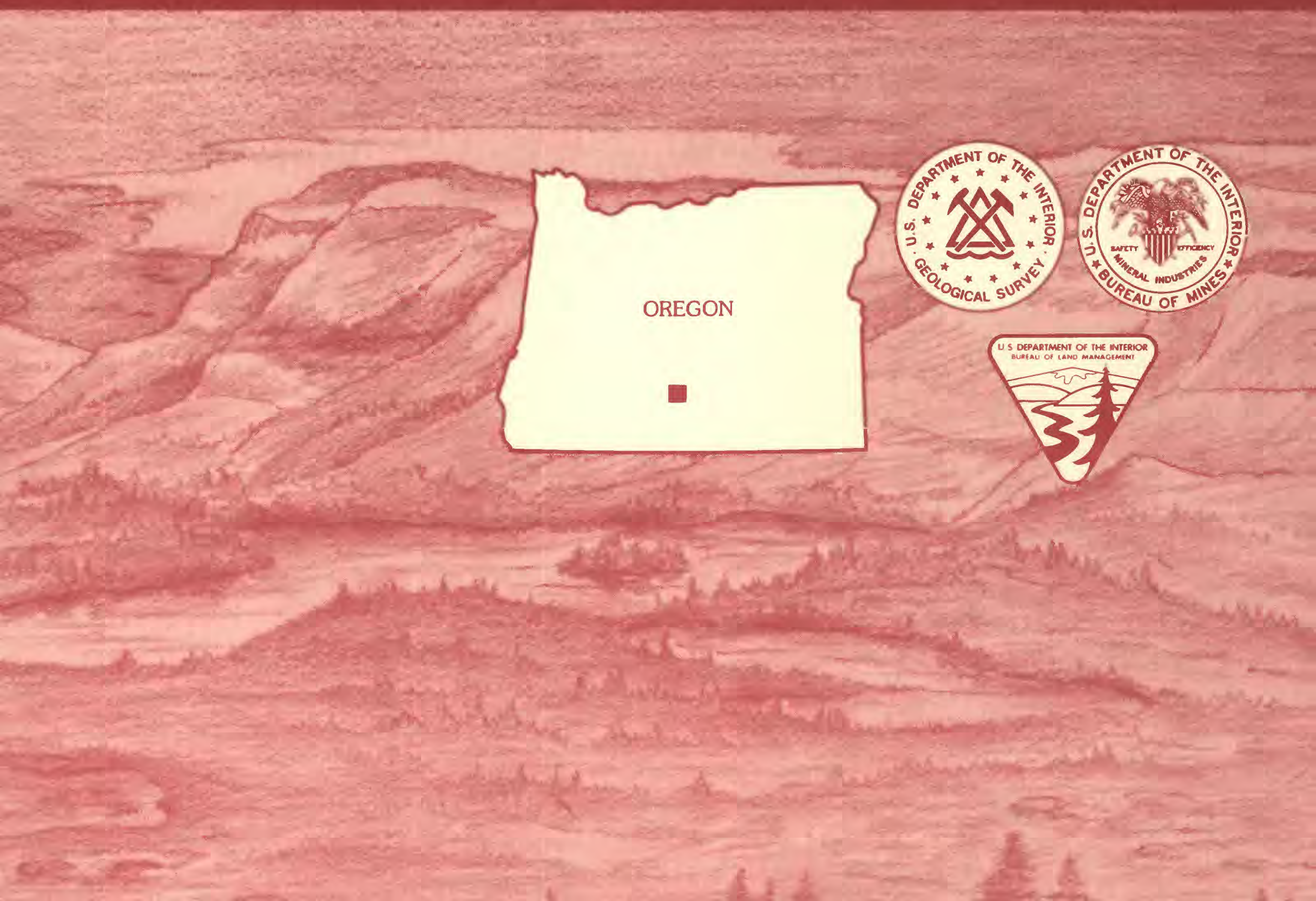
Mineral Resources of the Diablo Mountain Wilderness Study Area, Lake County, Oregon

U.S. GEOLOGICAL SURVEY BULLETIN 1738-D



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Chapter D

Mineral Resources of the Diablo Mountain Wilderness Study Area, Lake County, Oregon

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U.S. GEOLOGICAL SURVEY BULLETIN 1738

MINERAL RESOURCES OF WILDERNESS STUDY AREAS:
SOUTH-CENTRAL OREGON

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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STUDIES RELATED TO WILDERNESS

Bureau of Land Management Wilderness Study Areas

The Federal Land Policy and Management Act (Public Law 94–579, October 21, 1976) requires the U.S. Geological Survey and the U.S. Bureau of Mines to conduct mineral surveys on certain areas to determine the mineral values, if any, that may be present. Results must be made available to the public and be submitted to the President and the Congress. This report presents the results of a mineral survey of part of the Diablo Mountain Wilderness Study Area (OR–001–058), Lake County, Oregon.

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FIGURES

Mineral Resources of the Diablo Mountain Wilderness Study Area, Lake County, Oregon

By Michael F. Diggles, Harley D. King, Mark E. Gettings, James E. Conrad, Don L. Sawatzky, *and* Gerilyn S. Soreghan
U.S. Geological Survey

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SUMMARY

Abstract

At the request of the U.S. Bureau of Land Management, approximately 85,470 acres of the Diablo Canyon Wilderness Study Area was evaluated for identified mineral resources (known) and mineral resource potential (undiscovered). In this report, the area studied is referred to as the "wilderness study area" or "the study area." Any reference to the Diablo Mountain Wilderness Study Area refers only to that part of the wilderness study area for which a mineral survey was requested by the U.S. Bureau of Land Management. Fieldwork was conducted in 1986, 1988, and 1989 to assess the mineral resources and resource potential of the study area.

No energy or mineral resources were identified in the study area, but brines within lake and playa sediments contain concentrations of chemical components suitable for the production of soda ash, boron compounds, and sodium sulfate. Possible byproducts include potash, salts, bromine, lithium, magnesium compounds, and tungsten. Limestone from the study area could be used in the recovery process of brine components. The study area includes thermal springs and lies within 2 mi of the Summer Lake Known Geothermal Resource Area (KGRA). In the western part of the study area, the mineral resource potential is moderate for undiscovered resources of soda ash, boron compounds, and sodium sulfate as well as byproduct magnesium compounds, salts, potash, bromine, lithium, and tungsten associated with brines. In a small south-central part of the study area, the mineral resource potential is low for low-grade high-tonnage epithermal hot-spring gold-silver deposits and for magnesium from dolomitic limestone. The resource potential of the entire study area is moderate for low-temperature geothermal energy useful for agricultural and building heating and is low for oil and gas.

Manuscript approved for publication, August 27, 1990

Character and Setting

The Diablo Mountain Wilderness Study Area is just east of Summer Lake (fig. 1), about 45 mi north of Lakeview, Oreg. It lies on the northwest edge of the Basin and Range physiographic province, in the volcanic plateau region lying south of the Blue Mountains and east of the Cascade Range. The region west of Summer Lake and continuing south of the study area is part of the poorly defined Modoc Plateau physiographic province that separates the Basin and Range and the Cascade Range physiographic provinces. Consolidated rocks within the study area consist mostly of Tertiary basalt and tuffaceous sedimentary rocks (see "Appendixes" for geologic time chart). The low-lying areas are covered by Quaternary alluvial-fan, sand-dune, playa, lacustrine, fluvial, and landslide deposits. The principal structural features of the area are normal faults that have large vertical offsets. These faults are concentrated at the margins of large horst and graben typical of the Basin and Range province.

Identified Mineral Resources

No mineral resources have been identified within or adjacent to the study area, but brines within lake and playa sediments, sampled from shallow auger holes, contain concentrations of chemical components suitable for the production of soda ash, boron compounds, and sodium sulfate. Possible byproducts include potash, salts, bromine, lithium, magnesium compounds, and tungsten. Limestone from the study area could be used in recovering soda ash, boron compounds, sodium sulfate, and magnesium compounds from brine. The area includes thermal springs and lies within 2 mi of the Summer Lake Known Geothermal Resource Area (KGRA).

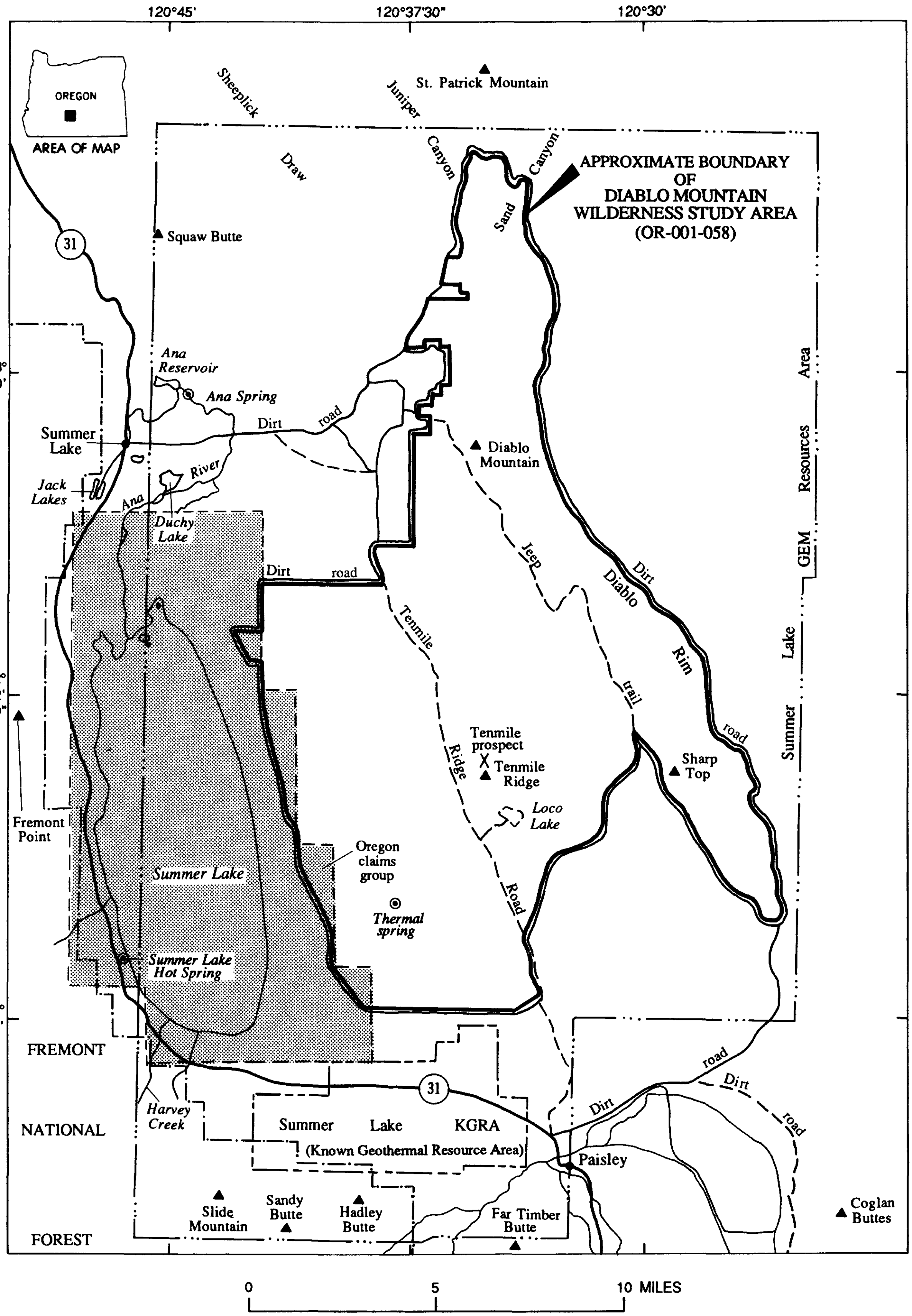

Figure 1. Index map showing location of Diablo Mountain Wilderness Study Area, Lake County, Oregon.

Mineral Resource Potential

The western part of the Diablo Mountain Wilderness Study Area has moderate mineral resource potential for commodities associated with brines: soda ash, boron compounds, and sodium sulfate as well as byproduct magnesium compounds, salts, potash, bromine, lithium, and tungsten. A low mineral resource potential for low-grade high-tonnage epithermal hot-spring gold-silver deposits in the area of Tenmile Ridge is suggested by the presence of opal in some altered-basalt outcrops and by the presence of mercury in a nearby prospect. The mineral resource potential is low for magnesium from dolomitic limestone in the area of Tenmile Ridge. The entire study area has moderate geothermal energy resource potential for low-temperature thermal water useful for agricultural and building heating. The Summer Lake KGRA is 2 mi south of the study area. Thermal springs at Ana Springs and Summer Lake Hot Spring are near the study area, and one known thermal-water spring was observed within the study area. Oil and gas resource potential is low throughout the study area.

INTRODUCTION

This mineral survey was requested by the U.S. Bureau of Land Management and is the result of a cooperative effort by the U.S. Geological Survey and the U.S. Bureau of Mines. An introduction to the wilderness review process, mineral survey methods, and agency responsibilities was provided by Beikman and others (1983). The U.S. Bureau of Mines evaluates identified resources at individual mines and known mineralized areas by collecting data on current and past mining activities and through field examination of mines, prospects, claims, and mineralized areas. Identified resources are classified according to a system that is a modification of that described by McKelvey (1972) and U.S. Bureau of Mines and U.S. Geological Survey (1980). U.S. Geological Survey studies are designed to provide a scientific basis for assessing the potential for undiscovered mineral resources by determining geologic units and structures, possible environments of mineral deposition, presence of geochemical and geophysical anomalies, and applicable ore-deposit models. Goudarzi (1984) discussed mineral assessment methodology and terminology as they apply to these surveys. See "Appendixes" for the definition of levels of mineral resource potential and certainty of assessment and for the resource/reserve classification.

Location and Physiography

The Diablo Mountain Wilderness Study Area includes approximately 85,470 acres and is 45 mi north of Lakeview and 5 mi north of Paisley, Oreg. (fig. 1). Elevations in the area range from 4,300 ft near the shore of Summer Lake to 6,147 ft at the summit of Diablo Mountain. Access to the region is via Oregon State Route 31 connecting U.S. Highways 395 north of Lakeview and 97 south of Bend. Access to the area is provided by dirt roads from State Highway 31. Access within the study area is by four-wheel-drive vehicle on jeep trails and by mountain bicycle and by foot. The climate is semiarid, and the average annual precipitation is about 12 in.; sparse rainfall in the area results in only intermittent stream flow. The region contains several lakes, of which Summer Lake is one, that occupy closed basins. Vegetation consists of low-growing desert shrubs, mostly sagebrush, greasewood, creosotebush, burroweed, and boxthorn.

Procedures

The U.S. Geological Survey conducted detailed field investigations of the Diablo Mountain Wilderness Study Area in the summers of 1986, 1988, and 1989. This work included making a detailed geologic map (Diggles and others, 1990), collecting geochemical, petrologic, and geochronologic samples, and examining outcrops for evidence of mineralization. Generalized geology is shown in figure 2.

The U.S. Bureau of Mines work on the Diablo Mountain Wilderness Study Area was done in two phases. The central and eastern parts of the area were examined by Willett (1987), and the western part of the area was studied by Peters and Willett (1989). These studies included library search of pertinent geological and mining literature. U.S. Bureau of Land Management master title plats and current mining claim recordation data, as well as Lake County mining claim records were examined. Information was also obtained from the U.S. Bureau of Land Management Lakeview District Office, the Oregon Department of Geology and Mineral Industries, Portland, and the U.S. Bureau of Mines Mineral Industries Location System and other files and records.

U.S. Bureau of Mines fieldwork was done during spring 1986 and June 1988. A search was conducted for all mines, prospects, and mineralized areas in and within 1 mi of the study area. Samples include 45 sediment, 2 brine, 26 water (predominantly from auger holes), 21 alkali-crust (from surfaces of alkali flats adjacent to auger holes), 34 rock (randomly chipped from homogeneous outcrops), and 4 sand samples; 1 auger-hole sediment sample was collected for mineral identification by X-ray diffraction (halite). Mineralized sites were examined and sampled. Results of analyses of these samples are on file at the U.S. Bureau of Mines, Western Field Operations Center, E. 360 Third Ave., Spokane, WA 99202.

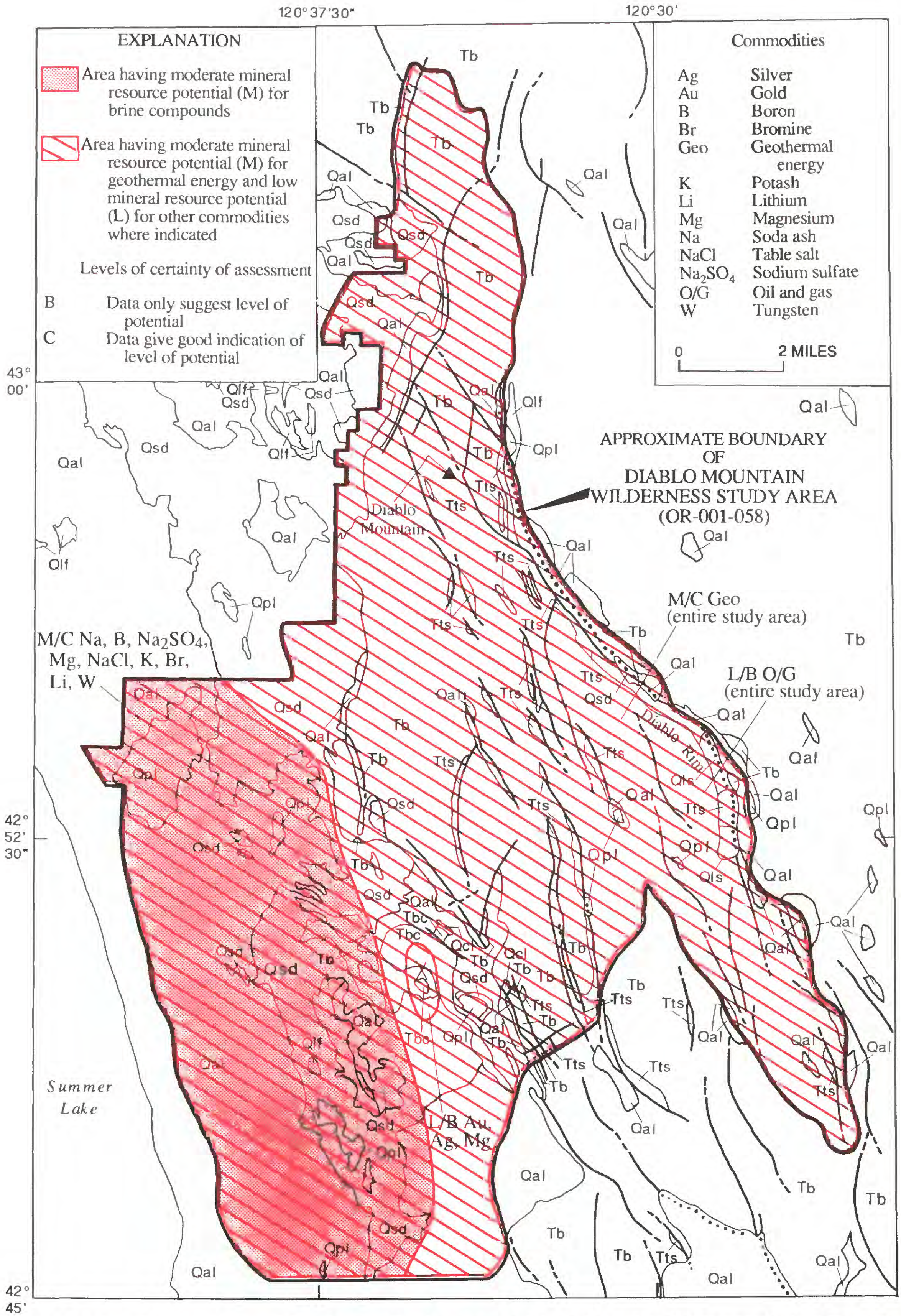

Figure 2. Mineral resource potential and generalized geology of Diablo Mountain Wilderness Study Area, Lake County, Oregon. Geology generalized from Diggles and others (1990).

Previous Studies

Waring (1908) discussed the geology and water resources of south-central Oregon. The eastern halves of the Klamath Falls and Crescent 1° by 2° quadrangles have been mapped by Walker (1963) and Walker and others (1967), respectively. Peterson and McIntyre (1970) presented the geology and mineral resources of part of Lake County. An assessment of geology, energy, and minerals in the Summer Lake GEM Resources Area (fig. 1) was presented in Mathews and others (1983). Geology of the Summer Lake area was discussed more extensively in Conrad (1953) and Travis (1977). Mineralized waters at Summer Lake were discussed by Van Denburgh (1975). Structural geology of the Summer Lake area is emphasized in Fuller and Waters (1929), Donath (1962), Donath and Kuo (1962), and Lawrence (1976).

Description of map units

Qal Alluvium (Quaternary)—Alluvial fan deposits and stream deposits of gravel, sand, and silt

Qsd Sand dunes (Quaternary)—Large areas of windblown sand composed of ash, pumice, and rock-forming mineral grains, mostly alkali feldspar and quartz

Qpl Playa deposits (Quaternary)—Clay, silt, sand, and some evaporite deposits. Contains tephra at depth

Qlf Lacustrine and fluvial deposits (Quaternary)—Unconsolidated clay, silt, and gravel

Qls Landslide deposits (Quaternary)—Unstratified mixtures of basaltic and tuffaceous sedimentary rocks. Includes faulted blocks, rubble, and talus

Qcl Claystone (Quaternary)—Mostly montmorillonite; locally includes marl, micrite, caliche, and opal-bearing travertine

Tbc Basaltic cinders (Tertiary)—Red and reddish black cinders and near-vent flows; scoriacious rocks and altered basalt

Tb Basalt (Tertiary)—Gray to dark-gray plagioclase-phyric olivine basalt flows having subophitic to diktytaxitic texture. Includes minor basalt-flow breccia. Crystals of labradorite are partly to completely enveloped in clinopyroxene. Pyroxene also forms interstitial grains. Locally interbedded with dolomitic limestone of Pliocene(?) age in vicinity of Tenmile Ridge (see fig. 1)

Tts Tuffaceous sedimentary rocks (Tertiary)—Semi-consolidated interbedded white, light-yellow, and cream-colored lacustrine and fluvial sedimentary rocks that consist mostly of tuffaceous sandstone and siltstone and locally contain arkosic sandstone and pebble conglomerate. Contains alkali feldspar, clay minerals, zeolites, and secondary silica minerals. Age and correlation uncertain but presumably mostly of middle and late Miocene age (Walker, 1977)

—— Contact

-----. Fault—Dashed where approximately located, dotted where concealed

X Tenmile prospect

Figure 2. Continued.

Acknowledgments

The writers greatly appreciate the cooperation of Dennis Simontacchi and Doug Troutman of the U.S. Bureau of Land Management in Lakeview, Oreg., for supplying information about claim records, geology, history, and logistics. Appointment of a field assistant was based on a recommendation by the National Association of Geology Teachers (NAGT); Gerilyn S. Soreghan was employed through the program. The authors are also grateful to Larry Hill, Paisley, Oreg., for geographic information about the study area and the surrounding region and especially for taking them to the thermal springs (fig. 3). John Withers of Paisley provided historical background, and John Cremin of Lakeview and Harold J. Dyke of Adel, Oreg., provided historical and technical information on the Tenmile (Sundown) limestone claim group. Steven Carpenter, Robert Deal, and Robert B. Kistler of U.S. Borax, Los Angeles, Calif., Gail Moulton of Kerr-McGee, Trona, Calif., and Dwight Harris of Clayton, Wash., contributed information on evaporite mineral commodities. Rex McKee of Weyerhaeuser Corp., Longview, Wash., provided information on chemicals used in wood processing. Ronald Geitgey, Oregon Department of Geology and Mineral Industries, Portland, and Dennis Simontacchi and Doug Troutman of the U.S. Bureau of Land Management, Lakeview, offered important geologic, historical and logistical advice. Kent Keller of Washington State University, and Walter Ficklin and Alan Driscoe of the U.S. Geological Survey, Lakewood, Colo., provided information on ground-water geochemistry. U.S. Geological Survey personnel A.S. Van Denburgh, Reno, Nev., and G.I. Smith, Menlo Park, Calif., provided information on the geology and geochemistry of closed-basin lakes. U.S. Bureau of Mines personnel, Paulette Atringer, Salt Lake City, Utah, and Dennis Kostic, Washington, D.C., provided information on evaporite mineral processing and economics. Field assistants in the U.S. Geological Survey geochemical sampling program were Steven Smith and Janet Jones. James Canwell, U.S. Bureau of Mines Western Field Operations Center, assisted with laboratory studies. U.S. Bureau of Mines Western Field Operations Center geologists David Benjamin and Terry Neumann assisted in the field during the spring of 1986.

APPRAISAL OF IDENTIFIED RESOURCES

By Thomas J. Peters *and* Spencee L. Willett
U.S. Bureau of Mines

Mining and Mineral Exploration History

Lake County mining records indicate that the Oregon claims group (fig. 3), a large block of 326 placer claims, was located in 1901 by an eight-person association and was relocated by the same claimants in 1906. The claims group extended from 2 mi north to 1 mi south of Summer Lake and as much as 2 mi east and 1 mi west; it included the entire lake and surrounding playa. The discovery, according to Lake County mining records, was for "... the valuable metals, sodium and potassium and their compounds of bicarbonate of soda, carbonate of soda and potassium sulfate, in paying quantities held in solution and in deposit, ..." The claimants were Charles M. Sain, John T. Reid, Schuyler Duryee, W.F. Brock, and William, Charles, Canby, and Elwood Balderston. The eastern part of the Oregon Claims group extended into the western part of the study area.

With the outbreak of World War I, foreign potash supplies were cut off, and the price for them increased from $0.80 to $8.00 per unit (20 lb). In 1916, the first successful plants to produce potash and other evaporite minerals from brine came on line at Searles Lake, Calif. (Teeple, 1929). On December 16, 1914, the State of Oregon leased the mineral rights to soda salts in Abert and Summer Lake on a royalty basis (Hartley, 1915). Ambitious development plans included a 270-mi pipeline north to the Columbia River and a large hydroelectric plant, an investment of about $7,000,000 (Phalen, 1916, p. 107-108). Outside but adjacent to the south boundary of the study area (fig. 3) are remnants of a water retention levee and an evaporation pond. These were apparently developed in 1918; John Withers, a local rancher, recalls that much money and effort was spent that year by a crew of men led by one Jason Moore. After the armistice, the potash price dropped and by mid-1919 was at $1.75 to $2.00 per 20-lb unit. Perhaps this was the main reason for not continuing the work at Summer Lake.

In March 1974, a group of claims including the Tenmile prospect and six others was located for limestone on the northeast side of Tenmile Ridge. Claimants included Harold J. and Marie Dyke of Adel, Oreg., Frances M. Foster, Con O'Keefe, Laura Shine, Jerry and Julia Singleton, and Morgan Verling. John Cremin (Lakeview, Oreg.) examined the prospect in 1980, brought it to the attention of the authors, and reported that exposures of the limestone extend into the study area.

The Oregon Claims Group

The Oregon claims group, inactive since 1918, covered all of Summer Lake, including the west margin of the Diablo Mountain Wilderness Study Area (fig. 3). The prospect was primarily for brines; no conventionally mineable beds of evaporite minerals are known. Summer Lake waters are not sufficiently concentrated to be a source of resource-bearing brine. In 1969, the lake, with a maximum water depth of about 3 ft, contained a calculated total of only 1 million short tons of mineral salts; however, the top 5 ft of lake-bottom and marginal sediments contained 15 to 20 million short tons of evaporite minerals. The greatest quantities of evaporite minerals are under the eastern playa rather than under the lake (Van Denburgh, 1975). Seasonal variation of fresh water and evaporation renders the solute concentration too inconsistent for the lake waters to constitute a brine source for year-round processing. Interstitial brines sampled from auger holes (Peters and Willett, 1989, tables A-1 and A-2) are much higher in solutes than the lake-water samples reported by Van Denburgh (1975, table 4).

Within the study area, brine-hosting lake and playa sediments define a mineral area extending more than 2 mi east of the claims group. Much of this area has a veneer of windblown sand as much as several tens of feet thick. Several flat-floored topographic depressions, displaying white surface efflorescence characteristic of areas underlain by evaporative brine, have formed windows through the sand.

Field Methods

Samples from 21 hand-auger holes from within the study area east of Summer Lake are described by Peters and Willett (1989, plate 1, tables A-1 and A-2). Samples consist of alkali crust (efflorescence), augered sediment, and, where available, auger-hole brine; several springs and seeps were also sampled.

Lake and playa sediments are interbedded. Deeper holes typically were collared in brown silt-, clay-, and fine-sand-sized playa sediments and extended into black silt- and clay-sized lake sediments. Only one evaporite bed, 0.4 ft of halite, was encountered during augering. Several holes ended in coarse, clean, black basaltic beach or stream sand. Permeable beds, along with soluble evaporite beds at depth, are essential for pumping brine from the sediments and recharging them with ground water. Such beds also are needed for recharging the ground water with new mineral salts. Clay-dominant facies that have high brine content may not yield enough brine and contained-evaporite mineral components for commercial exploitation.

Sampling of the mineral area by hand auger yields data on the mineral and brine composition of the top few feet and allows comparison with chemical data from analogous mineral systems that are better understood. An appropriate place for comparison is Searles Lake, Calif., about 500 mi to the southeast, where evaporite commodities have been extracted from brines and evaporite deposits for more than 50 years (Smith, 1979). Meaningful quantitative resource estimation, however, requires drilling and subsurface sampling.

Brine Commodity Evaluation

Brine samples were analyzed for cation (+) and anion (−) components of evaporite commodities that include soda ash, boron compounds, sodium sulfate, salts, potash, and lithium. Samples were also analyzed for arsenic and antimony, which are not only possible toxic contaminants but are also indicators of nearby epithermal mineralization or mineralizing processes. The auger-hole sediments and alkali crusts were analyzed for major-element oxides and 36 trace elements. Possible products, based on component concentrations and commodity economics, include soda ash (sodium carbonates), boron compounds, and sodium sulfate (fig. 3). Possible byproducts include potash, salts, bromine, lithium, magnesium compounds, and tungsten; their production may be feasible in conjunction with other commodities. Processing of many of the products could be facilitated by treating them with dolomitic limestone, which is also present in the study area.

Our brine analyses were compared to published analyses of brines from Searles Lake, Calif. (Smith, 1979, tables 5, 16, and 22). Ranges of concentration of possible significance now or in the foreseeable future were chosen by using the Searles Lake operation as a guide. Our cutoffs are lower than those for the Searles Lake brine concentrations because (1) low concentrations in surface samples do not preclude higher concentrations at depth, (2) advances in extractive technology allow utilization of lower grade brines

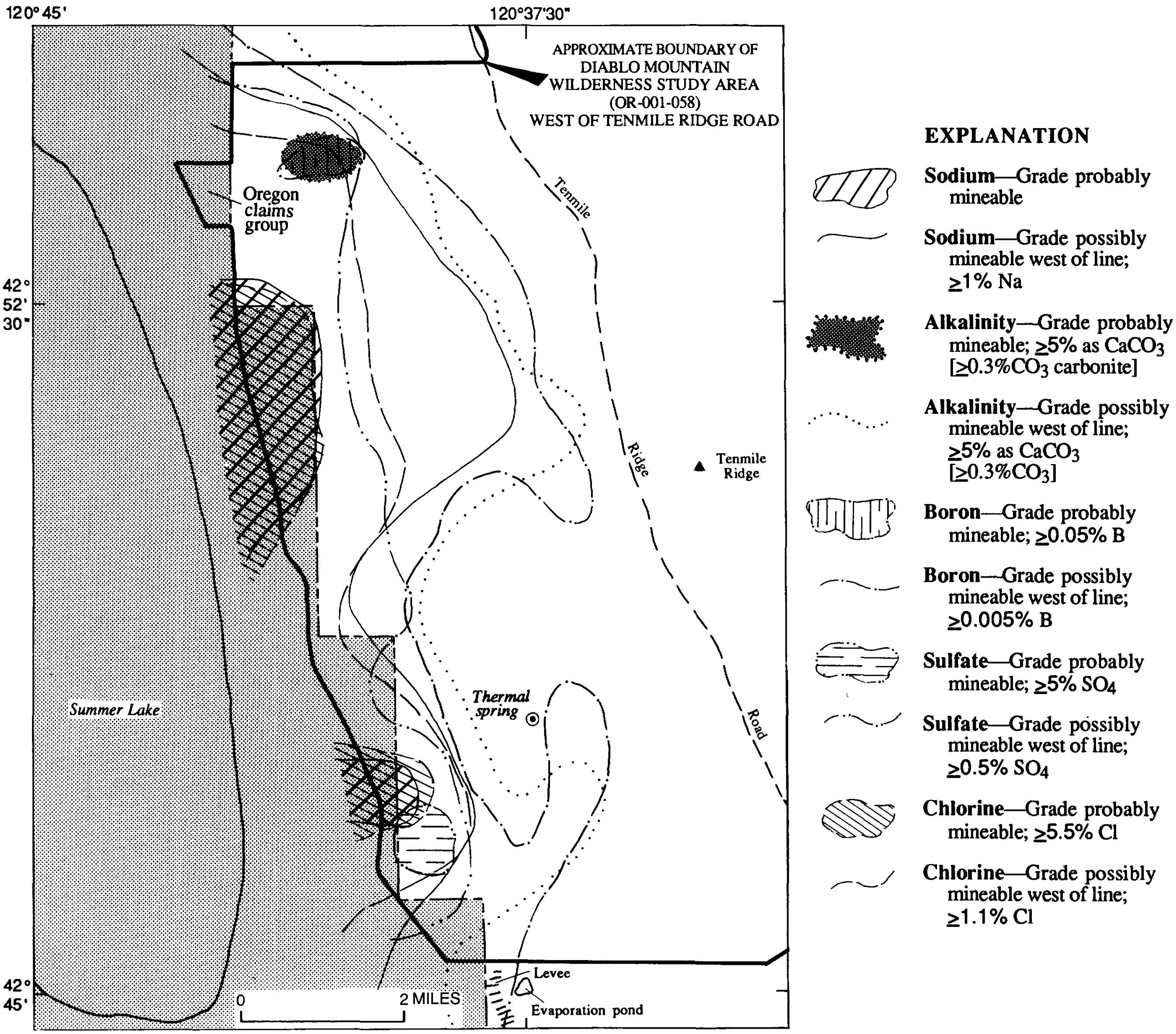

Figure 3. Concentrations of chemical components of brine commodities in ground water in western part of Diablo Mountain Wilderness Study Area, Oregon. Brine concentrations not mapped across all of Oregon claims group.

(Smith, 1979), (3) the advantage of large-scale application of such technology is inherent in designing new facilities, and (4) possible markets may be closer. Two categories of brine commodity occurrence, based on chemical component concentrations, were chosen: a grade probably mineable, and a grade possibly mineable (fig. 3). Occurrences of probable economic concentrations are defined as approximately equal to or greater than 50 percent of the grade of Searles Lake brines for all products except boron, which is of higher unit value. The grades of possibly mineable brines in the study area are equal to or greater than 10 percent of the grade of Searles Lake brines. Boron could possibly be mined economically from lower grade brines than those at Searles Lake by using advanced technology in new plant design (Gail Moulton, oral commun., 1989). Grades of brine components at least as good as the possibly mineable grade were observed at 12 auger sites and at 4 seeps.

The areal distributions of brine components in the study area were analyzed for possible mining products by plotting isocon maps (contour maps of chemical concentrations) of the sodium, alkalinity (as $CaCO_3$), boron, sulfate, and chlorine concentrations (Peters and Willett, 1989, figs. 3–6). Those maps were generalized and combined for this report, and areas interpreted to have probably mineable grades are denoted by patterns (fig. 3). Isocons were defined by the kriging method (Bridges, 1985), and all isocons were smoothed using Golden Software's SURFER software on a Microsoft-DOS-based desktop computer. Isocons of concentrations within brine or in sediment samples were similarly plotted for all byproduct components, except tungsten (Peters and Willett, 1989, figs. 7–11). Fourteen additional isocon, specific conductance, and isocon/specific conductance ratio maps were also prepared (Peters and Willett, 1989, plate 2). Grades of brine components having possible economic significance extend east of the Oregon claims group, but the highest grades are in the claim-block vicinity.

The Tenmile and Other Dolomitic Limestone Prospects

A dolomitic limestone of Pliocene(?) age is locally interbedded with basalt flows at the Tenmile and other dolomitic limestone prospects. It appears to have formed as an apron along the east, northeast, and north flanks of Tenmile Ridge and may extend for 2 mi to the northwest. It crops out discontinuously through a veneer of sand dunes and desert pavement. Four samples of the dolomitic limestone were collected (Peters and Willett, 1989). The rock is suitable for brine mineral processing and agricultural applications. Usually the thickness could not be determined, but Harold Dyke (oral commun., 1988) reports the rock is as thick as 30 ft northeast of Tenmile Ridge. No resources were estimated because of limited exposure.

Geothermal Energy

One thermal spring was observed in the study area, and thermal water was present in one auger hole (Peters and Willett, 1989). There are no known geothermal resources in the study area; however, the Summer Lake KGRA is 2 mi south of the south boundary.

Mineral Economics

Soda Ash

Soda ash (sodium carbonate, Na_2CO_3) has been recovered by Kerr-McGee Chemical Corporation from brines at Searles Lake by two methods: an older evaporation process, and a direct carbonation process. The evaporation process involves heating the brines, which causes the double salt burkeite ($Na_2CO_3{\cdot}2Na_2SO_4$) and table salt (NaCl) to precipitate. The remaining liquor is rapidly cooled, and potassium chloride is precipitated and filtered out. The remaining brine is supersaturated with sodium borate, which is precipitated after the addition of "seed" crystals (Gail Moulton, oral commun., 1989).

In the direct carbonation process, brine is mixed with carbon dioxide (CO_2) gas. At Searles Lake (Parkinson, 1977), carbon dioxide is produced from powerplant flue gases; but traditionally, carbon dioxide has been produced from lime kilns.

Uses of soda ash and of a daughter product, caustic soda, are undergoing steady growth, especially in the Pacific Northwest and in Pacific Rim countries, because of increased application in the bleaching of paper pulp. Alkali bleaching is ecologically preferable to the current acid process that uses chlorine compounds, which produce highly carcinogenic dioxine waste products. Soda ash and derivative products are widely used in the fluxing of metals and have important applications and markets in the aluminum industry in the northwest and in the developing Pacific Rim countries, particularly China.

Soda ash was produced by five companies operating five plants in Wyoming and by one company operating two plants in California during 1987; total estimated value was $600 million. Industrial use of soda ash was in the following proportions: glass, 53 percent; chemicals, 20 percent; soap and detergents, 10 percent; flue-gas desulfurization, 4 percent; pulp, 3 percent; paper, 3 percent; and other uses, 7 percent (D.S. Kostick, in U.S. Bureau of Mines, 1988, p. 147). In 1987, the United States exported 2.2 million short tons of soda ash; 23 percent went to the largest importer, China, and a total of 47 percent went to all Asian countries, the largest export market (D.S. Kostick, in Mining Engineering, 1988, p. 416).

Boron Compounds

Generalized boron concentrations of the brines in the study area are shown on figure 3. Processing of these brines probably would be similar to extraction methods at Searles Lake, Calif., where brines containing boron are mixed with a liquid extractant that removes boron from the brine. Boron is then purged from the extractant with sulfuric acid that produces boric acid [$B(OH)_3$]. Sodium and potassium sulfate remain in the liquor and can be recovered.

Boron, though unfamiliar to most people, has many uses. Borates have been used as a flux in metal smithing since their introduction into Italy from Mongolia in the 13th Century, and they were used to add strength to glass by medieval European artisans. Elemental boron was isolated in 1808. The boron mineral tincal ($Na_2B_4O_5(OH)_4 \cdot 8\ H_2O$) was discovered at Teels Marsh, Nev., in 1872, and ulexite ($NaCaB_5O_6(OH)_6 \cdot 5\ H_2O$) was discovered in Death Valley, Calif., in 1881. By 1927, underground mining of a massive tincal and kernite ($Na_2B_4O_6(OH)_2 \cdot 3\ H_2O$) deposit had begun at Boron, Calif. Mining was converted to open-pit methods in 1957. U.S. Borax annually produces about one-half of the world's boron from these deposits. Kerr-McGee produces boron compounds as a coproduct of solution mining of soda ash at Searles Lake (Trona, Calif.). For further detail about the boron industry, see P.A. Lyday, in U.S. Bureau of Mines (1985, p. 91–102). The United States is currently the largest producer of boron compounds at 52 percent, and Turkey produces 39 percent (P.A. Lyday, in U.S. Bureau of Mines, 1988, p. 26–27).

Of the boron compounds produced, 59 percent are used in glass making, 7 percent in soaps and detergents, 7 percent in agriculture, and 27 percent in other uses (Lyday, in U.S. Bureau of Mines, 1988, p. 26). Borosilicate glass withstands severe temperature changes without cracking. Borate compounds are used as metal solvents and fluxes in the metals industry, as both herbicides and plant nutrients in agriculture, in fire retardants, and in heat-resistant ceramic products such as tiles that protect the Space Shuttle from the heat of reentry. Elemental boron fibers are used with tungsten-steel alloys for high strength in helicopter rotors; boron nitrite approaches the hardness of diamond and is more heat resistant. Sodium borohydride is used in the bleaching of ground wood (Rex McKee, oral commun., 1989), and there are many additional applications for boron compounds.

Sodium Sulfate

Sodium sulfate occurs as two economically important minerals: mirabilite or Glauber's salt ($Na_2SO_4 \cdot 10\ H_2O$), and thenardite (anhydrous Na_2SO_4). Almost all commercial deposits are lacustrine evaporites (W.I. Weisman and C.W. Tandy, in Lefond, 1975, p. 1081–1082). Sodium sulfate can be extracted from brine as a coproduct of soda ash and boron compounds. Only about 48 percent of sodium sulfate comes from natural sources; most is manufactured as a byproduct of chemical and rayon factories. End uses are in soap and detergents, 46 percent; pulp and paper, 36 percent; and glass and miscellaneous uses, 18 percent (D.S. Kostic, in U.S. Bureau of Mines, 1988, p. 148). The study area is closer to pulp and paper markets in the northwestern states than are current sources of sodium sulfate.

Byproduct Brine Commodities

Production of six byproduct commodities from the study area may be feasible: table salt (NaCl), potash (K_2O; or muriate of potash, KCl), bromine, lithium, magnesium compounds, and tungsten. Byproduct salts are produced at Searles Lake, Calif., and two companies in Portland, Oreg., currently buy imported Mexican salts for the manufacture of caustic soda and chlorine compounds. It may be economical to recover magnesium compounds from the site of the Oregon claims group. A local source of dolomitic limestone to be used in processing the brines would make additional magnesium available for byproduct compounds. The additional investment needed to extract byproducts from a resource-producing brine, even at low concentration, may be somewhat small. Distribution of byproduct concentrations and uses are discussed in more detail by Peters and Willett (1989).

Dolomitic Limestone

The dolomitic limestone occurrence along Tenmile Ridge may be useful for its possible application in brine commodity processing. Carbon dioxide produced from the calcination of limestone or dolomite is used to remove calcium from brines, thus allowing further separation of soda ash, boron compounds, and sodium sulfate. A calcination byproduct, calcium hydroxide can then be used to convert soluble magnesium salts into insoluble magnesium hydroxide, which in turn can be calcined to produce magnesia. Another proposed use of the limestone is as a soil conditioner; this may be feasible if there is enough limestone and if low-cost rail transportation is available in conjunction with development of other mineral commodities.

Geothermal Energy

Summer Lake Hot Spring (fig. 2) produces 116 °F water at a rate of 21 gallons per minute (Peterson and McIntyre, 1970) and is developed as a resort. That thermal spring and three other geothermally significant wells are included in the Summer Lake KGRA (Oregon Department of Geology and Mineral Industries, 1982, wells Lk–7, 8, 9, and 10). Of special interest are the Collahan wells Lk–9 and Lk–10, which have water temperatures of 212 °F and 231 °F, respectively, but do not produce dry steam, the most efficient medium for electric power generation. However, water temperature at Summer

Lake KGRA is much higher than the 100 °F minimum needed for power production by the binary systems process (Rinehart, 1980). The brines at these geothermal springs are also possible metal sources (Schultze and Bauer, 1975; Blake, 1974).

Miscellaneous Mineral Commodities

Windblown sand covers most of the surface, perhaps 20,000 acres, of the western part of the study area but does not appear to be a marketable resource because it does not contain valuable minerals and is too remote for construction purposes. Outcrop areas of basalt (Travis, 1977, plate 1; Diggles and others, 1990) total about 1.5 to 2 mi^2 near Tenmile Ridge. The basalt lacks special chemical characteristics and has no special physical characteristics, such as splitting into flat plates suitable for facing stone. Basalt is a high-bulk low-value material which, in the study area, would only be useful as crushed road metal. Ample sources of road metal are present outside the study area.

Conclusions

Study-area brines, sampled from shallow auger holes, host occurrences of the chemical components of soda ash, boron compounds, and sodium sulfate, which may be extracted by solution mining. Byproduct candidates include potash, salts, bromine, lithium, magnesium compounds, and tungsten. The sample data suggest solution-mineable resources, but drilling will be required for estimates. Limestone from the study area could be used in agricultural applications or in recovering soda ash, boron, and magnesium compounds from brine. Geothermal energy near the study area could be used to generate electric power.

Bulk commodity transport by railroad is available from Lakeview, Oreg., 45 highway mi to the southeast. There are no weight restrictions on the 55-mi-long Great Western Railroad shortline from Lakeview to Alturas, Calif.; rail distance from Alturas to Portland, Oreg., is 415 mi. Railroad infrastructure could be extended from Lakeview to a new mine site for about $200,000 per mi (land not included) (Edward Emmel, Oregon Department of Transportation, Salem, oral commun., 1989), possibly in conjunction with other bulk product development such as perlite from the Tucker Hill deposit, 14 mi southeast of the study area (Wilson and Emmons, 1985). In this scenario, brine minerals could be shipped by rail directly to Portland, a total distance of about 520 mi; this is a substantially shorter distance than shipment from a present producing area, the Green River trona district in southwest Wyoming.

Markets for brine-mineral products appear to be undergoing steady growth, especially in the Pacific Northwest and in Pacific Rim countries. Soda ash and a daughter product, caustic soda, and sodium borohydride have received increased use in the bleaching of paper pulp. Alkali bleaching is ecologically preferable to the current acid process that use chlorine compounds and produce a carcinogenic dioxin waste product. Soda ash, soda-ash products, and boric acid are widely used in the fluxing of metals and are used in the aluminum industry in the Pacific Northwest and in China. Evaporite commodities are essential to the backbone industries of many civilizations and to many new applications and advanced materials.

Recommendations for Further Work

Due to the possible economic importance of various mineral commodity occurrences in the Diablo Mountain Wilderness Study Area, further studies are recommended. More detailed mapping and site-specific studies, including drilling, should probably be carried out to determine depths and thicknesses of these occurrences. Work should be conducted jointly by the U.S. Bureau of Mines and the U.S. Geological Survey.

ASSESSMENT OF MINERAL RESOURCE POTENTIAL

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Geology

Stratigraphy

The Diablo Mountain Wilderness Study Area is underlain by sedimentary and volcanic rocks of Tertiary and Quaternary age. They are generally flatlying but are broken by normal faults. Tertiary rocks in the study area consist of tuffaceous sedimentary rocks, basalt flows, basaltic pyroclastic rocks, tuffaceous sedimentary rocks, rhyolitic tuff, and dolomitic limestone.

Tuffaceous sedimentary rocks underlie much of the study area. They are semiconsolidated, interbedded white, light-yellow, and cream-colored lacustrine and fluvial sedimentary rocks that consist mostly of tuffaceous sandstone and siltstone and locally contain arkosic sandstone and pebble conglomerate. They contain alkali feldspar, minor amounts of clay minerals, zeolites in amygdules, and secondary silica minerals. Their age and correlation are uncertain, but they are presumably mostly of middle and late Miocene age (Walker, 1977).

Basalt flows underlie most of the high country in the study area. The basalt is medium-gray to dark-gray, is plagioclase phyric, contains olivine, and has subophitic to diktytaxitic texture. Crystals of labradorite are partly to completely enveloped in clinopyroxene. Pyroxene also forms interstitial grains. The basalt is olivine-normative tholeiite (Irvine and Barager, 1971), rich in aluminum, magnesium, and calcium oxides (Al_2O_3, MgO, CaO) and depleted in titanium, sodium, and potassium oxides (TiO_2, Na_2O, and K_2O). A potassium-argon age determination on a basalt sample from the Diablo Rim shows an age of 6.3±0.4 million years (Ma), or latest Miocene (Diggles and others, 1990). The underlying tuffaceous sedimentary rocks erode readily and cause landslides of the basalt.

A dolomitic limestone of Pliocene(?) age north and east of Tenmile Ridge is locally interbedded with the basalt flows. It is present on the flanks of the ridge and crops out discontinuously among the dunes to the northwest.

Red and reddish-black basaltic cinders and near-vent flows crop out in one area on Tenmile Ridge. These are unconsolidated, fine to coarse, scoriaceous oxidized rocks. Luedke and Smith (1982) report this volcanic center as a basaltic (46–54 percent silica) cinder cone with an age of less than 5 Ma. A recently determined potassium-argon age of the cinders, however, is 6.6±0.3 Ma (Diggles and others, 1990). The cinders are quartz-normative alkali-olivine basalt (Irvine and Barager, 1971) rich in TiO_2, Na_2O, and K_2O and depleted in MgO and CaO. Zones of altered basalt flows are cut locally by veinlets and dikelets of opal-bearing travertine. Vesicular basalt flows are locally altered and amygdaloidal; minor amounts of zeolite fill some amygdules. There is also minor basalt-flow breccia in the study area.

Quaternary sediments consist of alluvium, dune, playa, lacustrine, fluvial, landslide, and claystone deposits. The alluvium consists of unconsolidated deposits of sand, gravel, ash, and pumice that formed in flood plains and fill the stream channels. The dune sand is composed of ash, pumice, and mineral grains, mostly alkali feldspar and quartz. Playa deposits are made up of clay, silt, sand, and some evaporites and contain tephra at depth (Simpson, 1989). Lacustrine and fluvial deposits consist of unconsolidated clay, silt, and gravel. They are commonly covered by meadow or marsh vegetation. Landslide deposits, present mostly on the east flank of Diablo Rim, are unstratified mixtures of basalt and tuffaceous sedimentary rock. Here, as elsewhere, they commonly develop where a basalt rim overlies tuffaceous sedimentary rocks. The claystone consists mostly of montmorillonite produced by decomposition of volcanic ash. Locally it includes deposits of marl, micrite, caliche, and opal-bearing travertine.

The Summer Lake basin was occupied by pluvial Lake Chewaucan. Sediments in the basin include tephra from several large volcanic eruptions. Between 19 and 12 thousand years ago, landslides from Winter Rim, west of Summer Lake, locally compressed and deformed the sediments (Simpson, 1989).

Structure

The study area lies on the northwest edge of the Basin and Range physiographic province. Summer Lake occupies a closed basin bounded by ridges that have fault-scarp fronts (Phillips and Van Denburgh, 1971). The structural geology of the study area is dominated by high-angle north-northwest-trending normal faults that have cut the range into blocks. J.J. Rytuba (oral commun., 1987) suggested that the Summer Lake area, including the area to the east, now covered with dunes, may be a large caldera and may have associated gold resource potential. G.W. Walker (oral commun., 1987), however, noted that no known ash-flow tuff sheet is correlated with the basin. The concurrence of regional north-northwest-trending fault zones with older caldera structures and silicic intrusions is emerging as one of the most viable means of locating gold deposits in this part of the Basin and Range (Rytuba, 1989). The Diablo Rim is the most extensive scarp resulting from this faulting. A discussion of an inferred intrusion is included in the "Geophysics" section. The study area is bounded on the northeast by the north-northwest-trending Brothers fault zone that has been interpreted as a transcurrent structure that bounds the northwest edge of the Basin and Range physiographic province (Lawrence, 1976). The area on the west side of Summer Lake and south of the study area is part of the poorly defined Modoc Plateau physiographic province that separates the Basin and Range and the Cascade Range physiographic provinces (Macdonald, 1966). Vertical offset in the study area is apparent at the margins of large fault-bounded horst and graben typical of the Basin and Range.

Geochemistry

Methods and Background

A reconnaissance geochemical survey was conducted in the Diablo Mountain Wilderness Study Area in the summers of 1986, 1988, and 1989 (Adrian and others, 1990). Stream sediments, nonmagnetic heavy-mineral concentrates of stream sediments, rocks, and vegetation were used as the sample media in this survey. The vegetation samples, along with rock samples, were used as sample media in the valley area of the western part of the study area where appropriate sediment for stream-sediment or heavy-mineral-concentrate sampling was not available. Samples were collected from a total of 158 sites and included 71 minus-80-mesh stream sediments, 17 plus-80-mesh stream sediments, 70 nonmagnetic heavy-mineral concentrates from stream sediments, 61 rocks, 29 Big Sagebrush (*Artemisia tridentata* Nuttal), 38 Black Greasewood (*Sarcobatus vermiculatus* [Hooker] Torrey), and 9 playa deposits.

Stream sediments were selected as a sample medium because they represent a composite of the rock and soil exposed upstream from the sample site. Nonmagnetic heavy-mineral-concentrate samples provide information about the chemistry of a limited number of minerals in rock material eroded from the drainage basin upstream from each sample site. Many minerals present in the nonmagnetic fraction of heavy-mineral concentrates may be ore forming or ore related if mineralization processes have been active in the area. The selective concentration of minerals permits determination of some elements that are not easily detected in bulk stream-sediment samples.

The purpose of the vegetation sampling was to look for any evidence of mineralized rock in bedrock underlying the clastic surficial deposits in the valley area of the western part of the study area. The predominant large plant in that area is greasewood, a halophyte or salt-tolerant plant. The literature of biogeochemical exploration for mineral deposits contains little information on the use of greasewood as a sample medium. Therefore, a traverse was taken along and outside the south boundary of the study area where both greasewood and sagebrush grow, and a sample of each was collected at each site for comparison of analytical values. The use of the sagebrush in biogeochemical exploration for mineral deposits is well established, particularly for gold exploration (Erdman and Olson, 1985; Erdman and others, 1988) and also may be useful for base-metal exploration (Lovering and Hedal, 1983). Another reason for the plant-sampling traverse along and outside the south boundary is the presence there of several northwest-trending concealed faults that might be conduits for mineralizing fluids. Mineralized rock, if it formed, also might be present along the same faults to the north within the study area. Root depths for these plants have been reported as 59 ft for the greasewood and 33 ft for the sagebrush (Brooks, 1983). Such depths, if attained by plant specimens used in this study, might be sufficient for uptake of elements emanating from the substrate and might provide useful information.

Mineralized rocks were sought but not observed; most rock samples appear fresh and unaltered. Some moderately altered rocks were collected near Tenmile Ridge. Some rock samples were collected to provide information on geochemical background values; however, most of the rock samples were collected to see if analyses might reveal any indications of mineralization that were not visually recognizable.

Rock samples were crushed and pulverized to less than 80-mesh prior to analysis. Stream-sediment samples were seived using 80-mesh stainless-steel sieves, and the minus-80-mesh fraction was used for analysis. For some stream-sediment samples, the fraction greater than 80 mesh and less than 18 mesh was obtained by sieving and then used for analysis. The heavy-mineral concentrate was produced by panning minus-10-mesh stream sediment to remove most of the quartz, feldspar, organic materials, and clay-sized material. Bromoform (specific gravity 2.86) was then used to remove any remaining light mineral grains not removed during panning. The resultant heavy-mineral concentrate was separated by use of an electromagnet into three fractions: a magnetic fraction chiefly of magnetite, an intermediately magnetic fraction consisting largely of mafic rock-forming minerals, and a nonmagnetic fraction composed dominantly of light-colored rock-forming accessory minerals and primary and secondary ore-forming and ore-related minerals. The nonmagnetic fraction was split into two fractions; one split was used for analysis and the other for visual examination with a binocular microscope.

The sagebrush and greasewood samples were collected by clipping, with pruning shears, new growth, including stems with attached leaves, from three to six of the healthiest and most robust plants within an area as large as about 50 ft in diameter. Samples were collected in 11-in. by 17-in. cloth sample bags that were more than half filled for each sample. The plants sampled were generally about 3 ft tall but ranged from about 2 ft to 6 ft tall. Plant samples were washed in tap water, dried in an oven at 40 °C, and then pulverized in a Willey mill. Splits of the dry, pulverized plant material were ashed in a muffle furnace during a 24-hour period with a maximum temperature of 450 °C.

Sample Analysis

Nonmagnetic heavy-mineral-concentrate, stream-sediment (both size fractions), rock, and playa samples were analyzed for 31 or 35 elements using a direct-current arc emission spectrographic method (Grimes and Marranzino, 1968). Except for the concentrates, these samples were also analyzed for antimony, arsenic, bismuth, cadmium, and zinc by inductively coupled plasma–atomic emission spectroscopy (ICP–AES) and for gold and mercury by atomic absorption (methods described in Crock and others, 1987). The playa-silt and evaporite samples were also analyzed for lithium by ICP–AES (Lichte and others, 1987) and for thorium and uranium by delayed neutron counting (McKown and Millard, 1987).

All plant-ash samples were analyzed for 40 elements by ICP–AES (Lichte and others, 1987). The plant-ash samples were also analyzed by another ICP–AES method (Motooka, 1988) for nine of the same elements (arsenic, gold, silver, bismuth, cadmium, copper, molybdenum, lead, and zinc) and for antimony. This method was used to obtain lower limits of determination for most of the elements analyzed. Gold was also analyzed in the plant-ash samples by flameless atomic absorption spectrophotometry with a graphite furnace atomizer, using a slightly modified version of the method described in O'Leary and Meier (1986). This method provides an exceptionally low limit of determination, 1 part per billion (ppb). Unashed material from 24 of the sagebrush samples and 16 of the greasewood samples was also analyzed by hydride generation–atomic absorption spectroscopy for arsenic and selenium by modified versions of methods described by Crock and Lichte (1982) and Sanzolone and Chao (1987), respectively.

Results and Interpretation

An anomalous silver value of 50 parts per million (ppm) was detected in a nonmagnetic heavy-mineral-concentrate sample collected in the southern part of the study area, about

2 mi northeast of Tenmile Ridge. Iron oxide, which can become enriched in silver by adsorption (Chao and Theobald, 1976), was noted in the sample during examination with binocular microscope and may be the source of the silver concentration. Otherwise, a mineral to explain the silver concentration was not identified. A slightly anomalous value of tin (500 ppm) was detected in the same concentrate sample and in a concentrate from an adjacent stream. A mineral to explain the tin concentrations was not identified in the concentrates. The tin concentrations may be due to the presence of cassiterite, variety wood tin, as was found to be the case in the Orejana Canyon Wilderness Study Area (Conrad and others, 1988) about 50 mi to the east. The tin concentration is questionably anomalous; it is the highest tin concentration observed in any concentrate from the Diablo Mountain Wilderness Study Area and may be of interest because of its occurrence with the silver, although the mutual occurrence may be only coincidental and not indicative of any elemental association. We conclude that the tin concentrations do not suggest the presence of a tin deposit. During a follow-up study in the drainage areas upstream from these sample-collection sites, rocks that include welded tuff, tuffaceous lacustrine deposits, and plateau-forming basalt flows were examined for evidence of alteration or mineralization, but none was noted. The anomalous concentrations may be derived from mineralization along a northwest-trending fault in the drainage areas.

No other notably anomalous concentrations of elements were detected in the concentrate sample discussed above or in any other nonmagnetic heavy-mineral-concentrate samples from the Diablo Mountain Wilderness Study Area. No anomalous concentrations were determined in any of the stream-sediment samples from the study area.

Anomalous gold values were measured in two sagebrush ash samples; one collected at the north boundary of the study area (site DM109 in Adrian and others, 1990) has 32 ppb gold, and one collected about a mile south of the study area boundary (site DM105) has 36 ppb gold. An anomalous antimony value (16 ppm) was determined in a sample of flow basalt (site DM117) collected from an outcrop 1.6 mi northeast of the site that has the 32 ppb gold. Anomalous values of arsenic (13–77 ppm) were measured in six rock samples from five sites (DM082, DM083, DM084, DM093, DM098) just west and southwest of Tenmile Ridge. An anomalous arsenic value (18 ppm) was also measured in a rock sample from about 3 mi southeast of Tenmile Ridge (site DM148). The samples containing the anomalous concentrations of arsenic consist of sand- and gravel-size grains of reddish scoriaceous pyroclastic basalt cemented and (or) permeated with calcium carbonate and having disseminated limonite. The arsenic may have become enriched in these samples by coprecipitation or absorption with the iron oxide. In this case, the arsenic anomaly would be nonsignificant, or not related to mineralized rock. Similar arsenic values (24–83 ppm) were measured in the salty evaporite samples; the highest one is for a sample from about a mile north of the study area.

Arsenic and antimony are commonly associated with epithermal gold deposits and are used as pathfinder elements for those deposits. The anomalous concentrations of these elements and of gold in the sagebrush ash samples are considered weak; the arsenic and antimony are not significant and are not related to mineralized rock at or near the surface. The anomalies may, however, be related to more mineralized rock at some unknown depth along one or more of the northwest-trending faults.

Geophysical Studies

Aeromagnetic Survey

An aeromagnetic survey including the Diablo Mountain Wilderness Study Area was flown and compiled under contract to the U.S. Geological Survey (U.S. Geological Survey, 1972). Total-field magnetic data in analog form were collected along flightlines in an east-west direction spaced at approximately 2-mi intervals at a constant barometric altitude of 9,000 ft. Corrections were applied to the data to compensate for diurnal variations of the Earth's magnetic field, and a regional field correction of 8 nanoteslas (nT) per mi in the direction N. 30° E. was subtracted to yield a residual magnetic anomaly dataset. An aeromagnetic map of the study area (fig. 4) was prepared from digitized analog data at a contour interval of 50 nT for comparison with geologic and topographic maps.

Because of the large terrain clearance (0.75–0.95 mi), short-wavelength features such as those due to small-displacement faults are not detected, and only larger features that have anomaly wavelengths of several miles or more are represented. The low aeromagnetic anomaly along the west and south edges of the study area has relatively little relief and reflects the thick, somewhat nonmagnetic sediments and playa deposits of Summer Lake. A low anomaly near the north tip of the area (F, fig. 4) also correlates with sedimentary rocks in that area (Walker and others, 1967). In the south-central part of the study area, an east-west-trending positive aeromagnetic anomaly of about 350-nT amplitude (A and D, fig. 4) is underlain by exposed volcanic rocks in its eastern half but extends well out into the sediments and playa deposits of Summer Lake to the west. The western part of this anomaly is very similar to a large anomaly southeast of the study area beneath sediments (B, fig. 4) and to a smaller but similar anomaly on the same trend just northwest of the study area (C, fig. 4). A smaller positive anomaly of about 200-nT amplitude lies in the northern part of the study area (E, fig. 4). The positive anomalies in the region correlate only in a general way with the mafic volcanic rocks mapped by Walker (1963), and the magnetic anomalies are largely inferred to reflect deeper structures. Within the study area, the dominant trends of the gradients defining the anomalies are east-west and northwest.

Gravity Survey

All available gravity data were obtained from computer files from the Defense Mapping Agency (1984). Data from a total of 412 stations within the area between lats 42°30′ and 43°15′ N. and longs 120°15′ and 121°00′ E. were compiled; 76 of those stations are within or near the borders of the study area. The average spacing between stations is approximately 8 mi. The observed gravity data are on the International Gravity Standardization Net datum (Morelli and others, 1974)

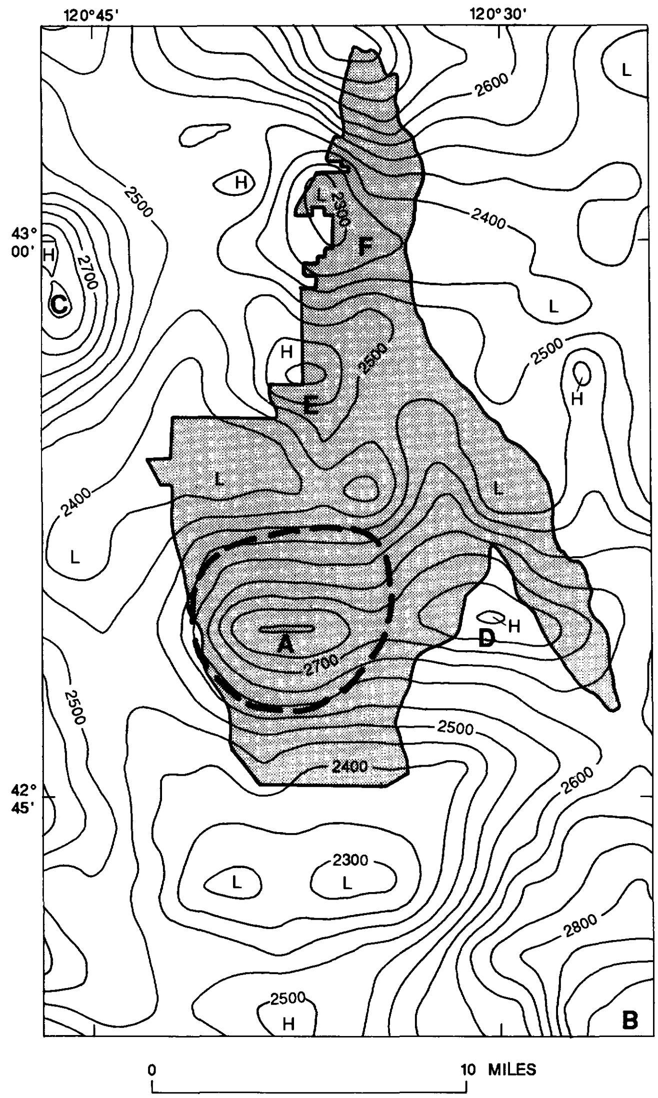

Figure 4. Aeromagnetic anomaly map of region including Diablo Mountain Wilderness Study Area, Oregon (shaded area). Contour interval 50 nanoteslas. H and L denote relative maxima and minima, respectively, of magnetic anomaly field. Dashed line is outline of inferred buried intrusion. A–F are features noted in text.

and were reduced to Bouguer gravity anomaly values using standard formulæ (Cordell and others, 1982). Terrain corrections were computed to a radius of 167 km around each station. A Bouguer-reduction density of 2,200 kilograms per cubic meter (kg m^{-3}) was used in anomaly computation because plots of station altitude versus Bouguer gravity anomaly showed the least correlation for this density and because the same value has been shown to be the most representative in similar volcanic sections (Williams and Finn, 1985). A gravity anomaly map of the study area and its surroundings was prepared (fig. 5).

Within and near the study area, the Bouguer gravity anomaly field is dominated by the large gravity low beneath the Summer Lake sedimentary rocks. Other significant anomalies within the study area are lacking, except for a single-station low near the east edge of the area (A, fig. 5) and a small high (B, fig. 5) near the center of the study area. The gravity anomaly gradients trend northwest and northeast and delineate inferred faults of the Summer Lake graben structure. Northeast-trending faults control the northern and southern termini of the area of deep sedimentary fill.

The gravity anomaly low over the sedimentary rocks is about 24 milligals (mGal) in amplitude, and simple model calculations imply a fill depth of about 2 km for density contrasts of approximately 300 kg m^{-3}. The locations of some boundary and cross faults inferred from the gravity anomaly field are shown on figure 5.

The prominent magnetic anomaly high in the south-central part of the study area (A, fig. 4) has a corresponding gravity anomaly high (B, fig. 5) that appears to be displaced to the east because of its superposition over the anomaly low due to the deep sedimentary fill. The source of both the magnetic and gravity anomalies in this area is inferred to be an intrusive mass (dashed outline, figs. 4 and 5), probably within the upper few kilometers of the crust. Outcrops of basalt beneath the anomaly extend westward well out into the sedimentary rocks (Walker, 1963) and may be evidence of uplift from the intrusive body; the young age of the flows and pyroclastic rocks suggests that they could be directly related to the intrusive mass. About 13 mi southeast of the study area, along the same sediment-filled graben structure (Walker, 1963), dacitic to rhyolitic domes are exposed in an area having a similar anomaly pair.

A magnetic anomaly high to the east (D, fig. 4) and a smaller one to the north (E, fig. 4) also may be due to intrusions or to extensions of the postulated intrusive mass into the sediments, but the gravity anomaly field is less clear. Northeast of the inferred intrusion (A, fig. 5), a gravity anomaly low is defined by only one station and therefore is not considered reliable; however, several nearby stations along the east boundary of the study area confirm that the gravity field is decreasing to some kinds of minima. If this part of the magnetic anomaly field is due to intrusive bodies, the gravity anomaly field suggests that the intrusions are less dense than the basaltic rocks cropping out in the eastern half of the study area and are more dense than the sedimentary rocks. Thus, a composition more felsic than basalt is suggested.

Finally, the gravity anomaly field indicates that the complex pattern of northwest- and northeast-trending faults mapped south of Summer Lake (Walker, 1963) continues beneath the sedimentary rocks near the south boundary of the study area (fig. 5). The steep gravity gradients in this area imply that steeply dipping normal faults bound the fault blocks. They also imply that the northeast-trending faults offset the axis of the gravity low and presumably the axis of thickest sedimentation in a left-lateral sense by about 6 mi.

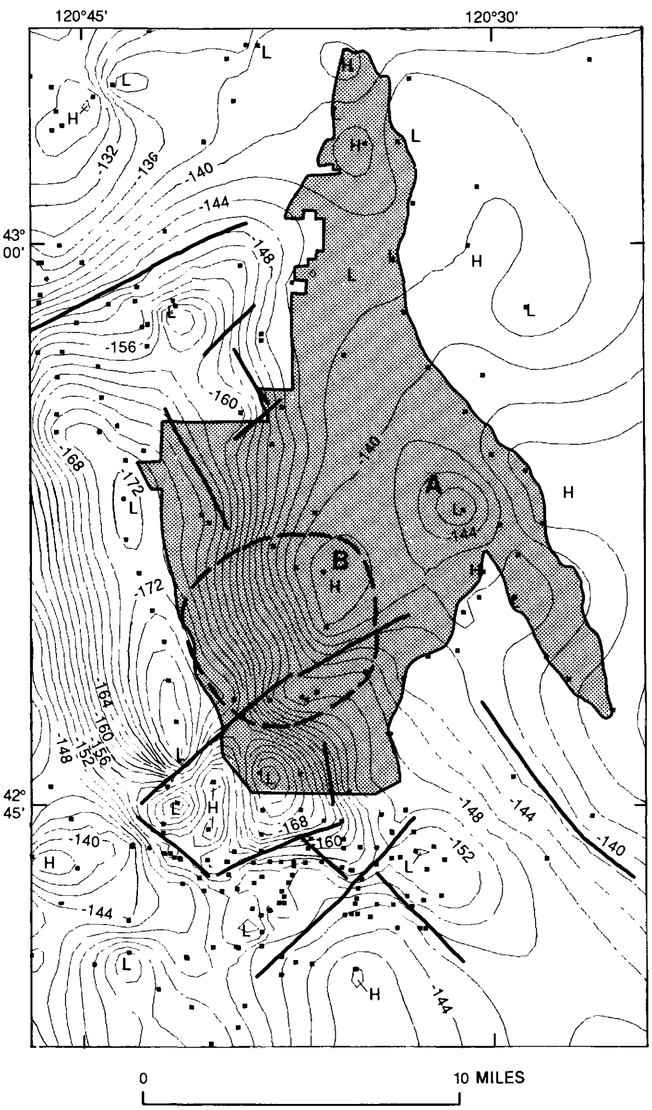

Figure 5. Bouguer gravity anomaly map of region including Diablo Mountain Wilderness Study Area, Oregon (shaded area). Contour interval 2 milligals; Bouguer reduction density used is 2,200 kilograms per cubic meter; H and L denote relative maxima and minima, respectively, in gravity anomaly field. Small squares represent gravity station locations. Dashed line shows outline of inferred buried intrusion. Heavy lines denote faults inferred from gravity anomaly field. A and B are features noted in text.

Remote Sensing

Linear features in LANDSAT multispectral scanner (MSS) images at a scale of 1:800,000 were mapped by photogeologic interpretation for the region of southeastern Oregon, and trend concentration maps were made. Linear features are the topographic and spectral expression of rock fracture patterns and other structural and lithologic lineaments. This expression can be enhanced or subdued by scanner resolution, sun orientation, atmospheric phenomena, and vegetation. Analysis of linear features in conjunction with geologic and geophysical maps may reveal new relations such as fracture control of mineralization.

Linear features of every orientation are well expressed on the surface in southeastern Oregon, except in terrains underlain by volcanic rocks. Locally, areas may show linear features related to faults or to rock joint systems. No linear features within the study area were discovered by remote sensing except along the faults already discussed. Linear features in the region surrounding the study area have two prominent trends. The dominant trend of N. 20° W. is concentrated northwest of the study area. The second trend, N. 20° E., consists of three aligned linear features as long as 6 mi that lie northeast of the study area.

Mineral Resource Assessment

The mineral resource potential of the Diablo Mountain Wilderness Study Area is moderate, certainty level C, for commodities associated with brines in the western part of the study area. Commodities that may be present beyond known occurrences are soda ash, boron compounds, and sodium sulfate; possible byproducts include magnesium compounds, salts, potash, bromine, lithium, and tungsten.

The Summer Lake Known Geothermal Resource Area (KGRA) is 2 mi south of the study area. There are thermal springs (66 °C) at Ana Springs north of the study area (Waring, 1908; Brown, 1957) and a thermal spring at Summer Lake Hot Spring west of the study area. A thermal spring and thermal water at a sample-collection site are present within the study area. The entire study area has moderate resource potential, certainty level C, for low-temperature geothermal energy useful for agricultural and building heating. Through the use of a low-boiling medium, perhaps electricity could be generated as well.

The mineral resource potential is low, certainty level B, in the area of Tenmile Ridge for low-grade high-tonnage epithermal hot-spring gold-silver deposits of the type defined by Berger (1985; 1986), Berger and Silberman (1985), and Berger and Singer (1987). These types of deposits have been recognized in the region south of the wilderness study area (Rytuba, 1989). The presence of opal among the altered-basalt outcrops in the Tenmile Ridge area and the presence of mercury in a prospect 4 mi southwest of the study area are additional favorable indicators of hot-spring-type gold-silver deposits. The presence of a felsic intrusive body in this area, inferred from the aeromagnetic and gravity anomaly data, further enhances the favorability of the Tenmile Ridge area for hot-spring precious-metal deposits. The Summer Lake basin may be a caldera-formed feature (J.J. Rytuba, oral commun., 1987). The regional north-northwest-trending fault zones cutting caldera structures and silicic volcanic centers are emerging as one of the most viable means of locating gold-silver mineral deposits in the northern Basin and Range (Rytuba, 1988; 1989).

The mineral resource potential is low, certainty level B, for magnesium from dolomitic limestone in the area of Tenmile Ridge.

The oil and gas resource potential is low, certainty level B, in the entire study area (Fouch, 1982; 1983). Because the sedimentary section for oil and gas sources and (or) reservoirs is thin and probably all of continental origin, this assessment could be too high.

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APPENDIXES

DEFINITION OF LEVELS OF MINERAL RESOURCE POTENTIAL AND CERTAINTY OF ASSESSMENT

LEVELS OF RESOURCE POTENTIAL

H **HIGH** mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a high degree of likelihood for resource accumulation, where data support mineral-deposit models indicating presence of resources, and where evidence indicates that mineral concentration has taken place. Assignment of high resource potential to an area requires some positive knowledge that mineral-forming processes have been active in at least part of the area.

M **MODERATE** mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate reasonable likelihood for resource accumulation, and (or) where an application of mineral-deposit models indicates favorable ground for the specified type(s) of deposits.

L **LOW** mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics define a geologic environment in which the existence of resources is permissive. This broad category embraces areas with dispersed but insignificantly mineralized rock, as well as areas with little or no indication of having been mineralized.

N **NO** mineral resource potential is a category reserved for a specific type of resource in a well-defined area.

U **UNKNOWN** mineral resource potential is assigned to areas where information is inadequate to assign a low, moderate, or high level of resource potential.

LEVELS OF CERTAINTY

A Available information is not adequate for determination of the level of mineral resource potential.
B Available information only suggests the level of mineral resource potential.
C Available information gives a good indication of the level of mineral resource potential.
D Available information clearly defines the level of mineral resource potential.

LEVEL OF RESOURCE POTENTIAL →

<table>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr><td rowspan="4">U/A
UNKNOWN POTENTIAL</td><td>H/B
HIGH POTENTIAL</td><td>H/C
HIGH POTENTIAL</td><td>H/D
HIGH POTENTIAL</td></tr>
<tr><td>M/B
MODERATE POTENTIAL</td><td>M/C
MODERATE POTENTIAL</td><td>M/D
MODERATE POTENTIAL</td></tr>
<tr><td rowspan="2">L/B
LOW POTENTIAL</td><td rowspan="2">L/C
LOW POTENTIAL</td><td>L/D
LOW POTENTIAL</td></tr>
<tr><td>N/D
NO POTENTIAL</td></tr>
</table>

LEVEL OF CERTAINTY →

Abstracted with minor modifications from:

Taylor, R.B., and Steven, T.A., 1983, Definition of mineral resource potential: Economic Geology, v. 78, no. 6, p. 1268-1270.

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RESOURCE/RESERVE CLASSIFICATION

	IDENTIFIED RESOURCES			UNDISCOVERED RESOURCES	
	Demonstrated		Inferred	Probability Range	
	Measured	Indicated		Hypothetical	Speculative
ECONOMIC	Reserves		Inferred Reserves		
MARGINALLY ECONOMIC	Marginal Reserves		Inferred Marginal Reserves		
SUB-ECONOMIC	Demonstrated Subeconomic Resources		Inferred Subeconomic Resources		

Major elements of mineral resource classification, excluding reserve base and inferred reserve base. Modified from McKelvey, V.E., 1972, Mineral resource estimates and public policy: American Scientist, v. 60, p. 32-40; and U.S. Bureau of Mines and U.S. Geological Survey, 1980, Principles of a resource/reserve classification for minerals: U.S. Geological Survey Circular 831, p. 5.

GEOLOGIC TIME CHART

Terms and boundary ages used by the U.S. Geological Survey in this report

EON	ERA	PERIOD		EPOCH	AGE ESTIMATES OF BOUNDARIES IN MILLION YEARS (Ma)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.010
				Pleistocene	1.7
		Tertiary	Neogene Subperiod	Pliocene	5
				Miocene	24
			Paleogene Subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	Mesozoic	Cretaceous		Late	96
				Early	138
		Jurassic		Late Middle Early	205
		Triassic		Late Middle Early	~240
	Paleozoic	Permian		Late Early	290
		Carboniferous Periods	Pennsylvanian	Late Middle Early	~330
			Mississippian	Late Early	360
		Devonian		Late Middle Early	410
		Silurian		Late Middle Early	435
		Ordovician		Late Middle Early	500
		Cambrian		Late Middle Early	[1]~570
Proterozoic	Late Proterozoic				900
	Middle Proterozoic				1600
	Early Proterozoic				2500
Archean	Late Archean				3000
	Middle Archean				3400
	Early Archean				(3800?)
pre-Archean[2]					4550

[1]Rocks older than 570 Ma also called Precambrian, a time term without specific rank.
[2]Informal time term without specific rank.

Mineral Resources of Wilderness Study Areas: South-Central Oregon

This volume was published as separate chapters A–D

U.S. GEOLOGICAL SURVEY BULLETIN 1738

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

CONTENTS

[Letters designate the separately published chapters]

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U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849