Mineral and Energy Resource Assessment of the Gallatin National Forest (Exclusive of the Absaroka-Beartooth Study Area), in Gallatin, Madison, Meagher, Park, and Sweet Grass Counties, South-Central Montana

U.S. Geological Survey Professional Paper 1654

U.S. Department of the Interior
U.S. Geological Survey

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Edited by Anna B. Wilson, Jane M. Hammarstrom, and Bradley S. Van Gosen

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This report is intended for use with U.S. Geological Survey Geologic Investigations Series I–2584, available online at: http://www.usgs.gov/

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

Reston, Virginia,
First Printing 2005

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

This report is also available online at:
http://www.usgs.gov/

Published in the Central Region, Denver, Colorado
Manuscript approved for publication March 30, 2001
Graphics by authors

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Library of Congress Cataloging-in-Publication Data

Mineral and energy resource assessment of the Gallatin National Forest (exclusive of the Absaroka-Beartooth study area), in Gallatin, Madison, Meagher, Park, and Sweet Grass counties, south-central Montana / edited by Anna B. Wilson, Jane M. Hammarstrom and Bradley S. Van Gosen.
p. cm.—(U.S. Geological Survey Professional Paper ; 1654)
Includes bibliographical references.
1. Mines and mineral resources—Montana—Gallatin National Forest. I. Wilson, Anna B. (Anna Burack). II. Hammarstrom, Jane Marie. III. Van Gosen, B.S. (Bradley S.), 1960– IV. Series.

TN24.M9 M55 2002
553′.09786′6—dc21 2001051109

ISBN: 0-607-97815-5

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PREFACE

By Jane M. Hammarstrom

In the early 1990's, the U.S. Geological Survey (USGS) was party to a joint Memorandum of Understanding with the U.S. Department of Agriculture Forest Service (USFS) and the U.S. Bureau of Mines[1] (USBM) to conduct and coordinate mineral resource assessments for the USFS. These assessments were designed to assist the USFS in meeting the requirements of the Wilderness Act of 1964 and the Forest and Rangeland Renewable Resources Planning Act of 1974, as amended by the National Forest Management Act of 1976. This information is used by the USFS to help formulate plans for management of Federal lands for the reasonably foreseeable future. These plans are updated on a cyclic basis (10 to 15 years) to consider existing and future desired land conditions, to include up-to-date available scientific data, and to reflect current resource-management practices. In addition, the National Environmental Policy Act of 1969 requires the Federal land-management agencies to consider the best available scientific information when preparing environmental impact statements and issuing land-use decisions.

Mineral resource assessments provide information about the types of rocks and mineral deposits that are present in an area, identify those parts of an area that are permissive for the occurrence of additional deposits of a specific mineral deposit type, and where the data are adequate, provide estimates of both the probable numbers of undiscovered deposits and the in-place resource. An assessment includes geologic maps as well as geochemical, geophysical, and mineral occurrence maps and information about the nature of potential undiscovered mineral deposits. In addition to providing answers to the questions what? where? and how much? with respect to mineral resources in the National Forests, these data can be combined with geoenvironmental models (du Bray, 1995) to evaluate environmental signatures for different types of mineral deposits. These data can also be used by ecologists and other scientists to delineate ecosystem subunits within Federal lands and to incorporate geologic information into other studies (for example, potential for natural or human-induced acid drainage, habitat delineation, and potential nutrient availability).

Historically, both the USGS and the USBM provided the USFS with minerals information from different perspectives. The USBM considered identified resource issues and the USGS focused on the geology and potential for undiscovered resources, as defined in 1980 (U.S. Bureau of Mines and U.S. Geological Survey, 1980). From 1990 to 1994, the USGS conducted a mineral and energy resource assessment of the Gallatin National Forest in Montana and the Custer National Forest in Montana and South Dakota. These studies evaluated the potential for the occurrence of undiscovered mineral resources and provided the USFS with current geologic and mineral-resource information. In 1993, the USBM completed an inventory and appraisal of identified mineral resources (that is, those resources for which location, quality, and quantity are already known) of the Gallatin National Forest. They also analyzed the socioeconomic impacts that might be derived from their development (Johnson and others, 1993). The USBM did not conduct a study of the Custer National Forest.

Federal lands included in the Gallatin and Custer National Forests contain more than 4 million acres, in 13 discontinuous blocks across southern Montana and into western South Dakota (fig. 1). In order to meet the Forest Service's most urgent needs for information about the potential for undiscovered resources for this large area, the USGS divided the Forests into several study units. The Absaroka-Beartooth study area (area 2, fig. 1), a 1.4-million-acre (5,700 km^2; 2,200 mi^2) parcel of land directly north of Yellowstone National Park and east of the Yellowstone River, covers parts of both National Forests and was the focus of the first phase of the study (Hammarstrom and others, 1993; Van Gosen, 1993; Hammarstrom and Gray, 1993). All of the metallic mineral production and most of the recent exploration activity in the Forests are concentrated in the Absaroka-Beartooth study area. The USBM analyzed the results of that study to estimate the portion of the undiscovered metal endowment that could be economically recovered and the probable regional impact of such development (Blackman, 1994). The USGS conducted separate studies for the Custer National Forest in the Pryor Mountains (area 3, fig. 1) of south-central Montana (Van Gosen

[1]Merged with the USGS in 1996.

and others, 1996) and for the Ashland Division (area 4, fig. 1) of the Custer National Forest of southeastern Montana (Van Gosen, 1996). Cursory review of the mineral resources of the easternmost parts of Custer National Forest (area 5, fig. 1), including the Sioux Division near Ekalaka, Montana, and extending into western South Dakota, revealed no evidence for locatable mineral resources, and these areas are not considered further.

This report, a mineral and energy resource assessment of the western and northern parts (area 1, fig. 1) of the Gallatin National Forest (exclusive of the Absaroka-Beartooth study area), completes the assessment studies of the Gallatin and Custer National Forests.

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Executive Summary

By Jane M. Hammarstrom

- The Gallatin National Forest (exclusive of the Absaroka-Beartooth study area, hereinafter referred to as the Forest) covers about 1.3 million acres in three discrete subareas: (1) the Bridger Range, (2) the Crazy Mountains, and (3) the Madison-Gallatin area, which is west of the Yellowstone River, borders Yellowstone National Park, and includes the Gallatin and Madison Ranges.

- The Forest (exclusive of the Absaroka-Beartooth study area) contains nine major assemblages of rocks: (1–3) ultramafic rocks, metamorphic rocks (noncarbonate), and marbles of Archean age; (4) metasedimentary rocks deposited along the southern margin of the Middle Proterozoic Belt basin, preserved in limited exposures in the Bridger Range; (5–6) sedimentary rocks of Paleozoic and Mesozoic age; (7–8) Cretaceous and Tertiary igneous intrusions and volcanic rocks; and (9) Holocene surficial deposits. The distribution of these rocks within the Gallatin National Forest is summarized on a geologic map compiled for this study at a scale of 1 inch = 2 miles (1:126,720) in digital form (Wilson and Elliott, 1995) and as a printed color map (Wilson and Elliott, 1997).

- More than 100 mines, prospects, and mineral occurrences are present in or near the study area. No mines were in production as of 1997; most prospects are raw and undeveloped, and few mining claims are actively maintained. Past production included asbestos (both anthophyllite and chrysotile), gold, silver, copper, lead, zinc, mica, corundum, and coal. These deposits are no longer economic. None of these inactive or abandoned hardrock mines pose significant threats to the environment (Montana Department of State Lands, 1995).

- The two most significant identified resources recognized in previous studies are the Pass Creek lead-zinc-silver-gold deposit in the Bridger Range and the Half Moon lead-copper-silver-gold deposit in the Crazy Mountains. Neither has been developed. Any future mining industry exploration in the area is likely to focus on finding extensions of these identified resources.

- Identified phosphate reserves and estimated resources are low grade and discontinuous. They have not been developed.

- Geochemical surface models based on multielement geochemical analyses of stream sediments indicate areas of anomalous concentrations of antimony, arsenic, bismuth, cobalt, copper, gold, iron, lead, manganese, molybdenum, nickel, silver, tungsten, and zinc. Some anomalous areas are related to known mineral occurrences; others are unexplained.

- Twenty-one mineral resource assessment tracts are defined as areas permissive for the occurrence of one or more types of mineral deposits. Tract delineation is based on geology, distribution of mines and mineral occurrences, geochemical and geophysical signatures of the rocks, and consideration of characteristics exhibited by mineral deposits from other nearby areas. Tracts in the Forest study area are permissive for more than 20 different types of mineral deposits.

- New geochemical data show (1) that Archean ultramafic rocks in the study area contain minor (parts-per-billion level) concentrations of platinum-group elements and gold, contain low concentrations of copper (<200 parts per million), and are locally enriched in chromium and nickel; and (2) no anomalous concentrations of copper, molybdenum, or gold are associated with representative Tertiary volcanic rocks and shallow intrusions of the Absaroka Volcanic field in the Tom Miner basin area. The latter area was examined because it is directly west of the mineralized and recently explored Emigrant mining district in the Absaroka-Beartooth study area of Gallatin National Forest (Hammarstrom and others, 1993).

- Porphyry copper and skarns are the only two types of undiscovered mineral deposits likely to be the targets of exploration in the reasonably foreseeable future because of their associated gold content. There is a low probability that deposits could occur in a number of different tracts throughout the study area, to a depth of 1 km. Modeling the total amount of in-place metal that could be contained in these deposits indicates a 50:50 chance of there being 210 metric tons of copper and 0.9 metric ton of gold. These preproduction estimates represent the equivalent of 0.01 percent of the copper and 0.3 percent of the gold produced in the United States in 1994. Given the lack of surface expression of such deposits, exploration costs alone could be prohibitive. These speculative resources are not likely to be economic in the foreseeable future.

- Energy resources include coal, oil, and gas. Coal was produced for local consumption before 1943. Highly prospective parts of the Electric coal field that lie within the study area near Gardiner are mainly on patented land. No significant amounts of hydrocarbons have been found within the study area. The parts of oil and gas plays defined within the region that extend into the study area are rated as having low to very low potential for hydrocarbons.

- The following facts suggest that mineral exploration and development within the Gallatin National Forest is unlikely in the foreseeable future:

    1. No mines or exploration projects are currently (1997) active.

    2. The types of mineral deposits that were mined in the area in the past are not currently economic.

    3. Much of the Forest lies either within the Lee Metcalf Wilderness, in a patchwork of private and Federal sections of land, abuts Yellowstone National Park, or is adjacent to private land already dedicated to recreational use.

    4. Identified resources and reserves of base metals and phosphate have not been developed.

    5. The area is a habitat for sensitive species such as grizzly bears.

    6. Substantiated resources and more prospective targets for exploration exist in the region outside the study area and in other parts of the Gallatin National Forest to the east. (See favorable tracts described in Hammarstrom and others, 1993.)

    7. The entire area lies within the Greater Yellowstone Area Ecosystem, which is currently being managed with a focus on preservation rather than resource development.

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Wilson, A.B., and Elliott, J.E., 1997, Geologic maps of the western and northern parts of Gallatin National Forest, Montana: U.S. Geological Survey Geologic Investigations Series Map I–2584, scale 1:126,720.

Note to reader: Measurement units in this report are generally given in the unit in which the measurement was made for this study or originally reported. Metal grades are typically reported in troy ounces (precious metals) per short ton or as percentage (copper, iron, lead, zinc). Grade and tonnage models used in mineral resource assessment report grades as grams per metric ton or as percentage; estimates of metals contained in undiscovered deposits are reported in metric tons of metal.

Note: The following conversion factors may be used to convert to metric units:
1 foot (ft) = 0.3048 meter (m)
1 square mile (mi^2) = 640 acres = 2.590 square kilometers (km^2)
1 troy ounce (oz)= 31.1 grams
1 short ton (st) = 2,000 pounds = 0.9072 metric ton (t)
1 troy ounce per short ton (opt) = 34.285 parts per million (ppm)

The following conversions are also useful to keep in mind in reading this report:
1 part per million (ppm) = 1 gram per metric ton
1 percent (%) = 10,000 parts per million
1 metric ton (t) = 2204.623 pounds = 32,151 troy ounces = 1.102 short tons

Some older literature uses “tonne” to refer to metric tons.

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Description of the Study Area

The 1.7-million-acre Gallatin National Forest borders several other National Forests and includes parts of five counties in south-central Montana (fig. A1). Parts of the Gallatin National Forest that are east and south of the Yellowstone River were included in the Absaroka-Beartooth mineral-resource assessment (Hammarstrom and others, 1993). In order to provide useful maps and facilitate discussion of the diverse geology of remaining areas of the Gallatin National Forest, we defined three discrete subareas within the western and northern parts of the Gallatin National Forest (fig. A1): (1) the Madison and Gallatin Ranges and West Yellowstone subarea, hereinafter referred to as the Madison-Gallatin subarea; (2) the Bridger Range subarea; and (3) the Crazy Mountains subarea. These subareas cover approximately 1.3 million acres (5,240 km^2, 2,024 mi^2). The Crazy Mountains and Bridger Range subareas are largely a checkerboard of private and Federal land (fig. A2). In addition to private in-holdings and corporate forests, the Madison-Gallatin subarea includes three parts of the Lee Metcalf Wilderness (fig. A2). Private lands (surface) may or may not include the mineral rights.

Madison-Gallatin Subarea

The Madison-Gallatin subarea includes all parts of the Gallatin National Forest that are west of the Yellowstone River and south of Bozeman (fig. A1). The subarea is immediately north and west of the northwest corner of Yellowstone National Park and falls within the boundaries of the Greater Yellowstone Area (Greater Yellowstone Coordinating Committee, 1991). The Greater Yellowstone Area (GYA), defined as Yellowstone National Park and parts of six surrounding National Forests, is internationally recognized for its natural treasures that include geothermal, wildlife, and scenic values. The GYA also supports many activities that contribute to local, State, and Federal economies, including mining, timber harvesting, livestock grazing, oil and gas development, outfitting, and tourism. The management of parks and forests in the GYA is coordinated by the Forest Service (U.S. Department of Agriculture) and the National Park Service (U.S. Department of the Interior).

The 225,544-acre (3,900 km^2, 1,506 mi^2) Madison-Gallatin subarea is bounded on the west by the Beaverhead National Forest along the crest of the Madison Range, on the south by the Targhee National Forest at the Idaho State line, and on the east by Yellowstone National Park (fig. A1). It includes parts of Gallatin, Park, and Madison counties (fig. A1), and parts of the Lee Metcalf Wilderness (fig. A2). The subarea includes Hebgen Lake (fig. A1) and surrounds private in-holdings associated with the Big Sky ski area. Major rivers draining the subarea the are the Gallatin, Madison, and Yellowstone Rivers (fig. A1). U.S. Geological Survey 1:250,000-scale topographic maps for the subarea are the Ashton and Bozeman quadrangles.

Bridger Range Subarea

The 168,124-acre (680 km^2, 263 mi^2) Bridger Range subarea includes the part of Gallatin National Forest that is west of State Highway 89 and north of Interstate 90 (I–90) (fig. A2). The subarea covers the Bridger Range in Gallatin County and an area northeast of Bozeman that extends into Park County and is separated from the Bridger Range by private lands along Bridger Creek and Highway 86 (figs. A1, A2). The Gallatin River and its tributaries drain the west side of the Bridger Range. Bridger Creek and its tributaries drain the eastern flank of the Bridger Range. All past mining and recent exploration in the subarea were concentrated in the western part of the Bridger Range (McCulloch, 1994). U.S. Geological Survey 1:250,000-scale topographic maps for the subarea are the White Sulphur Springs and Bozeman quadrangles.

Crazy Mountains Subarea

The 163,371-acre (661 km^2, 255 mi^2) Crazy Mountains subarea includes the part of Gallatin National Forest that is east of State Highway 89, west of State Highway 191, and north of I–90 in Meagher, Park, and Sweet Grass counties (figs. A1, A2). The subarea is in the southern two-thirds of the Crazy Mountains; the northern part of the mountain range is in Lewis and Clark National Forest. The Yellowstone River and its tributaries drain most of the Crazy Mountains. Spectacular alpine scenery, rugged high mountain terrain, lakes, and glaciers characterize the Crazy Mountains. Historical and exploration in the subarea have been confined to the Big Timber Canyon mining district, in the south-central part of the subarea. U.S. Geological Survey 1:250,000-scale topographic maps for the subarea are the White Sulphur Springs and Bozeman quadrangles.

Acknowledgments

This study was greatly facilitated by the assistance of many individuals in the field and in the office. Jim Shelden, U.S. Forest Service, Region 8, participated in the early phases of this study. A number of people at the Montana Bureau of Mines and Geology provided background information and discussed various aspects of Montana geology with us during the course of this

study, especially Dick Berg, Karen Porter, and Susan Vuke. Dave Lageson, Montana State University, gave us an introduction to the geology of the Bridger Range. The managers of the Big Sky ski resort provided access to private property that is surrounded by National Forest lands. Leslie Rosenberg-Dybel was our field assistant in the Crazy Mountains. A number of our U.S. Geological Survey (USGS) colleagues contributed to this study: Karl Kellogg, Mike O'Neill, and Russ Tysdal gave tours of their field areas, contributed to map compilation, and provided expert advice on the geology of the area during mineral assessment team meetings; Betty Skipp provided maps and advice on map compilation; and Mark Pawlewicz measured vitrinite reflectance. Many USGS geochemists in Denver and in Reston contributed to chemical analyses of stream sediments and whole rock samples; their individual contributions are acknowledged in Chapters D and E of this report.

The authors especially thank Russ Tysdal and Greg Spanski, U.S. Geological Survey in Denver, for their thoughtful and constructive reviews of this voluminous manuscript.

Previous Mineral Resource Studies

The U.S. Bureau of Mines (USBM) conducted an appraisal of the identified resources of the Gallatin National Forest (Johnson and others, 1993), concurrent with USGS studies in the Gallatin and Custer National Forests. The USBM study included an inventory of mines, prospects, and mineral occurrences in the entire Gallatin National Forest (including those parts of the forest that the U.S. Bureau of Mines (USGS) included in the Absaroka-Beartooth study area), summaries of the identified mineral endowment for significant mining districts, geochemical data for more than 1,000 rock samples, and an economic and socioeconomic analysis for selected mineral deposits. Significant resources within the northern and western parts of the Gallatin National Forest identified by that study, and in previous studies by other workers, are listed in table A1. Our study incorporates these findings and expands on them to consider the identified resources in terms of the types of mineral deposits they represent. Using this information in concert with other geologic information, we delineate lithologic environments in which a better than one in one million chance exists that a deposit of a given deposit type occurs is somewhere within the uppermost 1 km of the crust. Such areas are deemed to be "permissive" for the presence of undiscovered resources. Permissive tracts are delineated without regard for present-day economic significance.

A number of resource assessments were conducted for roadless areas within the Gallatin National Forest from 1964 to 1984 as part of the Forest Service's RARE and RARE II (Roadless Area Review and Evaluation) programs in response to the Wilderness Act of 1964. This law directed the USGS and the USBM to conduct mineral surveys of wilderness lands on a planned and recurring basis. Results of these and other studies and references are summarized in table A1. Several of these roadless areas were later incorporated in the Lee Metcalf Wilderness (fig. A2). A number of bills were introduced in Congress in 1992 through 1995 to expand wilderness areas in National Forests in the State of Montana (for example, H.R. 2473, S. 1696). None of these bills was enacted, but all included proposals to designate additional lands within the western and northern parts of the Gallatin National Forest as wilderness or as wilderness study areas.

In addition to the aforementioned studies, two other reports are relevant to the assessment of the Gallatin National Forest. In 1963, the USGS collaborated with the Montana Bureau of Mines and Geology to produce a statewide report on the mineral and water resources of Montana, at the request of Congress (U.S. Geological Survey and Montana Bureau of Mines and Geology, 1963). The report summarized the occurrence, distribution, and production history for a wide variety of metallic and industrial mineral resources throughout the State. The report included small-scale State maps (1 inch = 50 miles, equivalent to a scale of 1:3,168,000) of mineral occurrences and outlined lithologies that are possible sources of mineral resources, such as limestone and dolomite, and bentonite-bearing sediments, among others. In 1996, the USGS produced a digital database for a national mineral-resource assessment of undiscovered deposits of gold, silver, copper, lead, and zinc in the conterminous United States (Ludington and Cox, 1996).

Study Methods

The Gallatin National Forest study was conducted between 1992 and 1997 by compiling existing geologic, geochemical, geophysical, and mineral deposit data for the study area, acquiring new data through field work to fill in gaps in coverage of the study area, and applying a form of mineral-resource assessment as outlined by Singer (1993). This form of assessment is consistent with the methodology applied to other parts of the Gallatin and Custer National Forests (Hammarstrom and others, 1993) and differs from the previous studies in the area (listed in table A1), which emphasized commodities rather than types of mineral deposits. In the form of assessment adopted for this report, mineral deposit models are used to link deposit types with lithologic environments. A mineral deposit model is defined as a systematic arrangement of information that describes the essential attributes of a class of mineral deposits (Barton and others, 1995). A complete model includes both descriptive information including geologic characteristics and grade and tonnage data characterizing the quantitative aspects of an economic to subeconomic subset of thoroughly studied deposits belonging to the class. Therefore, in this application a deposit is assumed to be a mineral occurrence possessing the grade and tonnage characteristics of the model. Based on the geologic environment and the types of mineral deposits represented by the identified resources, tracts of land that the authors deem to be permissive for the existence of one or more mineral deposit types are delineated. The criteria used to define each permissive tract, (geologic, geochemical, geophysical, distribution of mines or mineral occurrence) are tabulated and discussed in Chapter G. A study area may contain a number of different permissive tracts, each containing a particular commodity such as gold, but in different types of mineral deposits. Furthermore, if a total commodity estimate for a particular commodity, such as gold, is desired, it can be obtained by summing the contributions of gold from each deposit type that contains gold from all of the permissive tracts in the study area that contain gold-bearing deposit types.

Knowledge of mineral deposit permissibility can also provide information about the potential extent of land disturbance or likelihood of generation of acidic mine waters in the event such deposits were discovered and developed or disturbed. For example, different types of gold deposits are mined in different ways (placer, underground, open pit), so knowledge of the expected type of mineral deposit helps land managers anticipate future land-disturbance scenarios. Different types of gold deposits have different characteristic mineral assemblages (pyrite-rich,

sulfide-poor) and host rocks (low or high acid-buffering capacity), so knowledge of deposit type provides a guide to probable environmental effects of mining.

Types of mineral deposits considered in this study are listed in table A2. A number of sources of mineral deposit models are available (Cox and Singer, 1986; Bliss, 1992). Mineral deposit models represent a synthesis of data that describe a group of well-studied deposits belonging to a class. Models are compiled from literature and observation for deposits on a global scale. Deposits that are grouped into models commonly form a discrete statistical population in terms of grade and tonnage. Mineral deposits are not necessarily economic, but they are by definition mineral occurrences of sufficient size and grade that they might be considered to have economic potential. We have attempted to classify the sites in the study area in terms of existing mineral deposit models (table A3). This does not imply that a particular site represents a mineral deposit, but rather that one or more characteristics of the site indicate a possible association with a particular mineral deposit model. Brief descriptions of the mineral deposit models used in this study are listed in table A3, along with references to more complete model descriptions. Models are grouped according to the lithologic environments with which they are associated. Table A3 also includes information about expected geochemical signatures and typical ore grades and tonnages associated with each deposit type. Not all the deposit types mentioned in table A3 are included in permissive tracts; occurrences of vein calcite and petrified wood, for example, are mainly of mineralogic interest. In addition, permissive areas for placer deposits are delineated on the basis of stream sediment geochemical anomalies rather than on lithologic criteria; thus, they represent areas of anomalous mineral interest along stream segments rather than permissive tracts based on particular lithologic environments.

Chapters B through F of this report describe the data that are used to delineate mineral resource tracts (fig. A3, table A4). Chapter B describes the geology of the study area, including new mapping that was done to fill in gaps that became apparent when previous geologic maps were compiled. All of our data are compiled at a scale of 1:126,720 (1 in. = 2 mi) to be compatible with Forest Service maps. Geologic maps for the three subareas are available in paper and digital formats (Wilson and Elliott, 1995, 1997). Most of the new mapping consisted of field checks to resolve discrepancies encountered in map compilation or to fill in gaps. However, a detailed geologic map (1:24,000 scale) of the Big Timber stock in the Crazy Mountains subarea was produced to provide a modern interpretation of the complex geology in that area (du Bray and others, 1993). Chapter C describes known deposits and mineral occurrences in terms of deposit types and summarizes past production and level of exploration. Regional geochemical and geophysical surveys are described in Chapters D and E, respectively. Chapter F contains new whole-rock geochemical data obtained for this study to help characterize mineral deposit types. In Chapter G, we combine all these data and establish criteria to delineate permissive tracts for various deposit types (table A4). For deposit types most likely to be of interest in the reasonably foreseeable future and for which we had suitable data and mineral deposit models, we provide probabilistic estimates of numbers of undiscovered deposits. For other deposit types, we attempt to provide a perspective on the importance of the deposit type as a source of commodities for the reasonably foreseeable future and in terms of long-term national mineral supply. Energy resources are described in Chapters H (coal) and I (oil and gas). Our assessment of the mineral and energy resources of the area is summarized in Chapter J in terms of the present, the likelihood for exploration and development on public lands in the reasonably foreseeable future, and the relative importance of the area for long-term mineral supply. Chapter J includes the results of our quantitative assessment. It is based on a computer simulation that combines the authors' estimates of numbers of undiscovered deposits with appropriate grade and tonnage models (Root and others, 1992a, b) to simulate the distributions of metals that could be contained in-place in undiscovered mineral deposits.

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Geology

By Anna B. Wilson, Jane M. Hammarstrom, Bradley S. Van Gosen, and Edward A. du Bray

U.S. Geological Survey Professional Paper 1654–B

U.S. Department of the Interior
U.S. Geological Survey

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Geology

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Introduction

The wide variety of mineral deposit types in Gallatin National Forest reflects the diversity of lithology and age of rock units present in the area and the complex tectonic history of the region. This chapter summarizes geologic mapping available for the study area; presents an overview of the regional geology and tectonics; describes the stratigraphy, with emphasis on lithologies that are permissive hosts for mineral deposits; and discusses some of the major structures. A generalized geologic map, simplified for this study from the 1:126,720-scale geologic maps by Wilson and Elliott (1997), is included as figure B1. It shows the distribution of major rock unit assemblages in the study area. Interested readers should consult the more detailed geologic maps as a companion document to this chapter. The distribution of the major rock unit assemblages and the significant structures form the fundamental geologic criteria used to delineate permissive tracts for various types of mineral deposits (chapter G). Table B1 shows the distribution of mineral deposit types present within the major rock unit assemblages and subareas of the study area shown in figure B1.

Geologic Mapping

Geologic maps of the study area region include one of the first geologic maps of the U.S. Geological Survey, the Livingston Folio (Folio 1), published by Iddings and Weed in 1894. Other early geologic studies in the Forest area include Wolff's 1892 description of the Crazy Mountains, Peale's 1896 Three Forks Folio, and Weed's 1899 map of the Little Belt Mountains quadrangle. These maps (scale 1:250,000) included descriptions of the general character and age of rocks and structures in the area and interpretations of the geologic history. More modern geologic maps are available for large parts of the Gallatin and Madison Ranges (for example, Tysdal and Simons, 1985; Simons and others, 1985; Tysdal, 1990; Erslev, 1982) and for the Bridger Range (McMannis, 1955), as well as for individual quadrangles or topical studies. A new geologic map of the southern part of the Crazy Mountains was prepared for this study (du Bray and others, 1993). Wilson and Elliott (1995, 1997) compiled the geology of the western (Madison-Gallatin subarea) and northern (Bridger Range and Crazy Mountains subareas) Gallatin National Forest at a scale of 1:126,720 (1 in. = 2 mi), the scale used by the U.S. Forest Service for visitor maps. This geologic map, the basis for the current mineral resource assessment, incorporates all available mapping for the study area, including unpublished field maps. Wilson and Elliott (1995, 1997) included an index map of all sources and references used in the compilation.

Overview of Regional Geology and Tectonics

The study area includes rocks that range in age from Archean to Holocene and spans some of the major tectonic provinces of the northern Rocky Mountains. The study area includes part of one of the major Archean shields of the United States, the Wyoming Province (Condie, 1976). Most of the Gallatin National Forest lies within the Central Rocky Mountain Foreland Province, a tectonic province characterized by Laramide uplifts cored by crystalline basement rocks. The northern part of the Bridger Range is in the Rocky Mountain Fold-Thrust belt (fig. B2). Principal tectonic events that affected the rocks of southwestern Montana are listed in table B2, as summarized by Miller and Lageson (1993) and references therein. These tectonic events are all manifested in different parts of the study area. The three subareas designated for this study are geographically and, for the most part, geologically discrete. A number of the Paleozoic and Mesozoic stratigraphic units are recognized throughout most of the study area; however, the nature of the Archean rocks and the character and distribution of Cretaceous and Tertiary igneous rocks vary markedly. The following discussion provides an overview of the geology and tectonic setting of each subarea. Major structural features of the study area referred to in the discussion are shown in figure B3 and discussed in more detail at the end of this chapter.

Madison-Gallatin Subarea

In southwestern Montana, the northern part of the Archean Wyoming Province is exposed in crustal blocks that were uplifted during the Tertiary. The Madison and Gallatin Ranges, separated geographically by the Gallatin River, represent one of these uplifted basement-cored structural blocks. Recent studies of the northern part of the Wyoming Province demonstrate that continental growth evolved by magmatism and accretionary tectonics during the Late Archean (Mogk and Henry, 1988; Wooden and others, 1988; Mogk and others, 1992). These studies identified a mobile belt in the North Snowy block of the Absaroka-Beartooth uplift, an area directly east of the study area (at the northeastern corner of the area shown in fig. B1*A*), as a major Archean crustal boundary. Archean terrane also occurs west of the study area in the Tobacco Root Mountains (10 to 20 mi west of the northwestern part of the area shown on fig. B1*A*) (Brady and others, 1994). Rocks to the west of the mobile belt are dominantly quartzofeldspathic gneiss and metasedimentary rocks deposited in a basinal platform setting.

The Archean rocks of the northern Madison Range are dominantly quartzofeldspathic gneisses metamorphosed to granulite grade and overprinted by amphibolite-grade retrograde

metamorphism (Spencer and Kozak, 1975). Recent studies in the northern Madison and Gallatin Ranges have recognized a number of geologic terranes, including a granulite-migmatite assemblage exposed in the Gallatin and Madison River Valleys, a granitoid batholithic complex, and an assemblage of metasupracrustal rocks metamorphosed to upper amphibolite to granulite facies (Salt and Mogk, 1985; Wooden and others, 1988).

The Madison Range is composed of various packages of Archean metamorphic rocks, which are overlain by Paleozoic and Mesozoic sedimentary rocks. These sedimentary rocks are intruded by a Cretaceous laccolithic complex at Lone Mountain near the Big Sky ski resort area in the Madison Range and in the

Gallatin Range along the western boundary of Yellowstone National Park (map unit Kda of Wilson and Elliott, 1997). The Madison-Gallatin block represents a Laramide-style foreland uplift that was folded, faulted, uplifted, and eroded prior to deposition of the middle Eocene Absaroka-Gallatin volcanic rocks (Simons and others, 1983; Miller and Lageson, 1993). By dating volcanic and intrusive rocks that predate and postdate deformation, Tysdal and others (1986) demonstrated that the Laramide defomation in the central part of the Madison Range was completed by the end of the Cretaceous. Miller and Lageson (1993), following McMannis and Chadwick (1964), concluded that the folding observed in the northern part of the Gallatin Range occurred during the Laramide orogeny. An angular unconformity lies at the base of the overlying Eocene-age volcanic rocks. These volcanic rocks and associated shallow intrusive centers represent the northwest part of the regionally extensive Tertiary Absaroka volcanic field (Chadwick, 1969, 1970, 1972).

The Madison-Gallatin structural block was uplifted and tilted to the southeast during Cenozoic uplift. The normal faults that bound the current range fronts are the result of Neogene crustal extension related to regional upwelling during passage of

the Yellowstone hotspot (Pierce and Morgan, 1992). During the Pliocene and Pleistocene, rhyolitic tuffs and flows erupted from the Yellowstone caldera (map units Qtf and Qr of Wilson and Elliott, 1997), blanketing the southeastern part of the Madison-Gallatin subarea; isolated patches of these volcanic deposits are preserved throughout the northern Madison Range. Recent movement along range front faults led to the catastrophic earthquake in 1959 at Hebgen Lake (fig. B3*A*) in the southern part of the Madison Range that created 18 mi (29 km) of new fault scarps, caused landslides, and warped the lake basin (U.S. Geological Survey, 1964; Witkind and Stickney, 1987). This area continues to be the most seismically active area in Montana, and parts of the Gallatin National Forest are therefore at risk for future landslide failures (Lageson and others, 1997).

Bridger Range Subarea

The Bridger Range is a north-trending anticlinorium defined by Paleozoic and Mesozoic sedimentary rocks and segmented by northwest-trending normal faults (McMannis, 1955). Archean metamorphic rocks in the southern Bridger Range, similar to those in the northern part of the Madison-Gallatin subarea, are juxtaposed against weakly metamorphosed sedimentary rocks of the Middle Proterozoic Belt Supergroup along the Pass fault (fig. B3*B*), also referred to as the Ross Pass fault, in the central part of the range (McMannis, 1955; Miller and Lageson, 1993). The fault was active in Middle and Late Proterozoic time and reactivated during the Paleocene (Lageson, 1989). This fault marks the tectonic boundary between Late Cretaceous-early Tertiary, Sevier-style deformation of the Helena salient in the Fold-Thrust Belt on the north and west with the Laramide uplifts of the Central Rocky Mountains Foreland province on the south and east (fig. B2). The Pass fault also is thought to represent the southernmost margin of the Middle Proterozoic Belt basin (Lageson, 1989).

Mafic dikes and sills of inferred Eocene age are the only intrusive rocks that crop out in the Bridger Range subarea. Volcaniclastic sedimentary rocks of the Upper Cretaceous Livingston Group and overlying Upper Cretaceous and Paleocene sedimentary rocks of the Fort Union Formation crop out along the eastern part of the subarea.

The western flank of the Bridger anticlinorium was downdropped during Neogene crustal extension to form the Gallatin Valley (Lageson, 1989), exposing three basement-cored anticlines along the uplifted crest of the southern part of the Bridger Range (Miller and Lageson, 1993).

Crazy Mountains Subarea

The Crazy Mountains are a high, rugged range that exposes both transitionally and strongly alkaline Tertiary intrusive complexes (du Bray and others, 1993). No rocks older than Cretaceous crop out. The core of the range is composed of a 5 by 8 mi (8 by 13 km), elliptical, composite intrusion of Eocene age—the Big Timber stock (see du Bray and Harlan, 1996). The stock intruded sedimentary rocks of the Upper Cretaceous and Paleocene Fort Union Formation (du Bray and others, 1993; Wilson and Elliott, 1995, 1997) and is flanked by a well-developed dike swarm (Roberts, 1972). Coeval, but geochemically distinct, strongly alkaline intrusive rocks crop out as dikes, sills, laccoliths, and small stocks in the northern and western parts of the Crazy Mountains. Du Bray and Harlan (1996) noted that the physiographic break that separates the northern and southern Crazy Mountains may represent an eastward extension of the Battle Ridge monocline (fig. B3*B*). This Late Cretaceous fold may reflect reactivation of the Middle Proterozoic normal fault system that forms the southern boundary of the Helena salient (embayment) of the Belt Basin, which separates Archean metamorphic basement rocks on the south from Middle Proterozoic Belt Supergroup metasedimentary rocks on the north (for example, the Pass fault in the Bridger Range, described previously). Contributions from fundamentally different types of underlying basement rocks, acting as crustal contaminants to the source mantle-derived melts of the Crazy Mountains alkalic rocks (Dudas and others, 1987; Dudas, 1991), may account for the geographic distribution of strongly versus transitionally alkaline rocks in the area (du Bray and Harlan, 1996). Based on compositional and geologic relationships, du Bray and Harlan (1996) proposed that the Big Timber stock documents the easternmost extent of mantle-dominated arc magmatism related to subduction, representing renewed arc processes inboard from the western edge of the early Cenozoic North American plate. In this scenario, the Big Timber stock is related to the igneous activity that succeeded earlier Cenozoic shallow subduction, which produced the large volcanic fields of the Absaroka Volcanic Supergroup and Challis Volcanics to the west of the Crazy Mountains. As subduction steepened, the subduction hingeline retreated westward, and development of an asthenospheric mantle wedge provided a heat source for renewed magmatism during the Eocene (du Bray and Harlan, 1996).

Major Rock Unit Assemblages

The geology of the northern and western parts of the Gallatin National Forest is represented by 33 rock units on the geologic maps prepared for this study (Wilson and Elliott, 1995, 1997). Most of these map units were combined into nine generalized rock unit assemblages (fig. B1) to focus on lithologies that are permissive for the occurrence of particular types of mineral deposits (table B1). Some of the assemblages are confined to only one or two of the three subareas described in this report (table B1). Five of the map units[1] shown by Wilson and Elliott (1995, 1997) are omitted from the nine assemblages because they do not fit entirely into any one lithologic category or are not known to host mineral deposits in the study area. Map unit symbols of Wilson and Elliott (1995, 1997) that were combined to form the rock unit assemblages are indicated in parentheses in the following discussion.

Archean Basement Rocks

Archean Metamorphic Rocks (Am)

Archean metamorphic basement rocks are exposed in the southwestern, northwestern, and east-central areas of the Madison-Gallatin subarea (fig. B1*A*) and in the southwestern part of the Bridger Range subarea (fig. B1*B*). No Archean rocks are exposed in the Crazy Mountains subarea. Lithologies include granitic to dioritic gneiss, migmatitic gneiss, pegmatite, quarzofeldspathic gneiss, amphibolite, mafic intrusive rocks (diabase and gabbro), volumetrically minor ultramafic rocks, schist (biotite, chlorite-hornblende, muscovite-quartz), and quartzite.

Near the southern part of the Madison-Gallatin subarea, Archean metamorphic rocks are divided into two distinct packages by the Madison mylonite zone (fig. B3*A*). Northwest of the mylonite zone, the rocks in this assemblage are generally 3.3 billion-year-old (3.3-Ga) tonalitic and trondhjemitic gneisses that were intruded by protoliths of 2.7-Ga granitic gneisses (Wooden and others, 1988). South of the mylonite zone, quartzite, biotite schist, and amphibolite are interlayered with 2.7–2.6-Ga dolomitic (Ad) and tremolitic (At) marbles (Erslev, 1983; Sumner and Erslev, 1988; Mueller and others, 1993). The northwestern package was thrust over the southeastern package, and both terranes were subjected to drag folding and retrograde metamorphism to epidote-amphibolite facies assemblages within the mylonite zone. The package of Archean metasupracrustal rocks (dolomitic marble, quartzite, schist, amphibolite) that crops out south of the mylonite zone is interpreted as a carbonate-quartz pelite shelf association (Erslev, 1983; Cherry Creek Metamorphic Suite of Sumner and Erslev, 1988) and has been correlated (O'Neill, 1999) with an Archean supracrustal sequence of rocks described by Heinrich and Rabbitt (1960) in the Gravelly and Ruby Ranges (about 15 and 30 mi, respectively) to the west of the study area. The rocks to the west include banded iron formation, which has not been observed in the rocks south of the mylonite zone in the study area.

In the northwestern corner of the Madison-Gallatin subarea near Cherry Lake (fig. B3*A*), the Archean basement rocks include volumetrically minor lenses of metasedimentary rocks (aluminous gneiss and schist, serpentinized marble, iron formation and quartzite) interlayered with amphibolite (Kellogg, 1993). In their study of the Precambrian evolution of the Spanish Peaks area (mainly north of the study area boundary), Spencer and Kozak (1975) suggested that the presence of conformable marble and quartzite layers interbedded with gneiss indicates a sedimentary origin. Mogk and McCourt (1995) noted that the high-grade Archean metasupracrustal rocks in the block forming the hanging wall of the northeast-trending Mirror Lake shear zone in the Spanish Peaks area (fig. B3*A*) record pressures of 8 to 10 kbar and temperatures in the range of 670° to 720°C. A 0.5-mile-wide (1-km-wide) inclusion of metasedimentary rocks in the dominantly gneissic footwall block of the fault records lower pressures (6–7 kbar) and higher temperatures (750° to 800°C) (Mogk and McCourt, 1995). Minor outcrops of carbonate in these metasupracrustal rocks of the northwestern part of the study area are necessarily included with the Archean metamorphic rocks map unit Am in Wilson and Elliott (1997) because of their small size. These carbonates are volumetrically minor, tectonically disrupted, very high grade rocks, and are not considered as permissive hosts for significant mineral deposits, such as talc.

The Archean metamorphic rocks exposed in the southwestern part of the Bridger Range subarea are primarily gneiss, but include schist, granite, quartzite, pegmatite, amphibolite, and mafic intrusive rocks (Wilson and Elliott, 1997).

The Archean metamorphic rocks are permissive hosts for pegmatites, corundum-sillimanite deposits, polymetallic vein deposits, and dimension stone (table B1).

Archean Marbles (Ad, At)

Thick sequences of Archean dolomitic and tremolitic marbles were mapped by Witkind (1969, 1972a) in the southernmost part of the Madison-Gallatin subarea. These rocks, in significant volumes, are confined to the metasupracrustal package of rocks south of the Madison mylonite zone. We show these rocks as a separate unit because correlative rocks elsewhere in southwest Montana host significant talc deposits (see Van Gosen and others, 1998). In addition, Witkind (1972b) noted that these carbonate rocks represent potential sources of construction materials (cement, crushed stone, rip rap).

Archean Ultramafic Rocks (Au)

In the Madison Range, small pods and lenses of serpentinized ultramafic rocks intrude the Archean metamorphic rocks. The ultramafic rocks are mapped primarily in the Madison Range, along and north of the mylonite zone. Small pods of peridotite (not shown in Wilson and Elliott, 1995, 1997) are also present in the Archean metamorphic rock assemblage north of the Spanish Peaks fault (fig. B3*A*) in the northwestern part of the

[1]The five units are Quaternary rhyolite (Qr), Tertiary conglomerate (Tc), Tertiary Fort Logan Formation (Tfl), Tertiary and Cretaceous Fort Union Formation (TKf), and undifferentiated Mesozoic and Paleozoic sedimentary rocks (MzPzu).

Madison-Gallatin subarea and just west of the Gallatin River near Table Mountain. Most of the mafic intrusions are mapped in the Spanish Peaks area (Wilson and Elliott, 1997).

Archean ultramafic rocks in the study area are permissive host rocks for mineral deposits of magmatic nickel, copper, platinum-group elements (PGE), chromite, serpentine-hosted asbestos, and vermiculite (table B1).

Proterozoic Metasedimentary (Belt Supergroup) Rocks (Ym)

The only Proterozoic rock units exposed in the study area are the Spokane and LaHood Formations (Wilson and Elliott, 1997, combined as map unit Ym), which crop out in the northern part of the Bridger Range subarea (fig. B1*B*). These

stratigraphic units are part of the Middle Proterozoic Belt Supergroup and were deposited between 1,450 and 850 million years ago (1,450–850 Ma) (Winston, 1986; Schmitt, 1988). The LaHood Formation, exposed directly north of the Pass fault, is a 11,550-ft-thick (3,500-m-thick) wedge of arkosic conglomerate, arkose, argillite, and limestone that is confined to an area that extends westward for about 80 mi (130 km) from the Bridger Range to the Highland Mountains (McMannis, 1963, 1965; Schmitt, 1988). The LaHood Formation is an important stratigraphic marker because it marks the southern extent and the only basin margin facies preserved for the Middle Proterozoic Belt basin; both submarine fan and alluvial fan depositional models have been proposed on the basis of stratigraphic and sedimentologic analysis (Schmitt, 1988).

Proterozoic metasedimentary rocks in the Bridger Range are permissive for sedimentary exhalative (sedex) lead-zinc, polymetallic replacement, and polymetallic vein deposits (table B1).

Paleozoic Sedimentary Rocks (Ꞓu, OꞒu, MDt, Mm, ℙMu, Ps, PMu)

Paleozoic sedimentary rocks (Cambrian to Permian) are exposed in the Madison-Gallatin (fig. B1*A*) and Bridger Range (fig. B1*B*) subareas. Map patterns of these rocks and overlying Mesozoic sedimentary rocks record pervasive Laramide folding. The strata in the Madison-Gallatin subarea include (from lowest

stratigraphic position to highest) the Middle Cambrian Flathead Sandstone, Wolsey Shale, Meagher Limestone, and Park Shale; Upper Cambrian Pilgrim Limestone and Snowy Range Formation (and laterally equivalent Red Lion Formation); Ordovician Bighorn Dolomite; Upper Devonian Maywood and Jefferson Formations; Upper Devonian and Lower Mississippian Three Forks Formation; Mississippian Madison Group; Upper Mississippian and Lower Pennsylvanian Amsden Formation; Pennsylvanian Quadrant Sandstone; and Lower Permian Shedhorn Sandstone (and its lateral equivalent, Phosphoria Formation). Total thickness of the Cambrian and Ordovician rocks (map unit O€u in Wilson and Elliott, 1997) is about 1,400 ft (425 m). The Three Forks, Jefferson, and Maywood Formations (map unit MDt) combine to reach a maximum thickness of about 700 ft (215 m). Madison Group rocks (map unit Mm; total thickness about 1,450 ft (440 m)), predominantly limestones with minor dolomites, form prominent cliffs and are locally fossiliferous. The Quadrant Sandstone, as thick as 315 ft (95 m), is composed mostly of well-sorted quartz sandstone. The underlying Amsden Formation, mapped to together with the Quadrant Sandstone (as map unit ℙMu), mainly consists of calcareous siltstone and shale. Outcrops of Permian rocks (map unit Ps), maximum total thickness of 225 ft (70 m), are discussed in the assessment of phosphate resources (fig. G7).

In the Bridger Range subarea, the sedimentary package is similar, but Ordovician rocks are absent. The complete sequence of Cambrian formations and the Upper Devonian Jefferson and Upper Devonian and Lower Mississippian Three Forks Formations in this mountain range have a maximum total thickness of about 3,100 ft (945 m). Mississippian Madison Group carbonate rocks are present from north to south along the entire western part of the subarea, where they form prominent cliffs and attain a thickness of as much as about 2,000 ft (610 m).

Paleozoic rocks proximal to intrusive centers could host skarn, polymetallic replacement, polymetallic vein deposits, and dimension stone in the study area. Thin, phosphatic layers of the Permian Phosphoria Formation may host upwelling-type phosphate deposits (table B1).

Mesozoic Sedimentary Rocks (JT̄Ru, Ju, Kul, Ku, Ke, Klv)

Mesozoic (Triassic to Cretaceous) sedimentary rocks are exposed in both the Madison-Gallatin (fig. B1*A*) and Bridger Range (fig. B1*B*) subareas. This assemblage is primarily composed of clastic rocks—sandstones, mudstones, and shales. Formations include the Lower Triassic Dinwoody Formation, Woodside Siltstone, and Thaynes Formation; Triassic Chugwater Formation; Middle and Upper Jurassic Ellis Group; Upper Jurassic Morrison Formation; Lower Cretaceous Kootenai Formation, Thermopolis Shale, and Muddy Sandstone; Upper Cretaceous Mowry Shale, Frontier Formation, Cody Shale, Telegraph Creek Formation, Eagle Sandstone, Virgelle Sandstone, Everts Formation, and Livingston Formation or Group.

In the study area, Mesozoic sedimentary rocks could host skarn, polymetallic replacement, and polymetallic vein deposits (table B1) where they are proximal to intrusive centers. Away from intrusive centers, they can host oil and gas and coal. Some units could be used for dimension stone.

Veins of optical grade calcite hosted by rocks of the Livingston Group were mined outside the Forest in the past (Stoll and Armstrong, 1958). These types of deposits have no modern resource significance but do represent geological curiosities that may be of interest to mineral collectors.

Cretaceous Intrusive Rocks (Kda)

Late Cretaceous laccoliths and related sills and dikes of porphyritic dacite and andesite form two intrusive centers in the Madison-Gallatin subarea—one at Lone Mountain along the western margin of the study area and another along the Gallatin River at Snowslide Creek (the “Gallatin River laccolith”) along the eastern boundary of the study area, just west of Yellowstone National Park (Tysdal and Simons, 1985; Tysdal, 1990).

An intrusive center at Lone Mountain and a minor center at Fan Mountain to the west formed a series of tabular bodies (Christmas tree laccoliths) that domed and intruded Cretaceous sedimentary rocks, which were previously deformed by movement along the Hilgard fault system (Tysdal and others, 1986). A date of 69–68 Ma on hornblende from laccolithic rocks that cut the Hilgard fault (fig. B3*A*) established the Cretaceous age of the intrusions and constrains the age of movement along the fault (Tysdal and others, 1986). Positive gravity anomalies are associated with both intrusive centers.

The Gallatin River laccolith and related sills were described by Iddings (1899) and mapped by Witkind (1969) as phenocryst-rich dacite porphyry. Like Lone Mountain and a number of other Cretaceous intrusions in the Gallatin Range, the Gallatin River body has a Christmas tree form and domed the Paleozoic sedimentary rocks that it intruded. The Cretaceous age is inferred on the basis of (1) field observations that show crosscutting relationships with pre-Madison Group rocks; (2) a nearly conformable roof of Madison Group limestones (Ruppel, 1972); and (3) compositional similarity to the dated Lone Mountain laccolith (Tysdal and Simons, 1985). The laccolith style of emplacement is characteristic of the hypabyssal Cretaceous intrusives in the Madison-Gallatin subarea and is quite different from the composite batholiths of Cretaceous age that crop out to the west in the Tobacco Root, Boulder, Pioneer, and Idaho batholiths.

McMannis and Chadwick (1964) described several small intrusive stocks, dikes, and sills of dacite porphyry and diorite near Storm Castle in the Gallatin Range as Tertiary (shown as map unit Ti in Elliott and Wilson, 1997). However, they also reported a Cretaceous age determination from hornblende andesite porphyry associated with the diorite and suggested that the diorite may be Cretaceous in age.

Cretaceous intrusive rocks are permissive hosts for porphyry copper, alkali-gabbro-syenite hosted copper-gold-platinum, gold-silver-telluride vein deposits, and dimension stone (table B1).

Tertiary Intrusive and Volcanic Rocks (Ti, Tv, Tt, Ta, Tqm, Tdg, Tcl, QTf)

Tertiary intrusive and volcanic rocks have a very different character in each of the three subareas. Rocks of the Eocene Absaroka Volcanic Supergroup, including the Golmeyer Creek and Hyalite Peak Volcanics (Chadwick, 1982), are prevalent throughout most of the east-central and northern parts of the Madison-Gallatin subarea (fig. B1*A*). Lithologies include volcanic flows and breccias, andesite and basalt flows, pyroxene trachyte porphyry (Witkind, 1972a), breccias, tuffs, conglomerate, sandstone, and channel-fill deposits (Chadwick, 1982; Simons and others, 1985). The Absaroka volcanic field covers 9,000 mi^2 (23,315 km^2) and represents the largest volcanic field of Eocene age in the northern Rocky Mountains (Chadwick, 1970; Smedes and Prostka, 1972). Total thickness of the volcanic pile is about 6,000 ft (1,828 m) (Montagne and Chadwick, 1982).

Tertiary intrusive centers represent the eroded roots of stratovolcanoes; these centers are an important locus of mineral deposits in the region (Hausel, 1982). In the Madison-Gallatin subarea, two subparallel, northwest-trending chains of intrusive-volcanic centers developed along preexisting (perhaps Precambrian) zones of weakness in basement rocks (Chadwick, 1970). These belts, 15 to 35 mi (24–56 km) apart, extend from the southern part of the Absaroka Mountains in Wyoming through the Gallatin Range. The northern belt parallels the Squaw Creek fault (fig. B3*A*) in the western Gallatin Range and the Cherry Creek fault in the Madison Range. The southern belt is aligned with the Spanish Peaks-North Meadow Creek-Bismark fault system (fig. B3*A*) (Montagne and Chadwick, 1982).

Trachyte, trachybasalt, and basalt are exposed near the southern part of the Madison-Gallatin subarea near West Yellowstone. Younger felsic volcanic rocks (map unit QTf), including Pleistocene Plateau Rhyolite (Central Plateau Member) and Pliocene and Pleistocene Yellowstone Group (including Huckleberry Ridge and Lava Creek Tuffs), are locally widespread, especially in the southern part of the Madison-Gallatin subarea (Wilson and Elliott, 1997). Although they are not known to host mineral deposits in the study area, these younger felsic volcanic rocks are included with the Tertiary intrusive and volcanic rocks for the purpose of the mineral assessment.

The Bridger Range has only two intrusive bodies exposed on the west flank of the range (fig. B1*B*): (1) a sill contained entirely within undivided Cambrian sedimentary rocks (Skipp and Peterson, 1965), and (2) a dike that crosscuts Mississippian to Lower Cretaceous rock units in the southern part of subarea (McMannis, 1955).

In the Crazy Mountains, transitionally alkaline rocks of the Eocene Big Timber stock intruded and metamorphosed Upper Cretaceous Paleocene rocks of the Fort Union Formation (du Bray and others, 1993). The earliest, and volumetrically dominant, phase of the composite stock is a medium- to coarse-grained hypidiomorphic granular gabbro and diorite that includes subordinate masses of pyroxenite along the contact. The second phase of the stock is finer grained and mostly quartz monzodiorite, also grading to quartz monzonite and minor granodiorite. The final phase of igneous activity associated with the stock is a compositionally (basalt to aplite) and texturally diverse dike swarm (du Bray and others, 1993).

Coeval, but geochemically distinct, strongly alkaline rocks such as nepheline syenite, malignite, analcite syenite, and theralite are restricted to the western and northern parts of the range and occur primarily as sills, laccoliths, small stocks, and dikes (Dudas, 1991; duBray and others, 1993).

The Tertiary intrusive and volcanic rock unit assemblage may host porphyry copper, gold-silver-telluride veins, and epithermal veins. They also contain petrified wood and may provide sources of dimension stone.

Quaternary Surficial Deposits (Qs)

Current landscape features in all three subareas were formed in the Quaternary. Glacial activity has shaped both the high country, river valleys, and the low lands near West Yellowstone. At least two major glacial periods influenced the landscape: (1) Bull Lake, about 160,000 to 100,000 years ago (Pierce, 1979; Phillips and others, 1997), and (2) Pinedale, about 45,000 to 15,000 years ago (Pierce, 1979; Sturchio and others, 1994; Gosse and others, 1995; Phillips and others, 1997). Unlithified sedimentary cover includes alluvium, colluvium, talus deposits, landslide deposits, earthflows, rock glaciers, glacial and glaciofluvial deposits, erosion surfaces, boulder fields, and alluvial fan and coalesced alluvial fan deposits. The area is still evolving and is tectonically active, as evidenced by the 1959 earthquake at Hebgen Lake that caused a landslide that dammed the Madison River, creating Earthquake Lake (fig. B3*A*; U.S. Geological Survey, 1964). Potential Quaternary deposits include heavy mineral and gold placer, petrified wood, and sand and gravel (table B1).

Structural Overview of Subareas

Madison-Gallatin Subarea

The Madison-Gallatin subarea (fig. A1) is part of a Tertiary structural block in the Central Rocky Mountain Foreland Province (Tysdal, 1986; Tysdal and others, 1986). It consists of a basement of Archean metamorphic rocks overlain by 3,000 to 4,000 ft (915 to 1,220 m) of Paleozoic rocks, predominantly carbonates, and more than 10,000 ft (3,050 m) of Mesozoic rocks, predominantly Cretaceous sedimentary rocks (Tysdal and Simons, 1985; Simons and others, 1985; Wilson and Elliott, 1995, 1997). Cretaceous intrusive rocks are present as laccoliths and related sills and dikes in the central Madison Range and in the Gallatin Range. Eocene and younger volcanic rocks, as thick as 6,000 ft (1,830 m) (Montagne and Chadwick, 1982), cover much of the Gallatin Range and parts of the Madison Range. Bedrock is locally concealed by Quaternary surficial deposits.

Archean Structure

Mogk and McCourt (1995) showed that the high-grade metasupracrustal rocks in the Spanish Peaks area are in fault contact with a diverse suite of Early, Middle, and Late Archean igneous rocks (Mueller and others, 1995) along a 0.5-mi-wide (1 km-wide) ductile shear zone that is related to a regional, Late Archean decollement. The predominantly gneissic terrane of the northern Madison and Gallatin Ranges is transitional between granitoid-dominant Archean rocks to the east, in the Beartooth uplift, and middle amphibolite facies metasedimentary rocks (marble, quartzite, biotite schist, chlorite schist) that crop out in the southern part of the Madison Range.

Thrust faulting within Archean rocks during the Early Proterozoic juxtaposed the metasedimentary rocks against the gneisses along the northeast-trending Madison mylonite zone (fig. B3*A*) in the southern part of the Madison Range of the study area (O'Neill, 1999; Erslev, 1982, 1983). Sumner and Erslev (1988) described the metasedimentary rocks (Cherry Creek Metamorphic Suite) of the southern Madison Range as a well-preserved carbonate-quartzite-pelite shelf association; these rocks south of the mylonite zone were largely unaffected by the Early Proterozoic deformation that was concentrated north of the mylonite zone. Early Proterozoic thermal metamorphism reset ages (based on K-Ar and Ar-Ar age determinations) for similar lithologies that crop out more extensively to the west in the Tobacco Root and Ruby Ranges (Sumner and Erslev, 1988; O'Neill, 1999). Although no rocks of Proterozoic age are present in the subarea, the entire area was affected by Early Proterozoic tectonic collisions (O'Neill, 1999).

Madison Mylonite Zone

The Madison mylonite zone is a major, northeast-trending, Early Proterozoic (1.9 Ga) shear zone that forms one of the fundamental tectonic features of southwestern Montana (Erslev, 1983; Erslev and Sutter, 1990). This basement-involved thrust fault may represent one of the tectonic elements of a largely concealed Early Proterozoic suture zone that follows the recurrently active Great Falls tectonic zone (fig. B2) (O'Neill and Lopez, 1985; O'Neill, 1999). The northwest-dipping Madison mylonite zone brought Archean quartzofeldspathic gneisses to the north over Archean metasupracrustal rocks to the south by northwest side up, reverse-slip movement (O'Neill, 1999). The fault zone extends from Red Rock Lakes (about 35 mi [56 km] west of West Yellowstone) to Livingston; mylonitic rocks west of the study area in the Gravelly Range and Horn Mountains are probably splays of the same structure (O'Neill, 1999). In the southern part of the Madison Range in the study area, the fault zone is nearly 2 mi wide (3 km) and associated with a 6-mi-thick (10 km) aureole of retrograde, epidote-amphibolite grade metamorphism (Erslev, 1982).

High-Angle Faults and Thrusts

During the Laramide (Late Cretaceous-early Tertiary) deformation, pre-Tertiary rocks of the Madison-Gallatin block were folded and faulted, mainly along preexisting northerly and northwesterly zones of weakness of Precambrian origin (Tysdal, 1986; Tysdal and others, 1986; Kellogg, 1994; Kellogg and others, 1995). Principal high-angle structures that formed at this time, from south to north (fig. B3*A*), include the Buck Creek, Spanish Peaks, and Squaw Creek fault systems. These three faults are subparallel, northwest-trending high-angle faults that dip steeply to the northeast. The Buck Creek fault is nearly vertical, has a maximum displacement of 5,900 ft (1,800 m), and is flanked by the Buck Creek anticline to the north and the Sphinx Mountain syncline to the south (Tysdal and others, 1986). No basement rocks are exposed along the Buck Creek fault, but basement is exposed along the Spanish Peak and Squaw Creek faults. Correlation of the Spanish Peaks fault with a regionally extensive fault system that extends 20 to 30 mi (32–48 km) west of the study area to the Tobacco Root Mountains, where it is known as the Bismark fault (Montagne and Chadwick, 1982; Schmidt and others, 1988), suggests that this fault represents a Precambrian structure that was reactivated during the Laramide orogeny (Garihan and others, 1983; Kellogg, 1994; Kellogg and others, 1995). The Spanish Peaks fault brought Archean metamorphic rocks on the north over rocks as young as Early Cretaceous to the south. The major movement along this fault is post-Late Cretaceous or Eocene (McMannis and Chadwick, 1964) and minimum vertical displacement is about 16,000 ft (4,875 m) (Tysdal and Simons, 1985). Elliott and others (1993) suggested that the Gardiner fault, which forms the southwestern boundary of the South Snowy Block of the Beartooth uplift directly east of the study area, probably extends northwest across the Gallatin and Madison Ranges and may represent a continuation of the Spanish Peaks structure. Intervening Tertiary volcanic rocks, however, cover and obscure the pre-Tertiary geology between these two areas.

The Squaw Creek fault, the southeastern extension of the Cherry Creek fault (Kozak, 1961), has been traced for about 15 mi (24 km). It placed Archean metamorphic rocks on the north against Paleozoic to Lower Cretaceous sedimentary rocks on the south with at least 4,500 ft (1,370 m) of stratigraphic separation. Detailed kinematic studies of the Squaw Creek fault zone by Miller and Lageson (1993) showed that there was no Laramide folding of the basement along the fault and that the basement behaved as a series of rigid blocks during Laramide deforma-tion due to the high angle of discordance between the basement foliation and the basement-cover contact. This non-rotational behavior of the basement during Laramide deformation contrasts with rotational behavior observed: (1) in the core of the Canyon Mountain anticline that forms the hanging wall of the Suce Creek thrust (fig. B3*A*) that carried basement rocks over Lower Cretaceous rocks in the northeastern corner of the Madison-Gallatin subarea; and (2) in the anticlines in the southern part of the Bridger Range (Miller and Lageson, 1993).

The Snowflake fault is a north-trending thrust in the east-central part of the subarea (fig. B3*A*) with a displacement of about 2,000 ft (610 m) (Simons and Lambeth, 1984). The Hilgard fault system, a series of westward-dipping imbricate thrusts, extends across the subarea north from Hebgen Lake to the Spanish Peaks fault, separating Archean rocks on the west from younger rocks on the east, and has a displacement of many thousands of feet (Tysdal and Simons, 1985; Tysdal, 1986, 1990).

Tertiary and Quaternary Extensional Features

Normal range-front faults on the west side of the Madison Range (west of the study area) were primarily responsible for uplifting and tilting the Madison-Gallatin block beginning in Tertiary time (Simons and Close, 1984; Simons and Lambeth, 1984), but most movement occurred during the late Cenozoic (Simons and others, 1985). These range-front faults are still active; segments of this fault system moved during the Hebgen earthquake in 1959 (U.S. Geological Survey, 1964).

There are a number of examples of structural inversions in the study area, where Tertiary basins occupy zones of weakness along crests of ramp anticlines that developed during the Laramide orogeny (Kellogg, 1994; Kellogg and others, 1995). Madison Valley (fig. B3*A*) is a half graben with normal faults along its eastern margin that probably flatten at depth and merge with thrusts; such thrust surfaces accommodated backsliding (Kellogg, 1994; Kellogg and others, 1995). Yellowstone (or Paradise) Valley is also a half graben basin. Most of the movement along the basin faults is post mid-Cenozoic (Montagne and Chadwick, 1982).

Bridger Range Subarea

The Bridger Range is a 25-mi-long (40 km), north-trending uplift of Archean metamorphic rocks and Proterozoic metasedimentary through Mesozoic sedimentary rocks (fig. B1*B*). The range overlaps the boundary of the Rocky Mountain Fold-Thrust Belt and the Central Rocky Mountain Foreland Province (Lageson, 1985; McMannis, 1955). The mutual boundary is the Pass fault (fig. B3*B*), which juxtaposes Proterozoic metasedimentary rock against Archean metamorphic rocks. This fault was active during the Middle and Late Proterozoic as a normal fault and reactivated during the Paleocene (McMannis, 1955; Lageson, 1989).

Sedimentary rocks of the Bridger Range are deformed into a composite, steep, north-northwest-trending fold. The east flank of the range consists of steeply dipping Phanerozoic sedimentary rocks, and the entire range is capped by Mesozoic sedimentary rocks (McMannis, 1955). The Pass fault divides the range into a southern part where the Paleozoic rocks lie on the Archean metamorphic basement rocks, and a northern part where Paleozoic rocks rest on Middle Proterozoic rocks of the Belt Supergroup (McMannis, 1955; Lageson, 1989; Lageson and others, 1983, p. 6).

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Mineral Resources

By Jane M. Hammarstrom

U.S. Geological Survey Professional Paper 1654–C

U.S. Department of the Interior
U.S. Geological Survey

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Mineral Resources

By Jane M. Hammarstrom

Introduction

Several hundred abandoned mines, prospects, or mineral occurrences are known within, or in close proximity to, the northern and western parts of the Gallatin National Forest. As of 1993, the most recent year for publication of the state mining directory (McCulloch, 1994), no mines or exploration projects were active within the study area. Historically, mineral production has not been very important from this part of the Gallatin National Forest. This is in sharp contrast to areas east and west of the study area, including the eastern parts of the Gallatin National Forest (part of the Absaroka-Beartooth study area) that host significant precious- and base-metal resources (Hammarstrom and others, 1993; Johnson and others, 1993). Most of the exploration and development of mines in the study area occurred in the early 1900's and ceased following a period of exploration for domestic sources of strategic and critical minerals during the Second World War. Many of the documented occurrences are of mineralogical and historical interest (such as corundum, asbestos, phosphate). However, these occurrences are unlikely to become exploration targets for mining in the future because the mineral products are no longer used or because of the low grades and small sizes of the deposits in the study area relative to readily available economic deposits elsewhere.

This chapter includes a tabulation of known mines, prospects, and mineral occurrences in the study area. In addition, the deposits are classified in terms of the deposit models described in Chapter A (tables A3 and A4), past production data are summarized, and recent mining-claim activity is reviewed. Chapter F includes chemical analyses of rocks associated with some of the deposits discussed here.

Data Sources

Many data sources were consulted to determine the distribution and nature of known and potential mineral resources in the study area. These include the U.S. Geological Survey's Mineral Resource Data System (MRDS) (Mason and others, 1996), the Minerals Availability System/Mineral Industry Location System (MAS/MILS) developed by the former U.S. Bureau of Mines (U.S. Bureau of Mines, 1995), Bureau of Land Management's Mining Claim Recordation System (MCRS) database for September of 1996, and State mining directories published by the Montana Bureau of Mines and Geology (McCulloch, 1994). Johnson and others' (1993) thorough review of mines and prospects in the Gallatin National Forest included a tabulation of locations, a review of the MAS/MILS database (U.S. Bureau of Mines, 1995) and property files, and summary descriptions of the nature of the occurrence, the workings and production, and information on samples and resources. Their analysis of the spatial distribution of active, and recently active, mining claims within the Gallatin National Forest showed that with few exceptions (noted in the following discussion), little mining industry activity has focused on the study area. Data from all of these sources were combined with information collected during selected site visits by the author to determine the types of mineral deposits present, or likely to be present, in the study area.

Locations of mines, prospects, and mineral occurrences from the MAS/MILS and MRDS databases are shown in figures C1 and C2. Because the two databases are different in scope and purpose, contain somewhat different data entry fields, and commonly contain slightly different locations for a site, we chose to show the data separately. The MRDS system emphasizes information about local geology, host rock, and mineralogy whereas the MAS/MILS system emphasizes production, development status, and mining method information and lacks the geologic detail necessary for classifying sites in terms of mineral deposit type. The MAS/MILS database is more comprehensive than MRDS with respect to leasable and saleable mineral sites (such as pumice, sand, and gravel). MAS/MILS sites are plotted according to the principal commodity listed in the database (fig. C1). MRDS sites (fig. C2) are subjectively assigned to the most appropriate mineral deposit model (table A3) based on the data in the MRDS record as well as site visits, and consideration of the geologic context of the site. Table C1 includes a subset of the data fields contained in the complete MRDS site record, keyed to the map locations plotted in figure C2.

Past Production

Data on past production for mines within the study area are scarce. Most of the workings within the study area are prospects (table C1), rather than developed deposits. Available records are limited for deposits that did produce, and these records commonly report production as "small" rather than as quantified tonnages of ore. Data on past production, reserves, and estimated resources are summarized in table C2.

Inactive and Abandoned Mines

Two recent studies address issues of environmental, health, or safety problems associated with inactive and abandoned mines in the State of Montana. These studies were not used in conducting this assessment but are mentioned to alert interested readers to the existence of additional data covering the study area.

The Montana Department of State Lands (1995) issued a summary report on abandoned hardrock mine priority sites based on a Hazardous Materials Inventory conducted for the Montana

Abandoned Mine Reclamation Bureau in 1993 and 1994. The inventory characterized and ranked abandoned hardrock mine sites and includes new data on the extent of workings and tailings based on site visits, as well as geochemical data for samples of water and solid materials. Inventory sites within and adjacent to the Madison-Gallatin subarea are noted in table C3. None of the sites inventoried is in the Bridger Range or Crazy Mountains subareas.

In 1992, the Northern Region of the United States Forest Service and the Montana Bureau of Mines and Geology initiated a systematic program to identify and characterize abandoned and inactive mines within or affecting National Forest lands in the State. This program responds to Federal mandates of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Under this program inventories have been completed for several forests (Hargrave and others, 1999; Madison and others, 1998; Marvin and others, 1995; and Metesh and others, 1994; 1995a, b; 1998). Mining district boundaries and districts names (figs. C1, C2) are those outlined on a new mining disrict map developed by the Abandoned Mines Reclamation Bureau and the Montana Department of State Lands. The new map (Chavez, 1994) incorporates all known mines and prospects into contiguous mining districts to facilitate site inventory. The districts include historical districts as defined in Sahinen (1935) and Gilbert (1935), as well as modified districts and new districts that were defined to include sites that did not fall within or near historical districts.

Madison-Gallatin Subarea

Approximately 100 inactive mines, prospects, and mineral occurrences lie in and near the subarea (figs. C1, C2). Except for a small amount of placer gold recovered from the Gallatin River drainage, the only locatable metal mine that produced was the Sunshine mine (fig. C2; tables C1 and C2, no. 8) where a small amount of lead, zinc, gold, and silver was recovered from a quartz vein prior to 1968. The site has subsequently been reclaimed by the Forest Service. More significant metal production came from polymetallic vein deposits in an area immediately northwest of the subarea boundary in the Norris (fig. C2) and Red Bluff mining districts, in an area that was historically called the lower Hot Springs district. These mines (Boaz, Josephine, Red Bluff) produced several thousand ounces of gold and silver as well as copper and lead from narrow quartz veins along shears in Archean gneiss (Pinckney and others, 1980). Scattered copper, base-, and precious-metal occurrences throughout the subarea probably represent polymetallic veins spatially associated with intrusive centers. The Apex group claims (fig. C2; table C1, no. 16) represent the only documented occurrence of skarn in the study area. At the Apex claims, slightly

anomalous copper and gold are reported in a small, lenticular, magnetite-bearing, skarn pod along a contact between andesite porphyry and limestone. Workings include caved adits, pits, and a shaft; no production is recorded for the site.

Although the subarea is relatively devoid of metallic mineral deposits, other commodities including asbestos (fig. C1; tables C2, C4), mica, and kyanite and related minerals have been produced in the past. Two different types of asbestos were produced in the subarea: chrysotile and anthophyllite. The only source of commercial chrysotile asbestos in the State of Montana, the Little Mile Creek (Cliff Lake) asbestos deposit (fig. C2; tables C1, C2, no. 41), produced more than 2,000 tons of asbestos until 1940. The chrysotile occurs in narrow veinlets in serpentinized marble in Archean rocks intruded by gabbro (see table F1 for chemical analysis of this gabbro). Perry (1948) attributed the failure of the mine to the small amount of asbestos present and the lack of long fiber forms of the mineral. A number of mines in the Forest produced anthophyllite (amphibole) asbestos from open pit and underground workings. At Table Mountain (fig. C2; table C1, no. 60), anthophyllite occurs with chromite and other minerals in amphibolite lenses surrounded by chromite-bearing (iron-rich) chlorite schist in Archean granitic gneiss. Becraft and others (1966) evaluated the asbestos and chromite occurrences in the Spanish Peaks Primitive Area (Table Mountain, Moon Lake, and others) and cited small deposit size, relatively low grade, and difficult access as detrimental factors to potentially economic deposits of both minerals. At the Karst deposit (fig. C2; tables C1–C3, no. 9), anthophyllite asbestos occurs in small bodies of altered peridotite (see table F1 for chemical analysis of this peridotite). Estimates of the percentage of asbestos in the rock that was mined range from 30 to 50 percent (Perry, 1948); near-vertical veins of asbestos fibers as long as 1 ft grew perpendicular to the wallrock, although some of the fibers are bent, preserving folds.

Archean metasedimentary rocks (aluminous gneiss and schist) in the northern part of the Madison Range host local deposits of aluminosilicate minerals (mostly sillimanite, some kyanite and corundum). These deposits were discovered by Reno Sales before 1900 and developed as domestic sources of abrasives in the early 1900's. The Beartrap corundum deposit (fig. C2, table C1, no. 51), which straddles the northwestern study area boundary, was explored in the 1940's but never produced. Two deposits that lie outside of the study area, the Elk Creek and Bozeman deposits (fig. C2, tables C1–C2, nos. 1 and 2) produced small tonnages of corundum. Exploration and development ceased as post-World War II demands for domestic sources of abrasives decreased and studies by the U.S. Bureau of Mines (Claybaugh and Armstrong, 1950) established the small size of the reserves. These corundum deposits probably formed by metamorphism of a white mica schist which itself

was formed from prior metamorphism and desilication of a precursor aluminous shale (Bakken, 1980). These deposits are quite different from the gem quality sapphire (corundum) deposits found elsewhere in Montana, such as the well-known Yogo deposits near Lewistown. Unlike the memorphic deposits in the Madison Range, the source of the Yogo sapphires is a Tertiary lamprophyre dike (Berg, 1990).

The U.S. Bureau of Mines (Johnson and others, 1993) reported a small amount of production of ilmenite from a heavy mineral placer deposit in the Spanish Creek Reservoir area just north of the study area boundary (fig. C2, table C1, no. 3), and they estimated ilmenite resources for the Gallatin River drainage (table C2).

Phosphate occurs in a number of localities in the central part of the subarea (Eldridge district, fig. C2) where rocks of the regionally extensive Permian Phosphoria Formation crop out at or near the surface in thin, discontinuous beds. Swanson (1970) estimated phosphate resources for Permian rocks in southwest Montana and concluded that the grades and tonnages of local occurrences of phosphate rock in the Madison-Gallatin subarea were too meager to warrant economic consideration.

A welded tuff capping Porcupine Ridge (fig. C2, table C1, no. 59) was worked for ornamental stone in the past (Berg, 1974). Talc is reported in dolomite at several localities (fig. C2, table C1, nos. 47, 48, 49) southwest of the study area (Berg, 1979). The dolomite unit continues into the study area, but no talc occurrences have been documented within the subarea boundaries.

Review of the Bureau of Land Management's mining claims database (MCRS) for Gallatin County, which covers most of the subarea, shows that a few lode claims located in the last 20 years in the Madison-Gallatin subarea were held until the early 1990's and then dropped. Some of the larger claim blocks were in the Hyalite Canyon area, east of Chestnut Mountain, and in the Rat Lake area (see MCRS for specific locations), all of which are in the Bozeman mining district (figs. C1, C2). The only recently active claim (for which assessment activity was recorded in 1995 or 1996) in the subarea is Pacer Corporation's Santa Ann lode claim located in sec. 35, T. 4 S., R. 4 E., an area east of Storm Castle in the Bozeman mining district.

The only site within the subarea cited in the Hazardous Materials Inventory of abandoned mine lands (Montana Department of State Lands, 1995) is the Karst asbestos deposit (fig. C2, table C3, no. 9); asbestos concentrations in water did not exceed U.S. Environmental Protection Agency standards. Two sites near the study area in the Norris mining district were cited, and other sites investigated within the study area were subsequently dropped from the State priority site list.

Bridger Range Subarea

All of the known mineral occurrences in the Bridger Range subarea lie on the western flank of the Bridger Range where Middle Proterozoic age rocks of the LaHood Formation, the lowermost unit of the Belt Supergroup, are in fault contact with Archean crystalline rocks to the south (Pass fault) and Paleozoic rocks to the northeast (Cross Range fault) (fig. B3*B*). The Pass Creek mine (fig. C2; tables C1, C2, no. 79) and adjacent Lower and Upper Cooper deposits (fig. C2, table C1, nos. 80, 81) produced copper, lead, zinc, gold, and silver prior to 1950 (table C2). The area was explored for stratiform base metal deposits intermittently until 1990. Johnson and others (1993) recognized two distinct types of mineralization in the district: (1) polymetallic veins that contain galena, sphalerite, pyrite, chalcopyrite, covellite, arsenopyrite, barite, molybdenite, cerussite, anglesite, and smithsonite in a quartz-carbonate matrix in gouge zones associated with the Cross Range fault and (2) stratiform sulfide-bearing replacement bodies containing pyrite, chalcopyrite, covellite, galena, and sphalerite in a limonite-quartz-carbonate-barite gangue in carbonaceous shale. The shales are interbedded with lithic arkoses in the LaHood

Formation. The second style of mineralization is typical of sedimentary-exhalative (sedex) deposits. Exploration interest in the area is due to the occurrence of economically significant sedex massive sulfide deposits in rocks of the lower part of the Belt Supergroup elsewhere. These include the Sheep Creek deposit 60 mi north of the subarea and anomalous gold associated with the LaHood Formation at the Golden Sunlight deposit about 50 mi west of the study area.

The lead isotopic signatures of galenas hosted by Middle Proterozoic Belt Supergroup rocks throughout the northwest fall into two distinct populations that represent Precambrian (Coeur d'Alene type) and Mesozoic to Cenozoic ages of mineralization (Zartman,1988). Galenas in shear-controlled, fracture-filling veins in the LaHood Formation along the Cross Range fault in the Bridger Range belong to a population of samples having lead isotopic signatures with high $^{207}Pb/^{204}Pb$ (Middle

Proterozoic, Coeur d'Alene type lead) in the Helena embayment (west of the Helena salient, Chapter B). These data show that the lead was introduced into the clastic sediments that became the LaHood Formation about the time of deposition or during early diagenesis, around 1,400 Ma (R.L. Zartman, written commun., 1994). These data provide permissive, though not definitive, evidence for an association of galena with sedex-type deposits rather than with polymetallic vein deposits related to Mesozoic or Tertiary intrusive centers. The stratigraphic setting, mineralogy, and stratiform nature of mineralization at Pass Creek are consistent with sedex-type deposits (Johnson and others, 1993). However, the classic zoning and alteration patterns associated with sedex deposits are not recognized, and lead that was originally deposited in Precambrian time could have been remobilized during later tectonic and igneous activity, thereby obscuring the primary nature of the ore deposit.

Johnson and others (1993) provided a map of the Pass Creek mining area, within the Bridger district, and calculated identified resources for vein deposits in the area (fig. C2; table C2, nos. 79, 81, 82, 88). They also suggested that shale-rich parts of the LaHood Formation north of the workings, and areas along the Cross Range Fault near Fairy Lake (sec. 22, T. 2 N., R. 6 E.), might have potential for additional deposits. More than 100 lode claims were located in the Pass Creek area in the western part of the Bridger Range in the 1970's and 1980's; however, no assessment work on these claims has been recorded since 1992.

The Mill Creek Canyon mine (fig. C2, table C1, no. 73) is reported as a minor barite occurrence (Berg, 1988). Galena and cerussite occur with barite in the workings along the Cross Range fault (fig. B3*B*), which suggests that this locality represents barite gangue associated with a polymetallic vein.

No other mineral deposit types have been recognized within the Bridger Range subarea. A number of calcite deposits (fig. C2, tables C1 and C2, nos. 82–89) just east of the subarea boundary were mined prior to 1950. Hydrothermal veins containing optical grade calcite (mined for use in gunsights in the 1940's), minor amounts of zeolite minerals (laumontite and stilbite), and chalcedony cut volcaniclastic sedimentary rocks of the Cretaceous Livingston Formation (Stoll and Armstrong, 1958). The Livingston Formation is present in the subarea (Wilson and Elliott, 1995, 1997), but no calcite occurrences are documented there.

Crazy Mountains Subarea

The only mineralized area in the Crazy Mountains subarea is the Big Timber Creek area (fig. C2, no. 90), on the northeast flank of Granite Mountain. Sulfide minerals (pyrite, chalcopyrite, galena, arsenopyrite, anglesite, and possibly tetrahedrite) are present in quartz veins along shear zones in locally altered diorite and quartz monzonite phases of the Eocene Big Timber stock (du Bray and others, 1993). A few tons of ore were reportedly shipped from the Stemwinder (fig. C2; tables C1, C2, no. 90). In the 1950's, the Half Moon Mining Company developed the Half Moon mine (fig. C2; tables C1, C2, no. 91) and reportedly produced some high-grade ore (Johnson and others, 1993). The Half Moon was the most extensively developed property in the district; workings include a small glory hole, several small pits, and adits (caved and flooded). Viking Exploration, Inc., drilled the property in the 1970's. The U.S. Bureau of Mines calculated identified resources of 116,000 tons of ore containing gold, silver, copper, and lead (Johnson and others, 1993). In the 1920's, an adit was driven along a fracture at the Kelly prospect (fig. C2; table C1, no. 92), but no ore was intercepted (Reed, 1950). All of these occurrences fit a model of polymetallic veins associated with the Big Timber stock, although zinc appears to be erratically distributed or absent (see Chapter D) compared to the other metals (copper, lead, minor gold, and silver).

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Geochemistry: Stream Sediments

By Robert R. Carlson and Gregory K. Lee

U.S. Geological Survey Professional Paper 1654–D

U.S. Department of the Interior
U.S. Geological Survey

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Geochemistry: Stream Sediments

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Geochemical Surveys

The geochemical contributions to the mineral resource assessment of the northern and western portions of the Gallatin National Forest (hereinafter referred to as the study area) were derived from data that include analyses of 946 stream-sediment samples from the U.S. Geological Survey (USGS) geochemical databases. Of these, 57 samples were collected by USGS personnel in 1992, and 889 were collected in 1976 as part of the National Uranium Resource Evaluation (NURE) program under the Department of Energy. In addition to the analyses performed on the USGS-collected samples, the archived NURE samples were reanalyzed by the USGS to provide analytical consistency and to obtain information for concentrations of elements that were not included in the Los Alamos Scientific Laboratory (LASL) reports (Bolivar, 1980; Shannon, 1980; Bendix Field Engineering Corporation, 1981).

Methods of Study

Analytical Techniques

Stream-sediment samples collected in 1992, together with archived stream-sediment samples collected previously for the NURE program, were analyzed for 40 elements by inductively coupled argon plasma-atomic emission spectroscopy (ICP–AES) using a method described by Crock and others (1983). These samples were also analyzed for 10 elements by ICP–AES using the method described by Motooka (1988). Low-level gold determinations were also performed using the graphite furnace atomic absorption (GF–AA) method described by O'Leary and Meier (1986). The only LASL data evaluated and included in this report were for samples analyzed by delayed neutron counting, neutron activation, and X-ray fluorescence for uranium, gold and thorium, and tungsten concentrations, respectively (Bolivar, 1980; Shannon, 1980; Bendix Field Engineering Corporation, 1981).

Methods of Geochemical Interpretation

The stream-sediment sample localities are quite evenly distributed in the Madison-Gallatin subarea but are more concentrated around the peripheries of the Crazy Mountains and Bridger Range subareas (fig. D1). Most gaps in the sampling occurred along high ridges, in bodies of water, and in a few areas inaccessible to NURE and (or) USGS sampling crews. Rock samples were collected at selected sites to determine sources for geochemical anomalies not attributable to known or expected mineralization; these data are reported in chapter F. Although concentrations for 41 different elements were determined by the analyses, the following 15 elements were considered to be of primary geochemical importance in the assessment of resource potential in the study area due to their areal distributions, associations, and potential relationships with the region's mineralizing systems and mineral deposits: silver (Ag), arsenic (As), gold (Au), bismuth (Bi), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), tungsten (W), and zinc (Zn).

Statistical Methods

The data produced from the GF–AA, ICP–AES, and selected LASL analyses were treated separately in terms of statistical reduction and the determination of anomaly thresholds. In each case, thresholds (highest background concentrations) were determined by calculating the highest reportable value below 2 standard deviations (2 σ) above the geometric mean for each selected element. Extrapolated areas of stream-sediment samples containing concentrations at or above these thresholds are plotted in figures D2–D10. Figures D11 and D12 show localities of stream-sediment samples (centered in a 2 mile-diameter circle) that produced analytical results of 50 parts per billion (ppb) or greater gold. This gold concentration approximates the 2 σ anomaly for all subareas.

Surface Modeling

Each of the elements presented in this report was modeled using Dynamic Graphics, Inc. EarthVision software. In this process, the scattered point data were interpolated using an algorithm described as a bi-cubic spline of minimum tension. The calculations were performed to produce a gridded array whose cell dimensions are one-half the average distance between sample points. The resultant continuous geochemical surface grids were used as input to the applied geographic information system (GIS). The ranges of the element surface values were constrained to the minimum and maximum data values of each modeled variable.

Geographic Information Systems (GIS)

Erdas, Inc., IMAGINE image-processing/GIS software was used to interpret the geochemical surface models and to integrate them with geospatial reference features. The EarthVision surface model grids were imported by IMAGINE, smoothed using bilinear interpolation resampling, and were color encoded to display the various elements and combination of elements. The

areas of color display were determined by calculating the means and standard deviations (sigmas) of the geochemical landscapes (surface models) within the study area. Those areas in excess of 2-sigma greater than the mean of each element concentration range were displayed. The resulting geochemical surfaces were draped over digital shaded-relief topography to provide geographic reference (figs. D2–D10). Analyzed samples from localities adjacent to the subareas were used in statistical modeling of anomalous surfaces, but the representation of those surfaces seen in figures D2–D10 have been attenuated (clipped) at the edge of a 5-km zone surrounding each subarea.

Geochemically Anomalous Areas

Following is a description of geochemical anomalies found in stream sediments within and proximal to the study area. The spatial context of the anomalies is provided, when applicable, in terms of location within the individual mineral potential tracts (see fig. A3, table A4); otherwise, the anomalies are geographically referenced.

Crazy Mountains Subarea

Crazy Peak Tertiary Porphyry Copper Tract

Several trace elements that could be associated with porphyry copper (copper-molybdenum, copper-gold) deposits were determined at slightly anomalous levels in and around the tract (figs. A3B, D2–D5). Of these, only molybdenum and silver anomalies, centered on the Eocene Big Timber stock (in the central part of the subarea) and extending to the northwest, suggest proximity to the center of a possible porphyry deposit. A much stronger signature of zinc, cobalt, manganese, arsenic, bismuth, and minor lead, centered on the stock, are indicative of a more distal relationship to any potential porphyry deposit. Several isolated occurrences of slightly anomalous antimony are seen on the perimeter of the tract but may not be related to the stock. Likewise, a concentration of slightly anomalous gold and copper values exists along the western boundary of the tract but is likely not associated with the stock (see Shields River tract discussion herein). The area of anomalous copper, silver, lead, zinc, arsenic, antimony, and bismuth north of the tract appears to be associated with the Loco Mountain stock (just outside the assessment area to the north of the Big Timber stock), not the Big Timber stock.

Big Timber Creek Polymetallic Veins Tract

The anomalous zinc, arsenic, antimony, bismuth, silver, manganese, and minor lead signatures centered on, and to the northwest and east of, the Big Timber stock (figs. A3B, D3–D5) are probably associated with polymetallic veins. Two gossany veins of country rock (igneous rocks of the stock) with visible galena, sphalerite, pyrite, and other sulfide minerals were observed near stream-sediment sample sites on Big Timber Creek and Milly Creek, north of Crazy Peak. The Half Moon mine (fig. C2, table C1, no. 91), which has visible galena and sphalerite, is located on the northeast flank of Granite Peak above Big Timber Creek and within the area of anomalous geochemistry.

Shields River Alkaline Gabbro-Syenite Gold Tract

Slightly anomalous gold values determined in samples collected from streams draining the central and southern portions of the tract (figs. A3B and D2) could be associated with alkaline gabbro-syenite hosted copper-gold-platinum-group deposits or gold-silver-telluride veins. Scattered minor occurrences of slightly anomalous copper, silver, and antimony are also shown in figures D2–D4. A change in general stream-sediment geo- chemistry (representing the exposed rock assemblage of the Shields River tract versus the main areas of the Crazy Peak and Big Timber Creek tracts) occurs along a drainage divide that separates these anomalies from the anomalies shown in the main areas of the Crazy Peak and Big Timber Creek tract.

Northern Gallatin Placers

Sites of stream-sediment samples containing gold concentrations of 50-ppb level or higher are shown in fig. D11. These values suggest that gold placer deposits may exist at or near these sites if sufficient alluvial sand and gravel accumulations are also present. Gold found in samples collected in the northern part and along the western boundary of the Crazy Mountains subarea was probably derived from the rocks of the Shields River tract, which dominate the stream-sediment composition. Sites along the southern boundary of the subarea appear to have rocks of the Crazy Peak and Big Timber Creek tracts as their sources of gold.

The gold-containing samples in and around the Bridger Range subarea are too few and too scattered to provide an estimate of possible sources. The lone occurrence to the west of the area could have any one of the Bridger Range subarea tracts (described herein) as its source. No known geologic or geophysical signatures exist that would explain the three occurrences in the southeast portion of the subarea.

Other Anomalous Areas

The area containing anomalous lead concentrations in the southeastern corner of the Crazy Mountains subarea (fig. D3) is unexplained. Because other anomalous trace elements that are normally associated with naturally occurring lead are not present, contamination from human activity is a possible source.

The area on the northeast flank of the subarea that contains anomalous concentrations of zinc, bismuth, cobalt, manganese, and iron is also unexplained. It is not considered to be a likely source area for these elements based on exposed geology and subsurface geophysical data. The anomalous concentrations of these elements either may represent contamination from human activities or define an area of higher concentrating capabilities for these elements.

Bridger Range Subarea

Flathead Pass Porphyry Copper Tract

Figures D2 and D4 show an area of anomalous arsenic, bismuth, molybdenum, and antimony centered on the tract (fig. A3B). These four elements are part of the group of associated elements that are indicators for possible porphyry copper (copper-molybdenum, copper-gold) deposits.

Bridger Range Polymetallic Veins Tract

Figures D3 and D4 show an area of anomalous arsenic, bismuth, and antimony centered in the tract and zinc and lead at scattered locations within the tract (fig. A3B), and its extrapolations. These elements are part of a group of associated elements that are indicators for possible polymetallic vein deposits.

Blacktail Mountain Skarn Tract

Figures D2–D4 show anomalous arsenic, antimony, bismuth, zinc, and molybdenum downstream from the southeastern end of the tract (fig. A3B). These elements are part of the groups of associated elements that are indicators for possible skarn-type deposits.

Pass Creek Sedimentary Exhalative Zinc-Lead Tract

Manganese, iron, molybdenum, lead, arsenic, antimony, and zinc anomalies can be associated with sedimentary exhalative (sedex) zinc-lead deposits. Figure D5 shows moderately to highly elevated manganese and iron concentrations downstream to the west and southwest of the tract (fig. A3B); figure D3 shows slightly elevated zinc and lead concentrations

downstream to the west of the northern end of the tract; figure D2 shows slightly elevated concentrations of molybdenum downstream to the west and on the eastern edge of the tract; and figure D4 shows anomalous concentrations of arsenic and antimony downstream to the east of the north end of the tract.

Other Anomalous Areas

Figures D2–D5 show anomalies of copper, lead, zinc, bismuth, cobalt, manganese, iron, and antimony in the northern end of the subarea. However, the geologic terrane (Wilson and Elliott, 1997) and geophysical aeromagnetic and

Bouguer gravity data (Chapter E) do not indicate potential mineralizing systems in this area. Figures D3 and D5 show anomalies of zinc, silver, cobalt, manganese, and iron in the southern end of the subarea, but the geologic terrane and geophysical data do not indicate that potential mineralizing systems are present. Further ground investigations for alteration minerals might provide an explanation for these anomalies.

Madison-Gallatin Subarea

Gallatin Range Tertiary Porphyry Copper, Epithermal Veins Tract

Geochemical indications of possible porphyry copper (copper-molybdenum, copper-gold) deposits or epithermal veins are suggested by anomalous tungsten (fig. D6) and cobalt (fig. D9) centered in the tract, and minor occurrences of gold, zinc, and bismuth (figs. A3A, D6, D7, D9) at the periphery. The spatial associations of these anomalous elements and the absence of other supportive trace-element anomalies, however, do not present a pattern of the expected geochemical zoning for porphyry copper (copper-molybdenum, copper-gold) deposits. Nor do they represent element assemblages typical of epithermal vein deposits (Cox and Singer, 1986).

Lone Mountain Cretaceous Porphyry Copper Tract

The observed anomalous trace elements that could be associated with porphyry copper (copper-molybdenum, copper-gold) deposits consist of minor lead and gold (figs. D6, D7) and extensive low-to-moderate concentrations of arsenic and antimony (fig. D8) that appear to be associated with exposed intrusive rocks of the Lone Mountain laccolith but also correspond spatially with exposures of the Livingston Formation in the area. A somewhat separate area of anomalous arsenic and antimony (fig. D8) extends considerably south of the exposed laccolith and Livingston Formation. Although typical of outer zones of porphyry copper (copper-molybdenum, copper-gold) deposits (Cox and Singer, 1986), the more southern arsenic and antimony anomaly lacks geochemical and geophysical signatures that would indicate a porphyry copper deposit association.

Snowslide Creek Cretaceous Porphyry Copper Tract

The only geochemical indication of possible porphyry copper (copper-molybdenum, copper-gold) deposits in this tract (fig. A3A) is an area of anomalous manganese and arsenic concentrations. These anomalies are centered on the tract and are shown in figure D8.

Big Sky Polymetallic Veins, Skarn Tract

The observed anomalous trace elements that could be associated with possible polymetallic vein deposits in the tract (fig A3A) are low-to-moderate levels of arsenic and antimony (fig. D8) and minor anomalies of zinc, copper, lead, silver, and gold (figs. D6, D7). The observed anomalous trace elements that could be associated with possible skarn-type deposits in the tract consist of low-to-moderate levels of arsenic and antimony, and minor anomalies of lead, gold, zinc, cobalt, iron, and copper (figs. D6–D9).

Gallatin River Polymetallic Veins Tract

Figures D6–D9 show minor scattered anomalies of zinc, copper, silver, gold, antimony, arsenic, bismuth, and manganese in the tract (fig. A3A). These elements are part of a group of associated elements that are indicators for possible polymetallic vein deposits.

Madison Mylonite Zone Polymetallic Veins Tract

Figures D6–D8 show scattered anomalies of copper, lead, zinc, arsenic, and antimony in the tract (fig. A3A). These elements are part of a group of associated elements that are indicators for possible polymetallic vein deposits.

Ramshorn Peak Skarn Tract

Observed anomalous trace elements that could be associated with skarn-type deposits in the tract (fig. A3A) consist of minor anomalies of copper, tungsten, gold, silver, lead, manganese, antimony, arsenic, and cobalt (figs. D6–D9). None of these anomalies, however, is spatially associated in a geochemical assemblage that characterizes any of the various skarn-type deposits (Cox and Singer, 1986).

Hyalite Peak Skarn Tract

The observed anomalous trace elements that could be associated with possible skarn-type deposits in the tract (fig. A3A) comprise low-to-moderate concentrations of iron, cobalt, and tungsten centered in the tract and minor scattered anomalies of zinc, gold, antimony, manganese, and bismuth (figs. D6–D9). The anomalous iron and cobalt that are spatially associated in the center of the tract are indicative of possible iron skarn-type deposits. A small area along the Gallatin River at the western edge of the tract shows an assemblage of anomalous zinc, manganese, cobalt, gold, and iron that could also indicate possible skarn-type deposits, most closely approximating the expected geochemical assemblage of lead-zinc skarns (Cox and Singer, 1986).

Hilgard Peak Nickel-Copper, Chromite Tract

Observed trace elements that could be associated with these types of deposits consist of minor anomalies of copper, nickel, chromium, and cobalt (figs. D9, D10). The assemblage of anomalous nickel, copper, cobalt (and iron) in the southeast corner of the tract (fig. A3A) is indicative of a possible gabbroic nickel-copper-type deposit (Cox and Singer, 1986).

Spanish Peaks Nickel-Copper, Chromite Tract

Observed trace elements that could be associated with these types of deposits consist of low-level nickel, copper, cobalt, and chromium anomalies. These anomalies are mostly concentrated in an extensive area at the southwestern edge of the tract (fig. A3A) and extending toward the middle of the tract (figs. D9, D10).

Gallatin Forest Placers

Sites of stream-sediment samples containing gold concentrations of 50-ppb level or higher are shown in figure D12. These values suggest that gold placer deposits may exist at or near these sites if sufficient alluvial sand and gravel accumulations are also present.

Other Anomalous Areas

The area of anomalous nickel, copper, cobalt, and chromium (figs. D9, D10) at the southern edge of the Madison-Gallatin subarea is characterized by Tertiary rocks of basaltic composition. This assemblage of elements in mafic rocks is indicative of possible gabbroic nickel-copper-type deposits and chromite deposits (Cox and Singer, 1986).

Near the southwest corner of the subarea is an assemblage of anomalous zinc, lead, copper, manganese, silver, arsenic, antimony, and bismuth (figs. D7–D9) that occur in an area of Archean dolomitic marble carbonate rocks. These elements, in this geologic setting, are indicative of possible skarn-type deposits, most closely approximating the expected geochemical assemblage of copper or lead-zinc skarns (Cox and Singer, 1986). Southeasterly along the subarea boundary is another assemblage of anomalous zinc, lead, antimony, manganese, and silver that occurs in an area of Paleozoic and Mesozoic carbonate rocks.

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Geophysics

By Dolores M. Kulik

U.S. Geological Survey Professional Paper 1654–E

U.S. Department of the Interior
U.S. Geological Survey

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Geophysics

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Introduction

Gravity anomalies (fig. E1) are caused by differences in density of igneous, metamorphic, and sedimentary rocks and their distribution within the Earth's crust. Differences occur where rocks with contrasting densities are juxtaposed by faulting and folding, intrusion, facies changes, or stratigraphic deposition. Magnetic anomalies (fig. E2) reflect differences in magnetic susceptibility caused by varying amounts of magnetic minerals in the rocks; the susceptibility of a rock generally depends only on its magnetite content. Magnetic anomalies usually reflect differences in magnetization only of igneous rocks and some metamorphic rocks. Sedimentary rocks, except for banded iron formation, are commonly considered nonmagnetic and produce anomalies only in unusual instances .

Gravity data are interpreted in terms of the average bulk density of bodies of rock, measured in grams per cubic centimeter (g/cm^3). The density of any particular rock is determined by the densities of the individual minerals that make up the rock, their proportions, and the porosity (amount of empty space between grains or crystals). Bulk density is the combination of grain densities of the minerals and the amount of open pore space with density of 0.0 g/cm^3 (the porosity); the higher the porosity, the lower the bulk density. The higher the density, the more the rock weighs per measured unit, and the greater is the attraction of gravity on it. As a simplification, a gravity map can be thought of as a pattern of weight distribution of the rocks.

Metamorphic rocks in the upper crust (such as gneiss, schist, quartzite) usually have relatively high densities (2.6–3.0 g/cm^3) because the metamorphic processes cause the compaction of the rocks (thus decreasing the porosity) and the growth of higher density minerals at the expense of lower density ones. Sedimentary rocks (such as, sandstone, siltstone, conglomerate) usually have lower densities (2.2–2.6 g/cm^3), and unconsolidated fill materials (such as sand, gravel) in valleys have densities lower still. Limestone is a notable exception, as it generally has a high density (2.6–2.8 g/cm^3); it has a very low porosity and is composed mostly of calcite (2.72 g/cm^3), which has a higher density than quartz (2.65 g/cm^3), the major constituent of most common sedimentary rocks.

The gravity anomaly associated with a rock body is also influenced by the rocks adjacent to the body. For example, a granitic intrusion with an average bulk density of 2.62 g/cm^3 will produce a high gravity anomaly if it intrudes a terrane of sandstone and siltstone with an average bulk density of 2.57 g/cm^3. The same granitic intrusion, however, will produce a low gravity anomaly if it intrudes a terrane of metamorphic rocks with an average bulk density of 2.70 g/cm^3. Thus, the character of the anomaly depends on the densities of rocks in the surrounding area.

Gravity data are usually presented as a Bouguer anomaly map—that is, a map of variations in measured gravity values from the theoretical, or expected, values at the points of measurement. A mathematical correction, known as the Bouguer correction, has been applied to the data to account for the gravitational attraction of the rocks between the elevation of the measurement and a standard datum (usually sea level). The unit of gravity measurement is the mGal (milligal) and represents a measure of acceleration.

As the gravity map shows the distribution of rock density, the aeromagnetic map shows the distribution of magnetic intensity (the degree of rock magnetization). Magnetic intensity depends on the magnetic susceptibility of the rock (mainly its magnetite content) and the distance of the rock from the sensor of the magnetometer used to measure it. Some minerals other than magnetite (such as hematite, ilmenite, pyrrhotite) contribute to the susceptibility. Magnetic anomalies may be caused by differences in lithology (hence differences in magnetic susceptibility) or differences in depth of burial of the magnetic sources in the crystalline basement rocks. The measured intensity decreases with the distance of the magnetic source from the sensor; thus, a deeply buried rock will have a lower measured intensity than the same rock measured at the surface.

The gradients of magnetic anomalies are caused by the degree of contrast in magnetic susceptibility between adjacent rock sources and by the depth at which the bodies lie. Magnetic data are measured in nanoteslas (nT), which are equal to a previously used unit, the gamma. Both are equal to 10^{-5} oersted or 0.00001 gauss.

Most magnetic surveys are measured from aircraft, and the distance to the magnetic source is an important influence on the measured intensity. If the survey aircraft flies at a constant elevation, magnetic sources in peaks and ridges will be closer to the sensor than similar rocks in the valleys and flat-lying country. Magnetic surveys are often "draped"; that is, the pilot attempts to maintain a constant elevation above the topography (for example, 400 ft). Computer programs may be used to compare constant flight elevation to topography, and the measured intensity is mathematically corrected for the differences in elevation. Computer programs are also used to extrapolate survey values upward or downward. This means that the measured values are changed by mathematical computation to the values that would have been measured if the survey had been flown at a different elevation. These techniques allow a survey flown at one elevation to be compared directly to another flown at a different elevation, or an undraped survey to be compared to a draped one. If many surveys are mathematically converted in this way to a single style and elevation, they may be merged into one data set and plotted as a single map. This process has been used to produce the magnetic anomaly map (fig. E2).

Data Sources

Gravity Data

Gravity data for this study were obtained from files maintained by the Defense Mapping Agency of the U.S. Department of Defense. These data were supplemented by approximately 120 stations measured by the author in 1992. Stations measured for this study were established using a Worden gravimeter W–177. The data were tied to the International Gravity Standardization Net 1971 at base station ACIC–0673 at Livingston, Mont. (U.S. Defense Mapping Agency, Aerospace Center, 1974) Station elevations were obtained from benchmarks, spot elevations, and interpolated estimates from topographic maps at 1:24,000 and 1:62,500 scales. Elevations are accurate to ±20–40 ft. The error in the Bouguer anomaly is less than 2.5 mGal for errors in elevation control. Bouguer values were computed using the 1967 gravity formula (International Association of Geodesy, 1967) and a reduction density of 2.67 g/cm^3. Mathematical formulas are given in Cordell and others (1982). Terrain corrections were made by computer for a distance of 167 km from each station using the method of Plouff (1977). The combined gravity data are shown in figure E1 as a complete Bouguer gravity anomaly map with a contour interval of 5 mGal.

Aeromagnetic Data

Residual total intensity aeromagnetic data are shown in figure E2 with a contour interval of 100 nT. Individual surveys of the aeromagnetic map were projected to Cartesian coordinates. The data from each survey were interpolated to a 0.5 km × 0.5 km square grid and the regional field was mathematically removed. Data were continued upward or downward and draped at 1,000 ft (305 m) above terrain. Each survey was then regridded and merged to adjoining surveys. Details of the processing techniques are given in McCafferty (1991).

Geophysical Interpretations

Gravity stations are sparse in parts of the study area, and contours are based on gridded data which were mathematically interpolated between randomly located measurements. Similarly, some of the aeromagnetic data are measured on widely spaced flightlines, interpolated between lines, and gridded and contoured by computer programs based on mathematical algorithms. These data are adequate only to interpret basic structural relationships and cannot be used, in themselves, to locate or define individual mineral deposits. Gravity and magnetic data may be used to identify local or regional structural features that may control mineralization (such as fault zones that are mineralized or served as conduits for mineralizing fluids), locate buried intrusive bodies, or define the subsurface extent of rock units (for instance, high-density, low-susceptibility carbonates) that may be hosts for mineralization.

Magnetic and (or) gravity data can help to define the location and extent of intrusive bodies that may host porphyry deposits, and may be the source for adjacent epithermal vein deposits. Carbonate rocks within 5 km of the intrusive centers are potential hosts for skarn deposits. The carbonate rocks typically are associated with high gravity values and low magnetic values. The geophysical anomalies may be useful in determining whether carbonate rocks are present beneath shallow cover within this 5-km area. Polymetallic veins also commonly occur within a 5-km radius of intrusive centers, and tracts may be defined by the central anomalies associated with the intrusive centers. The geophysical interpretations are grouped according to the central intrusive tracts (porphyry and epithermal vein deposits) and the associated skarn and polymetallic tracts that surround each intrusive center.

The gravity and magnetic anomalies identified in figures E1 and E2, respectively, are discussed by subarea within the western and northern parts of the Gallatin National Forest and are keyed, where appropriate, to the mineral resource tracts (table A4, fig. A3) identified for this report. A geophysical anomaly may extend over more than a single tract, and, conversely, it is possible that no anomalies may be associated with a particular tract.

Madison-Gallatin Subarea

Spanish Peaks Tract

The potential for mineral deposits in the Spanish Peaks area is defined by ultramafic rocks. Ultramafic intrusive bodies within Archean rocks in the Spanish Peaks area may be defined by magnetic high anomalies (M16a, M16b, fig. E2). However, anomaly M16b is surrounded by low anomalies in a pattern characteristic of porphyry intrusive systems.

Hilgard Peak and Madison Mylonite Zone Tracts

High magnetic anomalies (M17, M18, fig. E2) define probable bodies of ultramafic rocks within the Archean basement. In the northern part of the Hilgard Peak tract, the pattern of magnetic anomalies centered on M18 also has characteristics similar to those of porphyry intrusive systems. Higher magnetic am-plitudes and gradients in the Hilgard Peak area differentiate these rocks from Archean units mapped to the south. Regional northeast-trending gradients and changes in character in both gravity and magnetic data are associated with a change in basement composition across a major structural boundary in southwestern Montana, of which the Madison mylonite zone is a part. Part of this regional gradient limits the southern extent of the Hilgard Peak tract.

Lone Mountain and Big Sky Tracts

A series of high magnetic anomalies (M14, fig. E2) is associated with Upper Cretaceous dacitic and andesitic intrusive

rocks that crop out near Lone Mountain (map unit Kda of Wilson and Elliott, 1997; Tysdal and others, 1986) and define the probable subsurface extent of the intrusives. The gravity pattern in the area arises predominantly from the underlying Archean basement rocks. No gravity anomalies are clearly correlated with the outcropping intrusive rocks or the associated magnetic anomalies when plotted at a larger scale (1:126,720), suggesting that these intrusives have no appreciable density contrast with the basement.

Snowslide Creek and Ramshorn Peak Tracts

A high magnetic anomaly (M15, fig. E2) is associated with outcrops of Cretaceous intrusive rocks. Part of a more extensive gravity high (G8, fig. E1) is spatially associated with the intrusive rocks as defined by the magnetic anomaly, but the gravity high arises from a combination of the underlying Archean metamorphic basement block and the Paleozoic carbonate rocks of the Ramshorn Peak skarn tract.

Gallatin Range, Hyalite Peak, and Gallatin River Tracts

The magnetic signature of mixed high and low magnetic anomalies of local extent, high gradient, and moderately high magnitude that occurs over the Gallatin Range is typical of a complex of multiple intrusions and associated extrusive rocks. In the southern part of the Gallatin Range tract, there are no well-developed high anomalies with surrounding low anomalies, a pattern that is characteristic of porphyry systems. In the northern part of the Gallatin Range tract, several well-developed magnetic highs (M11, fig. E2) are surrounded by lows and are, in addition, separated by a Y-shaped pattern of magnetic lows (M12, fig. E2) that suggests a major fracture system where magnetite has been destroyed by hydrothermal alteration.

Generally high gravity values and relatively low magnetic values are associated with Paleozoic carbonate rocks north (G6, fig. El; M13, fig. E2) and southwest (G7, fig. E1) of the intrusive centers of the Gallatin Range tract. The Gallatin Range intrusive center lies astride the regional boundary between different basement blocks.

Bridger Range Subarea

Magnetic and gravity highs (M1, fig. E2; Gl, fig. E1) occur over Archean rocks in the southern Bridger Range. A gravity low (G2, fig. E1) in the central part of the range occurs over Proterozoic rocks. The low-gravity anomaly is defined by only one survey point but should probably be considered valid, as logical sources for the anomaly include the comparatively low density of Proterozoic rocks rather than the higher densities of the adjacent Archean and Paleozoic carbonate rocks. A broad gravity high (G3, fig. E1) culminates at the northern end of the range and extends north-northeast over Paleozoic carbonate rocks in the northern part of the study area. A gravity high (G4, fig. E1) along the Battle Mountain monocline (fig. B3*B*) suggests that the monocline involves Paleozoic rocks in the subsurface.

A magnetic high (M1, fig. 2E) occurs over the Archean metamorphic rocks in the southern part of the range, and magnetic lows occur over nonmagnetic Paleozoic carbonate rocks southeast of the Archean rocks (M2, fig. E2), and where thrust faulting has created an unusually thick Paleozoic section (M3, fig. E2).

Flathead Pass, Blacktail Mountain, and Bridger Range Tracts

A magnetic high (M4, fig. E2) occurs near Flathead Pass and is typical of the high-amplitude, high-gradient, discrete anomalies characteristic of shallow intrusions. Two similar magnetic highs (M5, fig. E2) occur northwest of the study area boundary. The Flathead Pass, Blacktail Mountain, and Bridger Range tracts are defined on the basis of these anomalies. Similar, isolated, high-amplitude, high-gradient anomalies (M6, fig. E2) occur over a thick section of Cretaceous sedimentary rocks along a trend that extends northeast from the southern part of the Bridger Range. These could suggest a structurally controlled series of shallow intrusions; however, close inspection of the geologic and magnetic maps revealed that the isolated high anomalies occur where flightlines cross the same upper Cretaceous sedimentary rocks. Ground magnetic measurements and short traverses were made at 36 locations both east and west of the Bridger Range. The relatively high magnetic values occurred where the Cretaceous Eagle Sandstone is present in the near subsurface. The Eagle Sandstone contains detrital magnetite and is correlative with the Virgelle Sandstone farther north in western Montana, which has relatively high magnetic susceptibility and produces measurable high magnetic anomalies. The high values on these traverses did not occur directly over the Eagle Sandstone where it crops out, and susceptibility measurements of surface samples were not anomalous. It is likely either that the thickness of the unit where it crops out is insufficient to produce anomalies, or that the magnetic susceptibility has been destroyed by weathering. The magnetic highs consistently occurred adjacent to the Eagle Sandstone outcrops where the dipping unit is shallowly buried, is protected from surface weathering and erosion, and is somewhat thicker as a result. It is impossible to determine with the available data whether the magnetic anomalies, including that at Flathead Pass (M4, fig. E2), are caused by shallow intrusions or the unusual magnetic susceptibility of the Eagle Sandstone. The sills within the Flathead Pass and Blacktail Mountain tracts are probably deuterically rather than hydrothermally altered, and the veins of the Pass Creek area (Bridger district) (fig. C2), which lies within the Bridger Range tract, lack apparent association with felsic intrusions. Therefore, the more likely source of the magnetic anomalies is interpreted to be the sedimentary rocks rather than a buried intrusive.

Crazy Mountains Subarea

Crazy Peak and Big Timber Tracts

The magnetic data here show the typical signature of a porphyry system. A high magnetic anomaly (M7, fig. E2) is associated with intrusive rocks in the core of the Big Timber

stock and is surrounded by magnetic lows (M8, fig. E2) caused by destruction of magnetite by hydrothermal alteration. At a larger scale, the highest gradient of the anomaly defines the subsurface edges of the intrusive core, but it is not apparent at the scale of the map in figure E2. A second magnetic high (M9, fig. E2) and similar surrounding lows occur to the north of the study area at Loco Mountain, indicating a second intrusive system is present there. A gravity high anomaly (G5, fig. E1) is associated with the intrusive rocks of the Crazy Mountains; no gravity anomaly is associated with the Loco Mountain body as no gravity data exist in this area.

Shields River Tract

A northeast-trending magnetic gradient (M10, fig. E2) separates the Shields River area from the high anomaly associated with Crazy Peak. It is part of a more extensive regional trend expressed in gravity and magnetic data and alignments and (or) terminations of structural features in southwestern Montana and, as discussed earlier, represents a major feature in the basement. At this location (M10a, fig. E2), it is offset approximately 35 km northwest from its expression in the Madison mylonite zone (M10b, fig. E2). The offset occurs along a major northwest-trending fault system that is expressed in this part of the study area by the southwestern front of the Madison Range (Wilson and Elliott, 1997). Unlike the magnetic signature of the intrusive rocks of the Crazy Mountains, the magnetic signature over the Shields River area (SR, fig. E2) is a composite pattern of high and low anomalies of only local extent and less than 300 nT magnitude.

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Geochemistry: Rocks

By Jane M. Hammarstrom and Bradley S. Van Gosen

U.S. Geological Survey Professional Paper 1654–F

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Geochemistry: Rocks

By Jane M. Hammarstrom and Bradley S. Van Gosen

Introduction

Whole-rock geochemical data were acquired for 59 rock samples collected during this study. The purposes of the geochemical study were: (1) to document the geochemical signature of various deposit types in order to classify deposits and interpret stream-sediment data; (2) to look for commodities that were not sought in past exploration or resource assessments (such as platinum-group elements in ultramafic rocks); (3) to analyze altered rocks away from known deposits to aid in assessment for undiscovered resources; and (4) to contribute background and baseline geochemical data to national geochemical databases.

The 59 samples selected for analysis were grouped into four major rock suites, and different combinations of analytical techniques were used for each suite (table F1) depending on the purpose of the analysis. Complete chemical analyses for major, minor, and trace elements were obtained for volcanic and metamorphic rocks, whereas partial analyses for a suite of metals and minor elements were obtained for highly altered rocks such as gossans and jasperoids. All samples were prepared and analyzed in USGS analytical laboratories in Denver, Colo., Reston, Va., and Menlo Park, Calif. Methods of analysis, references, and analysts are cited in table F1. Data are presented in separate tables (tables F2–F9) for each suite. Sample localities are plotted in figure F1 and keyed to the data tables. Information on samples is in two tables, one of which contains locations, sample descriptions, and in some cases petrographic and modal data; the other table contains the chemical data, grouped by rock types and subareas.

Geochemical Results

Mafic and Ultramafic Igneous Rocks and Amphibolites of the Madison-Gallatin Subarea

Samples of mafic and ultramafic igneous rocks and amphibolites that may represent metamorphosed basaltic rocks were collected from several parts of the Madison-Gallatin subarea (tables F2, F3). These rocks were sampled to characterize the nature of the mafic/ultramafic assemblages in the area and to characterize their trace-element contents that can indicate a potential for magmatic mineral deposits, especially chromium, nickel, copper, gold, and platinum-group elements. Samples include small, ultramafic bodies mapped by Kellogg (1995) in the Madison Range and previously described as having komatiitic affinities (Pinckney and others, 1980) as well as diabase and amphibolite associated with asbestos deposits and with vermiculite. Some of these samples contain elevated (>1,000 parts per million [ppm]) concentrations of chromium and nickel. Copper concentrations are generally low (<350 ppm). Most of the samples contain detectable platinum-group elements in concentrations ranging from about 5 to 25 parts per billion (ppb) total. Platinum : palladium ratios are variable. Gold concentrations range from <2 ppb to 35 ppb.

Metamorphic Rocks and Pegmatite of the Madison-Gallatin Subarea

Metamorphic rocks and pegmatites (tables F4, F5) were analyzed to characterize the extreme aluminous compositions associated with corundum-sillimanite deposits and to look for rare metals such as beryllium. These rocks contain 33 to 53 weight percent Al_2O_3. No elevated concentrations of lithium, beryllium, or other rare elements were found.

Cretaceous and Tertiary Igneous Rocks of the Madison-Gallatin Subarea

A variety of Cretaceous and Tertiary igneous rocks were analyzed (tables F6, F7) to look for geochemical signatures that would suggest a porphyry style of copper, molybdenum, or gold mineralization and to evaluate the degree of alkalinity of the igneous rocks, as a guide to areas that might be more or less prospective for gold deposits. None of the samples contain elevated concentrations of copper. Samples include variably altered (see descriptions in table F6) volcanic flows and hypabyssal intrusive rocks. Two samples were collected from an area outside of the Forest near Big Sky to examine the metal and trace-element signature of rocks associated with the Cretaceous Lone Mountain igneous intrusive complex. These rocks were studied by Tysdal and others (1986) who presented major element chemistry for several samples. Neither of the two samples we studied from the Lone Mountain area (tables F6, F7, key nos. 18, 19) contains anomalous concentrations of the elements (gold, lead, arsenic) associated with the stream-sediment signatures in the area (see Chapter D). Major element compositions of these two samples are similar to those reported by Tysdal and others (1986, table 1).

Two samples of alkalic rocks (trachyte porphyry key nos. 21, 22) in the West Yellowstone area contain 5 to 10 ppb platinum-group elements. Gold was detected in only one of the samples from this group of rocks (trachyte porphyry key no. 22 contains 2 ppb gold). This area may warrant further study because a number of recent studies have suggested that alkaline rocks may be prospective for gold and platinum-group elements (see Mutschler and others, 1985). None of the rocks

from the Tom Miner Basin area or the Big Creek stock carried anomalous gold, copper, or molybdenum. This is of particular interest for resource assessment because of the mineralization and recent exploration associated with the Emigrant intrusive center across Paradise Valley to the east. A number of the samples from the Fridley Peak area (tables F6, F7, key nos. 32–38) showed evidence for hydrothermal alteration (bleaching, chalky feldspars, opaline silica); but no stockwork quartz veining was observed, and none of these samples have elevated trace-element signatures for arsenic, selenium, molybdenum, copper, gold, or other metals that would suggest that they are prospective for mineral deposits associated with intrusive systems (such as porphyry deposits and epithermal veins).

Altered Rocks (Vein, Gossan, Fault Gouge, Skarnoid, Jasperoid) of the Madison-Gallatin, Bridger Range, and Crazy Mountains Subareas

Partial analyses were obtained for samples of assorted types of altered rocks (skarnoid, gossan, jasperoid, fault gouge, and so forth) that could be indicative of undiscovered mineral deposits (tables F8, F9) and to document trace-element signatures of some rocks that were known to be associated with mineral deposits to help interpret stream-sediment geochemical signatures. Samples of contact metamorphosed limestone (skarnoid) associated with the Lone Mountain andesite (tables F8, F9, key no. 40) and with an andesite sill near Storm Castle (tables F8, F9, key no. 41) were analyzed for potential skarn metal associations. The term skarnoid is used for these bedded, rather than massive, replacements following the definition of "skarn-like rocks of uncertain or complex origin" proposed by Einaudi and Burt (1982).

Concentrations of copper, lead, and zinc in fault gouge (table F9, key no. 53) are similar to vein ores (table F9, key nos. 51, 56, 57) and are elevated relative to metal concentrations in country rock limestone, shale, and arkose (table F9, key nos. 52, 54, 55) in the Johnson Canyon mine area in the Bridger Range. A porphyritic andesite dike collected in the Crazy Mountains area that contained disseminated sulfide minerals (tables F8, F9, sample no. key 49) lacks any anomalous metal concentrations; in contrast, a composite sample of mineralized gossan (tables F8, F9, key no. 48) from the Half Moon mine area and a pyritic andesite porphyry from the Cave Lake area (tables F8, F9, key no. 50) each contain anomalous copper, lead, and silver. None of these samples contains elevated zinc (<200 ppm), so the source of the zinc anomalies detected in stream sediments

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Mineral Resource Assessment

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Mineral Resource Assessment

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Introduction

This mineral resource assessment was conducted using the three-part form of assessment developed by Singer (1993) and adopted by the U.S. Geological Survey as a template for evaluating mineral potential. This assessment follows the format used for studies of other parts of the Gallatin and Custer National Forests (Hammarstrom and others, 1993; Van Gosen and others, 1996) and uses mineral deposit models to establish criteria for delineating tracts of land that are permissive for the occurrence of particular types of mineral deposits. The authors of this report delineated permissive tracts and made estimates of numbers of undiscovered deposits for selected deposit types in April of 1994. The assessment was conducted at a scale of 1:126,720 using a new geologic map compilation (Wilson and Elliott, 1995) as the lithologic base.

We compared the available data for the Gallatin National Forest with the descriptive data contained in mineral deposit models (table A3) to delineate 21 tracts of land (table A4) that are geologically permissive for particular types of mineral deposits within 1 km of the Earth's surface. Tracts were arbitrarily assigned geographic names for easy reference. Some tracts are permissive for more than one deposit type at the scale of the assessment. Similarly, a number of different tracts in a study area may be permissive for the same deposit type (for example, porphyry copper deposits) because the lithologic environment with which the deposit type is associated can occur in a number of discrete geologic packages of similar rock types.

Tracts represent a synthesis of available geologic information. Their utility is not restricted to mineral resource assessment, however. Tracts can provide a base for a variety of ecological and environmental studies because they delineate an area in which the rocks share a common set of physical and chemical characteristics and history of development. Therefore, a tract can serve as an important data layer in understanding water quality and habitat. The distinctive geochemical signatures of some tracts may indicate hostile or friendly environments for various species. Designated and proposed wilderness areas are included in tracts, although these areas may be closed to mineral entry.

This chapter is organized by geographic subarea, lithologic environment, and mineral deposit types associated with those lithologic environments. For each lithologic environment within a geographic subarea, we discuss the rationale for delineating tracts. Tracts are shown as page-size figures at a scale of 1:500,000. Each tract map is accompanied by a table that documents the criteria that were used to delineate that tract. Mineral occurrences may or may not indicate the presence of a mineral deposit. Not all of the mineral occurrences described in Chapter C are included in permissive tracts because of uncertainties about the significance of the occurrence or lack of geologic information. Because of interest in recreational placer mining on Federal lands, we address areas of reported past placer activity and areas where stream-sediment geochemical data suggest that gold may be present as mineral deposits associated with unconsolidated deposits. Areas of anomalous gold are not delineated as tracts based on lithologic environment but are linked to geochemical anomalies described in Chapter D. We also discuss the significance of the types of deposits that may be present and the likelihood for mineral exploration and development in the reasonably foreseeable future. All quantitative aspects of the assessment are discussed in Chapter J.

Madison-Gallatin Subarea

Mineral Deposits Associated with Mafic and Ultramafic Meta-Igneous Intrusions

A number of different types of mineral deposits of copper, nickel, platinum-group elements (PGE), and (or) chromite can be associated with layered intrusions or with small "alpine-type" intrusions (Thayer, 1964) of mafic to ultramafic composition. Metamorphism of such rocks can result in the formation of serpentinites with associated asbestos deposits, and further supergene alteration of serpentinized rocks can lead to the formation of vermiculite deposits.

In southern Montana, ultramafic rocks are known to occur in two of the five major Archean rock assemblages described by Erslev (1983) for the northwestern part of the Wyoming Province, the region in Wyoming and adjacent States underlain by rocks of Archean age (Houston and others, 1992): (1) small, scattered ultramafic pods in granitic to tonalitic gneiss complexes interlayered with amphibolites and metasedimentary rocks; and (2) the Stillwater Complex of the Beartooth Mountains, a layered mafic intrusion that hosts important resources of copper, nickel, platinum-group elements, and chromite (Czamanske and Zientek, 1985). Recent studies by Mueller and others (1993) and by Mogk and others (1992) have shown that Archean rocks in the Wyoming Province preserve a collage of different terranes that represent distinct lithologic assemblages. One of these, the "Montana metasedimentary terrane" (Mueller and others, 1993), includes the study area. Within the subarea, these rocks contain small pods of ultramafic rocks and border a quartzofeldspathic granitic gneiss complex, which is thrust over the southern part of the supracrustal package along the Madison mylonite zone. Ultramafic rocks are noted in two parts of the study area: (1) an area we delineated as the Hilgard Peak tract

along the Madison mylonite zone (Erslev, 1983), and (2) in the Spanish Peaks area (Spencer and Kozak, 1975).

There is no evidence for a layered intrusion comparable to the 48-km-long Stillwater Complex (Absaroka-Beartooth study area) in the eastern part of the Gallatin National Forest. However, the primary nature (layered intrusion or podiform "alpine" type intrusion) of most of the small ultramafic bodies is obscured by metamorphism and tectonic disruption. For this reason, we define tracts that contain ultramafic bodies as permissive for the occurrence of a variety of deposit types of magmatic origin associated with ultramafic and mafic intrusions. Chromium resources associated with ultramafic rocks at the Table Mountain deposit in the Madison-Gallatin subarea (table C2, no. 71) were estimated by Becraft and others (1966). On a regional scale, nickel deposits and platinum-enriched layered complexes have been documented in ultramafic rocks hosted by Archean metasupracrustal rocks of the Cherry Creek Group in the Ruby Range (Sinkler, 1942; Desmarais, 1981) and the Tobacco Root Mountains (Horn and others, 1992) to the west of the study area. Wilson and Elliott (1995, 1997) include rocks equivalent to the Cherry Creek Group in map unit Am (Archean metamorphic rocks) on the geologic map of the western part of the Gallatin National Forest.

Detailed examination of all of the outcrops of ultramafic rocks in the study area was beyond the scope of this study; however, we did acquire chemical data for selected samples to analyze PGE, gold, nickel, copper, chromium, and other elements (table F3). Routine analyses and stream-sediment surveys do not normally include PGE determinations, and these elements (platinum, palladium, rhodium, iridium) were not sought in previous investigations. Special analytical techniques must be used to analyze for PGE because they occur in very low (parts per billion) concentrations, even in rocks that would be considered economically important. Largely on the basis of the mapped distribution of Archean ultramafic rocks (map unit Au of Wilson and Elliott, 1995, 1997) in the study area, we delineated two permissive tracts for mineral deposits associated with ultramafic rocks: Spanish Peaks and Hilgard Peak.

Permissive Tracts for Magmatic Deposit Types

Spanish Peaks

Pinckney and others (1980) evaluated the mineral resource potential of the Beartrap Canyon Instant Study Area, at the northwestern corner of the Spanish Peaks area, as having a low to moderate potential for magmatic nickel, based on the presence of sills of mafic to ultramafic composition that they interpreted as komatiites (fig. G1, table G1). In addition, they mapped 20 small ultramafic bodies and noted the occurrence of many more. They described these rocks as small pipes or plugs of syntectonic pyroxenite or dunite that deformed the sediments around them and were subsequently metamorphosed. They interpreted conformable layers of amphibolite interbedded with gneisses and quartzites in the area as metamorphosed lava flows and sills that are chemically equivalent to the intrusive rocks. An aeromagnetic anomaly is associated with these amphibolites and the ultramafic intrusive rocks (M14 in fig. E2). Altered peridotite is also present near the Karst asbestos deposit (table C1, no. 9). No known magmatic deposits are associated with these ultramafic bodies. New data on PGE and other metals acquired for this study (Chapter F) show that PGE are present in low concentrations (<30 ppb total); nickel concentrations range from less than 100 ppm to more than 2,000 ppm and Ni:Cu ratios are high.

Vermiculite occurrences in weathered biotite alteration zones adjacent to mafic or ultramafic rocks have been recent exploration targets in Montana (table G1). However, the mica at the Mica Creek deposit (table C1, no. 14) in the Spanish Peaks tract does not expand sufficiently to be classified as vermiculite (Perry, 1948), and the deposit is probably too small to warrant further exploration.

Hilgard Peak

The Hilgard Peak tract is based on the mapped distribution of Archean quartzofeldspathic gneisses and amphibolites locally intruded by ultramafic rocks and includes a migmatite complex associated with the Madison mylonite zone (fig. G1, table G2). This package of rocks is similar to that in the Spanish Peaks tract and separated from it by intervening Cretaceous igneous rocks of the Big Sky tract. Although the ultramafic pods along the mylonite zone reportedly contain nickel (the mineral pentlandite) and are of academic interest, they have not been evaluated for PGE. The entire tract is within the Lee Metcalf Wilderness and is therefore closed to mineral entry.

Mineral Deposits Associated with Regionally Metamorphosed Rocks

The regionally extensive Precambrian Cherry Creek Metamorphic Suite includes metasedimentary and metavolcanic rocks. These rocks are included in map unit Am (Wilson and Elliott, 1995, 1997). The metasedimentary rocks include aluminous pelitic sequences metamorphosed to schists or gneisses, which locally contain sources of sillimanite-group minerals (sillimanite and kyanite). At one time, these deposits were considered to have economic potential and were explored (see discussion in Chapter C). Because immense resources of the sillimanite group of minerals exist in the United States, notably in the Appalachian area and in Idaho (U.S. Bureau of Mines, 1995), it is unlikely that the permissive tracts within the forest would ever be examined for refractory mineral resource development. Two tracts are permissive for these types of deposits, Spanish Peaks and Hilgard Peaks (fig. G1). These are the same tracts that locally contain small ultramafic intrusions.

All of the economically significant talc deposits in southwest Montana are hosted by Archean dolomitic marbles that occur within the Cherry Creek Suite (Berg, 1979). Although no deposits have been discovered in the Gallatin National Forest, dolomitic marbles (mapped separately as unit Ad by Wilson

and Elliott, 1995, 1997) constitute a permissive lithology for talc deposits in the Earthquake Lake tract (fig. G2). Berg (1979) noted that although dolomite is found in the landslide caused by the 1959 Hebgen Lake earthquake in the Madison River Canyon and has been mapped in the area, the only two reported talc occurrences in the Madison Range are minor occurrences of impure talc associated with ultramafic rocks and asbestos deposits.

Mineral occurrences of base and (or) precious metal veins are spatially associated with some of the major faults in the study

area, including the Madison mylonite zone and the Spanish Peaks fault. These occurrences are described as polymetallic veins with the caveat that they may instead represent low-sulfide gold-quartz veins or, especially in the case of copper occurrences, local movement of metals scavenged by ground water or by metamorphic fluids during tectonism.

Permissive Tracts for Metamorphic Deposit Types

Spanish Peaks

Because the small plugs of ultramafic rocks in the Spanish Peaks tract are hosted by regionally metamorphosed, locally

aluminous rocks that contain known occurrences of corundum and sillimanite, and because the scale of this assessment and available data preclude more detailed tract delineation, the permissive tract includes rocks that may host a variety of disparate deposit types (fig. G1, table G1). The corundum-sillimanite deposits in and near the tract have been thoroughly described in the literature (Bakken, 1980; Clabaugh and Armstrong, 1950). While of mineralogic interest, these deposits are unlikely to ever be economic because of ready sources of better-grade refractory materials elsewhere. Gem corundum is an important mineral in Montana (the famous Yogo sapphires); however, the corundum in the Spanish Peaks area is not of gem quality and represents a very different type of mineral deposit from the deposits that produced the gem-quality sapphires.

Hilgard Peak

The Hilgard Peak area holds even less potential for sillimanite group minerals than the Spanish Peaks tract (fig. G1, table G2). A single occurrence of corundum is reported along the Madison fault (table C1, fig. C2, no. 26).

Earthquake Lake

The Earthquake Lake tract outlines Archean dolomitic marbles (map unit Ad of Wilson and Elliott, 1995, 1997) that outcrop south of the Madison mylonite zone (fig. G2, table G3). These marbles are part of the Cherry Creek Metamorphic Suite (Erslev, 1983), a package of metasupracrustal rocks that are overthrust by a tonalitic to granitic quartzofeldspathic gneiss complex along the Madison mylonite zone (Mueller and others, 1993). Talc is present in dolomitic marble at the Little Mile Creek asbestos deposit (tables C1 and C2, fig. C2, no. 41) as well as in alteration zones around ultramafic rocks. The contact metamorphic talc is unlikely to be of economic significance because of its very local occurrence and impurities. To date, there is no evidence for significant hydrothermal deposits such as those that formed in similar rocks in the Ruby and Gravelly Ranges to the west of the study area (Berg, 1979). Remote sensing data or soil surveys (Blount and Parkison, 1991) could be used to evaluate the potential for talc in the tract.

Madison Mylonite Zone

The area along the mylonite zone hosts scattered vein occurrences of copper and silver in Precambrian gneiss (fig. G6, table G4). The nature of these veins is enigmatic, and we loosely refer to them as “polymetallic veins” although we have no evidence relating them to any felsic intrusion. The metamorphic quartz vein deposit type such as the low-sulfide gold quartz vein deposit model (table A3) may be more appropriate, but gold is typically absent and no anomalous concentrations of arsenic, the best pathfinder element for these types of deposits, are observed in the geochemical data (fig. D8). These veins may simply represent fluid movement along faults. On the basis of a number of prospects and on stream-sediment geochemistry, Simons and others (1983) outlined an area of low potential for copper and silver in the Madison Roadless area. Johnson and others (1993) identified a number of additional prospects and analyzed samples that showed low-grade copper and silver resources. We delineated the Madison mylonite tract to include these data; however, further work would be needed to understand the nature of these occurrences, and existing data suggest that these veins do not contain significant economic resources.

Mineral Deposits Associated with Felsic Intrusions and Volcanic Rocks

Tonalitic to granitic gneisses of Archean age that crop out north of the Madison mylonite zone represent the metamorphosed equivalents of large complexes of felsic intrusions. Pegmatite dikes that are associated with these metamorphosed granitic rocks crosscut a variety of different feldspathic gneisses in the southern Madison Range (Erslev, 1983). The pegmatites contain coarse crystals of plagioclase and microcline as well as quartz and mica. A small amount of mica was reportedly produced from some of the pegmatites (fig. C2, table C1).

At least three episodes of post-Precambrian felsic magmatism are recognized in the Madison-Gallatin subarea: Cretaceous, Eocene, and Quaternary. Intrusive centers of Cretaceous and Eocene age are important loci of mineral deposits in other parts of southwestern Montana and in eastern parts of the Gallatin National Forest. However, at the present levels of erosion, the exposed intrusive rocks in the Madison-Gallatin subarea appear to be barren or only weakly mineralized. A number of different types of mineral deposits may be associated with post-Precambrian felsic intrusions and related volcanic rocks (see table A3) falling into four major categories: (1) porphyry-related, (2) epithermal veins, (3) skarn, and (4) polymetallic vein and replacement. Skarns typically form in carbonate rocks adjacent to intrusive complexes. Polymetallic veins develop along fractures in any rock type occurring proximal to an intrusive center at distances as much as 5 km from the contact. Epithermal veins can form in volcanic rocks that may overlie intrusive centers. Therefore, permissive tracts that are delineated for intrusive centers (for example, for porphyry deposits) may be paired with surrounding tracts permissive for skarns or veins if suitable host rocks are present. In addition to this spatial relationship, the presence or absence of carbonate rocks and fracturing surrounding intrusive centers also plays a role in determining whether or not permissive tracts for skarns or vein and replacement deposit types are created.

Cretaceous intrusive centers (map unit Kda of Wilson and Elliott, 1995, 1997) in the study area take the form of laccoliths with associated dikes and sills. Compositionally, these intrusions are porphyritic dacites to andesites. Tysdal and others (1986) established Cretaceous ages for the laccolithic rocks of the Madison Range at Lone Mountain and at Fan Mountain, and for welded tuffs from the basal part of the Livingston Formation. Similar rocks (hornblende-bearing dacite porphyry) are present at the eastern edge of the subarea near Yellowstone National

Park and are described as the Gallatin River laccolith (Iddings, 1899; Witkind, 1969; Ruppel, 1972). Ruppel (1972) described another group of Cretaceous intrusions of this form in Yellowstone National Park (Indian Creek laccolith, Gray Peak laccolith, Fan Creek sills, Snowshoe laccolith). Regionally, the Cretaceous intrusive centers tend to hold even less promise for porphyry-type mineralization than the Eocene centers of the Absaroka Volcanic field.

Eocene intrusive rocks (map unit Ti of Wilson and Elliott, 1995, 1997) and related volcanic rocks (map unit Tv of Wilson and Elliott, 1995, 1997) of the Absaroka Volcanic field occupy much of the northeastern part of the Madison-Gallatin subarea. The Absaroka Volcanic Province (Chadwick, 1970) represents a deeply eroded field of andesitic and basaltic stratovolcanoes, tuffs, flows, and reworked deposits (Smedes and Protska, 1972; Chadwick, 1970). The field covers more than 8,000 mi^2, and the volcanic centers are aligned along structurally controlled, northwesterly zones that cut across the eastern part of Yellowstone National Park. At least 10 of the volcanic centers host porphyry copper deposits (Hausel, 1982). The Absaroka Volcanics in the Madison-Gallatin subarea lie at the northwestern end of the volcanic field, where the oldest of the three subunits—the calc-alkaline rocks of the Washburn Group—is exposed. All of the mineralized volcanic centers recognized thus far are to the south and east, in the younger and more heterogeneous rocks of the Sunlight and Thorofare Creek Groups. Chadwick (1969) mapped and described the dacitic to andesitic stocks, lava flows, and breccias in the northern Gallatin Range. Chemical analyses of some of these rocks were obtained for this study to evaluate the potential for porphyry copper mineralization (table F7). Although the area was not extensively or systematically sampled, none of the samples showed elevated concentrations of copper or other elements indicative of porphyry-type mineralization at exposed levels.

Permissive Tracts for Pegmatite Deposit Types

Spanish Peaks

Six pegmatite mica occurrences are reported within the Spanish Peaks tract (fig. G1, table G1; fig. C2, table C1, nos. 4, 5, 39, 52–54). A small amount of sheet mica was produced from the Thumper Lode mica mine (fig. C2, table C2, no. 5). Most of the production of mica from pegmatites of southwestern Montana occurred during World War II because of a government subsidy for mica mining (Heinrich, 1949), and most of the productive deposits are found to the west of the Gallatin National Forest.

Hilgard Peak

Mica is reported at one pegmatite locality in the Hilgard Peak tract (fig. G1, table G2), the Anvil occurrence (fig. C2, table C1, no. 38). It is unknown if any production occurred.

Permissive Tracts for Porphyry Copper and Epithermal Vein Deposit Types

Lone Mountain

The Lone Mountain tract (fig. G3, table G5) contains the Cretaceous intrusive rocks associated with the Lone Mountain laccolith. No mines or prospects are associated with the tract. Some of the rocks are hydrothermally altered (see table F6), but a number of features that would suggest porphyry copper type mineralization have not been recognized. For example, no concentric zoned alteration pattern, stockwork quartz veins, supergene zones, breccias, copper enrichment in stream sediments or rock samples, or other geochemical signature typical of porphyry deposits have been recognized. Simons and others (1983) included the tract in a geologic terrane designated as having probable mineral-resource potential. We consider the area permissive for a porphyry system in the absence of exploration data that would rule out such an occurrence. Such a deposit could be present in the subsurface; however, much of the area is private land held by timber companies or is dedicated to recreational use (Big Sky ski area) or wilderness.

Snowslide Creek

Snowslide Creek is a permissive tract for porphyry copper deposits centered on the Cretaceous Gallatin River dacite porphyry laccolith (fig. G3, table G6). The tract boundary extends beyond the study area to reflect possible subsurface extensions of the laccolith suggested by the magnetic signature (M17, M18 in fig. E2). Witkind (1969) mapped the area and noted that "mineral deposits were not found, and it seems unlikely that any are present." Where the roof of the laccolith is in contact with rocks of the Madison Group, the limestone is contact metamorphosed. One small orebody of magnetite skarn was explored in the 1920's (the Apex group of claims, table C1, fig. C2, no. 16). A permissive tract for skarn associated with the Gallatin River laccolith is delineated as Ramshorn Peak.

Witkind's (1969) descriptions of the petrology of the laccolith do not suggest any extensive alteration, sulfide minerals, or quartz stockwork that would indicate porphyry-style mineralization at the present levels of exposure. He does describe rare, rounded quartz phenocrysts as well as altered phenocrysts of plagioclase feldspar, hornblende, and magnetite set in a holo-crystalline microgranitic groundmass. Also, his chemical analyses (Witkind, 1969, table 5) show that the laccolith is calc-alkaline, and somewhat volatile rich (about 3 weight percent water and carbon dioxide). The magnetic signature of the laccolith (magnetic high surrounded by lows) is compatible, but not compelling, evidence for porphyry-type mineralization.

Gallatin Range

The Gallatin Range tract includes Tertiary intrusive and volcanic rocks of the Absaroka Volcanic field (fig. G4, table

G7). This tract is permissive for the occurrence of porphyry copper (-molybdenum, -gold) deposits and for epithermal veins. The tract, as drawn, is quite large, and outlines the extent of mapped intrusive and volcanic rocks. Intervening areas of exposed Archean metamorphic rocks and Paleozoic sedimentary rocks are excluded; this accounts for the digitate western boundary of the tract. No mines or prospects exist in the tract. On the basis of porphyry deposits known to occur

elsewhere in the volcanic field, including due east of the tract across Paradise Valley at Emigrant (in the Absaroka-Beartooth area, see Hammarstrom and others, 1993) and a lack of detailed exploration in the area, the area is considered permissive for undiscovered deposits. However, the stream sediment and limited rock geochemical sampling conducted for this study (table F6) provide no indications of any particular favorable areas in the tract. Although no epithermal veins have been recognized, observations of opaline silica and hydrothermal alteration in shallow intrusions in the vicinity of the Big Creek stock (Chadwick, 1982) suggest that a more thorough evaluation of the area for epithermal hot-spring gold deposits may be warranted.

Permissive Tracts for Skarn or Polymetallic Vein and Replacement Deposit Types

Ramshorn Peak

Carbonate rocks within a 5-km radius of the Gallatin River laccolith considered permissive for the occurrence of skarn deposits are delineated as the Ramshorn Peak tract (fig. G5, table G8). One deposit of this type is known. The Apex group of prospects (fig. C2, no. 16) were explored in the 1920's but have no record of production. Witkind (1969) described samples of ore found in a cabin on the site that were composed of magnetite and hematite; the sample was analyzed for iron and shown to contain 73.32 weight percent iron as Fe_2O_3. Witkind (1969) also noted garnet, epidote, pyrite, sphalerite, galena, malachite, and chrysocolla(?) near the workings. The Bureau of Mines resampled the site during their investigation of identified resources in the Gallatin National Forest (Johnson and others, 1993) and described a copper- and magnetite-skarn pod 550 ft long and 3 ft wide, developed by an 83-ft shaft, 5 caved adits, and 2 pits. They reported anomalous concentrations of copper and gold (0.01 oz/ton) for select samples. The mineralogy of the ore and gangue (magnetite, and calc-silicate minerals such as garnet and epidote) indicate contact metamorphic processes that resulted in skarn formation were operative at the contact of the laccolith. Given the nature of laccoliths, there may be additional deposits under sills near the surface or along other parts of the contact, wherever carbonate rocks may have been in contact with the intrusions. In southwestern Montana, gold-bearing copper-iron skarns are important exploration targets; for example, these are the types of deposits present in the New World mining district near Cooke City. Most of the productive skarns in the region are hosted by the Cambrian Meagher Formation rather than the Madison Group, and most are related to Tertiary rather than Cretaceous magmatism. Detailed exploration might reveal potentially economic skarn deposits associated with the tract; however, no future exploration is expected due to the proximity to Yellowstone National Park and designated wilderness areas.

Hyalite Peak

Paleozoic carbonate rocks proximal to Tertiary intrusions of the Absaroka Volcanic Province (Gallatin Range tract) are permissive for the occurrence of skarn deposits (fig. G5, table G9). No deposits of this type have been recognized in the study area, or for that matter, in association with the mineralized (porphyry copper-molybdenum, -gold) Emigrant intrusive center across Paradise Valley to the east. There are, however, skarn and replacement deposits associated with carbonates at Tertiary intrusive contacts elsewhere in the province. Therefore, in the absence of data to rule out undiscovered deposits, we consider the tract permissive. The differences in style of mineralization between these Tertiary intrusives and those that lie along the Cooke City sag zone to the east may reflect (1) levels of exposure of the intrusive centers, because the New World deposits are more deeply eroded than the porphyritic plugs of the Gallatin Range tract, or (2) differences in carbonate protoliths, because the host carbonate at New World is the Cambrian Meagher Formation whereas the study area is higher in the Paleozoic section and most of the exposed carbonate is Mississippian Madison Group.

Big Sky

All rocks in a 5-km radius of the Cretaceous Lone Mountain laccolith are permissive for polymetallic vein deposits (fig. G6, table G10); carbonate units in the same area are permissive for skarns. No deposits of these types are recognized. There is limited amount of calc-silicate alteration (skarnoid) associated with contact metamorphism of the Lone Mountain laccolith, but no apparent mineralization (tables F7 and F8, no. 40). Although the tract is not considered to have any potential for undiscovered deposits at the surface, we cannot rule out the possibility of deposits within 1 km of the surface, and therefore we include the area in a permissive tract.

Gallatin River

All rock types within a 5-km radius of the Gallatin Range porphyry copper tract and the Snowslide Creek porphyry copper tract are permissive for the occurrence of polymetallic vein deposits (fig. G6, table G11). The only example of a known deposit of this type in the tract is the Sunshine mine (table C2, fig. C2, no. 8). There are a number of scattered occurrences of copper, gold, or silver along shear zones throughout the tract. These occurrences may represent fluid movement along faults,

rather than mineralization driven by a hydrothermal system associated with a felsic intrusion. Fluid inclusion studies of quartz veins in the area might help resolve the nature of the fluids (metamorphic or hydrothermal) that gave rise to these occurrences.

Mineral Deposits Associated with Sedimentary Rocks

The Permian Shedhorn Sandstone is present throughout much of the Madison-Gallatin subarea (map units Pmu and Ps of Wilson and Elliott, 1995, 1997). The Shedhorn Sandstone is the lateral equivalent of the Phosphoria Formation, which hosts significant phosphate deposits to the west of Gallatin National Forest.

Permissive Tract for Phosphate Deposit Type

Madison-Gallatin Phosphate

Thin, shaly phosphate beds are present on a local scale in the middle part of the Lower Permian Shedhorn Sandstone (fig. G7, table G12). The Shedhorn Sandstone is the most voluminous Permian rock in the study area. The Permian stratigraphic section includes local tongues of most members of the Phosphoria and Park City Formations. In the study area, Permian rocks are exposed on the flanks of large synclines and along the Gardiner fault. The tract outlines known phosphate rock occurrences, areas delineated as permissive in previous studies (Swanson, 1970; Simons and others, 1983, 1985; Roberts, 1972), and mapped surface exposures of Permian rocks. See table G12 for a discussion of the quality and quantity of phosphate in the study area.

Mineral Deposits Associated with Unconsolidated Deposits

The Madison-Gallatin subarea contains small, scattered placer gold workings. One heavy mineral placer deposit near the study area was evaluated for ilmenite resources in the Gallatin River drainage. Because of the scattered nature of the occurrences, the lack of established placer districts, and the lack of significant source rocks for lode gold deposits, no discrete tract was delineated for placers.

Madison-Galatin Placers

Stream-sediment geochemical data (Chapter D) were used to note areas where anomalous concentrations of gold have been recognized in the past (fig. D12, table G13). For this study, anomalous is defined as 50 ppb gold or greater. See figure D12 for prospective sites for placer workings. A small amount of gold was produced in the early 1900's from small-scale workings along the Gallatin River and its tributaries.

Bridger Range Subarea

Mineral Deposits Associated with Sedimentary Rocks

The only representative of the Middle Proterozoic Belt Supergroup of rocks in the study area is the LaHood Formation in the Bridger Range. Schmitt (1988) described the LaHood Formation as "a 3500 meter thick wedge of arkosic conglomerate, arkose, argillite, and limestone which crops out along the southern margin of the Belt basin in southwestern Montana." Because Belt rocks host economically significant mineral deposits (Coeur d'Alene mining district and Blackbird in Idaho, the Sullivan deposit in Canada), these rocks have been the subject of extensive study and mineral exploration (Roberts, 1989). Most of the mineral deposits in Belt rocks, such as the Sheep Creek copper-cobalt deposit near White Sulphur Springs, are in finer grained rocks that may represent lateral equivalents of the coarse clastic turbidite sequences of the LaHood Formation preserved along the southern margin of the basin (Himes and Petersen, 1990). Synsedimentary sulfide mineralization in the LaHood Formation is recognized at the world class gold deposit at the Golden Sunlight mine near Whitehall (Foster and Smith, 1995). At Golden Sunlight, most of the mineralization is epithermal gold associated with Cretaceous felsic alkaline intrusions and breccias that intruded Proterozoic sedimentary rocks. However, low-level gold (0.01 oz/ton) in sulfide-rich horizons in Proterozoic rocks led Foster and Smith (1995) to suggest that some of the metals in the highly mineralized breccia pipe may be derived from remobilized synsedimentary sulfide mineralization in the Proterozoic sediments.

Permissive Tract for Sedimentary-Exhalative Zinc-Lead Deposit Type

Pass Creek

The mapped surface extent of the LaHood Formation in the Gallatin National Forest is delineated as the Pass Creek tract (fig. G8, table G14). The Pass Creek mine (table C2, fig. C2, no. 79) produced a small amount of ore, and the area has been explored in the past 20 years without any further development. Johnson and others (1993) conducted a detailed bedrock and soil sampling study in the area of the Pass Creek mine and documented anomalous areas for lead, zinc, silver,

unlike that at the Golden Sunlight mine near Whitehall, Montana.

Mineral Deposits Associated with Felsic Intrusions and Volcanic Rocks

Surface exposures of Tertiary(?) sills are the only evidence for igneous activity in the Bridger Range. However, magnetic signatures (Chapter E, fig. E2) are characteristic of shallow, buried intrusions; therefore, we delineated permissive tracts for several deposit types associated with possible intrusive centers. The absence of any known deposits or prospects related to these types of deposits suggests that the near-surface potential for undiscovered mineral deposits related to igneous rocks in the Bridger Range is only marginally permissive. We were compelled to delineate a permissive tract for these deposit types based almost solely on the geophysical evidence because existing geochemical data are not comprehensive for the area and because we are extending consideration to a depth of 1 km below the surface. We caution that there is no evidence that a buried intrusion, should it exist, would necessarily host any economically exploitable mineral deposits.

Permissive Tract for Porphyry Copper Deposit Type

Flathead Pass

The tract (fig. G9, table G15) is based on a magnetic high anomaly (M4, fig. E2) characteristic of a shallow buried intrusion. The only surface expression of igneous rocks in the area are the Tertiary(?) sills that intrude Middle Cambrian and Cretaceous sedimentary rocks near the Forest boundary. No mines, prospects, or mineral occurrences are associated with the tract. The stream-sediment geochemical signature (fig. D4) shows that an area of anomalous arsenic, bismuth, and antimony is centered on the tract.

Permissive Tracts for Skarn or Polymetallic Vein and Replacement Deposit Types

Blacktail Mountain

The Blacktail Mountain tract includes all carbonate rocks within a 5-km radius of the Flathead Pass tract (fig. G10, table G16). The tract extends to the northwest corner of the study area because carbonate rocks there may host skarn or vein deposits spatially associated with a buried intrusion that lies beyond the study area boundary. Anomalous arsenic and antimony are detected in stream sediments (fig. D4) downstream from the southeastern corner of the tract.

Bridger Range

The Bridger Range tract outlines all metamorphic and sedimentary rocks within a 5-km radius of the Flathead Pass tract, based on the logic that polymetallic vein deposits could be present distal to a hypothetical buried intrusion associated with the Flathead Pass tract (fig. G11, table G17). An area of anomalous arsenic in stream sediments is centered on the tract (fig. D4). Polymetallic vein occurrences at the Pass Creek Mine (table C2, fig. C2, no. 79) and those associated with the Cross Range fault at Corbly Gulch (table C1, fig. C2, no. 74) are not associated with any known intrusions and may simply represent fluid movement that accompanied regional metamorphism rather than intrusion-related mineralization or mineralization of sedimentary-exhalative origin. All of the structurally controlled polymetallic vein occurrences are confined to an area south of the hypothetical buried intrusion delineated by geophysics in the Flathead Pass permissive tract.

Crazy Mountains Subarea

The geology of the Crazy Mountains area is complex because two different suites of igneous rocks were emplaced during the Eocene. Both of these igneous suites have alkalic to subalkalic chemical affinities and are related to the Central Montana Alkalic Province (Larsen, 1940). In contrast, the Eocene rocks of the Absaroka Volcanic Province to the south (Madison-Gallatin subarea) are predominantly calc-alkalic in chemical affinity.

As part of this study, du Bray and others (1993) mapped the Big Timber stock in the southern Crazy Mountains, and in companion studies, du Bray (1995) and du Bray and Harlan (1996) documented the geochemistry of the Big Timber stock and related the petrogenesis of the magmas to subduction and magmatic-arc processes in the early Cenozoic. The Big Timber stock is an elliptical, 8- by 13-km, shallow intrusion surrounded by a radial dike swarm (du Bray and Harlan, 1996). The stock is transitionally alkaline and consists of a core of quartz monzodiorite (map unit Tqm of Wilson and Elliott, 1995, 1997) surrounded by diorite and gabbro (map unit Tdg of Wilson and Elliott, 1995, 1997), and a quartz monzodiorite porphyry (map unit Tcl of Wilson and Elliott, 1995, 1997).

The other Eocene suite in the study area (map unit Ta of Wilson and Elliott, 1995, 1997) consists of strongly alkalic mafic rocks of unusual compositions (malignite, nepheline syenite, analcite syenite, theralite). Dudas (1991) documented the chemistry and paragenesis of these strongly alkalic rocks. These rocks crop out in the northwest corner of the Crazy Mountains subarea and at one location in the southwest corner of the subarea, at Ibex Mountain.

Mineral Deposits Associated with Alkaline to Subalkaline Rocks

Porphyry copper deposits (in the broad sense) are associated with a wide range of igneous rock types that can have calc-alkaline to alkaline (syenite) chemical affinities. Sillitoe (1979) and Cox and Singer (1992) demonstrated that rock type is not a good indicator of porphyry copper potential. However, strongly alkalic rocks are not known to be important hosts for porphyry copper deposits. In contrast, a number of recent studies have documented association between alkalic intrusions and gold (+ telluride, + PGE) mineralization in the western Cordillera (Mutschler and others, 1987, 1991). Although some workers would lump all these deposit types together in a broad "porphyry" category, we chose different mineral-deposit models for the two Eocene igneous suites in the Crazy Mountains subarea. For the transitionally alkaline rocks associated with the Big Timber stock, we examined the available data in terms of porphyry copper and related mineral-deposit models. For the strongly alkalic rocks, we examined the data in terms of an alkaline gabbro-syenite association mineral-deposit model developed for the mineral resource assessment of the Absaroka-Beartooth study area (M.L. Zientek, *in* Hammarstrom and others, 1993, p. G75–G78).

Permissive Tract for Porphyry Copper (-Gold) Deposit Type

Crazy Peak

The boundary of the Crazy Peak tract (fig. G9, table G18) is based on the mapped geologic contacts (Wilson and

Elliott, 1995, 1997) and extended to reflect subsurface extensions of the intrusive complex, as suggested by the magnetic data. The stream-sediment geochemical signature (figs. D2–D5) associated with the stock suggests that the stock is at least permissive for the presence of porphyry-type mineralization. Disseminated sulfides are present locally in some of the dikes. Prospects along shear zones indicate that some metals are associated with the complex; all of the identified resources are in polymetallic vein deposits.

Permissive Tract for Polymetallic Vein Deposit Type

Big Timber Creek

All rocks within a 5-km radius of the Crazy Peak porphyry tract are permissive for polymetallic vein occurrences (fig. G11, table G19). Three mines and prospects of this type (tables C1 and C2, fig. C2, nos. 90–92) were explored in the past and produced a small amount of ore containing lead, silver, copper, gold, and zinc. Johnson and others (1993) evaluated the Half Moon deposits and estimated inferred resources based on a sampling of the veins (see table G19). Stream-sediment anomalies (figs. D3–D5) centered on the tract (zinc, lead, arsenic, silver, manganese) are probably associated with polymetallic veins.

Mineral Deposits Associated with Strongly Alkaline Rocks

Permissive Tract for Alkaline Gabbro-Syenite Hosted and Gold-Silver-Telluride Vein Deposit Types

Shields River

Strongly alkaline rocks in the northwestern and southwestern parts of the Crazy Mountains subarea are permissive for the occurrence of copper-gold-PGE deposits and for gold-telluride veins (fig. G12, table G20). No examples of these types of deposits are recognized in the study area, and no

mineral occurrences indicate any particular potential for these deposit types. A change in streams-sediment geochemistry (Chapter D) that occurs along a drainage divide suggests that this tract may have a distinctive signature from the Crazy Peak and Big Timber Creek tracts. Samples from streams that drain the central and southern parts of the tract are slightly anomalous in gold (fig. D2).

Mineral Deposits Associated with Unconsolidated Deposits

Quaternary surficial deposits (map unit Qs of Wilson and Elliott, 1997) are present along streams that radiate out from the topographic high formed by the Big Timber stock in the Crazy Mountains. These are the most likely areas for placer deposits to have formed.

Northern Gallatin Placers

No placer production is reported from the Crazy Mountains subarea, and no discrete tract for potential placer deposits was delineated (fig. D11, table G21). We refer the reader to figure D11 for areas where anomalous (>50 ppb) concentrations of gold were detected in stream sediments.

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Energy Resource Assessment: Coal Geology and Minable Coal Resource Potential of the Western and Northern Parts of the Gallatin National Forest, Montana

By John W. M'Gonigle

U.S. Geological Survey Professional Paper 1654–H

U.S. Department of the Interior
U.S. Geological Survey

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Introduction

The Gallatin National Forest (fig. A1) contains coal in sedimentary rocks of Jurassic and Cretaceous age. Some of these coals were mined in the Forest area from 1870 to 1943, providing metallurgical (coke), steam, and domestic heating coal. The purpose of this chapter is to summarize the coal geology as described in the literature in previous studies and to estimate the potential for the occurrence of minable coal in the study area.

Geologic Setting

The portion of the Gallatin National Forest in southwest Montana that was assessed for coal resources is in the Gallatin and Madison Ranges along the north and west borders of Yellowstone National Park and includes part of the Bridger Range as well as the Crazy Mountains. As discussed in some detail elsewhere in this volume, and as shown in figure B1, the lithologies in the study area range in age from Precambrian through Holocene (Wilson and Elliott, 1995, 1997). The Madison Range is largely composed of Archean metamorphic rocks overlain by Paleozoic and Mesozoic sedimentary rocks, all of which are locally cut by Cretaceous and Tertiary intrusive rocks. The exposures of Archean metamorphic rocks and Paleozoic and Mesozoic sedimentary rocks in the Gallatin Range are more limited than they are in the Madison Range because these rocks are overlain by widespread units of Tertiary volcanic rocks, largely of the Absaroka Volcanic Supergroup. Precambrian rocks in the study area in the Bridger Range include Proterozoic sedimentary rocks as well as Archean metamorphic rocks; the overlying sedimentary sequence includes the Paleozoic and Mesozoic rocks found in the Madison and Gallatin Ranges, as well as some of the Cretaceous Livingston and Cretaceous and Tertiary Fort Union Formations in the Crazy Mountains basin. The Crazy Mountains are principally Fort Union Formation and Tertiary igneous rocks that have intruded the Fort Union.

Folding and faulting that has defined the Madison, Gallatin, and Bridger Ranges began in the Late Cretaceous Laramide deformation (Tysdal, 1986). Extensional or block faulting that has outlined the modern topographic mountains and basins began in the Tertiary and has continued into the present (Pardee, 1950; Roberts, 1972; Witkind and others, 1964).

None of the Precambrian rocks in Montana contain any coal or carbonaceous deposits. Most of the marine and terrestrial sedimentary deposits of Paleozoic and Mesozoic age in the region also lack coal or carbonaceous shale beds. The stratigraphic units that have been mined for coal in western Montana, and which are present in the Gallatin National Forest, are of Mesozoic age. These include the Jurassic Morrison Formation, the Lower Cretaceous Kootenai Formation, and the Upper Cretaceous Eagle Sandstone (Calvert, 1909; 1912b; Fisher, 1909; Lorentz and McMurtrey, 1956; Scholes, 1985; Roberts, 1966). Of these, the Eagle Sandstone has been the only important unit for coal mining in the study area. The stratigraphic relation of these units to other formations is shown in figures H1 and H2.

Mesozoic Rocks

The Morrison Formation, the Kootenai Formation, and the Eagle Sandstone are continental and continental-marine rocks, deposited during periods of regression or retreat of marine waters. During the Paleozoic and through much of the Mesozoic into the late Jurassic, marine waters occupied what is now the Cordilleran region of the Western United States, and the Gallatin National Forest area of western Montana was the site of predominantly marine shelf deposition onto rocks of the North American craton. Various positive elements influenced the deposition of the marine and shallow marine sediments from time to time and in places throughout the region, and at times the area was above sea level so that no marine deposition occurred. Tectonic uplifts late in the Jurassic destroyed the shelf area of the western sea, and the uplifted terrain formed the western margin of a newly formed Western Interior Basin, which ultimately extended from the Arctic Ocean to the Gulf of Mexico (Kauffman, 1977; McMannis, 1965; Peterson, 1988). Toward the end of Jurassic time, most of western and all of eastern Montana lay in this basin, in which fluvial, swamp, and lake sediments, now termed the Morrison Formation, were deposited (Moritz, 1951; Peterson, 1986, 1988). In Cretaceous time this basin became the Western Interior Seaway, which was occupied by marine waters invading from the north and south (fig. H3). Subsequent continuation of uplifts throughout the Cretaceous in the Sevier Orogenic belt of the Cordilleran region, which was centered to the west of Montana, produced large amounts of debris that were periodically carried eastward into the basin and the Western Interior Seaway (McMannis, 1965; Peterson, 1986; Sloss, 1988).

The Kootenai Formation (figs. H1, H2) was one of the first of a series of nonmarine to marginal marine clastic deposits that accumulated from the debris shed from the western highlands into the Cretaceous inland seaway, and sediments were laid down unconformably across locally eroded Morrison Formation strata (McMannis, 1965; Ruppel, 1972). Succeeding deposits of nonmarine to marginal-marine Cretaceous units, including the Eagle Sandstone, accumulated during times of marine regression and were subsequently buried by marine strata during later transgressions of the sea (Weimer, 1960; Gill and Cobban, 1973; Kauffman, 1977). These deposits are wedge-shaped in section view, are over- and underlain by marine sediments, and pinch out eastward into marine rocks, as depicted in figures H1 and H2. Fluctuations in the Cretaceous seaway shorelines during transgressions and regressions were linked to variations in the rates of sediment supply from the western highlands and to basin subsidence rates; worldwide variations in sea level also may have played a part (Vail and others, 1977; Haq and others, 1987; Molenaar and Rice, 1988).

Depositional settings of the Eagle Sandstone have been studied in detail by a number of geologists (for example, Hanson and Little, 1989; Hearn and Hansen, 1989; Rice, 1976; Rice and Shurr, 1983; Roberts, 1966, 1972; Shurr and Rice, 1986). These studies provide models that illustrate, in general, the influence of paleogeography and depositional settings on the accumulation of coal deposits that are associated with marine strata.

Swamps have the potential for creating deposits of peat that can be transformed into coal. Despite the potential, significant peat deposition is dependent upon just the right balance between sediment input, subsidence, and water levels in a basin of deposition. Local variations in these conditions will, of course, affect the continuity of a deposit. Preservation of a peat deposit is dependent upon burial and preservation beneath continental and marine sediments without significant erosion during the clastic sedimentation of the overlying strata. The coal associated with shoreline deposits in bays, estuaries, and lagoons may be replaced landward (upstream) by coals in continental deposits associated with streams in lower and upper delta settings and, farther upstream, with purely fluvial streams in sedimentary basins. Deposition and preservation of coal deposits in the Eagle Sandstone are generally good in western Montana, and the most favorable sedimentary conditions were apparently met in the vicinity of Livingston (fig. H4).

Rice and Shurr (1983) described the Eagle Sandstone as consisting of a series of thick, blanketlike sandstones that were deposited in wave-dominated and interdeltaic environments. They divided the Eagle Sandstone into three members in northern and north-central Montana, very similar to the subdivision made by Weed (1899). The basal Virgelle Sandstone Member (fig. H2) was interpreted as representing backshore to shoreface deposits along a prograding sandy shoreline. Several widespread coals are present in the member, which indicate that extensive swamps formed behind the prograding shoreline. An informal middle member was interpreted as representing a coastal plain environment with channel sandstones, swamps, lakes, and bays in which sandstone, mudstone, shale, and coal accumulated. Coal beds in the middle member are generally thin, discontinuous, and lignitic; but in the lower part of the middle member they are more continuous and as thick as 3 ft (0.9 m). An informal upper member is considered to represent shoreface sandstone and tidal flat sandstone, siltstone, and shale. Some delta destruction with shoreface erosion of the middle member took place as the seas began another westward transgression, making a transitional change upward into the offshore marine shale of the overlying Claggett Shale, shown in figure H4 (Rice, 1976; Rice and Shurr, 1983; and Shurr and Rice, 1986). A very generalized model of the Eagle facies and environments is shown in figure H4; the east limit of the Eagle coastal sandstone facies at one point in time is shown where in abuts the marine shelf sandstone facies. The coastal sandstone also extends westward, buried under overlying marine and nonmarine rocks (figs. H1 and H2). An idea of the shifts in the Eagle shoreline may be gained from strandline positions shown by Gill and Cobban (1973) (fig. H5). Apparently the nonmarine and shoreface rocks of the Eagle extended somewhat farther east than the present site of Billings (fig. H4). The westward extent of the Eagle is not so well defined.

The Virgelle Sandstone member of the Eagle Sandstone is identifiable throughout the Gallatin National Forest, but middle and upper members, seen in the Bridger Range and in the Billings and Livingston areas, lose their identity to the south and west. In northern Yellowstone National Park, the Eagle is 777 ft (236 m) thick on the west face of Mount Everts. There it was described as consisting of two members: the Virgelle Sandstone, about 163 ft (50 m) thick, and an overlying, much thicker (614 ft, 187 m) upper coal member made up of interbedded sandstone, shale, carbonaceous shale, and coal (Fraser and others, 1969). At Mount Everts, the Virgelle Sandstone Member grades downward into the marine Telegraph Creek Formation, and the overlying coal member of the Eagle is gradational upward into the Everts Formation, according to Fraser and others (1969). Ruppel (1972), however, stated that an erosional unconformity separates the Eagle Sandstone from the overlying Everts Formation. Fraser and others (1969) designated a 1,250-ft (380 m) thick part of Mount Everts as the type section of the Everts Formation. They made a probable correlation of the Everts Formation with the Cokedale Formation of the Livingston Group (Roberts, 1963), although the Everts lacks volcanic material, a characteristic of the Livingston Group. Fraser and others (1969) interpreted the Everts as representing the continental part of a delta, with mixed lagoonal, paludal, and fluvial deposits. They pointed out that the type area of the Everts Formation was probably well drained, as coal and carbonaceous shale deposits in the unit are rare at this location.

To the west, and toward the source areas for the sediments in the continental deposit, the Everts and Two Medicine Formations increasingly replace most of the Eagle Sandstone (figs. H1 and H2); only the Virgelle Sandstone Member of the Eagle is recognizable in the Madison Range (Tysdal and Simons, 1985; Tysdal and Nichols, 1991). The areas where the Eagle Sandstone and Everts(?) Formation are exposed in the study area are shown in figure H6 and in greater detail on the geologic map of the area compiled for this study (Wilson and Elliott, 1995, 1997).

Coal Geology

Morrison Formation Coal

Earlier in the 20th century, coal was mined north of the Bridger Range in the Great Falls-Lewiston coal field, from what is now considered to be the Jurassic-age Morrison Formation (Bateman, 1966) with estimated reserves of 750 million short tons of bituminous coal (Scholes, 1985). Previously, Calvert (1909) had placed the coal of the Lewiston field in the Kootenai Formation, a stratigraphic position assignment supported by Combo and others (1949).

In the Gallatin National Forest some coal occurs locally in the upper parts of the Jurassic Morrison Formation. Simons and others (1983) reported 1–4-ft (0.3–1.2 m) seams of coal in slumped blocks of Jurassic rocks at Coal Canyon, east of Mount Hebgen, 2 mi (5 km) outside of the Gallatin Divide Roadless Area but inside the Gallatin National Forest. Analysis of this coal showed it to have a heating value of 11,000 BTU, and it contained 12 percent ash (Simons and others, 1983).

Witkind (1969) described the geology of the Tepee Mountain quadrangle, which covers the area of Jurassic coal mentioned by Simons and others (1983). The exposure of Morrison Formation in the quadrangle is isolated and limited in extent, as it occurs in a synclinal fold along the crest of a ridge. Witkind did not report finding the coal seams mentioned by Simons and others (1983); but nearby, in a streambed east of Coal Canyon (center sec. 25, T. 11 S., R. 4 E.), he found an isolated exposure of Morrison strata capped by a 2- to 3-ft- (0.6–1 m) thick, thin-bedded to platy carbonaceous seam. Witkind (1969) thought

that this seam might be correlative with a coal bed that commonly is found at the top of the formation throughout central Montana (referred to in reports by Fisher, 1908; Lammers, 1939; Brown, 1946; Vine, 1956). Witkind noted that Hall (1961) apparently saw no such seams in Morrison strata exposed to the north in the Gallatin National Forest. Witkind (1969) found that, in most places, upper beds of the Morrison Formation that are in contact with the (overlying) Kootenai Formation are of claystone, although Condit (1918, p. 115) noted some 49 ft (15 m) of "shale and clay with carbonaceous layers beneath the conglomeratic sandstone of the Kootenai at Indian Creek, MT, some 15 miles (24 km) to the northwest." Witkind felt that the absence of the carbonaceous shale from much of the Tepee Creek quadrangle might be the result of pre-Kootenai erosion.

Fraser and others (1969) found some coal near the top of a measured section of the Morrison Formation at Cinnabar Mountain, which is about 6.5 mi (10 km) northwest of Gardiner (fig. H6), just within the boundary of the study area (fig. A1). They measured 10 ft (3 m) of carbonaceous shale overlying 2 ft (0.6 m) of lignitic, flaky coal. These rocks do not crop out elsewhere in the Gardiner area.

Thus, the reported occurrences of Morrison Formation coal in the study area are few. The coals are generally found in exposures of limited extent and commonly are of low grade or contain numerous carbonaceous partings. Apparently the carbonaceous zone in the upper part of the formation is either lenticular or not preserved everywhere beneath the erosion surface that occurs across the top of the Morrison Formation in this region. There are no reported occurrences of coal mining in the Morrison Formation in the study area, and the probability of minable coal being present in Morrison Formation in the Gallatin National Forest is low.

Kootenai Formation Coal

Coal from a synclinal fold was mined from 1910 to 1920 in the 6-mi^2 (16 km^2) Lombard coal field, near Lombard (fig. H6) (Lorentz and McMurtrey, 1956; Johnson and others, 1993, appendix B). The Lombard field is about 15–19 mi (25–30 km) west of the Bridger Range and the Gallatin National Forest. The coal-bearing rocks are considered to be in the Morrison Formation (Bateman, 1966) but were previously placed in the Kootenai (Lorentz and McMurtrey, 1956; Lupton, 1914). The coal has coking properties but also has high ash and high sulfur contents, which decrease its value for that use. Combo and others (1949) report an analysis of the coal that shows it has values of 10,060 BTU, 29.7 percent ash, and 8.2 percent sulfur. The coal lies structurally below the Lombard thrust plate, which is on the west. Combo and others (1949) pointed out that the coal beds were much distorted by shearing and squeezing, and while some beds mined were 6 ft (1.8 m) thick, overall the coal occurs in pockets and lenses. Locally, some of the coal has been metamorphosed to graphite because of the distortion and shearing, according to Combo and others (1949), although Lorentz and McMurtrey (1956) ascribe this change to the effect of intrusions of dacite along the Lombard thrust fault.

The Kootenai Formation is found within the Gallatin National Forest, but no coal deposits nor carbonaceous shale

has been noted in the formation during previous work (McGrew, 1977a–c; McMannis, 1955; Simons and others, 1983; Skipp, 1977; Skipp and Peterson, 1965; Tysdal and Simons, 1985; Tysdal, 1990; Witkind, 1969). It appears unlikely that any such deposits will be found in the Kootenai Formation in the study area, so the probability of minable coal being present in the formation is very low.

Eagle Sandstone Coal, Madison and Gallatin Ranges

The Eagle Sandstone has historically been the most important coal-producing unit in this part of Montana. Good summaries of the history of coal mining include discussions by Roberts (1966) and Johnson and others (1993). The principal uses of the coal before the turn of the 20th century were for steam generation in railroad locomotives and to make coke for use in the smelters at Anaconda, Butte, Helena, and Great Falls (Roberts, 1966). The demand for coke declined greatly after the early 1900's. Coal production in the study area for power and steam generation also declined steadily. Production ceased after 1942 because the railroads switched to oil and because of the continuing enormous production of Tertiary coal by strip mining in eastern Montana and Wyoming. The historical mining areas that relate to the study area include the Electric coal field and part of the Meadow Creek district of the Livingston coal field (fig. H6).

Electric Coal Field

Early publications about this coal mining area include those by Weed (1891) and Iddings and Weed (1894). At that time the coal field was called the Cinnabar coal field, named for Cinnabar Mountain at the north end of the field. Subsequent studies of the area, made in greater detail, include those by Calvert (1912b) and by Fraser and others (1969). Calvert (1912b) applied the name "Electric field" to this area for the local name of the railroad station that shipped the coal. The field covers an area of about 20 mi^2 (50 km^2) (Calvert, 1912b), of which the total productive area was 3 mi^2 (8 km^2) (Fraser and others, 1969). Three mining areas in this field include the Aldridge and Electric districts on the south side of the Yellowstone River and the Little Trail Creek district on the north side of the river.

The Electric coal field is bounded by faults of considerable displacement on the north, west, and east sides (Iddings and Weed, 1894; Calvert, 1912b; Fraser and others, 1969). For example, at least 10,000 ft (305 m) of Phanerozoic rocks were eroded before Eocene time on the north side of a fault that bounds the field on the north (Fraser and others, 1969). Fraser and others describe the mining districts south of the Yellowstone River as being on the southwest limb of a syncline formed by drag on this fault, and the Little Trail Creek district, which is on the north side of the river adjacent to the Gardiner fault, as being in the highly deformed drag zone of the fault. The Bowers mine, mentioned by Iddings and Weed (1894), is in the Little Trail Creek district. Fraser and others (1969) found that coal in the Eagle Sandstone is very locally exposed in the drag zone from the Little Trail Creek district southeastward past the town of Gardiner and into Yellowstone National Park. Given the cover of younger strata over the Eagle Sandstone and the deformation of the coal beds in the drag zone, Fraser and others (1969, p. 81) concluded, "intelligent prospecting for coal seems out of the question. Mining would be extremely difficult, and, because of the current instability of the rock, hazardous." Furthermore, "there appears to be no scientific way to estimate coal tonnage and no meaningful way to evaluate or use such estimates should they be made" (Fraser and others, 1969, p. 82).

In the Aldridge and Electric mining districts of the Electric coal field, on the south side of the Yellowstone River, several mines produced coal from three coal beds (Weed, 1891); Calvert (1912b) reported that only the highest of the three was worked to any extent, as it was consistently coking in quality. This bed is as much as 5 ft (1.5 m) thick (Fraser and others, 1969).

Johnson and others (1993) estimated coal resources in a 3.2-mi^2 (8 km^2) area in the northern part of the field from the three coal beds described by Calvert (1912b); they calculated the field contains 20 million tons of potentially minable coal on private land within the nominal forest boundary. They gave an average value of 11,733 BTU/lb, 0.76 percent sulfur, and 18 percent ash. Previously, Scholes (1985) estimated that the field contains 25 million short tons of bituminous coal, with an average value of 11,410 BTU/lb, 1.3 percent sulfur, and 14.7 percent ash. Lower tonnages were given by Fraser and others (1969), who quoted a written communication from Paul Averitt wherein he inferred that the original resources in the No. 1 (upper) coal bed in the field were about 7 million tons. Allowing for past production and mining losses, Averitt calculated the estimated recoverable resources in the bed would be on the order of 3 million tons.

It should be noted that the continuity of the coal beds in the Electric field has not been tested toward the south and southwest, but the coal field is given a high potential for minable coal (fig. H6). Much of the field and its projection southward, while within the nominal National Forest boundary, is on patented land, as shown on the surface-minerals management map of this area (Bureau of Land Management, 1978).

Livingston Coal Field

Parts of the Livingston coal field cross areas of the Gallatin National Forest study area (fig. H6). The geology and coal resources of this field were described in great detail by Roberts (1966), to which publication the reader is referred for an excellent summary of the general geology of the region and of the coal resources of the Eagle Sandstone in this part of Montana. Roberts applied the name Livingston to the several mining districts that make up the field; several names had been applied previously to the coal mining area, such as Bozeman, Trail Creek, and Yellowstone coal fields. Earlier reports on the area include those by Eldridge (1886), Weed (1891), Iddings and Weed (1894), Storrs (1902), and Calvert (1912a). None of these are as detailed as the Roberts (1966) report.

Most of the coal mines and the mining districts of the Livingston coal field are just outside of the boundaries of the Gallatin National Forest, and the various attitudes of the coal-bearing Eagle Sandstone are such that the coal-bearing strata do not extend into the subsurface beneath the Forest. Along the east-west trend of the main part of the Livingston coal field the Eagle Sandstone strata dip generally northward. The Eagle in the Meadow Creek and Trail Creek districts lies in a syncline and has limited lateral extent.

Meadow Creek and Trail Creek Districts

The southeastern part of the Meadow Creek district (fig. H6), where it meets the northwestern part of the Trail Creek district (Roberts, 1966), extends into the forest in parts of secs. 1, 2, 11, and 12, T. 3 S., R. 7 E., and the SW1/4 sec. 7, T. 3 S., R. 8 E. A very small part of the Trail Creek district, containing short sections of the Maxey, Middle, and Bottamy coal beds crosses the nominal forest boundary, occupying patented land in the NE1/4NE1/4 sec. 5, T. 4 S., R. 8 E. This is shown in a generalized fashion in figure H6 and in detail on the map of the Maxey Ridge quadrangle map by Roberts (1964b), and on plate 1 of Roberts (1966). The surface-minerals management map of this area (Bureau of Land Management, 1978) shows these districts to be all on patented (private) land.

The Eagle Sandstone in this part of the Meadow Creek district is exposed diagonally across this area of the study area (fig. H6). It is confined to a 600- to 2,000-ft- (180–600 m) wide strip along the trough of a tightly folded syncline trending northwestward and does not extend beyond the boundaries of the

patented land. In this segment of the Meadow Creek district, the Monroe, Planishek, and Harrison mines produced small amounts of coal for domestic use from the Maxey bed, as did the Moran mine from the Big Dirty bed (see Roberts, 1964b and 1966 for locations of these mines). There is no record of any production from the other small prospects or mines that are shown in this area on the maps by Roberts (1964b, 1966). The Monroe mine had 18.5 inches (47 cm) total coal, and the Harrison 34 inches (86 cm) to about 39 inches (99 cm) (Calvert, 1912a; Roberts, 1966). The Planishek mine is near the Harrison mine, and presumably the Maxey bed had about the same thickness in both mines. No data were found in the literature on the thickness of the Big Dirty bed in the Moran mine. These particular beds were not included in the estimated coal reserves in the Eagle Sandstone of the Livingston coal field calculated by Roberts (1966, table 8), but it is clear that coal resources in this part of the

Meadow Creek district must make up a rather small percentage of the total he calculated (300.8 million short tons) for the entire Livingston coal field. As all of the mines in these parts of the Meadow Creek and Trail Creek districts were never large producers, and all were closed by the 1930's (Roberts, 1966), the area is given only a moderate potential for minable coal (fig. H6).

Bridger Canyon District

The Eagle Sandstone was prospected for coal in the Bridger Canyon district, which is south of the Gallatin National Forest boundary at the southern end of the Bridger Range, and north of the western end of the Meadow Creek district (fig. H6). This area was mapped and discussed by Roberts (1964a, 1966). There are two coal beds in the steeply dipping to overturned Eagle Sandstone at Bridger Canyon: the lower is 4 ft (1.2 m) thick and the upper is 6 ft (1.8 m) thick. Both beds have many partings and are "dirty" (contain much detrital material) throughout. No mines were ever developed in this district (Roberts, 1966).

Eagle Sandstone Coal, Bridger Range

The Eagle Sandstone continues northward from the Bridger Canyon district and into the Gallatin National Forest in the Bridger Range (fig. H6). The Eagle is near the top of the Paleozoic and Mesozoic strata that make up the core of the range. The Eagle and overlying Mesozoic rocks dip generally steeply eastward to overturned along the eastern flanks of the range, where they are overlain by Tertiary rocks in the Crazy Mountains basin (Wilson and Elliott, 1995, 1997). The geology of the range was described by McMannis (1955), and several geologic quadrangle maps covering parts of the Gallatin National Forest in the range have been published (McGrew, 1977c, d; Skipp, 1977; Skipp and Hepp, 1968; Skipp and McMannis, 1971; Skipp and Peterson, 1965). McMannis (1955) indicates that the Eagle Sandstone thins northward in the Bridger Range from a thickness of about 600 ft (180 m) at the south end of the range to about 100 ft (30 m) at the northern end. He describes it as being made up of sandstone with intercalated carbonaceous shales and very thin coal seams. Skipp (1977) also mentions that the Eagle Sandstone in the Wallrock quadrangle contains carbonaceous material and that thin coal seams are present, and McGrew (1977c, d) describes carbonaceous material in the Eagle Sandstone in "cannonball" concretions. No mention of carbonaceous material or of coal beds in the Eagle Sandstone is made in the other four quadrangle maps.

Apparently prospecting for coal was largely unsuccessful along outcrops of the Eagle Sandstone in the Bridger Range. Of the geologic maps, only the Fort Ellis quadrangle (Roberts, 1964a) at the south end of the range shows coal prospect pits (at Bridger Canyon), and even here no mines were developed (Roberts, 1966). There are not enough data available to make any coal resource estimates for the Gallatin National Forest in the Bridger Range. It is doubtful that there are any minable coal deposits in this part of the study area, and it is assigned a low potential for minable coal in the Eagle Sandstone (fig. H6).

Everts(?) Formation Coal, Madison Range

In the Madison Range in the western part of the Gallatin National Forest (fig. H6) the Everts(?) Formation, overlying the Virgelle Sandstone Member of the Eagle Sandstone, is about 1,400 ft (425 m) thick. The lower 200–300 ft (60–90 m) is made up of thin interbeds of mudstone, siltstone, shale, coal, and minor sandstone, as well as some thicker, trough-crossbedded sandstone (Tysdal, 1990; Tysdal and Simons, 1985). Coal in this unit was sampled in several places (Simons and others, 1983). A 2-ft (0.6 m) thick bed, measured at a caved adit on the border between secs. 11 and 14, T. 7 S., R. 1 E., had a heating value of 6,000 BTU. Samples from sec. 31, T. 8 S., R. 3 E., where there are two 5-ft (1.5 m) beds of impure coal, gave values of 3,000–4,000 BTU and 65 percent ash; one sample from sec. 3, T. 9 S., R. 3 E. gave a value of 12,000 BTU and 11 percent ash, although other samples from this locality gave much lower values (Simons and others, 1983). There are several 1- to 2-ft (0.3–0.6 m) beds in this area, and an exploration adit and small trenches; this locality was also visited by Hall (1961), who collected several Upper Cretaceous leaf fossils from a bed above the coal in the abandoned adit. Summarizing the coal geology, Simons and others (1983) stated that "coal occurs in several places in Cretaceous sedimentary rocks, but known seams are thin, discontinuous, and of low quality." Further, "the potential for minable coal resources is low." This is similar to the observation of Fraser and others (1969) who, discussing the Everts mountain section in northern Yellowstone National Park, stated that the Everts Formation contains no discrete coal beds above the Eagle Sandstone contact and few thin coal beds elsewhere.

A fairly large area of the Gallatin National Forest is underlain by the Everts(?) Formation and Virgelle Sandstone Member (undivided on the geologic maps of the area mentioned previously), but little is known about the coal in this unit. It has been prospected in some places, as mentioned previously but never mined. To date the coal beds that have been examined are thin, discontinuous, and of generally low quality, so it seems doubtful that there would be much minable coal in the Everts(?) Formation in the study area. In this report the formation is assigned a low potential for minable coal (fig. H6).

Crazy Mountains Coal

The portion of the Crazy Mountains that is occupied by the Gallatin National Forest (fig. H6) is underlain principally by the Fort Union Formation intruded by calc-alkalic and alkalic dikes, sills, laccoliths, and small and large stocks (Iddings and Weed, 1894; Weed, 1899; Stone, 1909; Simpson, 1937; du Bray and others, 1993). Farther west in the Crazy Mountains basin, toward the Bridger Range, strata of the Livingston Group, stratigraphically below the Fort Union Formation and above the Eagle Sandstone, are exposed (Weed, 1893; Skipp and McGrew, 1972; Roberts, 1963). The Eagle Sandstone and the Livingston Group underlie the Fort Union Formation and the Crazy Mountains at varying depths, as depicted in cross sections by Iddings and Weed (1894) and Weed (1899).

In much of eastern Montana and Wyoming, the Fort Union Formation contains a large number of thick coal beds, but

Simpson (1937) noted that the Fort Union in the vicinity of the Crazy Mountains contained only a few thin (1- to 2-inch-thick, 2.5–5 cm), impure, and local lenses of coal. Some prospecting was done in the basin east of the Crazy Mountains, but none of the coal had commercial value. Simpson stated (1937, p. 26), "in marked contrast with the Fort Union of most other areas, these rocks can be classed as not coal bearing."

Skipp and McGrew (1972) locally found a 2-ft- (0.6 m) thick lignitic coal at the base of the Livingston Group west of the Crazy Mountains, but there is no record of testing or development of the bed.

The Eagle Sandstone is exposed in outcrops to the north of the Gallatin National Forest, along the northern end of the Crazy Mountains east and west of the towns of Lennep and Martinsdale. Weed (1899) stated that the Eagle was about 200 ft (60 m) thick in this area, and contained thin lignitic seams in the upper shaly part of the formation. Stone (1909) examined these exposures and found the coal beds to be thin and ashy. Although the exposures were prospected and locally mined for domestic use, he concluded that the deposits had no commercial value.

Considering the information available, it is concluded that the area of the Gallatin National Forest in the Crazy Mountains contains no minable coal deposits in the Eagle Sandstone or in the Fort Union Formation.

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Energy Resource Assessment: Oil and Gas Plays of the Gallatin National Forest, Southwest Montana

By William J. Perry, Jr.

U.S. Geological Survey Professional Paper 1654–I

U.S. Department of the Interior
U.S. Geological Survey

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Introduction

The Southwest Montana oil and gas province (fig. I1, province 29) lies north and northwest of Yellowstone National Park and east and southeast of the Rocky Mountain Fold-Thrust Belt (fig. B2) in the southwestern part of Montana (Perry, 1995a). About 90 percent of the Gallatin National Forest study area lies within this oil and gas province. Three major Laramide uplifts exist in the province: (1) the Blacktail-Snowcrest, (2) Madison-Gravelly, and (3) the Beartooth uplifts. The Bridger uplift represents the remains of the southern part of a fourth Laramide uplift. The Madison-Gallatin subarea includes the Madison Range portion of the second uplift. The Crazy Mountains subarea includes the area of the Crazy Mountains intrusive complex to the north, between the Helena salient of the Rocky Mountain Fold-Thrust Belt to the west and the Crazy Mountains basin to the east. The Bridger Range subarea, which includes the Bridger Range, spans the boundary of two oil and gas provinces (fig. I1), the Southwest Montana Province (province 29) and the Montana Thrust Belt Province (province 27) (Perry, 1995a, b).

This assessment is based on assessments of the Southwest Montana Province (Perry, 1995a) and the Montana Thrust Belt Province (Perry, 1995b) that were conducted for the 1995 national assessment of United States oil and gas resources. Standard numeric designations for oil and gas provinces and for individual plays from that assessment are adopted in this report and are shown in figure I1. Plays are assigned 4-digit numbers. The first 2 digits refer to the oil and gas province (29 for the Southwest Montana Province; 27 for the Montana Thrust Belt Province). The second two digits refer to the play within that province.

The entire Phanerozoic stratigraphic sequence varies widely across the region of the Gallatin National Forest study area (Perry, 1990, 1995a). No significant amounts of hydrocarbons have been found in the study area. East of the Madison-Gallatin subarea, along the Nye-Bowler structural trend (Nye-Bowler lineament in fig. I1), three heavy oil (asphaltic) accumulations (10°–13° API, American Petroleum Institute gravity index) of black oil have produced small quantities of oil by steam injection (Perry and LaRock, 1993).

Most of the plays overlap one or more of the subareas of the Gallatin National Forest defined for this study (fig. I1). The Madison-Gallatin subarea includes parts of several oil and gas plays. The western part of the Nye-Bowler wrench zone oil and gas play (2903) includes the northeastern tip of the Madison-Gallatin subarea (fig. I1). Two small areas of the Tertiary Basins oil and gas play (2907, Bozeman Valley and Upper Madison Valley), overlap the forest boundary along the southwestern edges of the Bridger Range and Madison-Gallatin subareas (fig. I1). Additional plays, the Madison Subthrust oil play (2905), which includes the Madison Range portion of the Madison-Gallatin subarea, and the southern Big Sky basin area of the Basement Structure play (2908) portion of the central Madison-Gallatin subarea, were discussed but considered to have a play probability of 0.1 or less (Perry, 1995a). Therefore, they were not quantitatively assessed. Of the six conventional hydrocarbon plays assessed by Perry (1995a) in province 29, the western part of the Crazy Mountains and Lake Basins Cretaceous gas play (2901) and Crazy Mountains and Lake Basins (Paleozoic) oil play (2910; same area as 2901) includes the southeastern part of the Bridger Range subarea and the western part of the Crazy Mountains subarea (fig. I1). The central and northern part of the Bridger Range subarea was included in the Helena Salient gas play, play 2704 (Perry, 1995b). A discussion of these plays is relevant to the undiscovered oil and gas resource potential of the Gallatin National Forest study area.

Crazy Mountains and Lake Basins Cretaceous Gas Play (2901)

This confirmed play occupies approximately 4,400 mi^2 in the northeastern part of province 29. The Crazy Mountains basin part of the play excludes the area of the early Tertiary Crazy Mountains laccolith and igneous dike swarm and therefore excludes most of the Crazy Mountains subarea. The play includes part of the Lake Basin wrench fault zone (fig. I1). The play is bounded on the northeast by Hailstone dome, on the east by the Pryor uplift and Bighorn Mountains, on the south by the Nye-Bowler wrench fault zone (Nye-Bowler lineament in fig. I1), and on the west by the Helena Salient of the Montana Thrust Belt (fig. B2). It is a confirmed structural play, characterized by relatively small Cretaceous gas fields in structural and combination structural-stratigraphic traps.

Reservoirs

Numerous Cretaceous sandstones have reservoir potential, primarily the Lower Cretaceous Muddy, Dakota, and Lakota gas sands and the Upper Cretaceous Frontier, Eagle (including Virgelle Member), and Judith River Sandstones. Porosities in the gas-producing fields range from about 12 to 18 percent, and permeabilities range from about 25 to 90 mD (millidarcies) (Tonneson, 1985). Reservoir sands appear to be generally less than 100 ft thick and are bounded by marine shales in the eastern part of the play (east of the study area, and east of the area of fig. I1).

Abundant volcaniclastic rocks occur in the western part of the play, where the sands are generally of much poorer reservoir quality.

Source Rocks

Cretaceous source rocks include the Skull Creek (occurs in eastern Montana; the lithic equivalent of the shale in the middle part of the Thermopolis Shale of the study area), Thermopolis, Muddy, Frontier, Cody, and Mowry Formations. According to data from Burtner and Warner (1984), the Mowry and Skull Creek Shales contain 1 percent or less total organic carbon (TOC) and predominantly Type III woody to herbaceous gas-prone kerogen. Migration of natural gas from these source rocks into adjacent Cretaceous sandstone reservoirs probably took place during early Tertiary time.

Traps

Traps are on generally north-south trending, partly fault-bounded anticlines (Tonneson, 1985) and are the result of Cretaceous to early Tertiary Laramide deformation. Trap size varies

from 2,500 to 6,700 acres for the discovered fields (Tonneson, 1985). Seals appear to be the overlying Cretaceous shales. Producing depths range from less than 1,000 ft to 3,925 ft. However, the maximum depth for undiscovered Cretaceous gas accumulations may be as much as 20,000 ft near the western margin of the play west of the Crazy Mountains intrusive complex.

Exploration Status and Resource Potential

Cumulative gas production through 1992 was 29 BCFG (billion cubic feet of natural gas) for the Big Coulee gas field, directly north of Hailstone dome and just east of the eastern edge of figure I1 (Jacobson and others, 1993). Three other small (less than 10 BCFG) gas fields just south of the Lake Basin fault zone in the eastern Crazy Mountains basin lie farther east of the eastern boundary of figure I1 (eastern part of play 2901 of Perry [1995b]). Only one of these has produced more than 5 BCFG (Jacobson and others, 1993), and all are essentially depleted. No hydrocarbons have been produced nor commercial hydrocarbon productions established from within the area of figure I1. Other fields in this play have produced less than 1 BCFG. The western part of this play has been sparsely drilled, whereas the eastern part has been more intensely explored. I judge that at least three gas fields of at least 6 BCFG remain to be discovered in this play, that they will be relatively small, and they will lie east of that portion of the play included in the Crazy Mountains subarea, because of the proximity to the Crazy Mountains laccolith, dike swarm, and related intrusive rocks (Harlan and others, 1988).

Crazy Mountains and Lake Basins Oil Play (2910)

The Crazy Mountains and Lake Basins oil play occupies the same area as the Crazy Mountains and Lake Basins Cretaceous gas play (2901), that is, the Crazy Mountains basin exclusive of the early Tertiary Crazy Mountains laccolith and igneous dike swarm, and Reed Point syncline exclusive of the Cretaceous Sliderock Mountain intrusive-extrusive complex (fig. I1). The play also includes part of the Lake Basin wrench fault zone, and the west and south flanks of the Hailstone dome. The play is bounded on the west by the Helena Salient of the Rocky Mountain Fold-Thrust Belt (fig. B2). It is a hypothetical stratigraphic play characterized by relatively small carbonate (Waulsortian) mud mounds.

Reservoirs and Traps

Waulsortian mud mounds as much as 300 ft thick occur in the Paine Member of the Lodgepole Formation, Mississippian Madison Group, east, west, and north of the play area. These are composed of lime mudstone, sparry calcite, and skeletal debris. They are commonly dolomitized, resulting in good secondary porosity. Sinkholes and zones of karstic porosity in the upper part of the Madison Group are part of the major Madison aquifer system and are likely flushed in the play area.

Source Rocks

Paleozoic source rocks are poorly known in the play area. The Bakken-equivalent Upper Devonian to Lower Mississippian oil-prone mudstone is very thin to absent, and Permian Phosphoria source rocks are absent (Peterson, 1985). The east-west-trending Big Snowy trough (in the northern part of the Central Montana trough, fig. B2), an approximately 50-mi-wide late Paleozoic paleotectonic sag, extends east-southeastward from the Helena salient north of the Crazy Mountains and north of the Lake Basin fault zone into eastern Montana (Peterson, 1985). Southward migration of hydrocarbons from this trough into the area of the later Crazy Mountains basin could have occurred prior to Late Cretaceous and early Tertiary subsidence of much of the play area. In the western part of the area, the Madison Group has been exposed to relatively high geothermal gradients, is generally deeply buried, and may have been subjected to temperatures beyond the range of liquid hydrocarbon stability.

Exploration Status and Resource Potential

Few wells have penetrated the Madison Group in the play area. Most appear to have contacted fresh to brackish water. In order for hydrocarbons to be present in Waulsortian mounds in the lower part of the Madison Group, the generally tight, thin-bedded Lodgepole must be reservoir-separated from the top of the Madison. Traps may be very subtle; locally, the Lodgepole is very shaly. Such shale intervals may provide bottom seals for fresh- to brackish-water circulation. The presence of through-going open vertical fractures would destroy such seals. Because of hydrocarbon source and possible seal problems, the play likely has a low to very low probability of success. The probability of occurrence of an undiscovered accumulation of at least minimum size (1 MMBO [million barrels oil] or 6 BCFG) is considered to be 0.2. The likelihood is considered much more remote (probably less than 0.01) for that portion of the play included in the Crazy Mountains subarea because of the proximity to the Eocene Big Timber stock and other igneous rocks in the Crazy Mountains (du Bray and others, 1993; Harlan and others, 1988).

Nye-Bowler Wrench Zone Oil and Gas Play (2903)

The Nye-Bowler lineament (fig. I1), or wrench zone, was defined by Wilson (1936) as a zone of faults and en-echelon folds extending west-northwest across the northern part of the Bighorn basin. Differences in thickness of upper Campanian and Maastrichtian stratigraphic units across the zone, greater by an order of magnitude than differences in middle Campanian thicknesses, indicate more intense lateral and vertical movements during late Campanian and Maastrichtian time; even greater differences indicate a maximum intensity during deposition of the continental Fort Union (Late Cretaceous to early Paleocene) time (Wilson, 1936). Deformation had ceased by

Eocene time when the pre-Wasatch erosion surface was developed.

The Nye-Bowler wrench zone extends westward to include the line of intrusive igneous bodies represented by the Sliderock Mountain (fig. I1) intrusive complex in the Absaroka-Beartooth study area (du Bray and others, 1994). To date, no hydrocarbons have been discovered in this area; the western part of play 2903 has had no hydrocarbon production and is a hypothetical resource. The area includes a zone of en-echelon anticlines that are considered prospective (Perry, 1990) and likely are restricted to the sedimentary cover above a zone of strike-slip in the Precambrian basement. The confirmed part of the play lies east of the intrusive complex (Sliderock Mountain, fig. I1) and outside the Gallatin National Forest study area. The hypothetical part of the play, which includes part of Gallatin National Forest, lies west of the complex.

Reservoirs

Reservoirs in the demonstrated part of the play east of the Sliderock Mountain intrusive complex include numerous Cretaceous sandstones—Eagle, Virgelle, Kootenai (Greybull), Lakota, and Judith River—of variable reservoir quality and thickness (Tonneson, 1985).

Source Rocks

Source rocks for the gas, and possibly the oil, in the eastern part of the play are inferred to be Cretaceous marine shales—the Skull Creek, Thermopolis, Mowry, and Cody. The heavy oil north of the Beartooth Front is considered to be from the Permian Phosphoria Formation (Claypool and others, 1978). If so, then the migration barriers presented by the Late Cretaceous Laramide uplifts of northwestern Wyoming and southwestern Montana could not have been present at the time of hydrocarbon generation and migration unless unidentified Phosphoria source rocks are present east of these uplifts. Hydrocarbons from Cretaceous source rocks were generated during latest Cretaceous through early Tertiary time.

Traps

Traps are domes and en-echelon anticlines along the Nye-Bowler wrench fault zone, as described previously.

Exploration Status and Resource Potential

The eastern end of the Nye-Bowler wrench fault zone (play 2903), east of Sliderock Mountain, includes the fields discussed by Perry and LaRock (1993). This area has been extensively explored for hydrocarbons, and no oil or gas fields have been discovered since 1967. Heavy oil production has been abandoned as noncommercial. Only one field is still in operation and that is only for gas storage; it lies east of the Absaroka-Beartooth study area (Perry and LaRock, 1993). Nonconventional oil resources are abundant in the form of heavy oil, which requires steam injection or other unconventional methods to produce. Conventional undiscovered hydrocarbon resources appear modest.

The western part of the play has not been thoroughly explored; undiscovered oil and gas resources are assigned to this hypothetical part of the play. The extreme western edge of the play, including the northern part of the Madison-Gallatin subarea, likely has the least potential because seals were likely breached when steeply dipping to vertical fracture pathways extended to the surface.

Tertiary Basins Oil and Gas Play (2907)

The hypothetical Tertiary Basins oil and gas play (fig. I1) is based on the premise that oil and gas from older source rocks have generated hydrocarbons in Tertiary time, which may have been sealed in traps in the deeper parts of several small Tertiary basins in the Southwest Montana Province. From northeast to southwest, Bozeman Valley (Madison-Gallatin basin, 97 mi^2), which extends into the southwest margin of the Bridger Range subarea; Upper Madison Valley (281 mi^2), which extends into the southwestern part of the Madison-Gallatin subarea; and Sage Creek-Upper Ruby (202 mi^2), which is southwest of the study area, are among the largest and deepest of these basins. These are outlined as part of the Tertiary Basins oil and gas play (fig. I1). These basins are normal-fault bounded on at least one side, contain as much as 9,000 ft of Tertiary sediments, and are the result of Basin-Range extension and associated strike-slip faulting; the deepest is a narrow slot more than 14,700 ft deep in the northern part of Upper Madison Valley (Ruppel, 1993). The southwestern basins are floored by middle Eocene volcanic rocks emplaced between about 49 and 44 Ma (Hanneman, 1989). These, or the Archean or Paleozoic basement rocks to the northeast, are unconformably overlain by late Eocene to early Miocene devitrified volcaniclastic and lacustrine rocks associated with locally derived coarse clastic rocks (Fields and others, 1985).

Reservoirs

Inferred reservoir sands occur in the lower parts of the basin fill; details of reservoir quality are unknown or at least unpublished.

Source Rocks

Source rocks may include oil-prone lacustrine rocks or gas-prone coaly rocks in the lower part of the basin fill, but such have not been described in this province. A more likely inferred source is Paleozoic rocks beneath or on the margins of these basins, which were not buried deeply enough to become

supermature with respect to oil generation until the high heat flow associated with Tertiary extension occurred (based on analogies with the Great Basin of the Western United States).

Traps

Where studied in detail (A.R. Tabrum, Carnegie Museum, written commun., 1985; Hanneman, 1989; Hanneman and Wideman, 1991), these basins are structurally very complex and are broken by faults into a number of subbasins. Such faults may provide traps for hydrocarbons sealed by younger, fine-grained volcaniclastic rocks. Calcic paleosol zones (Hanneman and Wideman, 1991) may also act as seals to the upward migration of hydrocarbons.

Exploration Status and Resource Potential

Very few (probably less than six) significant wells have been drilled in Tertiary basins in the Southwest Montana Province. Considering the structural complexity of these basins, they are essentially untested. However, these basins have no demonstrated source-rock potential, and the largest, the Upper Madison Valley, rests primarily on high-grade Archean metamorphic rocks. The Upper Madison Valley extends into the very southwestern part of the Madison-Gallatin subarea of the forest. Therefore, a relatively low probability (0.24) of occurrence of a hydrocarbon accumulation of minimum size (1 MMBO or 6 BCFG) was assessed.

Helena Salient Gas Play (2704)

The Helena Salient of the Montana Thrust Belt lies east of the Boulder batholith (fig. B2). Anticlinal and thrust imbricate closures within the salient define the Helena Salient gas play, a hypothetical structural play slightly more than 3,600 mi^2 in area. The central part of the play area contains 12,000–25,000 ft of Middle Proterozoic sedimentary rocks, unconformably overlain by about 9,000 ft of Phanerozoic sedimentary rocks. Nearly one-half of the Phanerozoic section is Cretaceous, chiefly Upper Cretaceous siliciclastic and volcanic rocks. The salient forms a portion of the Belt Embayment, an inferred aulacogen during Middle Proterozoic time and a region of locally intense igneous activity during Late Cretaceous and early Tertiary time. The portion of the Bridger Range subarea that extends into the play area consists of a relatively small (less than 23 mi long) north-trending basement-cored uplift of latest Paleocene to earliest Eocene age which locally exhumed and rotated earlier thin-skin thrust belt structures (Lageson, 1989).

Reservoirs

Anticipated reservoir rocks include Pennsylvanian and Permian sandstones, Devonian and Mississippian carbonates, and Cretaceous sandstones with fracture-enhanced porosity. In outcrop, these rocks appear to have very little primary porosity. Karstic porosity may be present near the top of the Mississippian Madison Group, and Waulsortian mounds are present near the base of the Madison in the play area (Precht and Shepard, 1989).

Source Rocks

Recently acquired Middle Proterozoic samples from the play area contain minimal organic matter and show evidence of a regional Precambrian thermal event that heated the rocks to temperatures greater than 200°C (Pawlewicz, 1994; T.A Daws, G.A. Desborough, and M.J. Pawlewicz, written commun., 1993). Surface samples of Cretaceous rocks in the western part of the play are supermature with respect to liquid hydrocarbons, mature in the central part of the play, footwall to the Lombard Thrust, and immature to the east. Three samples of Late Mississippian Heath-equivalent Lombard black shale from the immediate footwall of the Lombard Thrust fault (fig. B2) contain 2.7–2.89 percent TOC and are gas prone (HI range 30–54, OI range 28–68, and S2 range 0.85–1.47, T.A. Daws, written commun., 1983; see Tissot and Welte, 1978, p. 443–447). Devonian Bakken-equivalent and Permian Phosphoria oil-prone source rocks appear to be thin to absent in the play. Timing of hydrocarbon generation probably coincided with thrusting: Late Cretaceous to Paleocene. Intrusive activity in the northern part of the play area and along the western margin of the play appears to be dominantly Late Cretaceous.

Traps and Resource Potential

Hypothetical traps are thrust-cored anticlines and thrust-imbricate culminations in the footwall and east of the Lombard thrust fault (fig. B2). The depth range expected for natural gas in the play is from 500 to 20,000 ft. None of the source rocks sampled in the play east of the Lombard thrust were oil prone, even though these rocks were in the oil window. Therefore the chance of finding significant oil in this play is remote. That part of the play in the Bridger Range subarea has been exhumed as part of the late Laramide Bridger Range uplift and has very low (<0.1) probability of containing significant hydrocarbons.

Madison Subthrust Oil Play (2905)

This hypothetical structural play is based on the premise that oil may be trapped in the Laramide basement-involved Hilgard thrust system (see Chapter B) in the south-central part of the Southwest Montana Province (province 29, fig. I1) (Kellogg and others, 1995). Here, Archean through Paleozoic rocks of the Hilgard fault system (Tysdal, 1986, 1990) were thrust eastward over Cretaceous rocks of the Big Sky basin to the east during Maastrichtian (Late Cretaceous) time (Tysdal and others, 1986). The western part of the Hilgard thrust fault system was breached

and dropped during late Tertiary to Quaternary time by the still active Madison Range extension fault system (Tysdal, 1986). The Madison subthrust oil play extends from the lip of the easternmost thrust to the Tertiary Madison Range normal fault system on the west, a distance of generally less than 6 mi (Tysdal, 1990).

Reservoirs

Possible reservoir rocks in the area (from map descriptions by Tysdal, 1990) include Pennsylvanian and Permian sandstones that range from about 115 to 315 ft thick and limestones of the Mississippian Madison Group that are as thick as 1,450 ft. Possible zones of karstic porosity are present in the top of the Madison in this area; the remainder is likely to have very low intergranular porosity. Cretaceous sandstones as much as 400 ft thick may also have reservoir potential.

Source Rocks

Pre-Cretaceous source rocks are thin to absent in the area of this play. Cretaceous source rocks are also lean and gas prone in this area (references given in Perry, 1990). Pre-thrust migration of hydrocarbons from richer Paleozoic source rocks to the west to early formed traps in this play area would provide a possible source.

Traps

Inferred anticlinal and (or) thrust imbricate structural traps blanketed by Cretaceous shales need to be present beneath the overriding Precambrian basement-involved thrusts of the Hilgard system. Overturned footwall rocks as old as the Mississippian Madison Group are exposed (Tysdal, 1990) such that prospective traps are breached. Hydrocarbons originally trapped beneath the Hilgard thrust system could also have been expelled during extension faulting through steeply dipping to vertical extension fracture networks.

Exploration Status

No wells have been drilled in this play. Data from the one nearby drillhole to the east indicated no shows of oil or gas and indicated abundant freshwater in the upper part of the Madison Group. No seeps or other surface indications of hydrocarbons have been reported.

Resource Evaluation

Cretaceous intrusive activity has affected the northern part of the play area, and Upper Cretaceous rocks of the Livingston Group contain abundant volcanic ash (Tysdal and others, 1986). In summary, the hydrocarbon potential of this play appears to be low to very low: a play probability of 0.1 was assessed chiefly on the basis of the likelihood of breached seals and absence of surface or subsurface indications of hydrocarbons. Only the southern 40 percent of this play extends into the study area.

Basement Structure Play (2908)

This hypothetical play includes two areas: the southern Big Sky basin (394 mi^2), which lies chiefly in the central Madison-Gallatin subarea, and the Ruby basin (805 mi^2) west of the study area. This play is based on the hypothesis that hydrocarbons may have been trapped by early formed basement-involved structures with closures of less than 1,000 ft. Many of these structures may not be represented by the structural attitudes at the surface of unconformably overlying younger rocks. Northwest-trending structures may have been actively growing during late Paleozoic time (Maughan, 1983). Small north-northwest-trending anticlines are present in the northern part of the Ruby basin area (Mann, 1960). Other such structures appear to be present farther southwest in the basin as indicated by gravity modeling (Kulik and Perry, 1988) and by seismic profiles. Ruby basin forms the northwestern margin of the late Paleozoic Wyoming shelf (Perry, 1986). Deep drillholes in the Ruby basin and uplift south of the play area indicate a gradually northward thickening of the upper Paleozoic sequence across the area from the Monida paleohigh, where upper Paleozoic rocks are locally only 310 ft thick (Perry, 1986). The Big Sky basin is a small Cretaceous basin containing several northwest-trending structures. At least one of these structures is demonstrated by Tysdal (1986) to predate the Late Cretaceous Hilgard thrust system along the western margin of the basin. Big Sky basin contains a thin sequence of upper Paleozoic rocks comparable to those of Ruby basin (Perry, 1990). The "Christmas-tree laccolith" dated by Tysdal and others (1986) as latest Cretaceous occupies much of the northern part of the Big Sky basin. The presence of this laccolith provides not only a minimum age for Hilgard thrusting but also severely reduces the oil potential of this basin. The two basins were part of the much larger intracratonic foreland basin (that included the present northern Bighorn basin) along the western margin of the Western Interior Cretaceous seaway (fig. H3) until latest Cretaceous time. Hornblende from laccolithic rocks that intruded the Hilgard thrust system was dated using K-Ar and $^{40}Ar/^{39}Ar$ methods (Tysdal and others, 1986); the dates indicate that thrusting along the western margin of the Big Sky basin occurred prior to 68 Ma.

Reservoirs

Possible reservoir rocks in both basins include Early and Late Cretaceous sandstones (generally less than 300 ft thick), thin Permian sandstone, Pennsylvanian Quadrant Sandstone (50 to 200 ft thick), and Mississippian Madison limestones with possible karstic porosity at the top.

Source Rocks

Paleozoic rocks in the Ruby basin are postmature with respect to oil generation (Perry and others, 1983); no values are available for the Big Sky basin. Lower Cretaceous rocks are

considered gas prone and are expected to be relatively impoverished in organic carbon (Perry and others, 1983; unpub. data).

Exploration Status

Two deep drillholes in the southern one-third of the Ruby basin area contained no shows of oil or gas. The American Quasar no. 29–1 Peet Creek-Federal well (Perry, 1986, fig. 1), drilled along the southern margin of the play area, also yielded no hydrocarbons. This drillhole yielded brackish water from Devonian rocks below 11,000 ft, suggesting deep circulation of ground water along the nearby Centennial Extension (normal) fault. The Phillips Petroleum no. 1 Carrot basin drillhole in the southern part of the Big Sky basin (Perry, 1990, fig. 1) was dry. The structure on which it was drilled appears to contain brackish water in the Madison limestones, suggesting deep ground-water circulation and absence of a seal for hydrocarbons (Perry, 1990).

Resource Potential

These findings suggest that the Big Sky and Ruby basins have low to very low hydrocarbon potential. The play probability was rated very low (0.08) for the occurrence of an undiscovered hydrocarbon accumulation of the minimum size, based in large part on the occurrence of fresh to brackish water and no hydrocarbons, as well as thin, impoverished source rocks in wells drilled to 1993.

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U.S. Geological Survey Professional Paper 1654–J

U.S. Department of the Interior
U.S. Geological Survey

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Summary and Outlook

By Jane M. Hammarstrom, Anna B. Wilson, Bradley S. Van Gosen, Dolores M. Kulik, Robert R. Carlson, Gregory K. Lee, and James E. Elliott

Introduction

For land-use planning and effective land stewardship, Federal land managers need information about the nature, location, quantity, and relative importance of mineral and energy resources that have been mined in the past, as well as those that might be sought in the future. To meet those needs, the U.S. Geological Survey conducted a mineral- and energy-resource assessment of the Gallatin National Forest study area using an approach that considers the types of mineral deposits (Singer, 1993) that could occur as well as the commodities that could be produced from them. This approach is intended to provide land managers with a perspective on the likelihood and nature of minerals activity in the western and northern parts of the Gallatin National Forest for the reasonably foreseeable future. In addition, the maps and other data compiled in this report can be incorporated into other types of land-use evaluations where geologic or lithologic base maps, data on chemical signatures of rocks and stream sediments, or information about abandoned mines and prospects are needed.

Parts of the Gallatin National Forest east of the Yellowstone River were assessed along with adjacent parts of Custer National Forest in a report on the Absaroka-Beartooth study area (Hammarstrom and others, 1993). Parts of the Gallatin National Forest west of the Yellowstone River (Madison-Gallatin subarea), in the Bridger Range (Bridger Range subarea), and in the Crazy Mountains (Crazy Mountains subarea) are assessed in this report. Much of the Madison-Gallatin subarea was evaluated in previous small-scale mineral resource assessments that were used as part of the process of determining the suitability of parcels of Federal land for wilderness designation (much of the land is now closed to further mineral entry). Data from previous studies were incorporated with new information acquired for this study and used to compile a new geologic map for the area at a scale of 1:126,720 (Wilson and Elliott, 1995, 1997). This new map was used in conjunction with geochemical data, geophysical data, information about mines, prospects, and mineral occurrences, and descriptive mineral deposit models to delineate tracts in the Gallatin National Forest study area that are geologically permissive for the occurrence of one or more types of mineral deposits. No mines or exploration projects were active in the study area as of 1997, and recently active mining claims are few.

Mineral Resources

Identified Resources

The U.S. Bureau of Mines (USBM) compiled information on the identified resources in the Gallatin National Forest, computed a list of the most significant identified resources, and conducted an economic and socioeconomic analysis of the mineral deposits in the study area that are most likely to be developed in the near future (Johnson and others, 1993). Of the 22 significant identified resources listed in that study, only two mineral deposits are in parts of the Gallatin National Forest covered by this report: (1) the lead-zinc-silver deposits of the Pass Creek mine area in the Bridger Range subarea, and (2) the precious- and base-metal veins at the Half Moon mine in the Big Timber district in the Crazy Mountains subarea. Neither of the deposits was included in the USBM economic analysis of deposits most likely to be developed (Johnson and others, 1993). However, calculated reserves for these deposits (table A1) do statistically fit the grade and tonnage models for their respective mineral deposit types (table A3), although neither has had any recent activity. No significant identified resources occur in the Madison-Gallatin subarea, although a variety of different types of mineral deposits were mined on a small scale in the past. The USBM study (Johnson and others, 1993) concluded that new exploration activity may be expected in the Pass Creek mine area in the Bridger Range should there be a real dollar rise in precious- or base-metal prices; however, most new exploration in the Gallatin National Forest was expected to focus on the Emigrant, Stillwater, Independence, and New World mining districts east of the Yellowstone River in the Absaroka-Beartooth study area (fig. A1). Recent uncertainty about the future of mining on Federal land in the New World district, and on Federal land proximal to Yellowstone National Park in general, has affected mining industry interest in the area and may continue to dissuade exploration in the foreseeable future.

Quantitative Assessment of Undiscovered Mineral Resources

The authors of this report classified mines, prospects, and most mineral occurrences in terms of general mineral deposit types (Chapter C) and delineated permissive tracts within the Gallatin National Forest study area for more than 20 general types of mineral deposits (Chapter G). However, there were only two types of deposits for which the available geologic and deposit model data warranted a quantitative estimate of undiscovered resources. The reasons for this are (1) the assessor must be confident that the undiscovered deposits are appropriately characterized by the descriptive mineral deposit model and the grade and tonnage models before proceeding with a quantitative assessment, and (2) most of the deposit types in the Madison-Gallatin subarea are somewhat unconventional deposit types that are not adequately described by existing grade and tonnage models.

Most of the types of mineral deposits exploited in the past would not be economic today, and resources identified in past assessment studies have not been developed. These include deposits of asbestos, sillimanite-group minerals, minor occurrences of base and precious metals, and phosphate resources. However, two types of deposits not recognized in the past that have been the subject of recent mining industry interest and may be present in the study area are porphyry copper deposits (in the broad sense) and gold-bearing skarn deposits. The rationale for delineating permissive tracts for these deposit types is documented in Chapter G. The process of estimating numbers of undiscovered deposits and metal endowments for these deposit types is discussed herein.

Estimates of numbers of undiscovered mineral deposits are subjective judgments based on geologic data and the assessor's expert knowledge of the deposit type. The estimates represent a consensus of the authors' individual estimates of the least likely numbers of deposits at each of five levels of confidence. The basis for each assessor's estimate may include consideration of the rate-of-occurrence of a deposit type in a well-explored area, recognition of mineralized target areas based on understanding of ore-forming processes, and spatial relationships among deposit types (Bliss and Menzie, 1993; Drew and Menzie, 1993). Probabilistic estimates of numbers of undiscovered deposits were combined with appropriate grade and tonnage models in a computer program to simulate the amount of metal that could be contained in undiscovered deposits in the study area (table J1). The computer program, Mark3, is used as a tool to convert probabilistic estimates of numbers of undiscovered deposits of a given type into distributions of contained metal (Root and others, 1992) using a Monte Carlo simulation technique and grade and tonnage data from a set of well-characterized deposits. Mark3 processes the estimates of numbers of undiscovered deposits to produce a deposit distribution curve and assign a probability to each deposit scenario ranging from the possibility of 0 deposits to a maximum equal to the number of deposits estimated at the 1 percent confidence level.

The deposits included in the models used are not necessarily economic; they are only defined as mineral occurrences of sufficient size and grade that they might, under favorable circumstances, be considered to have economic potential (Cox and Singer, 1986).

Five tracts (table A4; Gallatin Range, Lone Mountain, Snowslide Creek, Flathead Pass, and Crazy Peak) covering 1,771 km^2 (684 mi^2) are deemed permissive for the occurrence of porphyry copper deposits within 1 km of the surface; however, no deposits of this type have been discovered in the study area. The assessment team reached a consensus estimate (table J1, input) of 0 deposits at the 90 percent, 50 percent, and 10 percent confidence levels, and 1 deposit at the 5 percent and 1 percent confidence levels for a porphyry copper deposit occurring somewhere within the permissive areas that would have a grade and a tonnage characterized in the North America porphyry copper deposit model (Hammarstrom and others, 1993). Mark3 translates these estimates into a deposit distribution (probabilities sum to 1) in which there is a 0.925 probability (92.5 percent chance) of 0 deposits and a 0.075 probability (7.5 percent chance) of 1 deposit.

Four tracts (table A4; Ramshorn Peak, Hyalite Peak, Big Sky, and Blacktail Mountain) covering 1,360 km^2 (525 mi^2) are permissive for the occurrence of skarn deposits, based on the occurrence of carbonate rocks proximal to intrusive centers. Gold may occur as a coproduct or byproduct of skarns dominated by copper, iron, or zinc-lead (Theodore and others, 1991). In the past, iron and base metals were produced from skarns; however, today, most skarns are sought for their gold content, such as those in the New World district. The assessment team estimates that there are 0 deposits at the 90 percent confidence level, 1 deposit at the 50 percent level, 2 at the 10 percent level, 3 at the 5 percent level to a maximum of 4 deposits at the 1 percent confidence level (table J1, input). One skarn deposit, the Apex (fig. C2, table C1, no. 16), is known in the area, and the laccolithic shape of many of the intrusive complexes suggests that skarn could have formed at shallow depths in carbonate rocks below sheets of intrusive rock extending out from the main bodies of laccoliths. Although surface indications for either skarn (such as, extensive calcsilicate development at contacts) or for porphyry deposits (such as, stockwork quartz veining or ubiquitous well-developed alteration zones) are lacking, our estimates recognize the potential for the occurrence of these deposits at depth based on our data. In the Absaroka-Beartooth study area, both porphyry copper and gold-bearing skarn deposits are associated with intrusive complexes that are similar in age and chemical affinity to those in the study area.

Results of the computer simulation (table J1, output) predict a mean expected value of less than one porphyry deposit and about one skarn deposit. The predicted cumulative in-place metal and ore distributions attributable to the two deposit types combined are shown graphically in figure J1, and quantile results are reported in table J2. These data show that, if the assessors' appraisal of the potential for these deposits is accurate, there is a 50:50 chance of there being at least 210 metric tons of copper concentrated in undiscovered porphyry and skarn deposits in the study area. The mean expected value for copper is 190,000 metric tons; however, the graph shows that there is only a 10 percent probability of the mean value being realized or exceeded. In some cases, mean expected values are reported where all of the quantile values are zero. This occurs because the estimates of numbers of deposits were input for the 5 and 1 percent quantiles and the output is reported only to the 10 percent quantile. The input was carried out to low probabilities to reflect the assessors' belief that the number of undiscovered deposits are likely to be small, but nonnegligible. Quantile metal estimate values are not additive because they represent ranked data. Mean values, however, are additive so the mean expected value for copper in undiscovered porphyry deposits (160,000 metric tons) plus the mean expected value for copper in undiscovered skarn deposits (31,000 metric tons) comprise the mean expected value for copper (191,000 metric tons) reported in table J2.

In contrast to these results, the results of a similar exercise conducted for the Absaroka-Beartooth study area indicated a 50:50 chance of there being at least 3,100,000 metric tons of copper in undiscovered deposits. Given recent trends in domestic copper production, it is unlikely that the Gallatin

National Forest would be a likely exploration target for copper. Gold might be of more interest; the alkalic chemical signature of many of the igneous rocks may warrant more detailed studies for gold potential in the area. However, there are many more interesting gold target areas elsewhere in Montana. Montana produced 13.6 metric tons of gold in 1994 (U.S. Bureau of Mines, 1995) and ranked fifth in domestic gold production. The mean expected value of in-place (not produced) gold in the study area is 10 metric tons, which is an order-of-magnitude lower than the mean expected value for in-place gold of 200 metric tons in the Absaroka-Beartooth study area (Hammarstrom and others, 1993). To put these estimates into perspective, consider that the mean estimates for undiscovered resources in the western and northern parts of Gallatin National Forest represent only 0.3 percent of the gold and 0.01 percent of the copper produced in the United States in 1994 (U.S. Bureau of Mines, 1995).

No quantitative assessment was attempted for the two metallic mineral deposit types most likely to be the focus exploration in the foreseeable future, the sedimentary-exhalative type deposits represented by the Pass Creek mine in the Bridger Range or the polymetallic vein type deposits represented by the Half Moon mine area in the Crazy Mountains. The reasons for this omission are twofold: (1) the tracts have not been completely explored and additional resources are more likely to be associated with extensions of identified resources rather than with discrete new deposits, and (2) uncertainties about appropriateness of existing descriptive and grade-tonnage models for these deposit types in the study area.

Energy Resources

A number of coal fields border, and partly extend into, the Madison-Gallatin and Bridger Range subareas of the Gallatin National Forest study area. Coal is locally present in sedimentary rocks of Jurassic and Cretaceous age. Some coal mining occurred in the study area before 1943, mainly for steam generation and for smelters. In recent years, Montana coal production has shifted to the huge Tertiary deposits that are strip mined in the eastern part of the State. Several areas in the Gallatin National Forest have a low to moderate potential for coal (fig. H6). Areas of high coal potential include the Electric coal field (fig. H6, no. 1), which is mainly on patented land in the study area west of the Yellowstone River, and parts of the Livingston coal field and Trail Creek district outside the Forest (fig. H6, nos. 2, 4).

No significant amounts of hydrocarbons have been found in the Gallatin National Forest. Parts of six oil and (or) gas plays overlap parts of the study area (fig. I1). Most of these plays have a low to very low hydrocarbon potential. Some parts of these plays are prospective for undiscovered hydrocarbon fields, especially the Crazy Mountains and Lake Basins Cretaceous gas play. However, any undiscovered fields are likely to lie east of the Gallatin National Forest boundary in the Crazy Mountains area. The presence of igneous intrusions in the study area, such as the Crazy Mountains stock and the igneous activity associated with the Cretaceous Livingston Formation and a number of intrusive centers, has an adverse effect on the hydrocarbon potential of oil and gas plays in the study area.

Industrial Mineral Resources

Industrial or salable mineral resources were not specifically addressed in this study. The new geologic maps of the Gallatin National Forest (Wilson and Elliott, 1995, 1997) can be used as a basis for determining distributions of rock types that could serve as local sources of these commodities. Local sources of construction materials are available in the study area. In his detailed mapping of the Henrys Lake quadrangle at the southern edge of the Gallatin National Forest, Witkind (1972) included a lithologic map of potential construction materials such as volcanic rocks for building stone and riprap, unconsolidated silt, sand, and gravel for aggregate and road fill, and carbonate rocks that could be used for Portland cement. Most of these rock types extend farther north into the Madison-Gallatin subarea. Witkind emphasized that appropriate engineering tests would need to be done to determine the suitability of particular rock types for specific uses, and he also noted that the some of the limestones contain chert and siltstone, which adversely affects their potential for use as concrete aggregate.

Outlook

For the reasonably foreseeable future, any interest in exploiting metallic mineral resources in the Gallatin National Forest study area is likely to center on further evaluation of existing identified sedimentary-exhalative resources at the Pass Creek mine in the Bridger Range subarea (tables C1 and C2, fig. C2, no. 79) and the polymetallic vein-type resources at the Half Moon mine in the Crazy Mountains subarea (tables C1 and C2, fig. C2, no. 91). Potential for development of new metallic mineral deposits appears limited to porphyries and skarns that would be of interest for their gold content. However, the very modest potential estimated for the existence of new deposits is not likely to stimulate extensive exploration. Porphyry deposits represent low-grade, large tonnage deposits that are typically developed as open pit, heap leach deposits with a lot of ground disturbance. Skarns are smaller, generally higher grade deposits, and a number of discrete targets may be present around an intrusive complex. Both underground and open-pit mining methods are used to exploit skarns. Detailed exploration, especially geophysics, would be required to identify targets and assess the viability of any potential mineral deposits in the study area. The uninspiring gold values in stream-sediment geochemical analyses and the lack of significant historical placer activity suggest that the potential for placer gold type deposits is also minimal. A number of facts argue against mineral development within the Gallatin National Forest study area for the reasonably foreseeable future: (1) the few historical deposits in the study area have ceased operations; (2) there is essentially no exploration in the area; (3) much of the area is classified as wilderness, which is closed to mining (mineral entry), or developed for private recreational use; (4) the area is habitat for sensitive species, such as grizzly bears; (5) existing identified resources of base metals and phosphate have not been developed; and (6) the area is within the Greater Yellowstone Area, which is currently being managed with a focus on preservation rather than development.

Any future exploration of identified oil and gas plays is likely to concentrate on parts of the plays outside of the Gallatin National Forest boundaries. Coal was produced for local consumption before 1943. Parts of the Electric coal field that lie within the study area near Gardiner are mainly on patented land.

The future exploration and development of known and potential mineral and energy resources in the study area is unlikely because most of the prospects in the area represent mineral occurrences that are too small or too low in grade to be economic, even under favorable economic circumstances. Types of deposits that were mined in the study area in the past (asbestos, mica, corundum) are uneconomic today. In contrast to the limited potential for mineral resources, the geologic resources of the area are unique and preserve examples of rocks that represent most of geologic time, examples of environments of deposition of rocks that range from ancient seas to volcanoes to modern earthquakes, and alpine landscapes that reflect the complex geologic history of the area.

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