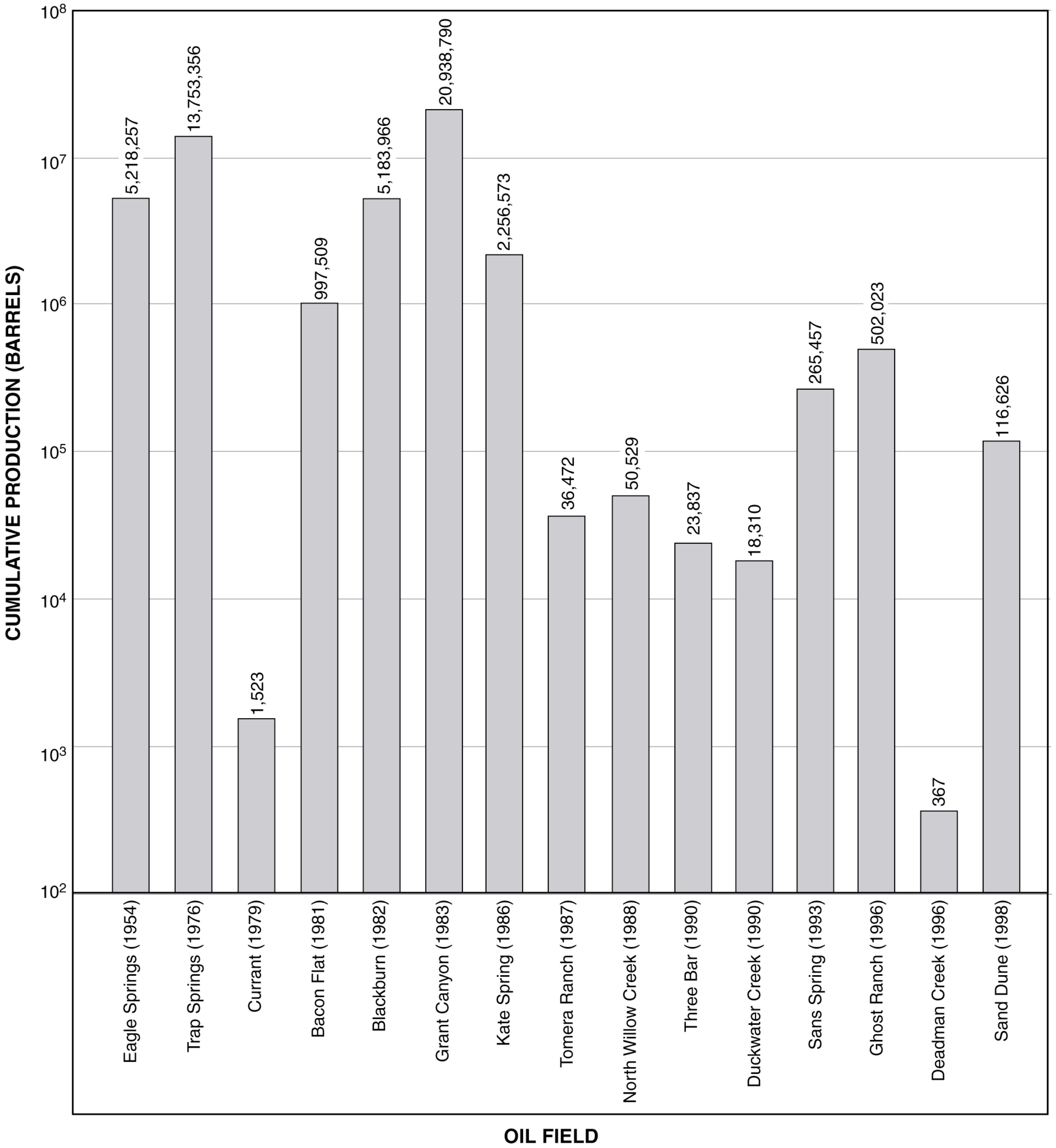

Figure 32. Cumulative Nevada oil production, through 2006, by field, with year of discovery in parentheses.

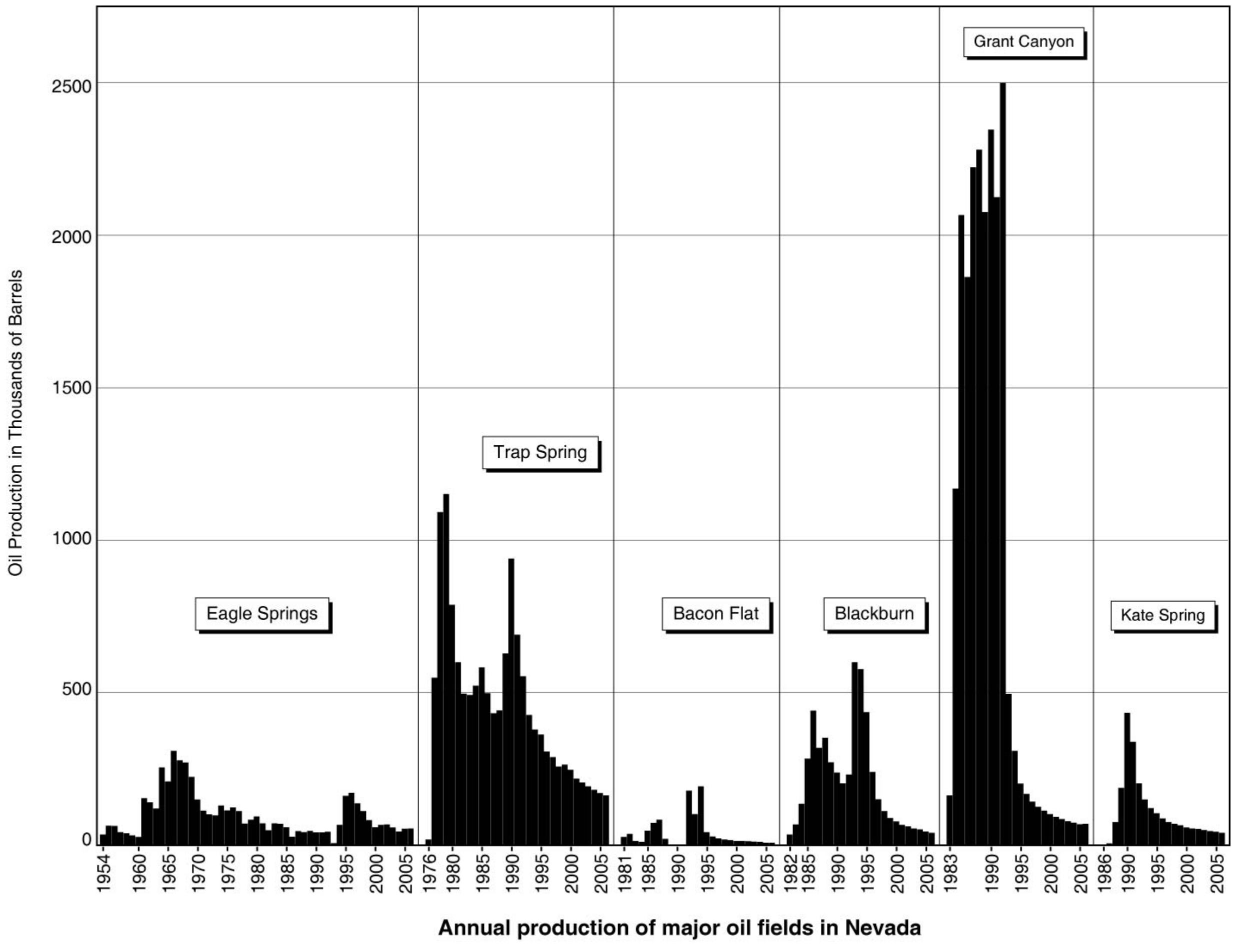

Figure 33. Production histories of Nevada's largest oil fields (from Davis, 2007).

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