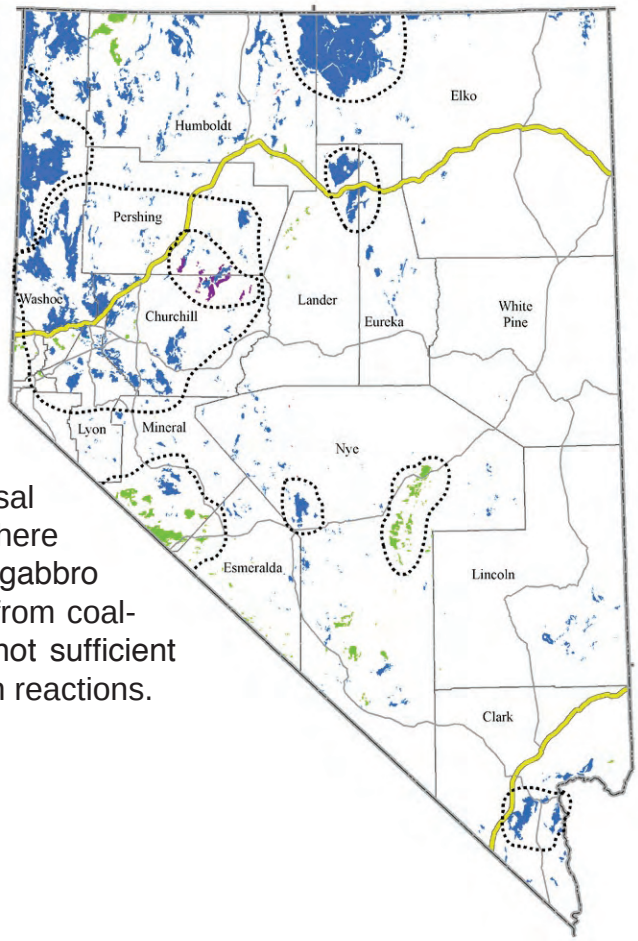
Nevada Bureau of Mines and Geology Report 52

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

Daniel M. Sturmer
Daphne D. LaPointe
Jonathan G. Price
Ronald H. Hess



This report investigates the potential for disposal of CO_2 by reaction with rocks in Nevada. There are sufficiently large volumes of basalt and gabbro to consider reaction of those rocks with CO_2 from coal-fired power plants, but in Nevada there are not sufficient quantities of other potential rock types for such reactions.

2007

Nevada Bureau of Mines and Geology
Mackay School of Earth Sciences and Engineering
College of Science
University of Nevada, Reno

CONTENTS

EXECUTIVE SUMMARY 1

INTRODUCTION 1

Theoretical Considerations Regarding Reactions with Rocks and Minerals **2**

MAFIC AND ULTRAMAFIC ROCKS IN NEVADA 5

Geochemistry **7**

Procedure for Evaluating Mafic Volcanic Fields **10**

Procedure for Assessing Mafic Rock Volume **10**

Description of Selected Mafic Rock Fields **11**

Northwestern Washoe County **11**

Owyhee Plateau **11**

Battle Mountain Area **14**

Southern Washoe/Storey/Lyon/Churchill Counties **14**

Humboldt Mafic Lopolith, Churchill and Pershing Counties **14**

Southwestern Mineral/Northwestern Esmeralda Counties **14**

Reveille/Pancake Ranges, Eastern Nye County **14**

San Antonio Mountains, Western Nye County **25**

Southern Clark County **25**

OTHER NEVADA MINERAL RESOURCES THAT COULD BE AMENABLE TO SEQUESTRATION OF CO_2 28

Significant Iron Deposits of Nevada **28**

Buena Vista Hills **28**

Cortez Mountains **32**

Jackson Mountains **32**

Dayton Area **32**

West-Central Nevada **33**

Gabbs Area **33**

Yerington Area **33**

Pumpkin Hollow Deposit **33**

Significant Manganese Deposits of Nevada **33**

Other Minerals Amenable to Carbonation **34**

Gilbert Wollastonite Deposit **34**

Gabbs Brucite Deposit **34**

DISCUSSION 34

CONCLUSIONS AND RECOMMENDATIONS 35

ACKNOWLEDGMENTS 36

REFERENCES 36

APPENDIX I* - Geochemical Data on Mafic Rocks in Nevada

APPENDIX II* - Calculated Normative Mineral Compositions of Mafic Rocks in Nevada

APPENDIX III* - Calculated Volumes of Mafic Rocks in Nevada

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

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 and others, 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).

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] + $\mathbf{O_2}$ [from the atmosphere] = $\mathbf{CO_2}$ [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 weight). The total amount of carbon in the Earth's atmosphere is approximately 730 gigatons (Intergovernmental Panel on Climate Change, 2001).

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

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 and others, 2005). This report follows up with a more detailed evaluation of one of the unconventional approaches—sequestration through reaction with minerals and rocks.

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 and others, 1995, 1997; Butt and Lackner, 1997, Goff and Lackner, 1998; O'Conner and others, 2002; Voormeij and others, 2004; Mazzotti and others, 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.

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 and others (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. Nevada 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

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 and others, 1974, and Robie and Hemingway, 1995; modified from Price and others, 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)
7. $2NaAlSi_3O_8$ (albite in plagioclase) + CO_2 (gas) = Na_2CO_3 (sodium carbonate) + Al_2O_3 (alumina or corundum) + $6SiO_2$ (quartz)
8. $Mg_6Si_4O_{10}(OH)_8$ (antigorite) + $6CO_2$ (gas) = $6MgCO_3$ (magnesite) + $4SiO_2$ (quartz) + $4H_2O$ (water)
9. $Mg(OH)_2$ (brucite) + CO_2 (gas) = $MgCO_3$ (magnesite) + H_2O (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		

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 and others (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 and others (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

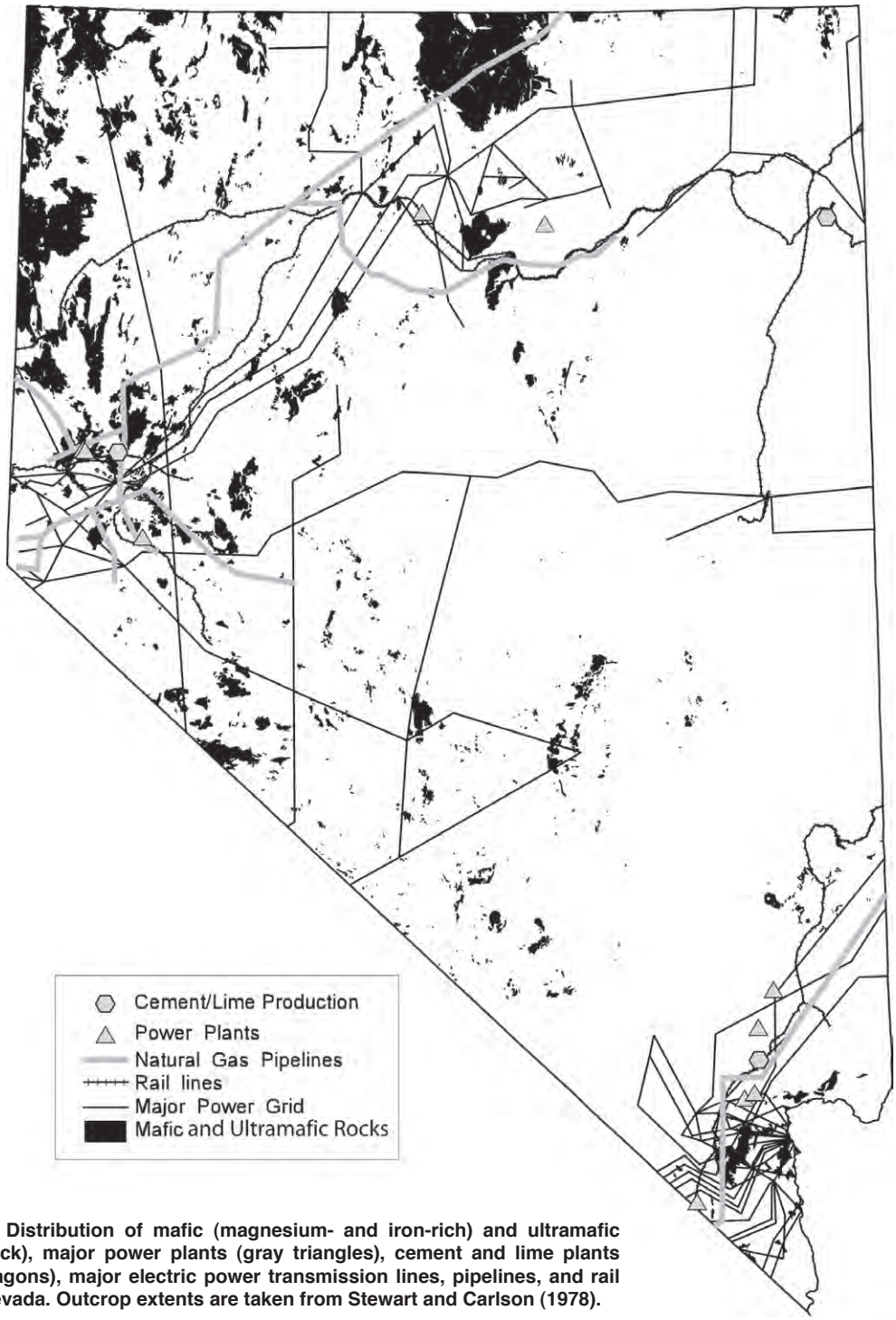


Figure 2. Distribution of mafic (magnesium- and iron-rich) and ultramafic rocks (black), major power plants (gray triangles), cement and lime plants (gray hexagons), major electric power transmission lines, pipelines, and rail lines in Nevada. Outcrop extents are taken from Stewart and Carlson (1978).

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 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), and others cited below.

The oldest lithosphere in Nevada is a promontory of the Archean Wyoming province in northeastern Nevada (Lush and others, 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 and others, 2004; Dubendorfer and others, 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 and others, 1999; Sears and Price, 2000, 2003; Stewart and others, 2001; Li and others, 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 and others (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 and others, 1980; Wernicke, 1981; Miller and others, 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-

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

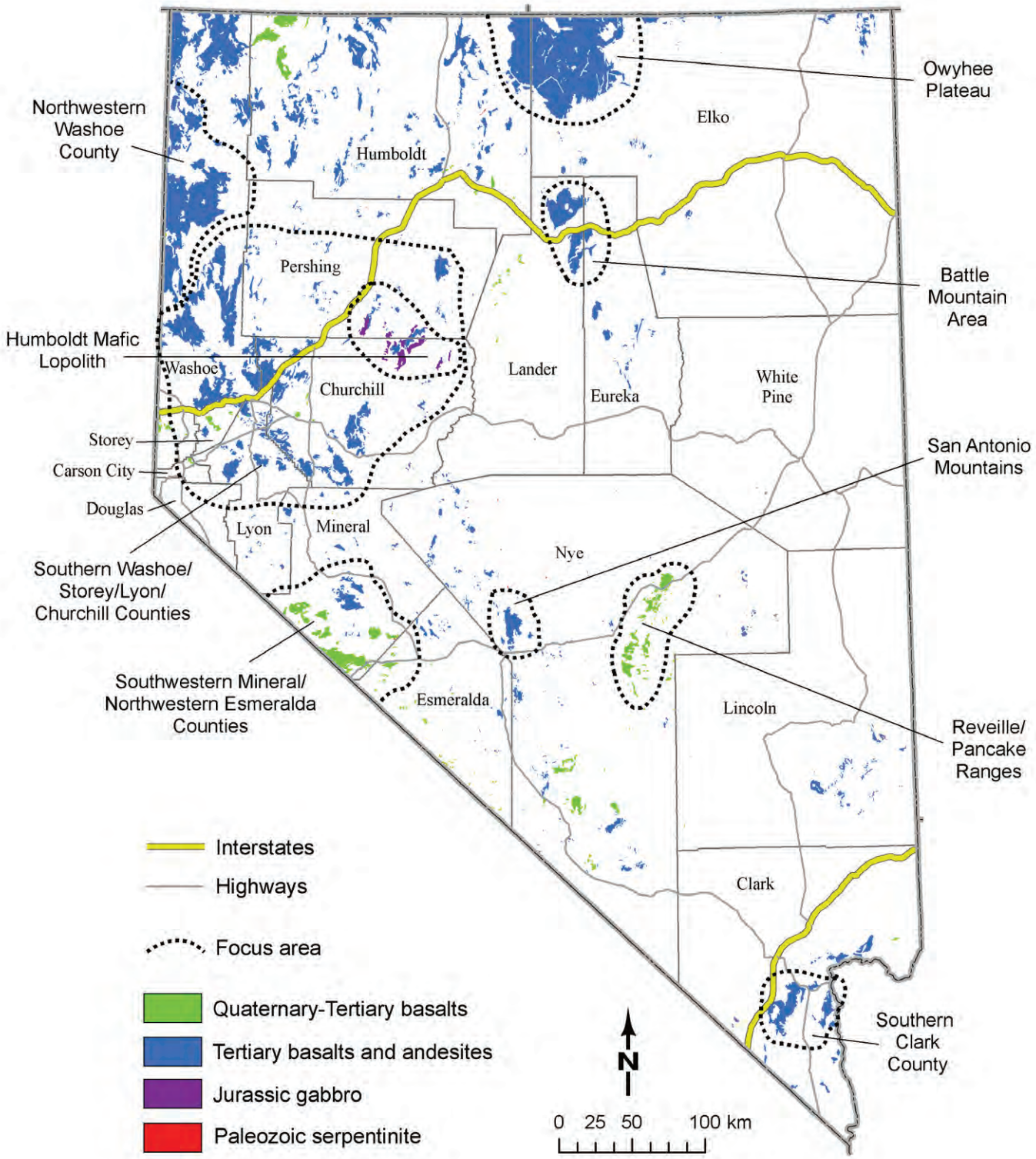


Figure 3. Mafic and ultramafic rocks in Nevada outlining the nine focus areas for this study. Outcrop extents are taken from Stewart and Carlson (1978).

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 and others, 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 and others, 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 and others, 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 and others, 1999; Garside and others, 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 and others, 1991; Rash, 1995; Yogodzinski and others, 1996; Smith and others, 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 and others, 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 and others, 1989; Glazner and Ussler, 1989; Fitton and others, 1991), late Cenozoic asthenospheric upwelling (Fitton and others, 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 and others, 1991; Kempton and others, 1991) and mantle lithosphere (Hedge and Noble, 1971; Mark and others, 1975; Leeman, 1982; Menzies, 1989; Fitton and others, 1991; Kempton and others, 1991; Rogers and others, 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 and others, 1994; John and others, 2000b; Wallace and John, 2000; Leavitt and others, 2000; Ponce and Glen, 2002; Grauch and others, 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 and others, 1988; Lum and others, 1989; Menzies, 1989; Rogers and others, 1995). Lum and others (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/appendix_1). Most of the analyses were found in the NAVDAT (http://navdat.kgs.ku.edu) and PETROS (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).

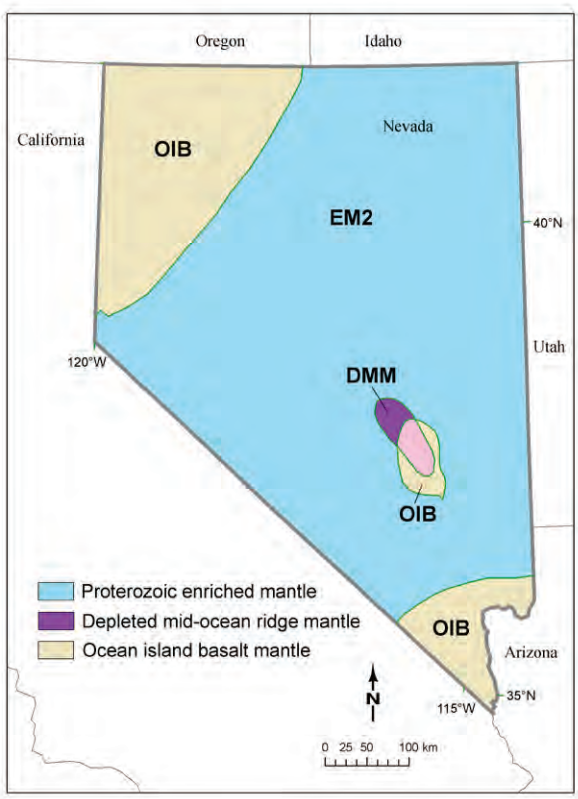


Figure 4. Lithospheric mantle domains in Nevada, based on seismic tomography, heat flow, and xenolith thermobarometry. Locally domains are overprinted. DMM = depleted mid-ocean ridge basalt mantle; EM2 = enriched mantle domain; OIB = ocean island basalt mantle. The sub-Archean lithospheric mantle domain 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).

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	0.8	50.7	21.20
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

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/appendix_2). 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).

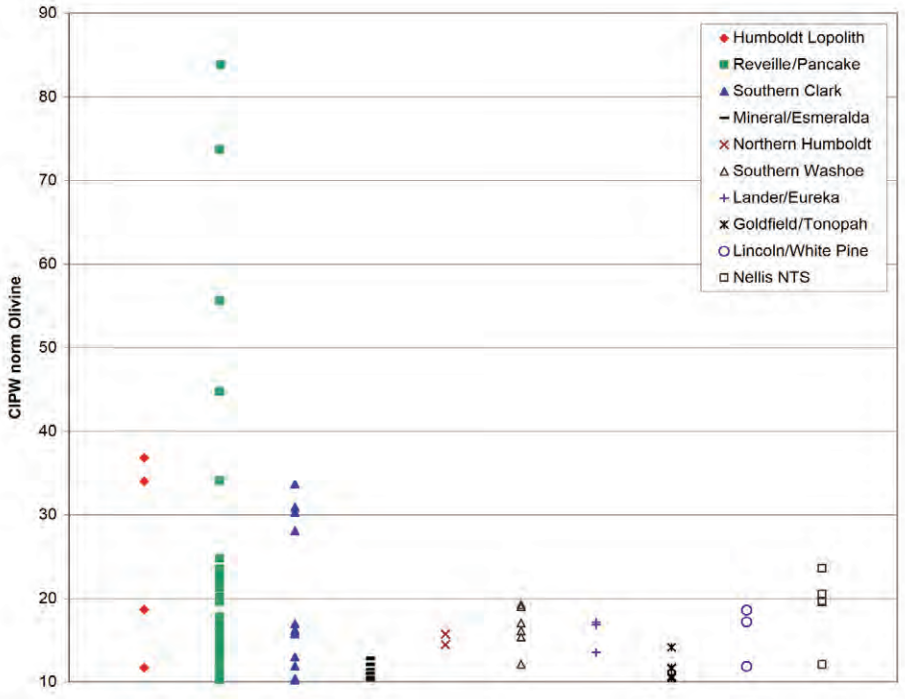


Figure 5. CIPW normative olivine values for some mafic rocks in Nevada (with olivine greater than 10%).

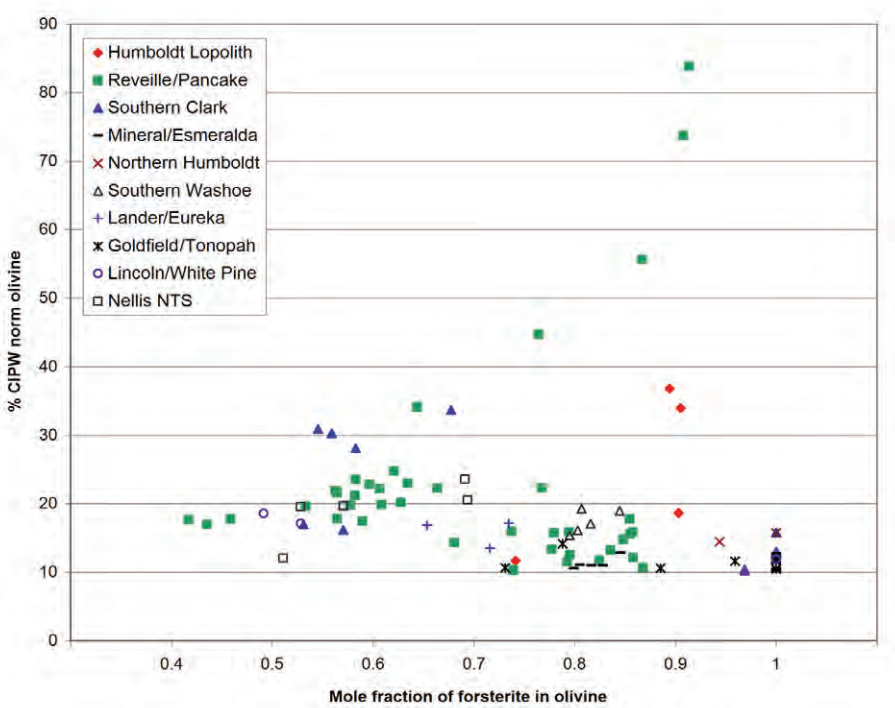


Figure 6. Normative forsterite vs. normative olivine for some mafic rocks in Nevada with normative olivine greater than 10%.

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.

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.

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/appendix_3. Each field is briefly described below.

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).

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 and others (1996).

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 exists 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.

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

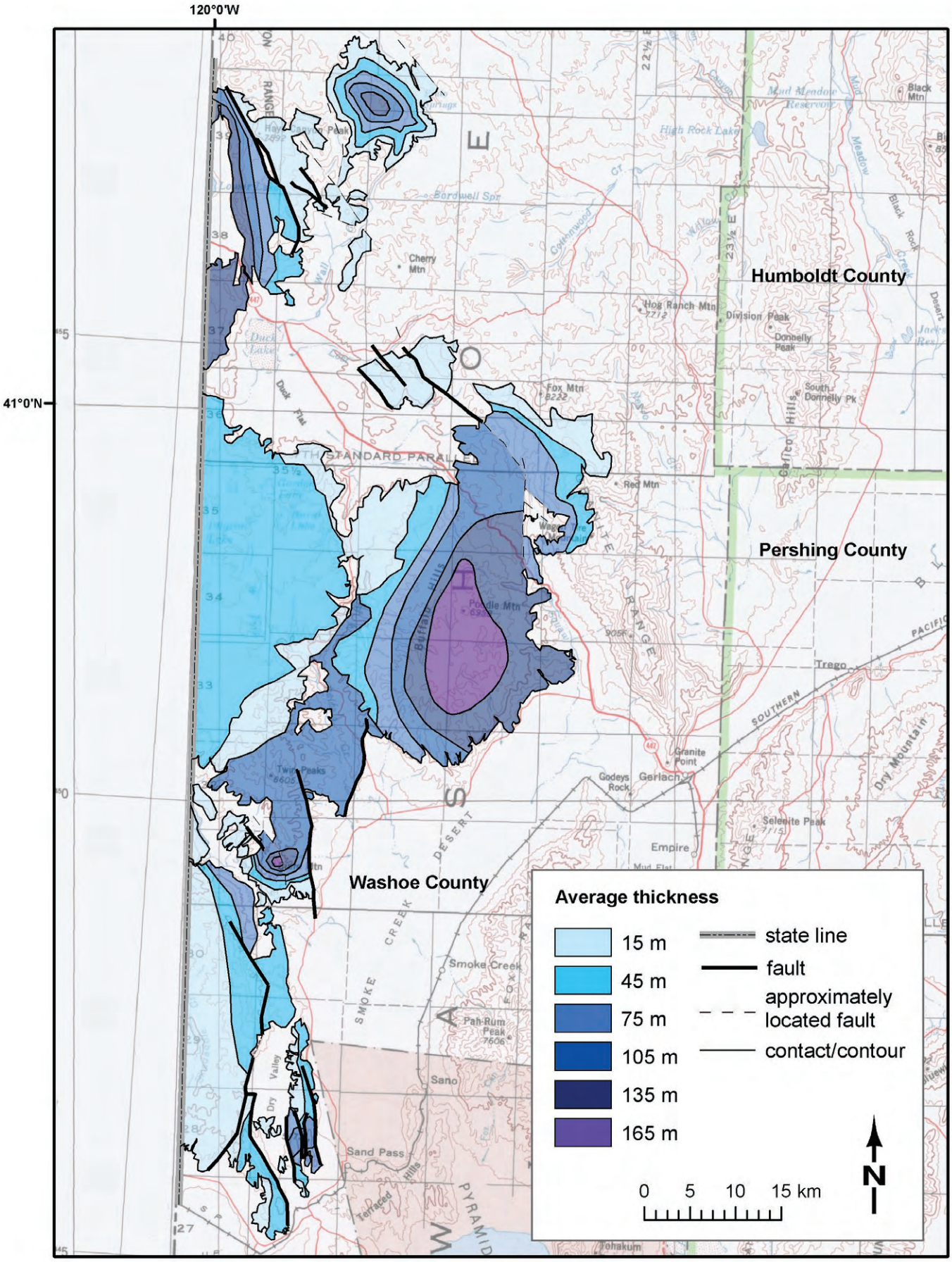


Figure 9. Mafic rock isopach map of northwestern Washoe County.

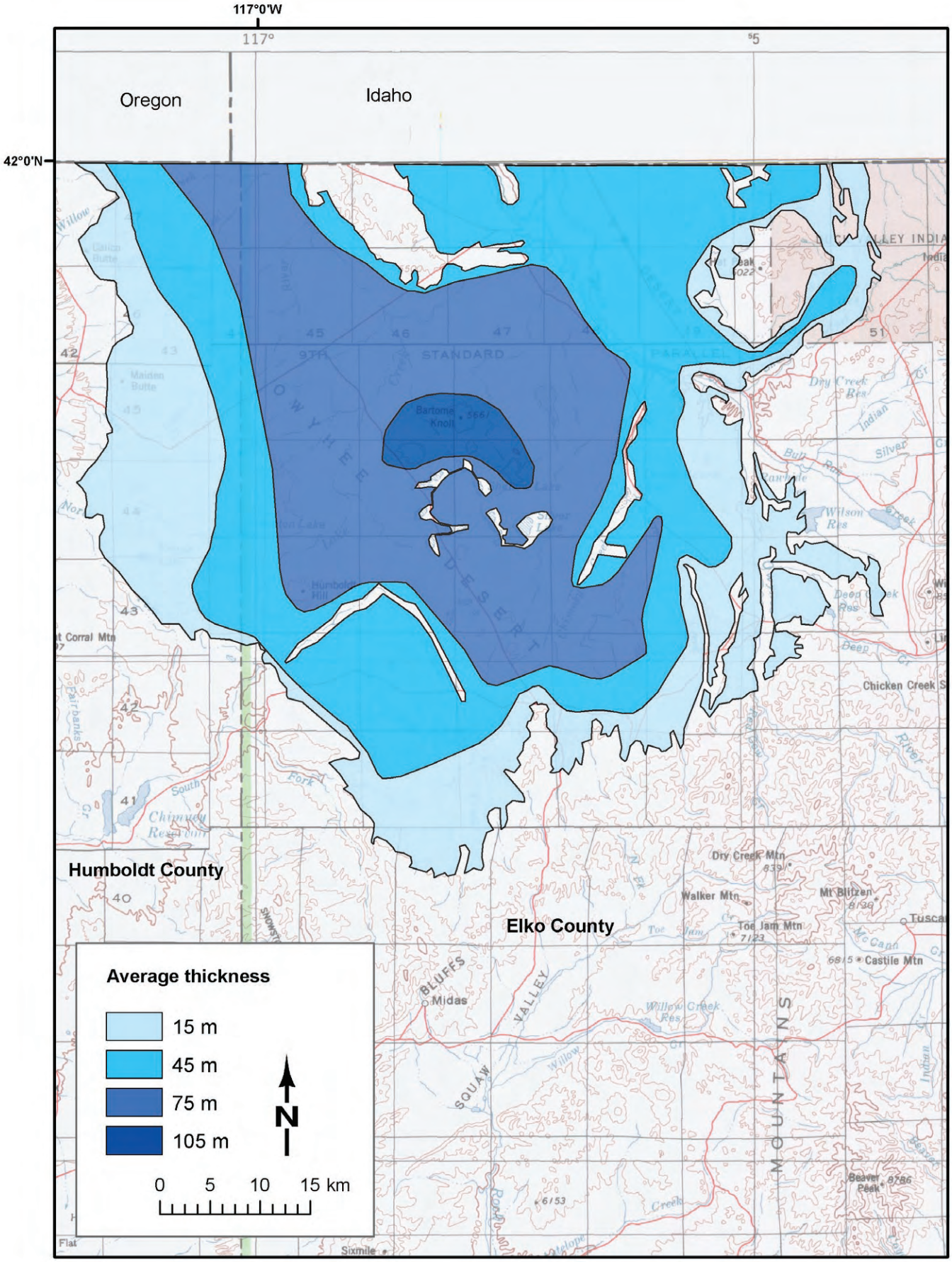


Figure 10. Mafic rock isopach map of the Owyhee plateau area, Humboldt and Elko Counties.

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 and others, 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 and others, 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 and others, 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 and others, 2000; Faulds and others, 2003a, b; Henry and others, 2004; Drakos, 2007). More recent lava flows, including the Lousetown (11–6 Ma, John and others, 1999; Schwartz, 2001) and McClellan Peak (1.5–1.44 Ma, Silberman and McKee, 1972; Morton and others, 1980; John and others, 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 and others, 1982; Farmer and others, 1989; Yogodzinski and others, 1996; Smith and others, 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 and others (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 and others, 1996).

Mafic volcanism began ~14 Ma in the Reveille Range and continued until ~3 Ma (Rash, 1995; Yogodzinski and others, 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 and others, 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 and others, 1991; Rash, 1995; Yogodzinski and others, 1996). Following the eruption

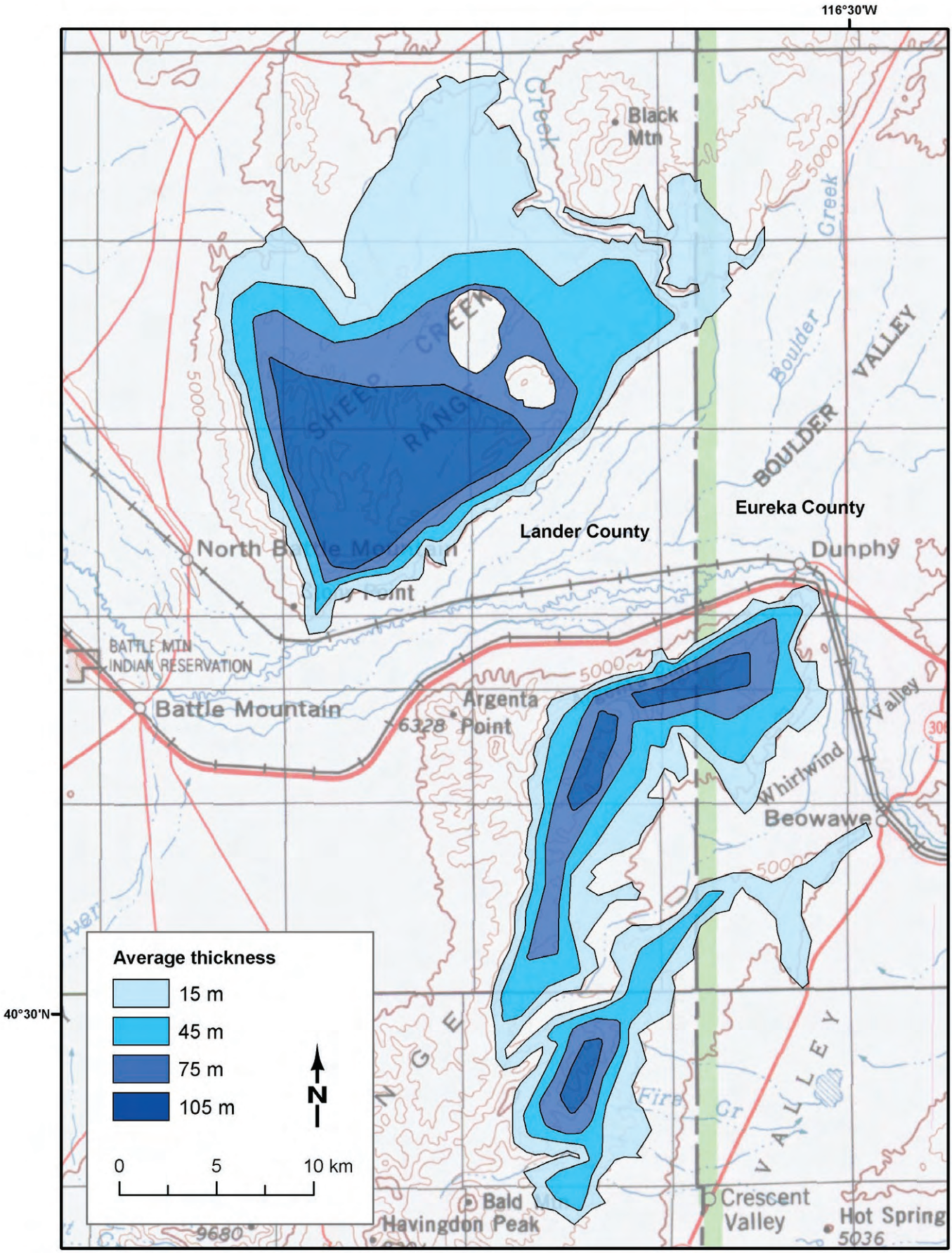


Figure 11. Mafic rock isopach map of the Battle Mountain area, Lander and Eureka Counties.

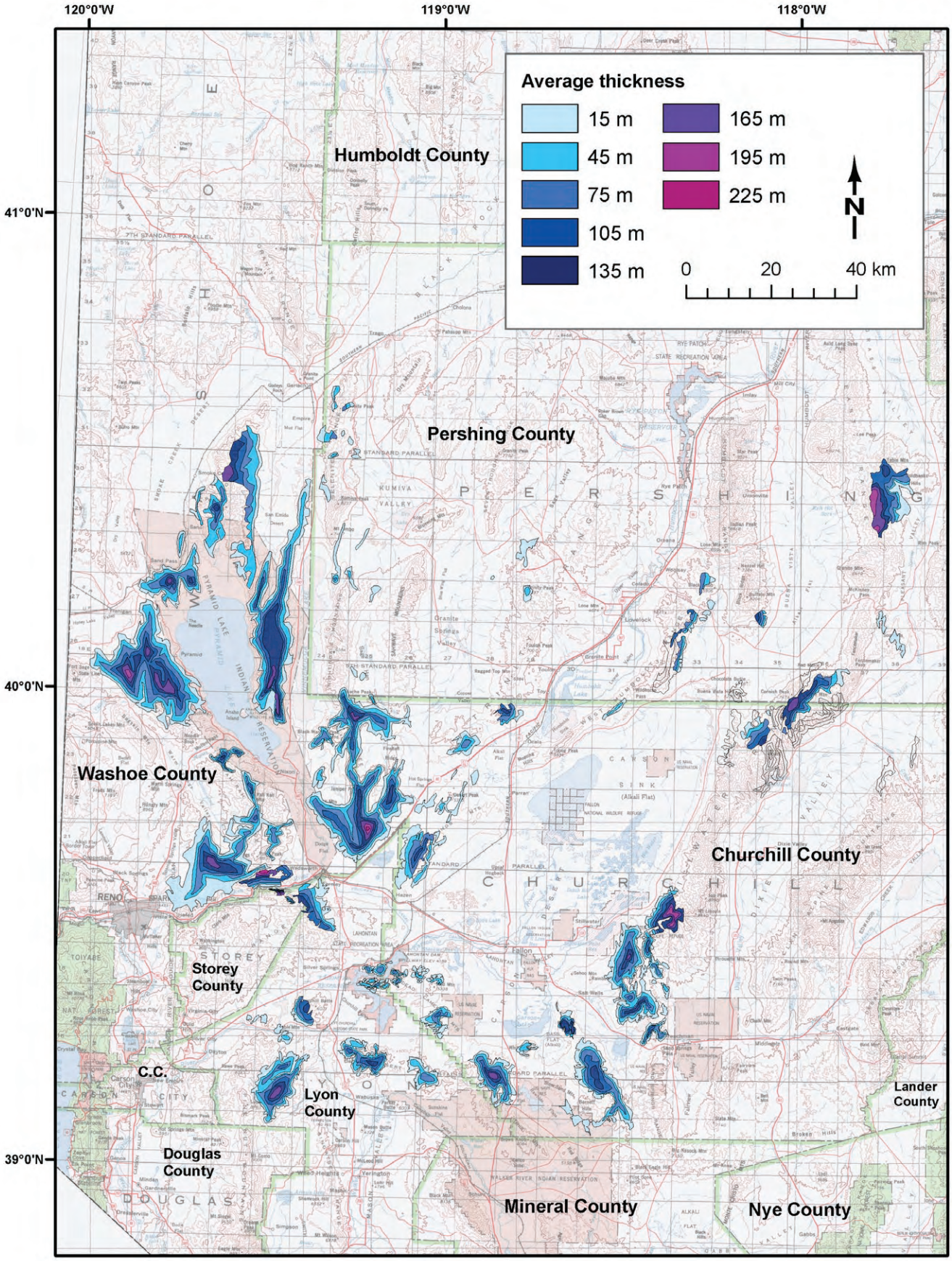


Figure 12. Cenozoic mafic rock isopach map of western Nevada, including southern Washoe, Storey, Lyon, Churchill, and Pershing Counties. Zoomed-in views are presented in Figures 13, 14, 15, and 17.

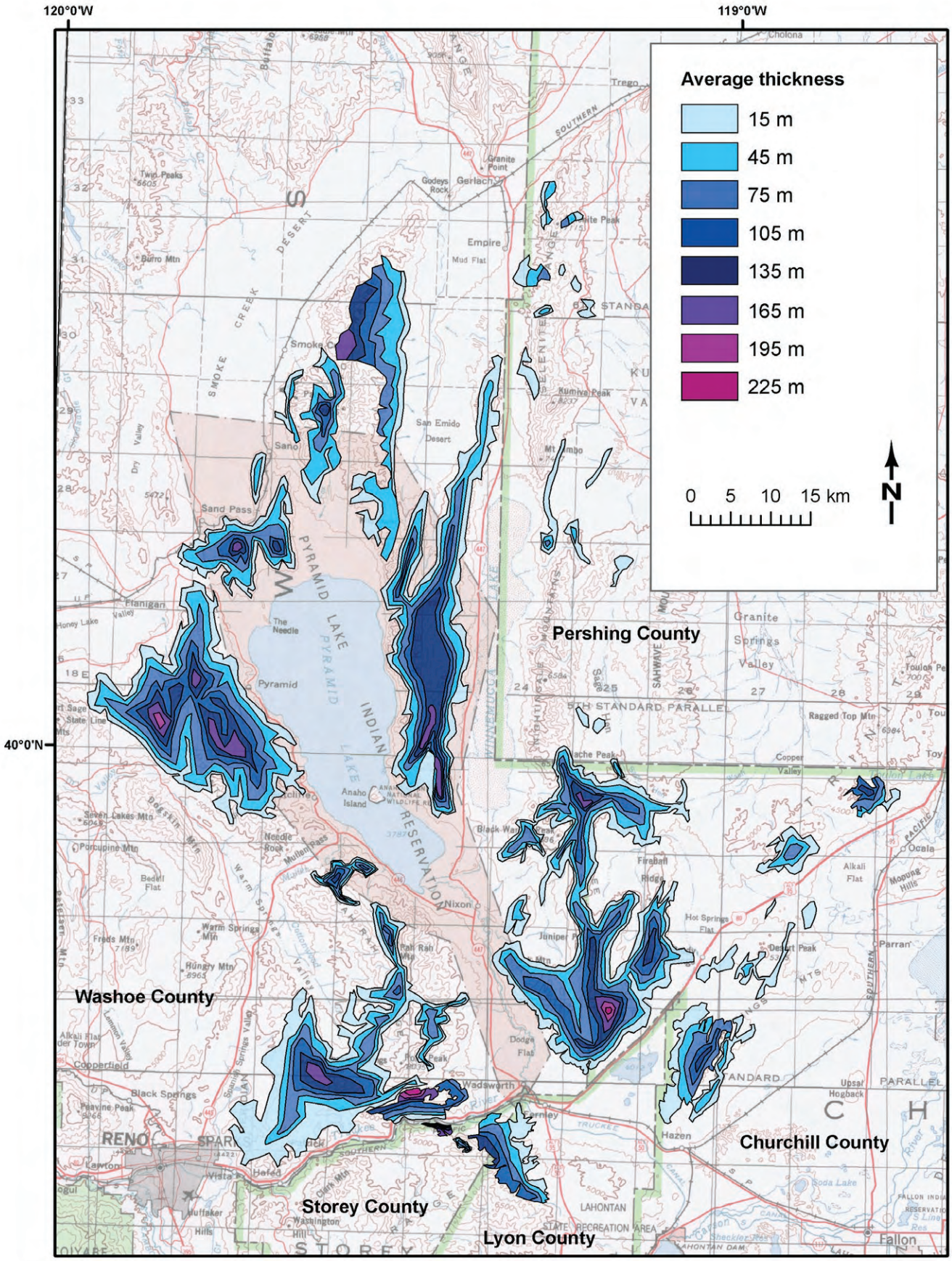


Figure 13. Cenozoic mafic rock isopach map of southern Washoe, Storey, northern Lyon, northwestern Churchill, and southwestern Pershing Counties.

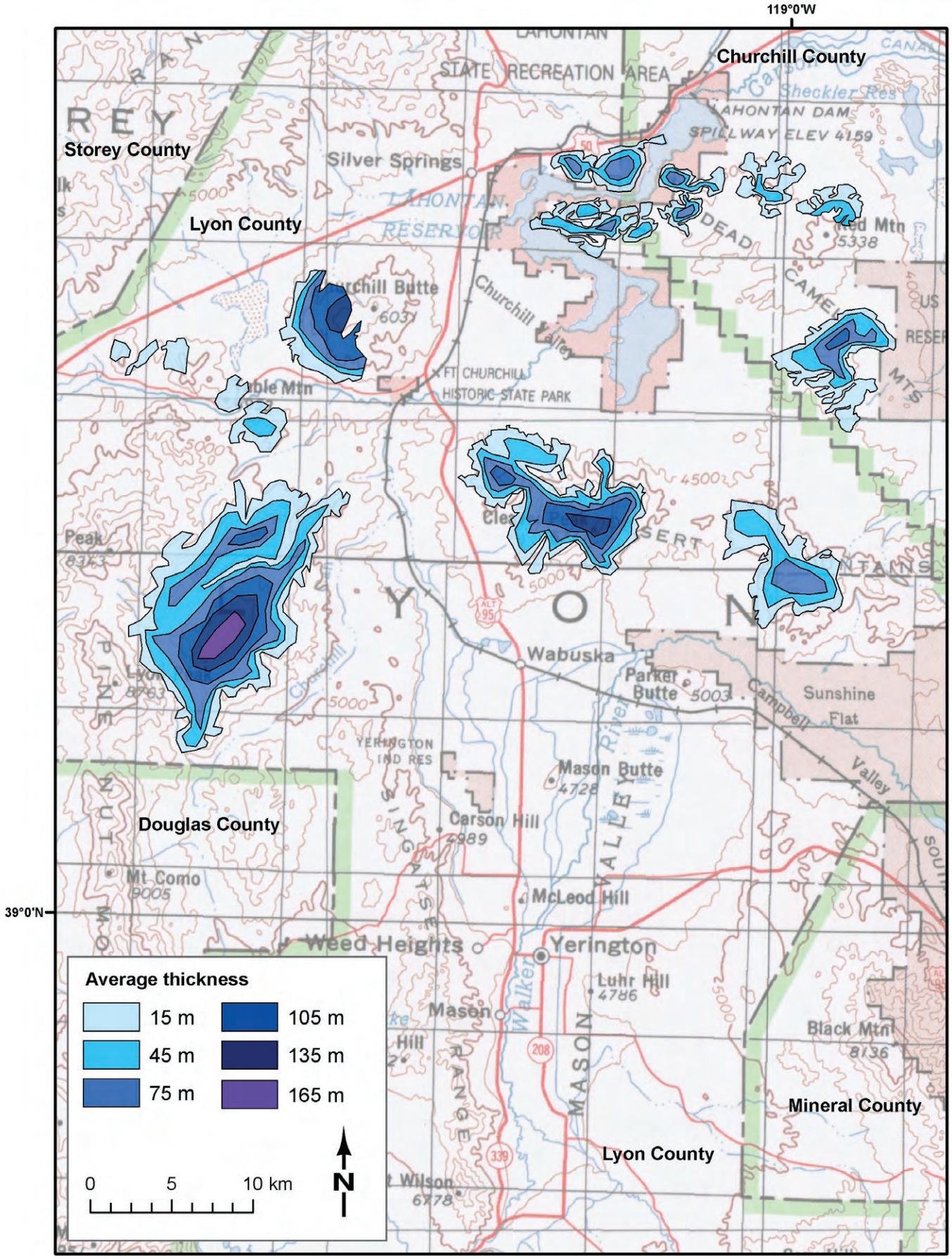


Figure 14. Cenozoic mafic rock isopach map of central Lyon and western Churchill Counties.

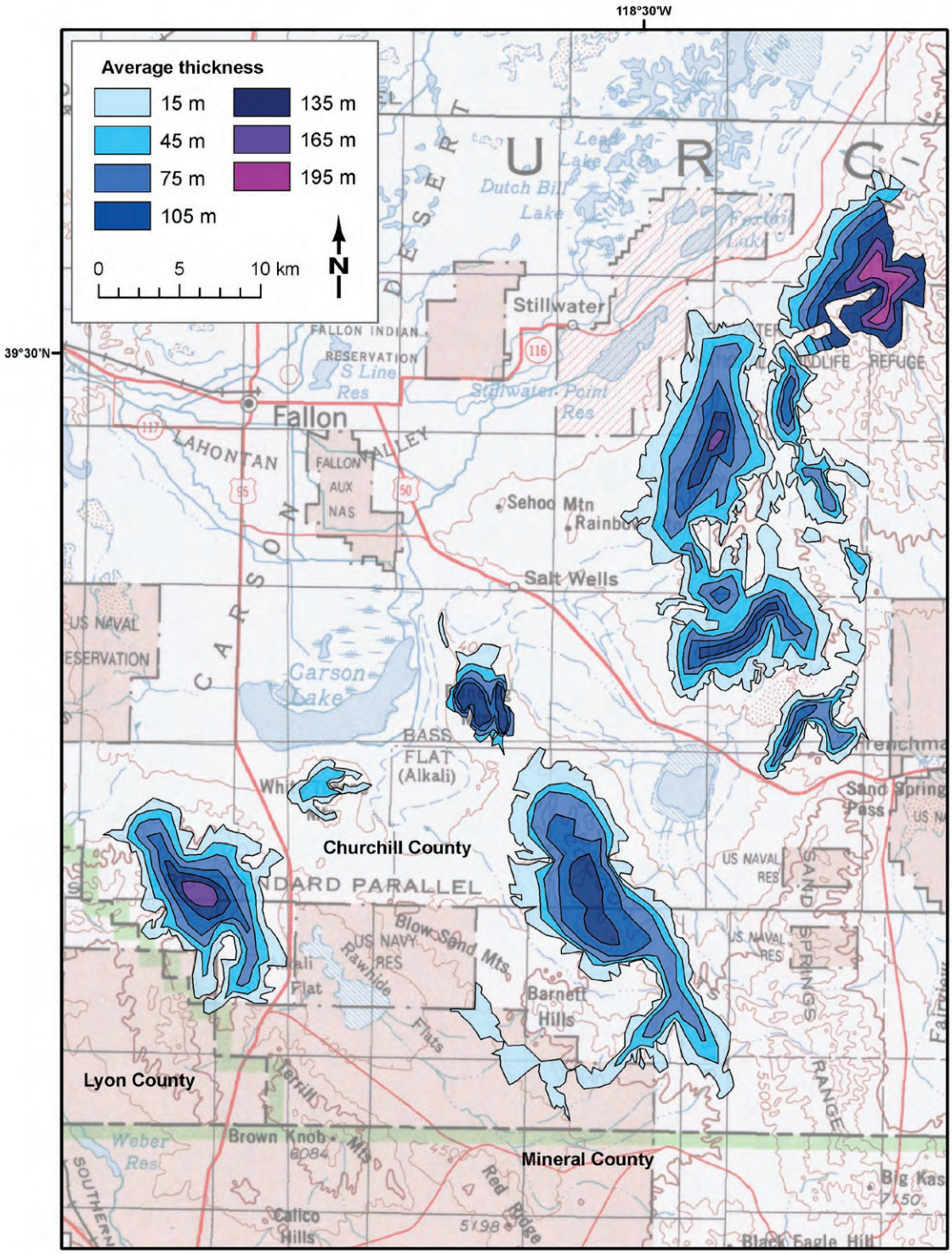
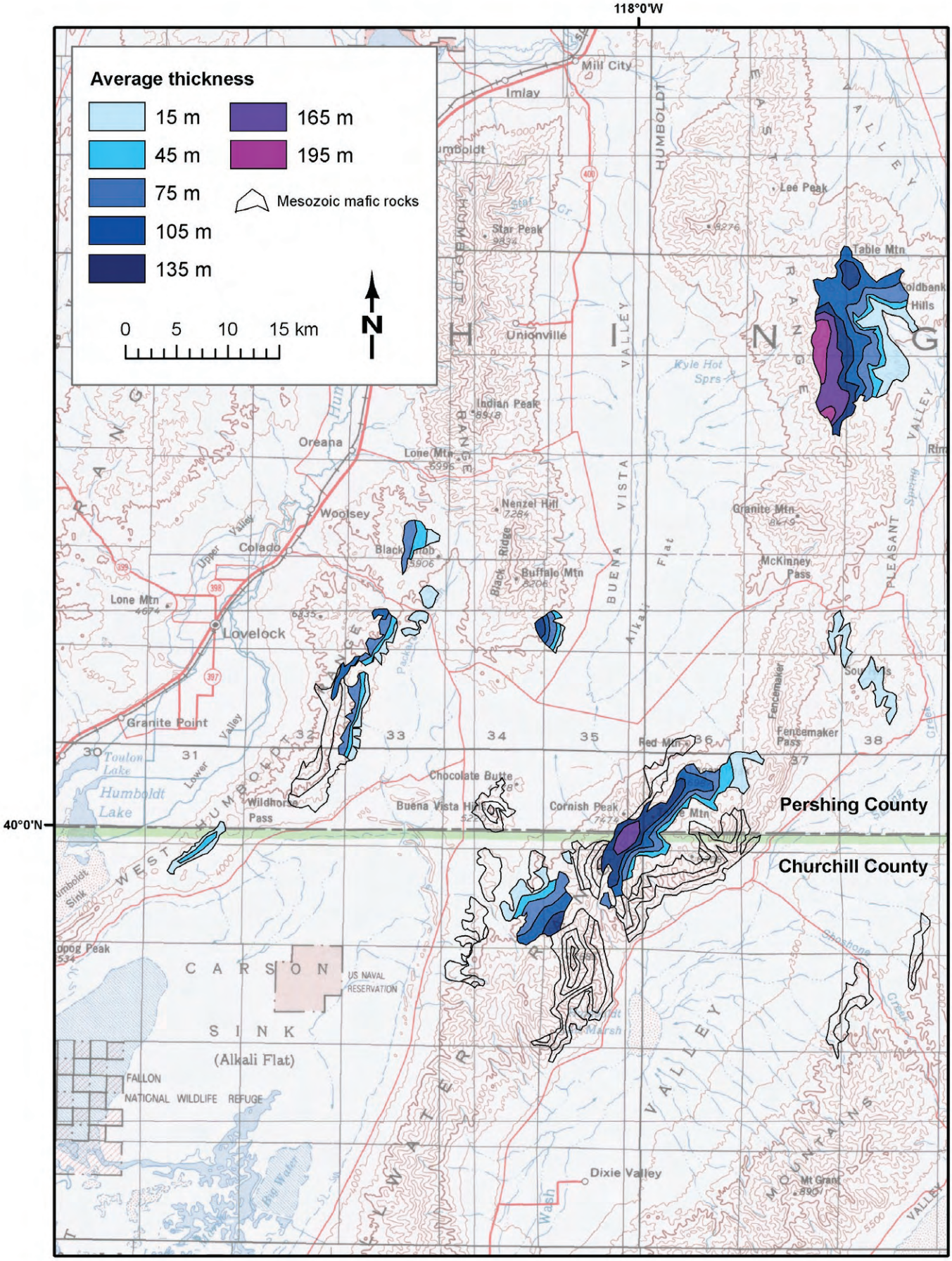


Figure 15. Cenozoic mafic rock isopach map of southwestern and central Churchill Counties.

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


118°0'W
40°0'N
Average thickness
15 m
45 m
75 m
105 m
135 m
165 m
195 m
Mesozoic mafic rocks
0 5 10 15 km
N
Pershing County
Churchill County
Mill City
Imlay
Lee Peak
Table Mtn
Star Peak
Unionville
Indian Peak
Oreana
Lone Mtn
Woolsey
Colado
Nenzel Hill
Granite Mtn
Black Mob
Buffalo Mtn
McKinney Pass
Lone Mtn
Lovelock
Granite Point
Toulon Lake
Humboldt Lake
Wildhorse Pass
Chocolate Butte
Buena Vista Hill
Cornish Peak
Red Mtn
Fencemaker Pass
CARSON SINK
(Alkali Flat)
US NAVAL RESERVATION
FALLON NATIONAL WILDLIFE REFUGE
Dixie Valley
Mt Grant
Kyle Hot Sprs
Table Mtn
Hills
HUMBOLDT
BUENA VISTA
VALLEY
RANGE
MOUNTAINS
WEST HUMBOLDT RANGE
Upper Valley
Lower Valley
Alkali Flat
Black Ridge
Fencemaker
PLEASANT VALLEY
Humboldt Sink
Big Water
Marsh
Shoshone Creek
Spring
Rim
Pacific
Humboldt
Star Cr
Kyle Hot Sprs
Wash
Creek
Valley
Mt Grant
Dixie Valley
Red Mtn
Cornish Peak
Chocolate Butte
Buena Vista Hill
Wildhorse Pass
Toulon Lake
Humboldt Lake
Granite Point
Lovelock
Lone Mtn
Colado
Woolsey
Oreana
Lone Mtn
Indian Peak
Unionville
Star Peak
Lee Peak
Table Mtn
Hills
Granite Mtn
McKinney Pass
Fencemaker Pass
Buffalo Mtn
Nenzel Hill
Black Mob
Mill City
Imlay
Humboldt
Dopog Peak
Humboldt Sink
Big Water
Marsh
Shoshone Creek
Spring
Rim
Pacific

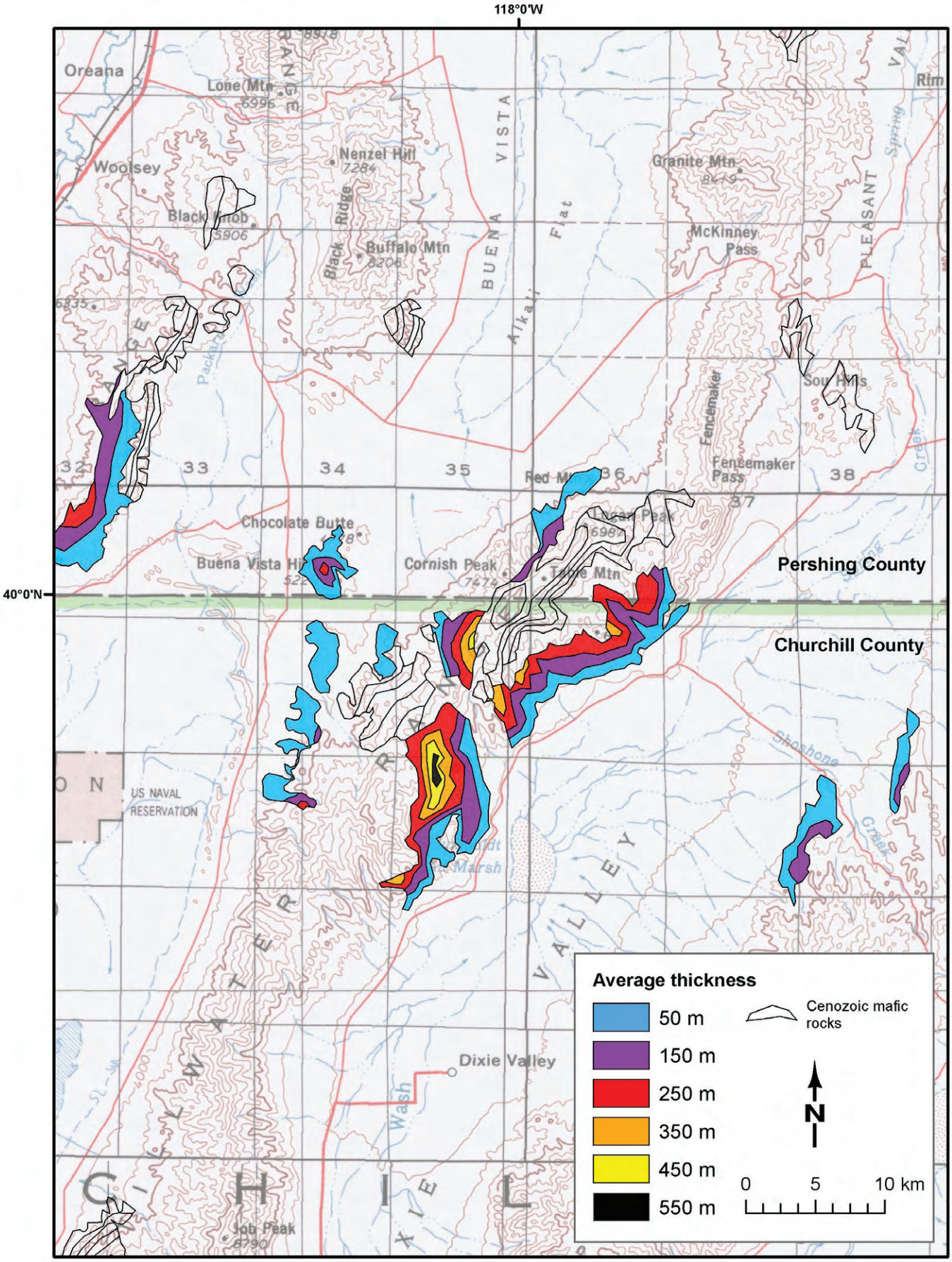


Figure 18. Mafic rock isopach map of the Humboldt lopolith, Churchill and Pershing Counties.

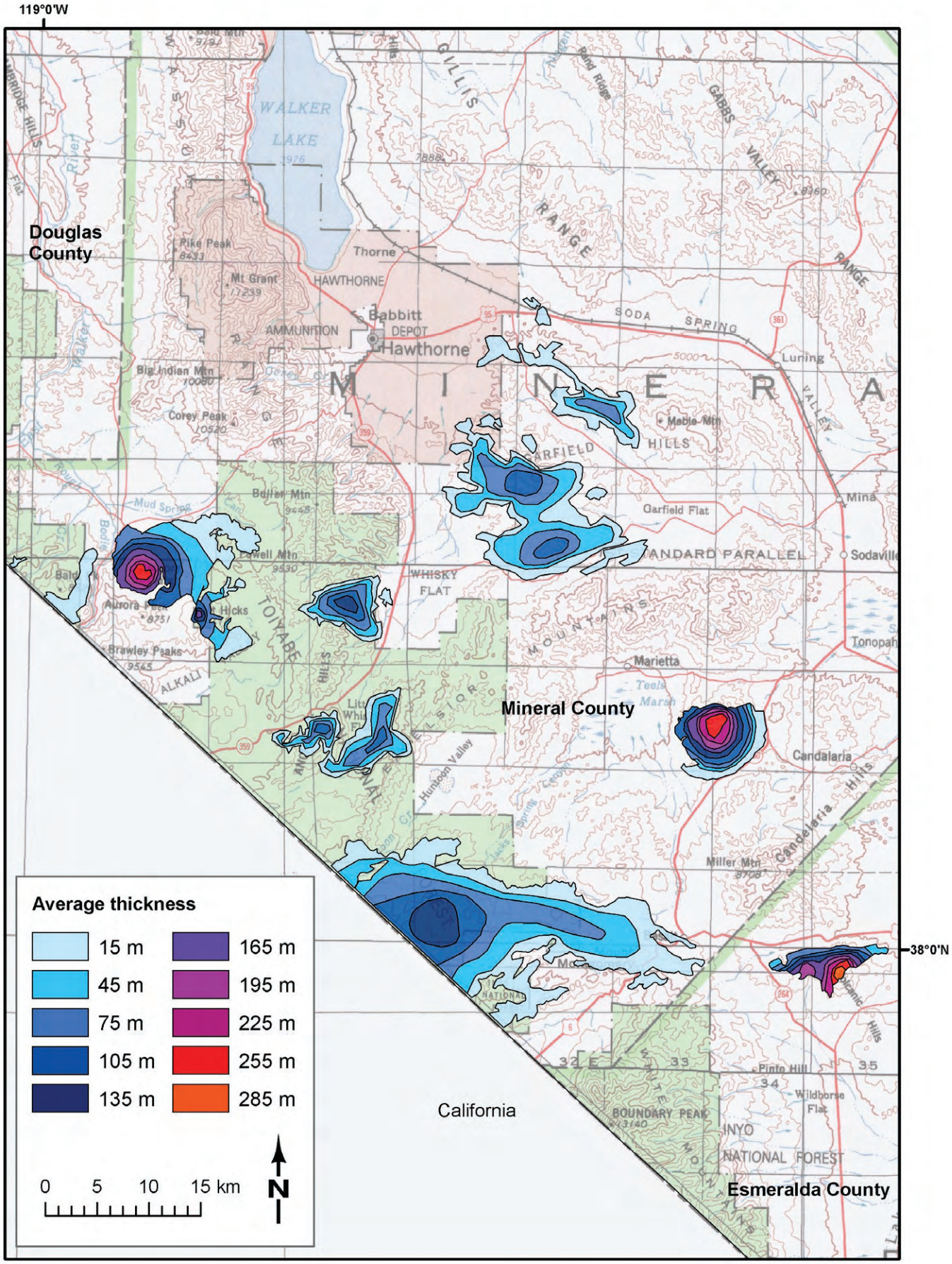


Figure 19. Mafic rock isopach map of southwestern Mineral and northwestern Esmeralda Counties.

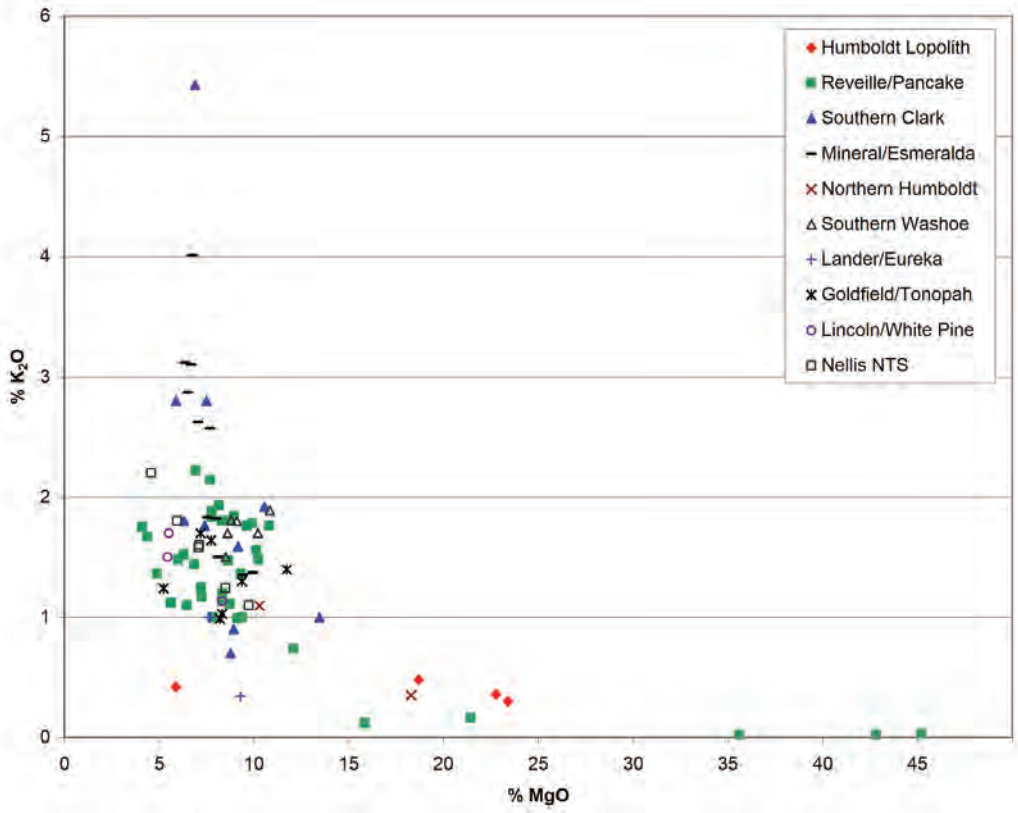


Figure 20. MgO versus K_2O for mafic rocks with CIPW normative olivine greater than 10%. Note that Mineral County mafic rocks have some of the highest K_2O values.

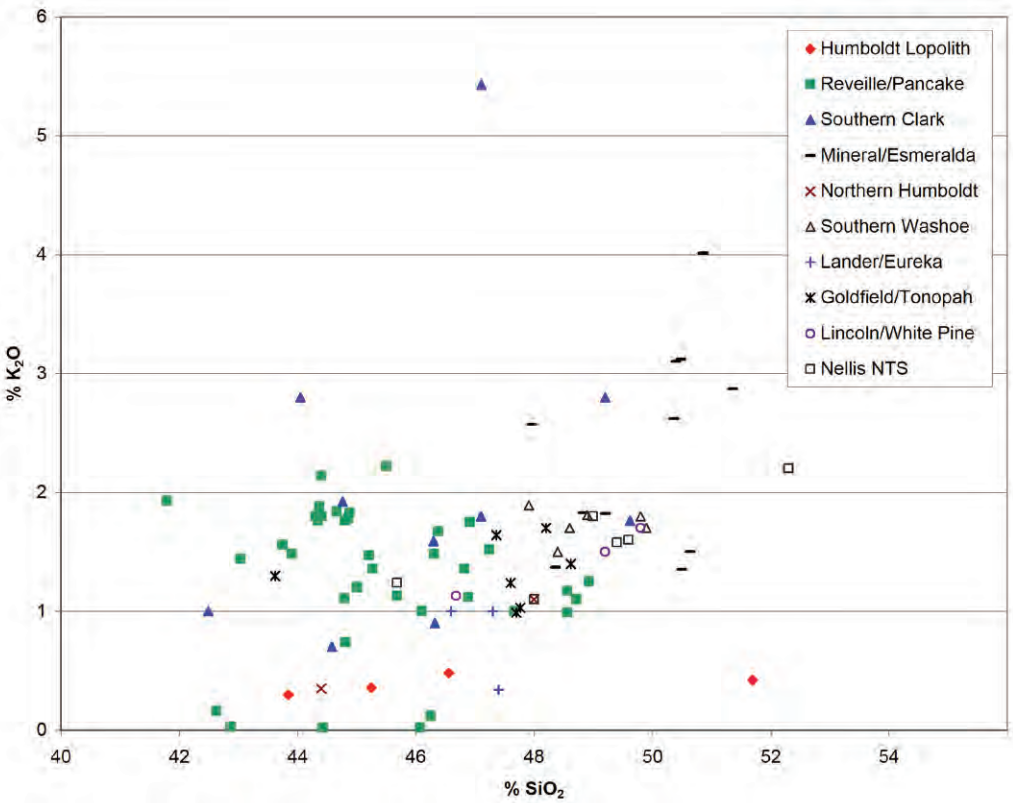


Figure 21. SiO_2 versus K_2O for mafic rocks with CIPW normative olivine greater than 10%.

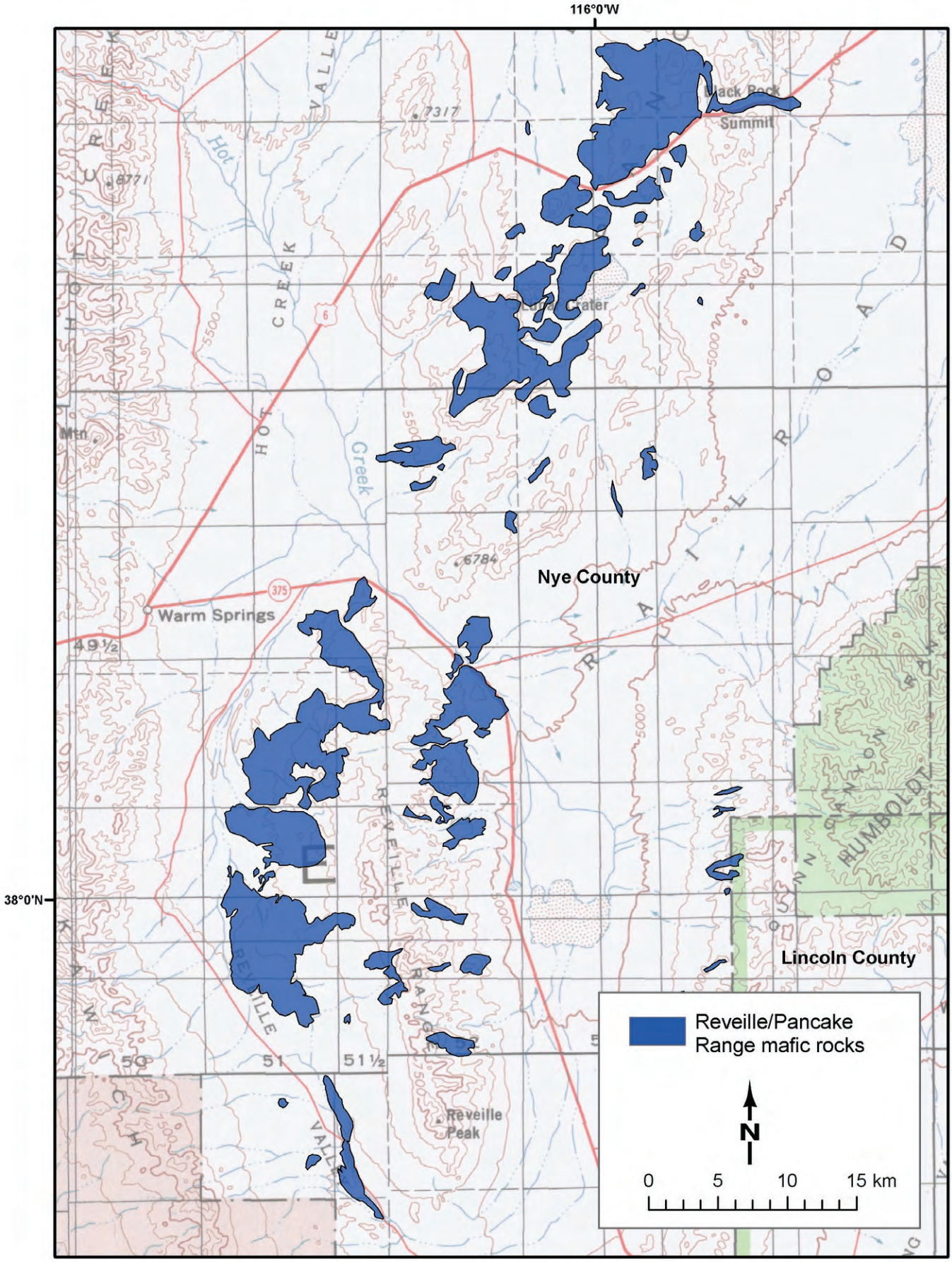


Figure 22. Mafic rock outcrops in the Reveille and southern Pancake Ranges, Nye County.

of 4.24–4.39 Ma trachytes (Naumann and others, 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 and others, 1991; Rash, 1995; Yogodzinski and others, 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 and others, 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 and others (1996) found that these basalts were derived from asthenospheric melts. The episode 2 basalts have $^{87}Sr/^{86}Sr$ of 0.7035 and εNd of +4.2, but the episode 1 basalts have more variable $^{87}Sr/^{86}Sr$ (up to 0.7060) and εNd (+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 and others, 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 and others (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 and others, 1986; Nielson and others, 1990), 3) 18.5–15.2 Ma basaltic andesite to rhyolite of the Patsy Mine Volcanics (Anderson, 1971; Anderson and others, 1972; Faulds and others, 1995; Faulds, 1996), 4) 15.2 Ma tuff of Bridge Spring (Anderson and others, 1972; Morikawa, 1994; Faulds and others, 1995) and the 15.0 tuff of Mount Davis (Faulds 1995; Faulds and others, 2002), 5) 15-~12 Ma basalt to basaltic andesite of the Mount Davis Volcanics (Anderson and others, 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 and others, 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 and others, 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 and others, 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

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).

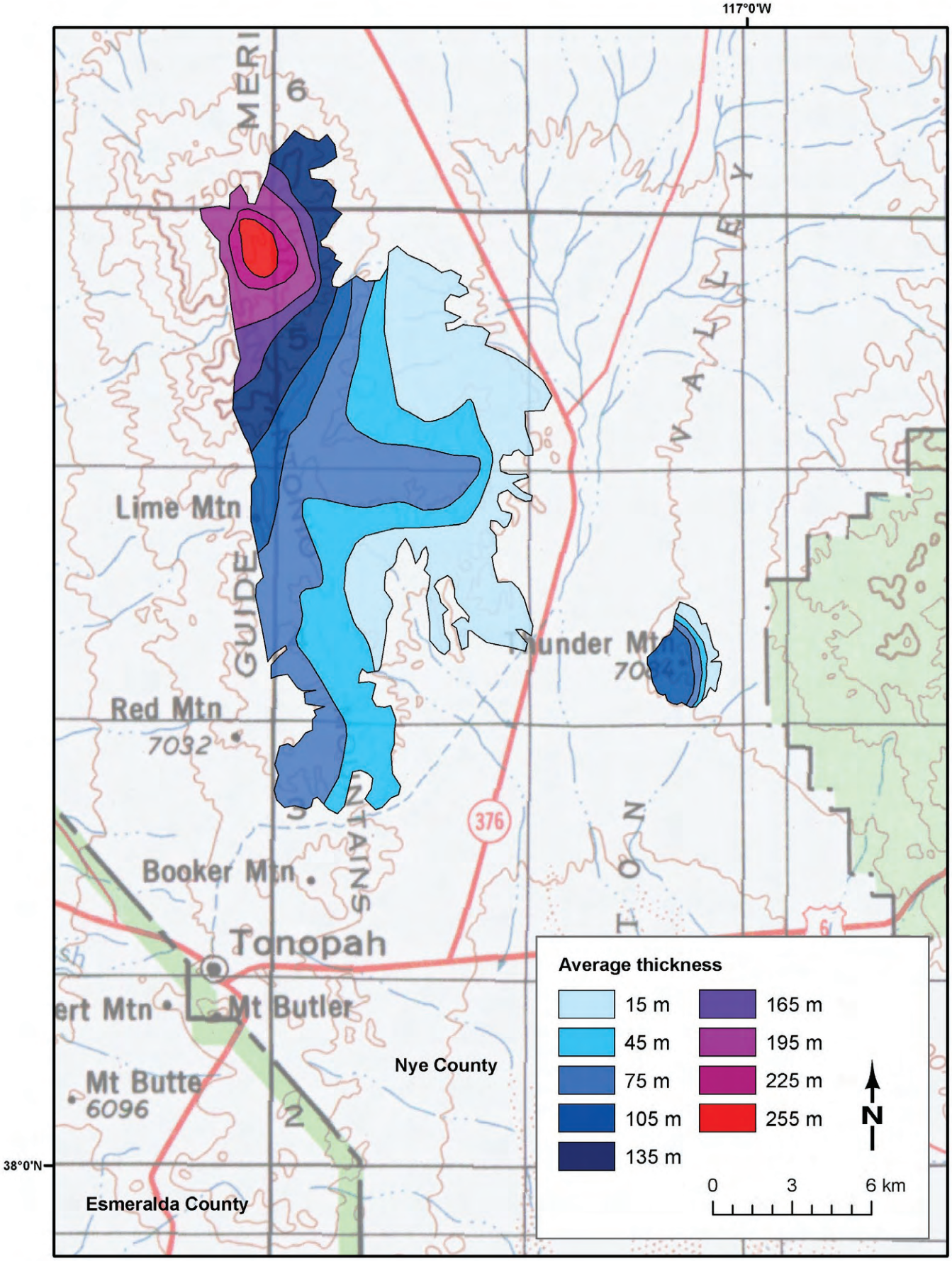


Figure 25. Mafic rock isopach map of the San Antonio Range, Nye County.

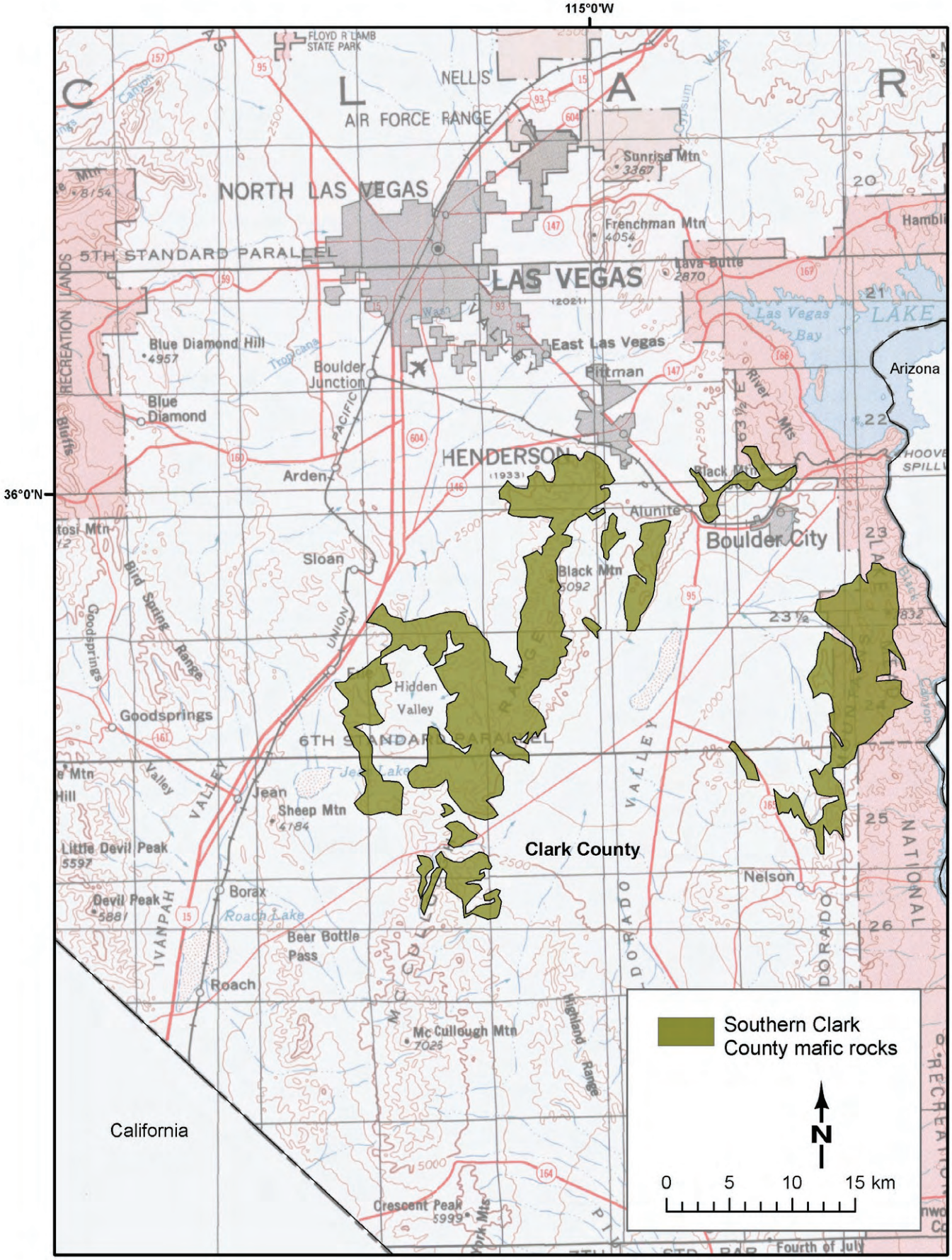


Figure 26. Mafic rock outcrops in southern Clark County.

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 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.

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

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 and others, 1962; Roberts and others, 1967).
- The Jackson Mountains of Humboldt County (Shawe and others, 1962).
- The Dayton area near the Lyon-Storey County line (Roylance, 1965; 1966; Reeves and others, 1958).
- The Gabbs area in northwest Nye County (Reeves and others, 1958).
- The Yerington area in Lyon and Douglas Counties (Reeves and others, 1958; Dilles and others, 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 for the deposits pre-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 the rate of 2500 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 and Archbold, 1969; Moore, 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

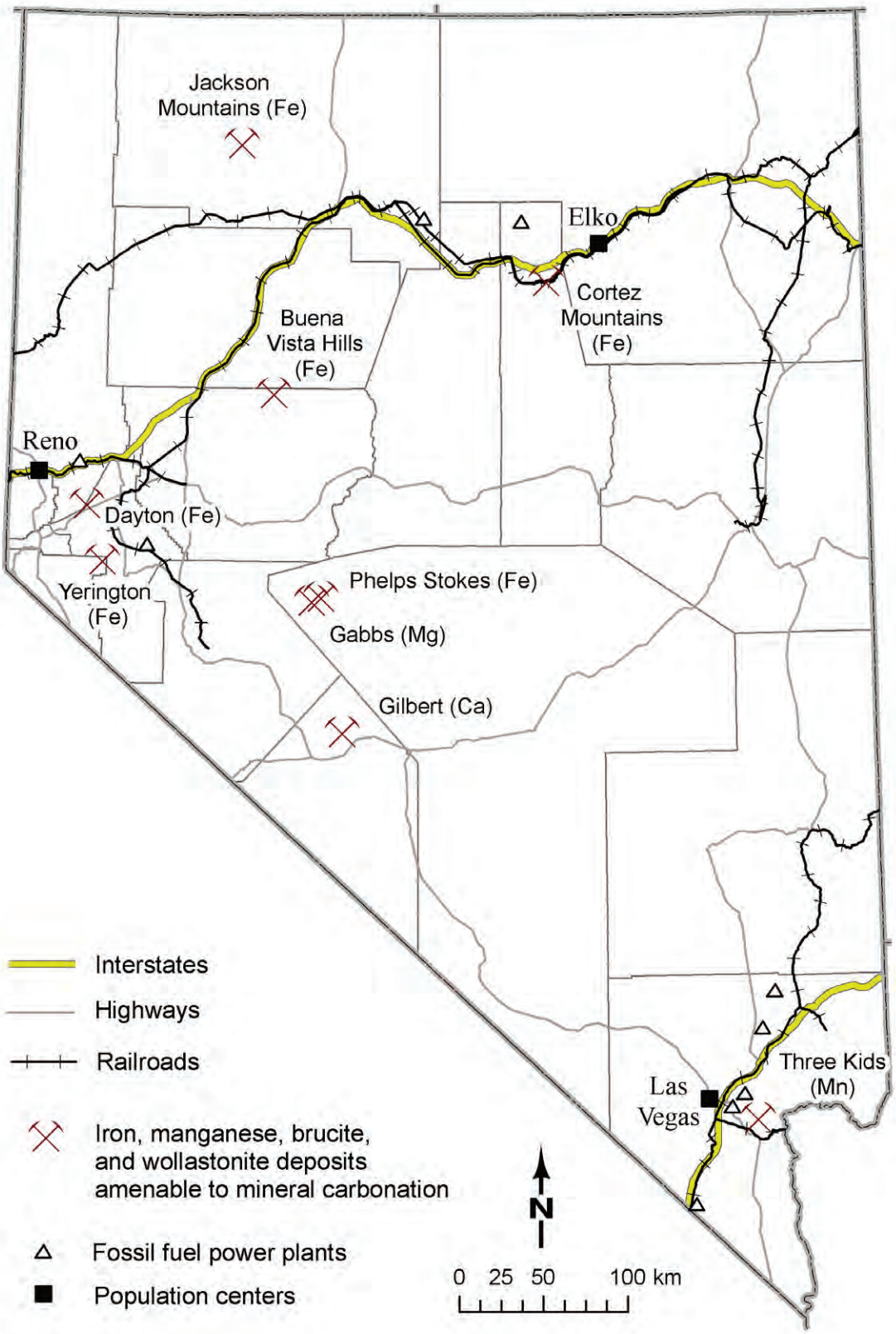


Figure 28. Location map of iron, manganese, and other mineral deposits amenable to mineral carbonation in Nevada, showing proximity to railways, highways, and existing power plants. Deposits include iron in the Buena Vista Hills, in the Cortez Mountains, near Dayton, in the Jackson Mountains, at the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

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	UTM Northing	UTM Easting	Latitude (NAD 27)	Longitude (NAD 27)	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.

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 x 10^5 m^3 (2.7 x 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 and others, 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 had dimensions of approximately 370 by 90 m, 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 and others, 1962). The Barth Mine continued minor production of iron ore through 1988 (Nevada Bureau of Mines and Geology, 1981;. 1982;. 1983;. 1984; 1987; 1988;. 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 and others, 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 and others, 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 and others, 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 x 10^7 m^3 (1.2 x 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 and others, 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 x 10^5 metric tons of Fe_3O_4 or 6.7 x 10^4 m^3 (6.7 x 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 km 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 and others, 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 and others, 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 file 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 and others, 1995; NBMG mining district file at www.nbmg.unr.edu/scans/5430/54300039.pdf and www.nbmg.unr.edu/scans/5430/54300043.pdf).

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 x 10^7 m^3 (4.8 x 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 and others, 1942; Hewett and others, 1963; Longwell and others, 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 and others (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 x 10^5 m^3 (2.4 x 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 x 10^5 m^3 (6.9 x 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 which 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.

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 and others (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 and others, 2005).

Mazzotti and others (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 km 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

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.

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.

ACKNOWLEDGMENTS

The research leading to this report was supported by a grant from the U.S. Department of Energy through the University of California and by the State of Nevada through the Nevada Bureau of Mines and Geology. We thank John Clinkenbeard, California Geological Survey, Curt Oldenburg, Lawrence Berkeley National Laboratory, and James Faulds, Nevada Bureau of Mines and Geology, for their reviews of a draft of the report. We also thank Jack Hursh and Jordan Hastings for assistance with figures and layout and Dick Meeuwig for editing the manuscript. The authors accept full responsibility for the content of this report.

REFERENCES

Albers, J.P., and Stewart, J.H., 1972, Geology and mineral deposits of Esmeralda County, Nevada: Nevada Bureau of Mines and Geology Bulletin 78, 80 p.

Anderson, R.E., 1971, Thin skin distension in Tertiary rocks of southeastern Nevada: Geological Society of America Bulletin, v. 82, p. 43-58.

Anderson, R.E., 1977, Composite stratigraphic section of Tertiary rocks in the Eldorado Mountains, Nevada: U.S. Geological Survey Open-File Report 77-483, 5 p.

Anderson, R.E., 1978, Chemistry of Tertiary volcanic rocks in the Eldorado Mountains, Clark County, Nevada, and comparisons with rocks from some nearby areas: Journal of Research U.S. Geological Survey, v. 6, p. 409-424.

Anderson, R.E., Longwell, C.R., Armstrong, R.L., and Marvin, R.F., 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geological Society of America Bulletin, v. 83, p. 273-288.

Armstrong, R.L., 1972, Low-angle (denudational) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah: Geological Society of America Bulletin, v. 83, p. 1729-1754.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic evolution of North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.

Atwater, T., and Stock, J., 1998, Pacific-North America plate tectonics of the Neogene southwestern United States: An update: International Geology Review, v. 40, p. 375-402.

Axen, G.J., Taylor, W.J., and Bartley, J.M., 1993, Space-time patterns and tectonic controls of Tertiary extension and magmatism in the Great Basin of the western United States: Geological Society of America Bulletin, v. 105, p. 56-76.

Ball, T.T., and Farmer, G.L., 1991, Identification of 2.0 to 2.4 Ga Nd model age crustal material in the Cheyenne Belt, southeastern Wyoming: implications for Proterozoic accretionary tectonics at the southern margin of the Wyoming craton: Geology, v. 19, p. 360-363.

Bartley, J.M., and Wernicke, B.P., 1984, The Snake Range décollement interpreted as a major extensional shear zone: Tectonics, v. 3, p. 647-657.

Bell, R.M., 1911, The Pioche District: Mines and Minerals, vol. 32, p. 164.

Blakely, R.J., and Jachens, R.W., 1991, Regional study of mineral resources in Nevada: Insights from three-dimensional analysis of gravity and magnetic anomalies: Geophysics, v. 51, p. 1491-1496.

Bonham, H.F., and Papke, K.G., 1969, Geology and mineral deposits of Washoe and Storey Counties, Nevada: Nevada Bureau of Mines and Geology Bulletin 70, 140 p.

Brandon, A.D., 1989, Constraints on magma genesis behind the Neogene Cascade arc: evidence from major and trace element variation of high-alumina and tholeiitic volcanics of the Bear Creek area: Journal of Geophysical Research B, v. 94, p. 7775-7798.

Brem, G.F., 1978, Petrogenesis of late Tertiary potassic volcanic rocks in the Sierra Nevada and western Great Basin [Ph.D. dissertation]: University of California, Riverside, 351 p.

Butt, D.P, and Lackner, K.S., 1997, A method for permanent disposal of CO_2 in solid form: World Resources Review, v. 9, no. 3, p. 324-336.

Carroll, S.A., and Knauss, K.G., 2006, Dependence of labradorite dissolution kinetics on CO_2(aq), Al(aq), and temperature: Chemical Geology, v. 217, p. 213-225.

Christiansen, R.L., and Yeats, R.S., 1991, Post-Laramide geology of the U.S. Cordilleran region: The Cordilleran orogen: Conterminous U.S.: Geological Society of America DNAG Volume G-3, p. 261-406.

Coats, R.R., 1985, The Big Island Formation, a Miocene formation in northern Elko County, Nevada, and adjacent Idaho, including a consideration of its composition and petrographic character: U.S. Geological Survey Bulletin, v. 1605-A, p. A7-A13.

Coney, P.J., 1980, Cordilleran metamorphic core complexes - an overview, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 7-34.

Cornwall, H.R., 1965, Mineral and water resources of Nevada: Nevada Bureau of Mines and Geology Bull. 65, 325 p.

Dalziel, I.W.D., 1992, On the organization of American plates in the Neoproterozoic and the breakout of Laurentia: GSA Today, v. 2, p. 237, 240-241.

Dalziel, I.W.D., 1997, Neoproterozoic-Paleozoic paleo-geography and tectonics: Review, hypothesis, environmental speculation: Geological Society of America Bulletin, v. 109, p. 16-42.

Davis, G.A., and Lister, G.S., 1988, Detachment faulting in continental extension: Perspectives from the southwestern U.S. Cordillera: Geological Society of America Special Paper 218, p. 133-159.

Davis, G.A., Anderson, J.L., Frost, E.G., and Shackelford, T.J., 1980, Mylonitization and detachment faulting in the Whipple-Buckskin-Rawhide Mountains terrane, southeastern California and western Arizona, *in* Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 79-129.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A.: American Journal of Science, v. 304, p. 105-168.

Deutch, J., Moniz, E.J., Ansolabehere, S., Beer, J., Ellerman, A.D., Friedmann, S.J., Herzog, H., Jacoby, H.D., Jaskow, P.L., McRae, G., Lester, R., Steinfeld, E., and Katzer, J., 2007, The future of coal-options for a carbon-constrained world: Massachusetts Institute of Technology, http://web.mit.edu/coal/.

Dickinson, W.R., 1997, Overview: Tectonic implications of Cenozoic volcanism in coastal California: Geological Society of America Bulletin, v. 109, p. 936-954.

Dickinson, W.R., 2001, Tectonic setting of the Great Basin through geologic time: implications for metallogeny, *in* Shaddrick, D.R., Zbinden, E., Mathewson, D.C., and Prenn, C., eds., Regional Tectonics and Structural Control of Ore: The Major Gold Trends of Northern Nevada: Reno, Geological Society of Nevada Special Publication 33, p. 27-53.

Dickinson, W.R., 2002, The Basin and Range province as a composite extensional domain: International Geology Review, v. 44, p. 1-38.

Dickinson, W.R., 2004, Evolution of the North American Cordillera: Annual Reviews of Earth and Planetary Sciences, v. 32, p. 13-44.

Dickinson, W.R., and Snyder, W.S., 1978, Plate tectonics of the Laramide orogeny: Geological Society of America Memoir 151, p. 355-366.

Dilek, Y., and Moores, E.M., 1995, Geology of the Humboldt igneous complex, Nevada, and tectonic implications for the Jurassic magmatism in the Cordilleran orogen, *in* Miller, D.M., and Busby, C., eds., Jurassic magmatism and tectonics of the North American Cordillera: Boulder, Colorado, Geological Society of America Special Paper 299, p. 229-248.

Dilles, J., Einaudi, M., Proffett, J., and Barton, M., 2000a, Overview of the Yerington Porphyry Copper District: Magmatic to Nonmagmatic Sources of Hydrothermal Fluids: Their Flow Paths and Alteration Effects on Rocks and Cu-Mo-Fe-Au Ores, *in* Dilles, J.H., Barton, M.D., Johnson, D.A., Proffett, J.M., and Einaudi, M.T., eds., Society of Economic Geologists Guidebook Series Volume 32, Part 1, Contrasting Styles of Intrusion-Related Hydrothermal Systems, p. 55-66.

Dilles, J., Proffett, J., and Einaudi, M., 2000b, Magmatic and hydrothermal features of the Yerington Batholith with Emphasis on the Porphyry Cu (Mo) Deposit in the Ann-Mason Area; Field Trip Day Two, *in* Dilles, J.H., Barton, M.D., Johnson, D.A., Proffett, J.M., and Einaudi, M.T., eds., Society of Economic Geologists Guidebook Series Volume 32, Part 1, Contrasting Styles of Intrusion-Related Hydrothermal Systems, p. 67-89.

Drakos, P.S., 2007, Tertiary stratigraphy and structure of the southern Lake Range, northwest Nevada: Assessment of kinematic links between strike-slip and normal faults in the northern Walker Lane [M.S. thesis]: University of Nevada, Reno, 165 p.

Duebendorfer, E.M., Chamberlain, K.R., and Fry, B., 2006, Mojave-Yavapai boundary zone, southwestern United States; a rifting model for the formation of an isotopically mixed crustal boundary zone: Geology, v. 34, p. 681-684.

Ducea, M., 2001, The California arc: Thick granitic batholiths, ecolgite residues, lithospheric-scale thrusting, and magmatic flare-ups: GSA Today, v. 11, n. 11, p. 4-10.

Ducea, M., and Saleeby, J.B., 1998, A case for delamination of deep batholithic crust beneath the Sierra Nevada, California: International Geology Review, v. 40, p. 78-93.

Eaton, G.P., 1982, The Basin and Range province; origin and tectonic significance: Annual Review of Earth and Planetary Sciences, v. 10, p. 409-440.

Energy Information Administration, U.S. Department of Energy, 2004, International coal production, http://www.eia.doe.gov/emeu/international/coalproduction.html

Energy Information Administration, U.S. Department of Energy, 2006a, World coal markets, International energy outlook 2006, 6 p., http://www.eia.doe.gov/oiaf/ieo/coal.html

Energy Information Administration, U.S. Department of Energy, 2006b, Quarterly coal report, October - December 2006, http://www.eia.doe.gov/cneaf/coal/quarterly/qcr_sum.html

Energy Information Administration, U.S. Department of Energy, 2006c, State and U.S. historical data, http://www.eia.doe.gov/overview_hd.html

Farmer, G.L., Perry, F.V., Semken, S., Crowe, B., Curtis, D., and DePaolo, D.J., 1989, Isotopic evidence on the structure and origin of subcontinental lithospheric mantle in southern Nevada: Journal of Geophysical Research B, v. 94, p. 7885-7898.

Faulds, J.E., 1995, Geologic map of the Mount Davis Quadrangle, Nevada and Arizona: Nevada Bureau of Mines and Geology Map 105, scale 1:24,000.

Faulds, J.E., 1996, Geologic map of the Fire Mountain Quadrangle, Nevada and Arizona: Nevada Bureau of Mines and Geology Map 106, scale 1:24,000.

Faulds, J.E., Bell, J.W., and Olson, E.L., 2002, Geologic map of the Nelson SW Quadrangle, Clark County, Nevada (with accompanying text): Nevada Bureau of Mines and Geology Map 134.

Faulds, J.E., dePolo, C.M., and Henry, C.D., 2003a, Preliminary geologic map of the Sutcliffe Quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 03-17, 1:24,000.

Faulds, J.E., Feuerbach, D.L., Miller, C.F., and Smith, E.I., 2001, Cenozoic evolution of the northern Colorado River extensional corridor, southern Nevada and northwest Arizona: Pacific Section of the American Association of Petroleum Geologists Publication GB 78, p. 239-272.

Faulds, J.E., Feuerbach, D.L., Reagan, M.K., Metcalf, R.V., Gans, P., and Walker, J.D., 1995, The Mt. Perkins block, northwestern Arizona: An exposed cross section of an evolving, preextensional to synextensional magmatic system: Journal of Geophysical Research, v. 100, p. 15,249-15,266.

Faulds, J.E., Henry, C.D., and dePolo, C.M., 2003b, Preliminary geologic map of the Tule Peak Quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 03-10.

Feuerbach, D.L., Smith, E.I., Walker, J.D., and Tangeman, J.A., 1993, The role of the mantle during crustal extension: geochemistry of volcanic rocks in the Lake Mead area, Nevada and Arizona: Geological Society of America Bulletin, v. 105, p. 1561-1575.

Fitton, J.G., James, D., and Leeman, W.P., 1991, Basic magmatism associated with late Cenozoic extension in the western United States: compositional variations in space and time: Journal of Geophysical Research B, v. 96, p. 13693-13711.

Friedmann, S.J., 2007, Geological carbon dioxide sequestration: Elements, v. 3, p. 179-184.

Garside, L.J., Castor, S.B., Henry, C.D., and Faulds, J.E., 2000, Structure, volcanic stratigraphy, and ore deposits of the Pah Rah Range, Washoe County, Nevada: Geological Society of Nevada Symposium 2000 Field Trip Guidebook No. 2, 132 p.

Gemmill, P., 1968, The geology of the ore deposits of the Pioche district, Nevada, *in* Ore Deposits of the United States 1933-1967: American Institute of Mining Engineers, p.1130.

Glazner, A.F., Nielson, J.E., Howard, K.A., and Miller, D.M., 1986, Correlation of the Peach Springs Tuff, a large-volume Miocene ignimbrite sheet in California and Arizona: Geology, v. 14, p. 840-843.

Glazner, A.F. and Ussler III, W., 1989, Crustal extension, crustal density, and the evolution of Cenozoic magmatism in the Basin and Range of the western United States: Journal of Geophysical Research B, v. 94, p. 7952-7960.

Goff, F., and Lackner, K.S., 1998, Carbon dioxide sequestering using ultramafic rocks: Environmental Geosciences, v. 5, p. 89-101.

Grauch, V.J.S, Rodriguez, B.D., and Wooden, J.L., 2003, Geophysical and isotopic constraints on crustal structure related to mineral trends in north-central Nevada and implications for tectonic history: Economic Geology, v. 98, p. 269-286.

Hedge, C.E. and Noble, D.C., 1971, Upper Cenozoic basalts with high Sr^{87}/Sr^{86} and Sr/Rb ratios, southern Great Basin, western United States: Geological Society of America Bulletin, v. 82, p. 3503-3510.

Henry, C.D., Faulds, J.E., dePolo, C.M., and Davis, D.A., 2004, Geology of the Dogskin Mountain Quadrangle, northern Walker Lane, Nevada: Nevada Bureau of Mines and Geology Map 148, scale 1:24,000.

Hewett, D.F., Fleischer, M., and Conklin, V.M., 1963, Deposits of manganese oxide: Economic Geology, v. 58, n. 1, p. 17-21.

Hewett, D.F., and Weber, B.N., 1931, Bedded deposits of manganese oxides near Las Vegas, Nevada: University of Nevada Bulletin, v. 25, no. 6, 17 p.

Hildenbrand, T.G., and Kucks, R.P., 1988, Total intensity magnetic anomaly map of Nevada: Nevada Bureau of Mines and Geology Map 93a, 1:750,000 scale.

Humphreys, E.D., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology, v. 23, p. 987-990.

Hunt, C.B., McKelvey, V.E., and Weise, J.H., 1942, The Three Kids manganese district, Clark County, Nevada: U.S. Geological Survey Bulletin 936-L, 319 p.

Iddings, J.P., 1909, Igneous rocks, v. 1, p. 348-393: Wiley, New York.

Intergovernmental Panel on Climate Change, 2001, Climate change 2001, The scientific basis, http://www.grida.no/climate/ipcc_tar/wg1/index.htm.

Intergovernmental Panel on Climate Change, 2005, Carbon dioxide capture and storage, IPPC special report, http://www.ipcc.ch/activity/srccs/index.htm.

John, D.A., Brummer, J.E., Saderholm, E.C., and Fleck, R.J., 2000a, Geology of the Mule Canyon, Nevada, *in* Wallace, A.R., and John, D.A., eds., Volcanic history, structure, and mineral deposits of the north-central northern Nevada rift: Geological Society of Nevada, Geology and Ore Deposits 2000: The Great Basin and Beyond, Field Trip Guidebook no. 8.

John, D.A., Garside, L.J., and Wallace, A.R., 1999, Magmatic and tectonic setting of late Cenozoic gold-silver deposits in northern Nevada with an emphasis on the Pah Rah and Virginia Ranges and the northern Nevada rift, *in* Kizis, J.A., ed., Low-sulfidation gold deposits in northern Nevada: Geological Society of Nevada 1999 Spring Field Trip Guidebook: Geological Society of Nevada Special Publication no. 29, p. 65-158.

John, D.A., Hofstra, A.H., Fleck, R.J., Brummer, J.E., and Saderholm, E.C., 2003, Geologic setting and genesis of the Mule Canyon low-sulfidation epithermal gold-silver deposit, north-central Nevada: Economic Geology, v. 98, p. 425-463.

John, D.A., Wallace, A.R., Ponce, D.A., Fleck, R.B., and Conrad, J.E., 2000b, New perspectives on the geology and origin of the Northern Nevada rift, *in* Cluer, J.K., Price, J.G., Struhsacker, E.M., Hardyman, R.F., and Morris, C.L., eds., Geology and Ore Deposits 2000: The Great Basin and Beyond: Geological Society of Nevada Symposium, Reno, 2000, Proceedings, v. 1, p. 127-154.

Johnson, D.A. and Barton, M.D., 2000a, Buena Vista Hills, Humboldt Mafic Complex, *in* Dilles, J.H., Barton, M.D., Johnson, D.A., Proffett, J.M, and Einaudi, M.T., eds, Contrasting styles of intrusion-associated hydrothermal systems: Society of Economic Geologists Guidebook Series, v. 32, Part I, p. 145-162.

Johnson, D.A., and Barton, M.D., 2000b, Time-space development of an external brine-dominated, igneous-driven hydrothermal system: Humboldt mafic complex, western Nevada, *in* Dilles, J.H., Barton, M.D., Johnson, D.A., Proffett, J.M, and Einaudi, M.T., eds, Contrasting styles of intrusion-associated hydrothermal systems:

Society of Economic Geologists Guidebook Series, v. 32, Part I, p. 127-143.

Johnson, M.G., 1977, Geology and mineral deposits of Pershing County, Nevada: Nevada Bureau of Mines and Geology Bulletin 89, 121 p.

Karlstrom, K.E., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., and Ahall, K-I., 1999, Refining Rodinia: geologic evidence for the Australia-western U.S. connection in the Proterozoic: GSA Today, v. 9, no. 10, p. 1-7.

Kempton, P.D., Fitton, J.G., Hawkesworth, C.J., and Ormerod, D.S., 1991, Isotopic and trace element constraints on the composition and evolution of the lithosphere beneath the southwestern United States: Journal of Geophysical Research B, v. 96, p. 13713-13735.

Kleinhampl, F.J., and Ziony, J.I., 1985, Geology of northern Nye County, Nevada: Nevada Bureau of Mines and Geology Bulletin 99A, 172 p.

Lackner, K.S., Butt, D.P., and Wendt, C.H., 1997a, Magnesite disposal of carbon dioxide: The Proceedings of the 22nd International Technical Conference on Coal Utilization & Fuel Systems, March 16-19, 1997, Clearwater, Florida, U.S.A, p. 419-430.

Lackner, K.S., Butt, D.P., and Wendt, C.H., 1997b, Progress on binding CO2 in mineral substrates: Proceedings of the Third International Conference on Carbon Dioxide Removal, MIT, Cambridge Massachusetts, September 9-11, 1996, Energy Conversions and Management Supplement 38, p. S259-S264.

Lackner, K.S., Butt, D.P., Wendt, C.H., Goff, F., and Guthrie, G., 1997c, Carbon dioxide disposal in mineral form: Keeping coal competitive: Los Alamos National Laboratory Technical Report No. LA-UR-97-2094.

Lackner, K.S., Butt, D.P., Wendt, C.H., and Sharp, D.H., 1996, Carbon dioxide disposal in solid form: The Proceedings of the 21st International Technical Conference on Coal Utilization & Fuel Systems, March 18-21, 1996, Clearwater, Florida, U.S.A., p. 133- 144.

Lackner, K.S., Wendt, C.H., Butt, D.P., Joyce, E.L., and Sharp, D.H., 1995, Carbon dioxide disposal in carbonate minerals: Energy, v. 20, p. 1153-1170.

Leavitt, E.D., Goldstrand, P., Schmidt, K., Wallace, A.R., Spell, T., and Arehart, G.B., 2000, Geochronology of the Midas gold-silver deposit and its relationship to volcanism and mineralization along the northern Nevada rift, *in* Wallace, A.R., and John, D.A., eds., 2000, Volcanic history, structure, and mineral deposits of the north-central northern Nevada rift: Geological Society of Nevada Symposium 2000, The Great Basin and Beyond, Field Trip Guidebook No. 8, p. 157-162.

Leeman, W.P., 1982, Tectonic and magmatic significance of strontium isotopic variations in Cenozoic volcanic rocks from the western Untied States: Geological Society of America Bulletin, v. 93, p. 487-503.

Li, Z-X., Li, X., Zhou, H., and Kinney, P.D., 2002, Grenvillian continental collision in south China: new SHRIMP U-Pb zircon results and implications for the configuration of Rodinia: Geology, v. 30, p. 163-166.

Longwell, C.R., Pampeyan, E.H., Bowyer, B., Roberts, R.J., 1965, Geology and mineral deposits of Clark County: Nevada Bureau of Mines and Geology Bulletin 62, 199 p.

Lum, C.C.L., Leeman, W.P., Foland, K.A., Kargel, J.A., and Fitton, J.G., 1989, Isotopic variations in continental basaltic lavas as indicators of mantle heterogeneity: examples from the western U.S. cordillera: Journal of Geophysical Research B, v. 94, p. 7871-7884.

Lush, A.P., McGrew, A.J., Snoke, A.W., and Wright, J.E., 1988, Allochthonous Archean basement in the northern East Humboldt Range, Nevada: Geology, v. 16, p. 349-353.

Magnani, M.B., Miller, K.C., Levander, A., and Karlstrom, K., 2004, The Yavapai-Mazatzal boundary; a long-lived tectonic element in the lithosphere of southwestern North America: Geological Society of America Bulletin, v. 116, p. 1137-1142.

Mark, R.K., Lee Hu, C., Bowman, H.R., Asaro, F., McKee, E.H., and Coats, R.R., 1975, A high 87Sr/86Sr mantle source for low alkali tholeiite, northern Great Basin: Geochimica et Cosmochimica Acta, v. 39, p. 1671-1678.

Matlock, J.A; and Ohlin, H N, 1996, Lyon copper-iron skarn deposit, Yerington mining district, Lyon County, Nevada, *in* Green, S.M., and Struhsacker, E., eds., Geology and ore deposits of the American Cordillera; Trip A - Great Basin Porphyry Deposits: Geological Society of Nevada Field Trip Guidebook Compendium, 1995, Reno/Sparks, p. 121-129.

Mazzotti, M., Abanades, J.C., Allam, R., Lackner, K.S., Meunier, F., Rubin, W., Sanchez, J.C., Yogo, K., and Sevenhoven, R., 2005, Mineral carbonation and industrial uses of carbon dioxide: Intergovernmental Panel on Climate Change, 2005, Carbon dioxide capture and storage, IPPC special report, www.ipcc.ch/activity/srccs/index.htm, p. 320-338.

McGrail, P.B., Schaef, H.T., Ho, A.M., Chien, Y-J., Dooley, J.J., and Davidson, C.L., 2006, Potential for carbon sequestration in flood basalts: Journal of Geophysical Research, v. 111, B12201od.

McKelvey, V.E. and Wiese, J.H., 1949, Sketch map and sections of the Boulder City manganese deposit, Clark County, Nevada, U.S. Geological Survey 948-D, 1:6,100 scale.

Menzies, M.A., 1989, Cratonic, circumcratonic and oceanic mantle domains beneath the western United States: Journal of Geophysical Research B, v. 94, p. 7899-7915.

Miller, E.L., Gans, P.B., and Garing, J., 1983, The Snake Range décollement: an exhumed mid-Tertiary ductile-brittle transition: Tectonics, v. 2, p. 239-263.

Moore, J.G., and Archbold, N.L., 1969, Geology and mineral deposits of Lyon, Douglas and Ormsby Counties, Nevada: Nevada Bureau of Mines and Geology Bulletin 75, 45 p.

Moore, J.G., 1971, California-Nevada Iron Resources & Iron Ore Markets; USBM IC 8511, P. 204-205.

Moore, J.G., 2000, Exploring the highest Sierra: Stanford University Press, Palo Alto, California, 427 p.

Moores, E.M., 1991, Southwest U.S.-East Antarctic (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425-428.

Morikawa, S.A., 1994, The geology of the tuff of Bridge Spring, southern Nevada and northwestern Arizona [M.S. thesis]: University of Nevada, Las Vegas, 165 p.

Morton, J.L., Silberman, M.L., Thompson G.I., and Brookins, D.G., 1980, New K-Ar ages and strontium isotopic data from late Miocene and younger volcanic rocks of the northern Virginia Range, Nevada: Geological Society of America Abstracts with Programs, v. 12, no. 3, p. 143.

Naumann, T.R., Smith, E.I., Shafiqullah, M., and Damon, P.E., 1991, New K-Ar ages for Pliocene mafic to intermediate volcanic rocks in the Reveille Range, Nevada: Isochron West, v. 57, p. 12-16.

Nevada Bureau of Mines and Geology, 1981, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1980, p. 29.

Nevada Bureau of Mines and Geology, 1982, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1981, p. 34.

Nevada Bureau of Mines and Geology, 1983, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1982, p. 31.

Nevada Bureau of Mines and Geology, 1987, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1986, p. 25.

Nevada Bureau of Mines and Geology, 1988, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1987, p. 45.

Nevada Bureau of Mines and Geology, 1990, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1989, p. 29.

Nevada Bureau of Mines and Geology, 1991, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1990, p. 30-31.

Nevada Bureau of Mines and Geology, 1995, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1994, p. 39.

Nevada Bureau of Mines and Geology, 2000, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-1999, p. 20-21.

Nevada Bureau of Mines and Geology, 2001, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-2000, p. 21.

Nevada Bureau of Mines and Geology, 2002, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-2001, p. 45.

Nevada Bureau of Mines and Geology, 2003, The Nevada mineral industry: Nevada Bureau of Mines and Geology Special Publication MI-2002, p. 47.

Nevada Bureau of Mines and Geology Mining District file on Yerington Mining District, 1960s, Drill logs and other unpublished documents relevant to U.S. Steel's application for patent on the Lyon iron deposit.

Nielson, J.E., Lux, D.R., Dalrymple, G.B., and Glazner, A.F., 1990, Age of the Peach Springs Tuff, southeastern California and western Arizona: Journal of Geophysical Research, v. 95, p. 571-580.

Nilson, T.H., and Stewart, J.H., 1980, The Antler orogeny - mid-Paleozoic tectonism in western North America (Penrose Conference Report): Geology, v. 8, p. 298-302.

Nylen, D., 1998, Nevada Minerals... Iron: the boom that didn't: Nevada State Museum Newsletter, Volume XXVI, Number 4, July/August, 1998.

O'Connor, W.K., Dahlin, D.C., Rush, G.E., Dahlin, C.L., and Collins, W.K., 2002, Carbon dioxide sequestration by direct mineral carbonation: process mineralogy of feed and products: Minerals and Metallurgical Processing, v. 19, no. 2, p. 95-101.

Ohlin, H N; Gibson, P C; Matlock, J A, 1995, Geology of the North Deposit: Lyon copper-iron skarns, Yerington, Nevada [abs.]: Geology and Ore Deposits of the American Cordillera, Reno/Sparks, Nevada, 1995, Program with Abstracts, p. 59-60.

Ormerod, D.S., Hawkesworth, C.J., Rogers, N.W., Leeman, W.P., and Menzies, M.A., 1988, Tectonic and magmatic transitions in the western Great Basin, U.S.A.: Nature, v. 333, p. 349-353.

Ormerod, D.S., 1988, Late- to post-subduction magmatic transitions in the western Great Basin, U.S.A. [Ph.D. dissertation]: Open University, Milton Keynes, UK, 331 p.

Page, B.M., 1959, Geology of the Candelaria mining district, Mineral County, Nevada: Nevada Bureau of Mines Bulletin 56, 64 p.

Phinisey, J.D., 1995, Petrography, alteration, and mineralization of igneous dikes of the Jerritt Canyon District, Elko County, Nevada [M.S. thesis]: University of Nevada, Reno, 173 p.

Ponce, D.A., and Glen, J.M.G., 2002, Relationship of epithermal gold deposits to large-scale fractures in northern Nevada: Economic Geology, v. 97, p. 3-9.

Price, J.G., Hess, R.H., Fitch, S., Faulds, J.E., Garside, L.J., Shevenell, L., and Warren, S., 2005, Preliminary assessment of the potential for carbon dioxide sequestration in geological settings in Nevada: Nevada Bureau of Mines and Geology Report 51, 36 p.

Proffett, J.M. Jr., and Dilles, J.H., 1984, Geologic map of the Yerington district, Nevada: Nevada Bureau of Mines and Geology Map 77, 1:24,000.

Rash, K.B., 1995, Geology and geochemistry of Tertiary volcanic rocks in the northern Reveille and southern Pancake Ranges, Nye County, Nevada [M.S. thesis]: University of Nevada, Las Vegas, 171 p.

Reeves, R.G., 1964, Iron, *in* Cornwall, H.R., ed., Mineral and water resources of Nevada: Nevada Bureau of Mines and Geology Bulletin 65, 325 p.

Reeves, R.G. and Kral, V.E., 1958, Iron ore deposits of the Buena Vista Hills, Churchill and Pershing Counties, Nevada: Iron ore deposits of west-central Nevada: Nevada Bureau of Mines and Geology Bulletin 53, Part A.

Reeves, R.G., Shawe, F.R., and Kral, V.E., 1958, Iron ore deposits of west-central Nevada: Nevada Bureau of Mines and Geology Bulletin 53, part B.

Reynolds, S.J., and Spencer, J.E., 1985, Evidence for large-scale transport on the Bullard detachment fault, west-central Arizona: Geology, v. 13, p. 353-356.

Roberts, R.J., Montgomery, K.M., and Lehner, R.E., 1967, Geology and mineral resources of Eureka County, Nevada: Nevada Bureau of Mines and Geology, Bulletin 64, 152 p.

Roberts, W.L., Rapp, G.R., Jr., and Weber, J., 1974, Encyclopedia of minerals: Van Nostrand Reinhold Company, New York, 693 p.

Robie, R.A., and Hemmingway, B.S., 1995, Thermodynamic properties of minerals and related substances at 298.15 K and 1 bar (105 pascals) pressure and at higher temperatures: U.S. Geological Survey Bulletin 2131, 461 p.

Rogers, N.W., Hawkesworth, C.J., and Ormerod, D.S., 1995, Late Cenozoic basaltic magmatism in the western Great Basin, California and Nevada: Journal of Geophysical Research B, v. 100, p. 10287-10301.

Ross, D.C., 1961, Geology and mineral deposits of Mineral County, Nevada: Nevada Bureau of Mines and Geology Bulletin 58, 112 p.

Roylance, J.G., Jr., 1965, The Dayton iron deposits, Lyon And Storey Counties, Nevada; 10 papers presented at the AIME Pacific Southwest Mineral Industry conference, Sparks, Nevada: Nevada Bureau of Mines and Geology Report 13a, p. 125-141.

Roylance, J.G., Jr., 1966, The Dayton iron deposits, Lyon and Storey Counties, Nevada: Nevada Bureau of Mines Report 13, p. 125-141.

Schwartz, K.M., 2001, Evolution of the middle to late Miocene Chalk Hills basin in the Basin and Range-Sierra Nevada transition zone, western Nevada [M.S. thesis]: University of Nevada, Reno 160 p.

Scott, D.H., 1969, The geology of the southern Pancake Range and Lunar Crater volcanic field, Nye County, Nevada [Ph.D. dissertation]: University of California, Los Angeles, 209 p.

Scott, D.H., and Trask, N.J., 1971, Geology of the Lunar Crater volcanic field, Nye County, Nevada: U.S. Geological Survey Professional Paper 599-I, p. I1-I22.

Sears, J.W., and Price, R.A., 2000, New look at the Siberian connection: No SWEAT: Geology, v. 28, p. 423-426.

Sears, J.W., and Price, R.A., 2003, Tightening the Siberian connection to eastern Laurentia: Geological Society of America Bulletin, v. 115, p. 943-953.

Service, R.F., 2004, The carbon conundrum: Science, v. 305, p. 962-963.

Shawe, F.R., Reeves, R.G., and Kral, V.E., 1962, Iron ore deposits of northern Nevada, Nevada Bureau of Mines and Geology Bulletin 53, part C.

Sherlock, M.G., Cox, D.P., and Huber, D.F., 1996, Known mineral deposits in Nevada, *in* Singer, D.A., ed., An analysis of Nevada's metal-bearing mineral resources: Nevada Bureau of Mines and Geology Open-File Report 96-2, Chapter 10, p.10.1-10.38, 1:1,000,000.

Shoemaker, K.A. and Hart, W.K., 2004, Inferences on northwestern U.S. mantle architecture from geochronologic and isotopic studies of Owyhee plateau basaltic volcanism: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 246.

Silberman, M.L., and McKee, E.H., 1972, A summary of radiometric age determinations on Tertiary volcanic rocks from Nevada and eastern California: Part II, western Nevada: Isochron/West, no. 4, p. 7-28.

Smith, E.I., and Keenan, D.L., 2005, Yucca Mountain could face greater volcanic threat: Eos, Transactions, American Geophysical Union, v. 86, no. 35, p. 317-321.

Smith, E.I., Keenan, D.L., and Plank, T., 2002, Episodic volcanism and hot mantle: implications for volcanic hazard studies at the proposed nuclear waste repository at Yucca Mountain, Nevada: GSA Today, v. 12, no. 4, p. 4-10.

Smith, M. R., 1984, The Pumpkin Hollow magnesian iron-copper skarn, *in* Johnson, J.C. and R.C. Steininger, eds., Exploration for ore deposits of the North American Cordillera: The Association of Exploration Geochemists, 1984 Regional Symposium, Guidebook, Field Trip 10, p. 41-42.

Speed, R.C., 1962, Scapolitized gabbroic complex, West Humboldt Range, Nevada [Ph.D. dissertation]: Stanford University, Palo Alto, California, 227 p.

Speed, R.C., and Sleep, N.H., 1982, Antler orogeny and foreland basin: A model: Geological Society of America Bulletin, v. 93, p. 815-828.

Stewart, J.H., 1980, Geology of Nevada: A discussion to accompany the geologic map of Nevada: Nevada Bureau of Mines and Geology Special Publication 4, 136 p.

Stewart, J.H., 1991, Latest Proterozoic and Cambrian rocks of the Western United States—an overview, *in* Cooper, J.D., and Stevens, C.H., eds., Paleozoic Paleogeography of the western United States, II: Society for Sedimentary Geology (SEPM) Pacific Section, p. 13-38.

Stewart, J.H., and Carlson, J.E., 1978, Geologic map of Nevada: U.S. Geological Survey, scale 1:500,000.

Stewart, J.H., and Suzcek, C.A., 1977, Cambrian and latest Precambrian paleogeography and tectonics in the western United States, *in* Stewart, J.H., Stevens, C.H., and Fritsche, A.E., eds., Paleozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists Pacific Section, p. 1-17.

Stewart, J.H., Gehrels, G.E., Barth, A.P., Link, P.K., Christie-Blick, N., and Wrucke, C.T., 2001, Detrital zircon provenance of Mesoproterozoic to Cambrian arenites in the western United States and northwestern Mexico: Geological Society of America Bulletin, v. 113, p. 1343-1356.

Thoreson, R.F., Jones, M., Breit, F. Jr., Doyle-Kunkel, M., and Clarke, L., 2000, The geology and gold mineralization of the Twin Creeks gold deposits, Humboldt County, Nevada, *in* Crawford, E., ed., Geology and gold deposits of the Getchell region: Society of Economic Geologists Guidebook Series, v. 32, p. 175-187.

Trengove, R.R., 1959, Reconnaissance of Nevada Mn deposits: U.S. Bureau of Mines Report of Investigations 5446, p. 16-17.

Trexler, J.H., Jr., Cashman, P.H., Snyder, W.S., and Davydov, V.I., 2004, Late Paleozoic tectonism in Nevada: timing, kinematics, and tectonic significance: Geological Society of America Bulletin, v. 116, p. 525-538.

Tschanz, C.M. and Pampeyan, E.H., 1970, Geology and mineral deposits of Lincoln County, Nevada: Nevada Bureau of Mines and Geology, Bulletin 73.

U.S. Bureau of Mines, 1959, U.S. Bureau of Mines Report of Investigations No. 5446, p. 8-9, 20-21.

U.S. Department of Energy, Energy Information Agency (2004), Greenhouse gases, climate change, and energy: www.eia.doe.gov/oiaf/1605/ggccebro/chapter1.html

Vaniman, D.T., Crowe, B.M., and Gladney, E.S., 1982, Petrology and geochemistry of hawaiite lavas from Crater Flat, Nevada: Contributions to Mineralogy and Petrology, v. 80, p. 341-357.

Vanko, D.A., and Bishop, F.C., 1982, Occurrence and origin of marialitic scapolite in the Humboldt lopolith, northwestern Nevada: Contributions to Mineralogy and Petrology, v. 81, p. 277-289.

Voormeij, D.A., Simandl, G.J., and O'Connor, B., 2004, A Systematic assessment of ultramafic rocks and their suitability for mineral sequestration of CO_2: Division of Engineers and Geoscientists in the Forest Sector, Professional Engineers and Geoscientists of British Columbia, http://www.degifs.com/pdf/ultramafics%20in%20BC.pdf, 4 p.

Wallace, A.R., and John, D.A., eds., 2000, Volcanic history, structure, and mineral deposits of the north-central northern Nevada rift: Geological Society of Nevada Symposium 2000, The Great Basin and Beyond, Field Trip Guidebook No. 8, 176 p.

Weast, R.C., ed., 1971, Handbook of chemistry and physics: Chemical Rubber Company, Cleveland, Ohio.

Wernicke, B., 1981, Low-angle normal faults in the Basin and Range province: Nappe tectonics in an extending orogen: Nature, v. 291, p. 645-648.

Wernicke, B., 1992, Cenozoic extentional tectonics of the U.S. Cordillera: The Cordilleran orogen: Conterminous U.S.: Geological Society of America DNAG Volume G-3, p. 553-582.

Westgate, L.G., and Knopf, A., 1932, Geology and ore deposits of the Pioche District, Nevada: U.S, Geological Survey Professional Paper 171, 79 p.

Willden, R., 1964, Geology and mineral deposits of Humboldt County, Nevada: Nevada Bureau of Mines and Geology Bulletin 59, 164 p.

Willden, R., and Speed, R.C., 1974, Geology and mineral deposits of Churchill County, Nevada: Nevada Bureau of Mines and Geology Bulletin 83, 92 p.

Yogodzinski, G.M., Naumann, T.R., Smith, E.I., Bradshaw, T.K., and Walker, J.D., 1996, Evolution of a mafic volcanic field in the central Great Basin, south central Nevada: Journal of Geophysical Research, B, Solid Earth and Planets, v. 101, p. 17425-17445.

Zoback, M.L.C., 1978, Mid-Miocene rifting the north-central Nevada; a detailed study of late Cenozoic deformation in the northern Basin and Range [Ph.D. dissertation]: Stanford University, Palo Alto, California, 247 p.

Zoback, M.L., and Thompson, G.A., 1978, Basin and Range rifting in northern Nevada—clues from a mid-Miocene rift and its subsequent offset: Geology, v. 6, p. 111-116.

Zoback, M.L., McKee, E.H., Blakely, R.J., and Thompson, G.A., 1994, The northern Nevada rift: Regional tectono-magmatic relations and Miocene stress direction: Geological Society of America Bulletin, v. 106, p. 371-382.

Nevada System of Higher Education
2007

Board of Regents
Michael Wixom, *Chair*

Mark Alden
Stavros Anthony
Cedric Crear
Thalia M. Dondero
Dorothy Sewell Gallagher
Jason Geddes
Ron Knecht
James D. Leavitt
Howard Rosenberg
Jack L. Schofield
Steve Sisolak
Bret Whipple

James E. Rogers, *Chancellor*

University of Nevada, Reno
Milton D. Glick, *President*

College of Science
Jeffrey Thompson, *Interim Dean*

Mackay School of Earth Sciences and Engineering
James V. Taranik, *Director*

Nevada Bureau of Mines and Geology
Jonathan G. Price, *Director/State Geologist*

Scientific Research Staff

Economic Geology, Geologic Mapping, and Geologic Framework
Harold F. Bonham, Jr., *Research Geologist (Emeritus)*
Stephen B. Castor, *Research Geologist*
John W. Erwin, *Geophysicist (Emeritus)*
James E. Faulds, *Research Geologist*
Larry J. Garside, *Research Geologist*
Christopher D. Henry, *Research Geologist*
Liang-Chi Hsu, *Research Mineralogist (Emeritus)*
John L. Muntean, *Research Economic Geologist*
Keith G. Papke, *Industrial Minerals Geologist (Emeritus)*
Joseph V. Tingley, *Research Geologist (Emeritus)*

Geologic Hazards, Engineering Geology, and Geophysics
John W. Bell, *Research Engineering Geologist*
Geoffrey Blewitt, *Research Professor*
Bret Pecoraro, *Laboratory Assistant*
Craig M. dePolo, *Research Geologist*
William C. Hammond, *Research Scientist*
P. Kyle House, *Research Geologist*
Corné W. Kreemer, *Research Scientist*
Hans-Peter Plag, *Research Scientist*
Alan R. Ramelli, *Research Geologist*

Environmental Geology and Hydrogeology
Paul J. Lechler, *Chief Chemist/Geochemist*
Lisa Shevenell, *Research Hydrogeologist*

Science Education
Daphne D. LaPointe, *Research Geologist*

Research and Administrative Support Staff

Cartography, Publication Support
Jordan Hastings, *Chief Cartographer and GIS Manager*
Heather Armeno, *Cartographer*
Christine Arritt, *Cartographer*
Elizabeth Crouse, *Senior Cartographer*
Linda Goar, *Accounting Assistant*
Jack Hursh, Jr., *Cartographer*
Gary Johnson, *Information Systems Specialist*
Jennifer Mauldin, *Cartographer*
Kris R. Pizarro, *Cartographic Supervisor*
Dick Meeuwig, *Editor and Webmaster*
Susan Tingley, *Senior Cartographer (Emeritus)*

Analytical Laboratory
Mario Desilets, *Chemist/Quality Assurance Officer*

Information and Publication Sales
Ron Hess, *Chief Information Officer*
David Cornett, *Supply Assistant*
David Davis, *Geologic Information Specialist*
Martha Henson, *Administrative Assistant*
Charlotte Stock, *Sales Manager*

First edition, first printing, 2007, 50 copies
Printed by: UNR Copy Center

Editor: Dick Meeuwig
Graphics: Jack Hursh, Jordan Hastings, and Shelly deLaureal
Typography: Jack Hursh

The Nevada Bureau of Mines and Geology (NBMG) is a research and public service unit of the University of Nevada and is the state geological survey. NBMG is part of the Mackay School of Mines at the University of Nevada, Reno. NBMG scientists conduct research and publish reports on mineral resources, engineering geology, environmental geology, hydrogeology, and geologic mapping. Individuals interested in Nevada geology are encouraged to visit, call, or write NBMG or visit our homepage at www.nbmg.unr.edu.

When visiting NBMG by car, please stop at the information booth just inside the Center Street entrance on the south end of the Reno campus of the University of Nevada. Ask for the Mackay School of Mines map and directions to parking areas and the NBMG offices in the west wing of the Scrugham Engineering-Mines Building. Free parking for Publication Sales Office customers is located on the southwest corner of Palmer Engineering building.

Information Office (room 311)
Publication Sales Office (room 310)

Store hours: 8:00 a.m. to 3:00 p.m., Monday through Friday

NBMG publications and maps, U.S. Geological Survey maps, and related publications can be purchased at the Publication Sales Office or ordered over the Internet at www.nbmg.unr.edu/sales.htm.

Orders for publications or requests for information may also be made by telephone, fax, e-mail, or U.S. Mail.

Orders:		(775) 784-6691 ext. 2
Phone hours:		7:00 a.m. to 4:00 p.m., Monday through Friday
Fax:		(775) 784-1709
E-mail:	(orders)	nbmgsales@unr.edu
	(information)	nbmginfo@unr.edu
U.S. Mail:		Nevada Bureau of Mines and Geology Mail Stop 178 University of Nevada Reno, NV 89557-0178

The University of Nevada, Reno is an Equal Opportunity/Affirmative Action employer and does not discriminate on the basis of race, color, religion, sex, age, creed, national origin, veteran status, physical or mental disability, and in accordance with university policy, sexual orientation, in any program or activity it operates. The University of Nevada, Reno employs only United States citizens and aliens lawfully authorized to work in the United States.