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Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

U.S. Geological Survey Bulletin 2213

U.S. Department of the Interior
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Cover. Iron bog above Ophir, Uncompahgre National Forest, Colorado.

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

Edited by Viki Bankey

This report summarizes information on known mineral resources, delineates areas favorable for occurrence of undiscovered mineral resources for seven types of metallic mineral deposits having a reasonable chance of occurring, provides an assessment of coal resources, describes some of the environmental effects of historical mining, and identifies the distribution and quality of potential sources of crushed stone and sand and gravel for natural aggregate in the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests, Colorado

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Volume Contents

[Chapters are lettered]

Definition of Terms

Reserves. Economically recoverable mineral-bearing material in identified deposits (Brobst and Pratt, 1973).

Resources. Mineral-bearing material not yet discovered, or discovered material that currently cannot be recovered (Brobst and Pratt, 1973).

Identified resources. Specific bodies of mineral-bearing material whose location, quality, and quantity are known from geologic evidence (Brobst and Pratt, 1973). These resources are not particularly evaluated as to feasibility of mining and can be economic, marginal, or subeconomic.

Undiscovered resources. Unspecified bodies of mineral-bearing material surmised to exist on the basis of broad geologic knowledge and theory (Brobst and Pratt, 1973). These bodies can occur in known mining districts or in geologic terranes that presently have no discoveries. These resources are also not evaluated as to feasibility of mining and can be economic, marginal, or subeconomic.

Mineral deposit. An occurrence of sufficient size and grade that under the most favorable circumstance could be considered to have economic potential (Cox and others, 1986).

Mineral occurrence. A concentration of a mineral that is considered valuable by someone somewhere or that is of scientific or technical interest (Cox and others, 1986).

Ore deposit. A mineral deposit that has been tested and is known to be of sufficient size, grade, and accessibility to be producible and yield a profit (Cox and others, 1986).

Measurement Units

The grade and tonnage curves used in this study contain grades either as grams or as percent per metric ton. Thus the estimated amounts of metallic resources within an undiscovered deposit are reported in metric tons of metal. In many situations, units of measurement are noted as they were originally reported. Measurements originally made and reported in feet, in miles, in square miles, and in short (2,000-lb) tons, for example, are included here in their original units for clarity and to avoid misstatement of precision in conversion.

To convert	To	Multiply by
feet	meters	0.3048
miles	kilometers	1.61
pounds	kilograms	0.45
square miles	square kilometers	2.6

Equivalences useful for reading this volume include the following:

1 troy ounce (oz)	31.1 grams (g)
1 short ton	0.9072 metric ton (t)
1 troy ounce per short ton	34.285 parts per million (ppm)
1 part per million (ppm)	1 gram per metric ton (g/t)
1 percent (%)	10,000 ppm
1 metric ton (t)	32,154 troy ounces

Geologic Time Chart—Terms and Boundary Ages by the U.S. Geological Survey in this Report.

EON	ERA	PERIOD		EPOCH	AGE ESTIMATES OF BOUNDARIES (Ma*)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.010
				Pleistocene	1.7
		Tertiary	Neogene Subperiod	Pliocene	5
				Miocene	24
			Paleogene Subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	Mesozoic	Cretaceous		Late	96
				Early	138
		Jurassic		Late	
				Middle	
				Early	205
		Triassic		Late	
				Middle	
				Early	≈240
	Paleozoic	Permian		Late	
				Early	290
		Carboniferous Period	Pennsylvanian	Late	
				Middle	
				Early	≈330
			Mississippian	Late	
				Early	360
		Devonian		Late	
				Middle	
				Early	410
		Silurian		Late	
				Middle	
				Early	435
		Ordovician		Late	
				Middle	
				Early	500
		Cambrian		Late	
				Middle	
				Early	≈570†
Proterozoic	Late				900
	Middle				1,600
	Early				2,500
Archean	Late				3,000
	Middle				3,400
	Early				3,800?
pre-Archean††					4,550

*Millions of years prior to A.D. 1950.

†Rocks older than 570 m.y. also called Precambrian, a time term without specific rank.

††Informal time term without specific rank.

Selected Results

Undiscovered Mineral Resource Potential for Select Deposits in the Grand Mesa, Uncompahgre, and Gunnison National Forests, Colorado

By U.S. Geological Survey

This summary highlights the mineral resources of the forests and is directed toward land-use planners and other interested persons

- This study was undertaken at the request of the United States Department of Agriculture (USDA) Forest Service. The USGS assessment involved a team of scientists with expertise in geology, geochemistry, geophysics, economic geology, coal, mineral deposits, and resource analysis.
- The forests include part of the Colorado Mineral Belt, one of the most productive areas of base and precious metals in North America.
- Mining and mineral exploration have played a central role in the history of the forests since the late 1800's; several world-class mines are either in or adjacent to the forests, and smaller mines are abundant throughout the forests.
- Large tracts within the forests, including wilderness areas, contain indicators that suggest the presence of metallic mineral deposits.
- Twenty-two metallic mineral deposit types were identified in the forests. Mineral resource potential was assessed for seven of these deposit types: granite-hosted porphyry molybdenum, granodiorite-hosted porphyry molybdenum, sandstone-hosted uranium, volcanic-hosted massive sulfide, polymetallic vein, polymetallic replacement, and sediment-hosted redbed copper.
- The commodities most likely to occur are gold, silver, copper, lead, zinc, molybdenum, uranium, and vanadium.
- Permissive tracts for metallic minerals are shown in Chapter K, figure K2; Chapter I, figure I2; Chapter G, figure G1; chapter H, figure H1; Chapter L, figure L2; and Chapter J, figure J1.
- Favorable tracts for metallic minerals are shown in Chapter K, figure K3; Chapter I, figure I3; Chapter G, figure G2; Chapter G, figure G3; Chapter H, figure H2; Chapter L, figure L3; and Chapter J, figure J2.
- The forests have a high coal resource potential, with resources estimated at about 38 billion short tons, in areas underlain by the Mesaverde Group or the Mesaverde Formation. This value does not reflect economic, environmental, technological, or geologic restrictions affecting availability and recoverability.
- Tracts for aggregate suitable for asphaltic concrete and Portland cement concrete are shown in Chapter N, figures N1 and N2.

Introduction

By Viki Bankey

Chapter A of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

Edited by Viki Bankey

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Background

The U.S. Geological Survey (USGS) provides earth-science information to the United States Department of Agriculture (USDA) Forest Service, Bureau of Land Management (BLM), and other land-management agencies that is used to address land stewardship, resource sustainability, and environmental questions on Federal lands. For public lands of the Grand Mesa, Uncompahgre, and Gunnison National Forests and vicinity, an assembled panel of USGS scientists came together and summarized information on known mineral resources; delineated areas favorable for the occurrence of undiscovered mineral resources for seven types of metallic mineral deposits that have a reasonable chance of occurring; provided an assessment of coal resources; described some of the environmental effects of historical mining; and identified the distribution and quality of potential sources of crushed stone and sand and gravel for natural aggregate. This information is intended to help Federal agencies plan for potential mining activities, determine values for land exchanges, derive information on soils and habitats, plan for engineering and recreational projects, evaluate remediation plans, rehabilitate historical mines, and make land management decisions throughout western Colorado.

This mineral resource assessment of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests was produced to assist the USDA Forest Service in fulfilling the requirements of the Code of Federal Regulations (36CFR 219.22) and to supply information and interpretations necessary for mineral resources to be considered along with other kinds of resources (such as timber, wildlife, and recreation) in land-use planning. This report addresses the potential for undiscovered mineral and coal resources in the three national forests and surrounding greater study area and is based on information available as of 1998. The undiscovered-mineral resource assessment was conducted for only those deposit types for which there is a reasonable probability of occurrence. The completeness of each 1998 data set is further described in individual chapters of this report.

Together the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests are referred to as "the forests" in this report. Many of the data sets used in this report extend beyond the boundaries of the forests and cover parts of the San Juan, White River, and San Isabel National Forests, intervening BLM resource areas, and national park, State, and private land. For this report, a rectangle was defined to standardize the boundaries of most data sets, from lat 37°45′ N. to 39°30′ N. and from long 106° W. to 109° W. This rectangular area is referred to as the "greater study area." Within the greater study area, outlines of the three forests of this volume are shown in figure A1, and BLM lands are shown in figure A2. The general location of other national forests in the greater study area is also indicated in figure A1; however, they were not included in the mineral resource assessment of this volume.

The greater study area includes the BLM Uncompahgre Basin Resource Area and parts of the Grand Junction, San Juan, Gunnison, and Glenwood Springs Resource Areas. Where possible, the authors include data and mineral resource assessments for nearly 3.2 million acres (4,868 mi^2) of BLM land within the greater study area.

The forests lie within an area known as the Colorado Mineral Belt (Tweto and Sims, 1963), where mining of metallic commodities has historically been important. In the Uncompahgre Plateau and vicinity, in the western part of the greater study area, uranium mining was important during the 1950's, 1960's, and 1970's. The economic importance of continued mining in Colorado has diminished. However, issues still arise from the effects of past mining, such as the risks from inactive mines and decreased water quality, which land-use planners must address. Environmental geochemistry of high-priority watersheds was also investigated by Miller (1998, 1999), Bove and Knepper (2000), and Nash (2001). These studies focus on water data near Tertiary-age intrusions and hydrothermally altered rocks, the low-temperature processes controlling mobility of metals, acid drainage associated with pyritic systems, and natural acid mitigation by wallrock alteration, carbonate rocks, and alluvium.

Acknowledgments

Many individuals contributed data, ideas, and assistance to this study. Margo Toth developed a nice format for earlier reports (for example, Toth and others, 1993), which we used as a general guideline. Greg Lee and Anne McCafferty helped

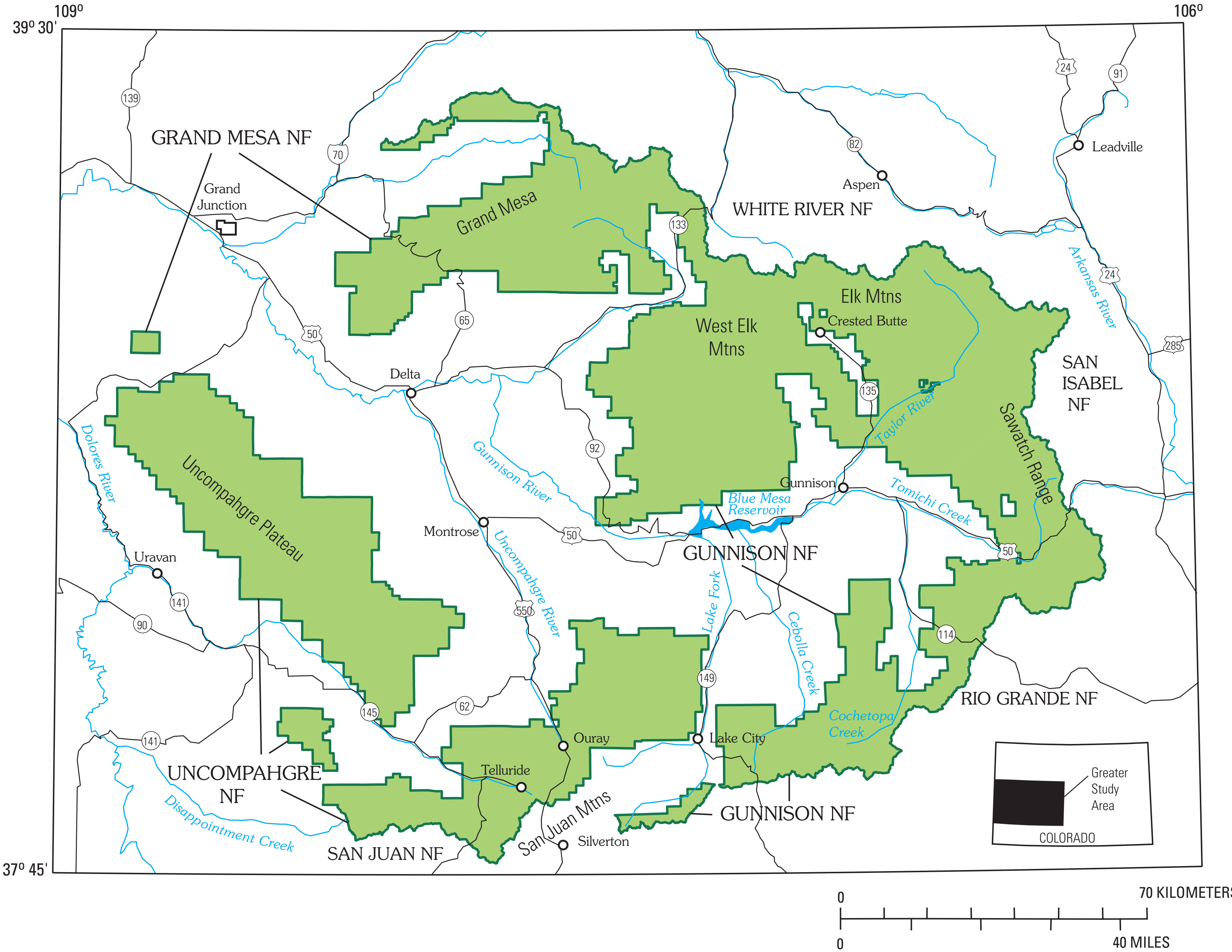

Figure A1. Grand Mesa, Uncompahgre, and Gunnison National Forests (green) within GMUG greater study area.

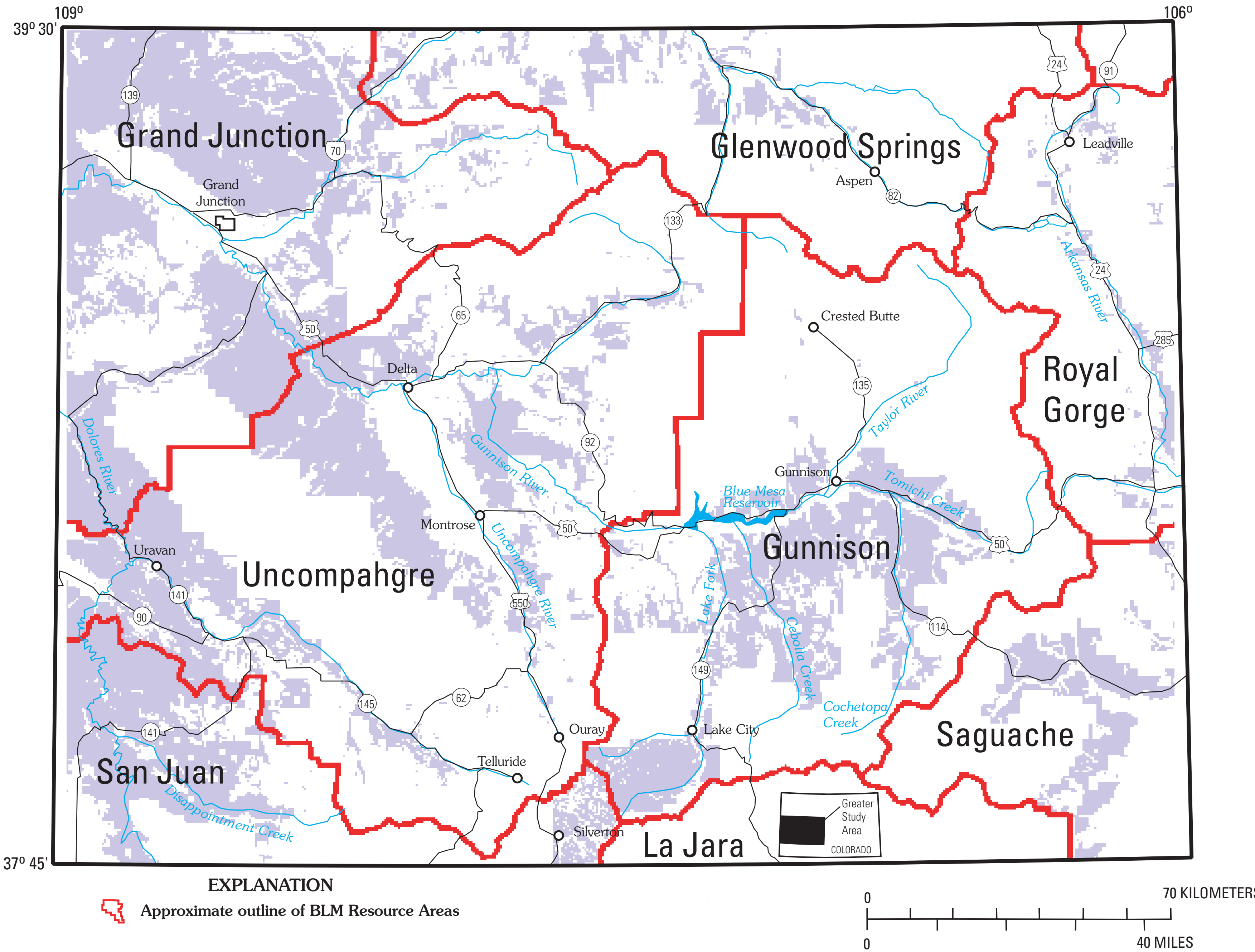

Figure A2. BLM land (purple) and named BLM Resource Areas within greater study area.

with the technical side of GIS. Greg Green worked with the digital geology to compile and attribute a cohesive data set. Samantha Tokash helped compile information and locations for mines.

Our reviewers helped to improve our ideas and presentation. They include Greg Lee (geochemistry); David Campbell and David Daniels (geophysics); Brad Van Gosen, Doug Nichols, and Ted Dyman (coal); David Lindsey and Robert Moench (geology); and Karl Evans, Donald Sweetkind, Richard Grauch, Robert Eppinger, and William Langer (mineral assessments).

Geographic Setting

The Grand Mesa, Uncompahgre, and Gunnison National Forests encompass about 3.12 million acres (4,868 mi^2) in west-central Colorado. The forests include much of the headwater regions of the Gunnison and Uncompahgre River watersheds (fig. A1). The Grand Mesa National Forest covers the Grand Mesa in the north-central part of the greater study area. The Uncompahgre National Forest is made up of three parcels. The largest parcel includes the Uncompahgre Plateau, an area of elevated Paleozoic strata between the Uncompahgre and Dolores Rivers. Southeast of the Uncompahgre Plateau, the remaining two parcels of the Uncompahgre Forest include part of the rugged and remote San Juan Mountains near the towns of Telluride and Ouray. East of the Uncompahgre Forest lies the Gunnison National Forest, which includes the east half of the broad circular band of forest land. This forest includes all of the Sawatch Range west of the Continental Divide, as well as the Elk and West Elk Mountains.

The topography of the forests typifies the central Rocky Mountains of Colorado and varies from valleys and plateaus to steep and rugged mountains, including many of Colorado's mountains exceeding 14,000 ft elevation. The forests adjoin the White River, San Isabel, Rio Grande, and San Juan National Forests (listed clockwise from north to south, fig. A1).

Parts of nine counties lie within the forests: Delta, Gunnison, Hinsdale, Montrose, Mesa, Ouray, Saguache, San Juan, and San Miguel. U.S. Highways 50 and 550 cross the area from northwest to southeast. Numerous other State and county roads extend through or to the forests. The major communities within and near the forests include the cities of Grand Junction, Delta, Montrose, and Gunnison. Former mining centers that have become small town recreational destinations include Crested Butte, Lake City, Telluride, and Ouray.

Geologic Setting

The geologic setting of western Colorado is a culmination of more than 1.8 billion years of geologic processes, which have yielded a breathtaking landscape. The oldest known rocks are 1.8–1.7 billion year old metamorphic and intrusive rocks. Preserved are accumulations of sediments and volcanic rocks deposited in an island-arc environment, which have been intruded by granitoids and later by 1.4 billion year old granites.

The Paleozoic Era opened with the invasion of shallow seas from the east that deposited the materials of sandstones, carbonates, and shales in fault-bounded basins. During the middle and late Paleozoic, regional mountain-building associated with the uplift of the Ancestral Rocky Mountains resulted in erosion and deposition of sediments, evaporites, and carbonates in basins adjacent to the ancient uplifts.

Erosion of the Ancestral Rocky Mountains continued into the early part of the Mesozoic. During the Late Triassic and Early Jurassic the environment changed from warm and humid to more arid, and great deposits of windblown sands accumulated. The continental desert environment gave way to an eastward-encroaching marine environment. Regional erosion was followed by a depositional environment of lakes and floodplain-deposited mud and silt. Regional compressive tectonism began to control paleogeography and sedimentary environment during the Cretaceous, with the onset of the Sevier orogeny throughout the Western Interior of North America.

The Laramide orogeny dominated the geologic history of the early part of the Cenozoic Era; regional mountain building and nonmarine sedimentation occurred in the Piceance and San Juan Basins. Tertiary stratovolcano and caldera eruptions formed the highlands of the San Juan, West Elk, and Elk Mountains. Rifting resulted in bimodal volcanism, and basalt flows extended across the Grand Mesa, San Juan volcanic field, and Flat Tops area. Silicic plutonism accompanied the regional rifting.

Miocene uplift exposed the region to erosion, forming a regional erosional surface that dissected earlier surfaces. Canyon cutting continued in Quaternary time, and a major climatic cooling brought on glaciation, which continued from about 500,000 years ago into the Holocene. During three glacial periods, ice almost totally covered the higher ranges, and the valleys were filled with glaciers; the modern alpine topography with deep U-shaped valleys is largely a product of glacial erosion. Holocene alluvium and glacial deposits are present in drainages and fans across the forests; these deposits consist of gravel, sand, and silt with varying degrees of consolidation.

Previous Assessments

The forests contain several wilderness areas (listed in table A1). Mineral resource assessments have previously been conducted for these wilderness areas as well as other BLM wilderness areas. Mineral resource assessments have also been conducted for three adjacent National Forests: San Juan, White River, and San Isabel (Van Loenen and Gibbons, 1997; Toth and others, 1993; Taylor and others, 1984).

Table A1. Previous mineral resource assessment studies of wilderness land in or near Grand Mesa, Uncompahgre, and Gunnison National Forests, Colo.

[Bold names indicate areas within the GMUG Forests]

Study area	Reference
Cannibal Plateau Roadless Area	Sharp and others, 1983.
Dominguez Canyon BLM WSA[1]	Toth and others, 1983, 1987.
Eagle Mountain BLM WSA	Soulliere and others, 1986.
Fossil Ridge WSA	DeWitt and others, 1985.
Gunnison Gorge BLM WSA	Armbrustmacher and others, 1989.
Handies Peak BLM WSA	Sanford and others, 1987.
La Garita WSA	Steven and Bieniewski, 1977.
Maroon Bells-Snowmass WSA	Freeman and others, 1985.
Mt. Massive WSA	Van Loenen and others, 1989.
Oh-Be-Joyful WSA	Ludington and Ellis, 1983.
Powderhorn WSA	Sharp and others, 1983.
Redcloud Peak BLM WSA	Sanford and others, 1987.
Tabeguache Creek BLM WSA	Dickerson and others, 1990.
Uncompahgre Primitive Area[2]	Fischer and others, 1968.
Uncompahgre Primitive Area Additions[3]	Steven and others, 1973, 1977.
West Elk WSA	Gaskill and others, 1977.
Wilson Mountains Primitive Area[4]	Bromfield and others, 1972.

[1] Wilderness Study Area (WSA).

[2] Currently the Big Blue Wilderness Area.

[3] Includes parts of the Big Blue Wilderness and Mt. Sneffels Wilderness Areas.

[4] Currently the Lizard Head Wilderness Area.

This report does not attempt to reconcile any differences between areas and quantitative values listed in earlier reports with the results in this report. More similarities occur than differences, because the assessments were based on the same or similar mineral deposit models and presumably the same criteria for evaluation. However, the data that were evaluated are not always the same. For example, some previous reports did not include geophysical data. Also, for this report, locations of mines and minerals were updated and verified where possible, and we used our new definition of mineralized areas as a defining criterion for many deposit models. The use of computer-selected areas to choose criteria from various databases has minimized subjective decisions that may have been used to refine permissive or favorable areas in earlier reports. Finally, in that the quantitative assessment is based on subjective decisions by scientists, it may differ from previous opinions regarding the potential for undiscovered deposits. The quantitative assessment process is discussed further in Chapter F, this volume.

Method for Identifying Favorable Areas for Undiscovered Mineral Resources

Mineral and coal resources are divided into three categories: locatable, leasable, and salable. Locatable minerals comprise all minerals for which exploration, development, and production are regulated under the Federal General Mining Law of 1872, and include most metallic resources and some industrial minerals. Leasable minerals are defined by the Mineral Leasing Act of 1920 to include oil, gas, coal, and several other minerals. Of those minerals, we assess herein only the undiscovered resources for coal. Salable minerals are defined by the Federal Materials Act of 1947 as those which have low unit value per ton, which are dependent on easy access to transportation, and which are generally used near the production site. These resources include dimension stone, aggregate, and sand and gravel.

The cornerstone of the USGS mineral resource assessment was preparing, applying, and disseminating a set of georeferenced digital data, compatible with commonly used Geographic Information Systems (GIS). With the cooperation of the Colorado Geological Survey, a digital geologic map has been compiled (Day and others, 1999), and locations of igneous intrusions associated with base- and precious-metal deposits were added. The geologic setting for this vast study area is reviewed by Day and Bove (this volume, Chapter B). Aeromagnetic, gravity, aeroradiometric, and Landsat Thematic Mapper data sets, or derivative maps from these data, were prepared to help identify buried intrusions and associated hydrothermally altered rocks. Available geochemical stream-sediment data (Bove and others, 2000; Smith, this volume, Chapter C), and mine and mineral occurrence information and locations (Wilson and others, 2000) have also been compiled. Models of seven mineral deposit types were prepared to assess undiscovered mineral potential.

In order to assess the mineral resource potential of the GMUG greater study area, we outlined 36 mineralized areas (Wilson and Spanski, this volume, Chapter E). A mineralized area encloses a geographic area that is defined by the presence of mines, prospects, and (or) mineralized occurrences that belong to one deposit type or a group of genetically related deposit types in a distinct geologic setting. A mineralized area may include an entire district or portions of several mining districts, just as a mining district may include several mineralized areas. Twenty-five of the areas are based on the occurrence of a single mineral deposit type and 11 on multiple deposit types.

Mineral resource potential assessments were conducted for seven of the most significant deposit types within the GMUG greater study area. We began the assessment with an initial consideration of mineral types likely to be present in the area. Of these, we selected the most important, both historically and of future impact. These deposit types are granite-hosted porphyry molybdenum, granodiorite-hosted porphyry molybdenum, sandstone-hosted uranium, volcanic-hosted massive sulfide, polymetallic vein, polymetallic replacement, and sediment-hosted redbed copper. From descriptive models for these deposit types, criteria were determined to allow us to generate areas of permissive and favorable tracts. A GIS computer program was used to select these criteria from various geologic, geophysical, and geochemical data bases. Finally, quantitative assessments were performed on four of the deposit types that had adequate grade and tonnage models.

Upper Cretaceous strata are known to contain coal in the vicinity of the forests. The forests have a low to moderate coal resource potential in areas underlain by the Dakota Sandstone and a moderate to high coal resource potential in areas underlain by the Fruitland Formation, Mesaverde Group, or Mesaverde Formation. Contiguous areas of high coal resource potential in the Grand Mesa and Gunnison National Forests are estimated to have a combined coal resource of about 38 billion short tons. This study does not estimate coal reserves that can be economically produced at the present time.

Summary of Mineral Resource Assessments

Granite Porphyry Molybdenum Deposits

Granite porphyry molybdenum deposits are characterized by mineralization and by intrusion of high-silica, alkali-rich granite or rhyolite. Generally small and cylindrical, these high-silica stocks or plugs are thought to represent high-level cupolas that extend above large silicic plutons. The ore zones of the deposits are centered in or above the apical portion of the source granitic intrusion. More than 90 percent of the molybdenite is present in thin, moderately to steeply dipping stockwork veinlets. Hydrothermal alteration is associated with these deposits. Granite molybdenite systems are thought to be associated with the transition from compressive to extensional tectonism. The Mount Emmons and Redwell Basin deposits along with the nearby world-class Climax and Henderson deposits attest to the unique character of the Tertiary magmatic terrane that underlies the study area and its capacity to generate deposits of this type.

Areas classified as permissive are those that are underlain by Tertiary-age intrusions. As shown in Chapter G, figure G1, the permissive tract is quite extensive owing to the abundance of intermediate- to silicic-composition intrusions in the eastern 3/4 of the GMUG greater study area. These intrusions are absent within the more tectonically stable western 1/4 of the study area.

Specific characteristics of favorable tracts (Chapter G, fig. G2) include distinctive chemical composition of the intrusions (high-silica granite or rhyolite), anomalous geochemical values for tin, tungsten, or niobium, and the occurrence of molybdenite or other minerals such as fluorite. A small potential exists for the occurrence of one more deposit, based on the fact that two (Mount Emmons and Redwell Basin) out of the nine deposits used in the construction of the Climax-type grade and tonnage models lie within the study area, and that areas within the study area have been targets of repeated exploration interest. The repeated shows of exploration interest indicate that other knowledgeable parties believe in the possible existence of additional Climax-type deposits.

Granodiorite Porphyry Molybdenum Deposits

Granodiorite molybdenum systems are associated with small composite stocks, late-stage batholiths, and less commonly single phase stocks. Intrusions range from quartz monzonite to granodiorite. Deposits are fluorine deficient and distinct from their fluorine-rich, granite molybdenum counterparts. North American granodiorite deposits are mostly confined to Mesozoic and Tertiary intrusive rocks. The associated ore bodies are cylindrical, tabular, or irregular; mineralization was generally confined to stockwork veinlets developed in or around the roof of the intrusion. These veinlets contain molybdenite and quartz with pyrite, biotite, and minor carbonates. No molybdenum or copper has been produced from granodiorite porphyry molybdenum deposits in the GMUG greater study area or other parts of Colorado. However, several subeconomic granodiorite molybenum prospects have been located in western Colorado.

Areas classified as permissive are those that are underlain by Tertiary intrusions, identical to granitic deposits (Chapter G, fig. G1). Several intrusive units and correlative dikes are excluded from rocks characterized as permissive for mineralization based on previous mineral assessment and geologic studies. Specific characteristics of favorable tracts (Chapter

G, fig. G3) restrict intrusions to intermediate- to silicic-composition intrusions, dikes, hypabyssal stocks, and plugs ranging from quartz monzonite to granodiorite. Other criteria include the presence of anomalous geochemical values for lead, zinc, or silver, or a mine, occurrence, or mineralized site with sphalerite, galena, or chalcopyrite present or containing elevated lead, zinc, copper, silver, or gold. The small deposit potential determined in Chapter G recognizes the fact that the magmatic terrane that underlies the study area and dominated geologic events during Tertiary time is unique in terms of its molybdenum geochemistry. As each pulse of magmatic activity evolves, it gives rise to a series of intrusive and extrusive events in which later events demonstrate a tendency to become anomalously enriched in molybdenum. Owing to their size and the disseminated nature of the molybdenum mineralization, any undiscovered deposit would only be of interest to major mining companies. Under these circumstances, exploration interest in targets of this type is expected to be virtually nonexistent unless a major increase in market demand and price for molybdenum develops.

Sandstone-Hosted Uranium Deposits

Sandstone-hosted uranium occurrences are concentrated in two distinct geographic areas; one borders the GMUG area on the west (Uravan mineral belt) and a second, smaller area lies in the northwest corner of Gunnison County (Ruby-Irwin Mineralized Area). These occurrences are genetically similar—uranium minerals fill intergranular pore spaces and replace carbonaceous material, quartz grains, and interstitial cements in clastic rocks, mainly sandstones. A variety of sources of the uranium has been proposed: (1) sediment derived from incompletely weathered felsic rocks in the highland areas, (2) clays with adsorbed uranium that are delivered to the basin, or (3) detritus deposited on the basin floor. Oxidizing ground water percolated through these sediments, leaching uranium from volcanic glass, feldspars, and clay minerals, and transporting it. Where these uranium-bearing waters encountered reducing conditions around organic rich sediment layers, uranium was precipitated.

Permissive areas include feldspathic and carbonaceous sandstone units occurring interbedded with mudstones and shales (Chapter H, fig. H1). For favorable areas, increased importance is placed on evidence that mineralization has occurred, on anomalous geochemistry or radioactivity, or on evidence from previous reports (Chapter H, fig. H2). Under current free market conditions, sandstone-hosted uranium deposits in Colorado are noneconomic. Should price increase to dollar values of the high teens or above, expectation is strong that some existing mines with proven reserves would reopen, and exploration for new deposits of similar size and grade, considered highly likely to be present in the favorable tract areas, would resume.

Volcanic-Associated Massive Sulfide (VMS) Deposits

Volcanic-associated massive sulfide (VMS) deposits are located in the Dubois Greenstone belt, an area of Proterozoic volcanic and intrusive rocks exposed within the Gunnison uplift. VMS deposits contain copper, lead, and zinc as primary ore metals, and lesser amounts of silver and gold. VMS ores are deposited in structurally controlled zones from fluids in hydrothermal systems associated with underwater volcanoes and rifts. Permissive areas (Chapter I, fig. I2) are defined by three rock types that contain metavolcanic rocks, metasedimentary rocks, or both that are mapped as Xfh, Xf, and Xb of Day and others (1999). Favorable areas restrict the geology to Xf or Xfh, and include evidence of known mineralization (Chapter I, fig. I3). These areas lie east of Blue Mesa Reservoir near Gunnison. As in the past, VMS deposits in the greater study area will likely be valued for their gold content, with other commodities considered as byproducts.

Polymetallic Vein Deposits

Veins rich in copper, lead, and zinc, and carrying smaller amounts of silver or gold, form from rising, hydrothermal solutions. Polymetallic vein deposits form as part of complexly zoned subvolcanic systems and are known to form in rocks of many ages (Precambrian to Tertiary) and many compositions. The fundamental requirement is that the host rock be brittle enough to break and stay open, thus allowing a vein to fill open space. The southern area (Chapter J, fig. J2) generally hosts larger deposits that are related to Tertiary volcanic rocks. The western San Juan Mountains between Silverton and Telluride contain some of the best endowed veins in the study area. Deposits in the northeastern area tend to be smaller and occur in Proterozoic and Paleozoic rocks. These veins differ from the San Juan type in that they have more milky “bull” quartz and a relationship to early to middle Tertiary granitic stocks that appear not to have generated an extensive volcanic edifice.

Permissive criteria include the presence of mapped shallow, subvolcanic Tertiary intrusions or geophysical evidence for them (Chapter J, fig. J1). For favorable areas, increased importance is placed on evidence that mineralization has occurred, on anomalous geochemistry, and on proximity to caldera structures (Chapter J, fig. J2). Favorable potential is mainly associated with the probable existence of smaller undiscovered ore bodies, especially in areas adjacent to or directly beneath areas of currently known polymetallic vein occurrences. In the past, such an area would have been developed as a mine or as an extension to a mine. In today’s economic and environmental climate, large mining companies are unlikely to be interested in sporadic occurrences of this nature; however, these smaller occurrences might be attractive development targets for smaller entrepreneurial groups. The viability of these mineralized areas is dependent on economic factors rather than geology.

Polymetallic Replacement Deposits

Polymetallic replacement deposits commonly contain lead, zinc, copper, and silver sulfide minerals and have been historically important contributors to the total lead, zinc, copper, silver, and manganese produced in Colorado. Substantial amounts of gold or silver in these smaller deposits compensate for their limited volume and make them commercially attractive. Polymetallic replacement deposits are hydrothermal accumulations of sulfide minerals hosted in limestone, dolomite, or other chemically reactive (soluble) rock, adjacent to intrusions. Deposits range from small pods and veins to large, mixed-sulfide replacement bodies; the shapes are irregular and structurally and stratigraphically controlled. Deposits are predominantly hosted by carbonates with a minor number hosted in sandstone, evaporite (gypsum), calcareous shale, and occasionally, permeable zones in volcanic rocks.

Permissive areas are within 10 km of known or inferred felsic Cretaceous or Tertiary plutons and are underlain by Paleozoic, Mesozoic, or Cenozoic sedimentary rock units that contain permeable and chemically reactive lithologic units (Chapter K, fig. K2). To determine favorable areas, increased importance is placed on the presence of sedimentary rock units having a substantial carbonate component and on evidence that mineralization has occurred. Favorable areas cluster around the towns of Ouray, Silverton, and Telluride in the south and near and to the east of Crested Butte in the northwestern part of the study area (Chapter K, fig. K3). Favorable areas large enough to conceal district-size deposits that have not been extensively explored are lacking. However, the potential is high for the existence of new ore bodies in areas adjacent to, or beneath, currently known polymetallic replacement mineralized rocks. In today's economic and environmental climate, large mining companies are unlikely to be interested in occurrences of this nature; however, these smaller occurrences might be attractive development targets for smaller entrepreneurial groups.

Sediment-Hosted Copper Deposits

Copper occurs in sedimentary rocks of the salt anticlines of the Paradox Basin, the borders of the Uncompahgre uplift, and the Eagle Basin. Most known occurrences are small; however, deposits large enough to be productive occur in the salt anticline areas. Chapter L describes a new model for structurally controlled, sediment-hosted copper deposits found in the Paradox Basin, formed where basin brines rose through faults and permeable sandstone formations adjoining salt anticlines. Four tracts were determined to be permissive for the presence of sediment-hosted copper deposits; three areas in those tracts are further identified as favorable (Chapter L, figs. L2 and L3). One favorable area includes much of the Paradox Basin, a second encompasses the southwestern Uncompahgre uplift, and a third is located in and near the Eagle Basin. A viable near-term development potential is associated with these favorable areas. No quantitative assessment could be conducted.

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Review of the Geology of Western Colorado

By Warren C. Day and Dana J. Bove

Chapter B of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

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Review of the Geology of Western Colorado

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Abstract

The geology of western Colorado is a culmination of more than 1.8 billion years of Earth history, which has yielded a breathtaking landscape. This report's review of major geologic events provides the context necessary to understand accompanying chapters of this volume that cover the mineral resource endowment and the environmental consequences of hardrock mining in the region.

The oldest known rock units of western Colorado are the 1.8–1.7 billion-year-old Precambrian layered gneisses, schists, and massive intrusive rocks of the Yavapai geologic province. The gneisses and schists originated as sediments and volcanic rocks deposited in an island-arc environment, probably similar to the modern Indonesian archipelago. The Precambrian rocks were buried to depths of 10–15 kilometers, strongly deformed, recrystallized to metamorphic gneisses and schists, and intruded by ≈1.7 billion-year-old magmas. About 1.4 billion years ago, granite and associated intrusive rocks invaded the metamorphic rocks. The last episode of Precambrian activity, about 1.1 billion years ago, was marked by the intrusion of large masses of granite and associated mafic rocks.

During the billion years between formation of western Colorado's Precambrian rocks and the formation of Paleozoic rocks, weathering and erosion stripped off Precambrian rocks that were once so deeply buried. In the Paleozoic, about 540 Ma (million years ago), thin blankets of sand, carbonate, and clay were deposited in shallow seas on the North American continental shelf. Between about 440 and 280 Ma, the region was uplifted, creating the Ancestral Rocky Mountains. Quartz- and feldspar-rich sands, silts, and conglomerates eroded from these uplifted ranges filled restricted intermontane basins with thick redbed sediments as well as evaporite layers.

Erosion of the Ancestral Rocky Mountains continued into early Mesozoic time (250–230 Ma). Streams and rivers from the ancient highlands carried sand and mud out onto alluvial plains and into deltas and lakes. During Late Triassic to Early Jurassic time (≈210 Ma), the climate changed from warm/humid to arid; great deserts of windblown sand formed in western North America. In western Colorado this episode of Earth's history (≈205 Ma) is recorded in the rocks of the Glen Canyon Group, comprising the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. Subsequently, during the Middle Jurassic, an eastward-encroaching sea laid down sediments which consolidated as the Carmel Formation of the San Rafael Group. As the Middle Jurassic sea retreated, the arid desert conditions returned, bringing the environment recorded in the Entrada Sandstone and Wanakah Formation of the San Rafael Group. Much of the San Rafael Group was then eroded and covered by stream and lake deposits of the Morrison Formation. From Late Jurassic through Early Cretaceous time, low-gradient streams meandered across flood plains, mud flats, and saline basins.

During Late Jurassic and Early Cretaceous time (≈160–96 Ma), streams and basins deposited mud and silt of the Morrison Formation and, in places, sands and conglomerates of the Lower Cretaceous Burro Canyon Formation. Where the Burro Canyon is not present, above the Morrison lie sandstones, shales, and coal seams of the Dakota Sandstone, one of the most extensive geologic formations in the Western Interior of North America. The Dakota formed in an eastward-advancing sea, which subsequently deposited the deeper water sediments of the Mowry, Mancos, and Pierre Shales and sands of the Frontier Sandstone and Ferron Sandstone Members of the Mancos Shale. The great inland sea then retreated, and along its shores in deltas, marshes, and lagoons were deposited the nonmarine sand, shale, and coal deposits of the Mesaverde Group (or Formation).

Regional mountain-building and associated advances and retreats of the inland sea were the controls on the region during the Cretaceous. The mountain-building events consisted of two main pulses: the older, called Sevier, affected rocks generally outside this area, whereas the younger, called Laramide, produced many of the mountain ranges of western Colorado, including the Uncompahgre, White River, Sawatch, and Gunnison uplifts (as well as the Gore Range and Front Range). Uplifts of the ancestral Rockies were rejuvenated and new mountain ranges formed; basins also formed between the uplifts, creating centers of deposition for marine sediments and detritus from the uplifts. Two of these basins formed in western Colorado—the Piceance Basin of northwestern Colorado and adjacent Wyoming, and the San Juan Basin of southwestern Colorado and adjacent New Mexico.

Following the Laramide event came several episodes of volcanism (≈30–22 Ma), some catastrophic; these formed the highlands of the San Juan and Elk Mountains. This time saw emplacement of many of the mineral deposits that occur in the

area known as the Colorado Mineral Belt. Miocene and early Pliocene rifting followed the great volcanic eruptions; rifting was accompanied by quiet eruptions of basalt flows on what are now Grand Mesa, the San Juan Mountains, and the Flat Tops of the White River uplift. In places, small rhyolite intrusions accompanying the regional rifting are mineralized with molybdenum. Miocene uplift led to erosional downcutting through earlier Eocene surfaces; in the Pliocene, uplift may have accelerated, and canyon cutting apparently continued into the Quaternary.

About 500,000 years ago, the climate began to cool: three times glacial ice filled the mountain valleys and almost totally covered the higher ranges. Colorado's alpine landscape of deep U-shaped valleys is largely a product of glacial erosion.

Introduction

The GMUG greater study area encompasses more than 52,820 km^2 of southwestern Colorado, of which USDA Forest Service lands account for approximately 12,740 km^2. This large area of western and southwestern Colorado encompasses a region of numerous ecosystems and diverse physiographies. For example, the San Juan Mountains in the southern part of the area host spectacular peaks more than 4,000 m in elevation and contain ecosystems that range from alpine, subalpine, to montane as defined by Fleischer-Mutel and Emrick (1984). In the eastern part of the study area, the Sawatch Range also contains several peaks greater than 4,000 m and has ecosystems that extend from the montane up to the alpine. In the western part of the study area, in the lower elevations (around 1,500 m) along the Colorado and Gunnison Rivers, ecosystems range into the upper Sonoran (of Fleischer-Mutel and Emrick, 1984).

The study area's wealth of information on the geologic history of Colorado is not only fascinating from an academic point of view but is also important to informed planning and land use. Mining and ranching shaped the early history of the Rocky Mountain region, and central and southwestern Colorado's mineral endowment played a major role. Early European settlement centered on the areas rich in mineral resources as well as along regions with water and arable soil for ranching.

Today, an ever-increasing source of revenue for the region is tourism, owing in large part to its spectacular geologic scenery. Tourist destinations include several towns such as Telluride, Crested Butte, Aspen, and Vail, all of which fall within this study area. The resulting economic development, however, has placed increased pressure on the transportation and housing infrastructures to accommodate the growing populations.

The demands of continuing development include new housing, roads, schools, and places of work, all of which are affected by the geologic setting. Sources for aggregate vital for new construction are a paramount issue; construction on swelling soils, such as those within the Morrison Formation, must be engineered to minimize damage to buildings, bridges, and roads. The effect of abandoned mine lands on water quality is a key issue for Federal and State agencies. The results of mining techniques employed more than a century ago are still with us today.

This report summarizes the complex geologic history of this large area and therein provides the regional framework for the integrated mineral and environmental studies in subsequent chapters. This report also provides the context for a companion digital geologic map compilation (Day and others, 1999) covering southwestern Colorado.

Proterozoic Eon

Regional Setting

The Precambrian rocks of the GMUG greater study area are among the oldest preserved rocks in the southern Rocky Mountains of Wyoming, Colorado, and New Mexico. The Precambrian rocks of the southern Rocky Mountain region have been divided into three large terranes, or tectonostratigraphic provinces, that have internally consistent ages of formation, rock types, and mineral deposits. The Archean rocks of the Wyoming province make up the northernmost Precambrian terrane. The northeast-trending Cheyenne belt forms the suture between the Archean rocks of the Wyoming province and the Proterozoic rocks of Colorado and New Mexico to the south (fig. B1). The Cheyenne belt is a zone of pulverized, recrystallized rock (mylonite) exposed in the Medicine Bow and Sierra Madre Mountains of Wyoming and Colorado (Houston and others, 1989). The Proterozoic rocks of the Yavapai province of northern and central Colorado and the Mazatzal province of New Mexico constitute the other two Precambrian terranes. Rocks of the Yavapai province range from 1.8 to 1.7 Ga (billions of years), whereas the rocks within the Mazatzal province range from 1.7 to 1.6 Ga (Silver, 1965, 1968; Van Schmus and Bickford, 1981; Reed and others, 1987).

Unlike the Archean-Proterozoic boundary represented by the Cheyenne belt, the Yavapai-Mazatzal tectonic boundary is poorly defined. Using several lines of evidence, Shaw and Karlstrom (1999) proposed that the boundary could only be narrowed to a 300 km-wide zone that trends northeastward through southern Colorado and northern New Mexico (fig. B1).

Proterozoic Rocks of Western Colorado

The Proterozoic rocks of the greater study area (map area, fig. B2) belong to the Yavapai province. These rocks are an amalgamation of 1.8–1.7 billion year old volcanic and associated sedimentary (supracrustal) rocks that have been

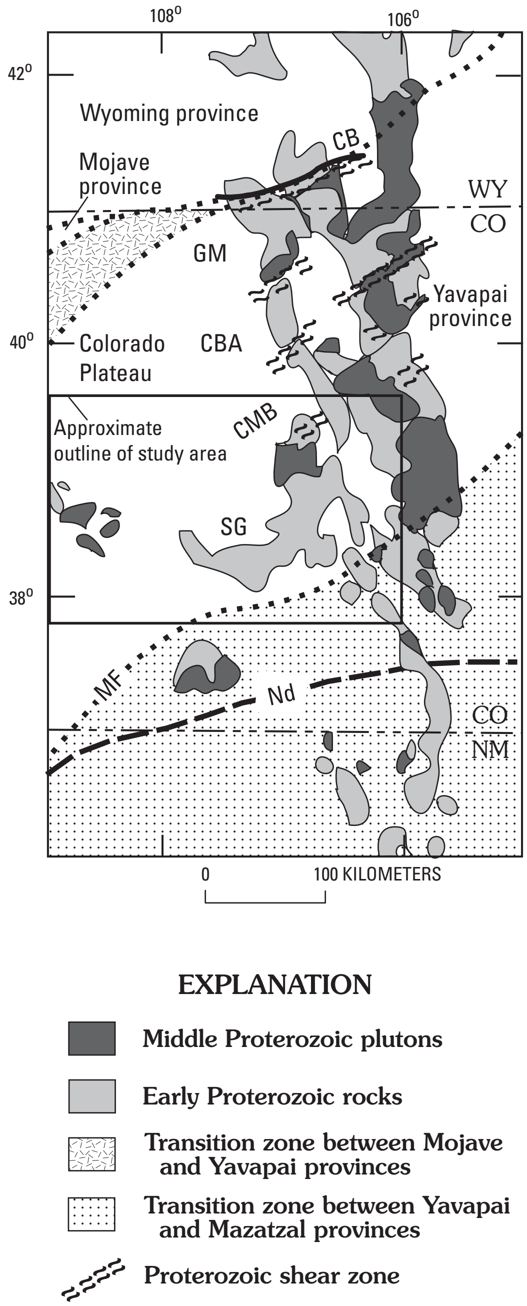


Figure B1. Precambrian terranes of Colorado and southern Wyoming. Modified from Shaw and Karlstrom (1999). MF (dotted line), deformational front of the Mazatzal province; Nd, neodymium model age boundary between the 2.0–1.8 Ga and 1.8–1.6 supracrustal rocks; CB, Cheyenne belt; GM, Green Mountain magmatic arc; CBA, composite back-arc; CMB, Colorado Mineral Belt; SG, Salida-Gunnison magmatic complex.

metamorphosed to upper greenschist to middle amphibolite grade. Granitic rocks intruded the supracrustal sequences during three broad time windows and formed distinct plutonic suites: the Routt Plutonic Suite (≈1.6–1.7 Ga), the Berthoud Plutonic Suite (≈1.4 Ga), and rocks of the Pikes Peak (≈1.1 Ga) batholith. According to Tweto (1987), deformation accompanied the emplacement of the Routt Plutonic Suite, whereas the Berthoud Plutonic Suite was a so-called anorogenic group that was emplaced passively into the supracrustal sequences. However, recent structural studies accompanied by new radiometric data have shown that emplacement of some of the ≈1.4 Ga Berthoud Plutonic Suite rocks throughout northern and central Colorado was accompanied by ductile deformation along major northeast-trending shear zones (Selverstone and others, 1997). The Pikes Peak Granite, east of the study area, is an anorogenic granite inasmuch as no regional deformation was associated with its emplacement (Smith and others, 1999).

The oldest Proterozoic supracrustal rocks in the study area can be further subdivided into low and medium metamorphic grades. Medium-grade metamorphic rocks, biotite schist, metapelite, amphibolite, quartz-feldspar and hornblende-biotite gneisses, form the basement of the northern part of the study area; they have been intruded by pegmatite, granite, and gabbroic dikes, sills, and plutons (Tweto, 1987). The protoliths for the biotite schist and metapelite were dirty sandstone and shale. The amphibolite represents metamorphosed dikes, sills, and (or) flows of basaltic magma. The gneissic rocks probably represent metamorphosed volcanic rocks and sediments. Reed and others (1987) showed that, based on U-Pb zircon dates, the Precambrian supracrustal rocks of the Yavapai province of Colorado decrease in age southward from the Archean-Proterozoic boundary (Cheyenne belt) in Wyoming (fig. B1). The northern part of the province (just south of the Cheyenne belt) is made up of the >1.75 Ga Green Mountain block, which may have formed in an island-arc setting. The central part of the Proterozoic rocks of Colorado belongs to a composite back-arc basin that was intruded by igneous rocks at about 1.70 Ga (and earlier). The southern part is made up of the Salida-Gunnison magmatic-arc complex; it contains plutons that range in age from 1.76 to 1.60 Ga.

The Salida-Gunnison magmatic-arc complex, described by Reed and others (1987), is part of the Dubois Greenstone belt, a package of volcanic, sedimentary, and granitic rocks of low metamorphic grade that crop out east and south of Blue Mesa Reservoir along the Uncompahgre uplift (fig. B2). The greenstone belt is made up of bimodal (felsic and mafic) volcanic rocks and associated volcaniclastic sediments interlayered with banded iron-formation, massive sulfide, and gold-bearing exhalative mineral deposits (Afifi, 1981; Hedlund and Olson, 1981; Knoper and Condie, 1988). Bickford and others (1989, and references therein) have noted two periods of volcanism and plutonism in the greenstone belt: an earlier episode that occurred from 1,770 to 1,760 Ma followed by plutonism from 1,755 to 1,750 Ma and a later episode of volcanism that spanned from 1,740 to 1,714 Ma with emplacement of granites from 1,725 to 1,714 Ma.

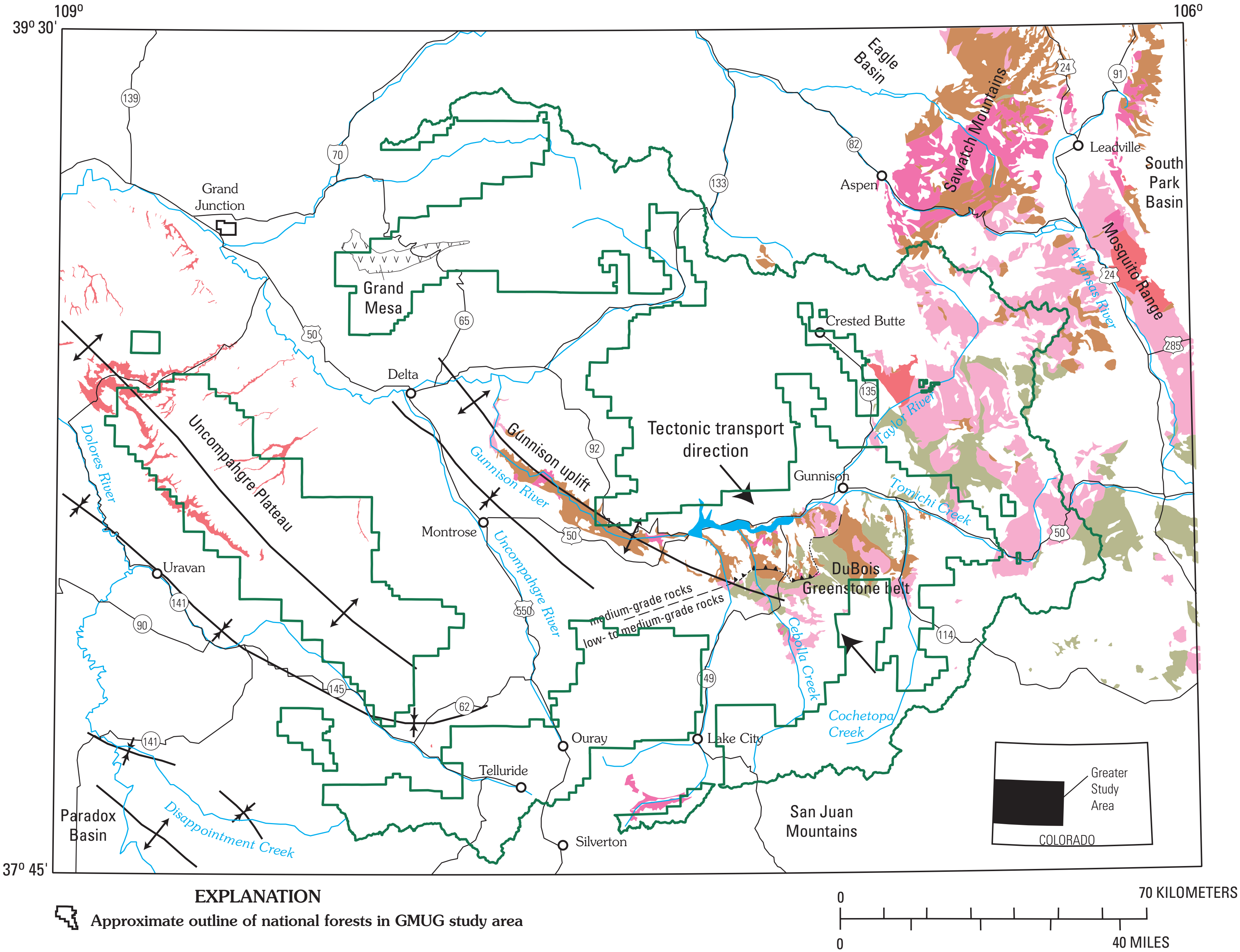


Figure B2 (above and following page). Generalized geologic map of the Proterozoic rocks in GMUG greater study area, showing location of the Dubois Greenstone belt.

EXPLANATION

Proterozoic units

Middle and Early Proterozoic

Granitic rocks—Includes intrusive units of granodiorite and granite (≈1,400 Ma age group)

Middle to Early Proterozoic granitic rocks and gneiss, undivided

Early Proterozoic

Granitic rocks—Includes intrusive units of granodiorite, monzonite, monzodiorite, and granite (≈1,700 Ma age group)

Felsic and mafic gneiss and schist—Interlayered metamorphosed felsic and mafic volcanic rocks and associated volcanogenic sedimentary rocks

Biotite schist—Biotite schist with interlayers of hornblende-rich mafic rocks, iron-formation, and felsic schist; dominantly metamorphosed graywacke, chemical sediments, mafic and felsic volcanogenic sedimentary rocks

Trace of tectonic boundary between the Proterozoic gneiss, schist, and granite of the medium metamorphic grade rocks of the composite back-arc rocks of central Colorado and the magmatic arc rocks of the Dubois Greenstone belt of low to medium metamorphic grade—Teeth on boundary indicate area where boundary is a south-vergent thrust fault

Anticline

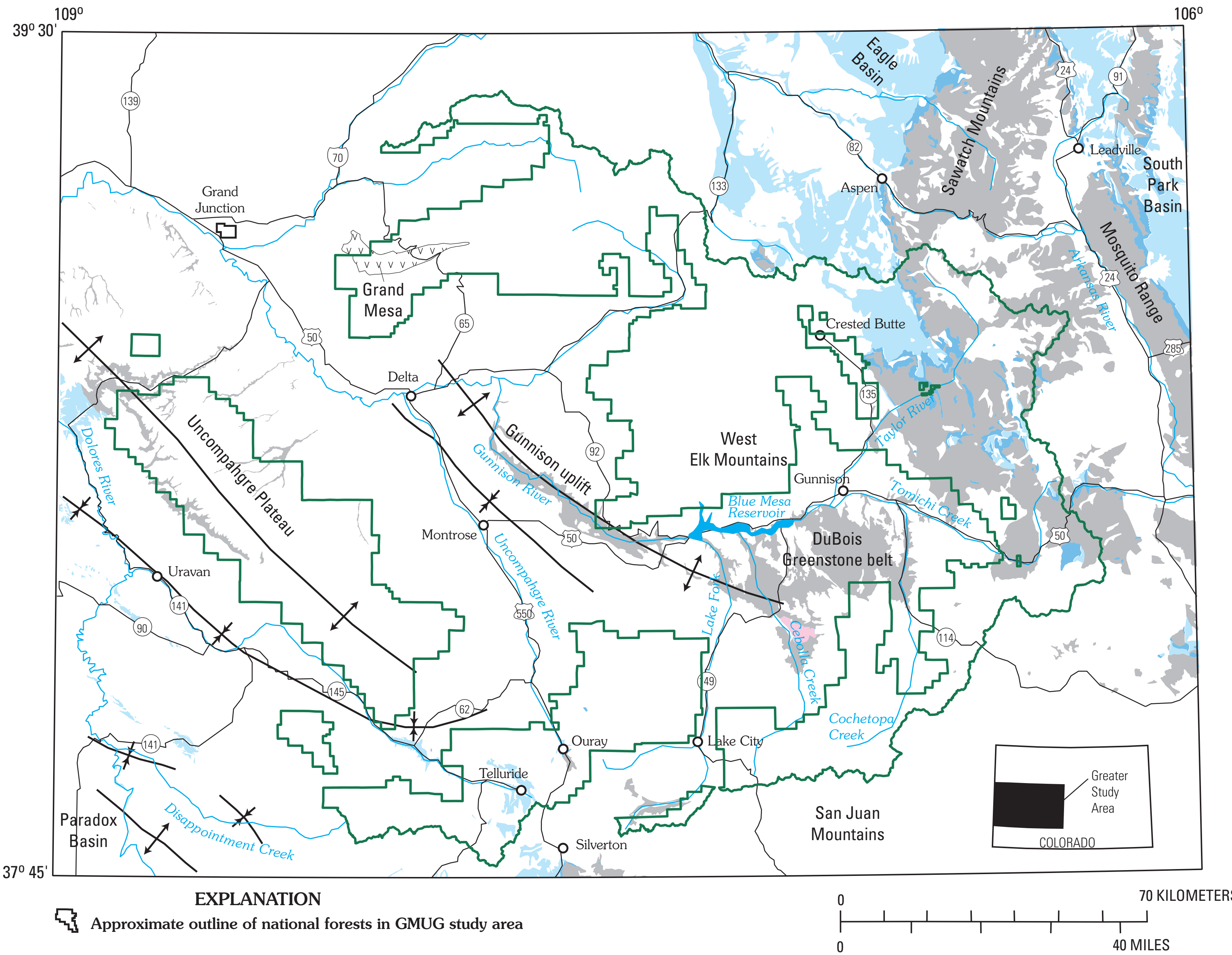
Syncline

Paleozoic Era

More than 1 billion years passed from the time the Proterozoic rocks exposed in western Colorado were deposited and the next major rock package was deposited during the Paleozoic. During this vast interval the Precambrian rocks were stripped off due to weathering and erosion, exposing rocks that were once buried more than 10 km deep in the Earth's crust. The Paleozoic history of the study area can be broadly grouped into two distinct periods of evolution (fig. B3). An early set of units (Cambrian through mid-Mississippian) record several cycles of marine transgression-regression, deposition having been primarily in shallow epicontinental marine environments. Later units (Pennsylvanian and Permian) record regional uplift, erosion, and basin formation associated with the growth and destruction of the Ancestral Rocky Mountains of Colorado (fig. B4).

Early and Middle Paleozoic

During the Paleozoic Era, what is now Colorado was part of the ancient continent of Laurentia. The Precambrian rocks, such as those in the mountain uplifts of the Rockies, formed the core of Laurentia. During the Paleozoic starting in about the Late Cambrian (≈520 Ma), shallow seas transgressed across the eroded Precambrian basement rocks, depositing sediments that became sandstone, shale, and relatively thin limestone and dolomite. In western Colorado, these rock units include the Upper Cambrian Sawatch and Ignacio Quartzites and overlying dolomites of the Peerless and Dotsero Formations (Haynes and others, 1972; Tweto and others, 1976;



EXPLANATION

Approximate outline of national forests in GMUG study area

Figure B3 (above and following page). Generalized distribution of exposed lower to middle Paleozoic (Cambrian-Mississippian) and upper Paleozoic (Pennsylvanian-Permian) rocks in GMUG greater study area. Precambrian basement rocks are also shown.

EXPLANATION

Paleozoic units

Permian and Pennsylvanian sedimentary rocks

Mississippian, Devonian, Ordovician, and Cambrian sedimentary rocks

Cambrian carbonatite intrusive rocks—Includes carbonatite, nepheline syenite, pyroxenite ijolite, melanite-orthoclase plutonic phases and magnetite-ilmenite-perovskite dikes

Precambrian units

Precambrian gneisses, schists, and granites

Anticline

Syncline

Tweto and others, 1978; Tweto, 1979; De Voto, 1990). A period of widespread erosion affected the Cambrian units, and not until the Early Ordovician (≈ 500 Ma) were marine sediments deposited again. In western Colorado, these Ordovician units include the Lower Ordovician Manitou Dolomite, Middle Ordovician Harding Sandstone, and Upper Ordovician Fremont Dolomite.

As reviewed by De Voto (1990), central Colorado experienced tectonic uplift along high-angle faults active during the Early Ordovician, exposing the Cambrian and Lower Ordovician rocks to local erosion (Tweto and others, 1976). Subsequent to Ordovician tectonism, units of the Chaffee Group were deposited in shallow basins during a continent-wide marine transgressive-regressive cycle upon the regional erosional unconformity. As exposed in the study area near Leadville, Colo., units of the Upper Devonian and Lower Mississippian Chaffee Group include the Parting Formation, Dyer Dolomite, and Gilman Sandstone. In the western and southwestern part of the study area, units deposited during this interval include the mudstones and dolomites of the Upper Devonian Elbert Formation and the fossiliferous Ouray Limestone (Steven and others, 1974; Campbell, 1996).

The Mississippian Leadville Limestone, overlying rocks of the Chaffee Group, represents a large-scale transgressive shelf carbonate sequence (Horton and Geissman, 1990), which in the northern part of the study area is dominantly dolomite. The Leadville has been divided into two units: the lower one is the Red Cliff Member, and the upper one is the Castle Butte Member (Beaty and others, 1988). The Red Cliff Member contains carbonate breccia composed of angular masses of coarse-grained dolomite in mudstone, and casts of halite and gypsum (Horton and De Voto, 1990), indicating deposition in a shallow-marine evaporitic environment much like that in the modern Persian Gulf. An erosional unconformity marked by dolomitic breccia lies at the top of the Red Cliff Member. This unconformity was interpreted to have resulted from subaerial emergence of the Leadville Limestone (De Voto, 1990). The Castle Butte Member consists of dominantly carbonate sand (packstones and grainstones) interpreted by Horton and De Voto (1990) to have been deposited within low-relief emergent areas in the ancestral Front Range–Wet Mountains area east of the study area. Regional karst erosion on the upper surface of the Leadville Limestone created sinkholes, undulating erosional surfaces, caves, and paleovalleys. These karst features later were important in channelization of ore-forming hydrothermal solutions that deposited Ba-Ag-Pb-Zn Sherman-type mineral deposits (Landis and Tschauder, 1990; Tschauder and others, 1990).

Late Paleozoic

The transgression-regression of shallow continental seas typical of early to middle Paleozoic time gave way in late Paleozoic time (Pennsylvanian and Permian Periods) to mountain building that resulted in the uplift and partial denudation of the Ancestral Rocky Mountains. Numerous fault-bounded structural basins formed adjacent to the uplifts, and into these actively subsiding basins were shed coarse boulders, gravel, and sand. In the study area these ancient highlands closely coincided with the present-day Uncompahgre uplift, Sawatch Mountains, and southern Mosquito Range (MacLachlan, 1972; Maughan, 1980; De Voto, 1980, 1990; Schenk and others, 1987; Houck, 1997). The upper Paleozoic strata were deposited in shallow, warm, westward-deepening continental seas

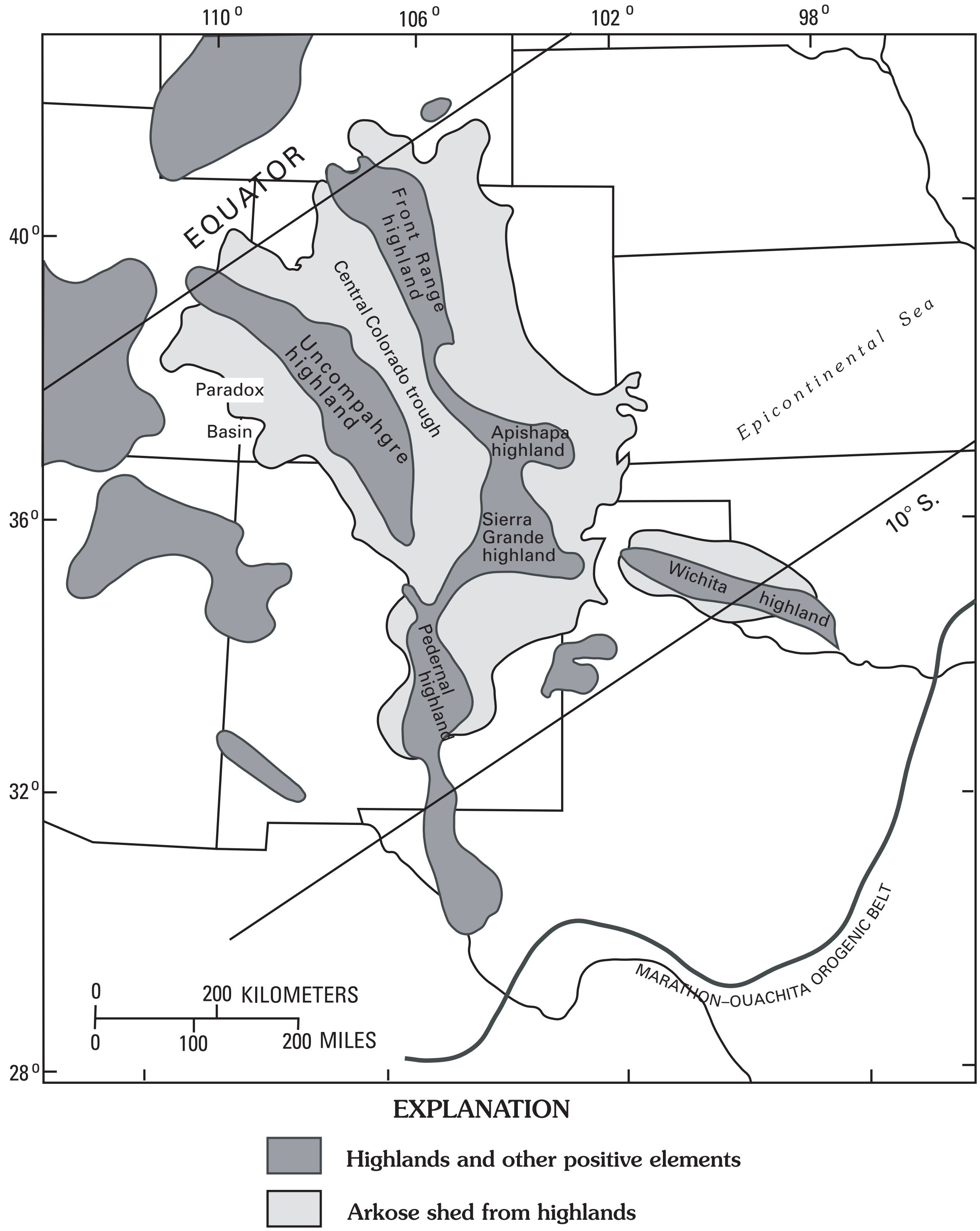


Figure B4. Paleogeographic setting of Ancestral Rocky Mountains highlands, approximate range of arkosic sediment shed from uplifted regions, location of the Central Colorado trough, and location of the equator during Middle Pennsylvanian to Early Permian time. Modified from Lindsey and Clark (1995).

that encroached eastward onto lowlands and interfingered with fluvial sedimentary environments adjacent to the highland regions. De Voto (1980) estimated that the Ancestral Rocky Mountains had as much as 3,000 m of relief. Houck (1997) has shown that the local tectonic movements along the basin-bounding faults control the thickness of sequences and lateral distribution of deposits within the basins. Extensive sequences of sand, gravel, evaporite, shale, and carbonate sediment accumulated deposits as thick as 2,745 m in the Paradox Basin and Eagle Basin (fig. B3). The Eagle Basin was part of the northwest-trending central Colorado trough (Mallory, 1972; Schenk and others, 1987). During and after deposition, ground water oxidized much of the sediment to reddish and ochre colors, giving rise to the descriptive term "redbeds" commonly applied to these sedimentary rock sequences.

In the southwestern part of the study area in the Paradox Basin (fig. B4), units of Pennsylvanian age were deposited unconformably upon the Devonian Ouray or Mississippian Leadville Limestones. Pennsylvanian units include the redbeds of the Lower and Middle Pennsylvanian Molas Formation and evaporites as well as the fluvial sandstone and fossiliferous marine limestone, siltstone, black shale, and gray sandstone of the Middle and Upper Pennsylvanian Hermosa Group. The lower part of the Hermosa Group is made up of fluvial sandstone interbedded with marine sandstone and shale of the Pinkerton Trail Formation. The middle part, the Paradox Formation, comprises evaporite and limestone deposits. The upper member, the Honaker Trail Formation, is made up of fluvial sandstone, shale, and limestone (Haynes and others, 1972; Williams, 1976; Cole and others, 1996). Within the Paradox Basin, the Elephant Canyon Formation lies at the top of the Hermosa Group and intertongues with the overlying Lower Permian Cutler Formation (Cole and others, 1996). In the San Juan Mountains the Rico Formation lies between the Pennsylvanian Hermosa Group and the Lower Permian Cutler Formation (Campbell, 1996). The Cutler Formation itself represents a continental sequence of finer grained near-shore redbeds, alternating with units of coarse-grained eolian sandstone (Haynes and others, 1972).

The Central Colorado trough (fig. B4) was a narrow, deep, structural and sedimentary basin (Mallory, 1972; Schenk and others, 1987; Houck, 1997) whose trend was northwest across the northern and central part of the study area. This fault-bounded basin was the site of Paleozoic deposition of the aforementioned Pennsylvanian Molas; the shale, carbonates, and sandstone of the Belden Formation; sandstone, grit, conglomerate, and shale of the Minturn Formation; the gypsum-rich Eagle Valley Evaporite; the conglomerate, mudstone, and redbeds of the Pennsylvanian and Permian Maroon Formation; and the sand of the Schoolhouse Member of the Maroon Formation (Johnson and others, 1990).

As reviewed by De Voto (1980), more than 3,050 m of marine and nonmarine Pennsylvanian rocks, and as much as 6,100 m of Pennsylvanian to Permian strata (Maroon Formation) occur in down-dropped blocks within the Central Colorado trough. Even-bedded shallow-marine siltstones and sandstones of the Lower Permian to Lower Triassic State Bridge Formation (Tweto and others, 1978) were deposited north of Aspen in the Central Colorado trough (fig. B4). This period represented clastic, carbonate, and evaporite deposition into the rapidly subsiding basin while the Ancestral Rocky Mountains were uplifted.

Mesozoic Era

Triassic

Shallow-marine Permian and Pennsylvanian sedimentation gave way to periods of erosion and weathering of the Ancestral Rocky Mountains during the Triassic. Much of North America emerged from the late Paleozoic seas in Early Triassic time to form a high continental landmass (Maughan, 1980) and formed part of the western coast of the ancient continent Pangea. Dubiel (1994) pointed out that during the Triassic the Western Interior of North America was about at the latitude of the paleoequator, subjecting the west coast of Pangea to monsoonal circulation. Rivers swollen with these heavy rainfalls washed large amounts of sediment off ancestral highlands onto adjacent tidal flats and shallow-marine settings. In southwestern Colorado, Early Triassic sediments are represented by the Lower and Middle(?) Triassic Moenkopi Formation, exposed on and west of the Uncompahgre Plateau (figs. B5 and B6). The Moenkopi Formation contains chocolate-brown ripple-bedded shale, brick-red sandy mudstone, reddish-brown and chocolate-brown sandstone, purple and reddish-brown arkosic conglomerate, and local beds of gypsum (Williams, 1976). The Moenkopi represents sediments deposited in offshore-marine to continental alluvial fan and marginal-marine, deltaic and eolian environments (Dubiel, 1994). In northwestern Colorado, Early Triassic sediments are recorded in the Permian and Lower Triassic State Bridge Formation, which is an orange-red to red-brown siltstone and sandstone (Tweto and others, 1978).

The Upper Triassic rocks of the Western Interior of North America are continental in origin, forming an assemblage of units deposited in alluvial, marsh, lacustrine, playa, and eolian environments (Stewart and others, 1972). In western Colorado, the Upper Triassic Chinle Formation overlies the Lower Triassic sedimentary rocks and is made up of red to reddish-brown siltstone interbedded with lenses of sandstone and shale as well as pebble conglomerate (Baars, 1972; Stewart and others, 1972; Dubiel, 1994). Meandering streams, point-bar, channel, and over-bank fluvial sediments trapped plant debris deposits within the Chinle. This organic material, later fossilized, created local reducing environments important for scavenging and precipitating uranium and vanadium dissolved in circulating ground water. Thus, the organic material became important for formation of the uranium and vanadium deposits on the Colorado Plateau (Baars, 1972). The finer grained siltstones and shales present in the upper part of the Chinle Formation record a period on the Colorado Plateau during the Late Triassic when the paleo-landscape was more subdued than during early Chinle time.

At approximately the same time the Chinle was being deposited in the Colorado Plateau region, the fluviatile, eolian, and lacustrine sediments forming the Upper Triassic Dolores Formation were being laid down. An angular unconformity beneath the Dolores Formation is evidence of uplift and

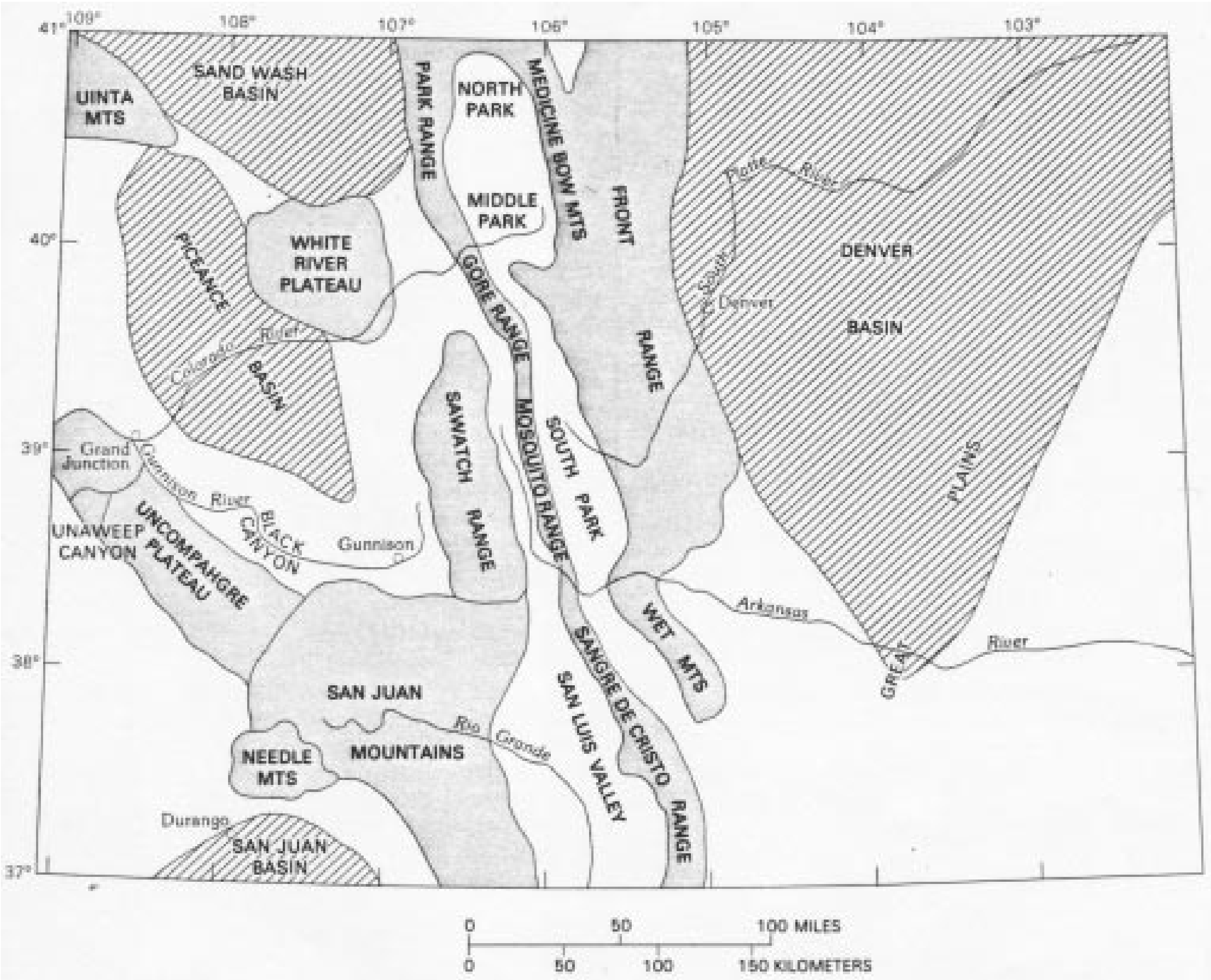


Figure B5. Tectonic province map of Colorado (modified from Tweto, 1980), showing distribution of uplifts and sedimentary basins of the western part of the State.

erosion during the Early Triassic (Campbell and Brew, 1996). Baars (1972) reported that the much coarser clastic material typical of the Dolores compared to that in the temporally equivalent Chinle is a result of the Dolores being closer to the source from the Uncompahgre uplift. Fossil leaves and bones are also found in the Dolores, suggesting that the climate was warm and humid.

Late Triassic Through Jurassic

The Late Triassic to Early Jurassic saw a dramatic change in the climate of western Colorado (Dubiel, 1994). The environment shifted from warm and humid to arid. Windblown sand deposits dominate the formations of Late Triassic age. Baars (1972) compared the Late Triassic of the Western Interior to that of the present-day Sahara Desert of North Africa, with great windblown sand dunes drifting throughout the region. These windblown sands, including the Lower Jurassic Glen Canyon Group, were deposited conformably on top of the Chinle Formation throughout the western and southern parts of the study area (Haynes and others, 1972; Cashion, 1973; Williams, 1976; Berman and others, 1980). The oldest unit in the Glen Canyon Group is the Wingate Sandstone, a fine-grained, well-cemented, eolian sandstone with beautifully preserved crossbeds and local stream deposits, indicating at least seasonal variation. The Kayenta Formation, the middle formation of the Glen Canyon Group, is an irregularly interbedded, fine- to coarse-grained sandstone-dominant unit with lesser quantities of shale and siltstone; thin beds of limestone- and shale-pebble conglomerate are locally present (Haynes and others, 1972; Williams, 1976). The latest Early Jurassic age Navajo Sandstone (Berman and others, 1980) is the youngest unit in the Glen Canyon Group. It also is a fine-grained, cross-stratified eolian sandstone, which blankets much of the western part of the area. The rocks of the Glen Canyon Group are well exposed across the Colorado Plateaus province, forming prominent cliffs in the Colorado National Monument, steep canyon walls throughout the Uncompahgre uplift, and striking features throughout the Four Corners region in the southwestern part of the study area.

The continental desert environment recorded in strata of the Triassic and Lower Jurassic Glen Canyon Group gave way to an eastward-encroaching marine environment, as preserved in the overlying Middle Jurassic San Rafael Group (Lucas and Anderson, 1997). In the study area the San Rafael Group is made up of (from oldest to youngest) the Carmel Formation, Entrada Sandstone, and Wanakah Formation. The thin-bedded silty shale, siltstone, and silty sandstone of the Carmel Formation lie disconformably upon the Glen Canyon Group rocks, evidence of a period of erosion in the region during the transition period between the Early and Middle Jurassic. The Carmel extends only a short distance into western Colorado and is absent in the central part of the State. Haynes and others (1972) interpreted its paleoenvironment as one of lacustrine or tidal-flat origin.

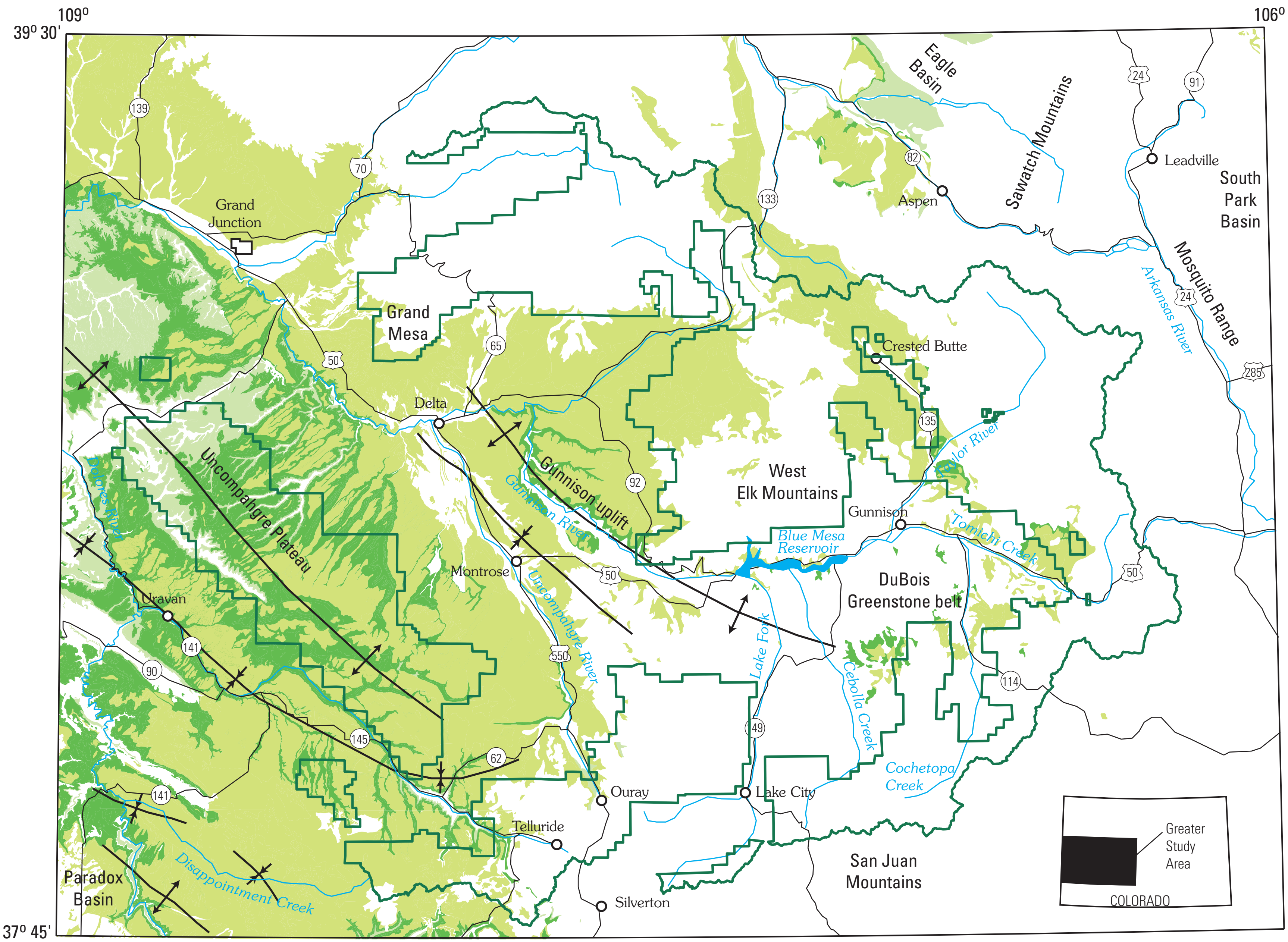
The withdrawal of the Carmel sea during the Middle Jurassic resulted in the deposition once again of continental sediments, such as the eolian Entrada Sandstone. The Entrada is a widespread unit throughout the area, forming prominent cliffs of "slickrock." The Entrada Sandstone is a white to buff, crossbedded to massive sandstone. As reviewed by Berman and others (1980), the Entrada represents windblown desert sand deposits that intertongue to the north and west with water-laid units of the same age. Subsequent marine incursion during the late Middle Jurassic resulted in deposition of Curtis and Summerville Formations (Lucas and Anderson, 1997). In the central and eastern part of the study area, the seas deposited sediment forming the glauconitic sandstone and oolitic limestone of the Curtis Formation (Tweto and others, 1978). In the southern and southwestern part of the area, the Middle Jurassic Summerville Formation—alternating thin beds of gypsiferous siltstone, fine-grained sandstone, shale, and characteristic mudstone—is interpreted as terrestrial in origin (Haynes and others, 1972; Cashion, 1973; Williams, 1976). Peterson (1988) suggested that the unit was deposited in a quiet, ephemeral shallow-water environment, perhaps along a coastal plain. Lucas and Anderson (1997) pointed out that the lithology, coupled with the lack of fluvial features, suggests that the depositional environment for the Summerville was a sabkha, large shallow playa, and tidal flat, where windblown sand provided the clastic sediment input. The fine- to coarse-grained, crossbedded eolian sandstone of the Junction Creek Sandstone Member of the Morrison Formation lies conformably atop the San Rafael Group rocks in the southwestern part of the study area, in the Cortez 1°×2° quadrangle (Haynes and others, 1972). Berman and others (1980) noted that the Upper Jurassic Junction Creek interfingers with and overlies the Summerville Formation throughout the Colorado Plateau.

The San Rafael Group is overlain throughout the region by the Upper Jurassic Morrison Formation. In the study area, the Morrison contains the Tidwell Member, Salt Wash Member, and the overlying Brushy Basin Member. Although the Salt Wash and Brushy Basin Members host uranium and vanadium deposits, the Salt Wash Member hosts significantly more ore and has been a world leader in production of these metals. (See Spanski and others, this volume, Chapter H.)

The base of the lower Morrison Formation lies on a regional unconformity on the San Rafael Group rocks and the Junction Creek Formation (where present). The Salt Wash Member of the Morrison contains thick discontinuous beds of fine- to medium-grained fluvial sandstone interbedded with variegated mudstone. Thin beds of limestone occur locally near its base. The Salt Wash Member has all the hallmarks of a fluvial deposit; the Salt Wash sandstone beds are cross-bedded, pebbly-conglomeratic, and quartzose. Mud, clay, and woody clasts and trace fossils are common (Anderson and Lucas, 1997). Turner-Peterson (1986) determined that the unit's trough crossbeds consistently indicate a northeasterly-flowing fluvial system that changed upsection to a more easterly stream flow environment.

The overlying Brushy Basin Member of the Morrison Formation is mostly varicolored claystone and bentonitic mudstone (altered volcanic ash) with a few lenses of gray sandstone, limestone, and chert-pebble conglomerate: it has much less sandstone than does the underlying Salt Wash Basin Member. Volcanic ash-rich beds, now zeolitized, are found throughout the Morrison but are especially concentrated in the Brushy Basin Member. Turner and Fishman (1991) suggested that the Brushy Basin Member was deposited in a large, saline and alkaline lacustrine basin, which they named Lake T′oo′dichi′. Anderson and Lucas (1997) took umbrage at this concept, noting sedimentological evidence for meander belt channels, giving evidence for a humid subtropical climate instead of an arid saline alkaline playa. Regardless of these differences in interpretation, the Morrison seems to have been deposited in an environment that changed through time from a regime dominated by stream influx to lake and flood-plain sedimentation marked by the input of volcanic ash through time. One of the most significant features of the Morrison Formation is the significant accumulation of vertebrate fossils including several species of sauropods, allosaurids, stegosaurids, and iguanodontids, several other species of dinosaurs, and more than 50 species of mammals (Anderson and Lucas, 1997).

The transition from the Late Jurassic to and through the Early Cretaceous in the western part of the study area along the Colorado Plateau region was a gradual change from the Jurassic lake and flood-plain-deposited mudstone and siltstone of the Brushy Basin Member of the Morrison upward to the fluvial sandstone and conglomerate interbedded lacustrine siltstone, shale, mudstone, and thin beds of impure limestone of the Burro Canyon Formation. Both the Morrison and Burro Canyon Formations evolved in continental environments



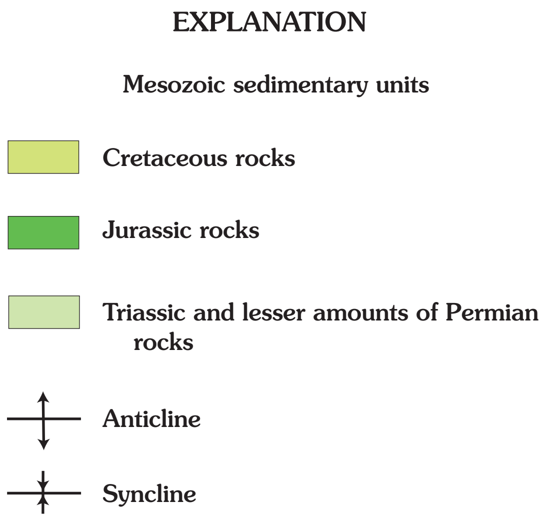
EXPLANATION

Approximate outline of national forests in GMUG study area

0 70 KILOMETERS

0 40 MILES

Figure B6 (above and following page). Generalized distribution of Mesozoic sedimentary units.



wherein low-gradient streams meandered across flood plains, mud flats, and saline basins.

Cretaceous

Regional compressive tectonism started to exercise control over the geography and sedimentary environment during the Cretaceous, with the onset of the Sevier orogeny. The Sevier orogenic belt during this time lay to the west in west-central Utah and was the result of crustal shortening experienced throughout the Western Interior of North America. (See Lawton, 1994.) The eastward-migrating orogenic front, caused by the collision of the continental North American plate with the Farallon oceanic plate, was marked by the dominantly north south trending Sevier orogenic thrust belt in eastern Utah and western Colorado. Foreland basins formed ahead and to the east of the advancing orogenic front. These asymmetric foreland basins were occupied by a large inland sea (Western Interior Basin) that extended from Alaska south to the modern Gulf of Mexico. Marine shale as well as terrestrially derived sediment shed from the orogenic belt was deposited into the basins, which were deepest along their western margins. The sedimentary basins thinned eastward as they onlapped onto the North American craton. From Early through Late Cretaceous, the eastward migration of the foreland basin progressively changed the depositional environment across the study area.

As the eastward-migrating sea advanced, blankets of beach sands and intervening carbonaceous shales were deposited, forming the Dakota Sandstone. The Dakota is one of the most extensive formations throughout the Western Interior of North America, representing a beachfront that transgressed eastward throughout Utah, across Colorado, and through the Great Plains. As such, its age varies depending on the paleogeographic location of a given point in relation to the advancement of the Cretaceous sea. The Dakota Sandstone is a quartzose sandstone interbedded with dark shale and shaly sandstone, and minor amounts of gray claystone, impure coal, and carbonaceous shale. Locally, the Dakota has a basal conglomerate. Because the unit is resistive to weathering, it forms a prominent stratigraphic marker horizon throughout the study area, forming hogbacks of buff sandstone.

As the Late Cretaceous inland sea transgressed eastward, deep-water marine sediments were deposited in the foreland basins. Within the study area, these depocenters included the Piceance Basin in northwestern Colorado and the San Juan Basin of southwestern Colorado and northwestern New Mexico as well as the Denver Basin east of the study area (fig. B5). Thick accumulations of carbonaceous sandstone and limestone as well as black shale of the Mancos Shale were deposited at this time. The lower part preserves thin-bedded brown sandy fossiliferous limestone and dark-gray shale (Juana Lopez Member) and sandstone (Frontier Sandstone and Ferron Sandstone Members) that give way upsection to the thick sequence of marine black shale of the main body (upper member) of the Mancos (Dyman and others, 1994). The Mancos Shale and its lateral and temporal (to younger) equivalent Pierre Shale to the east represent carbonaceous sediments that were deposited in stagnant, poorly oxygenated waters that preserved numerous marine fossils.

The continued eastward progression of the thrust front of the Sevier orogeny (see Lageson and Schmitt, 1994) uplifted and exposed the tectonic hinterland west of the study area in Utah to erosion, causing an influx of terrigenous sediments shed as tongues of sand within the upper part of the Mancos and younger sediments. The axis of the depositional system advanced eastward into the Denver Basin and Great Plains region as recorded by the nonmarine clastics, shale, and bituminous deposits of the Mesaverde Group (or Formation). These units were deposited in fluvial deltas, marshes, and lagoons that formed at the front of the advancing tongues of terrigenous sediments. The encroachment of the Cretaceous sea was erratic, resulting in shifting depositional facies that produced intertonguing of deeper water shales with the near-shore and fluvial sediments. In the Piceance Basin in the northern part of the study area (fig. B5), this shifting of depositional environments resulted in deposition of the Castlegate Sandstone, the Buck Tongue of the Mancos Shale (which represents an intertonguing of underlying deeper water facies of Mancos Shale with the clastic terrigenous sedimentary wedges of the Sego Sandstone), and the sandstone and interlayered shale deposits of the Mount Garfield, Hunter Canyon, Nelson, and Farrer Formations. Migration of the shoreline in the Piceance Basin caused changes in the depositional environment as the sandstone, shale, and coal seams of the lower part of the Mesaverde were deposited upon the terrigenous sediments. The upper part of the Mesaverde is dominated by sandstone that is interbedded with lesser amounts of shale and coal.

In the San Juan Basin the Mesaverde is composed of the massive marine sandstone horizons of the Point Lookout Sandstone, nonmarine crossbedded sandstone, claystone, and shale, coal seams, ironstone and limestone concretions of the

Menefee Formation, and the crossbedded marine sandstone and gray shale of the Cliff House Sandstone (Haynes and others, 1972). These carbonaceous sediments within the Mesaverde Group host important coal resources, discussed by Hettinger and others (this volume, Chapter M). In the Four Corners area of the San Juan Basin, the Point Lookout Sandstone represents accumulations of near-shore sand that mark one of the regressions of the Cretaceous sea. The overlying carbonaceous shale units of the Menefee Formation, which hosts coal-rich horizons, were deposited in a near-shore lagoonal and marshy edge of the retreating sea. Subsequent transgressive encroachment of the Cretaceous sea resulted in flooding of the near-shore environment of the Menefee Formation, laying down the beach sand of the Cliff House Sandstone.

In the San Juan Basin, transgression of the Cretaceous sea flooded over the Mesaverde Group, resulting in deposition of the marine Lewis Shale (Dyman and others, 1994). The Lewis is a clay-rich gray to black shale with rusty-weathering limestone concretions and contains thin beds of fine-grained sandstone near both the transitional top and base of the unit (Haynes and others, 1972). After deposition of the Lewis Shale, the shoreline of the Cretaceous sea again withdrew. With it the beach and near-shore facies sand deposits of the Pictured Cliffs Sandstone migrated across the San Juan Basin (Elder and Kirkland, 1994), and over it were laid the coastal-plain deposits of the Fruitland Formation (Molenaar, 1983). Alluvial-plain deposits of the Kirtland Shale onlapped and covered the Fruitland Formation coastal-plain sediments as a result of continued regression of the Cretaceous sea.

In northern Colorado the Lewis Shale is preserved on the White River Plateau (fig. B5), but it is absent in the Piceance Basin, where its time equivalent units are the nonmarine clastic sediments of the Mount Garfield and Hunter Canyon Formations (Dyman and others, 1994). These nonmarine clastic units represent the incursion of terrigenous sediments into the foreland basin that were being shed off of the Sevier orogenic hinterlands from the west in central Utah (Lawton, 1994).

Cenozoic Era

During the latest Cretaceous and early Cenozoic time, the Western Interior Cretaceous seaway began to withdraw northeastward across the region (Tweto, 1975). The regional geology was soon dominated by the Laramide orogeny, which in the study area resulted from east-west-directed regional compression that caused uplift of many of the mountain ranges and intervening basins exposed today. The Cenozoic Era in central to west-central Colorado was marked by four major geologic events: nonmarine sedimentation in the Piceance and northern San Juan Basins (early Paleocene to latest Eocene), formation of the San Juan volcanic field (middle Tertiary), shallow-level magmatic intrusion in the Elk Mountains region (Oligocene), and the formation of surficial deposits during the Pleistocene and Quaternary Periods.

Tertiary Sedimentary Deposits

Large and deep structural basins formed concurrently with Laramide uplift during Late Cretaceous to Eocene time (Tweto, 1975). Gravel and sand deposited in these basins record uplift of Laramide highlands. Like the mountains, several of the basins inherited their structure in part from late Paleozoic features (Tweto, 1975). In all the basins, Upper Cretaceous deposits derived from distant western sources associated with the Sevier orogeny were succeeded by Laramide orogenic clastic sediments derived from local positive tectonic features. In most basins, the youngest marine deposits (Late Cretaceous age) grade upward into and intertongue with coal-bearing brackish- and fresh-water sandstones and shales deposited during the Laramide orogeny.

In the study area the two main basins that hold Cenozoic sediments are the Piceance Basin in the north and the San Juan Basin in the south. The Piceance Basin is bounded by several extensive Laramide tectonic features, including the Uncompahgre, White River, Sawatch, and Gunnison uplifts (figs. B5–B7). The axis of the basin trends northwest and southeast, and maximum depositional thickness is about 12 km (Ochs and Cole, 1981). Tertiary sedimentary rocks within the basin include alluvial, deltaic, and lacustrine deposits of the Fort Union, Wasatch, Green River, and Uinta Formations. These Tertiary sedimentary rocks overlie thick Cretaceous sandstones and shales in the Mesaverde Group. From Late Cretaceous through Eocene time, the Piceance Basin was a catchment for both the eroded detritus from previously deposited sedimentary rocks and sediment derived from volcanic, intrusive, and pyroclastic rocks (Johnson, 1985). Early deposition in the basin (early or middle Paleocene) followed a period of widespread beveling of basins. The early sedimentary rocks are mostly conglomeratic and reflect the intensity of tectonic activity and the composition of the source rocks. Throughout most of the Piceance Basin, thin basal conglomeratic sandstone was deposited on the Cretaceous-Tertiary unconformity. The basal conglomerate may have been derived both from the underlying Mesaverde Group rocks and from the surrounding highlands. By late Paleocene time, large shallow lakes and swamps covered much of the basin. Gray and carbonaceous shale, thin coalbeds and fossiliferous limestones, and lenticular sandstones were deposited in these lacustrine and paludal environments. In latest Paleocene to early Eocene, huge wedges of mud and sand, dominantly of fluvial and alluvial origin, began to prograde from basin margins inward, possibly reflecting a period of renewed uplift of adjacent highlands. The described sequence of basal conglomerates, lacustrine and paludal rocks, and uppermost fluvial and alluvial mudstone and sandstone make up the Paleocene Fort Union and Eocene Wasatch Formations (Ochs and Cole, 1981).

In early Eocene time, a permanent fresh-water lake formed in the central and northwestern part of the Piceance Basin (Johnson, 1985). Lacustrine deposits of the Green River Formation mark the earliest stage of Lake Uinta and are characterized by low-grade oil shale, limestone, sandstone, and

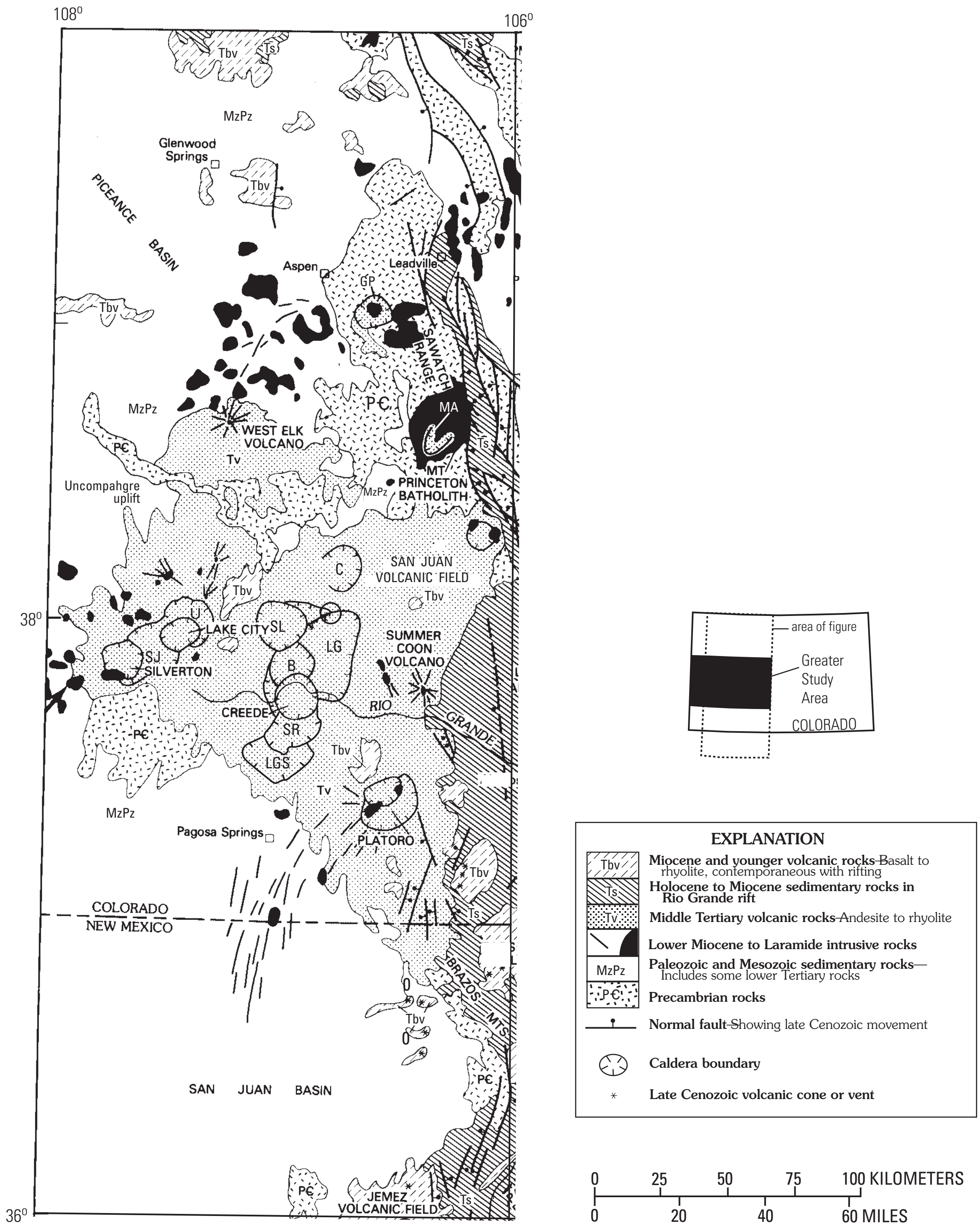


Figure B7. Generalized geology of San Juan volcanic field of southern Colorado. Modified from Lipman (2000). Calderas indicated by symbols are as follows: SJ, San Juan; U, Uncompahgre; LGS, La Garita South; SR, South River; B, Bachelor; SL, San Luis caldera complex; LG, La Garita; C, Cochetopa Park; MA, Mount Aetna; GP, Grizzly Peak.

kerogen-rich shale (Johnson and Keighin, 1981). The Green River Formation conformably overlies and intertongues with the older Wasatch Formation (Ochs and Cole, 1981). Lake Uinta expanded rapidly to cover most of the basin in late early to early middle Eocene. Salinity began to increase after this transgression and led to the precipitation of great quantities of saline minerals. The kerogen content of the Green River Formation far exceeds that of the earlier fresh water stage, and resulted in the formation of the economically important oil shale horizons within the formation. During the middle to late Eocene, a delta consisting mainly of volcaniclastic debris prograded southward across the basin, mostly filling the Piceance Basin portion of Lake Uinta.

During the late Eocene, Lake Uinta was gradually filled, first by volcaniclastics from the Absaroka volcanic field in Wyoming to the north, and later by sediments from local Laramide uplifts (Johnson, 1985). A deltaic complex named the Uinta Formation forms the youngest stratigraphic unit preserved within the Piceance Basin; erosional remnants of it occur across most of the basin.

Several sedimentary units in the southern portion of the study area were deposited along the northern margins of the San Juan Basin. These sedimentary units are generally the coarsest near the basin margins, as they were derived from the nearby highlands (Tweto, 1975). The uppermost Cretaceous and lower Paleocene Animas Formation contains coarse-grained andesitic clasts and records erosion of the major uplifts and volcanic centers in the northern and northeastern part of the San Juan Basin (La Plata Mountains area) (Cross and Larsen, 1935). The Nacimiento Formation, which is in part time-equivalent with the Animas Formation, represents deposition of fine-grained material in the southern part of the San Juan Basin by the same streams that carried the Animas in the north (Fassett, 1985). Although the Nacimiento Formation consists largely of shale and siltstone in the central part of the basin, it is typically characterized by sandstone and some conglomerate where it crops out in the study area (extreme northern part of the basin). The Eocene San Jose Formation is the youngest Tertiary sedimentary unit in the San Juan Basin. This formation consists of intertonguing sandstone, conglomerate, and shale derived from granitic rocks in a highland north of the basin. All the just-mentioned sedimentary units of the northern San Juan Basin are volumetrically minor in the study area and are generally less than about 30 m thick.

The Telluride Conglomerate (Eocene), which crops out mostly in the southwestern part of the study area, was important host for base- and precious-metal replacement ore in the southwest San Juan Mountains (Mayor and Fisher, 1972). The conglomerate was largely derived from large alluvial debris fans along the margins of the San Juan uplift (fig. B5) (Baars and Ellingson, 1984). The lower beds of this formation commonly contain fragments of red sandstone and gray limestone, whereas most of the clasts in the upper beds are gneiss, schist, and quartzite. This reversed stratigraphic sequence, as represented in the clasts, reflect the early stripping of sedimentary cover and later removal of the Precambrian core of the nearby uplift. The top of the Telluride Conglomerate is conformable with and grades into the tuffs and breccias of the San Juan volcanic field. The formation is about 300 m thick in the area west of Telluride and thins to about 10 m in the mountains west of Silverton (Baars and Ellingson, 1984).

Tertiary Volcanism and Associated Sedimentation

The material forming most of the volcanic rocks in the southern Rocky Mountains was erupted during Oligocene time, and originated from a single composite volcanic field, the so-called Southern Rocky Mountain volcanic field of Steven (1975). Although erosion prevents accurate estimations of the size of this field, it probably covered most of south-central Colorado and adjacent parts of New Mexico. The onset of caldera-forming eruptions in the Sawatch Range (Grizzly Peak and Mount Aetna calderas; fig. B7) (Fridrich and others, 1991) preceded the initiation of activity in the western and central San Juan volcanic field by about 6 million years (Steven and Lipman, 1976; Bove and others, 2000). Caldera sources within the central and western San Juan volcanic field account for nearly all the ash-flow units present within the study area. A total of 15 major ash-flow sheets were accompanied by recurrent caldera subsidence between 28.6 and 22.9 Ma in the western and central San Juan Mountains (Lipman, 2000). Some details of the Tertiary volcanic history of the study area are given here owing to its prominence in both the mineral resources of the region and associated environmental consequences.

The San Juan volcanic field is the largest erosional remnant of the Southern Rocky Mountain volcanic field. Erosionally preserved rocks of the San Juan field now occupy an area of more than 25,000 km^2 and have a volume of about 40,000 km^3 (Lipman and others, 1970). Volcanic materials were deposited in the San Juan Mountains in the middle Tertiary after erosion had stripped the sedimentary cover and cut into Precambrian rocks elevated by the Laramide Uncompahgre–Needle Mountains upwarp (Steven, 1975). The earliest volcanic activity in the San Juan field (about 35–30 Ma) produced the intermediate-composition lavas and breccias that erupted from scattered central volcanoes, forming the San Juan and Conejos Formations. Beginning about 30 Ma, the nature of the volcanic activity changed significantly. Tremendous volumes of ash and volcanic glass were explosively erupted about 30–26 Ma from caldera sources. At about 28–26 Ma, volcanism shifted to a bimodal assemblage dominated by basalt and rhyolite, concurrently with the onset of regional extension and the establishment of the Rio Grande rift (Tweto, 1975; Lipman and others, 1978).

The calderas of the San Juan volcanic field formed within a cluster of precaldera stratovolcanoes. Although the detailed distribution of the precaldera rocks has been obscured, the remnants of some of these volcanic centers can be recognized (fig. B7). The vent regions are identified by thick sequences of andesitic to dacitic lavas, explosion breccias, and agglutinates intruded by stocks and radial dike swarms. Deep basins were filled by volcaniclastic sediments, tuffaceous conglomerates, and mudflow breccias shed from the surrounding stratovolcanoes (Steven and Lipman, 1976). These voluminous deposits are referred to as the San Juan Formation in the western San Juan volcanic field, and they are lithologically analogous to the Conejos Formation in the central and eastern San Juan field (Luedke, 1996; Lipman, 2000).

Western San Juan Mountains

Five major calc-alkaline (dacitic to low-silica rhyolite) ash-flow sheets erupted from caldera sources (Ute Ridge, Blue Mesa, Dillon Mesa, Sapinero Mesa, and Crystal Lake Tuffs) in the western San Juan volcanic field from 28.6 to 27.4 Ma (Bove and others, 2000). Even after erosion, ash-flow sheets associated with these calderas extend as much as 80 km from their sources and are present just south of the West Elk volcano (fig. B7). Eruption of the 29.1 Ma Ute Ridge Tuff produced the Ute Creek caldera, the oldest in the western San Juan caldera complex (fig. B7). The next caldera to form was the Lost Lake caldera, which produced the widespread Blue Mesa Tuff (28.4 Ma). Both the Lost Lake and Ute Ridge calderas were infilled by later lavas and related pyroclastics. The Ute Ridge and Blue Mesa Tuffs are only preserved in distal outflow sheets.

Collapse of the San Juan and Uncompahgre calderas took place about 28.4-28.2 million years ago in association with major ash-flow eruptions of the Sapinero Mesa Tuff and possibly early eruption of the less voluminous Dillon Mesa Tuff (Lipman and others, 1973; Steven and Lipman, 1976). The Uncompahgre caldera formed an irregular depression about 20 km in diameter west and southwest of Lake City. The San Juan caldera formed nearly concurrently about 20 km west of the Uncompahgre caldera. The Sapinero Mesa Tuff has been subdivided into three major units—the main body of the Sapinero Mesa (outflow), the Eureka (intracaldera fill), and the Picayune Megabreccia Members (Lipman and others, 1973). The Picayune Megabreccia Member commonly lies stratigraphically below and intertongues with the Eureka Member (Lipman and others, 1976), and consists of a chaotic assemblage of precaldera rocks that slid from the oversteepened walls of the San Juan and Uncompahgre calderas. The Eureka graben, which is a downdropped keystone fault zone along the crest of the elliptical resurgent dome of the coalesced San Juan–Uncompahgre calderas, is an important host to mineralization that postdates these calderas by about 5–15 million years (m.y.) (Lipman and others, 1976).

The 27.6 Ma Silverton caldera, which is nested within the San Juan caldera (28.2 Ma), collapsed in response to eruption of the Crystal Lake Tuff (Lipman and others, 1976; Bove and others, 2000). The Crystal Lake Tuff forms a relatively small volume ash-flow sheet in comparison with deposits related to other calderas in the San Juan volcanic field (Steven and Lipman, 1976). The Crystal Lake Tuff is mostly absent within the Silverton caldera undoubtedly owing to erosion within this relatively shallow depression. Present within the Silverton caldera itself is a thick sequence of finely porphyritic dacitic-andesitic lavas (Burbank and Luedke, 1969; Yager and others, 1998); these lavas are generally referred to as the Burns Member of the Silverton Volcanics (Lipman and others, 1973; Burbank and Luedke, 1969; Yager and others, 1998). This thick package of lavas largely erupted along the ring fracture zones of the earlier collapsed San Juan and Uncompahgre calderas, prior to collapse of the Silverton caldera (Lipman and others, 1976).

Collapse of the Lake City caldera postdated all other caldera-related eruptions in the western San Juan Mountains by more than 4 million years. It is thought to be associated with bimodal magmatism related to the onset of extensional tectonism in this general region at about 25 Ma (Lipman and others, 1978). The Lake City caldera, which is nested within the older Uncompahgre caldera, formed in response to the eruption of the Sunshine Peak Tuff at 22.9 Ma. Accumulations of related ash-flow material exceeded 300 km^3, the majority of which ponded within the caldera along with subsidence-related breccias. A large quartz syenite pluton was intruded into the intracaldera fill, causing resurgence of the caldera. The resurgent intrusions were derived from the same alkalic magma chamber that produced the caldera-forming ash-flow eruptions (Hon and Lipman, 1989; Hon, 1987). Continued volcanic activity produced a thick sequence of dacitic post-caldera-collapse lavas and intrusions that accumulated near the eastern margin of the caldera. These lavas and intrusions were host to subeconomic molybdenum-copper mineralization and to one of the largest alunite deposits in the Western United States (Bove and others, 2000).

A large swarm of calc-alkaline intrusions was emplaced between about 26 and 25 Ma over a broad region of the western San Juan Mountains (Bove and others, 2000). These intrusions range from large stocks and sills at Mt. Wilson west of Ophir and Sultan Mountain near Silverton to smaller plugs intruded near Capitol City in the Lake City area (fig. B7). Although the overall size of the exposed intrusions decreases from west to east, this may be an artifact of erosion rather than a reflection of their actual size. These intrusions vary from simple to complexly zoned and in many places are associated with veins and disseminated and stockwork molybdenum-copper mineralized rocks (Ringrose and others, 1986; Slack, 1980; Caskey, 1979; Pyle, 1980). Many of these intrusions are completely crystalline and cut through the entire ash-flow sequence, suggesting that they may represent cores of now-eroded stratovolcanoes that fed thick sequences of lavas nearby (Lipman and others, 1973). Alternatively, the widespread distribution of intrusions suggests that they represent the uppermost portion of the underlying batholith rising into and consuming the earlier volcanic pile—similar to the emplacement of the Boulder batholith into the Elkhorn Mountains Volcanics in Montana (Lipman and others, 1976).

Central San Juan Mountains Caldera Cluster

The six calderas of the central cluster, as in the other calderas of the volcanic field, formed within a locus of precaldera volcanoes. Following early ash-flow eruption from the western San Juan calderas, explosive activity converged in the central San Juan region, beginning with eruption of the Masonic Park Tuff at 28.3 Ma and then the enormous Fish Canyon Tuff from the La Garita caldera (35×75 km; fig. B7) at 27.6 Ma (Lipman, 2000). Ensuing central San Juan calderas (Bachelor, South River, San Luis caldera complex, and Creede), which were sources of smaller volume and more areally restricted tuff sheets, were nested within the much larger La Garita and La Garita South calderas.

The dacitic Fish Canyon Tuff, long recognized as the world's largest ash-flow sheet, both spread widely beyond and ponded within its source caldera. The current volume of this ash-flow sheet has been estimated to exceed 5,000 km^3, which is nearly five times greater than the largest of the other 22 ash-flow sheets within the San Juan field (100 to >1,000 km^3) (Lipman, 2000). Present outcrops of Fish Canyon Tuff outflow extend to nearly 70 km laterally from the La Garita caldera.

The San Luis caldera complex (fig. B7) is now recognized as the composite source of three sizable ash-flow sheets: the Rat Creek, Cebolla Creek, and Nelson Mountain Tuffs. These ash-flow sheets are all similar in composition, ranging from dacite to rhyolite, and record three separate subsidence events. Outflow of the Nelson Mountain Tuff filled the inferred Cochetopa Park caldera, located about 20 km northeast of the San Luis caldera complex (fig. B7). The inferred Cochetopa Park caldera, which is in the Gunnison National Forest (Chapter A, fig. A1), is bounded by a horseshoe-shaped complex of faults that represents a hinged subsidence feature (Steven and Lipman, 1976). Thick accumulations of Nelson Mountain Tuff within this inferred caldera were intruded and overlain by thick rhyolitic flows. The eroded remnants of this rhyolitic mass still persist as the feature called the Cochetopa dome.

The Creede caldera formed during eruption of the Snowshoe Mountain Tuff at about 26.9 Ma and is thought to be the youngest of the central San Juan calderas. The dacitic intracaldera tuff is as much as 2 km thick, although the outflow sheet is less than 100 m thick and is generally limited to the central San Juan caldera cluster (Lipman, 2000). Resurgent doming resulted in the formation of a moat area between the resurgent dome and outer margin walls of the caldera. Sedimentary fill within this moat basin consists largely of finely laminated shale and sandstone, together called the Creede Formation (Steven and Ratté, 1973; Lipman, 2000).

Most calderas of the central San Juan field were filled rapidly after subsidence by andesite to rhyolite lavas and domal masses interleaved with ash-flow tuffs as well as minor sediments. The lavas were erupted from central volcanoes within or on the margins of the calderas, whereas the major tuff units are associated with younger adjacent calderas (Lipman, 2000). Intrusions associated temporally and spatially with the central San Juan calderas are relatively minor in volume and distribution, range from granite to andesite, and represent late stages of caldera magmatism. The intrusive rocks are commonly associated with weak argillic and pyritic alteration products; however, no evidence of significant mineralization has yet been found (Lipman, 2000).

The overall patterns of alteration and mineralization related to the central San Juan calderas are highly influenced by north-trending faults that were recurrently active throughout this caldera cycle. Localization of major mineralization events in the Creede district was also probably due to sustained magmatic activity and thermal flux over central parts of the subvolcanic batholith related to caldera eruptions (Lipman, 2000).

Late Basalts and Rhyolites of the Central San Juan Mountains Caldera Cluster

In the early Miocene, the nature of volcanism changed markedly. Although the Oligocene volcanics of the San Juan field are mostly intermediate lavas and more silicic ash-flow tuffs, the younger rocks are largely a bimodal assemblage of basalt and silicic alkalic rhyolite (Lipman and others, 1969). The basaltic rocks of the Hinsdale Formation are mainly alkali olivine basalt flows; however, andesites are also common. The basalt flows, which are now much eroded, cap high flat mesas and typically rest upon older ash-flow units. The rhyolites consist of small, scattered volcanic necks, plug domes, and the ash-flow sheet related to the 23 Ma Lake City caldera. Basalt and rhyolite were erupted intermittently throughout the Miocene and Pliocene, forming a widespread thin veneer over the older volcanic rocks. Miocene-age alkali basalt on Grand Mesa is also part of the bimodal basalt-rhyolite suite and is roughly equivalent to the basalts of the Hinsdale Formation. Basaltic rocks on Grand Mesa are largely confined to plugs and related feeder dikes. The maximum preserved thickness of the basalt flows on Grand Mesa is about 240 m (Tweto and others, 1978).

Sawatch Range Calderas and Related Mount Princeton Batholith

The ≈34 Ma Mount Aetna and Grizzly Peak calderas are located in the south-central Sawatch Range (fig. B7). The Mount Aetna caldera complex consists of three main elements: (1) the 36.6 Ma Mount Princeton pluton, (2) the 34.4 Ma Mount Aetna caldera, and (3) chemically evolved 30 Ma granitic intrusions (Johnson and others, 1989). The Mount Princeton pluton (batholith, fig. B7) is elliptical (24×36 km), compositionally zoned, and flat-topped. It is interpreted to represent the plutonic roots of a caldera in which all evidence of the volcanic edifice and collapse structure has been completely removed by erosion (Johnson and others, 1989). The Mount Aetna caldera consists of two collapse structures (12 and 25 km in diameter) that have been deeply eroded, exposing the precaldera floor. Pyroclastic eruptive components from this caldera are only preserved in the southern part of the caldera complex. The younger evolved granites are a subgroup of granites that are associated with significant mineralization episodes in Colorado (Johnson and others, 1989).

The Grizzly Peak caldera is located on the crest of the Sawatch Range, about 30 km north of the more deeply eroded Mount Aetna caldera (fig. B7). Early rhyolitic volcanism (Grizzly Peak Tuff) culminated in the collapse and formation of the 17×23 km Grizzly Peak caldera at 34 Ma (Fridrich and others, 1991). Approximately half of the erupted tuff ponded within the caldera margins. Only small remnants of outflow Grizzly Peak Tuff have been found more than 20 km away from the caldera margins (Fridrich and others, 1991). Following collapse, the caldera was resurgently domed, in part by the emplacement of a granodiorite laccolith, now exposed by erosion. A belt of dacite to rhyolite dikes and small stocks formed across the center of the domed caldera. Late felsic resurgent intrusions are spatially associated with hydrothermal alteration and weak mineralization resembling that found in porphyry molybdenum deposits (Fridrich and others, 1991).

Plutonic and Volcanic Rocks in the Elk Mountains Region

In contrast to Tertiary igneous rocks of the San Juan volcanic field, which are largely volcanic, those preserved in the Elk Mountains region are largely epizonal plutons. The Elk Mountains region, as used in this report, includes the Elk Mountains, Ruby Range, Treasure Mountain dome, and West Elk Mountains. However, the age and sequence of rock types are very similar in these two areas (Lipman and others, 1969). Igneous activity in both, dominantly of intermediate composition, occurred during late Oligocene time and produced large volumes of intermediate-composition rocks and their comagmatic silicic differentiates. As in the San Juan volcanic field, small volumes of bimodal mafic and silicic rocks were erupted in Miocene and Pliocene time (Lipman and others, 1969).

Upper Cenozoic rocks of the Elk Mountains region are mostly intrusive and can be divided into granodiorite plutons of Oligocene age, Miocene and younger? mafic dikes, and highly evolved granite to rhyolite stocks, plugs, and dikes of Miocene age. The Oligocene stocks, laccoliths, sills, and dikes consist mainly of granodiorite and granodiorite porphyry and intrude rocks as young as the Eocene Wasatch Formation in the Elk Mountains region. Available age data (Mutschler and others, 1981; Cunningham and others, 1994) indicate that these intrusions were emplaced between 34 and 29 Ma.

Studies by Mutschler and others (1981) group the Oligocene Intrusive Suite of the Elk Mountains area into several main stages based on age, mode of emplacement, and relationship to mineralized rocks. Stage A includes large plutons of equigranular to porphyritic granodiorite, and includes the Sopris, Snowmass, and Whiterock plutons, as well as the Italian Mountain intrusive complex. Mineralized material associated with these intrusions occurs dominantly as polymetallic disseminated and vein replacements along margins of the intrusions. Intrusions of stage B include sills, laccoliths, and dikes of granodiorite porphyry composition. Contact metamorphism is minimal in stage B intrusions, and they are not known to be associated with any significant mineralization. Stage D intrusions are small andesite to granodiorite stocks in a northeast zone, several of which are the centers of radial or linear dike swarms. Stage D intrusions extend from the West Elk Mountains and are present along and beyond the crest of the Ruby Range. Products of mineralization associated with these intrusions include chalcopyrite-pyrite-molybdenite deposits and other miscellaneous vein and replacement deposits.

Late Bimodal Rocks in the Elk Mountains Region

Small mafic dikes cut the Oligocene granodiorites in the Elk Mountains regions and are thought to be Miocene and early Pliocene in age (Lipman and others, 1969). The composition of these mafic rocks is similar to that of the basalts of the Hinsdale Formation of the San Juan volcanic field, the alkali basalts on Grand Mesa, and basalts in the Flat Tops areas to the north. Silicic Miocene intrusive rocks include the granite of Treasure Mountain (Mutschler and others, 1981), rhyolite to granite intrusions related to the Mount Emmons and Redwell Basin molybdenum deposits (White and others, 1981; Thomas and Galey, 1982), and other miscellaneous domes, dikes, and small intrusions throughout the area.

Late Tertiary and Quaternary Unconsolidated Deposits

A major period of uplift, erosion, and deposition started in early Miocene and continued through Pliocene time, significantly disrupting and dissecting an Eocene regional erosion surface (Epis and others, 1980). Uplifted mountain blocks were deeply eroded, and the resulting debris was deposited in basins and channels bordering the mountain ranges. Uplift may have accelerated during the Pliocene, cutting deep canyons that characterize the mountain flanks. Pliocene canyon cutting apparently continued into Quaternary time until a stable base was achieved. Canyon cutting and pedimentation continued in Quaternary time, but a major climatic cooling event initiated glaciation, which continued from about 500,000 years ago into the late Pleistocene, ending approximately 15,000 years ago (Epis and others, 1980). During three glacial maxima, ice almost covered the higher ranges, and the alpine valleys were filled with glaciers. The modern alpine topography of deep U-shaped valleys and sharp peaks and ridges is largely a product of glacial erosion (Mierding and Birkeland, 1980). Glacial advances deposited numerous sheets of till and outwash gravel in stream valleys.

Holocene alluvium is present in drainages and fans across the national forests and consists of gravel, sand, and silt with varying degrees of consolidation. In some places, alluvium of Pliocene and Pleistocene(?) age is present on ridges. Landslide deposits are common in the study area; semi-steep slopes underlain by Mancos Shale, and the Wasatch Mesaverde Formation are particularly prone to landslides.

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Regional Sediment and Rock Geochemistry

By Steven M. Smith

Chapter C of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

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Regional Sediment and Rock Geochemistry

By Steven M. Smith

Abstract

A geochemical data set prepared for the GMUG project contains analyses for 13,314 sediment samples and 5,957 rock samples. These data allowed calculation of baseline concentrations of elements within the GMUG region and identification of areas with relatively high or low abundances.

Source and Description of Geochemical Data

The USGS National Geochemical Database (Hoffman and Marsh, 1994; Smith, 2000) contains data for a large number of geochemical samples from within the GMUG greater study area. Data for sediment and rock samples were retrieved from the USGS National Geochemical Database within an area bounded by lat 37°30′ N. to 39°45′ N. and long 105°45′ W. to 109°15′ W. This region includes the GMUG greater study area plus an extra 15-minute-wide buffer zone that was added to reduce edge-effect errors produced by surficial modeling of geochemical data. Data for samples of unique, unusual, or nonrepresentative material were removed. Data records were also removed if the sample was not analyzed by total-digestion chemical methods for elements of interest to this study. Data for 56 stream-sediment samples, collected during the 1996 and 1997 field seasons to fill gaps in the geographic coverage and to evaluate the geochemical signatures of mineral deposit types, were added to the project geochemical data sets. The resultant GMUG project geochemical data sets contain analyses for 13,314 sediment samples and 5,957 rock samples.

The data for geochemical samples retrieved from the USGS National Geochemical Database were derived from two primary sources: (1) rock and sediment samples collected since 1966 for various USGS projects in support of mineral resource assessment studies, energy resource studies, element distribution studies, ore deposits research, lithologic geochemistry research, and geologic mapping; and (2) sediment samples collected during 1976–79 for the National Uranium Resource Evaluation (NURE) Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) program. Table C1 lists USGS projects for which the stream-sediment and rock data were collected and includes references for associated reports. Some of the rock samples could not be identified with specific projects. Table C2 lists the projects responsible for collection of the NURE sediment data that are used in this study. Other known geochemical data from the GMUG greater study area that were not used are listed in table C3. Most of these data were not available in digital form.

The USGS sediment and rock samples were analyzed by DC-arc emission spectrography (Grimes and Marranzino, 1968; Golightly and others, 1987), inductively coupled plasma–atomic emission spectroscopy (Lichte and others, 1987; Briggs, 1996) or delayed neutron counting analysis (McKown and Millard, 1987). The number of elements analyzed and the determination limits varied with slight modifications in these analytical methods over the years represented in the data set.

The NURE samples were analyzed by energy dispersive X-ray fluorescence, DC-arc emission spectrography, delayed neutron counting analysis and neutron activation analysis. The details of these NURE analytical methods can be found in many of the HSSR quadrangle reports (for example, Shannon, 1980a).

The new minus-80-mesh stream-sediment samples collected for the current study were analyzed for 40 elements by an inductively coupled plasma–atomic emission spectrometry (ICP-AES) total extraction method (Lichte and others, 1987; Briggs, 1996). The samples were decomposed using a mixture of hydrochloric, nitric, perchloric, and hydrofluoric acids at low temperatures as described by Crock and others (1983). Each digested sample was aspirated into the ICP-AES instrument and the concentrations of 40 elements were determined simultaneously.

Sediment Data

The sediment samples are primarily minus-80-mesh (USGS) or minus-100-mesh (NURE) stream sediments, although a few samples were collected from ponds or springs. Some USGS samples are listed in the USGS National Geochemical Database only as “unconsolidated sediments”; the exact sources of these samples are unclear. Most of the sediment samples were collected specifically to represent regional elemental variation. The NURE HSSR studies systematically

Table C1. Sources of geochemical data from previous USGS studies within GMUG greater study area.

Study area	Geochemical data reference
Black Ridge Canyons BLM WSA	Toth, Stoneman, and others, 1983; Bullock, others, and Fey, 1989.
Buffalo Peaks WSA	Domenico and others, 1984; Nowlan and Gerstel, 1985.
Cannibal Plateau Roadless Area	Sharp and Lane, 1983.
Chama-Southern San Juan Mtns. WSA	Brock and others, 1985.
Collegiate Peaks WSA	Fridrich and others, 1998, and unpublished data.
Dolores Project Area-Irrigation Studies	Butler and others, 1995.
Dolores River Canyon BLM WSA	Bullock, others, and Briggs, 1989.
Dominguez Canyon BLM WSA	Toth, Davis, and others, 1983; Toth and others, 1987, and unpublished data.
Eagle Mountain WSA	Soulliere and others, 1986, and unpublished data.
Flume Canyon BLM WSA	Gaccetta and others, 1990.
Fossil Ridge WSA	Adrian, Clark, and others, 1984; Clark and Adrian, 1984.
Geochemistry of Black Shales	Vine and others, 1969.
Geochemistry of Eocene Rocks	Vine and Tourtelot, 1973.
Gunnison Gorge BLM WSA	Bullock, Barton, Briggs, and Roemer, 1989.
Handies Peak BLM WSA	Sanford and others, 1987, and unpublished data.
Holy Cross WSA	Wallace and others, 1989, and unpublished data.
Hunter-Fryingpan WSA	Mosier and others, 1980; Ludington and Yeoman, 1980.
Maroon Bells-Snowmass WSA	McHugh and others, 1987.
Mt. Massive WSA	Van Loenen and others, 1989, and unpublished data.
Oh-Be-Joyful WSA	Ludington and Ellis, 1983, and unpublished data.
Palisade BLM WSA	Hovorka and others, 1983, and unpublished data.
Porphyry Mountain WSA	Mosier and others, 1980.
Powderhorn WSA	Sharp and Lane, 1983.
Redcloud Peak BLM WSA	Sanford and others, 1987, and unpublished data.
San Juan Geologic Mapping	R.G. Luedke, oral commun., 2000, and unpublished data.
San Juan NF Mineral Resource Assessment	Barton and others, 1992.
Sangre de Cristo WSA[1]	Adrian, Arbogast, and Zimbelman, 1984; Zimbelman, 1989.
Sewemup Mesa BLM WSA	Soulliere and others, 1983, and unpublished data.
Tabeguache Creek BLM WSA	Bullock and others, 1990.
Uncompahgre Primitive Area[2]	Fischer and others, 1968.
Uncompahgre Primitive Area Additions[3]	Steven and others, 1973; Steven and others, 1977.
Uncompahgre Project Area-Irrigation Studies	Crock and others, 1994; Butler and others, 1994; Butler and others, 1996.
Upper Arkansas River Basin	Church, 1993; Church and others, 1994; Smith, 1994.
West Elk WSA	Gaskill and others, 1977.
West Needle WSA[1]	Birmingham and Van Loenen, 1983; Van Loenen, 1985.
Westwater BLM WSA	Bullock, others, and Fey, 1989.
Wilson Mountains Primitive Area[4]	Bromfield and others, 1972.

[1] Study from outside of the GMUG greater study area but within the contiguous 15-minute buffer area.

[2] Currently the Big Blue Wilderness Area.

[3] Includes parts of the Big Blue Wilderness and Mt. Sneffels Wilderness Areas.

[4] Currently the Lizard Head Wilderness Area.

sampled the region at an average density of about one sample per 10 km^2 (Sharp and Aamodt, 1978). Within this regional coverage, NURE detailed studies (for example, Maassen and others, 1981) and USGS studies of proposed Wilderness Study Areas (WSA) sampled selected areas at densities of as much as one sample per 2.6 km^2. Figure C1 shows the distribution of sediment samples in the GMUG project data set.

Because of the extensive coverage and the representative nature of the samples, the sediment data can be used for various purposes. In this study, the data have been used to calculate baseline concentrations of elements within the region and to identify areas with relatively high or low abundances. By interpolating element concentrations between sample sites, we have constructed geochemical surface models and contour maps to show the distribution of elements across the GMUG greater study area. The data were also incorporated into the GIS Mineral Resource Assessment models as point measurements. (See chapter on mineral resource assessments for various deposit types included in this volume.)

The sediment geochemical data were modified slightly to accommodate the constraints of statistical, gridding, and mapping software applications. Owing to the number of different analytical methods and variations of these analytical methods, the data contain many differing analytical determination limits. Data above and below these determination limits

Table C2. Sources of geochemical data from National Uranium Resource Evaluation (NURE) Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) projects and NURE Detailed Studies within GMUG greater study area.

[The NURE data were retrieved from Smith (2000)]

Study area	Geochemical data reference
Cortez Quadrangle HSSR	Maxwell, 1977; Warren and others, 1979.
Denver Quadrangle HSSR[1]	Bolivar and others, 1978; Shettel and others, 1981.
Durango Quadrangle HSSR	Maxwell, 1977; Dawson and Weaver, 1979; Shannon, 1980a.
Grand Junction Quadrangle HSSR	Langfeldt and others, 1981.
Leadville Quadrangle HSSR	Planner and others, 1980.
Moab Quadrangle HSSR	Maxwell, 1977; Goff and others, 1979.
Montrose Quadrangle HSSR	Maxwell, 1977; Broxton and others, 1979.
Pueblo Quadrangle HSSR[1]	Shannon, 1978; Shannon, 1979b.
Sawatch Range Detailed Study	Maassen and others, 1981.
Tallahassee Creek, Badger Creek, Castle Rock Gulch, and Buffalo Gulch Detailed Study.[1]	Shannon, 1979a.
Trinidad Quadrangle HSSR[1]	Morris and others, 1978; Shannon, 1980b.
Vallecito Creek Special Study Area[1]	Warren and others, 1981.

[1] Study from outside of the GMUG greater study area but within the contiguous 15-minute buffer area.

Table C3. Additional sources of geochemical data for GMUG greater study area that were not included in this study.

[Most of these data were not available in digital form during the data compilation phase of this study. —, no known samples]

Study area	Rocks	Sediments	Geochemical data reference
American Flats–Silverton BLM Planning Unit	89	1203	Weiland and others, 1980.
Browns Canyon WSA	—	121	Leibold and others, 1987.
Cortez Quadrangle NURE Evaluation	45	1657	Campbell and others, 1982a.
Denver Quadrangle NURE Evaluation[1]	485	301	Hills and others, 1982.
Durango Quadrangle NURE Evaluation	156	118	Theis and others, 1981.
La Garita WSA	172	253	Steven and Bieniewski, 1977.
Leadville Quadrangle NURE Evaluation	267	12	Collins and others, 1982.
Moab Quadrangle NURE Evaluation	131	—	Campbell and others, 1982b.
Montrose Quadrangle NURE Evaluation	365	30	Goodnight and Ludlam, 1981.
Pueblo Quadrangle NURE Evaluation[1]	478	150	Dickinson and others, 1982.
San Juan Primitive Area[1, 2]	467	828	Steven and others, 1969.
Trinidad Quadrangle NURE Evaluation[1]	90	—	Johnson and others, 1982.

[1] Study from outside of the GMUG greater study area but within the contiguous 15-minute buffer area.

[2] Currently the Weminuche Wilderness Area.

(qualified values) were replaced either by real values of 0.7 times the lower determination limit or by null values.

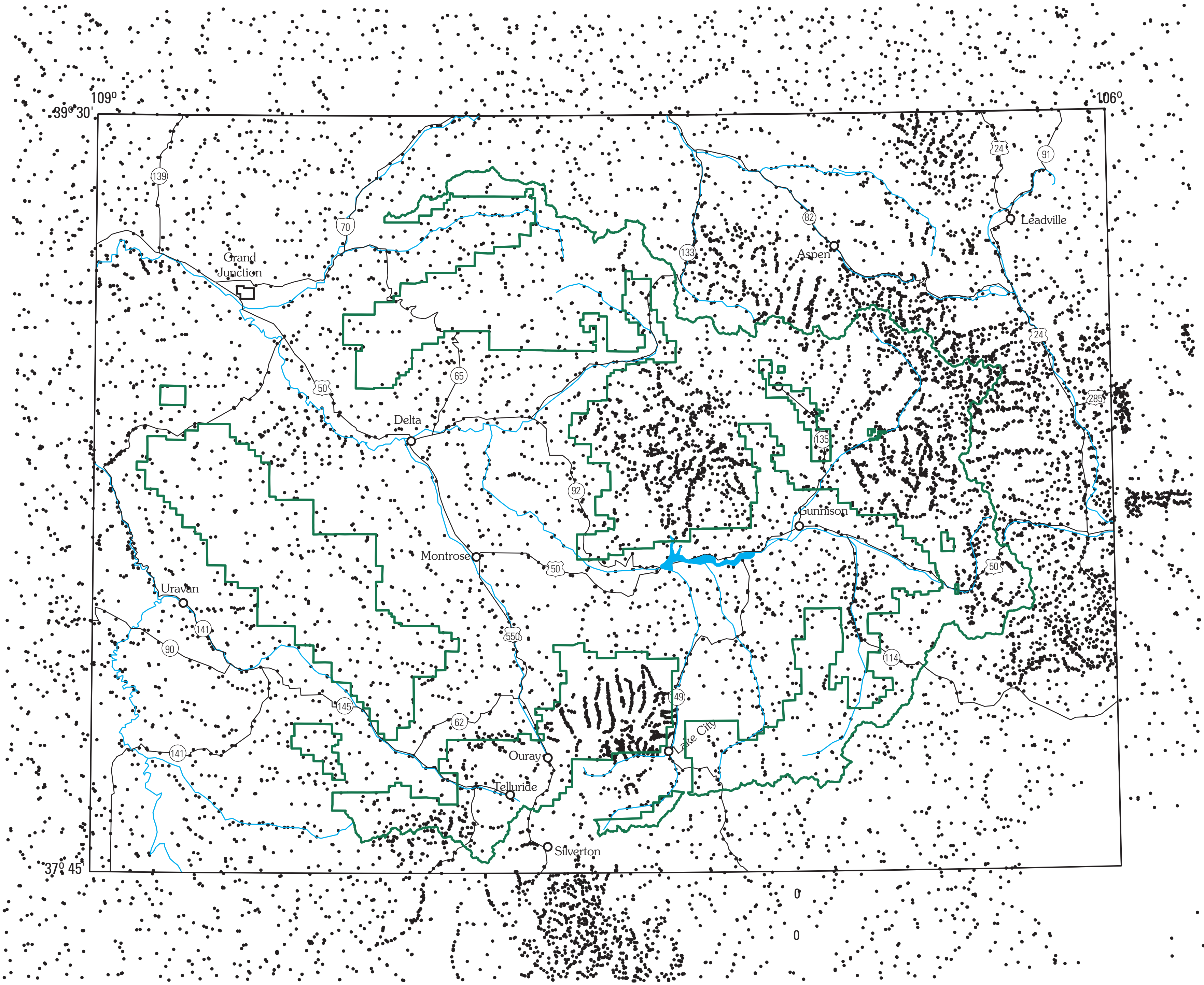
Rock Data

Unlike the sediment samples, rock samples were not collected systematically throughout the entire GMUG greater study area. Rocks were collected primarily around wilderness study areas and mining districts. Large areas of the GMUG greater study area were only sparsely sampled (fig. C2). Some rocks are representative samples of extensive geologic units, whereas other samples are of mineralized and altered rock from individual mine waste dumps.

The rock data are not appropriate for contouring or determining average baseline concentrations for the region, owing to the poor coverage and the mixture of mineralized and nonmineralized samples. Therefore, the rock geochemistry was used only as point data within the GIS Mineral Resource Assessment models. Only unqualified rock data were used. The qualified values (data outside of the determination limits) were neither replaced nor used in the GIS analysis.

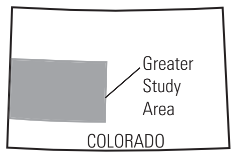
Gridding and Contouring

A geochemical “surface” model was interpolated for each element in the sediment data set using an algorithm in


109°
39° 30'
106°
37° 45'
Grand Junction
Delta
Montrose
Uravan
Ouray
Telluride
Silverton
Lake City
Gunnison
Aspen
Leadville
139
70
50
65
92
133
82
24
91
285
135
50
114
149
550
62
145
141
90
141
0
0

EXPLANATION

Approximate outline of national forests in GMUG study area



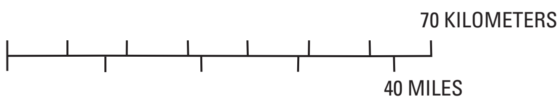


Figure C1(above and previous page). Localities of sediment samples (dots) collected within GMUG greater study area and a contiguous 15-minute buffer area.

Dynamic Graphics, Inc. EarthVision software that employs a bi-harmonic spline of minimum tension to create a continuous grid from scattered point data. As is common to most gridding algorithms, the interpolation of grid values into areas unconstrained by actual data points occasionally produces unrealistic high or low values. These “edge effects” may occur near the margins of the data set or within “holes” in the data distribution. To reduce the influence of these “effects,” we constrained the grid values to the range of maximum and minimum concentration values from the input data set. We eliminated most “edge effects” by including data from a 15-minute-wide buffer zone around the GMUG greater study area during the gridding process.

The grid files were imported into the ERDAS Imagine GIS package and masked to remove grid nodes outside the GMUG greater study area. The mean and standard deviation were calculated for the node values in each element grid and then compared with the mean and standard deviation of the input point data set to ensure that the grids closely modeled the input data. For modeling and contour display purposes, each grid was converted by a formula that calculates standard deviation units (*SDU*), as follows:

$$\frac{(X - X_m)}{\sigma} = SDU$$

where X is the individual grid value, X_m is the arithmetic mean for all grid values, σ is the standard deviation, and *SDU* is the resultant Standard Deviation Unit. The *SDU* values resulting from the equation measure, in units of standard deviation, the difference of each concentration value from the mean. Element grids transformed by the equation have a mean of zero and a standard deviation of one. Following the conversion of each grid, we reclassified the calculated *SDU* values into discrete categories by rounding each value to the nearest 0.5 *SDU*. Thus the mean *SDU* value of 0 actually represents a range from –0.250 to 0.249 *SDU*. (For example, for an element with a mean of 13 parts per million (ppm) and a standard deviation of 8, an *SDU* of 0 represents the concentration range from 11 to 14.9 ppm.) For elements with good sample and analytical coverage, the concentration range represented by 0 *SDU* can be used as one estimate of the mean local baseline concentration for that element.

The advantage of plotting *SDU* maps is that the distribution ranges of each element can be shown by a common scheme that is easily interpreted. This allows the user to quickly compare a large number of maps and assimilate the information with minimal effort. In addition, the *SDU* transformation can facilitate combining or comparing data from different sample media, analytical techniques, laboratories, or terranes. A limitation inherent to *SDU* maps is that the element ranges are dependent solely on the populations of element concentrations from the area of interest. Large standard deviation values caused by extreme outliers may suppress variation on the maps and hide subtle anomalies. In addition, this local range of element concentrations may or may not reflect the variability that is found worldwide. Thus the “hot” values plotted on *SDU* maps can highlight geologic terranes with only moderate enrichment that may not be of economic significance. Before using an *SDU* map to focus additional studies, the actual concentration values should be checked to confirm that the levels are high enough to warrant the follow-up work.

To address the issues of whether the *SDU* anomalies are of economic or environmental significance, we plotted some elements on sample location maps using symbols to represent multiples of crustal abundance estimates (Fortescue, 1992). This type of map is also more suitable than *SDU* maps for those elements with a very limited distribution of concentration values above analytical detection limits or for those sample media with limited geographical coverage, as in the case of GMUG rock geochemical data. The set of crustal abundance estimates, or Clarke Index values, used for this study is given in table C4. Multiples of the Clarke Index value are known as “Clarkes.” In a manner similar to the *SDU* maps, each concentration value was converted and then classified by rounding to the nearest 1.0 Clarke. A Clarke value of 1 thus represents a range of element concentrations from 0.50 to 1.49 Clarkes. (As an example, for an element with a crustal abundance estimate of 20 ppm, the concentration range represented by 1 Clarke is 10 to 29.9 ppm.) The concentration range represented by 1 Clarke can be used as one estimate of the global background range for an element. Clarke units are multiples of this background range.

Interpretive Maps

A large number of interpretive maps were created from the GMUG greater study area sediment and rock geochemical data, as follows:

***SDU* maps**		
antimony	copper	strontium
barium	gold	thorium
bismuth	lead	tin
cadmium	manganese	tungsten
chlorine	nickel	uranium
chromium	rubidium	vanadium
cobalt	silver	zinc
Clarke maps, sediment samples		
antimony	gold	scandium
arsenic	hafnium	silver
barium	lanthanum	strontium
bismuth	lead	thorium
cadmium	lithium	tin
chlorine	lutetium	tungsten
chromium	manganese	uranium
cobalt	molybdenum	vanadium
copper	nickel	ytterbium
dysprosium	niobium	zinc
europium	rubidium	zirconium
	samarium	
Clarke maps, rock samples		
arsenic	gold	thorium
barium	lead	tin
bismuth	manganese	tungsten
cadmium	mercury	uranium
chromium	molybdenum	vanadium
cobalt	nickel	zinc
copper	silver	

As an example, figure C3 is an *SDU* map showing the distribution of copper in sediments. The mean concentration of copper in sediment samples collected from the GMUG greater study area is 42 ppm. This is lower than the crustal abundance estimate of 68 ppm (table C4) recommended by Fortescue (1992) but is essentially equivalent to the regional baseline value of 40 ppm used by Smith (1994) in studies of the Upper Arkansas River Basin in Colorado. A number of areas containing elevated concentrations of copper can be identified in figure C3. Most of these highs are associated with areas of known mineralization, and the general pattern follows the trend of the Colorado Mineral Belt.

The distribution of copper in rock samples is illustrated as a Clarke map in figure C4. Only those rock samples having a copper concentration of 2 or more Clarkes are shown. Because of the large percentage of rocks collected from mineralized areas, the copper concentrations in rock data highlight several mining districts within the GMUG greater study area.

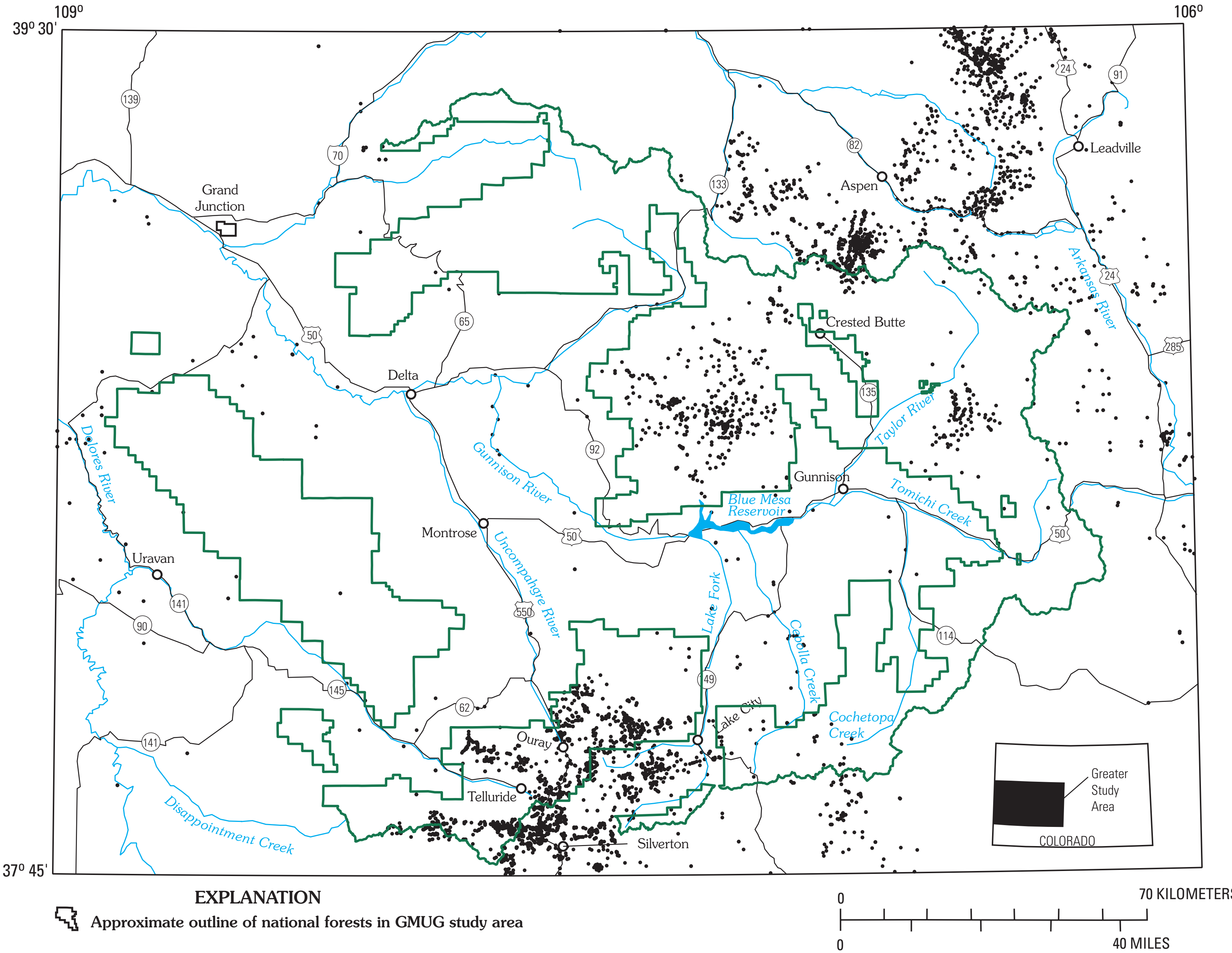


Figure C2. Localities of rock samples (dots) collected within GMUG greater study area.

Table C4. Clarke Index values for crustal abundance of selected elements; based on Fortescue (1992).

[Element concentrations are reported in parts per million (ppm: equivalent to micrograms/gram) unless otherwise noted; pct, percent]

Element	Clarke Index Value	Element	Clarke Index Value
Al	8.36 pct	Nb	20.0
Fe	6.22 pct	Li	18.0
Ca	4.66 pct	Pb	13.0
Mg	2.764 pct	Th	8.10
Na	2.27 pct	Sm	7.02
K	1.84 pct	Dy	5.00
Ti	0.632 pct	Yb	3.10
Mn	1,060	Hf	2.80
Ba	390	Cs	2.60
Sr	384	U	2.30
Zr	162	Eu	2.14
V	136	Sn	2.10
Cl	126	Be	2.00
Cr	122	As	1.80
Rb	78.0	Mo	1.20
Zn	76.0	W	1.20
Ni[1]	75.0	Lu	0.54
Ce	66.4	Sb	0.20
Cu[2]	40.0	Bi[1]	0.17
La	34.6	Cd	0.16
Co	29.0	Ag	0.080
Sc	25.0	Au	0.0040

[1] Bismuth and nickel values from Taylor (1964). Fortescue (1992) lists values of 0.0082 ppm Bi and 99 ppm Ni.

[2] Copper value from Smith (1994). Fortescue (1992) lists a value of 68 ppm Cu.

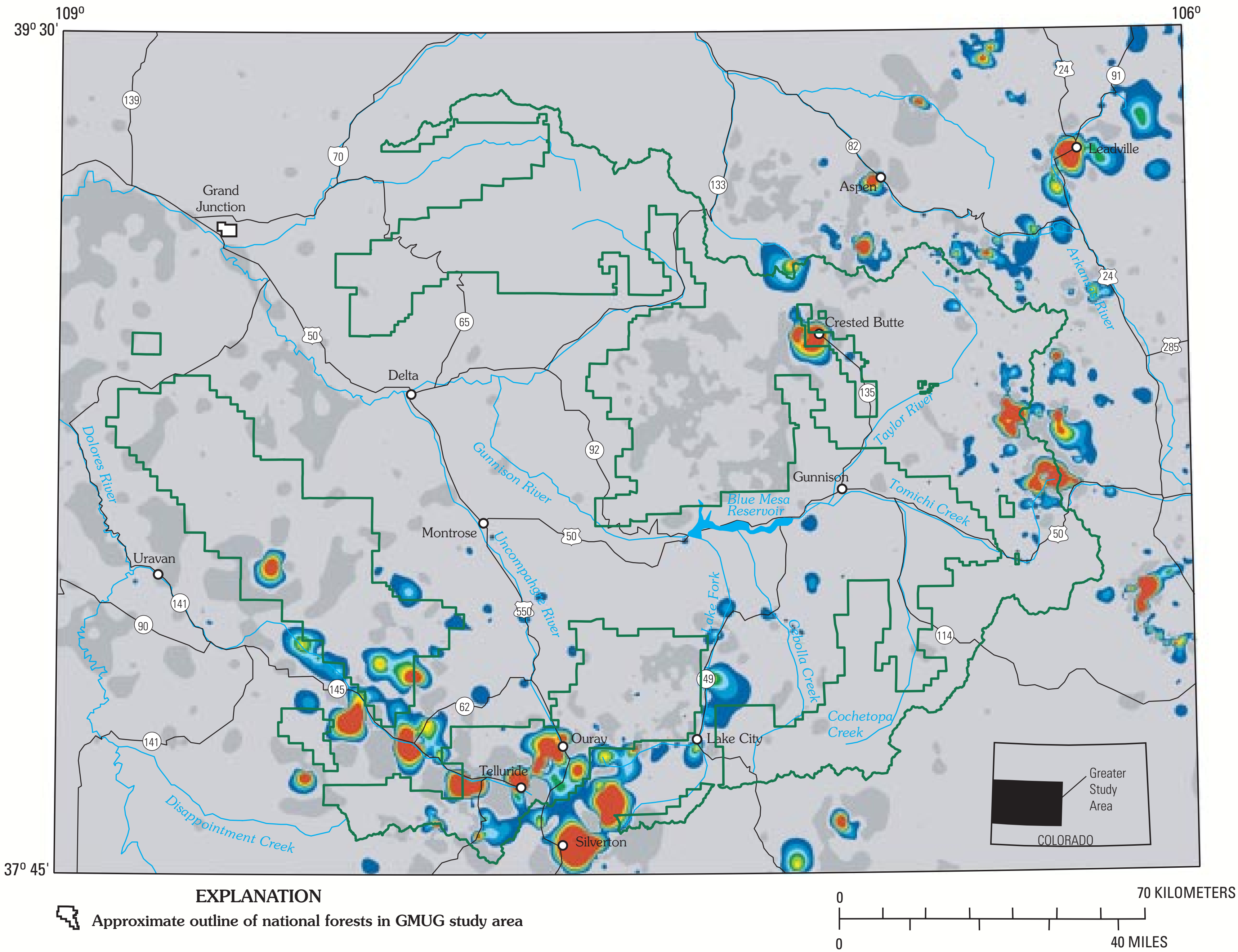
EXPLANATION

SDU	Concentration Range
-0.5	< 12 ppm Cu
0	12–73 ppm Cu
0.5	73–134 ppm Cu
1.0	134–196 ppm Cu
1.5	196–257 ppm Cu
2.0	257–318 ppm Cu
2.5	318–379 ppm Cu
3.0	379–441 ppm Cu
3.5	441–502 ppm Cu
4.0	> 502 ppm Cu

Mean = 42 ppm Cu

Standard Deviation = 122.5

Figure C3 (left and following page). Distribution of copper in sediment samples collected in GMUG greater study area. One Standard Deviation Unit (1.0 SDU) is element concentration range that is approximately one standard deviation above mean concentration range (0 SDU).


109°
106°
39° 30'
37° 45'
Grand Junction
Delta
Montrose
Uravan
Aspen
Leadville
Crested Butte
Gunnison
Ouray
Telluride
Silverton
Lake City
Blue Mesa Reservoir
Gunnison River
Uncompahgre River
Dolores River
Disappointment Creek
Lake Fork
Cebolla Creek
Cochetopa Creek
Tomichi Creek
Taylor River
Arkansas River
139
70
50
65
92
133
82
24
91
135
285
141
90
145
62
550
149
114
Greater Study Area
COLORADO
0
70 KILOMETERS
0
40 MILES
EXPLANATION
Approximate outline of national forests in GMUG study area

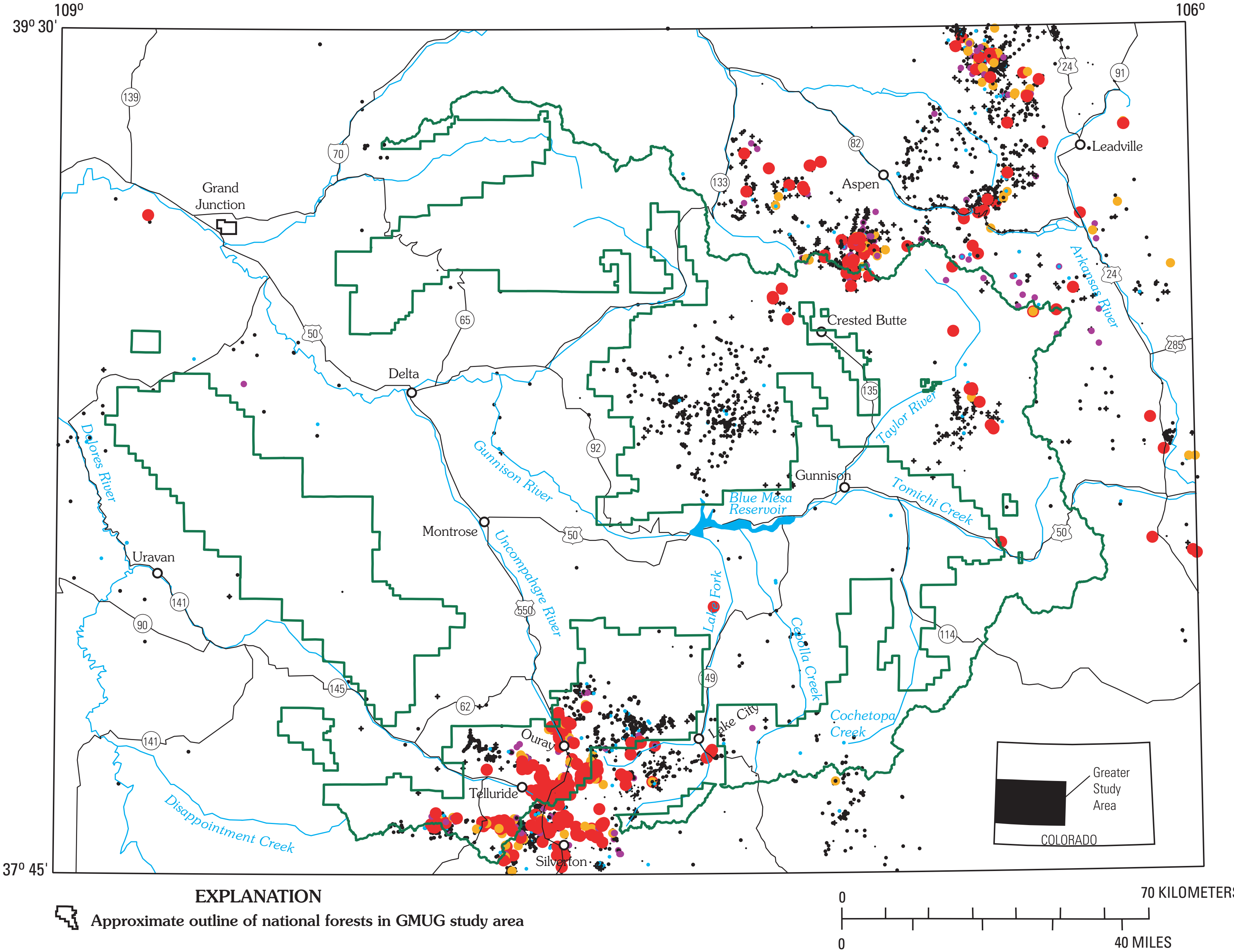


Figure C4 (above and following page). Distribution of copper in rock samples collected in GMUG greater study area. A Clarke Index Value is an estimated crustal abundance concentration for the element and is used as median of background range of concentrations. Clark units are multiples of background range.

EXPLANATION

	Clarke	Concentration Range
·	-	Not analyzed
+	-	Not detected (mult. limits)
•	< 2	< 60 ppm Cu
•	2 – 3	60–140 ppm Cu
•	4 – 10	140–420 ppm Cu
•	11 – 20	420–820 ppm Cu
●	> 20	> 820 ppm Cu

Clarke Index Value = 40 ppm Cu

Summary

The available digital geochemistry data from stream-sediment and rock samples collected within the GMUG greater study area were compiled, modeled, and interpreted. These results were then extensively used in the assessments of various mineral resource deposit types.

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Geophysical Studies

By Viki Bankey, Robert P. Kucks, and Kim Oshetski

Chapter D of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

Edited by Viki Bankey

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Geophysical Studies

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Abstract

Three sets of geophysical data, comprising gravity, aeromagnetic, and radiometric maps, were compiled from previous studies and interpreted for the GMUG greater study area.

Gravity Data

Gravity Map Preparation

The isostatic gravity anomaly map (fig. D1) for this report was produced using edited gravity data from stations collected during the past several decades; the data were extracted for this study from the Defense Mapping Agency gravity database, available from the National Geophysical Data Center, Boulder, Colo. Gravity measurements were obtained at single stations, and contoured values were mathematically interpolated between stations. These data were projected using a Lambert conformal conic projection having a central meridian of longitude 108° W. and a base latitude of 0°. They were gridded at a spacing of 2 km using the minimum curvature algorithm in the MINC computer program by Webring (1981).

Large, broad gravity anomalies caused by regional geologic features can often hide small anomalies that may be geologically significant for mineral assessments. To focus this study on shallower, more local anomalies, an isostatic gravity correction was applied to the Bouguer gravity data. This correction was made by removing from the Bouguer gravity field a model of the gravity expression caused by deficiencies in mass (compensating mass) that support topographic loads. The calculation of the isostatic model used averaged digital topography, a crustal thickness of 30 km, a crustal density of 2.67 g/cm^3, and a density contrast between the crust and upper mantle of 0.35 g/cm^3. The resulting isostatic gravity anomaly map (fig. D1) emphasizes anomalies produced by shallow sources and suppresses longer wavelength anomalies that are related to deep sources caused by isostatic compensation of mountain roots.

Gravity Map Interpretation

Gravity anomalies occur from the juxtaposition of rocks that have measurable density contrasts caused by structural or geologic features such as faults, folds, downwarps, intrusions, basin fill, lithologic contacts, or facies changes. The number and quality of gravity stations limit the accuracy of anomaly definition, especially in mountainous terrain where station spacing is often sparse. As a result, gravity stations may be too widely spaced to define or locate small mineral deposits, especially if density variations caused by a hydrothermal system are not large and the geologic setting is complex. However, on a regional scale, gravity mapping is a useful tool for locating structural breaks, folds, or zones of weakness, and for delineating intrusions. Because many of the regional structures in this area were initiated in Precambrian or Paleozoic times and later reactivated during the Laramide orogeny, gravity mapping can help delineate areas of long-standing crustal weaknesses that may have played a role in mineral formation.

Regional northeast-trending magnetic and gravity highs, lows, and gradients occur within and beyond the greater study area. The northeast-trending grain in a regional aeromagnetic map of Colorado has been interpreted as part of a Proterozoic zone or belt of en echelon shears 200 mi[1] wide that extends from the Grand Canyon to south of the Black Hills (Zietz and others, 1969). Northeast-trending shear zones and faults were recognized by Lovering (1935) and Tweto and Sims (1963) as influencing the location of Laramide intrusives and related ore deposits in the Colorado Mineral Belt.

Warner (1978, 1980) proposed a Middle Proterozoic wrench fault system of the San Andreas type that encompasses a zone about 100 mi wide that covers the entire forest study area. Warner postulated that this zone, which he named the Colorado lineament, can be traced from the Grand Canyon to Lake Superior and probably ceased as an active wrench-fault system about 1,700 m.y. ago. Regardless of their origin—tilted bedding planes, shear zones, or wrench-fault systems—these northeast-trending anomalous areas are of interest in mineral formation because they are probably zones of crustal weakness that may have provided conduits for later intrusions and possible mineralizing fluids.

[1]Measurement units are given in the system in which originally reported. To convert miles to kilometers, multiply by 1.61. To convert feet to meters, multiply by 0.3048.

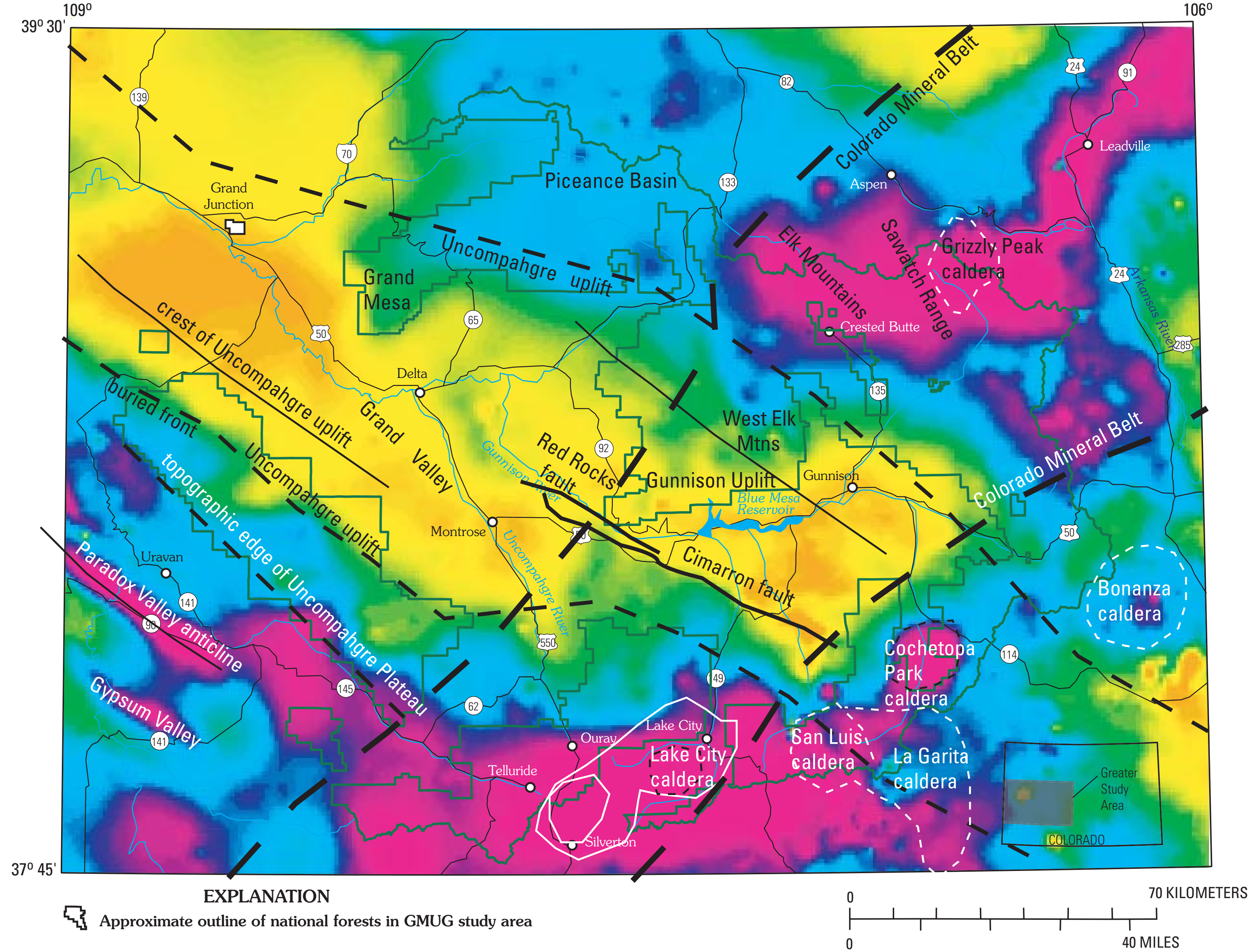

Figure D1. Isostatic gravity anomaly map of GMUG greater study area. Warm colors, high gravity values; cool colors, low gravity values.

Density values for rocks in the greater study area were compiled from reports covering this and adjacent areas, including Wallace and others (1988), Case and others (1992), and Toth and others (1993). The latter report summarizes eight sets of physical properties in the vicinity. For purposes of interpreting isostatic gravity anomalies in the greater study area, the following generalizations are made from the physical property data:

Proterozoic basement rocks in this area are heterogeneous in composition and in their physical properties. Proterozoic metamorphic and mafic igneous rocks, especially the amphibolites and gneisses, are the densest rocks in the area, varying from 2.70 to 2.89 g/cm^3. Proterozoic granitic and felsic rocks vary from average density (near 2.67 g/cm^3) to slightly less dense (2.64 g/cm^3) than average. Proterozoic rocks as a group are denser than Tertiary intrusive or volcanic rocks, but their densities may fall within the range of values that also characterize some sedimentary rocks.

Paleozoic sedimentary rocks vary in density: porous sandstones and siltstones have lower densities than average (2.40–2.60 g/cm^3); limestones and dolomites have high densities (as much as 2.85 g/cm^3). Many Mesozoic and Tertiary sedimentary rocks are commonly slightly less dense (2.30–2.50 g/cm^3) than Paleozoic sedimentary rocks.

The southernmost part of the study area lies on the north edge of an extensive 30–50 mGal (milligal) gravity low, called the Colorado Mineral Belt gravity low (Case, 1965), that trends southwest from the Front Range to the San Juan Mountains and cuts across many Laramide features. See the gravity map of Colorado (Abrams and Knepper, 1994) for a clear view of this gravity low. The Colorado Mineral Belt gravity low is attributed to a low-density, silicic, batholithic mass of Late Cretaceous to Tertiary age that is postulated to underlie a large part of the belt (Crawford, 1924; Case, 1967). An intracrustal origin for the gravity low, having an apex within a few thousand feet of the surface, a depth extending 40,000 ft below sea level, and a width averaging 15–20 mi, can be demonstrated by gravity models (Case, 1965; Tweto and Case, 1972; Isaacson and Smithson, 1976).

Figure D1 shows gravity highs in warm colors (yellows, oranges, and reds), and low values in blues, magentas, and purples. Regionally, gravity lows are associated with the high mountain areas of the West Elk Mountains, Elk Mountains, and the Sawatch Range in the northeast and the San Juan Mountains in the south. Gravity highs trend northwest-southeast across valleys in the area of figure D1 and are truncated by faults in many places. Although this pattern is unlike the more common pattern of gravity highs over mountains (cored by Proterozoic rocks) and gravity lows caused by low-density valley fill that are found elsewhere in Colorado (Abrams and Knepper, 1994), it is predictable from the density contrasts of the rocks in this area.

The low gravity values in the San Juan volcanic field are caused by thick, low-density pyroclastic rocks probably underlain by a large, concealed batholith genetically related to caldera formation (Plouff and Pakiser, 1972). Deep lows correspond to areas of mapped calderas such as the Lake City, San Luis, La Garita, and Cochetopa Park calderas. Additional geophysical interpretations of the area south of that of figure D1 (the San Juan National Forest) are given in McCafferty and others (1997).

The southwestern part of figure D1's area is characterized by narrow, linear gravity lows that mark salt-cored (very low density) anticlines in the Paradox Basin. These gravity anomalies are distinctive indicators for these features. Anticlinal axes were inferred from these gravity lows and were added to mapped anticlinal axes to use as a criterion in the assessment of sediment-hosted copper.

A northwest-southeast-trending gravity gradient correlates with the inferred southwestern boundary of the late Paleozoic ancestral Uncompahgre uplift (Hansen, 1965) and primarily reflects the 16,000–20,000 ft basement structural relief between the Paradox Basin and the crest of the uplift. This gravity gradient is not spatially associated with the topographic edge of the present-day Uncompahgre Plateau, although it correlates spatially with the Ridgeway fault. Case and Joesting (1972) have modeled geophysical anomalies across this boundary and interpreted the offset between the topographic edge of the Uncompahgre Plateau and the gravity gradient to be the result of a change in density within the heterogeneous Precambrian basement. They showed that low-density quartz monzonite and granite predominate in the southwest, whereas higher density biotite gneiss, gneissic granodiorite, and amphibolite form the core of the Uncompahgre uplift to the northeast and are shallowly covered in Grand Valley between Grand Junction and Montrose. The gravity gradient is also steepened by the wedging-out of about 4,000 ft thickness of low-density evaporites against the southwestern margin of the uplift. Case and others (1992) interpreted that the maximum gravity values indicated just west of Grand Junction mark the crest of the ancestral uplift.

A gravity gradient follows the Precambrian Cimarron and Red Rocks faults east of Montrose. Gravity values from northeast of this fault to Gunnison are high, caused by shallowly buried or exposed, high-density Proterozoic basement rocks (mafic or biotite gneisses and granites) of the Gunnison uplift (Tweto, 1980). Gravity values decrease to the north in the West Elk volcanic field, where quartz monzonite laccoliths intrude sedimentary rocks, and low-density ash-flow tuffs and volcanic gravels predominate. Gravity values become even lower to the northeast, in the topographically high Elk Mountains and Sawatch Range. These gravity lows are the combined result of the postulated batholith associated with the Colorado Mineral Belt and shallower low-density Tertiary intrusive rocks, some of which are exposed in places of deepest gravity lows.

Gravity values are moderately low in the Piceance basin and Grand Mesa areas where sedimentary rocks, some of which contain low-density evaporitic rocks, predominate.

The gravity gradient between low-density rocks of western Grand Mesa and high-density Proterozoic rocks of the Uncompahgre uplift in the valley to the west follows topography. This suggests a structural weakness that affected both features.

Magnetic Data

Magnetic Map Preparation

The aeromagnetic data (fig. D2) are a subset of the aeromagnetic compilation for the State of Colorado. The survey specifications, data quality, and processing methods are described by Oshetski and Kucks (2000). The individual grids were continued to 305 m (meters) above ground and merged into a single total field grid with a 1,000 m grid interval.

All magnetic bodies act as secondary magnets in the Earth's magnetic field and may produce positive and negative anomaly pairs (dipole anomalies). In Colorado, polarity effects typically show up as local lows along the north side of a magnetic high. In some areas, the polarity lows are too diffuse to be seen or are obscured by the fields of other nearby magnetic bodies. Polarity lows may complicate the interpretation of primary magnetic anomalies. To reduce the effects of polarity lows, the total field grid was reduced to the pole. The goal of reduction to the pole is to produce a magnetic map as though the area had been surveyed at the Earth's magnetic north pole in order to position the anomalies closer to their sources.

Aeromagnetic Map Interpretation

Aeromagnetic anomalies are caused by rocks that contain significant amounts of magnetic minerals (magnetite being the most common); these anomalies reflect variations in the amount and type of magnetic material and the shape and depth of the body of rock. In general, igneous rocks and some metamorphic rocks contain enough magnetic minerals to generate magnetic anomalies, whereas sedimentary and metasedimentary rocks are commonly weakly magnetic. Aeromagnetic anomaly maps are important tools in mapping surficial and buried igneous rocks. The features and patterns of aeromagnetic anomalies can also be used to delineate details of subsurface geology, including the locations of buried faults and the thickness of surficial sedimentary rocks.

A complicating factor in magnetic anomaly interpretation is the remanent magnetization direction of the rock, which may differ from the present-day magnetic field direction. If the remanent magnetization is sufficiently strong and in a different direction, the anomaly will be changed in amplitude, or shifted away from the source, or both. High-amplitude magnetic lows may indicate igneous rocks that acquired their magnetic properties during a period of magnetic field reversal; such magnetic lows are associated with some outcrops of Tertiary basaltic rocks in the San Juan volcanic field, near Telluride, Lake City, Ouray, and Silverton (south-central part of area of fig. D2).

Aeromagnetic anomaly maps have some limitations in their use to locate mineral deposits. Mineral deposits without associated magnetite or pyrrhotite are not expected to create magnetic highs. Some shallow deposits associated with magnetic intrusions may be severed from that source by subsequent faulting. Other deposits may have lost their early-stage magnetite during subsequent hydrothermal alteration. Tertiary stocks that intrude magnetic Proterozoic crystalline rocks could create small magnetic lows or highs over the stocks or show no anomalies at all, depending on the relative magnetizations of both stock and surrounding rocks.

Proterozoic rocks in this area have a wide range of measured magnetic susceptibilities: the Proterozoic granitoid and gabbroic rocks are generally the most magnetic (Moss and Abrams, 1985). Proterozoic metamorphic rocks are generally moderately magnetic, although Proterozoic metasedimentary rocks may be relatively nonmagnetic (Daniels, 1987).

Heterogeneous magnetite content in Proterozoic rocks causes many of the magnetic anomalies illustrated in figure D2, especially in the western part of the area, as noted by Case and Joesting (1972). For example, a linear string of positive magnetic anomalies correlates with exposed Precambrian granitic rocks along the southwestern margin of the Uncompahgre Plateau. Magnetic anomalies also arise from variation in depth to basement rocks, owing to uplifts and troughs of the buried basement surface. These anomalies are not significant for mineral assessments, except where they may indicate structures such as faults that were active in Precambrian time and reactivated since, and that may provide conduits for mineralizing fluids. However, gravity data provide a clearer picture of these structures, and gravity data were used to delineate such features in the assessment models (this volume).

Some Tertiary plutons are magnetic and produce conspicuous positive anomalies (Moss and Abrams, 1985; Campbell, 1985; Daniels, 1987), but where altered, they may produce relative magnetic lows or plateaus in the regional magnetic field. Other Tertiary intrusions have low susceptibilities and generate no magnetic highs; they may even produce magnetic lows where they intrude more magnetic Proterozoic rocks (Moss and Abrams, 1985; Campbell and Wallace, 1986).

Each igneous and metamorphic rock type of the GMUG greater study area (given in Day and others, 1999, with descriptions and detailed location information) was spatially compared with the magnetic anomaly map to determine which units had identifiable magnetic signatures (usually appearing as corresponding positive anomalies of comparable amplitude). We identified six igneous units with strong magnetic signatures. For example, middle Tertiary intrusive rocks (Tmi) commonly produce positive, high-amplitude anomalies in the greater study area. We were then able to infer additional shallowly buried Tmi units from the aeromagnetic map by visually correlating exposed Tmi with corresponding magnetic highs. We attributed nearby magnetic highs of similar size and amplitude to unexposed Tmi rocks and digitized the

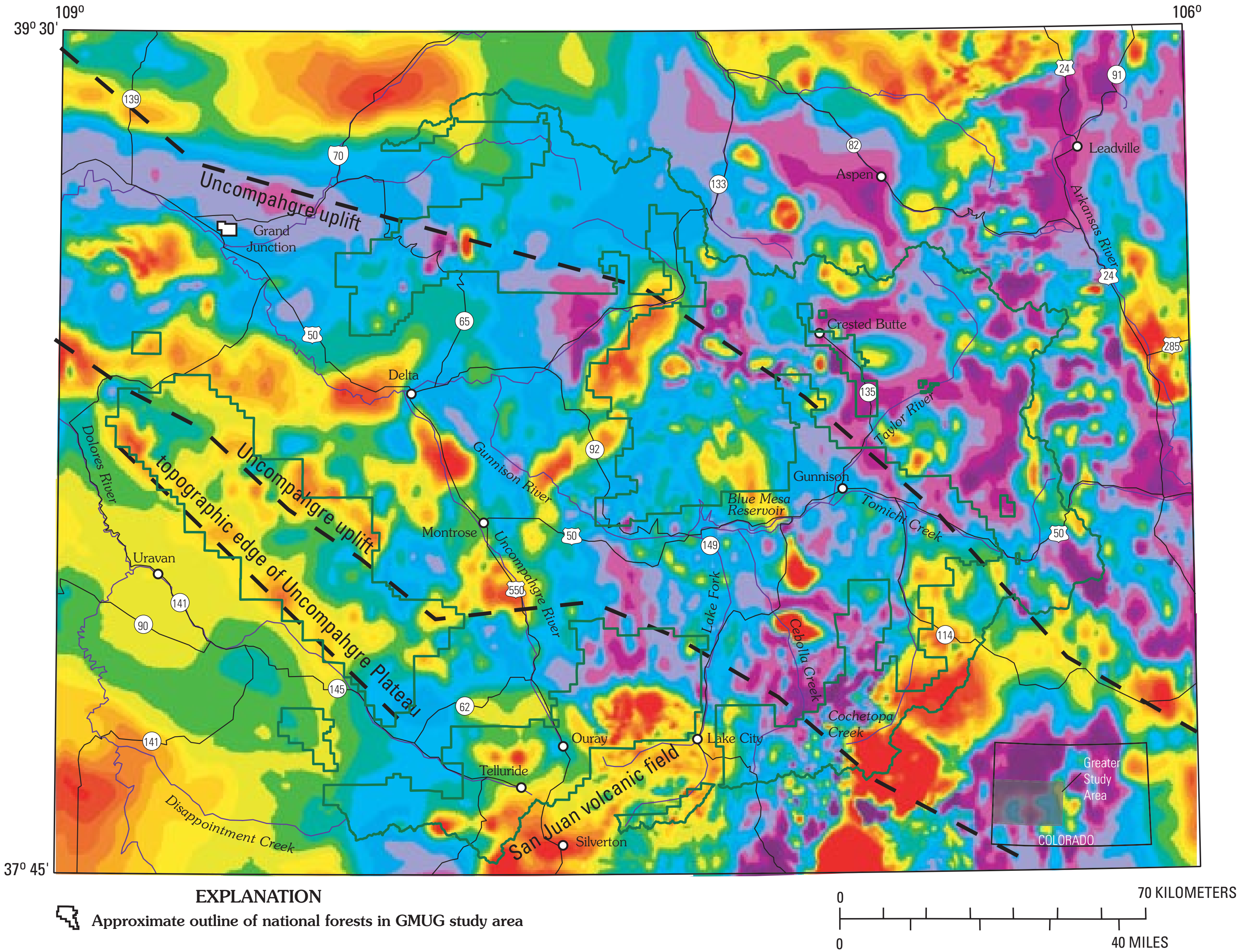

Figure D2. Aeromagnetic anomaly map of GMUG greater study area. Warm colors, high magnetic intensity; cool colors, low magnetic intensity.

inferred locations. Similar interpretive products were prepared for rock units Tbb (bimodal basalt), TKi (Laramide intrusive rocks), Tiql (Tertiary inter-ash quartz latitic lavas), Xg (1,700 m.y. age group granitic rocks), and Yg (1,400 m.y. age group granitic rocks). The map of inferred magnetic Tmi rocks was used in modeling the potential for molybdenum (Chapter G), polymetallic veins (Chapter J), and polymetallic replacement deposits (Chapter K). The maps for Tbb, Tki, and Tiql were also used in modeling polymetallic veins (Chapter J). Figure D3 shows the outlines of the inferred Tertiary intrusions used for modeling.

Aeroradiometric Data

Aeroradiometric Map Preparation

Aeroradioactivity is measured from low-flying aircraft. The instruments measure gamma rays emitted by isotopes of potassium (K), uranium (U), and thorium (Th) present in surficial rock and soil to about 12 in. depth. Aerial gamma-ray radioactivity data used in this report are from spectrometer surveys flown during the U.S. Department of Energy National Uranium Resource Evaluation (NURE) program (≈1974–1983). NURE surveys that include parts of the forest are those for the Leadville (Geometrics, 1979), Montrose (Geometrics, 1979), Moab (Geometrics, 1979), Cortez (Aero Service Division, 1979a), Durango (Aero Service Division, 1979b), and Grand Junction (Geodata Int., 1981) 1°×2° quadrangles. Data for these quadrangles were merged for the conterminous United States (Phillips and others, 1993; Duval and others, 1995), and subsets covering the greater study area were created for this report. The uranium data are shown in figure D4. Flightline spacing for these quadrangles is 3 mi east-west and 12 mi north-south.

The near-surface distribution of potassium, uranium, and thorium generally reflects bedrock lithology and modifications due to weathering, erosion, transportation, ground-water movement, and hydrothermal alteration. Common rock types readily discriminated by aeroradioactivity measurements include (1) more radioactive (greater concentrations of radioactive minerals) felsic igneous rocks, arkosic sandstones, and most shales and (2) less radioactive (lesser concentrations) mafic igneous rocks, (clean) quartzose sandstones, and most limestones. Specific rock formations were described in the original NURE survey reports, listed in the previous paragraph, as having higher uranium values; these are summarized in table D1.

Aeroradiometric Map Interpretation

The near-surface distribution patterns of potassium, uranium, and thorium as displayed by aeroradioactivity maps of the greater study area are similar, resulting from common rock-type associations for these elements. Mancos Shale, for example, shows higher radioelement values where it is exposed, especially in the western part of the greater study area. All three data sets have a distinct northwest-trending gradient that separates high radioelement values to the northeast from lower values to the southwest (fig. D4). The boundary corresponds to the Gunnison River in Grand Valley between Grand Junction and Delta and reflects the high radioelement values found in Mancos Shale exposures west of the river. Northeast of Grand Valley, high radioelement values are associated with Precambrian and Tertiary igneous rocks, although a spatial, formation-by-formation evaluation did not uncover a direct correspondence that could be used to map certain intrusive rocks as the magnetic data could.

The grid interval for the uranium anomaly map shown in figure D4 is 2 km. At this grid interval, these data cannot accurately display individual uranium spikes that are present in the original flightline data. Even in the Uravan mineral belt, a well-known uranium mineralized area, the data are not diagnostic. The original NURE reports, however, provide a detailed evaluation of individual uranium anomalies.

For the uranium-vanadium deposit model (Chapter H), a derivative calculation using thorium proved more valuable in determining favorable terrane than did the uranium data alone. Thorium generally has a more consistent distribution pattern than potassium or uranium, because thorium is the least mobile of these elements. We selected areas where the uranium:thorium ratio is greater than 1 standard deviation above its mean and where thorium is less than 1 standard deviation below its mean (Aero Service Division, 1979a, b). The results clearly delineate the Uravan mineralized area, among others, and are shown in Spanski and Bankey, this volume, Chapter H, figure H2.

Uranium mines and mineralized areas are further discussed in the chapter on sandstone-hosted uranium deposits (this volume, Chapter H).

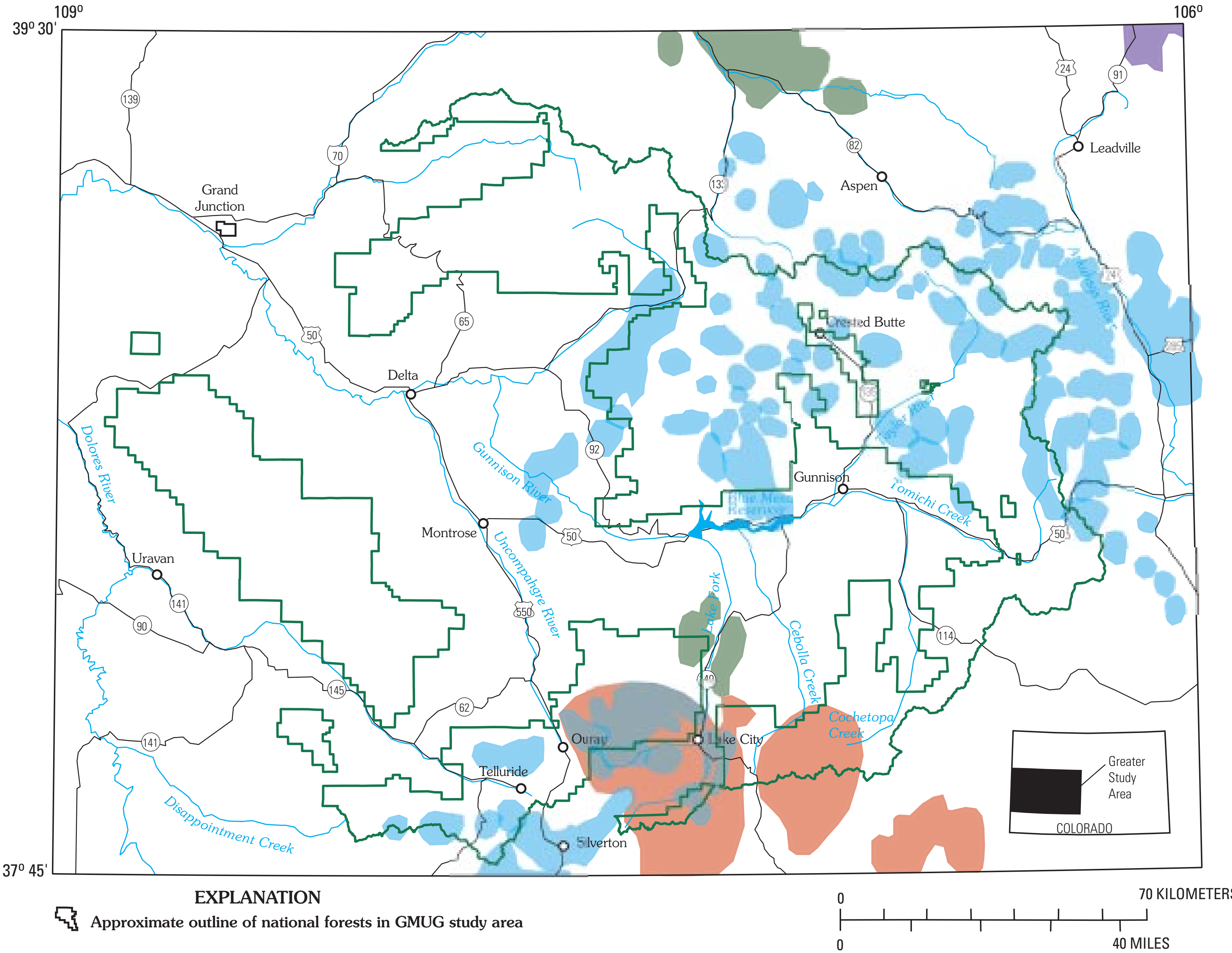

Figure D3. Outline of Tertiary plutons inferred from aeromagnetic data. Red, Tiql; green, Tbb; light blue or gray, Tmi; dark blue, Tki.

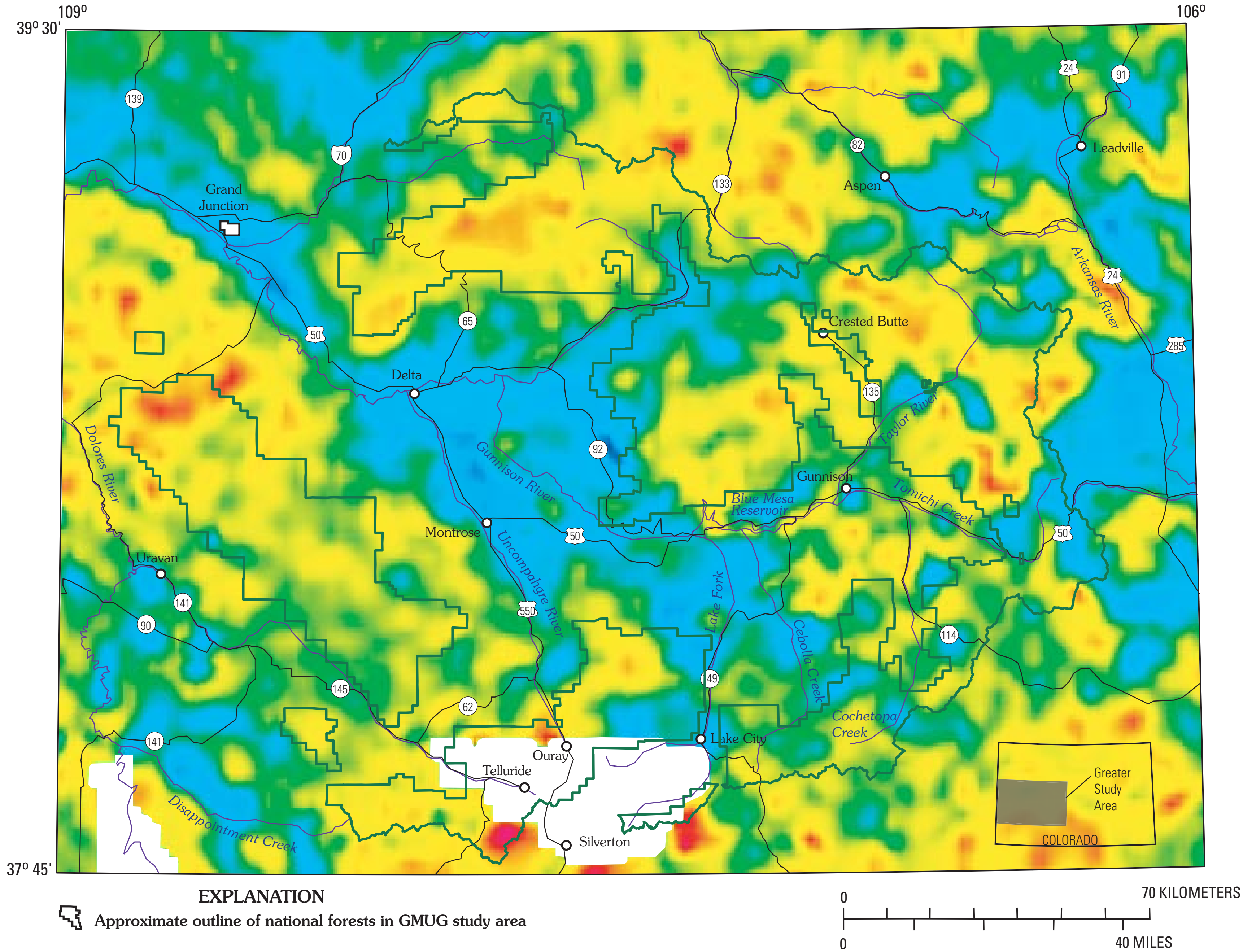

Figure D4. Uranium values of GMUG greater study area. Cool colors, lower values; warm colors, higher values of uranium. Areas in white in southern part of map area have no data.

Table D1. Summary of stratigraphic units containing anomalous uranium as described in NURE reports.

[See Day and others (1999) for condensed information on these units]

Age	Stratigraphic unit	Unit symbol as used in NURE reports	Uranium content
Quaternary (Q)	Alluvium………………	Qa, Qg	Especially overlying Tertiary Uinta Formation.
Tertiary (T)	Intrusives, volcanics such as Sunshine Peak Tuff, Huerto Fm.	Ti, Tst, Thu, Tv, Tki	
	Uinta Formation………	Tu	Known host for uranium.
	Green River Formation..	Tg, Tgp, Tgl	Known host for uranium.
Cretaceous (K)	Mesaverde Group……...	Kmv, Kmvl, Kmvu, Kh	Subeconomic in Colorado, but produces in Wyoming.
	Mancos Shale…………	Km, Kmgs, Kmu, Kml, Kfd	Areally large but subeconomic uranium deposits.
	Dakota Sandstone……	Kd, KJdm, Kdb, KJdj, KJdw, KJde	Subeconomic uranium deposits.
	Burro Canyon Formation	Kbc, Kdb	Subeconomic uranium deposits.
Jurassic (J)	Morrison Formation…..	Jm, Jms, Jmb, Jmj, Jmw, Jmwe, Jme, KJdm, KJdj, KJdw, KJde	Major uranium deposits, especially in the Salt Wash, Brushy Basin, and Recapture Members.
	Summerville Formation	Jse	Subeconomic uranium deposits.
	Entrada Sandstone……	Je, Jwe, Jme, KJde, Jmwe, Jse, J₮mc, J₮md	Subeconomic uranium deposits.
	Wanakah Sandstone….	Jwe, Jmw, Jmwe, KJdw, J₮mc, J₮md	Large, low-grade deposits, source rock for Rifle mines.
	Navajo Sandstone……	J₮n	Subeconomic uranium deposits.
	Kayenta Formation….	₮k, ₮kw, ₮kwc	Subeconomic uranium deposits.
Triassic (₮)	Wingate Sandstone….	₮w, ₮kw, ₮wc, ₮kwc	Subeconomic uranium deposits.
	Chinle Formation……	₮c, ₮wc, ₮kwc, J₮mc, ₮Pcs	Major uranium deposits, especially in the conglomerate members and Moss Back Member.
	Moenkopi Formation..	₮m	Production noted.
Permian (P)	Cutler Formation…….	Pc, ₮Pdc	Subeconomic uranium deposits, especially in arkosic member.
Permian and Pennsylvanian (P₱)	Maroon Formation…..	P₱m, P₱wm	Subeconomic uranium deposits.
	Rico Formation………	P₱rm	Subeconomic uranium deposits.
Pennsylvanian (₱)	Belden Formation…….	₱b, ₱mb, ₱mbe	Host rock for deposits at Marshall Pass.
	Hermosa Formation…..	₱h, ₱hu, ₱hp, P₱rm	Especially associated with potassium salts.
Ordovician	Harding Sandstone……	MOr	Host rock for Little Indian No. 36 mine.
Precambrian	Undivided granite, especially fault breccia, shear zones, and fracture-controlled subeconomic uranium deposits.	Yg	Host rock for structurally controlled deposits in Cochetopa Creek, Powderhorn district, and Frying Pan claims.

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Distribution of Mines and Mineralized Areas

By Anna B. Wilson and Gregory T. Spanski

Chapter E of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

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Distribution of Mines and Mineralized Areas

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Abstract

In order to assess the mineral resource potential of the GMUG study area, we outlined 38 mineralized areas. A mineralized area encloses a geographic area that is defined by the presence of mines, prospects, and (or) mineralized occurrences that belong to a single deposit type or to a group of genetically related deposit types in a distinct geologic setting. A mineralized area may include an entire district or portions of several mining districts.

Introduction

The term "mining district" as used in Colorado is an artifact of the State's days as a territory prior to statehood in 1876. During this period, mining districts were created by the miners in a mining camp acting as an association with a charter and by-laws. Such an association provided a form of self-rule intended to bring order to mining-related activity. Boundaries were ill defined and subject to change at the discretion of the association. The discovery of a new deposit could result in the creation of a new district with a new charter or, if the discovery were near an existing district and the claimant agreed to honor the charter, inclusion within the existing district. With statehood and the establishment of formal county governments in Colorado, the need for self-rule that the mining district provided was no longer required. Claims were recorded with the county, and laws were set by the State. The mining district nomenclature, however, endured. Claimants continued to cite district names in claim location descriptions, a practice that continues to this day. However, Henderson (1926, p. 62) noted that "many of the names used represent nothing more than the guess or whim of the locator, and many of the commonly used names of local districts are carried miles away and across county lines." Using the mining district as a guide to location or as an indicator of the types of deposits being developed and commodities produced became unreliable.

To deal with these geographic ambiguities, we have introduced the concept of the mineralized area. A mineralized area encloses a geographic area that is defined by the presence of mines, prospects, or mineralized occurrences that belong to a single deposit type or a group of genetically related deposit types. A mineralized area may include an entire district or portions of several mining districts. Where practical, a mineralized area is given the name of one of the more prominent mining districts or mining settlements that is within its bounds. Where this is not feasible, a new name is assigned that is geographically descriptive, or the name of a productive or well-known mine located in the area is used. We have not attempted to apply mineralized areas to the placer mining districts as defined by Parker (1961) and have not included placer districts in the following discussion of mineralized areas.

Many of the data used to outline the mineralized areas have been extracted from site records for mines, prospects, and occurrences contained in U.S. Geological Survey (USGS) and U.S. Bureau of Mines (USBM) data files. For this project, A.B. Wilson, M.J. Crane, and M.D. Woodard (U.S. Geological Survey) verified as many of these data records as possible and added many more sites from information extracted from references and maps during the verification process (Wilson and others, 2000). Locations of approximately 1,300 sites are believed to be accurate to within about ½ mi of their actual ground position. In addition, about 1,000 sites could not be verified from references but could be generally located using data (such as Township and Range or descriptive information) in the database records: these sites are believed to be accurate to within about 1 mi. About 200 of the sites in the data files could not be plotted owing to insufficient location data.

Using the digital compilation of the published 1:250,000 geologic maps by Day and others (1999) as a base, A.B. Wilson and G.T. Spanski delineated 40 mineralized areas in the GMUG restricted study area (fig. E1, table E1) utilizing data about individual mineral occurrences and regional information on bedrock geology, geologic setting, geochemistry, and major structural features. Brief descriptions for each of the mineralized areas follow, arranged in a generally clockwise direction with respect to figure E1.

Mineralized Areas

The following is a brief description of the mineralized areas in the GMUG restricted study area, Colorado (fig. E1). This description includes a review of the historical names of the mining districts, mine names, deposit types, general geologic setting, and available production information. This background is vital for understanding the metallogeny of the region and also provides a solid foundation for studying the effects of

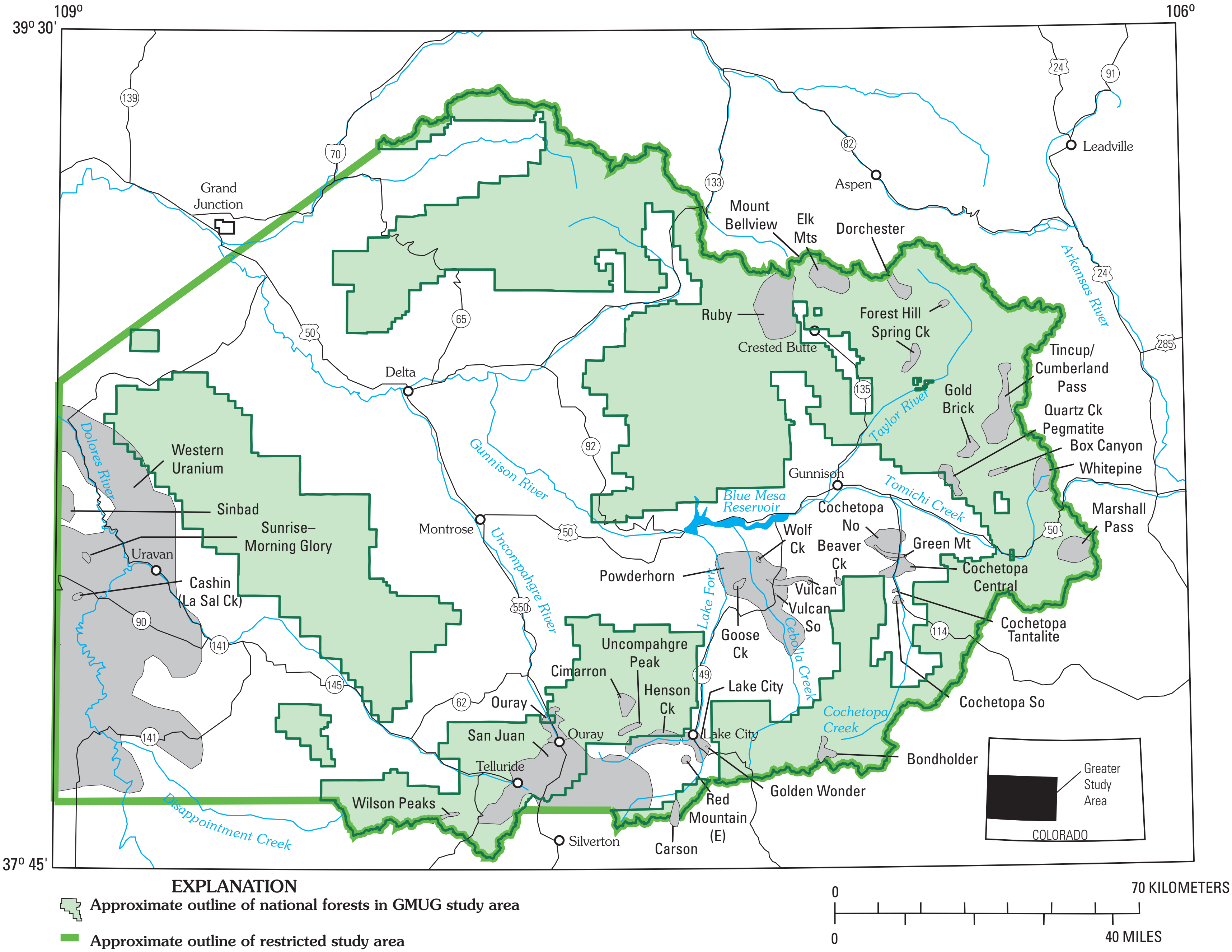

Figure E1. Metallic mineralized areas (shaded areas) shown within GMUG greater study area.

Table E1. Metallic mineralized areas and deposit types in GMUG forests and Uravan area.

Area name	Deposit type
Beaver Creek	Kuroko massive sulfide
Bondholder	Polymetallic vein
Box Canyon	Low-sulfide gold
Carson	Polymetallic vein
Cashin (La Sal Creek)	Redbed copper
Cimarron	Polymetallic vein
Cochetopa central	Vein U
Cochetopa north	Low-sulfide gold
Cochetopa south	Vein U
Cochetopa tantalite	Pegmatite
Dorchester	Polymetallic vein and replacement
Elk Mountains	Polymetallic vein and replacement
Forest Hill/Italian Mountain	unknown
Gold Brick	Polymetallic vein
Golden Wonder	Hot spring
Goose Creek	Low-sulfide gold
Green Mountain	Kuroko massive sulfide
Henson Creek	Polymetallic vein
Lake City	23 m.y. barite precious metal
Marshall Pass	Vein U
Mt. Bellview	Cu-Mo porphyry
Ouray	Polymetallic vein and replacement
Powderhorn	Th veins
Quartz Creek Pegmatite	Pegmatite
Red Mountain (east)	Cu-Mo porphyry
Ruby	Polymetallic vein
San Juan	Polymetallic vein and replacement
Sinbad	Redbed copper
Spring Creek	Polymetallic replacement
Sunrise/Morning Glory	Polymetallic veins and replacement
Tincup/Cumberland Pass	Polymetallic veins and replacement
Uncompahgre Peak	Vein U
Vulcan	Kuroko massive sulfide
Vulcan south	Kuroko massive sulfide
Western Uranium	Uranium
Whitepine	Polymetallic vein and replacement
Wilson Peaks	Polymetallic vein
Wolf Creek	Low-sulfide gold

past mining on the environment. Additional descriptions and references can be found in Wilson and others (2000).

Ruby

The Ruby area is nearly synonymous with the Irwin, Ruby, Mount Emmons, and Redwell Basin mining districts. It is in the Oh-Be-Joyful (Gaskill and others, 1967), Mt. Axtell (Gaskill and others, 1987), and Marcellina Mountain (Gaskill and Godwin, 1966) quadrangles. This area hosts polymetallic veins and porphyry Climax-type molybdenum deposits. Well-known mines in the area are the Daisey, Keystone, and Standard (Micawber). This area also includes the well-documented but never mined Mount Emmons molybdenum deposit.

In the Ruby area, Oligocene felsic sills, dikes, and stocks intrude Cretaceous to Tertiary sandstones and shales.

Especially in the southern part of the area, brilliant, red-orange-yellow pyritic altered rock is adjacent to intrusions (Red Lady Basin, Redwell Basin).

Silver mining in the Irwin part of the district began in 1874 when it was "still part of the Ute Indian Reservation and effectively ended by 1890. The Ruby Chief and Bullion King mines, followed by the Forest Queen and Ruby King mines were the district's early principal producers" (Ellis, 1983, p. 4). The first two mines were obliterated by snowslides in 1882 and 1884, respectively (Ellis, 1983, p. 4). Only the Forest Queen continued to operate intermittently, "reaching $1 million in production by 1915" (Socolow, 1955, p. 52–53).

Base-metal and silver ores were mined intermittently from fissure veins on the flanks of Mount Emmons. The largest producers were the Daisey, Keystone, and Standard (Micawber) mines. Two major molybdenum deposits were discovered in the 1970's in the Mount Emmons-Redwell Basin areas (Thomas and Galey, 1982). Neither has been developed.

Mount Bellview

The Mount Bellview area, in the southeastern part of the Snowmass Mountain quadrangle (Mutschler, 1970), surrounds a zoned granodiorite to quartz monzonite intrusive complex. The intrusions are hydrothermally altered. A 1,200-m diameter hornfels aureole in Mancos Shale host rock surrounds the intrusive complex, and local quartz-molybdenite veinlets are also present (Lynch and others, 1985). The only mine in the area, the Silver Spruce, consists of three adits on a vein along the intrusion-Mancos Shale contact. The mine produced a small amount of silver and lead ore in 1933–1934, and molybdenum is present in most samples (Weisner and Bieniewski, 1984). Although probably not of sufficient grade and tonnage to rank as a "deposit," this area is shown as a mineralized area because of previous exploration interest and indications such as surface alteration and geochemistry which suggest that a mineralizing event took place.

Elk Mountains

The Elk Mountains mineralized area, about 20 mi north of Crested Butte, includes the historic Elk Mountain district and the town of Gothic. It is primarily on the Gothic quadrangle (Gaskill and others, 1991) and extends into the southern part of the Maroon Bells quadrangle (Bryant, 1969). Other workers (for example, Plumlee and others, 1995; Streufert and Cappa, 1994) have depicted the Elk Mountain mining district as three distinct areas in close proximity. We have chosen to consolidate the entire area into one mineralized area containing several small polymetallic vein and replacement and skarn deposits. The best known of these deposits is the Sylvanite mine. Mineralized veins in the area contain sphalerite, galena, and chalcopyrite. Gold and silver, in unknown forms, were also present. "Mineralization is widespread but the veins are small and irregular" (Vanderwilt, 1947, p. 101). The area is in Pennsylvanian to Upper Cretaceous sedimentary rocks intruded by the Oligocene White Rock pluton (Gaskill and others, 1991; Bryant, 1969).

Dorchester

The Dorchester mineralized area is in the Pearl Pass and Italian Creek 7½-minute quadrangles. It includes most of the historic Dorchester mining district (including the Taylor River and Taylor Park areas), about which extremely little is known geologically. The host rocks are Paleozoic sedimentary rocks overlying 1,700 Ma granitic rocks that were intruded by 33.9 Ma tonalite of the Italian Mountain Intrusive Suite (Fridrich and others, 1998). Only a few small mines, the Hope, Bull Domingo, Clara, Star, and Ender, are mentioned in the literature (Garrett, 1950; Harrer and Tesch, 1959; Prather, 1961; Slebir, 1957). These mines are presumed to be polymetallic vein and replacement deposits.

Forest Hill

The Forest Hill area includes a small part of the historic, but poorly defined Taylor Park mining district (Vanderwilt, 1947, p. 107) in the Italian Creek 7½-minute quadrangle. The only known mines are the Forest Hill and Paymaster, which are both polymetallic replacement and polymetallic vein deposits (Wilson and others, 2000). The Paymaster is at the southern margin of the Grizzly Peak caldera at the fault contact of the middle rhyolite subunit of the Oligocene Grizzly Peak Tuff inside the caldera with Early Proterozoic metasedimentary gneiss intruding the granite of Henry Mountain surrounding the caldera (see Fridrich and others, 1998). The Forest Hill mine is in these same Early Proterozoic rocks outside the caldera margin. Granite of Henry Mountain and the rhyolite are both iron-stained and cut by quartz-pyrite veinlets. A small Eocene felsic dike of Winfield Peak and Middle Mountain is present in the granite between the two mines (Fridrich and others, 1998).

From 1932 to 1945, as many as three lode mines were operating in the Taylor Park district (Vanderwilt, 1947). The Forest Hill and Paymaster are assumed to be two of these. However, because the reported production figures were combined with the Tincup district, only 19 oz gold, 14,726 oz silver, 2,500 lb copper, 454,900 lb lead, and 24,400 lb zinc is directly attributable to Taylor Park during this time frame (Vanderwilt, 1947, p. 108).

Spring Creek

Spring Creek is a small area in the Matchless Mountain 7½-minute quadrangle that includes polymetallic replacement and replacement manganese deposits at the Doctor and Barium Maggie mines. Paleozoic (from Cambrian to Pennsylvanian) sedimentary rocks form a narrow south-trending "peninsula" in the mineralized area adjacent to 1,700 Ma granitic rocks on the east and west (Tweto and others, 1976; Day and others, 1999). North-trending faults are mapped in the peninsula. Oligocene intrusive rocks are exposed to the northeast and may also be buried in the vicinity of the mine workings.

The only known significant mine in the district is the Doctor mine, which produced an unknown amount of "silver-bearing lead carbonate in 1880 and 1890 and at least 17,000 tons zinc carbonate in 1917 and 1918" (Vanderwilt, 1947, p. 106). "The last recorded production was 641 tons of sorted zinc carbonate from the dump in 1937 and 1938 that yielded 203,000 pounds of zinc and 25,900 pounds of lead" (Vanderwilt, 1947, p. 107).

Tincup/Cumberland Pass

The Tincup/Cumberland Pass mineralized area includes most of the historic Tincup and Quartz Creek mining districts on the north and south flanks of Cumberland Pass on the Tincup, Cumberland Pass, and Fairview Peak 7½-minute quadrangles. 1,700 Ma granitic rocks are overlain by Paleozoic (Cambrian to Pennsylvanian) sedimentary rocks (Tweto and others, 1976; Day and others, 1999). Oligocene (38–26 Ma) intrusive rocks are exposed throughout the area which is on the west margin of the Mount Aetna volcanic area at the south end of the Mount Princeton batholith (Toulmin and Hammarstrom, 1990).

Much of the area contains polymetallic replacement deposits in the Paleozoic carbonates. In the southern part of the mineralized area, there are base and precious metals in quartz veins in Precambrian rocks (Wilson and others, 2000; USGS, 1999a; Dings and Robinson, 1957). Tungsten-molybdenum veins in the Cumberland Pass area were explored in the 1970's (USGS, 1999a). Graphite deposits occur at the southeast edge of the area (Dings and Robinson, 1957).

Total production credited to the historic Tincup mining district from 1901 to 1935 was 298 oz gold, 26,446 oz silver, 177 lb copper, and 153,820 lb of lead (Vanderwilt, 1947, p. 109). Half the tonnage came from one mine, and the remainder from seven mines. In 1932 and 1933 the district produced a "small amount" of ore. Production from 1938 to 1941, and possibly 1934–1937, was combined with Taylor Park and could account for as much as 82 oz gold, 7,164 oz silver, 3,000 lb copper, 152,700 lb lead, 115,000 lb zinc (Vanderwilt, 1947, p. 108) included in the figures credited to Taylor Park. From 1934 to 1943, as many as three lode mines in the historic Quartz Creek district produced 186 oz gold, 3,781 oz silver, 150 lb copper, and 13,560 lb lead (Vanderwilt, 1947, p. 104).

Gold Brick

The Gold Brick area includes only the northernmost part of the historic Gold Brick mining district. This area is on the Fairview Peak and Pitkin quadrangles and includes polymetallic vein deposits at the Carter, Raymond, Sandy Hook, Chronicle, Gold Links, and Grand Prize mines (Crawford and Worcester, 1916; Hill, 1909; Wilson and others, 2000). Almost the entire area is underlain by ≈1,700 Ma granitic rocks and interlayered felsic and hornblende gneiss (Tweto and others, 1976; Day and others, 1999).

The principal ore is gold-silver-lead in veins in Precambrian granite and gneiss. In the 4 × 1 mi productive zone, numerous mines have produced chiefly gold with some silver, lead, and copper. The ore is low tonnage, but high grade, and all the underground workings are only a few hundred feet beneath the surface, except for the Carter mine, which extends to a depth of 1,500 ft (Crawford and Worcester, 1916). "Nearby sedimentary formations *** have not been productive" (Vanderwilt, 1947, p. 103). From 1932 to 1942, between 3 and 13 lode mines produced 69,566 tons ore, which yielded 16,395 oz gold, 45,657 oz silver, 2,350 lb copper, and 218,990 lb lead (Vanderwilt, 1947, p. 103).

Quartz Creek Pegmatite

Although it is not a metallic mineralized area, Quartz Creek Pegmatite is shown on the map (fig. E1) because the numerous mines indicate an historical mining interest in the area. The area overlaps the Parlin and Pitkin quadrangles and includes the Brown Derby mine, a pegmatite deposit known for its lithium content and mineral specimens of cleavelandite and lepidolite (Staatz and Trites, 1955).

Box Canyon

Box Canyon is an ill-defined area on the Whitepine and Pitkin quadrangles in the vicinity of the vaguely located Independence and Campbird mines (not to be confused with the Camp Bird mine in the San Juan Mountains) and prospects in the Precambrian rocks. Precambrian (≈1,700 Ma) granitic rocks and biotitic gneisses and migmatite are unconformably overlain by Paleozoic units and Upper Cretaceous Mancos Shale (Tweto and others, 1976; Day and others, 1999).

As of 1909, the Independence had been inactive for several years, as the deposit was entirely exhausted (Hill, 1909, p. 38). Although "considerable production [was] claimed for the early years," 573 tons of ore yielded 69 oz of gold and 10 oz silver in 1932, 1938, and 1939 (Vanderwilt, 1947, p. 98).

Whitepine

The Whitepine, or Tomichi, area overlaps the Whitepine and Garfield quadrangles. In the Whitepine area, Paleozoic sedimentary strata overlie ≈1,700 Ma granitic rocks (Tweto and others, 1976; Day and others, 1999). Both are intruded by a 39–32 Ma rhyolite and quartz monzonite to granite intrusive stock of the Mount Princeton batholith (Bove and Knepper, 2000). Tertiary extrusive rocks are present along the northeast margin of both the intrusion and the mineralized area. All of the numerous small, but productive mines are in or adjacent to the stock: none is in the Precambrian rocks. The mines exploited lead, silver, zinc, and minor copper from polymetallic vein and replacement deposits (Dings and Robinson, 1957). Gold was important locally. The northern part of the area also hosts an iron skarn, but the iron ore was not of commercial grade (Dings and Robinson, 1957; Harder, 1909).

Initially, oxidized silver and lead ore were the primary commodities. Later, primary lead and zinc were the valuable ores. Some gold, silver, and copper were recovered, as was a small amount of iron ore from a magnetite deposit. Most of the ore is classified as (1) replacement ores in limestone and dolomite, (2) contact deposits (skarn), and (3) fissure veins (Vanderwilt, 1947, p. 112). Of the mines in the area, the Akron was the most productive. Between 1901 and 1950 it produced nearly 100,000 tons of ore containing 724 oz gold, 474,160 oz silver, 232,783 lb copper, 20,751,676 lb lead, and 25,629,942 lb zinc (Dings and Robinson, 1957).

Marshall Pass

The Marshall Pass area is in the Pahlone Peak quadrangle (Olson, 1977). It includes the stratabound and vein uranium mines and occurrences in Harding Quartzite, Belden Formation, and veins in any rock occurring in the vicinity of the Chester fault zone. Early Proterozoic metasedimentary and metavolcanic rocks and pegmatitic granite are east of the fault. Cambrian and Pennsylvanian sedimentary rocks are west of the fault. At the Pitch mine, uranium occurs in brecciated Mississippian Leadville Limestone in the footwall of the Chester fault zone (Goodknight, 1981).

The major mines in the area produced nearly 1.3 million lb of uranium oxide from approximately 113,000 short tons of ore between 1956 and 1963 (Nelson-Moore and others, 1978; Nash, 1988). Numerous small mines were superseded in the 1980's by a large open pit at the Pitch mine, where reserves of 2.1 millions tons of ore containing 7.14 million lb of 0.17 percent uranium oxide were reported (Nash, 1979, 1988; Ward, 1978).

Cochetopa North

The Cochetopa North area, on the Iris quadrangle, includes the northeastern part of the Gunnison Gold Belt and parts of the historic Cochetopa, Green Mountain, or Gold Basin mining districts (Vanderwilt, 1947, p. 100–101). The geologic setting for this area has been reviewed by Afifi (1981a, 1981b), Bickford and others (1989), Day and others (this volume), Drobeck (1981), Olson (1976a), and Sheridan and others (1981). The area is mapped as interlayered Proterozoic felsic and mafic metavolcanic rocks that are overlain by Jurassic Morrison Formation and Junction Creek Sandstone, and by Oligocene-age volcanic tuffs and breccias (Olson, 1976a). Locally there are biotitic and migmatitic gneisses and granitic rocks. Mines in this area are hosted in the Proterozoic rocks and occur as low-sulfide shear-zone-hosted lode gold deposits. Examples include the Lucky Strike, Maple Leaf, Lubricator, and Mineral Hill mines. "The veins *** are relatively small and contain primarily gold. A small production is reported" (Vanderwilt, 1947, p. 193).

Workings at the Lucky Strike (at the west end of the mineralized area) are about 200 ft deep and 600 ft long. The ore vein is about 2–4 ft wide in massive iron-stained to white quartz containing tourmaline. Reportedly, the ore contains from 1 to 2 oz gold per ton. A small amount of copper and possibly tellurium is in the "waste pulp" (Hill, 1909, p. 37–38). A visit to this site revealed recent activity including a newly roofed building, a new cyanide tank, and a fenced leach pond (Anna Wilson and Warren Day, unpub. field data, July 28, 1998).

The Maple Leaf mine (at the east end of the mineralized area) is developed on a free-milling massive gold-bearing quartz vein containing both gold and silver in east-west-striking veins in coarse diorite (Hill, 1909, p. 38). The mine was closed in 1908 but appears to have been worked intermittently since then (Anna Wilson and Warren Day, unpub. field data, July 28, 1998). This deposit is a low-sulfide gold-bearing quartz lode deposit. The geologic map of the Iris quadrangle (Olson, 1976a) shows this as a quartz vein in amphibolite. The inclined and caved adit follows a shear zone approximately 10 ft wide striking nearly due east. Chalcopyrite is visible in the quartz vein.

Green Mountain

As outlined, the Green Mountain area lies within the Iris (Olson, 1976a) and Houston Gulch (Olson, 1976b) quadrangles and probably connects the northeasternmost part of the Gunnison Gold Belt (Drobeck, 1981) with the southern part of the historic Cochetopa Creek mining district. Felsite, felsite porphyry, amphibolite, and metasedimentary rocks of the Dubois Greenstone (Olson, 1976a,b) host several Kuroko-type massive sulfide deposits including the Denver City mine on the west end, and the Alaska and Yukon mines on the east end.

At the Denver City mine, discovered in 1898 (USGS, 1999a), sulfide ore (containing sphalerite, pyrite, and minor chalcopyrite and pyrrhotite) occurs in a stratabound lens parallel to the host rhyolite (felsite) (Drobeck, 1981, p. 280). Local gold and silver enrich the value of the deposit. Production records are not available (USGS, 1999a). Workings on the Alaska and Yukon mines date to the late 1800's (USGS, 1999a). Only five ore cars of 4–11 percent copper ore were produced from the Yukon, and only four ore cars of 34 percent zinc ore, 10 tons of 0.7 oz gold ore, and 15 tons of 11 percent copper ore were produced from the Alaska mine (Drobeck, 1981, p. 281).

Cochetopa Central

Cochetopa Central is a relatively large area that overlaps onto the Iris (Olson, 1976a), Houston Gulch (Olson, 1976b), Sawtooth Mountain (Olson and Steven, 1976a), and Razor Creek Dome (Olson and Steven, 1976b) quadrangles and is roughly equivalent in its geologic and metallogenic setting to the Southern Cochetopa mineralized area. It includes mines and occurrences with vein or stratabound uranium mineralization occurring in Precambrian or Mesozoic rocks in the vicinity of the Los Ochos fault and related faults (Wilson and others, 2000; McCulla, 1980, Malan and Ranspot, 1959).

Geologic maps (Olson, 1976a, b; Olson and Steven, 1976a, b) show that the area lies within a deeply eroded Proterozoic basement complex of low-grade metamorphosed mafic and felsic volcanic rocks and their associated sediments, which were later intruded by granite. The basement is unconformably overlain by a generally flat lying sequence of Jurassic and Cretaceous sedimentary rocks and Oligocene volcanic rocks. Major faulting trends east-west and is steeply dipping, showing major movement during Laramide time.

Originally the Cochetopa region was mined for gold, but after 1955 uranium was the commodity of choice. Veins of pyrite-marcasite-pitchblende occur along Los Ochos fault zone; however, most ore was produced from stratabound deposits in sandstones in the Jurassic Morrison Formation and some in the Cretaceous Dakota Sandstone. Virtually all of the 1.35 million lb of uranium oxide produced from 1956 to 1963 came from the Los Ochos mine complex (Nelson-Moore and others, 1978).

Cochetopa Tantalite

Like the Quartz Creek Pegmatite area, this area, which is on the Sawtooth Mountain quadrangle (Olson and Steven, 1976a), is not a metallic mineralized area. It is shown as a distinct area only because of its density of prospects and proximity to known metallic deposits. The area was prospected for pegmatite deposits in Precambrian granite, but none was developed (USGS, 1999a). No production has been recorded.

Cochetopa South

This area on Sawtooth Mountain quadrangle (Olson and Steven, 1976a) includes vein uranium deposits in Precambrian granite that is overlain by younger sedimentary rocks. Originally the district was mined for gold and base metals from small gold-bearing veins in Precambrian rocks. Of the known mines, only the LaRue has recorded production. From 1954 to1960, it produced 7 tons of ore, yielding 28 lb U_3O_8 and 16 lb V_2O_5 (Nelson-Moore and others, 1978; Malan and Ranspot, 1959; Olson, 1988, p. 19).

Wolf Creek

This tiny area, on the Carpenter Ridge quadrangle (Hedlund and Olson, 1973), outlines possible low-sulfide gold deposits (the Keezer and Lilly Belle?) (USGS, 1999a) in 1,400 Ma alkalic and mafic rocks. This area overlaps a much larger area of thorium–rare-earth element (Th–REE) veins (see Powderhorn, following). Both properties may have been prospected for tungsten (scheelite) (Argall, 1943). Apparently, the properties have not been productive (USGS, 1999a).

Beaver Creek

This tiny area on the Spring Hill Creek quadrangle (Olson and others, 1975) may be an extension of the Vulcan district. The two mines in this area, the Midland and Continental (Wilson and others, 2000), are Kuroko massive sulfide deposits very similar to those in the Vulcan area. The two mineralized areas are separated here, based on intervening host lithologies. The only reported production was gold-silver ore from the Continental mine in 1932 when 46 tons of ore assayed 1.28 oz/t gold and 0.05 oz/t silver (USGS, 1999a). Zinc may be present (USGS, 1999b).

Goose Creek

Goose Creek is an area in the Gateview quadrangle (Olson and Hedlund, 1973), within the Th–REE veins of the Powderhorn area, that contains low-sulfide gold deposits. Geologically, it is similar to the Vulcan area, which is in the same rock units to the east (Hedlund and Olson, 1974), but that area hosts massive sulfide deposits. Occasional small shipments of lead-silver and gold-silver-copper ore were recorded from this area of Precambrian granite and schist overlain by Oligocene ash-flow tuffs. The only production since 1931 (in 1939 and 1940) was 30 tons of ore that yielded 1 oz gold, 178 oz silver, 400 lb copper, and 1,400 lb lead (Vanderwilt, 1947, p. 104).

Vulcan

The Vulcan area, on the Powderhorn quadrangle (Hedlund and Olson, 1974), is also known as the Cebolla, Vulcan, Domingo, or White Earth district (Vanderwilt, 1947). This area includes some of the region's more important Kuroko massive sulfide deposits, such as the Vulcan and Mammoth–Good Hope. Together, these mines are an Environmental Protection Agency Superfund Site. These deposits are in a narrow greenstone belt included in the 1,700 Ma felsic and hornblendic gneiss unit (Tweto and others, 1976; Day and others, 1999).

Gold was produced from lenses of pyrite-rich rock in Precambrian metavolcanic rocks, part of a submarine volcanic province. Much of the pyrite has little or no gold content.

Sphalerite is the most common sulfide ore (Sheridan and others, 1981). Small shipments of lead, gold-silver, and copper-gold-silver ores were reported from other veins. Iron and manganese deposits have been described, but no production has been recorded. The 75 tons of ore mined in 1932, 1933, 1934, and 1941 yielded 55 oz gold, 208 oz silver, 100 lb copper, and 100 lb lead (Vanderwilt, 1947, p. 100). In addition, these deposits may have produced another half million dollars (or about 25,000 oz gold) between 1898 and 1902, and 250 oz gold and 1,200 oz silver in 1919 (Drobeck, 1981). Most of the precious metals (gold-silver tellurides) are in chalcedony veinlets (Drobeck, 1981).

Vulcan South

Vulcan South is a small area outlining the Old Lot mine, a Kuroko massive sulfide deposit, in the Powderhorn quadrangle (Hedlund and Olson, 1974). The area is mapped almost entirely as 1,700 Ma felsic and hornblendic gneiss (Tweto and others, 1976; Day and others, 1999). Intervening Precambrian granite precluded connecting this area to the Vulcan area. The only recorded production in 1931 and 1934 totaled about 308 oz gold and 300 oz silver (USGS, 1999a).

Powderhorn

The Powderhorn area covers a broad area with Th–REE veins and carbonatite prospects in the Powderhorn (Hedlund and Olson, 1975), Rudolph Hill (Olson, 1974), Gateview (Olson and Hedlund, 1973), Carpenter Ridge (Hedlund and Olson, 1973), and Big Mesa (Hedlund, 1974) quadrangles. It includes the historic Powderhorn district and part of Gunnison Gold Belt. As outlined, the area includes the Wolf Creek, Goose Creek, Vulcan South, and much of the Vulcan mineralized areas.

Early Proterozoic Dubois Greenstone and Powderhorn Granite is intruded by the latest Proterozoic or Cambrian Iron Hill alkalic complex (originally mapped as limestone of Iron Hill by Larsen, 1942). The area is cut by the northwest-striking Cimarron fault (Armbrustmacher, 1980; Olson and Hedlund, 1981). At the core of the complex is the Iron Hill carbonatite stock.

According to the MRDS database (USGS, 1999a), the area has been prospected since the late 1880’s, when magnetite was recognized. The magnetite was never valuable as iron ore because it contained much titanium (perovskite). “Prospectors either mistook magnetite-perovskite for base-metal sulfides or believed that it indicated sulfide presence at depth” (USGS, 1999a). From 1935 to 1944 and again from 1958 to 1961, vermiculite, used in insulation, plaster, tile, and fireproofing, was mined; no production figures are available. Thorium was discovered in 1949 and prospected and studied until 1956, but none was ever produced. It wasn’t until 1956 that Iron Hill was recognized as a niobium-bearing carbonatite. Since then, there have been several development and feasibility studies for extracting titanium oxide, rare-earth elements, and niobium ores; however, no substantial production of any of these commodities is recorded.

Bondholder

The Bondholder area is roughly equivalent to the Bondholder district on the Stewart Peak and San Luis Peak (Lipman and Sawyer, 1988) quadrangles. It is in the center of the San Luis caldera in Oligocene volcanic rocks including inter-ash flow quartz latitic and andesitic lavas and breccias, Rat Creek Tuff, and quartz latite of Baldy Cinco. Several small heterogeneous hypabyssal intrusive rock units consist of equigranular to coarsely porphyritic gabbro, diorite, granodiorite, monzonite, and quartz monzonite emplaced during the period of ash-flow eruptions (Steven and others, 1974; Day and others, 1999). Minor Quaternary glacial drift is locally exposed. The area may include polymetallic vein deposits in Tertiary volcanic rocks. Prior to Steven and Bieniewski (1977), no reports about the Bondholder area were available. Most of the previous work in the region has focused on the Creede district, on the same trend and several miles to the south.

Earliest records of prospecting date to 1887 with the staking of three mining claims in the vicinity of the Cascade mine (Steven and Bieniewski, 1977). At the Cascade mine, three short tunnels follow irregular curving and branching mineralized fractures with only local concentrations of ore-grade material. Numerous workings in the vicinity of the Woodmansee mine have lead, zinc, and silver values approaching ore-grade. In the 1960’s the Allara tunnel was driven “to explore the ground below old workings on the hillside above” (Bieniewski, 1977). None of the mines was economically significant. Bieniewski (1977) attributes at most $100,000 from production in the entire Bondholder area in comparison with the approximately $81 million from Creede.

Carson

Carson area is a small area, historically known as Carson Camp, on the Lake San Cristobal and Finger Mesa quadrangles. The Carson volcanic center is a 29 Ma monzonite to quartz monzonite plug (Bove and Knepper, 2000) intruding intermediate lavas and breccias and andesites and rhyolites of the Henson and Burns Members of the Silverton Volcanics (Steven and others, 1974; Day and others, 1999). Quaternary glacial drift, especially in Wager Gulch, and landslide material are present locally.

Discontinuous and irregular “gashes and fractures” in the Carson volcanic center contain ore minerals in polymetallic veins in altered porphyry (Larsen, 1911). Ore containing silver and lead with copper (primarily in enargite, chalcopyrite, and galena) and some gold in barite gangue varies in these zones from a few inches to 18 in. wide (Larsen, 1911). Mineralized rock extends south across the divide at the head of Wager Creek into the head of Lost Trail Creek (Vanderwilt, 1947, p. 114), and the area's more productive mines, the St. Jacob and George III, are outside the GMUG Forests. Bog iron deposits are known in Wager Gulch (Larsen, 1911).

Red Mountain (East)

Red Mountain (East), on the Lake San Cristobal quadrangle, is an altered 22.9 Ma complex of hydrothermally altered dacitic lavas and intrusions that formed on the eastern margin of the coeval Lake City caldera (Bove and others, 2000; Bove and Hon, 1990; Bove, 1988). In the 1970's drill hole exploration delineated reserves of 70 million metric tons of alunite (Bove and others, 2000). Subeconomic porphyry molybdenum and copper mineralized rock is present several hundred meters below the surface (Bove and others, 2000). No development has taken place.

Lake City

The Lake City area (also known as the Lake Fork or Lake San Cristobal mining district) straddles the Lake City and Lake San Cristobal quadrangles on the northeast flank of the Lake City caldera. Host rocks include Oligocene Dillon Mesa Tuff, Sapinero Mesa Tuff and its Eureka Member, Carpenter Ridge Tuff and its Bachelor Mountain Member and Outlet Tunnel unit, Fish Canyon Tuff, and Henson and Burns Members of the Silverton Volcanics (Tweto and others, 1976; Day and others, 1999). The area includes 23 Ma barite-bearing precious-metal veins and slightly older quartz-base-metal veins (Slack, 1980; Bove and others, 2000). After the initial flurry of activity in the late 1800's, most of the mines have been abandoned or worked only intermittently.

Notable mines in the area include the Golden Fleece (originally the Hotchkiss), which was discovered in 1874 and produced high-grade gold-telluride ore. As of 1926, it was credited with total production of $1.4 million (Henderson, 1926, p. 51; Irving and Bancroft, 1911, p. 14). The Pelican mine produced silver ore intermittently from 1891 to 1960. The ore minerals apparently were freibergite (argentiferous tetrahedrite), pyrargyrite, and galena (Irving and Bancroft, 1911, p. 97). Fanny Fern mine produced silver primarily from tetrahedrite (Brown, 1926, p. 14). In 1920–1923 and 1931, the mine produced at least 1,250 tons of ore yielding about 74,000 oz of silver and 65 oz of gold (computed from MRDS data, USGS, 1999a). Black Crook mine operated intermittently for 12 years until 1903. In 1884, it produced 1,277 tons of ore valued at $124,447 (Irving and Bancroft, 1911, p. 116). Apparently it also produced intermittently from 1913 to 1953. Some production occurred from numerous other small mines in the area (Wilson and others, 2000; USGS, 1999a).

Golden Wonder

The Golden Wonder is a single mine, not a district. It is singled out from other deposits in the area because of its unique hot spring deposit type in an intrusive volcanic breccia pipe (Slack, 1980). Recorded production includes two carloads in 1906, unrecorded amounts in 1913 and 1935–1937, 63 tons in 1939 (63 oz silver, 46 oz gold), 700 tons in 1961 (205 oz silver, 81 oz gold), and 45 tons in 1981.

The Golden Wonder mine was recognized as unique by Irving and Bancroft (1911, p. 101), but it was classified by them as a "true replacement deposit." Billings (1983) and Billings and Kalliokoski (1982) classified the deposit as a hot springs-type gold-telluride deposit. The ore occurs within a rhyolite flow-dome complex that was emplaced along the ring fracture zone of the Uncompahgre caldera (Billings, 1983). Productive portions of the vein were emplaced in a zone of closely spaced en echelon fractures. Two ore assemblages are present: gold-bearing chert (chert type) and pyrite-marcasite-sulfosalt (sulfide type). The chert type occurs in pods bounded by the fracture surfaces in areas where hydrothermal waters could pond. The sulfide type is found along the vein structure in between the high-grade chert-type pods where the vein structure was more constricted (Billings, 1983; Kalliokoski and Rehn, 1987). Two types of hydrothermal breccias are also present: the silicified dikes with fragments of sulfide and chert veins locally contain gold, whereas the argillically altered dikes do not (Billings, 1983).

Henson Creek

Henson Creek area includes the polymetallic vein deposits in the eastern part of the historic Galena district on the Lake City, Uncompahgre Peak, and Redcloud Peak quadrangles. This mineralized area is on the northeast edge of the 23 Ma Lake City caldera (Bove and others, 2000; Slack, 1980). Host rocks include Oligocene pre- and inter-ash flow andesitic lavas and breccias, intrusive rocks emplaced during the period of ash-flow eruptions, and Pliocene and Miocene plugs, dikes, and small flows of bimodal rhyolitic rocks (Tweto and others, 1976; Day and others, 1999). There are two main groups of vein deposits: 26 Ma quartz-base-metal veins that are generally tangential to ring fractures of the Lake City caldera and contemporaneous with intrusions in the Capitol City area, and 23 Ma barite-precious metal veins radial to Red Mountain (Bove and others, 2000; Slack, 1980). Ore ranges from mediocre to extremely rich; it is primarily composed of argentiferous galena, argentiferous tetrahedrite (freibergite), native silver, chalcopyrite, and sphalerite. Much of the ore was the result of secondary enrichment and oxidation that were concentrated in the upper parts of the mines, but by 1903 the rich deposits were depleted and the region began its decline (Irving and Bancroft, 1911).

Silver-lead ore was discovered in the Ute and Ulay veins in 1871 (Vanderwilt, 1947, p. 439), and production began in

1874. Together, the veins of the Ute-Ulay mine are among the largest producers of silver and lead in Colorado with about $12 million (gross) as of 1911 (Irving and Bancroft, 1911, p. 14, 89). Production continued intermittently from 1918 to 1967, and some cleanup work was done in 1980 (USGS, 1999a). The adjacent Hidden Treasure has produced ore worth at least another $700,000 (Irving and Bancroft, 1911, p. 89).

Other productive mines include the Ocean Wave, which was discovered in 1876 and ceased production in 1906. It claimed a total production of more than $115,000 (Irving and Bancroft, 1911, p. 86). The Yellow Medicine mine produced $40,000 worth of ore prior to 1896 (Irving and Bancroft, 1911, p. 78) and small amounts intermittently until 1952 (USGS, 1999a). The Czar shipped ore in 1899 (Irving and Bancroft, 1911, p. 14), but the cost to separate the lead and zinc made these shipments unprofitable (Irving and Bancroft, 1911, p. 76). The property was revived briefly in the 1950's (USGS, 1999a). The Capitol City mine was discovered in 1882 and last produced ore in 1954 (USGS, 1999a). The Big Casino mine was discovered in 1876. Although its owners claimed assays ran as high as 200–412 oz silver per ton of ore (Irving and Bancroft, 1911, p. 81), the values for 1927, 1928, and 1968 indicate that 100 tons of ore contained 3,167 oz silver, less than 2 oz gold, 56,534 lb lead, and 51,351 lb zinc (USGS, 1999a). No other production records are available. No production is recorded prior to 1967 for the Pride of America (Sanford and others, 1986) adjacent to the Big Casino (USGS, 1999a). In 1967–1968 and 1976–1977, more than 1,000 tons of ore (containing more than 13,000 oz silver, 182,000 lb lead, and 247,000 lb zinc) were produced (USGS, 1999a). The ore in both mines was galena and freibergite (Irving and Bancroft, 1911, p. 81).

Uncompahgre Peak

The Uncompahgre Peak area, straddling the Wetterhorn Peak (Luedke, 1972) and Uncompahgre Peak quadrangles, is on trend with regional structure in Oligocene volcanic rocks (Tweto and others, 1976; Day and others, 1999). It includes two similar vein uranium occurrences, the Beth and the Eagle and Mary Alice (Nelson-Moore and others, 1978; Steven and others, 1977; Wilson and others, 2000).

The Beth group of unpatented claims produced 18 tons of ore containing 68 lb of U_3O_8 ore in 1958–1961 (USGS, 1999a). The Eagle and Mary Alice claims are inactive prospects that never produced. To the best of our knowledge, no mining activity has occurred and no mineral exploration interest has been shown in the area for nearly 40 years (Nelson-Moore and others, 1978; Steven and others, 1977).

Cimarron

The Cimarron area also straddles the Wetterhorn Peak (Luedke, 1972) and Uncompahgre Peak quadrangles, north of the Uncompahgre Peak mineralized area. A west-north-west-trending zone of small intrusions in the northern part of the area are exposures of a 30 to 35 Ma quartz monzonite to monzonite volcanic center (Lipman and others, 1976). The Matterhorn Peak stock, at the southern part of the area, is 26 Ma quartz monzonite to monzonite (Lipman and others, 1976; Bove and others, 2000).

The Silver Jack, at the northeast corner of the area, is the only productive mine. It was last worked in 1931 and supposedly produced a small amount of silver and lead ore (probably galena), but no known records of production exist (USGS, 1999a). The Dix and Cimarron Chief, at the southern part of the area in the Matterhorn Peak stock, consist of 240 unpatented claims (USGS, 1999a). Together they constitute an inactive, only slightly developed, molybdenum prospect consisting of several prospect trenches and pits, and one shallow shaft.

Ouray

As shown, the Ouray area, on the Ouray quadrangle (Luedke and Burbank, 1962), encompasses much of the historic Ouray or Uncompahgre mining district (Luedke and Burbank, 1981). This area includes mineral deposits north of the San Juan volcanic field that are hosted in Paleozoic and Mesozoic sedimentary rocks adjacent to Laramide intrusive rocks (Tweto and others, 1976; Day and others, 1999). The area hosts polymetallic vein and replacement deposits. Major deposits include the American Nettie, Bachelor (including Wedge and Neodesha), Mineral Farm, and Pony Express.

The Bachelor mine (including the Wedge and Neodesha mines) was a large intermittent producer (USGS, 1999a): as of 1905 it was credited with $3.5 million in production (Cross and others, 1907, p. 17). Between 1942 and 1946 it produced an additional 201,000 pounds(!) silver, 2,080,000 lb lead, 1,300,000 lb zinc, and 71,000 lb copper (USGS, 1999a). Ore minerals included galena, sphalerite, chalcopyrite, argentiferous tetrahedrite, and pearceite (Bastin, 1923, p. 70). Locally chalcocite, chrysocolla, argentite, and native silver may also occur (Bastin, 1923, p. 72).

Although the American Nettie is listed as a small intermittent producer (USGS, 1999a), between 1889 and January 1905 it produced 23,641,316 lb of ore valued at $1,464,923.35 (Irving, 1905, p. 70). This ore averaged $123.12 per ton, or 6 oz gold per ton of sorted rock (Irving, 1905, p. 70). When the mine was last worked is not known.

As of 1905, ore values in the Mineral Farm and Pony Express mines were described as "extremely irregular and *** uniformly low" (Irving, 1905, p. 73). Ore from the Pony Express averaged $30 per ton; the average value of the Mineral Farm ore was so low it didn't pay to mine it (Irving, 1905, p. 73).

Production for this area is included with all production from Ouray County for the period 1946–1958. It is not possible, from published reports, to determine the production from the Ouray mineralized area. As of 1988 the American Nettie

(Au, Ag, Pb, Zn) was in an exploration and development stage with one employee (Streufert and Ohl, 1989); Black Girl (Ag, Au, Pb, Zn) was on "standby"; and the Bachelor (Ag, Au) was being explored and rehabilitated.

San Juan

The San Juan mineralized area encompasses all or part of numerous historic mining districts including Burrows Park, western Galena (Henson Creek), Eureka, S. Ouray, Sneffels, Telluride, Ophir; Red Mountain, and Lower San Miguel (Placerville) districts (Plumlee and others, 1995). The area overlaps four counties—Hinsdale, Ouray, San Juan, and San Miguel, and seven quadrangles—Mount Wilson (Bromfield and Conroy, 1963), Ophir (Luedke, 1996), Telluride (Burbank and Luedke, 1966), Ironton (Burbank and Luedke, 1964), Ouray (Luedke and Burbank, 1962), Handies Peak (Luedke and Burbank, 1987), and Redcloud Peak. The mineralized area is centered on the San Juan caldera in the northwestern part of the San Juan volcanic field.

Each of the mining districts has unique characteristics, yet overall, most of the deposits are classified as polymetallic veins and replacements for mineral resource assessment purposes. Numerous well-studied mines are in this area, including the well-known Idarado and Camp Bird mines, and dozens of others. The area could easily have been expanded to the south into the Silverton area. However, that would extend it outside the GMUG forest area; thus an arbitrary southern boundary was drawn. The references listed herein provide more information.

Wilson Peaks

Wilson Peaks area includes only the mineralized part of the Mount Wilson mining district, straddling the Dolores Peak (Bush and Bromfield, 1966) and Mount Wilson (Bromfield and Conroy, 1963) quadrangles. The Wilson Peak stock, composed mostly of granodiorite and quartz monzonite, intruded Mancos Shale, Telluride Conglomerate, and Tertiary volcanic rocks. Most of the mines and prospects in the area are polymetallic veins in the stock. Locally, some veins cut the contact between metamorphosed and sedimentary rocks (Bromfield and others, 1972).

West- and southwest-striking vein systems are offset by thin barren north-striking veins (Varnes, 1947, p. 428). Productive veins were quartz-filled fissures containing pyrite, chalcopyrite, and arsenopyrite, with lesser amounts of galena, sphalerite, tetrahedrite, stibnite, and calcite. High values of gold occur along with chalcopyrite and galena in narrow pay streaks within fine-grained diorite facies of the diorite. In coarser grained parts of the intrusion, the gold may be associated with arsenopyrite (Varnes, 1947; Bromfield and others, 1972).

Except for the lack of phyllic alteration products and molybdenum, the zone of disseminated and vein-filling chalcopyrite in the quartz monzonite phase of the Wilson Peak stock is similar to that associated with other porphyry copper-molybdenum deposits. The exposed stock may be the deep part of an eroded porphyry system (Van Loenen and others, 1997, p. 71). The small area of exposed volcanic rocks may have potential for Creede-type epithermal veins (Van Loenen and others, 1997, p. 86–87).

Between 1882 and 1898, the Silver Pick mine produced 6,030 tons of ore containing 94,923 oz silver and 32,442 oz gold (USGS, 1999a; Bromfield, 1967, p. 91). The Morning Star produced some ore between 1878 and 1903, 667 tons of ore from 1904 to 1914 (Bromfield, 1967, p. 88), and a small amount in 1952 (USGS, 1999a). Other figures are unknown.

Western Uranium

A number of historic mining districts that contain sandstone-hosted uranium-vanadium deposits, including Gateway (Vanderwilt, 1947, p. 141), Uravan, Bull Canyon, Gypsum Valley, Slick Rock (Chenoweth, 1981, p. 166), Paradox, and Uravan Mineral Belt (USGS, 1999a; Fischer and Hilpert, 1952), have been combined to form the Western Uranium area (Wilson and others, 2000). In this area, the Permian to Upper Cretaceous sedimentary rock sequence is of predominantly terrestrial origin. Structures present include a series of parallel northwest-trending salt-cored anticlines; associated steeply dipping faults with small displacement cut the fold flanks parallel to the fold axes (Williams, 1964; Haynes and others, 1972; Day and others, 1999). More than 1,200 mines and mineralized sites have been identified in the region (Chenoweth, 1981, p. 166).

Deposits were first mined for radium from 1898 to 1923 (Finch, 1967). In the mid 1930's and continuing through World War II, emphasis shifted to vanadium production for the alloy-steel industry (Chenoweth, 1996, p. 97). Interest in recovery of uranium started in 1942 with the Manhattan project. In 1947, the newly created Atomic Energy Commission contracted to buy uranium concentrates. Production peaked in 1960 and grew under a program of government price supports, which ended in 1970 (Chenoweth, 1996; 1981). Demand from the nuclear energy industry sustained production until 1990, when the last mill shut down (Chenoweth, 1996, p. 95). Between 1947 and 1982, the Uravan Mineral Belt produced 85 million lb of uranium oxide (calculated from Chenoweth, 1996, p. 98; USGS, unpub. data), and 427 million lb of vanadium oxide was produced between 1947 and 1982 (USGS, unpub. data). Vanadium production prior to 1947 amounted to less than a tenth of that produced after 1947.

Sinbad

The Sinbad area includes redbed copper deposits in Sinbad Valley, including the Copper Rivet and Pyramid (Wilson and others, 2000). The area overlaps the Juanita Arch

(Shoemaker, 1955), Roc Creek (Shoemaker, 1956), and Dolores Point South quadrangles and is surrounded by uranium deposits. The area is underlain by Pennsylvanian to Jurassic sedimentary rock units, especially Hermosa, Cutler, Chinle, and Moenkopi Formations (Williams, 1964; Day and others, 1999). The copper deposits are structurally controlled, in veins and disseminated zones or horizons along cross-faults on the flank of a salt anticline.

As of 1921, there had been “considerable prospecting” at the Pyramid and Copper Rivet properties (Coffin, 1921). In 1940 and 1942 the area shipped 30 tons of ore containing 9 percent copper and 4 oz silver per ton (Vanderwilt, 1947, p. 142). The small tonnage of low-grade copper ore was deemed unsuitable for acid leaching and not adaptable to open-cut mining operations (Traver, 1947, p. 491).

Sunrise/Morning Glory

This area includes known redbed copper deposits on the Roc Creek (Shoemaker, 1956) quadrangle. The area is underlain by Triassic Chinle, and Jurassic Kayenta and Wingate Formations on the flank of a salt anticline (Williams, 1964; Day and others, 1999). The veins and disseminated deposits are structurally controlled along the northern extension of the Cashin fault (Coffin, 1921, p. 220).

Very little ore has been shipped from any of the properties in the West Paradox Valley. The Sunrise mine, on a N. 22° E.-trending fault, “produced 12 cars of ore assaying better than 30% copper and containing from 6 to 10 ounces of silver per ton” (Coffin, 1921, p. 220). The Fairview claim “encountered a little ore,” and the Morning Glory was a prospect (Coffin, 1921, p. 220).

Cashin (La Sal Creek)

he Cashin area, on the Paradox quadrangle (Withington, 1955), is roughly equivalent to the La Sal Creek mining district. Its redbed copper deposits are concentrated along northeast-trending faults in Permian to Jurassic sedimentary rock units on the flank of the Paradox salt anticline (Williams, 1964; Day and others, 1999). Major deposits in the area include the Cashin and Cliffdweller (USGS, 1999a).

The ore is concentrated along two intersecting fault fissures in the Dolores Formation (Vanderwilt, 1947, p. 151). Adjacent to the fissures, chalcocite impregnates sandstone. Native copper with some native silver is found in breccia zones. Copper sulfides in many places occur higher in the fissures than the metallic copper. The fissures have been developed by several hundred feet of tunnels and winzes (Vanderwilt, 1947, p. 151). Before 1920, an unspecified amount of ore was shipped that contained 35–50 percent copper with 8–10 oz silver per ton (Vanderwilt, 1947, p. 154). From 1937 to 1945 between one and three lode mines, presumably including the Cashin and Cliffdweller, produced 97 oz gold, 59,537 oz silver, and 1,462,200 lb copper (Vanderwilt, 1947, p. 153).

Exploration drilling has revealed a reserve of 10.9 million tons of 0.55 percent copper at the Cashin Mine (Anonymous, 1995).

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Qualitative and Quantitative Mineral Resource Assessment Methodology

By Gregory T. Spanski and Viki Bankey

Chapter F of

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Abstract

We conducted an assessment of mineral resource potential for a select number of deposit types within the GMUG greater study area, beginning with an initial consideration of mineral types likely to be present in the area. Of these, we selected the most important, both those historically and those having potential for future development. Included for assessment are granite- and granodiorite-hosted porphyry molybdenum, sandstone-hosted uranium, volcanic-associated massive sulfide, polymetallic vein, polymetallic replacement, and sediment-hosted redbed copper deposits. From descriptive models for these deposit types, we determined criteria to allow us to identify areas of permissive and favorable resource potential. Finally, quantitative assessments were performed on four of the deposit types that had adequate information available (grade and tonnage models).

Mineral Deposit Types in the GMUG Greater Study Area

Information about the geoenvironmental and physical characteristics of mineral deposit types has been assembled in descriptive models. For examples, see Erickson, 1982; Eckstrand, 1984; Cox and Singer, 1986; Roberts and Sheahan, 1988; Bliss, 1992; Hoover and others, 1992. The information in a descriptive model is used to identify areas where deposits are likely to occur, to judge the degree of that likelihood, and to classify known mineral occurrences. Identification is based on how closely geologic conditions in an area agree with those in the descriptive model or on the presence of mineral occurrences that represent the deposit type.

Mineral deposit types initially considered in the GMUG area are listed in table F1. They were identified through comparisons of geoenvironmental settings observed in the study area and mineral occurrences. The geologic conditions used to qualify each deposit type for consideration are listed with examples of known mineral occurrences where available. Model numbers correspond to those used in Cox and Singer (1986).

The mineral resource potential was assessed for seven deposit types: granitic and granodioritic porphyry molybdenum, sandstone-hosted uranium, volcanic-associated massive sulfide, polymetallic vein, polymetallic replacement, and sediment-hosted redbed copper. Their selection is based on both the prominent role that these deposit types have played in the area's mining history and the expectation that these are the most likely deposit types for development in the foreseeable future. Results are detailed in the following chapters of this volume.

In the case of the other 15 deposit types considered (table F1), available information is insufficient to support either a belief in a more-than-negligible probability for undiscovered deposits or an expectation for significant near-term exploration or development under any foreseeable economic scenario, with one exception. That exception is the vein- and sediment-hosted uranium occurrences that occur in the Marshall Pass and Cochetopa areas. Several deposits, the Pitch mine and the Thornburg (Los Ochos) mine, have produced 1.2 and 1.4 million lb respectively of U_3O_8 (Goodknight and Ludlam, 1981). However, these deposits are not amenable to quantitative evaluation. Controversy surrounding their genesis (Olson, 1988) prevents their identification with a specific deposit model, and in the absence of a descriptive model, formal resource potential tracts cannot be delineated. It is reasonable to expect that interest in exploration for similar deposits will occur during periods of favorable market conditions for uranium. The focus on where that interest might occur depends upon the genetic model on which the exploration philosophy is based. Insights on areas of future interest regarding these deposits are summarized by Goodknight and Ludlam (1981).

Delineation of Permissive and Favorable Mineral Deposit Potential Tracts

A mineral deposit potential tract defines an area where the known or inferred geologic conditions at the surface or in the shallow subsurface suggest that the probability of one or more undiscovered deposits existing is more than negligible.

Table F1. Deposit types compatible with geologic environments in GMUG forests.

Deposit type	USGS Model No.[1]	Terrane favorability characteristics[2]	Known examples[3]
Granite-hosted porphyry Mo.	16	High-silica granite (rhyolite) to alkalic plutonic and hypabyssal intrusions asociated with contemporaneous extensional tectonism. Polymetallic vein mineralization with accessory fluorite, rhodochrosite, high-temperature tungstates, or Climax Mo type mineralization. Propylitic alteration zones with anomalous levels of Cu, Pb, Mo, Sn, F, U, Rb, W, Nb, Ta, and (or) Zn. Multi-stage intrusive history of development in a high-silica granite or alkalic plutonic system. Volcanic vent or caldera complex exhibiting multiple resurgent events.	Elk Mtn. (Gothic) dist./ AMAX drilling project. Quartz Creek dist./ Morning Glory mine. Ruby dist./ Mt. Emmons (Red Lady Basin), Redwell Basin prospects.
Granodiorite-hosted porphyry Mo.	21a	Porphyritic granodioritic to quartz monzonitic (calc-alkaline) intrusions emplaced in a convergent plate boundary environment. Polymetallic vein and (or) polymetallic replacement and (or) skarn mineralization. Anomalous levels of Cu, Mo, Au, Ag, W, B, Sr, Pb, Zn, As, Sb, Se, Te, Mn, Co, Ba, and (or) Rb in soil/stream sediment/rock.	Capitol City area. The Blowout. Matterhorn Center.
Sandstone-hosted U-V	30c*	Feldspathic alluvial to fluvial sandstone with localized reduced facies zones or felsic tuffaceous volcaniclastic sandstone. Sandstone-hosted U mineralization. Anomalous levels of background radioactivity in soils and ground water. Anomalous levels of U, V, Mo, Se, Cu, and Ag in soil/stream-sediment samples.	Ruby (Irwin) dist./ Standard mine, Jenny claims. Uravan Mineral Belt.
Volcanic-associated massive sulfide.	28a	Presence of Proterozoic bimodal (mafic or felsic) metavolcanic or associated metasedimentary rocks. Areas proximal to felsic volcanic centers. Regions within or adjacent to known mineralized areas containing VMS deposits and prospects. Anomalous enrichments in Zn, Cu, and Au in stream-sediment samples.	Gold Basin (Green Mtn) dist./ Graflin mine. Iris dist./ Denver City, Shawnee #33 mines. Cochetopa dist./ Alaska-Yukon mine. Goose Creek dist./ Headlight, Anaconda mines. Vulcan dist./Good-Hope, Vulcan, Midland mines.
Polymetallic veins (PMV)	22c	Presence of intermediate to felsic (calc-alkaline) shallow, subvolcanic Tertiary intrusions or geophysical evidence for them. Polymetallic vein, polymetallic replacement, skarn, and (or) porphyry mineralization. Geochemically anomalous concentrations of Cu, Pb, Zn, or detectable Ag or Au. Dominant fractures such as those related to calderas and caldera-related structures or zones of extensional tectonic activity. Hydrothermal alteration minerals and zones of propylitic alteration and (or) silicification of carbonate rocks.	Elk Mtn. (Gothic) dist./ Sylvanite mine. Goldbrick dist./ Carter-Raymond, Gold Links mines. Tincup dist./ Jimmy Mack, Deacon, Indiana mines. Tomichi (Whitepine) dist./ Spar Copper, Lilly mines. Quartz Creek dist./ Bon Ton, Complex, Ida May mines. Taylor Park dist. Lake Fork (Lake San Cristobal) dist./Gold Quartz mine. Galena (Henson Creek) dist./ Ute-Ulay, Pride of America, Vermont-Ocean Wave, Dolly Varden mines. Cimarron dist./ Silverjack mine. Burrows Park (Whitecross) dist./Champion mine. Sherman dist. Carson Camp dist./ Bachelor mine. Larson Center area. Matterhorn Center area. Upper Cow Creek Center area. Eureka (Mineral Point, Poughkeepsie) dist.

Table F1. Deposit types compatible with geologic environments in GMUG forests.—Continued

Deposit type	USGS Model No.[1]	Terrane favorability characteristics[2]	Known examples[3]
Polymetallic replacement.	19a	Permeable or chemically reactive rocks, especially carbonates, proximal to known or inferred Tertiary or Cretaceous felsic intrusive (plutonic or calc-alkaline hypabyssal) rocks. Polymetallic replacement, polymetallic vein, skarn, and (or) porphyry mineralization. Anomalous levels of Ag, Pb, or Zn in stream-sediment or rock samples. Localized areas of dolomitization or silicification of limestones and (or) jasperoid or calc-silicate alteration of carbonate rocks and (or) argillic-propylitic alteration of carbonate rocks and (or) argillic-propylitic alteration of igneous rocks.	Elk Mtn. (Gothic) dist./ minor occurrences. Tincup dist./ Tincup, Drew, Gold Cup mines. Tomichi (Whitepine) dist./ Akron, Erie, Eureka-Nest Egg, Morning Star mines. Quartz Creek dist./ Maid of Athens, Silent Friend mines. Spring Creek dist./ Doctor mine.
Sediment-hosted redbed Cu.	30b.2*	Clastic sedimentary rocks containing permeable stratigraphic intervals. Salt-cored anticlines and associated prominent faults near axial zones of anticlines. Evidence of mineralizing activity commonly associated with Cu-U-V.	La Sal dist./ Cashin mine.
Thorium-rare earth veins	11d	Alkalic plutonic rocks (inclusive of carbonatites). Thorite- and (or) monazite-bearing quartz veins. Anomalous levels of Th-oxide in alkalic rocks and Th and REE in soil/ stream sediment.	Powderhorn area/ Genie 32, May Queen, Badger 1, Little Johnnie 1 & 2, Black Mica mines, Whitney prospect.
Carbonatite	10	Carbonatite and associated alkalic plutonic rocks. Zones of fenitized and brecciated rocks. Anomalous levels of Nb and (or) REE in soil/ stream sediment.	Powderhorn (White Earth) dist.
Epithermal quartz-alunite veins.	25e	Felsic volcanogenic and hypabyssal calc-alkaline rocks. Areas of pervasive acid-sulfate alteration or advanced argillic alteration with alunite, pyrophyllite, kaolinite and cristobalite. Massive opaline or chalcedonic silicification of permeable rocks. Porphyry and (or) polymetallic replacement mineralization. Anomalous levels of Au, As, Cu, base metals, Te(?) and W in soil/ stream sediment. Prominent through-going faults and fractures.	Red Mountain area.
Epithermal quartz-adularia veins.	25c+ 25d	Subaerial accumulations of volcanogenic rocks of intermediate to felsic calc-alkaline to alkaline composition. Caldera complex exhibiting resurgent intrusive activity. Precious-metal-bearing quartz-adularia-calcite vein mineralization. Quartz-alunite vein or hot spring mineralization. Prominent through-going faults or fractures. Silicic, argillic to advanced argillic, phyllic, and propylitic zoned alteration with low sulfide content. Gold placer mineralization. Anomalous levels of Hg, Au, As, Sb, Cu, Se, Te, Mo, Zn, and (or) Pb in soil/ stream sediment.	Lake Fork (Lake San Cristobal) dist./ Golden Fleece, Gold Quartz mines.
Creede epithermal veins.	25b	Intermediate to felsic calc-alkaline plutonic and hypabyssal rocks or bimodal volcanic rocks. Caldera complex exhibiting resurgent intrusive activity. Creede epithermal vein mineralization. Epithermal quartz-alunite vein, polymetallic replacement and (or) placer gold mineralization. Prominent through-going faults or fractures and (or) fractures and faults associated with doming and caldera evolution. Anomalous levels of Au, As, Sb, Hg, Cu, Ag, Pb, and (or) Zn in soil/ stream sediment.	Bondholder dist./ Cascade, Woodmansee Tunnel mines.
Placer Au-PGE	39a	Tertiary to recent terrace and alluvial deposits. Anomalous levels of Au, Ag, As, Hg, Sb, Cu, Fe, and (or) S in stream sediment. Gold placer, porphyry, polymetallic vein and replacement, quartz adularia and alunite vein, low-sulfide gold-quartz vein or other gold-bearing mineralization.	Gunnison River placers. Elk Mtn. placers. Goldbrick placers. Powderhorn placers. Taylor Park placers. Tincup placers. Union Park placers. Unaweep placers. LaSal Creek placers. Naturita placers. Uncompahgre placers. Eureka placers. Lower San Miguel placers.

Table F1. Deposit types compatible with geologic environments in GMUG forests.—Continued

Deposit type	USGS Model No.[1]	Terrane favorability characteristics[2]	Known examples[3]
Fe skarn	18d	Carbonate or carbonate-bearing sedimentary rocks near the margins of intermediate to felsic plutonic rocks. Polymetallic vein and (or) replacement mineralization.	Elk Mtn. dist./ Iron King mine. Tomichi (Whitepine) dist./ Iron King mine. Tincup dist./ Cumberland mine.
Low-sulfide Au-qtz veins.	36a	Metavolcanic and metasedimentary (greenschist to middle amphibolite facies) rocks. Low-sulfide gold-quartz vein, placer gold and (or) Kuroko volcanogenic massive-sulfide mineralization. Anomalous levels of As, Ag, Pb, Zn, and (or) Cu in soil/ stream sediment. Prominent compressional high-angle faults and shears. Areas of carbonate alteration proximal to quartz and calcite veins.	Box Canyon dist./ Independence, Campbird mines. Wolf Creek area/ Lilly Belle mine. Goose Creek dist. Willow Creek dist./ Ute Trail mine. Vulcan dist./ Continental mine. Cochetopa dist./ Black Cat, Lubricator, Maple Leaf mines. Gold Basin (Green Mtn.) dist./ Mineral Hill, Lucky Strike, Lulu mines. Cebolla dist./ Cashier, Rainbow claims.
Distal disseminated Ag-Au.	19c	Permeable sedimentary and clastic volcanogenic rocks occurring within 20 km of intermediate to felsic plutonic or hypabyssal intrusive rocks. Distal disseminated, porphyry Cu, skarn, and (or) polymetallic vein or replacement mineralization. Areas of silicification and (or) argillization. Anomalous levels of Hg, As, Sb, with or without Au in soil/ stream sediment.	Ouray area/ Dakota Fm. south of the Blowout stock.
Hot spring Au-Ag	25a	Felsic plutonic and hypabyssal intrusions and (or) rhyolitic volcanogenic centers. Geothermal hot springs. Areas of chalcedonic sinter, massive silicification, stockworks, or quartz-adularia veins and (or) breccias cemented by quartz. Epithermal quartz vein and (or) hot spring Hg mineralization. Anomalous levels of Au, As, Sb, Hg, and Te in soil/ stream sediment.	Lake Fork (Lake San Cristobal) dist./ Golden Wonder, Golden Fleece mines.
Hot spring Hg	27a	Mafic to intermediate hypabyssal intrusions and (or) basaltic to andesitic volcanic rocks. Geothermal hot springs. Areas of siliceous sinter with minor pyrite or Fe-oxides. Hot spring mineralization. Anomalous levels of Au, As, Sb, Hg, and Te in soils/ stream sediment.	Cochetopa dist./ Mercury mine.
Volcanogenic U	25f	High-silica rhyolite extrusive or hypabyssal rocks. Volcanogenic U vein mineralization. Anomalous levels of Li, Hg, As, Sb, F, Mo, W, and REE in soil/ stream sediment.	Uncompahgre Peak area/ Beth mine.
Pegmatite U	N.A.[4]	Basement complex of uranium-bearing pegmatite, granite gneiss, quartz monzonite and granite rock. Anomalous levels of Pb, Zn, Th, V, and Y in rock/ soil/ stream sediment. Areas of strong argillic alteration.	Harry Creek area/ Lookout Grp., Hidden Reserve Grp., Marshall Pass No. 5 claims.
Sediment-hosted V	N.A.	Intraformational unconformities in permeable sandstone overlain by limestone and localized in a zone marginal to the depositional edge of the capping limestone. Sediment-hosted, stratiform chromium-bearing micaceous and (or) sediment-hosted roscoelite mineralization.	Placerville dist./ Omega, Joe Dandy, Pocahontas mines.
Sediment- and vein-hosted U.	N.A.	Prominent, deep crustal thrust faults along which crystalline and sedimentary rocks are juxtaposed. Sedimentary carbonate and carbonaceous sandstone, siltstone, and shales unconformably overlain by intermediate to felsic volcanoclastic rocks. Hypabyssal rhyolite intrusive rock.	Marshall Pass dist./ Pitch, Little Indian #36 mines. Cochetopa dist./ Los Ochos Grp., T-2 mine. Tomichi (Whitepine) dist./ Big Red #22 mine, Akron tunnel, Big Red #39 claim. Jacks Cabin area/ North Star claims.

*No grade or tonnage models available.

[1]Modified from Cox and Singer, 1986; Bliss, 1992.

[2]Geo-environmental or physical features suggesting deposit-type compatibility.

[3]Names of district or area / mineralized site(s).

[4]N.A., not available.

Singer (1993) has suggested that negligible in this context equates with a deposit occurrence probability of between 1 in 100,000 and 1 in 1,000,000. Land in the study area where that probability is greater than the latter value is classified *permissive*. Areas within a permissive tract that are believed to have a probability that is significantly greater than negligible are defined as *favorable*.

Mineral potential classifications of permissive or favorable are subjective interpretations based on geologic and mineral occurrence information available at the time that indicates deposit presence. Descriptive models provide guidance on what kinds of information, such as mineral occurrence, regional geologic, geotectonic, petrologic, geochemical, and geophysical data, indicate the presence of a deposit. We gain a sense of the relative importance of each data set and its meaningful data threshold values from looking at conditions in other areas where these deposit types are found. Minimum conditions are established for each deposit type and expressed as *delineating criteria*. For example, the presence of carbonate rocks is a delineating criterion for defining areas as permissive for replacement deposit types. Lateral buffers (radial distances) are applied to point, line, and area data to include shallowly buried extensions of a feature and to minimize errors caused by mislocation or inadequate sampling of an area that has a non-negligible potential.

In general, permissive lands are defined using criteria that discriminate between areas that could host a deposit and ones that could not. Where the condition is absent, potential for existence of the related deposit type is considered negligible. Mapped geology is commonly the primary delineating criterion. Favorable lands are defined using delineating criteria that attest to the probable existence of deposit-generating processes and the intensity of that activity. Examples would be the presence of distinctive alteration mineral assemblages, specialized sedimentary depositional environments, anomalous trace-element geochemistry, or known occurrences of the deposit type or a genetically related deposit type. For each of the seven deposit types assessed in this study, the delineation criteria used to identify permissive and favorable tracts are listed in a table within each chapter. Area (in square miles) of permissive and favorable tracts are listed in table F2.

After the delineation criteria are determined, permissive and favorable tracts are computer generated using the commercial IMAGINE geographic information system (GIS)

Table F2. Areas (in square miles) and percentages calculated for permissive and favorable tracts for mineral resource assessments (Chapters G–L).

[Total area includes all public and private lands; USFS (USDA Forest Service) area includes only area within the GMUG forests; BLM area includes only area managed by the Bureau of Land Management. Areas and percentages rounded to the nearest whole number]

Assessment model name	Total area (mi^2) [percent of area]	USFS area (mi^2) [percent of area]	BLM area (mi^2) [percent of area]
GMUG study area, no model	19,800	4,868	5,092
porphyry molybdenum - *permissive*	3,144 [16]	1,371 [28]	320 [6]
porphyry molybdenum - granitic - *favorable*	2,832 [14]	1,242 [26]	295 [6]
porphyry molybdenum - granodioritic - *favorable*	737 [4]	324 [7]	95 [2]
uranium - *permissive*	6,656 [34]	1,628 [33]	2,650 [52]
uranium - *favorable*	1,352 [7]	94 [2]	955 [19]
massive sulfide - *permissive*	1,373 [7]	220 [5]	288 [6]
massive sulfide - *favorable*	558 [3]	176 [4]	163 [3]
polymetallic vein - *permissive*	6,880 [35]	2,374 [49]	950 [19]
polymetallic vein - *favorable*	2,973 [15]	1,200 [25]	334 [7]
polymetallic replacement - *permissive*	5,133 [26]	1,832 [38]	739 [15]
polymetallic replacement - *favorable*	1,674 [8]	618 [13]	150 [3]
sediment-hosted copper - *permissive*	3,128 [16]	806 [17]	1,360 [27]
sediment-hosted copper - *favorable*	441 [2]	195 [4]	247 [5]

software from Erdas, Inc. Boolean logic statements (commonly AND or OR) that express each delineation criterion are used to combine data taken from gravimetric, magnetic, and radiometric surveys, Landsat imagery, rock and sediment geochemistry, mineralized areas, mine and prospect locations, and tectonic, stratigraphic, and structural analyses. These data are stored in vector or raster format in theme layers. For example, stratigraphic, lithologic, and structural data are stored in a geologic map theme layer. Delineation criteria with applied buffers (for example, 500 m surrounding a mineral location of gold) are used to identify areas within the theme layer where required conditions exist. Permissive areas are determined by selecting and combining delineating criteria from pertinent theme layers (for example, either Tertiary intrusions from the geology theme layer or positive aeromagnetic anomalies from the aeromagnetic theme layer, or both). In this report, areas are shown as either permissive for the selected deposit type or not permissive.

The process we used to combine theme layer areas to determine favorability tracts is known as bitmapping and is illustrated in figure F1. In bitmapping, a unique bit value from a power of 2 series (1, 2, 4, 8, 16, 32, etc.) is assigned to selected areas within a rasterized theme layer. When theme layers are combined using the GIS program, bit values are added where theme areas are superposed, producing derivative areas having bit values that are unique for the combination. For example, a sum of 19 can only result from the superposition of areas with bit values of 16, 2, and 1. The sum, therefore, describes each of the input criteria that makes the area favorable. Whereas the permissive maps only show *where*, the favorable maps also show *why*.

Note, however, that bitmap values do not rank areas of mineral potential: an area with a sum bit value of 18 does not necessarily possess a potential that is greater than an area with a sum bit value of 15. Theme combinations wholly determine potential, and for tract delineation purposes, only two meaningful levels of potential are distinguished: permissive and favorable. By definition, a favorable area must also be defined first as permissive. Therefore, a mask is used on the derivative bitmap to eliminate areas that are not permissive.

Complex relationships among the criteria can be displayed using color variations on the figures showing favorable tracts. For example, if anomalous geochemistry is only a delineating criterion in combination with other criteria, favorable areas will not be colored where geochemistry is the only criterion. Where a large number of theme layers are combined, the potential for complexity escalates rapidly. Three theme layers can generate as many as 7 unique derivative areas, and five theme layers can give rise to 31 derivative areas. In such cases, the figures are simplified by displaying similar criteria in the same color, and this will be indicated in the explanation.

Quantitative Assessment of Locatable Mineral Resource Potential

Quantitative mineral resource potential of an area is expressed in estimates of the probable numbers of undiscovered economic to marginally economic deposits believed likely to exist within the area and estimates of the amounts (endowments) of ore and recoverable commodities likely to occur in those deposits. We used the “three-part” assessment methodology (Singer, 1975) developed by the USGS in the 1970’s. It is subjective and assumes that the undiscovered deposits represent one or more distinct deposit types. Each deposit type is characterized by a set of physical and genetic attributes common to a group of known mineral deposits that represent the deposit type. Where data characterizing the size (tons of ore) and commodity grades of economic to marginally economic deposits are available as grade and tonnage models, the number of undiscovered deposits can be estimated. The latter information can in turn be used to estimate the ore and commodity endowments likely to be associated with these undiscovered deposits. Quantitative results are presented in a probabilistic format to emphasize the uncertainties inherent in the assessment process. The three parts of the methodology are discussed in greater detail in the following section. A comprehensive discussion of the three-part assessment methodology and the procedure used to estimate endowments is found in Singer (1993) and Root and others (1992).

Grade and Tonnage Models

Grade and tonnage models are used to define the size and grade of deposit-size occurrences, where deposit refers to only those occurrences that have been commercially exploited or are believed to have a potential to be commercially developed in the future. These models must be available before opinions concerning the probability of additional deposits occurring can be formulated. The mean and variance of the size and grade distributions of these deposit populations are used for that purpose. The models are also critical in quantifying the endowment aspects of an undiscovered deposit population.

In this study, grade and tonnage models in Cox and Singer (1986) or modified versions from it have been used to estimate undiscovered deposit populations and ore and commodity endowments for four of the seven deposit types we assessed. These were the two molybdenum deposit types, the volcanic massive sulfide type, and the polymetallic replacement type. In the absence of grade and tonnage models for polymetallic vein deposits, sandstone-hosted uranium-vanadium deposits, and sediment-hosted redbed copper deposits, provisional minimum deposit size and grade parameters were used for the sole purpose of tract delineation. Provisional values are established from values that, given the commodities involved and development considerations, would likely define

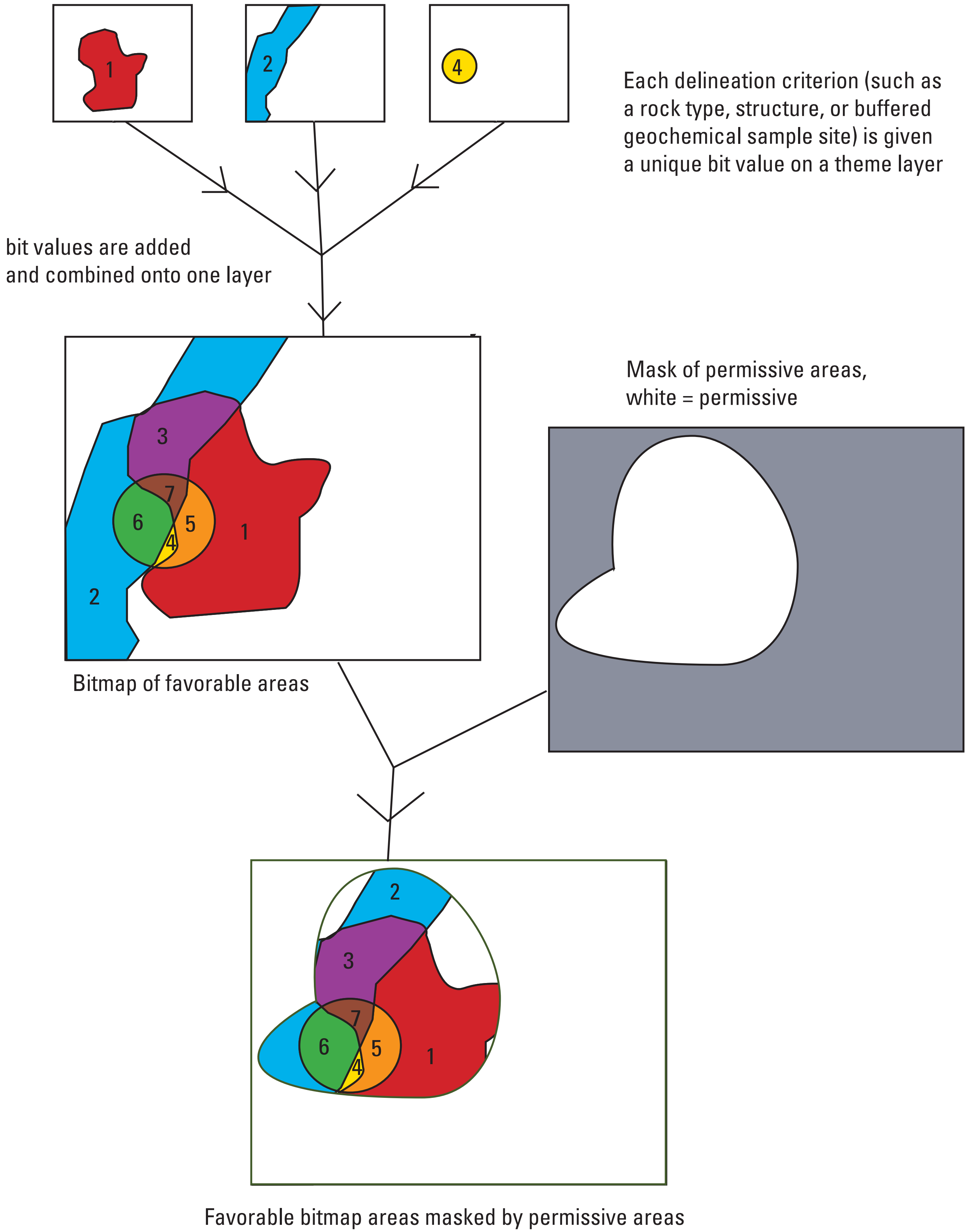

Figure F1. Bitmapping favorable criteria.

the minimum grade and tonnage for occurrences considered to be marginally economic at the time of this study. Provisional values cannot be used to estimate numbers of undiscovered deposits or to estimate ore and commodity endowments.

Estimation of Undiscovered Deposits

The estimation of undiscovered deposits allows us to quantify the resource potential of an area for the deposit types that are permissive in the geologic environment present. The deposits being estimated are presumed to possess grade and tonnage characteristics consistent with those used to construct the grade and tonnage models. Where available data do not support that assumption, quantification of resource potential was not included. Without new size and grade data and with inappropriate existing grade and tonnage models, no valid basis exists for estimating undiscovered deposits. For the volcanic-hosted massive sulfide deposit type, the grade and tonnage data were modified to include only Precambrian deposits. We believe that these models portray a range of grades and tonnages that might be present in the study area. Model median and population variance values are used as guides in conceptualizing the undiscovered deposits.

The estimates of deposits are generated by a team of individuals with an understanding of the geology and metallogeny of an area and the genesis of the deposit types being assessed. Each estimate reflects what the team members agree is the largest number of undiscovered deposits believed likely to be present. For each deposit type assessed, five estimates are generated at five levels of confidence including a high level of confidence (90 percent), intermediate estimates at the 50 percent, 10 percent, and 5 percent, and a highly speculative degree of confidence at the 1 percent confidence level. Estimation certainty is reflected in the magnitude of change occurring between estimates in the five-tier sequence. For example, levels of confidence percentages of 90, 50, 10, 5, and 1 may result in respective numbers of undiscovered deposits of 1, 1, 2, 5, and 11. These numbers of undiscovered deposits indicate that the assessors are fairly certain that one or two undiscovered deposits are present; however, the large spread in values at the low level of confidence indicates much greater uncertainty. The overall evaluation process is subjective but is based on the best professional opinions given the data available. A wide variety of approaches is used to predict numbers of undiscovered deposits (Singer, 1993). Team members are free to employ any procedure of which they are confident as long as deposit model size and grade consistency are honored.

Locations of undiscovered deposits within the study area are not directly addressed in the assessment process. The same data used to delineate mineral potential tracts are used to estimate numbers of undiscovered deposits, and we might assume that they would likely be within favorable areas as opposed to merely permissive areas. However, it should not be assumed that any predetermined percentage of an undiscovered deposit population would or should necessarily occur in a given mineral potential tract.

Estimation of Endowments

Resource endowments are measures of the total quantities of ore and recoverable commodities that are associated with an undiscovered deposit population. Like the undiscovered deposit estimates on which their measure depends, the estimates are reported in a probabilistic format. Undiscovered deposit estimates along with the appropriate grade and tonnage model data are input into a Monte Carlo simulation routine (Mark3 Simulator). The computer-based simulator (Root and others, 1992) generates 4,999 hypothetical undiscovered deposit scenarios that are statistically consistent with the deposit estimates and the grade and tonnage models. The ore and commodity endowment results for each scenario are used to construct cumulative frequency distributions from the smallest endowment to the largest for each commodity and for ore. Results can be used in economic analyses, land-use planning, or designing remediation and (or) mitigation of environmental impacts that might occur from future mineral exploration or development. A few demonstrative endowment values are summarized in tables in this volume: see Chapter I, table I2, and Chapter G, tables G3 and G6. Included are the estimated commodity and ore endowments at the 90th, 50th, and 10th percentiles of the frequency distributions and the mean endowments. The probabilities of these mean endowments are also included, because the means can be highly skewed and misleading where the estimates of undiscovered deposits reflect a high degree of uncertainty at the low confidence levels. These tables also list the probabilities for each of the possible deposit scenarios including no deposits. More complex endowment summaries are presented in graphical format in Appendix F1 of this chapter, together with guidelines on how the graphs may be interpreted.

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Appendix F1. Mark3 Mineral Resource Endowment Estimates

Estimated ore and commodity endowments for undiscovered deposit populations for three types of deposits expected to be present within the GMUG greater study area have been simulated using the U.S. Geological Survey Mark3 Simulator (Root and others, 1992). Input to the simulator for each deposit type includes the estimates of numbers of undiscovered deposits, estimated at the 90th, 50th, 10th, 5th and 1st percentile levels of confidence, and the grade and tonnage model data. The undiscovered deposit estimates are fit to a frequency distribution model that calculates an occurrence probability for each of the possible deposit populations that fall within the range from zero up to the number of deposits estimated at the 1st percentile. A Monte Carlo simulation methodology is used to compute theoretical ore and commodity endowments that would be associated with each of 4,999 hypothetical deposit scenarios. In each scenario, a number representing the number of deposits expected to be present is chosen, followed by the selection of a tonnage and commodity grades for each deposit. Commodity endowments are calculated for each deposit and summed for that scenario. The frequency with which any given grade, tonnage, or number of deposits is used in a scenario is determined by their respective frequency distribution models. The ore and commodity endowment estimates resulting for the 4,999 scenarios are sorted in order of increasing value and displayed in cumulative frequency graphs. To assist the user in interpreting these graphs, a brief explanation of the display format used follows.

Explanation of Graphical Display of Mark3 Output

The 4,999 hypothetical ore and commodity endowment estimates resulting from a Mark3 Simulator run are sorted in order of increasing value and graphically displayed in a log linear plot of ore or commodity endowment versus proportion of simulations. The cumulative frequency plot is used because probabilistic conclusions concerning the ore and metal endowment potential of an area can be drawn directly from these displays.

Key interpretive elements of a typical plot of Mark3 results (fig. F2) are cross referenced by letter to the following descriptive explanations.

A Title—Identifies the mineral deposit type, the undiscovered deposit estimates input (in parentheses) and endowment (ore or commodity) plotted. In the example, ore endowment estimates are displayed for a hot-spring Au-Ag deposit type where the estimates of undiscovered deposits input is 2, 4, 9, 15 and 25 at the 90th, 50th, 10th, 5th and 1st confidence levels respectively.

B Vertical axis (left)—Linear scale of proportion of simulation scenarios, graduated in 0.1 increments.

C Horizontal axis—Logarithmic scale of endowments in metric tons. In the example, ore endowment ranges from 6,300 to 6,300,000,000 t (metric tons) and is expressed in millions of metric tons.

D Endowment value—Open circles denote endowment values occurring at 5 percentile intervals. The values are also listed in a table appearing to the right of the graph (figs. F3–F7). In the example, the ore endowment at the 35th percentile is 72 million metric tons.

E Minimum endowment—Solid circle denotes the minimum non-zero endowment value simulated. Annotation includes the value of the endowment and the proportion of simulations producing a zero endowment, noted on the flattened extension of the endowment curve to the left of the symbol. In the example, the minimum ore endowment is 170,000 t of ore, and 0.04 or 4 percent of the simulations contained no ore endowment.

F No endowment field—A shaded field denotes that portion of the simulation scenarios that had no endowment. This field will always be present in that every deposit distribution includes some finite probability of there being no deposits. Zero ore endowments result where a no-deposit condition is modeled in a scenario. Zero commodity endowments result where either a no-deposit scenario is modeled or the commodity grade model shows that the commodity occurs in only a portion of the deposit of a deposit type. In the example, 4 percent of the simulation scenarios were run under the assumption that no deposits were present. The remaining 96 percent were run with the assumption that from 1 to 25 deposits were present.

G Maximum endowment—Denoted with an open circle. Annotated with the value of the largest ore or commodity endowment simulated. In the example, the largest ore endowment is equivalent to 1,800 million t.

H Median endowment—Denoted with an open circle and annotated with an endowment value. Half of the 4,999 simulation scenarios have smaller endowments and half have larger endowments. In a probabilistic sense, given the simulation conditions, the probability of an endowment being larger or smaller is 50 percent or equal. In the example, the median ore endowment is equal to 110 million t. The probability of an endowment greater or smaller than 110 million t is equal.

I,J Endowments at the 10th and 90th percentiles—Denoted with open circles and annotated with endowment values. Values commonly reported in the past assessments as defining the upper and lower limits of the endowment. Highlights the simulated endowment scenarios that are symmetric about the median excluding the more erratic values occurring in the tails of the endowment distributions. In the example, the ore endowment at the 10th percentile is 18 million t and the 90th percentile 470 million t. One may therefore assume that there is an 80 percent probability **K** of an ore endowment between 18 and 470 million t in size being present.

L Mean endowment—An open square denotes the mean endowment. It is annotated with an endowment value and the proportion of scenarios that have endowments smaller than the mean. In the example, 67 percent (0.67) of the simulation scenarios **M** had ore endowments smaller than the 190 million t mean, or a 67 percent probability exists that the ore endowment is less than 190 million t.

N Exceedance probability—Linear scale indicating the probability of a given endowment value being exceeded. The example shows that the probability of the presence of an endowment larger than the mean endowment of 190 million t is 33 percent probability. Any endowment can be tested by selecting an endowment on the horizontal axis and extending a line vertically to the endowment curve and then extending a horizontal line to the exceedance probability scale.

Figures F3–F7 enlarge on this theme and give additional data from the GMUG greater study area.

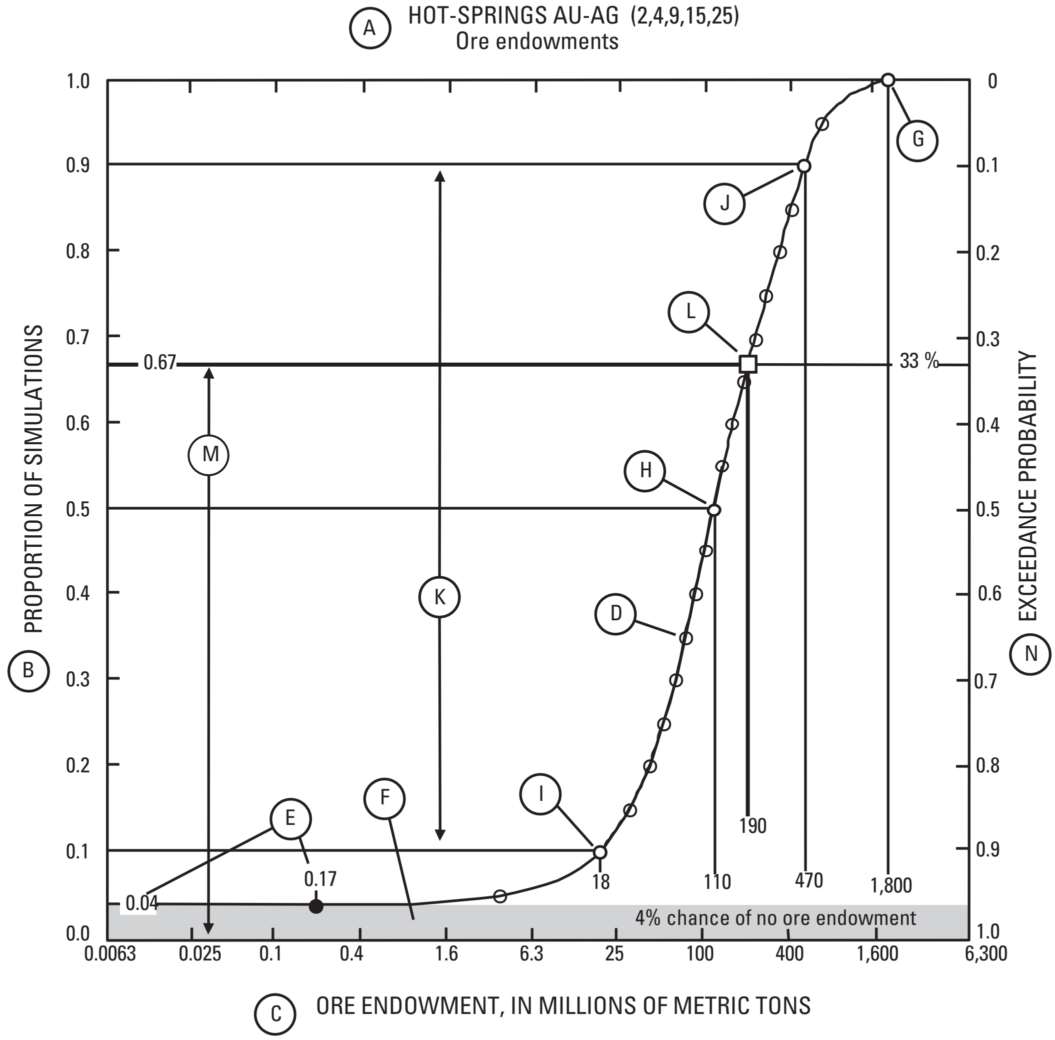
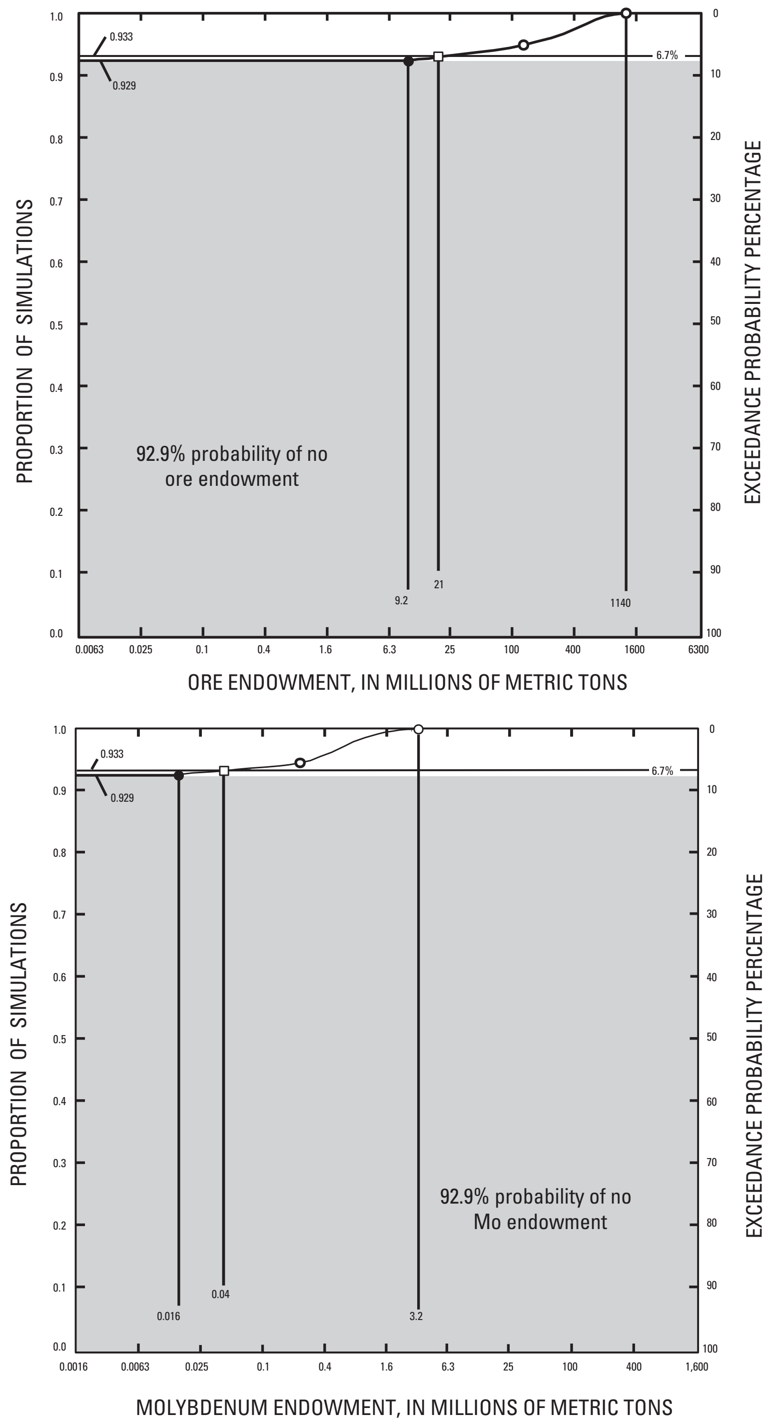


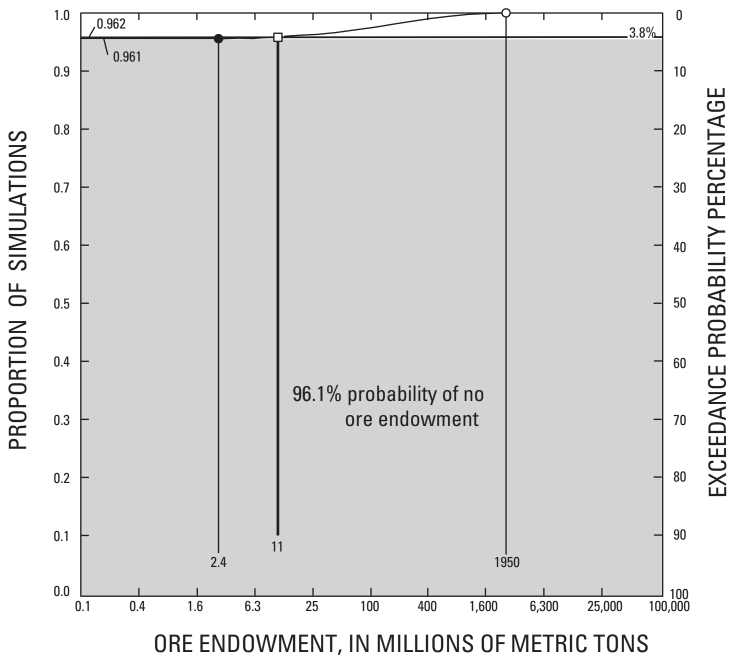
Figure F2. Example of a cumulative frequency plot of ore endowment estimates from a Mark3 simulation of undiscovered hot-spring gold-silver type deposits. Letters in circles are keyed to the preceding explanatory text.



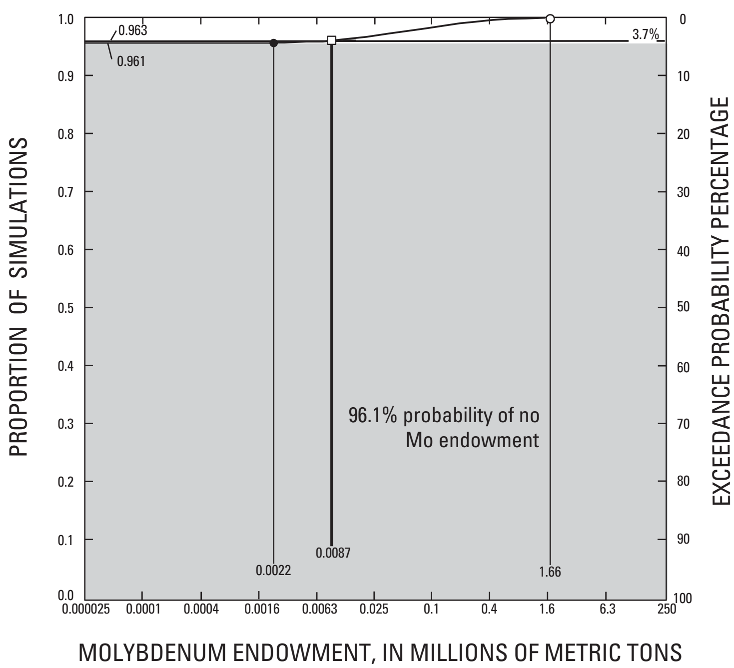
Percentile	Ore
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	120
100	1,140

Percentile	Moly.
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0.23
100	3.2

Figure F3. Climax-type porphyry molybdenum deposits: simulated Mark3 endowment distributions for ore and molybdenum occurring in undiscovered deposits in permissive tracts in GMUG greater study area.

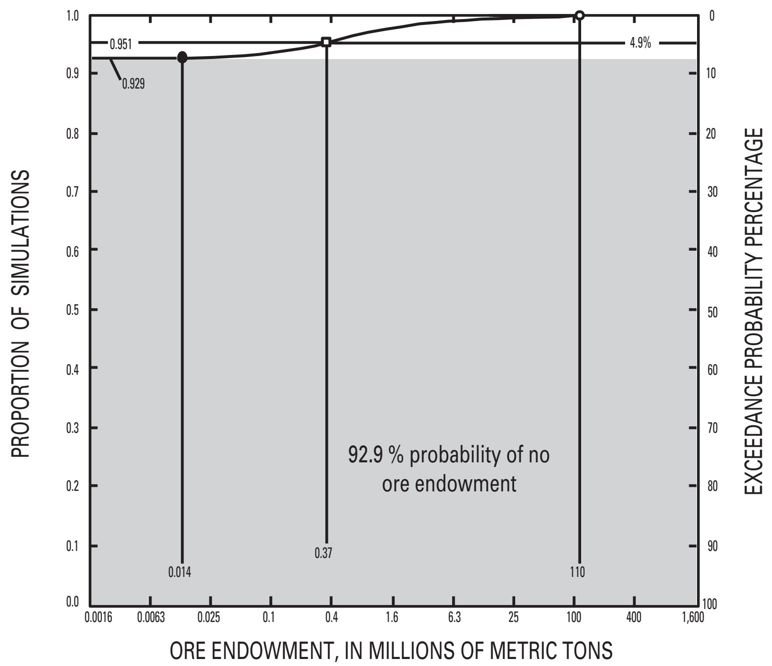


Percentile	Ore
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0
100	1,950

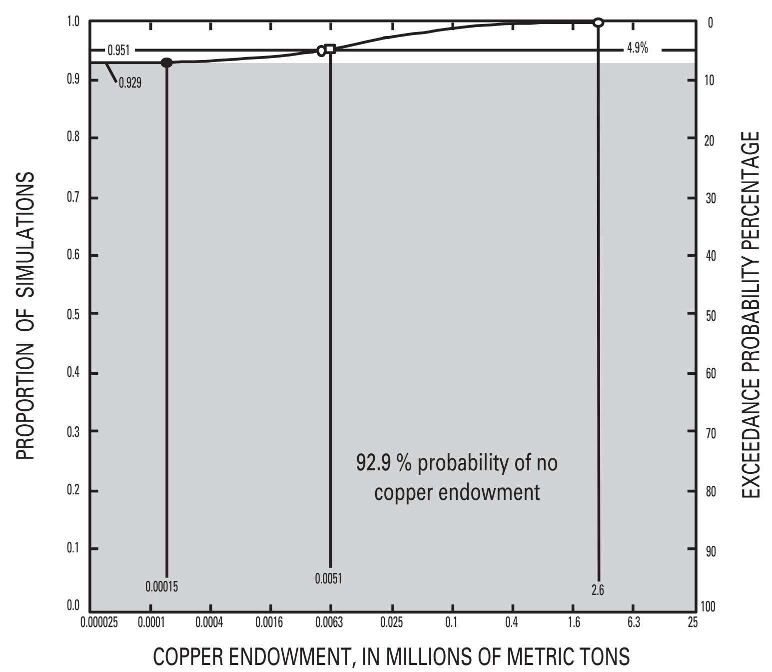


Percentile	Moly.
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0
100	1.66

Figure F4. Porphyry molybdenum, low fluorine deposits: simulated Mark3 endowment distributions for ore and molybdenum occurring in undiscovered deposits in permissive tracts in GMUG greater study area.

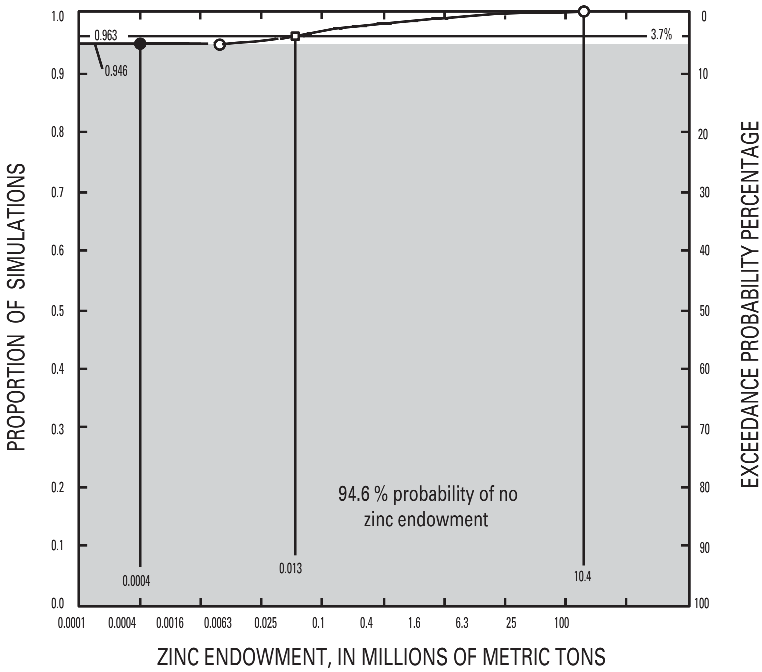


Percentile	Ore
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0.37
100	110

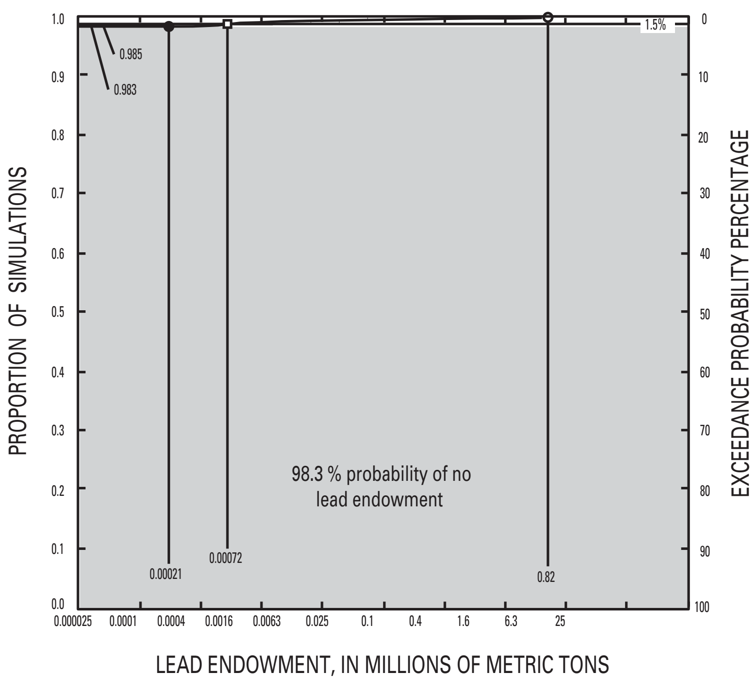


Percentile	Copper
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0.0048
100	2.6

Figure F5. Precambrian Kuroko-type massive sulfide deposits: simulated Mark3 endowment distributions for ore and copper occurring in undiscovered deposits in permissive tracts in GMUG greater study area.

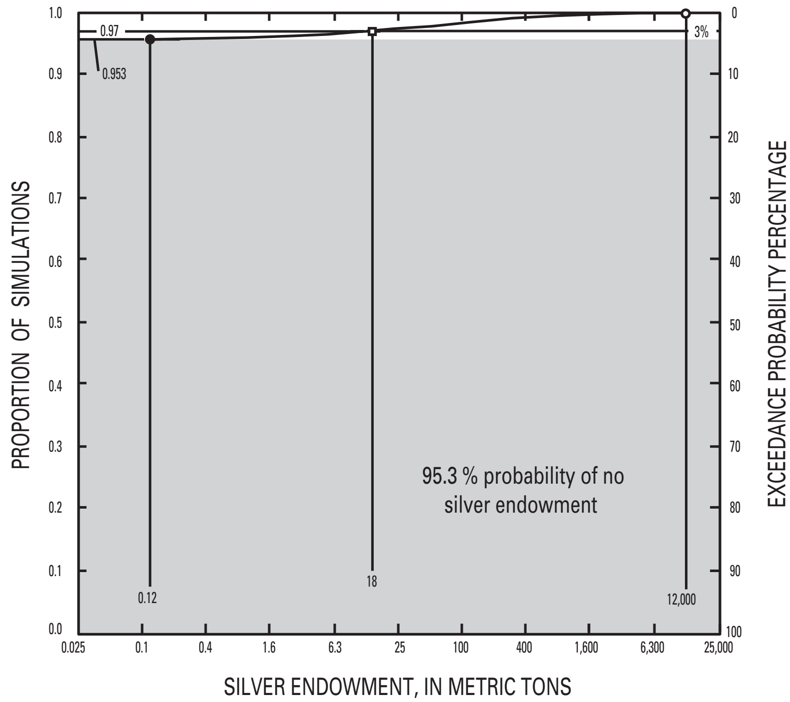


Percentile	Zinc
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0.0018
100	10.4

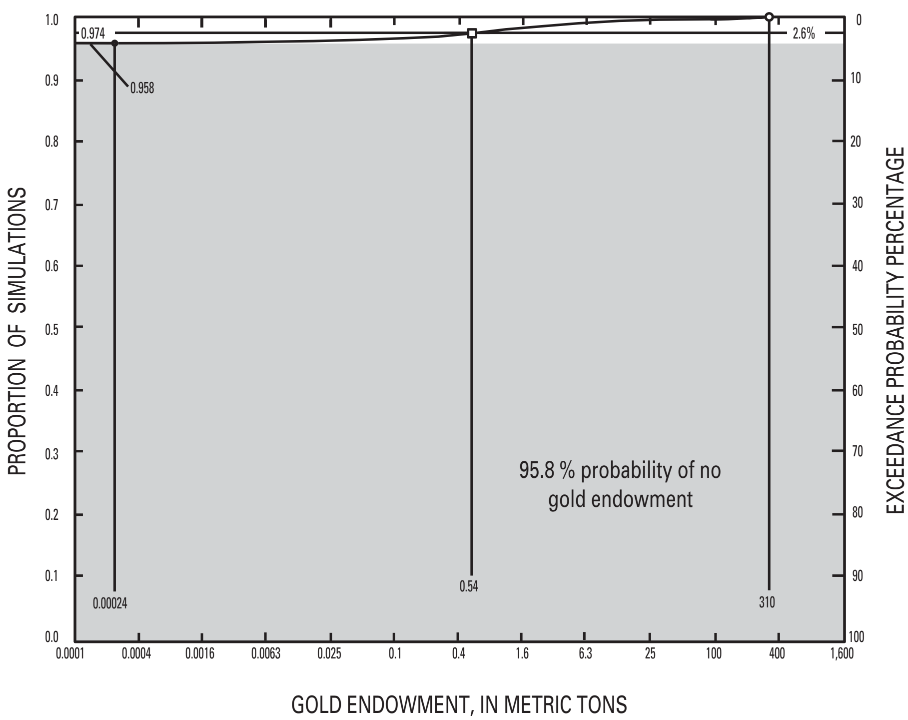


Percentile	Lead
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0
100	0.82

Figure F6. Precambrian Kuroko-type massive sulfide deposits: simulated Mark3 endowment distributions for zinc and lead occurring in undiscovered deposits in permissive tracts in GMUG greater study area.



Percentile	Silver
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0
100	12,000



Percentile	Gold
0	0
5	0
10	0
15	0
20	0
25	0
30	0
35	0
40	0
45	0
50	0
55	0
60	0
65	0
70	0
75	0
80	0
85	0
90	0
95	0
100	310

Figure F7. Precambrian Kuroko-type massive sulfide deposits: simulated Mark3 endowment distributions for silver and gold occurring in undiscovered deposits in permissive tracts in GMUG greater study area.

Mineral Resource Assessment for Porphyry Molybdenum Deposits

By Dana J. Bove, Daniel H. Knepper, Jr., Viki Bankey, Gregory T. Spanski, and Steven M. Smith

Chapter G of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

Edited by Viki Bankey

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Mineral Resource Assessment for Porphyry Molybdenum Deposits

By Dana J. Bove, Daniel H. Knepper, Jr., Viki Bankey, Gregory T. Spanski, and Steven M. Smith

Abstract

Porphyry molybdenum deposits that are economical to produce are large tonnage and bulk-mined by underground and open-pit operations. Molybdenite (MoS_2) is present in stockwork veinlets within variable host rocks that have been hydrothermally altered in a pattern roughly concentric to a complex of nested intrusions. Genetic models describing these deposits emphasize an important relation to the chemical composition of the related intrusive rocks. Deposits or mineral occurrences within the GMUG greater study area group into two main types: (1) high-silica granite and (2) granodiorite or quartz monzonite. In this chapter, we describe the geologic, geochemical, and geophysical characteristics of both types and discuss the likelihood of undiscovered deposits.

Granite Porphyry Molybdenum Deposits

Genetic Model for Granite Porphyry Molybdenum Deposits

Granite systems in North America, exemplified by the Climax, Henderson, and Mount Emmons deposits in Colorado (White and others, 1981; Carten and others, 1993), are present almost exclusively within the western United States and are the most significant of the porphyry molybdenum deposits in regards to ore-grade tonnage, and production history. Most granite molybdenum deposits contain between 50 and 1,000 million t (metric tons) of molybdenum ore (White and others, 1981), with a median of 200 million t (Cox and Singer, 1986). The average ore body ranges from 0.1 percent MoS_2 at the margins to average internal grades of 0.3 to 0.45 percent MoS_2 (White and others, 1981). Tin and tungsten are important byproducts in some deposits, whereas copper content is relatively low: Cu:Mo ratios range from 1:100 to 1:50 (White and others, 1981).

Granite porphyry molybdenum deposits are characterized by episodic mineralization and penecontemporaneous intrusion of high-silica (>74 percent SiO_2), alkali-rich granite or rhyolite. Generally small and cylindrical, these high-silica stocks or plugs are thought to represent high-level cupolas that extend above large silicic plutons (White and others, 1981). These small granitic plugs or stocks are highly differentiated and are characterized by the following general geochemical signature (Ludington, 1981):

F (>0.1 percent)	Rb (>250 ppm)	Sr (<50 ppm)
Cs (>10 ppm)	Nb (>50 ppm)	Ta (>10 ppm)
Ba (<300 ppm)	Sn (>5 ppm)	(U >10 ppm)
La (<50 ppm)	Y (>50 ppm)	

All dated deposits in the western U.S. are less than 50 Ma, whereas the five major deposits in Colorado (Climax, Henderson, Urad, Mount Emmons, and Redwell Basin) range from 33 to 17 Ma, and are mostly < 25 Ma (White and others, 1981). Granite molybdenite systems are thought to be associated with the transition from compressive to extensional tectonism (White and others, 1981; Ludington, 1981; Mutschler, Wright, and others, 1981; Carten and others, 1993). The ore zones of granite molybdenum deposits are centered in or above the apical portion of the source granitic intrusion. Generally elliptical in plan view and concave downward in cross section, the ore bodies have thicknesses of ≈130–330 m and vertical dimensions of about 330–660 m (Mutschler, Wright, and others, 1981; White and others, 1981). More than 90 percent of the molybdenite is present in thin, moderately to steeply dipping stockwork veinlets along with quartz, fluorite, and traces of biotite, potassium feldspar, pyrite, and sericite. Tungsten is generally concentrated in discrete zones in or adjacent to the molybdenite ore bodies, whereas pyrite and base-metal sulfide zones extend to higher levels and more laterally than the molybdenum and tungsten bodies. The base-metal sulfide zone consists of veins and veinlets containing galena, sphalerite, and pyrite with minor chalcopyrite, rhodochrosite, and fluorite; these veins typically extend outward into the peripheral host rocks. Although spatially associated with molybdenite ore bodies, the base-metal polymetallic veins typically postdate molybdenite mineralization and related hydrothermal alteration (Thomas and Galey, 1982; White and others, 1981; Wallace and others, 1968). However, isotopic studies (Stein and Hannah, 1985) indicate that lead within base-metal veins is predominantly derived from the

Tertiary-age stock(s) related to molybdenite mineralization, whereas only a minor component of the lead is scavenged from nearby host rocks.

Hydrothermal alteration associated with these deposits is consistent with the classic assemblages and patterns inherent to all molybdenum and copper porphyry deposits as described by Lowell and Guilbert (1970). In general, alteration changes from a potassic zone (secondary potassium feldspar and biotite) near the core of the deposit outward and upward into quartz-sericite-pyrite (QSP), argillic (quartz, kaolinite, smectite), and finally into propylitic alteration (primary minerals, chlorite, epidote, sericite, and calcite). The QSP zone, which contains as much as 10 volume percent pyrite (White and others, 1981), is an important signature in the exploration for these types of deposits.

Description of the Areas Containing Known Granite Porphyry Molybdenum Deposits

Three granite porphyry molybdenum deposits have been discovered beneath the slopes of Mount Emmons, which is about 6 to 8 km northwest of Crested Butte, Colo. (fig. G1). Two of these deposits are located deep (>600 m) beneath a high cirque basin north of Mount Emmons known as Redwell Basin. The third deposit is on the south side of Mount Emmons beneath the western rim of Red Lady Basin and is referred to as the Mount Emmons deposit.

The Mount Emmons deposit is a contact-related stockwork of quartz veinlets containing molybdenite along with fluorite, pyrite, and minor huebnerite that is draped over the top of an 18–16 Ma granite stock (Thomas and Galey, 1982; White and others, 1981). As defined by a 0.2 percent MoS_2 boundary, the deposit is a nearly circular 90 m thick ring in plan view that has an outside diameter of about 670 m. Ore reserves have been calculated at about 141 million t of rock with an average grade of 0.44 percent MoS_2 (Thomas and Galey, 1982). The Mount Emmons deposit is much richer and larger than the Redwell deposits and lies at a shallower depth (Thomas and Galey, 1982).

The uppermost molybdenite deposit in Redwell Basin is at a depth of about 730 m, where it is associated with a small intrusion of rhyolite porphyry. This cupola is surficially expressed as an intrusion breccia complex that was fed via a crackled zone of hornfels present between the deep rhyolite intrusion and the base of the breccia body. As defined by a 0.1 percent MoS_2 boundary, the upper deposit contains about 17 million t of rock that average 0.18 percent MoS_2 (Thomas and Galey, 1982). Rhyolite porphyry in the deep intrusion grades downward into a granite porphyry stock. The lower molybdenite deposit is about 300 m below the upper contact of the granitic stock.

Other known granite porphyry molybdenum occurrences are present throughout the GMUG greater study area (map area, fig. G1). References regarding the nature of these occurrences are found in the following section on application of the deposit model for a mineral resource assessment.

Application of the Deposit Model for a Mineral Resource Assessment of Granite Porphyry Molybdenum Deposits

The criteria used to define permissive and favorable tracts for granite porphyry molybdenum deposits are listed in table G1. Many of these criteria are summarized in the Climax molybdenum deposit model in Cox and Singer (1986; model 16) and were derived from numerous detailed studies of economic granite molybdenite deposits. (See White and others, 1981; Wallace and others, 1968; Thomas and Galey, 1982; Ludington, 1981; Mutschler, Wright, and others, 1981; Stein and Hannah, 1985.) Areas classified as permissive are those that are underlain by Tertiary-age intrusions as mapped in the database compiled by Bove and Knepper (2000) and Day and others (1999) or interpreted from aeromagnetic survey data (Bankey and others, this volume, Chapter D, fig. D3). Several intrusive units, which are not known to host any significant mineralization or related hydrothermal alteration, were excluded from the permissive tracts. Each of the intrusions included in the criteria was surrounded by a 1 km buffer to allow for the presence of covered deposits at depth.

Various combinations of criteria (table G1) were applied in delineation of favorable tracts for the GMUG study area. Distinctions between Criteria 2 and 3 intrusions were based on previous mineral assessment and geologic studies (Bove and others, 2000; DeWitt and others, 2000; Fridrich and others, 1998; Van Loenen and Gibbons, 1997; Cunningham and others, 1994; Sanford and others, 1987; Hon, 1987; Mutschler, Wright, and others, 1981; Mutschler, 1980). Specific characteristics of favorable tracts include distinctive chemical composition of the intrusions, the presence of diagnostic alteration minerals and assemblages, and the occurrence of molybdenite or other minerals such as fluorite.

Permissive Tracts

In the GMUG greater study area, 1,371 mi^2 is classified as permissive for the occurrence of granite porphyry molybdenum deposits (fig. G1). As shown in figure G1, the permissive tract is quite extensive, owing to the abundance of intermediate to silicic composition intrusions in the eastern 3/4 of the GMUG greater study area. These intrusions are absent in the more tectonically stable western part of the study area.

Favorable Tracts

In the GMUG greater study area, 1,242 mi^2 is classified favorable for the occurrence of granite porphyry molybdenum deposits (fig. G2, table G2). These lands represent about 90 percent of the permissive tract. The critical criteria used for

Table G1. Delineation criteria for granite porphyry molybdenum deposits in GMUG greater study area.

Diagnostic criterion for permissive tract delineation
1. Presence of Tertiary or very late Cretaceous hypabyssal intrusions or dikes (2 km buffer) as mapped by Bove and Knepper (2000), or inferred intrusions (2 km buffer) as interpreted from aeromagnetic data (this volume, Chapter D, fig. D3). Several intrusive units and correlative dikes are excluded from the permissive criteria based on previous mineral assessment and geologic studies (Bove and others, 2000; DeWitt and others, 2000; Fridrich and others, 1998; Van Loenen and Gibbons, 1997; Cunningham and others, 1994; Sanford and others, 1987; Hon, 1987; Mutschler, Wright, and others, 1981; Mutschler, 1980). Criterion met by map units Tbgt, Tbrh, Tbrhd, Tbdr, Tdp, Tlrh, Tlsy, Trh, Tqm, Tegd, Term, Termd, Tgm, Tiyg, TmiA, Twfm, Tiys, TmiD, TmiDd, Teqm, Teqmd, Tea, Tead of Bove and Knepper (2000).
Diagnostic criteria for favorable tract delineation (in addition to criterion 1)
2. Tertiary age felsic intrusions and dikes generally known to be granitic or rhyolitic (2 km buffer). Previous geologic and mineral assessment studies indicate that these intrusions are either unlike Climax-type intrusions (White and others, 1981) in their composition or mode of emplacement, or did not undergo mineralization or related hydrothermal alteration. Criterion met by map units Tbdr, Tlrh, Trh, and unit Tiyg as mapped by Bove and Knepper (2000).
3. Tertiary age high-silica, high-Nb, alkali rhyolite or granite intrusions or dikes (2 km buffer). Many are similar in composition and mode of emplacement to Climax-type rhyolites or granites (White and others, 1981), which are associated with major economic stockwork molybdenite deposits. Many of these intrusive units are associated with molybdenite mineralization or hydrothermal alteration indicative of granite porphyry molybdenum mineralization. Map units include Tbgt, Tbrh, Tbrhd, Term, Termd, Tgm, and Twfm (Bove and Knepper, 2000).
4. Criterion 2 or 3 and less than 24 Ma.
5. Surficial rock or stream-sediment samples contain Mo concentration exceeding 15 ppm (parts per million) (500 m buffer) or mines or occurrences with molybdenum in ore-related materials (1 km buffer) as reported in the MRDS and MAS databases (USGS, 1999a, 1999b).
6. Elevated concentrations of any of the following elements in stream sediments or rock samples: Sn ≥20 ppm, W ≥25 ppm, or Nb ≥40 ppm (500 m buffer) **or** mine, occurrence, or mineralized site with huebnerite, fluorite, wolframite, scheelite, tungsten, or topaz present (1 km buffer) or containing elevated F, Sn, W, Nb, Ta, Li, Be, or Rb (1 km buffer) as reported in the MRDS and MAS databases (USGS, 1999a, 1999b).
7. Magnetic anomalies interpreted to be Tertiary age intrusions as defined in criteria 2 and 3 (2 km buffer).

delineating favorable tract areas for granite porphyry molybdenum deposit occurrences are listed in table G1. In addition to meeting the permissive criterion requirement, these lands also meet one or more of the conditions listed in the favorable criteria. Tracts are grouped in broadly defined areas, and the criteria used to classify each of the tracts are identified (table G2).

West Elk Mountains Area (Area 1, fig. G2): This area covers a large part of the West Elk Mountains. Criteria used to delineate this tract include Miocene age (criterion 4), high-silica granite or rhyolite intrusions (criterion 3) in various combination with magnetic anomalies (criterion 7) (generally associated with more mafic, Oligocene plutons), local element enrichments in rocks or stream-sediment samples (Sn ≥20 ppm, W ≥25 ppm, or Nb ≥40 ppm) (criterion 6), and anomalous geochemical enrichments in rocks or stream-sediment samples for Mo (>15 ppm) or mines with molybdenum in ore-related materials as reported in the MRDS and MAS databases (USGS, 1999a) (criterion 5).

Specific subareas of interest in area 1 (fig. G2) include (A) the 12 Ma granite at Treasure Mountain (criteria 3 and 4) with associated molybdenite mineralization (criterion 5); (B) altered and mineralized Miocene age rhyolite dikes and a narrow intrusion (criteria 3 and 4) that cuts the Whiterock pluton northeast of Crested Butte; geochemical anomalies of criteria 5 and 6 are mostly associated with replacement and vein mineralization at the margins of the Oligocene age Whiterock granodiorite pluton (Mutschler, Ernst, and others, 1981), (C) the Mount Emmons and Redwell Basin molybdenum deposits, just west of Crested Butte, and (D) the Hunter Peak–Cataract Creek mineralized and altered area (Miller and Ficklin, 1976; Bryant, 1971) with anomalous concentrations of Sn, W, or Nb in stream sediments or rock samples (criterion 6) and anomalous Mo in stream sediment or rock samples or within mines (criterion 5).

Grizzly Peak Caldera Area (Area 2, fig. G2): This area is in and adjacent to resurgent granitic intrusions of the 35–33 Ma Grizzly Peak caldera and associated with the Winfield felsic stocks and plugs (≈39 Ma), the latter mostly within and adjacent to the Twin Lakes pluton. The resurgent intrusions of the Grizzly Peak caldera meet criterion 2, have significant magnetic anomalies (criterion 7), and are hydrothermally altered. The entire tract has an anomalous scattering of Sn, W, or Nb in stream sediments or rock samples (criterion 6). Areas surrounding the Winfield felsic stocks meet criterion 3, owing to the evolved nature of these intrusions, and have other criteria including magnetic anomalies (criterion 7), and dense clustering of molybdenum geochemical anomalies in stream or rock samples or within mines (criterion 5).

Fossil Ridge (Area 3, fig. G2): This tract in the Fossil Ridge area (DeWitt and others, 2002) is underlain by intrusions and dikes of highly evolved Oligocene rhyolite and granite

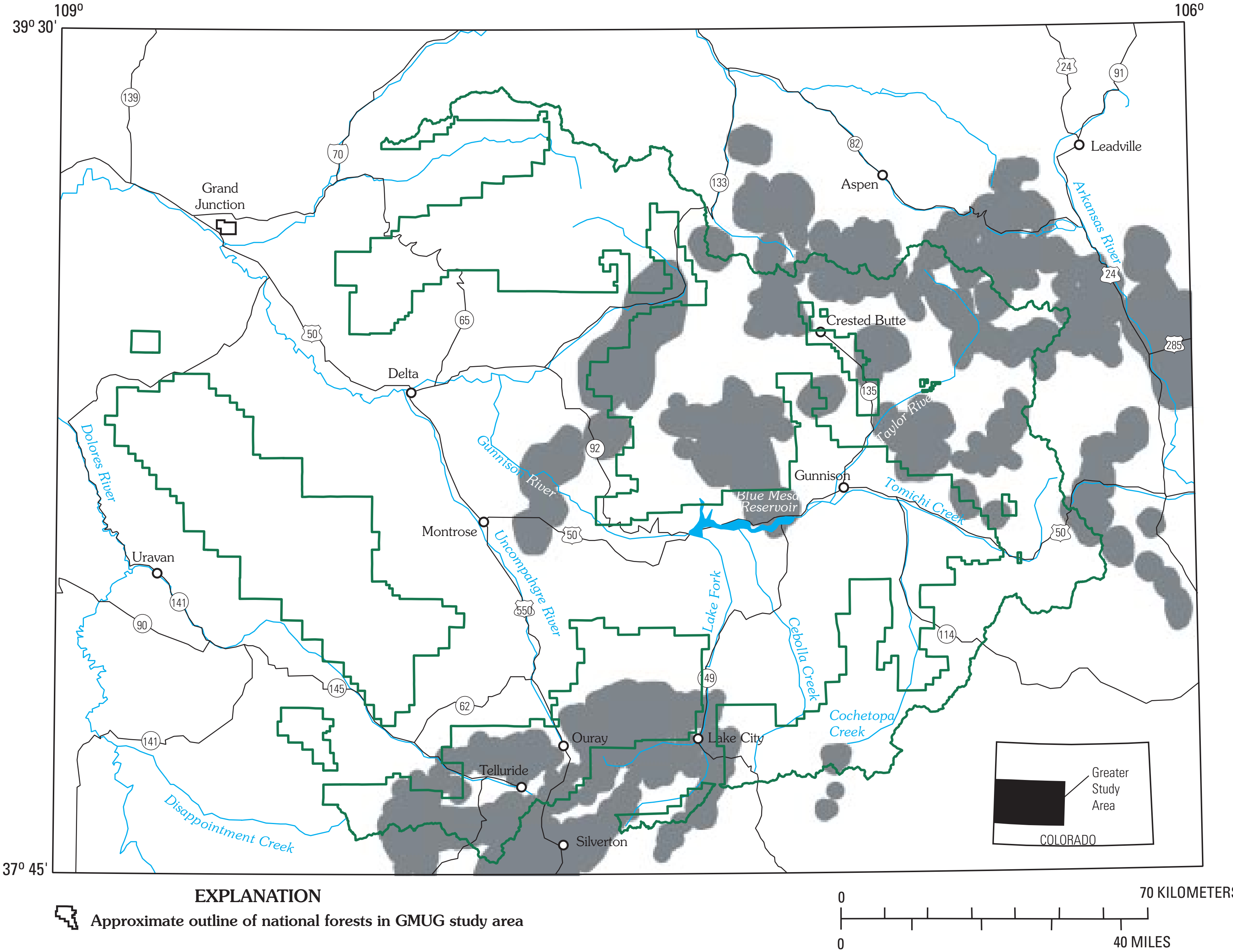

Figure G1. GMUG greater study area, showing permissive tracts (gray shade) for porphyry molybdenum deposits.

Table G2. Granite porphyry molybdenum tracts in GMUG greater study area.

Tract No.[a]	Tract name	Delineation criteria
P1	Permissive for granite molybdenum deposits	1
F1	West Elk Mountains	1, 3, 4, 5, 6, 7
F2	Grizzly Peak caldera	1, 2, 3, 5, 6, 7
F3	Fossil Ridge	1, 3, 5, 6
F4	Lake City caldera	1, 2, 3, 4, 5, 6, 7
F5	Silverton caldera	1, 3, 4, 5, 6

[a]P denotes a permissive tract, F, a favorable tract.

(criterion 3). These intrusions have anomalous concentrations of Sn, W, or Nb in stream sediments or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples or within mines (criterion 5). Molybdenum geochemical anomalies are very densely clustered in the vicinity of Cumberland Pass and Green Mountain (fig. G2). Most hydrothermal alteration in this tract, as detected by broad-band remote sensing, took place in the area surrounding Cumberland Pass and Green Mountain. The Tomichi dome, a Miocene (criterion 4) domal rhyolite intrusion (criterion 3) lies just outside the south end of this tract. However, unlike the Fossil Ridge intrusions to the north, this intrusion is unaltered and no occurrences of mineralized rock are reported.

Lake City Caldera Area (Area 4, fig. G2): This tract generally encompasses the Miocene age Lake City caldera, which is nested with the older Uncompahgre caldera (Oligocene). Intrusions within this tract are young (criterion 4) and meet criterion 2, but they lack characteristics such as evidence of molybdenite mineralization, diagnostic chemical composition, hydrothermal alteration, or mode of emplacement (Sanford and others, 1987; Hon, 1987) typical of criterion 3. Anomalous molybdenum in rocks, sediment, or mines in the vicinity of the Lake City caldera (criterion 5) is largely due to high Mo concentrations in the intracaldera Sunshine Peak Tuff, anomalous concentrations in polymetallic veins (as much as 1,000 ppm), and sparse dissemination around intrusions (Hon, 1987; Sanford and others, 1987). Magnetic anomalies (criterion 7) mostly coincide with intrusions related to resurgence of the Lake City caldera.

Favorable criteria in two smaller areas within this tract warrant further discussion. Molybdenum and associated geochemical anomalies or occurrences (criteria 5 and 6) in the vicinity of Handies Peak (fig. G2) are related to polymetallic vein mineralization (Sanford and others, 1987). A 17.1 Ma (criterion 4) high-silica rhyolite dike in the Cuba Gulch area meets criterion 3 and is associated with anomalous concentrations of Sn, W, or Nb in stream-sediment or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples or within mines (criterion 5). Field studies indicated that this dike is associated with mineralized pebble dikes, fluorite, and sparse molybdenum (Hon, 1987).

Silverton Caldera Area (Area 5, fig. G2): This large tract covers much of the Silverton caldera area. It contains numerous small intrusions and dikes of Miocene high-silica rhyolite (criteria 3 and 4). In addition, anomalous concentrations of Sn, W, or Nb occur in stream-sediment or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples and in mine samples (criterion 5). Molybdenum mineralization in the Red Mountain Pass and Anvil Mountain areas (fig. G2) was related to 23 Ma dacitic intrusions (discussed in the section on granodiorite molybdenum models). Large centers of pervasive hydrothermal alteration are centered in the Red Mountain Pass and Anvil Mountain areas but are generally related to the older dacitic intrusions (Bove and others, 2000). A Miocene rhyolite intrusion (criteria 3 and 4) in the Horseshoe Bend area (fig. G2) is associated with anomalous Mo in stream-sediment or rock samples (criterion 5), but molybdenite mineralization proved to be subeconomic during exploratory drilling in the 1970's (Van Loenen and Gibbons, 1997). Intense quartz-sericite-pyrite alteration is zoned around this intrusion.

Undiscovered Deposit and Endowment Potential

Results of the undiscovered deposit and endowment potential assessment are given in table G3. The five-fold estimation of numbers of undiscovered deposits at the 90th, 50th, 10th, 5th and 1st levels of confidence of 0, 0, 0, 1, 1 indicates that the presence of additional Climax molybdenum type porphyry deposits, having grade and tonnage characteristics similar to those depicted by Cox and Singer (1986), is not very likely. However, the estimate of one deposit at the 5 and 1 percent confidence levels suggests a small yet measurable potential for one more deposit occurring somewhere within a kilometer of the surface and within the bounds of the permissive and favorable tract areas. Inclusion of this small deposit potential acknowledges the fact that two (Mount Emmons and Redwell Basin) out of the nine deposits used in the construction of the Climax-type grade and tonnage models occur within the study area and that areas within the study area have been targets of repeated exploration interest for this type of deposit. The Mount Emmons and Redwell Basin deposits

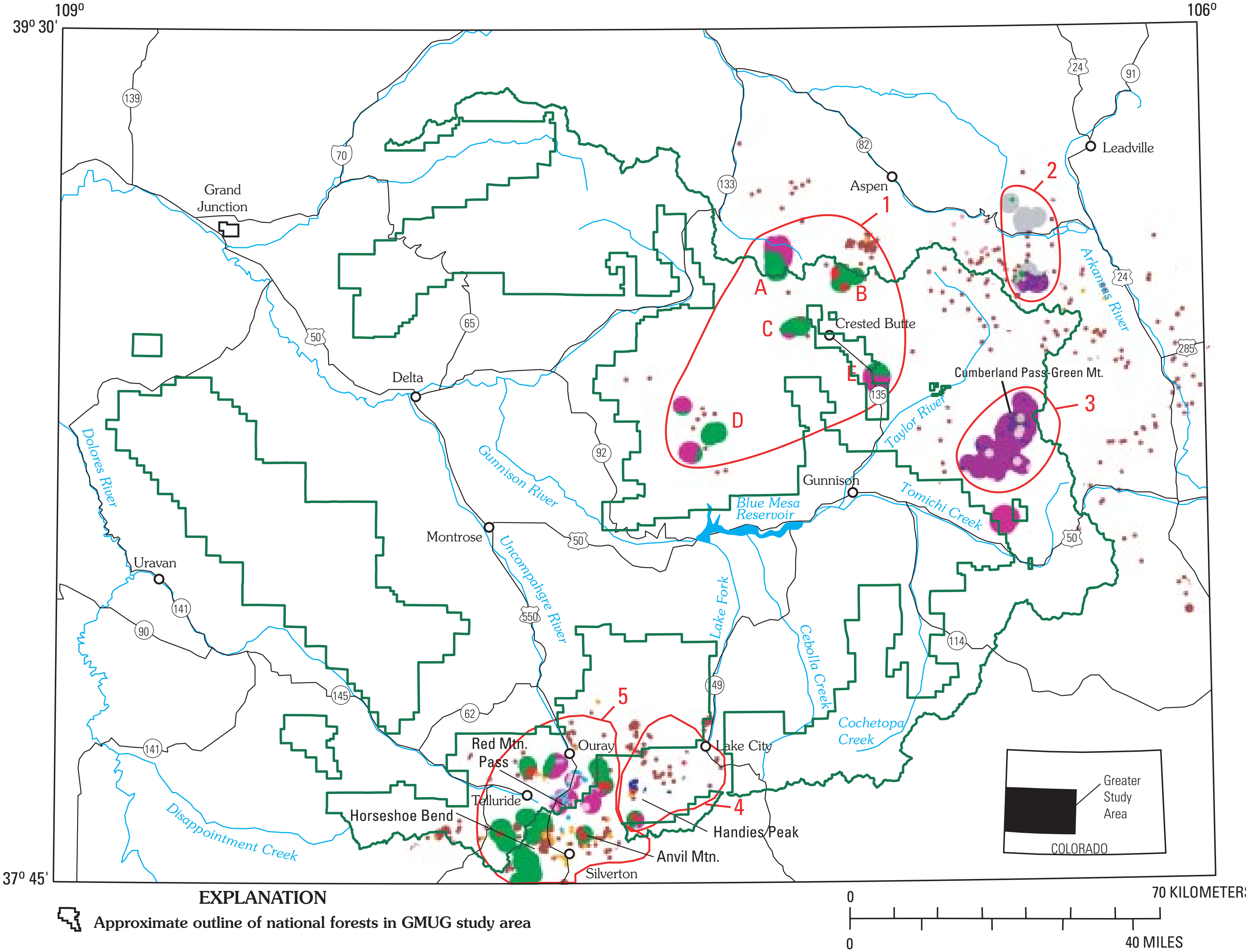

Figure G2 (above and following page). GMUG greater study area, showing favorable tracts for granite porphyry deposits. 1, West Elk Mountains area; A, granite at Treasure Mountain; B, dikes and intrusion that cut Whiterock pluton; C, Mount Emmons and Redwell Basin molybdenum deposits; D, Hunter Peak–Cataract Creek mineralized and altered area; 2, Grizzly Peak caldera area; 3, Fossil Ridge; 4, Lake City caldera area; 5, Silverton caldera area.

EXPLANATION

Criterion 3—Tertiary age high-silica, high Nb, alkali rhyolite or granite intrusions or dikes (2 km buffer)

Criterion 3 and less than 24 Ma (criterion 4)

Criterion 2 (Tertiary rhyolite or granite intrusions excluding criterion 3) and Mo anomalies or occurrences (criterion 5)

Criteria 2 or 3 and 5; with or without 4

Criteria 3, 4, and 5

Criteria 3 and 6

Criteria 2 or 3, 4, and 6

Criteria 5 and 6

Criteria 3, 5, and 6

Criteria 3 and 7 (magnetic anomalies inferred to be Tertiary age intrusions)

Criteria 3, 4 or 6, and 7

Criteria 6 and 7

Criteria 4, 6, 7, and 1 or 2

Criteria 1, 7, 6, and 5

Table G3. Summary of results of resource endowment potential assessment for undiscovered Climax-type porphyry molybdenum deposits within GMUG greater study area.

Mark3 inputs—Undiscovered deposit estimates:

Estimation confidence	90%	50%	10%	5%	1%
Deposits	0	0	0	1	1

Mark3 outputs—Deposit occurrence probability:

Number of deposits	0	1
Probability of occurrence	92.9%	7.1%

Resource endowment estimates (minimums):

Resource	Probability	Mean (probability)		
	90%	50%	10%	
Molybdenum	0	0	0	40,000 (6.7%)
Ore	0	0	0	2,200,000 (6.7%)

Endowment given in metric tons.

along with the nearby world-class Climax and Henderson deposits attest to the unique character of the Tertiary magmatic terrane that underlies the study area and its capacity to generate deposits of this type. The repeated shows of exploration interest indicate that other knowledgeable parties believe the existence of additional Climax-type deposits may be a possibility. If present, they are more likely to reside in the favorable tract areas and deeper regions of the 1,000 m zone of consideration, where exploration has been less thorough.

The low expectations for the existence of undiscovered deposits are reflected in the molybdenum and ore endowment simulation results summarized in table G3. The results show that within the permissive and favorable tract areas for Climax-type deposits, a 92.8 percent probability of no deposits is present, along with a 7.2 percent probability of one deposit; a no-deposit scenario is nearly 13 times more likely than a one-deposit scenario. For the Climax-type tracts, the Mark3 simulation indicates that at the 90, 50, 10 percent probability levels, both the molybdenum and ore endowments attributable to undiscovered deposits are likely to be zero. Expressed in terms of mean endowments, the mean molybdenum endowment for the area is expected to be about 40,000 t (metric tons) and the mean ore endowment, 21 million t.

A more meaningful understanding of the economic importance of the Climax-type deposit potential can be gained from looking at the endowment frequency plots in Spanski and Bankey, this volume, Chapter F, Appendix F1 (see fig. F3). In these plots it can be seen that there is less than a 7 percent probability for occurrence of a molybdenum endowment equal to or larger than the 40,000 t mean. Within the study area the known deposits at Redwell Basin and Mount Emmons have molybdenum endowments of 240,000 and 390,000 t, respectively; they have not been commercially developed. The median molybdenum endowment for the deposit population used to create the Climax-type grade and tonnage models is 388,000 t. The determination of commercial value of the Mount Emmons deposit is complicated by local considerations, and the Redwell Basin deposit may be too small for its depth of burial; however, to expect that a deposit containing 380,000 t of molybdenum would be near the development threshold is not unreasonable. The probability of an undiscovered deposit being present possessing a molybdenum endowment of more than 380,000 t is indicated to be less than 3.6 percent. In spite of this low probability, that a history of recurring interest in exploring for these types of deposits exists, driven by market fluctuations, is unlikely to change in the near future.

Granodiorite Porphyry Molybdenum Deposits

Genetic Model for Granodiorite Porphyry Molybdenum Deposits

Granodiorite molybdenum systems are exemplified by deposits and prospects at Buckingham, Nevada; White Cloud, Little Boulder Creek, and Thompson Creek, Idaho; and Boss Mountain, Endako, and Lime Creek, British Columbia (Soregaroli and Sutherland-Brown, 1976). The median size of these deposits is 94 million tons of ore averaging 0.085 percent MoS_2 (Cox and Singer, 1986; model 26b), which is slightly below the average ore grade of granite porphyry deposits. Byproducts, when present, include tungsten, copper, gold, silver, lead, and antimony. Some granodiorite systems are transitional to true granite porphyry deposits having Cu:Mo ratios of 1:10 to 1:30, whereas near end-member granodiorite deposits have Cu:Mo ratios ranging from 1:1 to 1:10 (Soregaroli and Sutherland-Brown, 1976; White and others, 1981).

Granodiorite molybdenum systems are associated with small composite stocks, late-stage batholiths, and less commonly single phase stocks. Intrusions range from quartz monzonite to granodiorite in composition; whole rock and trace-element chemistry is more similar to Cordilleran porphyry copper deposits (Lowell and Guilbert, 1970) than to granite molybdenum systems. Theodore (1982) classified granodiorite deposits as fluorine-deficient and considered this an important distinction from their fluorine-rich, granite molybdenum counterparts. North American granodiorite deposits are mostly confined to Mesozoic and Tertiary age intrusive rocks (Soregaroli and Sutherland-Brown, 1976).

Most ore-related intrusive bodies are cylindrical (<1,500 m in diameter) and elliptical to circular in plan view (Soregaroli and Sutherland-Brown, 1976; White and others, 1981). The associated ore bodies are cylindrical, tabular, or irregular in cross section; mineralization was generally confined to producing stockwork veinlets developed in or around the roof of the intrusion. These veinlets contain molybdenite and quartz with pyrite, biotite, and minor carbonates. Unlike the composition of veins within the granite molybdenum ore bodies, fluorite and fluorine-bearing minerals are absent. The central portion of most ore bodies contains high concentrations of tungsten, mostly in the form of scheelite. A halo of hypogene copper sulfides is typically situated above the central molybdenite zone and grades into peripheral zones of Pb-Zn and Au-Ag (Westra and Keith, 1981). Hydrothermal alteration related to granodiorite systems is similar to that of the granite molybdenum deposits (Lowell and Guilbert, 1970: Theodore, 1982). However, greisen and zones of pervasive silicification, which are common in granite molybdenum deposits (White and others, 1981), have not been reported. Other distinctions from granite systems include the lack of fluorine and tin-bearing minerals, and a more weakly developed potassic assemblage (Westra and Keith, 1981).

Description of the Areas Containing Known Granodiorite Porphyry Molybdenum Deposits

No molybdenum or copper has been produced from granodiorite porphyry molybdenum deposits in the GMUG greater study area or other parts of Colorado. However, several subeconomic granodiorite molybdenum prospects have been located in western Colorado. In the Middle Fork–Ophir Pass, Capitol City, Iron Beds, and Matterhorn Peak areas (fig. G3), a close spatial association is documented between subeconomic porphyry Mo-Cu mineralized rocks, base-metal sulfide veins, and 26–25 Ma monzonite to quartz monzonite intrusions (Bove and others, 2000; Ringrose and others, 1986; Slack, 1980; Caskey, 1979; Pyle, 1980). These mineralized and altered intrusions are part of a swarm of calc-alkaline intrusions emplaced between 26 and 25 Ma over a broad region of the western San Juan Mountains (Bove and others, 2000).

A weakly mineralized Mo-Cu porphyry system present in the Middle Fork–Ophir Pass area, west of Silverton (fig. G3), is temporally and genetically related to a late quartz monzonite phase (25 Ma) of the Sultan Mountain stock (Ringrose and others, 1986). At this locality, quartz-molybdenite stockwork veins associated with intense quartz-sericite-pyrite (QSP) altered rock are cut by molybdenite-bearing base-metal veins present mostly on the margins of the porphyry system (McCusker, 1982).

Widespread hydrothermally altered rocks in the Capitol City area (fig. G3) are also spatially zoned with respect to several small 26 Ma monzonite to monzogranite porphyry stocks. In some areas, however, alteration does not correspond spatially to intrusive rock outcrops, suggesting the presence of concealed intrusions at shallow depth. In addition to pyrite, disseminations of microscopic chalcopyrite are relatively abundant within the pervasively altered rock. Base-metal veins are also spatially associated with the intrusions and contain elevated concentrations of Sb, As, Bi, Cd, and Mo (Sanford and others, 1987).

Intrusions in the Iron Beds area (fig. G3) are related to areas of locally strong propylitization, some of which are overprinted by intense hydrothermal alteration with slight Cu, Mo, and Zn anomalies (Caskey, 1979). Areas of intense alteration typically grade from an inner zone of silicified rock outward into argillic, weak argillic, and finally into propylitized rock. No obvious concentric zoning of more intensely altered rock is apparent around the Iron Beds intrusions, indicating that the more intense alteration may have been related to deeper seated intrusion(s). Most quartz veins in the Iron Beds area are barren with no visible sulfides at the surface (Caskey, 1979).

The Matterhorn Peak stock, located about 2 km north of the Iron Beds area (fig. G3), comprises at least three separate intrusions that range in composition from monzonite to quartz monzonite porphyry (Pyle, 1980). A hydrothermal alteration halo zoned outward from silicic to QSP, and to propylitic assemblages is distributed concentrically around the westernmost of these intrusions. Molybdenum values range as high as 150 ppm in silicified zones, and visible molybdenite can be recognized in scarce veinlets (Pyle, 1980). Elevated copper concentrations (as much as 130 ppm) are generally restricted to argillic-altered rock, which also contains sparse disseminated chalcopyrite.

A quartz monzonite phase of the Wilson Peak stock contains a large zone of disseminated and vein-filling chalcopyrite (Bromfield and others, 1972). However, the stock lacks well-developed QSP alteration and molybdenum; associated veins are rich in gold rather than base metals.

Dacite porphyry intrusions dated 23 Ma at Red Mountain near Lake City, Colo., are associated with vertically and horizontally zoned hydrothermally altered rock and subeconomic Mo and Cu mineralization (Bove and Hon, 1992). The Red Mountain area is also known to host one of the largest replacement alunite deposits in the United States (Bove and

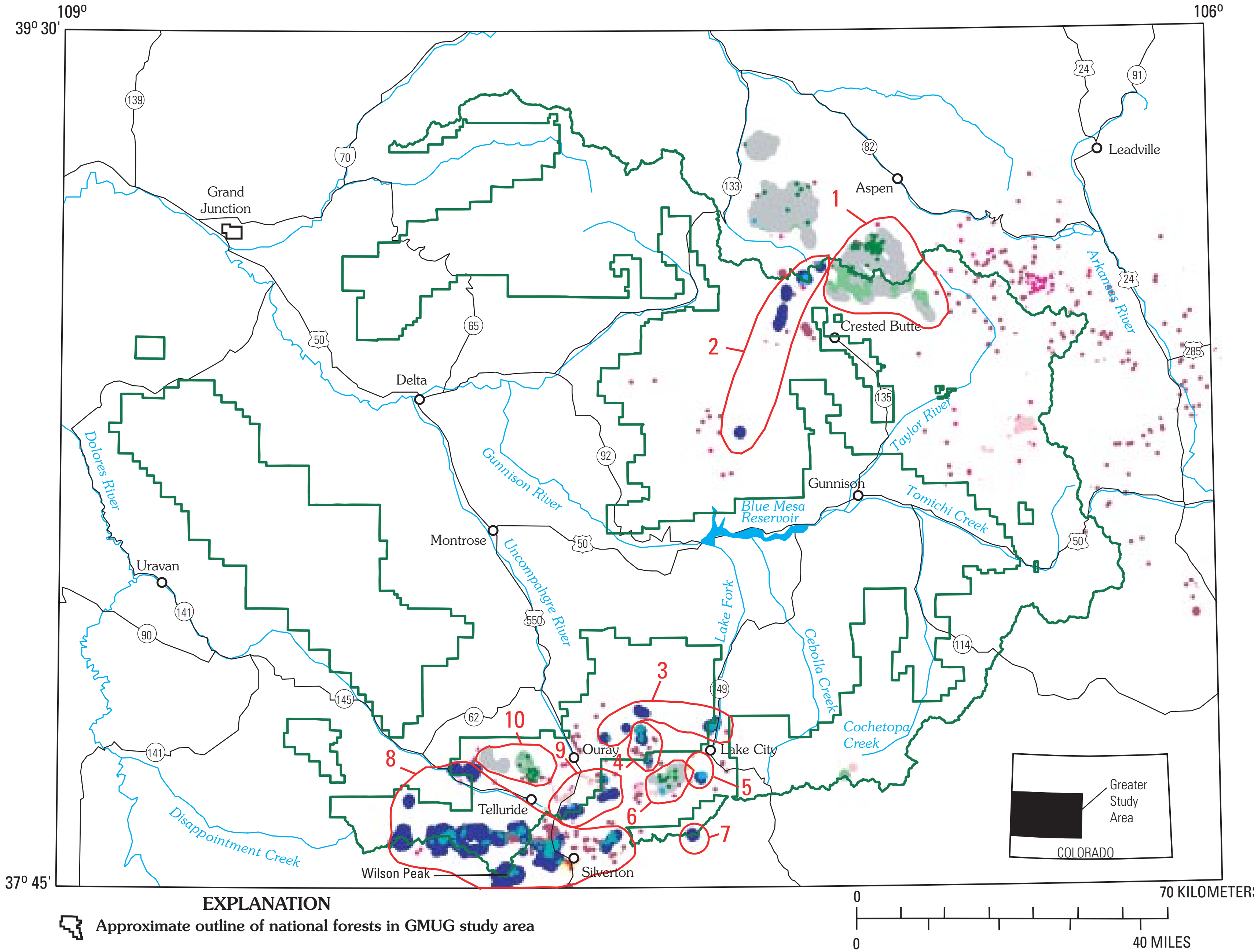

Figure G3 (above and following page). GMUG greater study area, showing favorable tracts for granodiorite porphyry molybdenum deposits. 1, Whiterock area; 2, Ruby area; 3, Cow Creek–Larson area; 4, Capitol City–Matterhorn Peak and Iron Beds; 5, East Red Mountain; 6, Lake City caldera; 7, Carson; 8, West Silverton; 9, Silverton caldera; 10, Sneffels Peak.

EXPLANATION

Criterion 5—Mo mines, geochemistry, mineralogy, buffered

Criteria 4 (hydrothermally altered) and 5

Criteria 4, 5, and 7 (magnetic anomaly inferred to be Tertiary intrusion)

Criteria 3 (known mineralized type of Tertiary intrusive) and 4

Criteria 2 or 3, and 5

Criteria 2 and 4

Criteria 2, 4, and 5

Criteria 2, 4, and 6 (elements associated with Mo in mines or geochemistry, buffered)

Criteria 2, 4, 5, and 7

Criteria 3 and 6

Criteria 3, 4, and 7

Hon, 1992). A weakly mineralized quartz monzonite intrusion in nearby Alpine Gulch is genetically associated with the Red Mountain intrusions (Bove and others, 2000). The Alpine Gulch intrusion has features associated with Cu and (or) Mo mineralization including fragmental dikes, tourmaline breccias, magnetite veinlets, and quartz veins containing pyrite, hematite, sphalerite, galena, and chalcopyrite (Bove and others, 2000). However, alteration haloes are conspicuously absent around this intrusion.

Application of the Deposit Model for a Mineral Resource Assessment of Granodiorite Porphyry Molybdenum Deposits

The criteria used to define permissive and favorable tracts for granodiorite porphyry molybdenum deposits are listed in table G4. Many of these criteria are summarized in the porphyry molybdenum low fluorine deposit model (Theodore, 1982; model 21b), and were derived from numerous detailed studies of economic granodiorite molybdenite porphyry deposits. Areas identified in the permissive model are those that are underlain by Tertiary-age intrusions as mapped in the GIS database compiled by Bove and Knepper (1999) and Day and others (1999) or inferred from aeromagnetic survey data (Chapter D, fig. D3). Several intrusive units, which are not known to host any significant mineralization or related hydrothermal alteration, are excluded from the permissive tract. Each of the intrusions included in the criteria was surrounded by a 1 km buffer to include a two-dimensional approximation to allow for the presence of covered deposits at depth.

Various combinations of all the “favorable” criteria (table G4) were applied to areas in the permissive tract to delineate favorable tracts in the GMUG study area. Distinctions between intrusions described in favorable criteria 2 and 3 were based on previous mineral assessment and geologic studies (Bove and others, 2000; Van Loenen and Gibbons, 1997; Cunningham and others, 1994; Sanford and others, 1987; Hon, 1987; Mutschler, Wright, and others, 1981; Mutschler, 1980).

Permissive Tracts

In the GMUG greater study area, 1,371 mi^2 is classified as permissive for the occurrence of granodiorite porphyry molybdenum deposits (fig. G1). As explained in table G4, these areas are coincident with Late Cretaceous to Tertiary intrusions that were given a 1 km buffer to include a two-dimensional approximation to allow for the presence of covered deposits at depth. As shown in figure G1, the permissive tract is extensive owing to the abundance of intermediate to silicic composition intrusions in the eastern 3/4 of the GMUG study area. These intrusions are absent in the tectonically stable western part of the study area.

Favorable Tracts

In the GMUG greater study area, 324 mi^2 is classified favorable for the occurrence of granodiorite porphyry molybdenum deposits (fig. G3, table G5). These lands represent about 24 percent of the permissive tract. The critical criteria used for delineating regions favorable for hosting granodiorite porphyry molybdenum deposits are listed in table G4. These criteria are more restrictive than those used to delineate the permissive tracts.

Whiterock Area (Area 1, fig. G3): This tract covers the Whiterock and Italian Mountain granodiorite plutons in the West Elk Mountains. Assessment criteria applicable within this tract include granodiorite plutons (criterion 3) that have locally undergone hydrothermal alteration (criterion 4). In addition, this tract is characterized by local base-metal geochemical anomalies in stream-sediment or rock samples (Pb ≥100 ppm, Zn ≥250 ppm, or Ag ≥1 ppm) (criterion 6) and anomalous geochemical enrichments in stream-sediment or rock samples for Mo (criterion 5) or mines with molybdenum in ore-related materials as reported in the MRDS and MAS databases (USGS, 1999a, 1999b). Magnetic anomalies (criterion 7) are also associated with these plutons. Disseminated pyrite, chalcopyrite, and molybdenite showings are present near intrusive contacts with sedimentary rocks (Mutschler, Ernst, and others, 1981) but have not been used as a factor in assessing deposit potential in the area.

Table G4. Delineation criteria for granodiorite porphyry molybdenum deposits in GMUG greater study area.

Diagnostic criterion for permissive tract delineation
1. Presence of Tertiary or very late Cretaceous hypabyssal intrusions or dikes (2 km buffer) as mapped by Bove and Knepper (2000), or inferred intrusions (2 km buffer) as interpreted from aeromagnetic data (this volume, Chapter D, fig. D3). Several intrusive units and correlative dikes are excluded from the permissive criteria based on previous mineral assessment and geologic studies (Bove and others, 2000; DeWitt and others, 2000; Fridrich and others, 1998; Van Loenen and Gibbons, 1997; Cunningham and others, 1994; Sanford and others, 1987; Hon, 1987; Mutschler, Ernst, and others, 1981; Mutschler, 1980). Criterion met by map units Tdp, Tlsy, Tqm, Tiys, TmiD, TmiDd, Teqm, Tea, Tead, Tegd, and TmiA of Bove and Knepper (2000).
Diagnostic criteria for favorable tract delineation (in addition to criterion 1)
2. Tertiary age intermediate to silicic composition intrusions and dikes (1 km buffer). Previous geologic and mineral assessment studies indicate that these intrusions are related to hydrothermal alteration or sparse mineralization. Criterion met by map units Tlsy, Tiys, Tea, Tead, Tegd, TmiA as mapped by Bove and Knepper (2000).
3. Tertiary age hypabyssal stocks, plugs, and dikes ranging from quartz monzonite to granodiorite in composition (1 km buffer). May represent cores of eroded volcanos or may be the uppermost portion of underlying calc-alkaline batholiths (Bove and others, 2000). Some intrusions are the centers of radial or linear dike swarms. Intrusions may range from simple to complexly zoned and in many places are associated with pervasive hydrothermal alteration with base-metal veins and subeconomic Mo-Cu mineralization as determined by previous geologic and mineral assessment studies (Bove and others, 2000; Van Loenen and others, 1997; Cunningham and others, 1994; Sanford and others, 1987; Hon, 1987; Mutschler, Ernst, and others, 1981; Mutschler, 1980). Map units include Tdp, Tqm, TmiD, TmiDd, and Teqm (Bove and Knepper, 2000).
4. Hydrothermally altered rock as interpreted using broad-band spectroscopy (Bove and Knepper, 2000) spatially coincident with intrusions.
5. Surficial rock or stream-sediment samples contain Mo concentration exceeding 15 ppm (parts per million) (500 m buffer) or mines or occurrences with molybdenum in ore-related materials (1 km buffer) as reported in the MRDS and MAS databases (USGS, 1999a, 1999b), or the area defined as a mineralized area containing granodiorite molybdenum (Wilson and Spanski, this volume, Chapter E).
6. Elevated concentrations of any of the following elements in stream sediments or rock samples: Pb ≥100 ppm, Zn ≥250 ppm, or Ag ≥1 ppm (500 m buffer) or mine, occurrence, or mineralized site with sphalerite, galena, chalcopyrite present (1 km buffer) or containing elevated Pb, Zn, Cu, Ag, or Au (1 km buffer) as reported in the MRDS and MAS databases (USGS, 1999a, 1999b).
7. Magnetic anomalies inferred to be caused by Tertiary age intrusions as defined in criteria 2 and 3, where associated with surficial rock or stream-sediment samples containing Mo concentrations exceeding 15 ppm or mines or occurrences with molybdenum in ore-related materials as reported in the MRDS and MAS databases (USGS, 1999a, 1999b) (2 km buffer).

Table G5. Granodiorite porphyry molybdenum tracts in GMUG greater study area.

Tract No.[a]	Tract name	Delineation criteria
P1	Permissive for granodiorite molybdenum deposits	1
F1	Whiterock-Italian Mountain	1, 2, 4, 5, 6, 7
F2	Ruby	1, 3, 4, 5, 6
F3	Cow Creek-Larson	1, 3, 4, 5, 6
F4	Capitol City-Matterhorn Peak	1, 3, 4, 5, 6
F5	East Red Mountain	1, 3, 4, 5, 6
F6	Lake City caldera	1, 3, 4, 5, 6
F7	Carson	1, 3, 4
F8	West Silverton	1, 3, 4, 5, 6
F9	Silverton caldera	1, 3, 4, 5, 6, 7
F10	Sneffels Peak	1, 2, 4, 5, 6

[a]P denotes a permissive tract; F, a favorable tract.

Ruby Area (Area 2, fig. G3): This tract encompasses a north- to northeast-trending band of small stocks and plugs of andesite to granodiorite (criterion 3)—some of which are the centers of radial or linear dike swarms—extending from the West Elk Wilderness along the crest of the Ruby Range (Ruby Peak, Mount Owen, Afley, Augusta, and Paradise Peak stocks) to the Elk Range and Mount Bellview (fig. G3). The southernmost stock, which is located in the West Elk Wilderness, is andesitic and associated with localized hydrothermal alteration (criterion 4). Gaskill and others (1977) reported geochemical anomalies associated with this altered intrusion; however, no metallic minerals other than pyrite were observed.

The small granodiorite stocks of the Ruby Range (criterion 3) are associated with hydrothermal alteration (criterion 4) and zoned metallic mineralization (Mutschler, Ernst, and others, 1981). The Paradise Pass stock at the north end of the Ruby Range is associated with hydrothermal alteration (criterion 4), local base-metal anomalies in stream-sediment or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples or within mines (criterion 5). The intrusion is cut by a stockwork of QSP veins that locally contain molybdenite and chalcopyrite (Mutschler, Ernst, and others, 1981); pervasive quartz-sericite-pyrite alteration is locally developed, especially along the margins of the stock.

Mount Bellview is the site of a zoned granodiorite to quartz monzonite intrusive complex (criterion 3). The intrusions are hydrothermally altered (criterion 4) with local base-metal anomalies in stream-sediment or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples or within mines (criterion 5). A 1,200 m diameter hornfels aureole in Mancos Shale host rock surrounds the intrusive complex, and local quartz-molybdenite veinlets are also present (Lynch and others, 1985).

Cow Creek–Larson Area (Area 3, fig. G3): This tract encompasses three eroded Oligocene age volcanic centers (from Larson, Cimarron, and Cow Creek volcanos) and associated intermediate composition stocks and dikes (criterion 3). The composite stocks are hydrothermally altered (criterion 4) and have local base-metal anomalies in stream-sediment or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples or within mines (criterion 5). Weak disseminated mineralization and alteration are related to emplacement of these stocks (Hon and others, 1986). Veins and mineralized shears are present along the margins of dikes and in radial fractures, and these also appear to be related to the volcanic complexes (Hon, 1987).

Capitol City–Matterhorn Peak (Area 4, fig. G3): This tract contains hydrothermally altered (criterion 4), Miocene age monzonite to quartz monzonite stocks and plugs (criterion 3) that extend northward from the Capitol City area to Matterhorn Peak (fig. G3). These intrusions coincide with anomalous Mo in stream-sediment or rock samples or within mines (criterion 5) and local base-metal anomalies in stream-sediment or rock samples (criterion 6). Scattered magnetic anomalies are also present within this tract and overlap with geochemical anomalies of criteria 5 and 6, further reinforcing the favorable designation. However, some magnetic anomalies are related to more silicic intrusions, which are discussed in the previous section on granite molybdenum systems, and for that reason the presence of a magnetic anomaly alone is not sufficient cause for applying a favorable classification.

East Red Mountain (Area 5, fig. G3): Tract includes hydrothermally altered (criterion 4) dacite porphyry intrusions (criterion 3) in the vicinity of Red Mountain (near Lake City) and an unaltered dacite to quartz monzonite intrusion (criterion 3) in nearby Alpine Gulch. Anomalous concentrations of base metals in stream-sediment or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples or within mines (criterion 5) are present in the area around Red Mountain. The Alpine Gulch intrusion is associated with anomalous base-metal concentrations in stream-sediment or rock samples (criterion 6). Details on mineralization related to these intrusions are found in the previous section describing areas containing known deposits.

Lake City caldera (Area 6, fig. G3): Includes quartz syenite intrusions (criterion 2) associated with the resurgence of the Miocene age Lake City caldera. Hydrothermal alteration is commonly present in or adjacent to these intrusions (criterion

4). Anomalous concentrations of base metals in stream-sediment or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples or within mines (criterion 5) are present in the vicinity of these intrusions. Convective circulation of large volumes of meteoric water during resurgence of the Lake City caldera appears to have scavenged base metals and molybdenum from related pyroclastic units with subsequent deposition into veins and fractures above and adjacent to these intrusions (Bove and others, 2000).

Carson (Area 7, fig. G3): Tract includes intermediate composition intrusive core of the Oligocene age Carson volcano (criterion 3); the intrusion and surrounding area is hydrothermally altered (criterion 4). Previous studies indicate that the central intrusion and adjacent lavas are irregularly altered and cut by fracture zones with quartz-barite-sulfide veins (Lipman and others, 1976).

West Silverton (Area 8, fig. G3): Within this large tract are hydrothermally altered (criterion 4), Oligocene age quartz monzonite to granodiorite stocks and plutons (criterion 3) that extend from Howardsville (east of Silverton) west to Mount Wilson (fig. G3). The surface rocks, stream sediment, mine occurrences, and mineralized sites near these intrusions contain anomalous concentrations of base metals (criterion 6) and anomalous levels of Mo (criterion 5). Areas of notable mineralization include the Middle Fork–Ophir Pass and Wilson Peak areas, discussed in a previous section.

Silverton caldera (Area 9, fig. G3): Tract contains Miocene age stocks and dikes of dacite porphyry in the vicinity of Houghton Mountain, Engineer Pass, and in the Red Mountain area, north of Silverton (fig. G3). Intrusions in these areas have undergone hydrothermal alteration (criterion 4) and locally coincide with geochemical anomalies of criteria 5 and 6, as well as magnetic anomalies (criterion 7). The dacite intrusions within this tract are similar in age, texture, and composition to alunitized and mineralized dacite porphyry intrusions at Red Mountain, near Lake City, and at the Summitville mine in the eastern San Juan Mountains (Bove and others, 2000). Combined geochemical anomalies (criteria 5 and 6) in the absence of criterion 2 or 3 intrusions are clustered in the areas of Mineral Creek and the Red Mountain Pass area; however, these anomalies are likely related to polymetallic vein and breccia deposits (see previous section describing areas containing known deposits).

Sneffels Peak (Area 10, fig. G3): This tract includes Oligocene Sneffels Peak granodiorite stock and similar intrusions (criterion 2) several kilometers to the west. These intrusions have been hydrothermally altered (criterion 4); however, only the area around Mount Sneffels has an associated anomalous base-metal and molybdenum geochemical signature (criteria 5 and 6). Mineralization in the vicinity of Mount Sneffels took place later than the emplacement of the stock (Miocene) and predominantly resulted in vein and replacement types of deposits (Lipman and others, 1976). Anomalous concentrations of base metals in stream-sediment or rock samples (criterion 6), and anomalous Mo in stream-sediment or rock samples or within mines (criterion 5) are present in the vicinity of these intrusions. Several aeromagnetic anomalies are related to these intrusions (criterion 7).

Undiscovered Mineral Deposit and Endowment Potential

Results of the undiscovered mineral deposit and endowment potential assessment are given in table G6. The estimation of numbers of undiscovered deposits at the 90th, 50th, 10th, 5th, and 1st levels of confidence of 0, 0, 0, 0, 2 indicates that the presence of additional granodiorite porphyry molybdenum, low fluorine-type deposits, having grade and tonnage characteristics similar to those depicted by Menzie and Theodore (1986), is not very likely. However, the estimate of two deposits at the 1 percent confidence level implies that a small yet measurable potential for up to two more deposits occurring within a kilometer of the surface exists. The small deposit potential recognizes the fact that the magmatic terrane that underlies the greater study area and that dominated geologic events during Tertiary time is unique in terms of its molybdenum geochemistry. As each pulse of magmatic activity evolved, it gave rise to a series of intrusive and extrusive events in which the later events demonstrated a tendency to become anomalously enriched in molybdenum. This process is clearly demonstrated by the younger granite systems and their associated Climax-type mineralization, and it is believed that the earlier evolving granodiorite systems also possessed this same intrinsic molybdenum geochemistry. Although there are no known examples of granodiorite porphyry molybdenum, low fluorine deposits, prospects of this type are present. Where deposits are present, they are more likely to occur in the favorable rather than the permissive tract areas and in the deeper regions of the 1,000 m zone of consideration or where a host terrane is buried by younger surficial materials.

Results of the Mark3 molybdenum and ore endowment simulations are also summarized in table G6. The results show that within the permissive and favorable tract areas for the granodiorite porphyry molybdenum, low fluorine-type deposits there is a 96.1 percent probability of no deposits being present, a 1.9 percent probability of one deposit and a 2 percent probability of two deposits. A no-deposit scenario is nearly 48 times more likely to occur than either a one- or a two-deposit scenario. The Mark3 simulation indicates that at the 90, 50, and 10 percent probability levels, both the molybdenum and ore endowments attributable to undiscovered deposits are zero. Expressed in terms of mean endowments, the mean molybdenum endowment is expected to be about 8,700 t and the mean ore endowment, 11 million t.

A better appreciation of the exploration and development potential associated with the deposit type can be gained through looking at the endowment frequency plots in Spanski and Bankey, this volume, Chapter F, Appendix F1 (see figs. F3 and F4). These plots show less than a 4 percent probability of any molybdenum endowment; however, the probability drops

Table G6. Summary of results of resource endowment potential assessment for undiscovered porphyry molybdenum, low fluorine deposits within GMUG greater study area.

Mark3 inputs—Undiscovered deposit estimates:

Estimation confidence	90%	50%	10%	5%	1%
Deposits	0	0	0	0	2

Mark3 outputs—Deposit occurrence probability:

Number of deposits	0	1	2
Probability of occurrence	96.1%	1.9%	2%

Resource endowment estimates (minimums):

Resource	Probability			Mean (probability)
	90%	50%	10%	
Molybdenum	0	0	0	8,700 (3.7%)
Ore	0	0	0	11,000,000 (3.7%)

Endowment given in metric tons.

even lower when economic viability is considered. There are no examples in the greater study area or in Colorado to use as an economic gauge; however, it is reasonable to apply the same parameters used for the Climax-type deposits. If a 380,000 t molybdenum endowment is used, the probability of that or a larger endowment occurring is only one half of 1 percent, and the simulation does not clarify whether that endowment is associated with one or two deposits. The 380,000 t constraint may be too large in light of the fact that a deposit of this type is being actively mined at Thompson Creek in Idaho, which has a reported endowment of 250,000 t of molybdenum (Cox and Singer, 1986). At this reduced level, the probability of occurrence increases only to 1 percent. Owing also to the size and the disseminated nature of the molybdenum mineralization, a deposit of this type would only be of interest to major mining companies. Under these circumstances, exploration interest in targets of this type will be virtually nonexistent unless market demand and price for molybdenum increase.

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Mineral Resource Potential Assessment for the Sandstone-Hosted Uranium Deposit Type

By Gregory T. Spanski, Viki Bankey, and Steven M. Smith

Chapter H of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

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Mineral Resource Potential Assessment for the Sandstone-Hosted Uranium Deposit Type

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Abstract

Sandstone-hosted uranium deposits occur in the Uravan mineral belt in the extreme western portion of the GMUG greater study area. From the late 1940's to the mid 1970's, the area has served as the source for the production of more than 63 million pounds of U_3O_8 and 330 million pounds of V_2O_5. In this study, an area of 6,700 square miles is identified as permissive for the presence of deposits containing endowments of more than 2.3 metric tons of U_3O_8. Approximately 1,500 square miles of these lands fall within the GMUG National Forests and 2,650 square miles are in land managed by the Bureau of Land Management. Data for anomalous levels of radioactivity, anomalous levels of uranium in stream sediments and water, the presence of existing occurrences, and previous assessment results suggest that some 1,350 square miles of the permissive area is believed to have substantially higher probability of hosting these deposits and is delineated as favorable. However, owing to the lack of grade and tonnage information about existing deposits, no estimates concerning the possible numbers of undiscovered deposits that might be present could be conducted. Past experience has shown that exploration and development activity related to these deposits are extremely sensitive to price fluctuations, which suggests that future increases in price above $15 per pound level would be a sufficient stimulus.

Introduction

Uranium hosted in sedimentary rocks occurs in five geographically distinct areas associated with the GMUG greater study area in western Colorado: the Uravan mineral belt, Placerville area, Marshall Pass area, Cochetopa area, and Ruby-Irwin area. Their existence is attributed to at least three different modes of origin. The Placerville occurrences represent mineralization that appears to have been controlled by a lacustrine shoreline effect. These deposits are predominantly vanadium rich: recorded production is 13 million lb of V_2O_5 with only minor byproduct uranium production (31 thousand lb of U_3O_8). The Marshall Pass and Cochetopa areas have a history of significant production (nearly 8 million lb) of U_3O_8; however, the origins of these deposits remain in question and have variously been attributed to either intrusion-related magmatic-hydrothermal activity (Malan and Ranspot, 1959) or supergene enrichment (Olson, 1988). Occurrences in the Uravan mineral belt and the Ruby-Irwin area are genetically similar and descriptively match the characteristics of the deposit model for sandstone-hosted uranium deposits (Turner-Peterson and Hodges, 1986). Deposits in the Uravan mineral belt have produced approximately 63 million lb of U_3O_8 and 330 million lb of V_2O_5 through the early 1970's (Nelson-Moore and others, 1978), whereas only occurrences have been found in the Ruby-Irwin area with no production. The sandstone-hosted uranium deposits have historically been the dominant producers of uranium and vanadium in the region and the more probable source of any future production. By comparison, the production from the other sediment-hosted deposits in the Placerville, Marshall Pass, and Cochetopa areas has been of minor interest, and in the absence of appropriate deposit models their potential cannot be assessed. This assessment effort is therefore wholly focused on evaluating the potential of the sandstone-hosted uranium deposits.

The U.S. Geological Survey has conducted an intensive long-term program of internal and contractual investigations of uranium occurrences in the United States, which culminated in the early 1980's with the publication of a series of reports of the National Uranium Resource Evaluation (NURE) contract study. Those reports summarized the then current understanding of how uranium deposits form, where they occur, and where new resources are likely to be found. Subsequent studies have not substantially altered the findings and conclusions in those reports. The discussion and delineation of assessment tracts that follow are largely based on the content of the NURE reports for the Moab (Campbell and others, 1982a), Cortez (Campbell and others, 1982b), Durango (Theis and others, 1981), Montrose (Goodknight and Ludlam, 1981), and Leadville (Collins and others, 1982) 1°×2° quadrangles and the Butler and Fischer (1978) review of uranium and vanadium resources in the Moab quadrangle.

Model for Sandstone-Hosted Uranium Mineral Deposits

A significant number of descriptive and genetic models have been proposed over the last half-century to explain the existence of sandstone-hosted uranium deposits. Examples of models include those of Fischer and Hilpert (1952), Finch (1967), Fischer (1968), Shawe (1976), Austin and D'Andrea, Jr. (1978), Mickle and Mathews (1978), Ruzicka and Bell (1984), and Turner-Peterson and Hodges (1986). Although differing in detail, such as ore genesis processes, the models are consistent on the broader descriptive aspects of these deposits and the geologic environments in which the deposits may be expected to occur.

Uranium in these deposits occurs in a low-valent form as primary uraninite (pitchblende) and coffinite with pyrite and sporadic marcasite. Organic debris is commonly plentiful. The uranium minerals fill intergranular pore spaces and replace carbonaceous material, quartz grains, and interstitial cements in clastic rocks, mainly sandstones. Individual mineralized zones may vary in form from tabular bodies concordant with formation bedding to discordant C- or S-shaped bodies that cut across bedding. The original sand bodies are generally immature, possessing a large proportion of lithic-tuffaceous and (or) feldspathic compositional grains, and occur as layers or lenses in interbedded sequences or interfingering with mudstone. Permeability is highly variable, caused by rapid changes in grain size or localized variation in the content of clay minerals, intergranular cements, or carbonaceous detritus. The original sand bodies were deposited in an arid to semi-arid, terrestrial (continental) environment, on a stable platform, foreland-interior basin, or shelf-margin tectonic setting, where stream gradients were low and channel meandering and formation of backswamp environments were dominant processes. These environments were coupled with an adjacent highland area in which erosion of felsic intrusive and pyroclastic rocks contributed sediment to the basin; nearby volcanic activity periodically deposited widespread air-fall tuffaceous detritus over the basin surface.

A variety of sources of the uranium has been proposed: (1) feldspathic detrital sediment derived from incompletely weathered felsic rocks in the highland areas, (2) clays with adsorbed uranium that are delivered to the basin, or (3) devitrifying tuffaceous detritus deposited on the basin floor. Oxidizing, bicarbonate-charged meteoric ground water percolating through these sediments leached uranium from diagenetically altering volcanic glass, feldspars, and clay minerals, and transported it in its high-valent (+6) oxidation state. Where these uranium-bearing waters encountered reducing conditions, uranium was precipitated as the low-valent (+4) oxide (uraninite) or silicate (coffinite). Possible agents responsible for producing the reducing conditions include buried organic or carbonized material, entrapped H_2S or methane gases produced by anaerobic bacterial activity, humic acids, or sulfide minerals, mainly pyrite. In the arid to semi-arid environment described, forest vegetation would be restricted to highland areas and lower gradient areas near the basin center or coastal plain. The overall low density of vegetation would be consistent with episodes of high runoff, flooding and rapid cutting and filling of basin sediments, and consequent rapid burial of vegetation carried in flood water. Reducing conditions would be preserved in the low-permeability, organic-rich muds accumulating in backswamp areas during the early stages of diagenesis by persistent high water table conditions and presence of entrapped bacterially generated gases. Oxidizing conditions would be restricted to the adjacent higher permeability, coarser grained channel-fill sands through which uranium-bearing ground water flowed basinward. Primary uranium mineralization occurred where the reducing and oxidizing conditions interfaced at the margins of organic-rich sediment layers and organic detritus buried in more permeable sand layers.

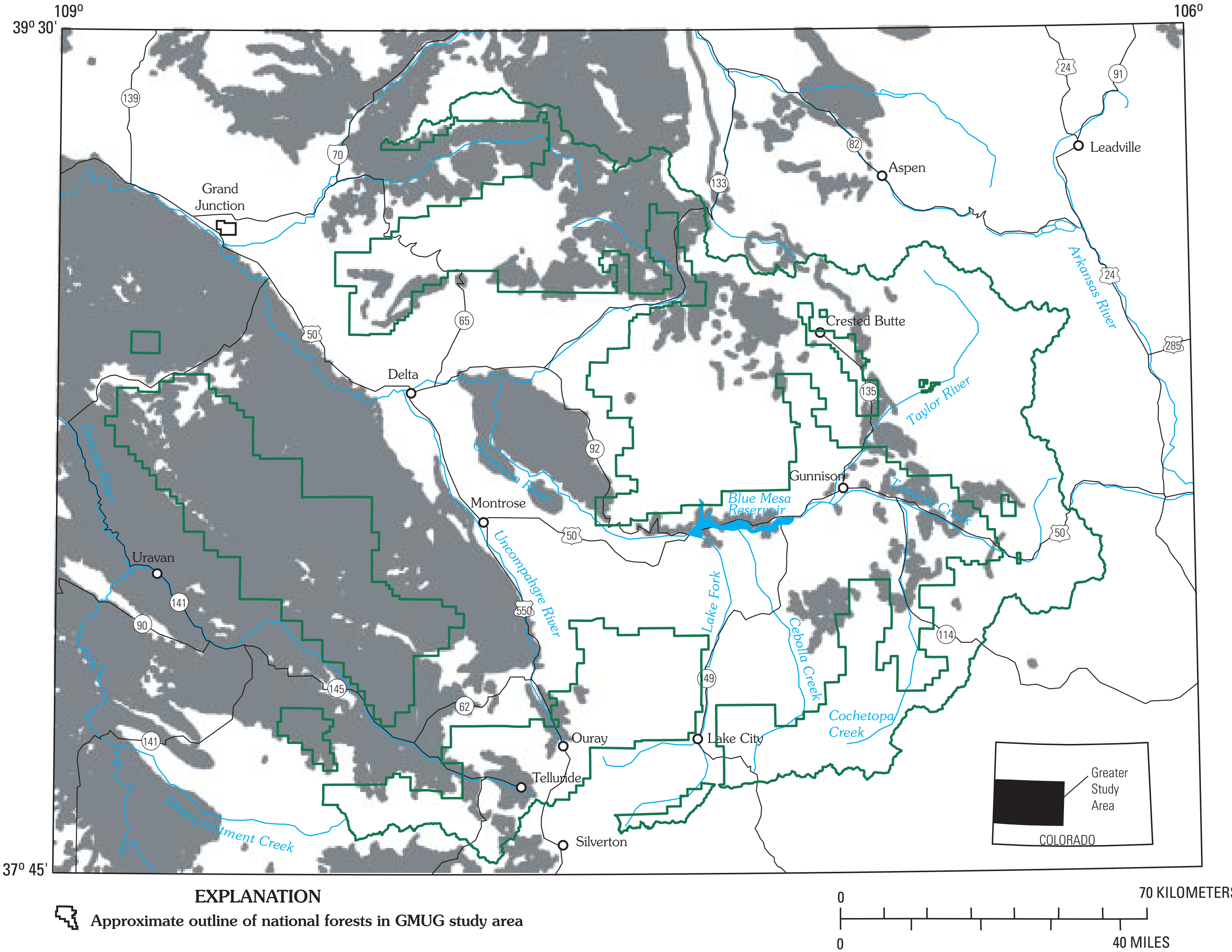
Description of Sandstone-Hosted Uranium Deposits in the GMUG Greater Study Area

Within the GMUG greater study area (fig. H1) and surrounding environs, significant deposits of the sandstone-hosted uranium deposit type occur in the Chinle, Morrison, and Cutler Formations; and minor occurrences are found in the upper member of the Hermosa Formation, Wingate Sandstone, Ohio Creek Member of the Mesaverde Formation, and Wasatch Formation. In addition the Burro Canyon, Rico, Moenkopi, Dolores, and Dakota Formations are reported to host occurrences of this type in areas adjacent to the GMUG area (Finch, 1967). Rock units containing uranium as described in NURE reports are listed in table D1 (chapter D, this volume).

Sandstone-hosted uranium type occurrences are concentrated in two distinct geographic areas; one lies west of the Uncompahgre National Forest (Uravan mineral belt) and a second, smaller area is in the northwest corner of Gunnison County (Ruby-Irwin area).

The Uravan mineral belt, initially defined by Fischer and Hilpert (1952) is the oldest uranium mining area in the United States. It forms a rough arc that trends in a southerly direction from just south of Gateway through Uravan to the Slick Rock area, a distance of approximately 115 km, and extends on into Utah. Bordering the east edge of a more broadly defined Uravan area, it is defined by the presence of nearly 1,200 documented occurrences and deposits (Nelson-Moore and others, 1978), hosted in sandstones and conglomerates of the Salt Wash and Brushy Basin Members of the Morrison Formation. Individual zones of mineralization in the Uravan mineral belt are typically elongated—either in a tabular shape conforming with bedding in the host sandstone (peneconcordant) or as less common roll-type deposits, which exhibit a C- or S-like cross section that cuts vertically across bedding. Size varies from a few metric tons of rock in a single occurrence to more than 1,000,000 t (metric tons), where one or more zones occur closely spaced in clusters.

Vanadium is also prevalent in these deposits. Vanadium-uranium ratios systematically increase in the mineral belt from north to south, from near 3:1 in the Gateway area to approximately 8:1 in the Slick Rock area. Primary (unoxidized) ores



EXPLANATION

Approximate outline of national forests in GMUG study area

Figure H1. GMUG greater study area, showing permissive tracts (shaded) for sandstone-hosted uranium deposits.

contain uranium oxide (uraninite) and silicate (coffinite) and the vanadium oxide (montroseite) and vanadium-bearing silicates (mica, chlorite and clay). In the near-surface oxidized zone, uranium vanadates (carnotite and tyuyamunite) are abundant. Ore minerals coat sand grains, fill pores, and in some cases replace sand grains, interstitial clays, calcite cement, and carbonaceous debris. Primary mineralization is restricted to reduced zones in the host sandstone, which are light gray to buff in color and contain disseminated pyrite and carbonized material. Where mineralized zones are weathered, the pyrite imparts a yellowish cast to the rock's color.

The host sandstones in the Salt Wash and lower part of the overlying Brushy Basin Members of the Morrison Formation occur as layers and lenses interbedded with mudstones. Thicker intervals of uniform sandstone are devoid of significant mineralized uranium. The depositional environment is interpreted to have been a large alluvial fan complex that spread out to the east into western Colorado from a source in east-central Utah. The Uravan mineral belt overlies the arcuate distal front of the fan complex where gradients flattened and streams began to meander and braid before entering either a marginal marine or a lacustrine environment nearer the basin center. Coarse sand collected in fluvial channels, and fine sand and clay-rich sediment accumulated in adjacent backswamp and fresh-water lake (lacustrine) flood-plain environments. Vegetation swept down in floods or growing on adjacent flood plains became commingled with, and buried in, the rapidly accumulating sediments. A shallow water table preserved and aided in the carbonization of entrapped organic matter. The long axes of the uranium deposits in the mineral belt are roughly normal to the trend of the belt and parallel to the expected direction of flow of the distributive streams and mineralizing ground water. The sediment source is hypothesized to have been a highland area to the southwest. Sandstones are feldspathic and mudstones are bentonitic, suggesting the presence of a significant component of volcanic ash in the distal part of the alluvial fan system. Ash is a suspected source of the uranium, along with vanadiferous and uraniferous heavy minerals present in the juvenile sandstones. Contemporaneous with deposition, flowage of evaporite deposits underlying the late Paleozoic Paradox basin superimposed an alternating pattern of slowly subsiding synclinal basins and slowly rising diapiric anticlinal ridges that dammed streams and produced temporary lakes in the synclinal areas. These conditions persisted during the early sedimentation of the Brushy Basin Member of the Morrison, where uranium deposits are also found.

Uranium host rocks are characterized by the presence of broad, continuous sandstone lenses and lenticular channel sandstones and conglomerates separated laterally and vertically by mudstone layers of variable thickness. Organic matter, ranging from tree-trunk size down to fine debris, was preserved and carbonized, where protected by high water tables. Uranium and vanadium were likely leached from feldspars, heavy minerals in sandstones, and tuffaceous horizons in mudstones and transported in ground water under oxidizing conditions, possibly at different times, basinward through the more porous and permeable channel sandstones. On meeting localized reducing conditions, uranium was deposited as oxides and silicates and vanadium as an oxide, coating sand grains, filling pore spaces, and replacing carbonized plant matter. Vanadium also invaded clay mineral structures, producing vanadium-rich clays. Mineralization is believed to have occurred early in the period of consolidation from sediment to sedimentary rock.

Uranium occurrences in the Ruby-Irwin area are hosted in carbon-bearing, fluvial channel-fill sands in thick alluvial-fan and alluvial-plain deposits (Upper Cretaceous Ohio Creek Member of Mesaverde Formation and Tertiary Wasatch Formation) that built to the west into the Piceance Basin from the rising Sawatch uplift during the Late Cretaceous and early Tertiary. The source of the uranium in these occurrences may have been the abundant volcanic debris that is found in the lower part of the Wasatch Formation. No uranium minerals have been identified, and the uranium is likely bound by adsorption in the carbonaceous debris found in the channel sands. Vanadium is present only in trace amounts.

Delineation of Mineral Resource Potential Areas for Sandstone-Hosted Uranium Deposits

The permissive and favorable mineral resource potential tracts, delineated in this study for sandstone-hosted uranium deposits, identify areas where there is believed to be more than a trivial probability of additional occurrences of deposit size existing. Their delineation is complicated by the confidentiality that surrounds grade and tonnage data for existing deposits and precludes the development of traditional deposit-based grade and tonnage models that are normally used to characterize the size and grade range for deposits. However, two studies do provide some insights that can be used to characterize deposit size for these deposits. In the NURE studies, geographic areas were delineated wherein the geologic environment was such that a minimum aggregated endowment of 100 tons (91 t) of U_3O_8 in rocks having an average grade not less than 100 ppm U_3O_8 could be presumed to be present. The U_3O_8 endowment of individual occurrences was not addressed. W.I. Finch and C.T. Pierson (written commun., 1992) proposed using clustered deposit and occurrence data in place of single values, thereby preserving confidentiality. Average grade and aggregate ore tonnage values for clusters of closely spaced ore bodies that had been or would likely be mined as a unit in any future mining effort were used to construct a set of grade and tonnage models. Using data for 64 clusters occurring in central Utah in geologic environments similar to those in the Uravan mineral belt, they obtained a value of 29,000 t and a grade of 0.18 percent U_3O_8 for a median cluster, which equates to a median endowment of 52 t of U_3O_8. Clusters range in size from 1,100 t to 7.38 million metric tons, and endowments range between 0.9 and 17,710 t of contained U_3O_8. Given these models, tracts are delineated for the potential existence of deposits that contain more than 2,000 t of ore and a U_3O_8 endowment of more than 2.3 t.

The tract delineation criteria listed in table H1 are largely based on those used in the NURE studies of the Moab (Campbell and others, 1982a), Cortez (Campbell and others, 1982b) and Montrose (Goodknight and Ludlam, 1981) quadrangles, the observed associations of uranium with sandstone summarized by Finch (1967), and the descriptive deposit model of Turner-Peterson and Hodges (1986). Criterion 1 is used to identify permissive tracts, in which the probability for the existence of deposits is more than negligible. Criteria 2 through 4 are applied in various combinations to the permissive terrane to highlight areas that have a higher probability for hosting deposits—the favorable tracts. Each criterion is supported by data that are widely available at 1:250,000 scale. Criterion 5 is included to ensure that the assessment results from the NURE program and the expertise that went into producing them were not overlooked in the current effort. Several additional "favorable criteria" listed would be appropriate for identifying favorable tracts, provided the data were available; they could prove useful in refining the boundaries of favorable areas in localized areas.

Buffers are used with point and area data to compensate for location inaccuracy, at 1:250,000 scale, to indicate the probable area of influence attributable to a class of point information, and to make allowances for lateral extrapolation of non-point information where control data are lacking. The values used are based on empirical precedent. Where several buffers may be applicable, the largest is used.

Permissive Tracts

The affinity that uranium occurrences and deposits have demonstrated for the feldspathic and carbonaceous sandstone units occurring interbedded with mudstones and shales in continental sedimentary sequences has long been known (Finch, 1967; Turner-Peterson and Hodges, 1986). In the study area occurrences and deposits are found in sandstone intervals of more than a dozen units (Finch, 1967; Nelson-Moore and others, 1978). However, to resolve each suitable sandstone unit for display at a scale of 1:250,000 is impractical; therefore, stratigraphic intervals containing several suitable sandstone intervals are used to define a permissive area.

In the GMUG study area a noncontiguous area of nearly 6,700 mi^2 is identified as having a permissive potential for sandstone-hosted uranium deposits through the application

Table H1. Delineation criteria for sandstone-hosted uranium deposits in GMUG greater study area.

[Map symbols in parentheses are those shown at 1:250,000-scale mapping (Day and others, 1999) that include the specified unit. Bold indicates the principal symbol for the lithologic unit]

Diagnostic criterion for permissive tract delineation
1. Feldspathic and (or) tuffaceous-bearing clastic sedimentary rock deposited in a predominantly continental (nonmarine) basin environment (includes all Permian through Jurassic age sedimentary rock units, the Cretaceous Dakota Sandstone and Ohio Creek Member of the Mesaverde Formation, and the Tertiary Wasatch Formation) known or inferred to be present within 1,500 m of the surface.
Diagnostic criteria for favorable tract delineation (in addition to criterion 1)
2. Presence of anomalous radioactivity as indicated by anomalous uranium:thorium ratio equal to or greater than one standard deviation above its mean and a thorium signal at least one standard deviation below its mean.
3. Presence of an anomalous level of uranium in stream-sediment (>10 ppm) or water (>10 ppm) sample (500 m buffer).
4. Presence of sandstone-hosted uranium occurrence or deposit (500 m buffer).
5. Area designated as favorable for subclass 243 or 244 type sediment-hosted uranium type deposits in the Morrison or Cutler Formations in the National Uranium Resource Evaluation (Moab, Cortez, or Montrose) quadrangle reports.
Other favorable tract criteria
6. Lithologies characterizing deposition in a lower (distal) alluvial-plain, a near-shore (nonmarine), or a delta-plain environment. Includes permeable, lenticular, lacustrine or lagoonal, feldspathic or arkosic, fine-grained sandstones, or channel-fill sandstones and (or) conglomerates, containing concentrations of carbonaceous matter interbedded with impermeable, tuffaceous siltstones and mudstones, known to be present within 1,500 m of the surface:
A. Salt Wash Member of Morrison Formation (**Jms**, Jm, Jmw, Jmwe, Jmj, Jmce, JTRmc)
B. Brushy Basin Member of Morrison Formation (**Jmb**, Jm, Jmw, Jmj, Jmwe)
C. Moss Back Member of Chinle Formation (TRc, TRwc, TRkwc)
D. Cutler Formation (**Pc**)
E. Ohio Creek Formation (**Two**)
F. Wasatch Formation (Two, **Tw**)
7. Presence of gray bentonitic (swelling) clay, or noncalcareous lacustrine mudstone interbedded with sandstone.
8. Presence of uranyl vanadate, phosphate, and (or) silicate mineralogy in oxidized surface exposures (500 m buffer).

Table H2. Sandstone-hosted uranium tracts in GMUG greater study area.

Tract No.[a]	Tract name[b]	Delineation criteria[c]
P30c.1	Western Slope-Intermountain-Piceance Basin Area	1
F30c.1	Uravan Area	1, 2, 3, 4, 5
F30c.2	Ruby-Irwin Area	1, 5

[a]P denotes a permissive tract, F a favorable tract followed by a deposit type model number.

[b]Area of permissive tracts includes the area of the favorable tracts lying within.

[c]Indicates the criteria used to delineate the lands in the tract. See table H1.

of criterion 1 (table H1). These lands (fig. H1) are underlain by sedimentary rocks formed for the most part under continental (nonmarine) depositional conditions, which persisted throughout western Colorado from the Late Pennsylvanian into the Cretaceous and again in the early Tertiary. The name, Western Slope–Intermountain–Piceance Basin Area, applied to the tract reflects the diversity of the area of coverage. The effective depth of consideration for classification purposes was extended to 1,500 m to achieve parity with that used in the NURE investigations. Approximately 1,630 mi^2 of the permissive tract lands falls within GMUG National Forest boundaries and an additional 2,650 mi^2 underlies land managed by the Bureau of Land Management.

Favorable Tracts

Approximately 20 percent (1,352 mi^2) of the lands in the permissive sandstone-hosted uranium tracts are classified as favorable through the application of criteria 2 through 5 in table H1. Less than 100 mi^2 occurs within forest bounds and 955 mi^2 underlies BLM land. The lands occur in two distinct areas, the Uravan Area and the Ruby-Irwin Area. Figure H2 and table H1 show what criterion or combinations of criteria were used and the relative impact each has on determining the final configuration of the favorable tracts. Criterion 4, singularly or in combination with 2 and (or) 3, is used to categorize approximately 300 mi^2 of the permissive terrane as favorable. Application of criterion 5 (favorable areas in NURE reports) categorizes an additional 1,054 mi^2 as favorable, increasing the area by nearly 350 percent. The presence of criterion 2 or 3 alone is not judged to be singularly sufficient justification to invoke a favorable classification. Little new information has been gathered on these deposits since the early 1980's, and the conclusions reached in the NURE investigations by Campbell and others (1982a, 1982b) and Goodknight and Ludlam (1981) remain valid. The interpretive approach and data support used to define favorable areas in the NURE studies equate well with those used in the present assessment.

Uravan Area: This area contains more than 98 percent of lands designated as favorable. The favorable determination is largely based either on the presence of a distal alluvial-plain lithofacies, which equates stratigraphically with the Salt Wash and Brushy Basin Members of the Morrison Formation, or on the presence of a sequence of arkosic sandstones and

EXPLANATION (fig. H1, next page)

Criterion 5—Previously identified favorable areas in the Morrison or Cutler Formations

Criterion 4—Uranium mines and prospects, buffered

Criteria 4 and 5

Criterion 4 or 5 or both and criterion 3—Anomalous geochemistry where U > 10 ppm

Criterion 4 or 5 or both and criterion 2—Anomalous radioactivity ratio

Criteria 2 and 3 and criterion 1 or 2 or both

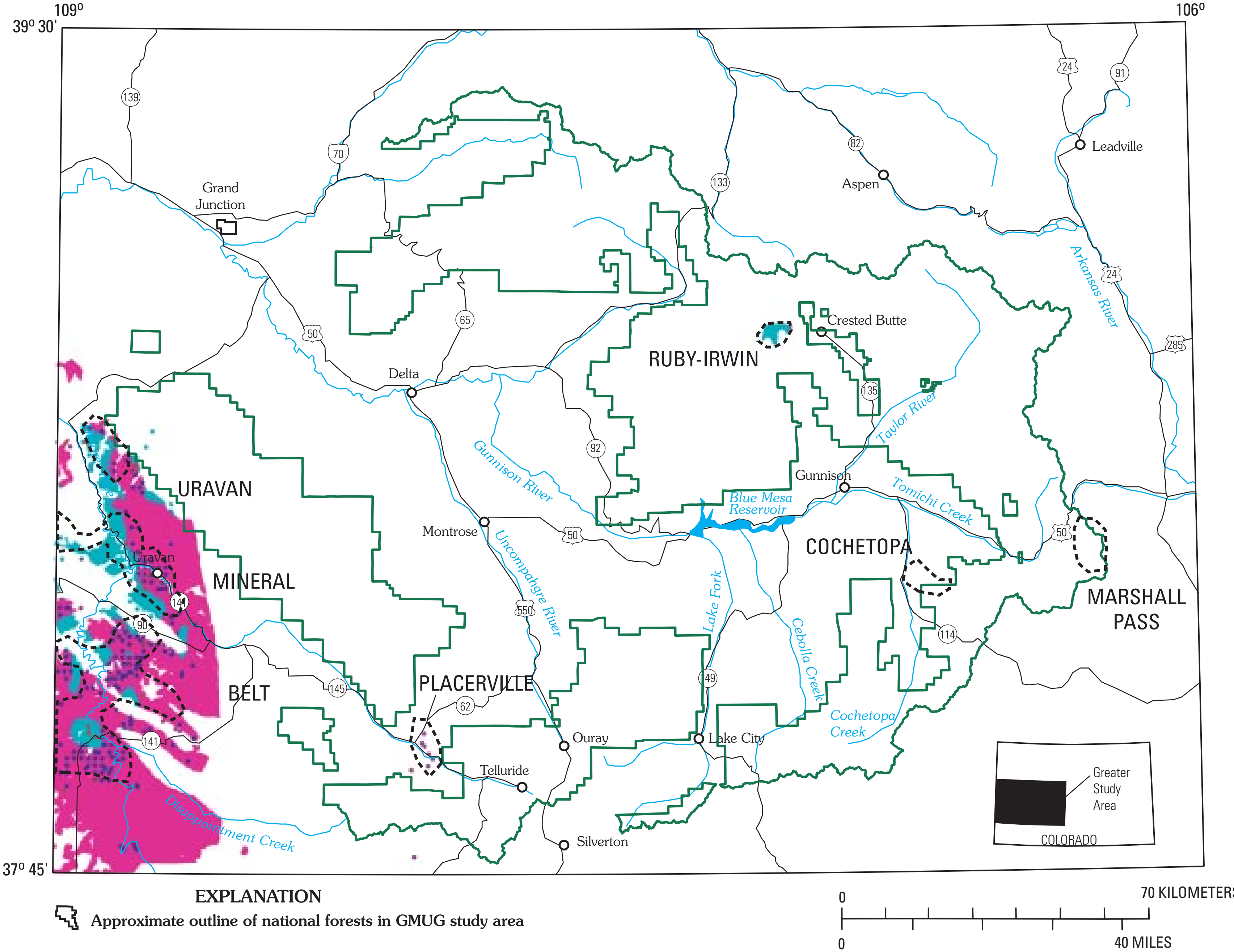


Figure H2 (above and previous page). GMUG greater study area, showing favorable tracts for sandstone-hosted uranium deposits. Dashed lines and labels show known uranium districts.

shales, deposited in an alluvial-fan environment dominated by meandering streams occurring in the upper part of the Cutler Formation. In fact, the Cutler and Salt Wash units overlap in a portion of the south half of the area.

Ruby-Irwin Area: This small area contains less than 2 percent of the favorable land; it lies to the west of Crested Butte (fig. H2). Its inclusion as favorable is based largely on the fact that it had been designated favorable in a NURE report (Goodknight and Ludlam, 1981). The classification is based on the presence of a stratigraphic interval of interbedded, fluvial, arkosic sands, conglomerates, siltstones, and volcanic debris deposited in a transitional environment between an alluvial fan and an alluvial flood plain. The interval includes the upper part of the Oak Creek Sandstone and lower part of the Wasatch Formation.

Marshall Pass, Cochetopa, and Placerville Areas: These three areas (fig. H2) are locations of known uranium deposits; however, we determined that these types of uranium deposits do not adequately fit the sandstone-hosted model studied in this report.

Undiscovered Deposit and Endowment Potential

The potential for new sandstone-hosted uranium deposits and quantitative estimation of their uranium and vanadium endowments cannot be assessed using the three-part methodology described in Chapter F of this volume. Although the deposit type has been descriptively modeled (Turner-Peterson and Hodges, 1986), the grade and tonnage characteristics of that fraction of occurrences that would be considered deposits have not been modeled. The cluster-based grade and tonnage models proposed by Finch and Pierson (1992) have never been formally recognized and should not be used for estimating resources in undiscovered deposits. In the absence of a recognized set of models, the numbers of undiscovered deposits cannot be estimated.

However, historical precedent and numerous scientific investigations conducted since the early 1950’s suggest that, within the bounds of the permissive and favorable tracts, a significant uranium and vanadium endowment is associated with the sandstone-hosted type of deposit. By 1999 more than 63 million lb of uranium oxide and 330 million lb of vanadium oxide have been produced from sandstone-hosted uranium deposits occurring in Permian, Triassic, and Jurassic age rocks in the Colorado portion of the Colorado Plateaus province. Most of that production occurred during a period from 1947 to 1968 when market pricing was subsidized and again from 1973 to 1987 when there was a rapid expansion of the nuclear energy industry; high prices and demand made lower grade ores economic. By 1990, however, all mining activity had ceased, not as a result of resource depletion, but rather in response to steep declines in demand and market price for uranium (Chenoweth, 1996). These declines were precipitated by the transition from a subsidized to a free market economy for uranium and associated contraction of the nuclear energy industry in the 1980’s. Under current free market conditions the sandstone-hosted uranium deposits in Colorado have become non-economic. This sensitivity to market price is demonstrated by the case of the Sunday mine in the Big Gypsum Valley of San Miguel County: this mine reopened in 1997 at a time when uranium oxide prices rose above $15/lb (Cappa, 1998). The mine closed again in 1999 after prices dropped back into the $10–$11/lb range (Cappa and Carroll, 2000). Future interest in development and exploration will be totally a function of market dynamics. At current price levels, development potential is extremely low. Should price increase into the high teens or above, there is a strong expectation that some existing mines with proven reserves will reopen, and exploration for new deposits of similar size and grade, which are highly likely to be present in the favorable tract areas, will resume.

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Mineral Resource Assessment for Volcanic-Associated Massive Sulfide Deposits

By Warren C. Day, Gregory T. Spanski, Viki Bankey, Anna B. Wilson, and Steven M. Smith

Chapter I of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

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Mineral Resource Assessment for Volcanic-Associated Massive Sulfide Deposits

By Warren C. Day, Gregory T. Spanski, Viki Bankey, Anna B. Wilson, and Steven M. Smith

Abstract

Precambrian volcanic rocks of the GMUG greater study area have historically produced copper, gold, silver, and lead in Kuroko-type volcanic-associated massive sulfide deposits, located primarily in the Dubois Greenstone belt, south of Gunnison, Colorado. Commonly, these massive sulfide deposits originally formed within bimodal (felsic and mafic) metavolcanic and associated metasedimentary rock packages that are proximal to felsic volcanic centers in clusters adjacent to one another. In areas where the base- and precious-mineral-rich rocks are exposed, the resulting erosion yields stream sediments with elevated concentrations of base and precious metals. We describe herein the characteristics of the Kuroko-type volcanic-associated massive sulfide deposits, briefly discuss their mode of origin, give an overview of the geologic setting for regions known to host such deposits, present the criteria used in the mineral resource assessment to highlight areas both permissive and favorable for such deposits, and discuss the results of the mineral resource assessment.

The robustness of the mineral resource assessment is limited to the quality and thoroughness of the data available at the regional scale. As such, the main diagnostic tools used for delineating tracts favorable for hosting Kuroko-type volcanic-associated massive sulfide deposits were the existing 1:250,000-scale geologic maps, mine and prospect location and mineral production information, regional stream-sediment data, all of which were augmented by new geochemical data on bedrock and mine dumps as well as onsite geologic observations made throughout the region specific for these deposits. Information lacking at the regional scale that would enhance the assessment would include maps of mineral alteration assemblages, detailed electromagnetic geophysical maps, and closely spaced stream-sediment, soil, and bedrock geochemical sampling. However, we identified several tracts that are favorable for hosting Kuroko-type volcanic-associated massive sulfide deposits within the GMUG greater study area.

Introduction

The GMUG greater study area hosts several volcanic-associated massive sulfide (VMS) mineral deposits within the Precambrian basement rocks. The VMS deposits are located within the Dubois Greenstone belt, which is a belt of Proterozoic volcanic and intrusive rocks exposed within the Gunnison uplift between Cochetopa Creek and the Lake Fork River in Gunnison and Saguache Counties, Colorado. The general character of the VMS deposits within the GMUG area is similar to that described in the Kuroko-type massive sulfide deposit model presented by Singer (1986) as well as models for volcanic-associated massive sulfide deposits presented by Hutchinson (1982), Franklin (1993), and Franklin and others (1981, 1998).

Model for Volcanic-Associated Massive Sulfide Mineral Deposits

Volcanic-associated massive sulfide (VMS) deposits contain copper, lead, and zinc as their primary ore metals and can carry lesser albeit important amounts of silver and gold. They occur as lenses, layers, and (or) disseminations of base-metal-bearing sulfide minerals within sequences of marine volcanic and associated sedimentary rocks. The host volcanic successions range from bimodal sequences of mafic and felsic rocks (Kuroko-type) to andesite-dominated sequences (Noranda-type). In both types the host rocks are generally subaqueous flows, tuffs, pyroclastic deposits, and volcanic breccias; many host successions are proximal to felsic volcanic domes. Worldwide, VMS deposits range in age from Archean to Cenozoic. They form both in island-arc and in mid-ocean ridge tectonic settings; however, the majority occur in island-arc sequences (Franklin and others, 1998) and especially within arc-related rift settings (Sawkins, 1990).

VMS ores are deposited from metalliferous fluids generated within thermally driven convective hydrothermal systems associated with subaqueous volcanism and rifting (Franklin and others, 1981, 1998; Hutchinson, 1982; Seyfried and Janecky, 1985; Poulsen and Hannington, 1996; Franklin, 1993). Cool seawater is circulated through piles of volcanic (basaltic) rocks adjacent to areas of active subaqueous volcanism and local subvolcanic intrusions, which heat the pore water, forming a hydrothermal convection system. Within such a hydrothermal system, the relatively cool hydrothermal fluids circulate deep within the volcanic pile. The steep geothermal gradient within the rift system, caused in part by shallow subvolcanic intrusions, heats the deeper circulating hydrothermal fluids. As they become hotter, the fluids leach base and precious metals along their journey through the volcanic rocks. The hot hydrothermal metal-bearing fluids then rise through the volcanic pile, ascending along structural pathways (faults and caldera margins), which focus the fluid flow, and form alteration pipes. At the termination of the convective system, the metalliferous fluids are debouched on the sea floor in hydrothermal vent zones (submarine hot springs). These metal-laden, hot, hydrothermal fluids (approximately 200°–300°C) mix with cool seawater and precipitate base- and precious-metal-bearing sulfide minerals. Discharge of the metalliferous hydrothermal fluids must be focused along a relatively small structurally controlled zone through a prolonged period of time to produce the high concentrations of metal-rich precipitants found in large VMS mineral deposits. Metals can be precipitated above the sediment-water interface as layered massive sulfide horizons and (or) as replacement deposits below the sediment-water subsurface.

Description of the Volcanic-Associated Massive Sulfide Deposits in the Study Area

Through an understanding of the geologic setting, character, and mode of origin of known VMS deposits, we can establish critical criteria to help us identify additional areas with potential to host undiscovered VMS deposits throughout the GMUG greater study area (map area, fig. I1). Known Kuroko-type VMS copper and zinc mineral deposits are exposed in the Dubois Greenstone belt (fig. I1). The greenstone belt is made up of bimodal (mafic and felsic) metavolcanic rocks and associated sedimentary rocks that have been variously intruded by synvolcanic to posttectonic granodiorite to granite plutons. The volcanic rocks were deposited in submarine environments, inasmuch as pillow structures are preserved in the basalts, and the felsic volcanic rocks and associated epiclastic sediments show subaqueous reworking (Hedlund and Olson, 1981). Afifi (1981) noted that volcanism was episodic, with intervals of quiescence marked by deposition of layered intervals of

EXPLANATION (fig. I1, next page)

Cochetopa area

1 Graflin mine (VMS; Cu, Zn, and native Au)
2 Denver City mine (VMS; Zn, Cu, Ag, Au, Pb, Sb, and Te)
3 Yukon mine (VMS; Cu, Zn, Ag, Au, and Pb)
4 Lulu mine (low-sulfide quartz/gold; Au)
5 Buzzard mine; Mineral Hill mine (low-sulfide quartz-gold; Au)
6 Lucky Strike (low-sulfide quartz-gold; Au)

Powderhorn area

7 Headlight mine (VMS; Cu, Ag, Au, and Zn)
8 Gunnison mine (Au-bearing chert, Ag, Cu, Pb, Te, and Se)
9 Champion shaft (Au-bearing chert)
10 Iron Cap mine (VMS and Au-bearing chert, Ag, Cu, Zn, and Pb)
11 Copper King mine (VMS; Au, Ag, and Cu)
12 Anaconda mine (VMS and Au-bearing chert, Ag, Cu, and Zn)
13 Old Lot mine (VMS; Au, Ag, Zn, Cu, and Pb)

Vulcan mine area

14 Vulcan/Good Hope mines (VMS; Au, Ag, Te, Cu, Zn, Sb, V, Bi, and As)
15 Midland mine (VMS; native Au, Ag, Pb, and Zn)

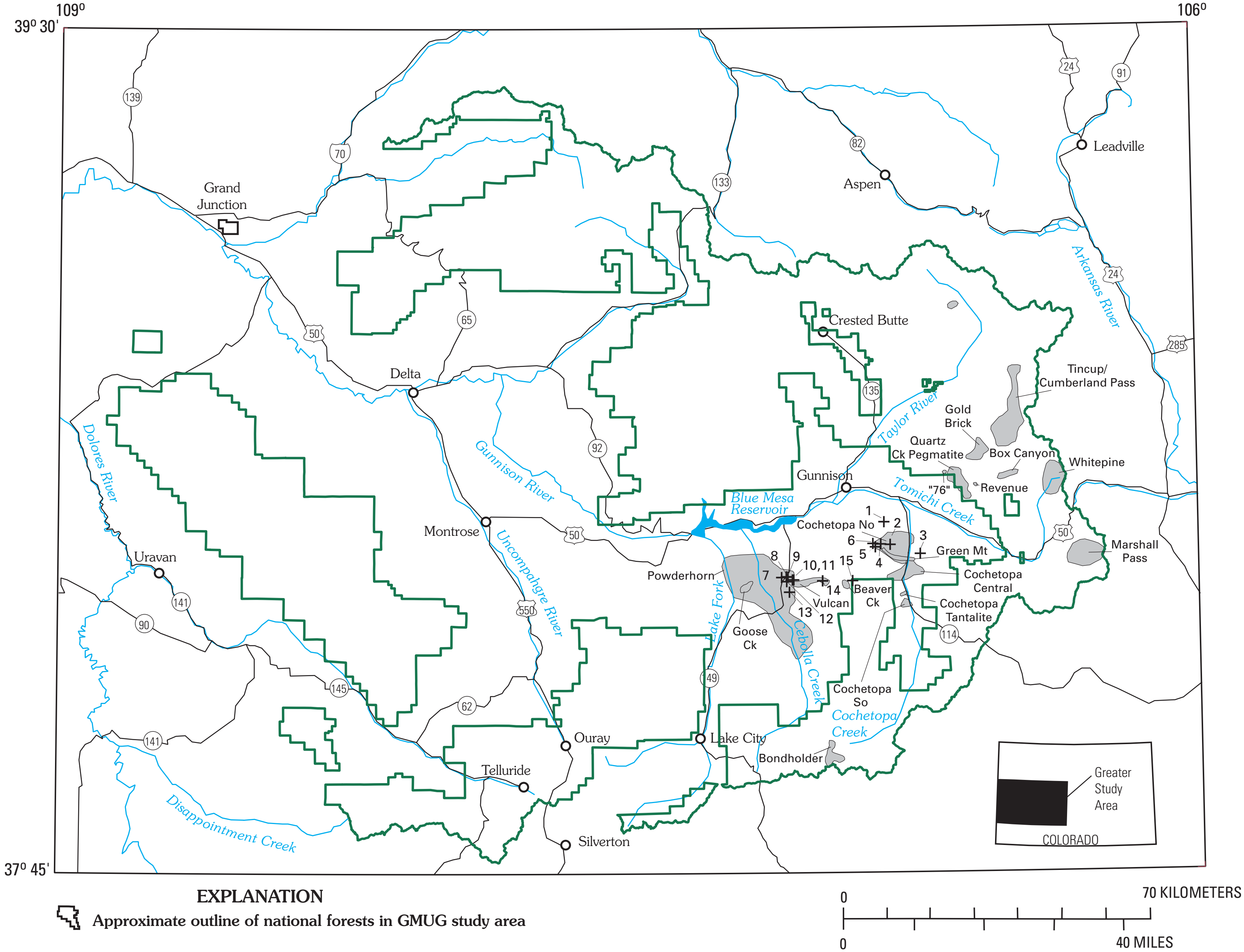

Figure I1 (above and previous page). Location, deposit type, and commodity recovered for selected Proterozoic mineral deposits in GMUG greater study area.

ferruginous chert and lean banded iron-formation. The Dubois Greenstone belt differs from most of the Proterozoic basement rocks of Colorado in that it has experienced a relatively low grade of metamorphism (upper greenschist to lower amphibolite facies), whereas most of the remaining Precambrian rocks are of higher grade (middle to upper amphibolite facies). In addition, although rocks within the belt have experienced at least two phases of regional deformation (Afifi, 1981; Knoper and others, 1991; Hetherington, 1994), they still have primary sedimentary and volcanic rock textures preserved (Hedlund and Olson, 1981).

The Dubois Greenstone belt is composed of two separate volcanic successions (Bickford and others, 1982; Knoper and Condie, 1988; Knoper and others, 1991; Wortman, 1991), both of which host VMS deposits. The older succession lies in the western part of the greenstone belt, in the Cebolla Creek area; it is made up of bimodal volcanic rocks (dominantly basalt) with horizons of ferruginous chert (some of which is gold bearing) as well as pyroclastic and epiclastic sedimentary rocks, all of which are intruded by granite. These rocks range in age from 1,780 to 1,750 Ma, and the granite intrusions are 1,755 to 1,751 m.y. old. The younger succession crops out in the eastern part of the greenstone belt, in the Cochetopa Creek area; it is also made up of bimodal volcanic rocks (Bennett and others, 1984) and is dominated by the felsic volcanic and volcaniclastic sediment component of the bimodal succession. Ages of the felsic volcanic rocks that host VMS mineral deposits in the eastern part of the Dubois Greenstone belt cluster between 1,741 and 1,730 Ma (Wortman and others, 1990). Metamorphism and peak deformation occurred prior to 1,713 Ma, which is the age of the late synkinematic tonalite of Gold Basin that crosscuts the deformational fabrics developed in the volcanic rocks (Wortman and others, 1990).

The mafic rocks in both volcanic successions are similar in composition to modern basalts that form in island-arc environments (Knoper and Condie, 1988). The textural features developed in the volcanic and sedimentary rocks indicate that the environment of deposition was submarine. The combination of coeval mafic and felsic volcanism and pretectonic granitoid plutonism indicates that the tectonic setting of the Dubois Greenstone belt is consistent with that of a rifted island-arc environment. This setting is similar to others known to host VMS deposits (Sawkins, 1990).

Two general classes of Precambrian-aged mineral deposits occur in the Dubois Greenstone belt: (1) syngenetic Kuroko-type VMS massive sulfide and associated gold-bearing ferruginous chert (exhalative) deposits, and (2) epigenetic low-sulfide gold-quartz vein deposits. Although there are several small examples of epigenetic low-sulfide gold-quartz vein deposits in the Dubois Greenstone belt, no significant deposit has been identified at the time of this study. Because evaluation of the mineral resource potential for epigenetic low-sulfide gold-quartz vein deposits is not being conducted in this report, discussion is limited herein. The Kuroko-type VMS deposits occur within piles of dacitic to rhyolitic lava flows and tuffs (Afifi, 1981; Drobeck, 1981; Sheridan and others, 1981). For example, in the western part of the Dubois Greenstone belt, the Headlight, Old Lot, Copper King, and Vulcan/Good Hope mines are in copper-zinc-bearing Kuroko-type VMS deposits hosted in dacitic to rhyolitic porphyritic and lapilli tuffs (fig. I1). The Vulcan/Good Hope Kuroko-type VMS deposit was the largest producer in the greenstone belt (Drobeck, 1981). Several gold-bearing ferruginous chert (exhalative) deposits, such as at the Gunnison mine and the Champion shaft, also occur in the western part of the greenstone belt (Nelson and Riesmeyer, 1983). The Anaconda and the Iron Cap mines (fig. I1) are hosted primarily within mafic metavolcanic rocks (Nelson and Riesmeyer, 1983) that have characteristics typical of both Kuroko-type VMS and exhalative gold deposits, inasmuch as they contain thin bedding-parallel stringers of auriferous ferruginous chert interlayered with massive sulfide horizons. Epigenetic low-sulfide gold-quartz vein deposits occur in the western part of the greenstone belt in the Powderhorn mineral area (Wilson and Spanski, this volume, Chapter E, fig. E1; this report, fig. I3) where fairly small, shear-zone-hosted systems are present in the mafic metavolcanic sequence in the Lake Fork River and Cebolla Creek areas (Olson and Hedlund, 1973; Hedlund and Olson, 1975).

The most notable syngenetic Kuroko-type VMS and ferruginous chert (exhalative) gold deposits in the eastern part of the Dubois Greenstone belt are those in the Iris district (Denver City and Graflin mines; fig. I1) described by Afifi (1981) and Drobeck (1981). These deposits are hosted in dacitic to rhyolitic tuffs and are intervals of stratabound lenses of sulfide minerals (chalcophyrite, sphalerite, pyrite, pyrrhotite, and accessory gold) that are parallel to the dip of the host rocks and have undergone all of the same phases of deformation as the host rocks.

Epigenetic low-sulfide gold-quartz vein deposits do occur in the eastern part of the greenstone belt in the Cochetopa area (fig. I1) and are represented by the Buzzard, Mineral Hill, Lulu, and Lucky Strike mines, as well as numerous other small occurrences (Olson, 1976; Afifi, 1981).

Application of the Deposit Model for a Mineral Resource Assessment of Volcanic-Associated Massive Sulfide Deposits

The criteria listed in table I1 were used for this reconnaissance mineral resource assessment to identify tracts of land with potential for undiscovered Kuroko-type VMS copper-zinc±gold deposits. These criteria were developed based on the genetic model presented previously, on the viable rock types within the GMUG greater study area, and on known styles of mineralization. Regional databases available for this GIS-based assessment include the digital geologic map data (Day and others, 1999), mines and prospect locations (Wilson and others, 2000), outlines of mineralized regions (Wilson

Table I1. Delineation criteria for tracts of land with potential for undiscovered volcanic-associated Kuroko-type VMS copper-zinc±gold deposits in GMUG greater study area.

[Details of the map units whose symbols appear here can be found in Day and others (1999)]

Diagnostic criterion for permissive tract delineation
1. Presence of Proterozoic bimodal (mafic and (or) felsic) metavolcanic and (or) associated metasedimentary rocks. Criteria met by map units Xfh, Xf, and Xb of Day and others (1999)
Diagnostic criteria for favorable tract delineation
2. Evidence of Proterozoic terranes dominated by metavolcanic rocks of bimodal (mafic and felsic) composition and proximal to felsic volcanic centers as characterized by thick accumulations of felsic metavolcanic and volcaniclastic metasedimentary rocks. Criteria met by map units Xfh and Xf of Day and others (1999).
3. Districts or mineralized regions containing VMS deposits and prospects.
4. Anomalous geochemical enrichments in stream-sediment samples for copper of greater than 100 parts per million and (or) zinc greater than 250 parts per million in areas permissive for hosting Kuroko-type VMS copper-zinc±gold deposits. Anomalous sample sites were given a 0.5 km buffer as an estimate for the zone of influence for the potential that a Kuroko-type VMS deposit may have on the stream-sediment signature.
5. Occurrence of base-metal Kuroko-type VMS mineralization products (1 km buffer). Differs from 2 above in that an occurrence may not be within a known mineral district.
Other favorable tract criteria, not used in this study because comprehensive regional data are not available
6. Alteration assemblage maps for prospective Proterozoic host terranes that would include the minerals sericite, calcite, epidote, chlorite, and (or) pyrite.
7. Detailed electromagnetic (E-M) geophysical maps showing relative conductivity that would highlight zones of sulfide mineralization that would typically result in highly conductive horizons in volcanic sequences.
8. Closely spaced stream-sediment, soil, and bedrock geochemical sampling across zones of known and inferred mineralization to identify zones with potential of hosting Kuroko-type VMS mineralization.

and Spanski, this volume, Chapter E), and the regional NURE stream-sediment database (Smith, 2000).

The digital geologic map and spatial data model used for the mineral resource assessments for the GMUG project are those of Day and others (1999). They generated the geologic data model using six published 1°×2° geologic quadrangle maps (Leadville, Montrose, Durango, Grand Junction, Moab, and Cortez). The six original maps were digitized, merged, clipped to the study area boundary (lat 37°45′–39°30′ N., long 106°–109° W.), and projected into a Lambert conformal conic projection. The spatial geologic data model was created from the resultant maps by developing common geologic map units for each map to be used throughout the area and attributing these common units for age, lithologic descriptions, rock type, economic geology, and natural aggregate characteristics.

A detailed set of assessment criteria could be developed that would include more data than are available in the regional databases assembled for this project. For instance, alteration mineral assemblages maps, detailed stream-sediment geochemical data, geophysical data such as electromagnetic (E-M) and ground magnetic studies would greatly enhance this type of assessment. However, the regional databases do permit outlining broad areas of both permissive and favorable natures that warrant further investigation for these types of deposits. These broad tracts also help identify for the Federal land-management agencies (USDA Forest Service and U.S. Bureau of Land Management) regions that may be impacted by future mineral resource development.

Permissive Tracts

Areas identified as “permissive” in the GMUG greater study area are those that meet the conditions set forth in criterion 1 (table I1); these are areas in which rock types are present that are consistent in terms of their petrology and environments of formation with those outlined in the Kuroko-type VMS model. These include the bimodal metavolcanic rock packages mapped as Xfh, the felsic metavolcanic rocks in unit Xf, and the metasedimentary rocks whose protolith could have been associated with Kuroko-type VMS copper-zinc±gold mineralization (unit Xb) (Day and others, 1999). Map unit Xb is dominantly biotite schist but locally contains both mafic and felsic volcaniclastic metasedimentary horizons, which are rock types known to host VMS deposits. Only parts of map unit Xb would qualify as rocks typically associated with VMS deposits, but all of the unit is included herein because the original protolith was not delineated in the source regional geologic maps used by Day and others (1999).

In addition to possibly hosting Kuroko-type VMS deposits, unit Xb is a candidate for hosting Besshi-type VMS deposits. The Besshi-type deposits form as lenses of sulfide minerals, hosted in sequences of mafic metavolcanic rocks, pelitic schist, quartz schist, and phyllite (Sawkins, 1990). Within the study area, map unit Xb locally contains horizons of mafic metavolcanic rocks and amphibolite (sills?), metagraywacke, pelitic schist, quartz-rich horizons, and phyllite. However, neither Besshi-type VMS deposits nor examples of

Besshi-type mineralization have been identified in or adjacent to the GMUG study area. In light of this, the area was not assessed for Besshi-type VMS deposits.

Areas permissive for hosting Kuroko-type VMS copper-zinc±gold deposits, outlined in figure I2, are treated as a single discontinuous tract underlain by Proterozoic units Xfh, Xf, and Xb (table I1). Major parcels are exposed in a belt trending westward from the western flank of the Sawatch Mountains for a distance of approximately 125 km. The breadth of exposure narrows to the west and its northern boundary approximates the course of the Gunnison and Taylor Rivers. The rock units present were deposited under subaqueous conditions adjacent to the Dubois Greenstone belt, which formed in a rifted island-arc environment.

Favorable Tracts

The criteria used for delineating regions "favorable" for hosting Kuroko-type VMS copper-zinc±gold deposits are listed in table I1. The criteria are conditionally more restrictive than those for permissive areas and are applicable only within areas designated "permissive." Proximity to felsic centers (map unit Xf) and (or) presence of bimodal volcanism and associated metasedimentary rocks (map unit Xfh) (criterion 2, table I1) are geologic conditions that show a strong correlation with known VMS deposits in the GMUG area. Field evidence also shows that the Kuroko-type VMS deposits discovered at the time of this study cluster within distinct regions (criterion 3, table I1). NURE stream-sediment data may be used to identify regions containing anomalous concentrations of the ore metals copper and zinc (criterion 4, table I1). Values greater than 100 parts per million for copper and 250 parts per million for zinc in stream-sediment samples can be interpreted as suggesting that somewhere within the watershed Kuroko-type VMS mineralization occurred. The stream-sediment samples are point data that represent a sampling of the rocks exposed within a given drainage basin. In consideration of the scale at which this assessment is being conducted, a buffer of 0.5 km was applied for each geochemically anomalous sample site to represent the area of influence attributed to the sample. Criterion 5 (table I1) deals with specific occurrences of base-metal VMS mineralization. Its effect in areas where VMS occurrences are clustered is somewhat redundant with that of criterion 3 (table I1); however, it does capture the importance of isolated VMS occurrences. A 1 km buffer is used around each site. The assessment technique of bit mapping employed herein (Spanski and Bankey, this volume, Chapter F) to delineate "favorable" lands does not weight the criteria as they are utilized. Therefore, areas underlain by rocks that meet more than one of the criteria for "favorable" designation receive the same final value as those underlain by only one such criterion.

The areas identified as being "favorable" for hosting Kuroko-type VMS mineral deposits are shown in figure I3. The region underlain by felsic metavolcanic rocks (map unit Xf) and bimodal metavolcanic rocks (map unit Xfh) is more limited than that outlined in the "permissive" assessment (fig. I2). Figure I3 shows the areas that satisfy the four individual critical criteria (table I1) as well as various combinations thereof.

The majority of the areas identified as being favorable for hosting Kuroko-type VMS deposits can be correlated with areas where mineralization is known to have occurred. For example, the westernmost area identified in figure I3 with criterion 2 (gray shade) lies within the Powderhorn, Goose Creek, Vulcan mine, and Beaver Creek mineral areas. The Vulcan mine area contains several tracts with various combinations of criteria (table I1), including areas within 1 km of a known Kuroko-type VMS deposit (criterion 5; green shade), within mineralized areas (criterion 3; dark blue shade), and coincidences of criteria 2, 3, 4 and 5 (red shade). The Beaver Creek area contains combinations of criteria 2, 3, and 5 (yellow shade), which corresponds to the area near the Midland mine, a VMS deposit that contained native gold as well as silver, lead, and zinc sulfide minerals (fig. I1). This western area (Powderhorn and Beaver Creek mineral areas) is identified as a region that warrants further exploration, owing to its favorable rank for hosting undiscovered Kuroko-type VMS mineral deposits.

The Cochetopa area, which is made up of the Cochetopa north, central, and south mineral areas as well as the Green Mountain mineral area (fig. I1) is also identified as being favorable for containing undiscovered Kuroko-type VMS deposits. The Cochetopa area contains the Graflin, Denver City, and Yukon mines, which are VMS deposits hosted in felsic volcanic rocks.

Several areas are identified as having the favorable bedrock types but lie outside of historical mining districts (units Xf and Xfh; criterion 2, table I1). Favorable Proterozoic rock units are mapped north and east of Tomichi Creek. Criterion 4 (NURE stream-sediment samples with anomalous concentrations of copper and (or) zinc; table I1) is met by several samples throughout this region. Note that several NURE stream-sediment sample sites with anomalous concentrations of copper and (or) zinc correspond to known mineral areas that have post-Precambrian age mineral deposits (this report, fig. I3; Chapter E, fig. E1). For example, the Tincup/Cumberland Pass, Gold Brick, and Quartz Creek Pegmatite mineral areas have anomalous stream-sediment sample sites. The area east of the Tincup/Cumberland Pass area has several such anomalous stream-sediment sample sites that may be associated with polymetallic vein-type mineralization (see Wilson and others, this volume, Chapter J), or with undiscovered Kuroko-type VMS mineral potential. Another area that meets critical criteria 2 and 3 (table I1) lies northeast of the Marshall Pass mineral area and south of U.S. Highway 50 (fig. I3). The anomalous stream-sediment sites do not correspond to a mine or prospect in the database assembled by Wilson and others (2000), nor to any historical mineral area. As such, this area may be favorable for hosting undiscovered Kuroko-type VMS copper-zinc±gold deposits. Further exploration is recommended for these areas that do not correspond to areas

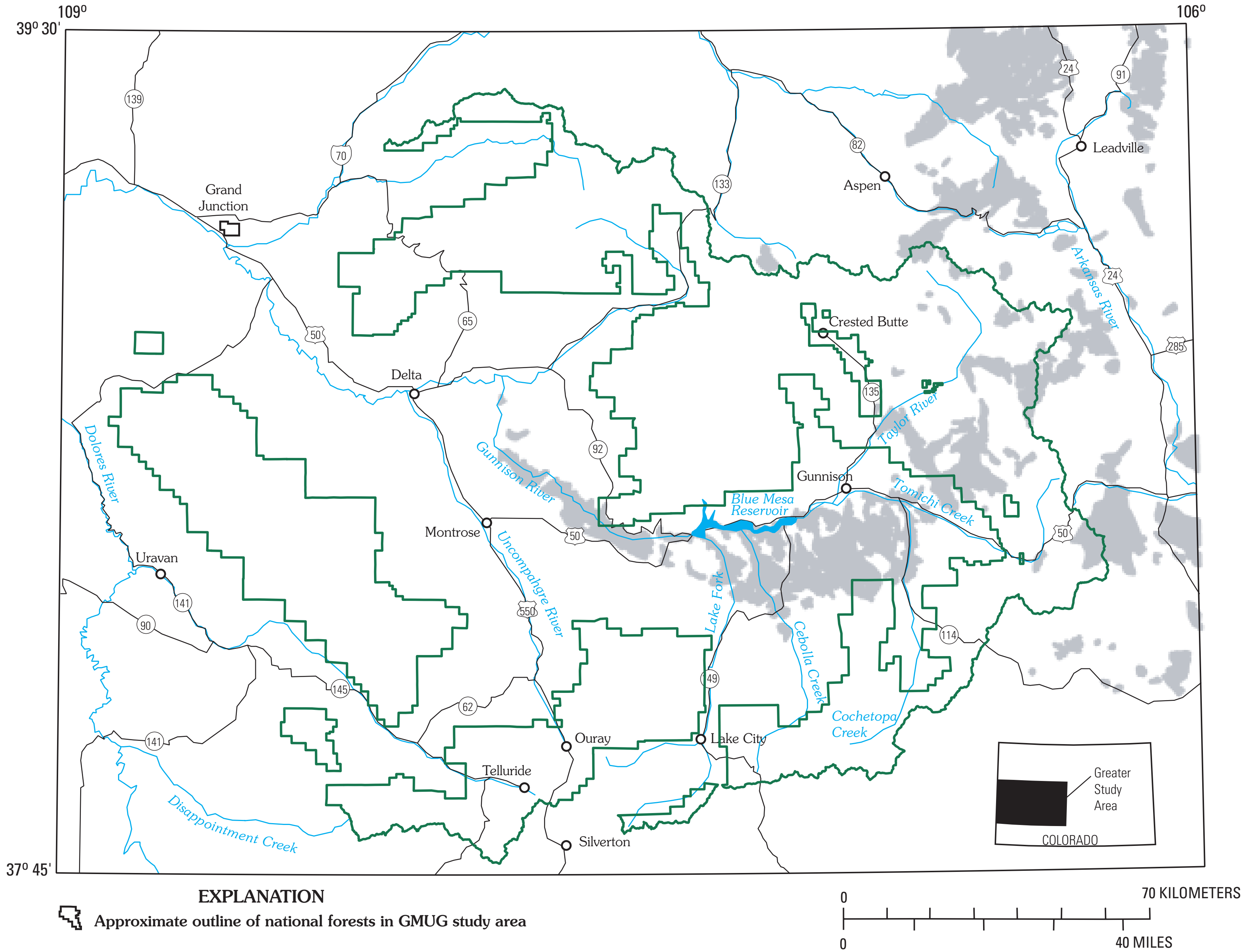

Figure I2. GMUG greater study area, showing permissive tracts (shaded) for hosting Kuroko-type VMS copper-zinc±gold deposits.

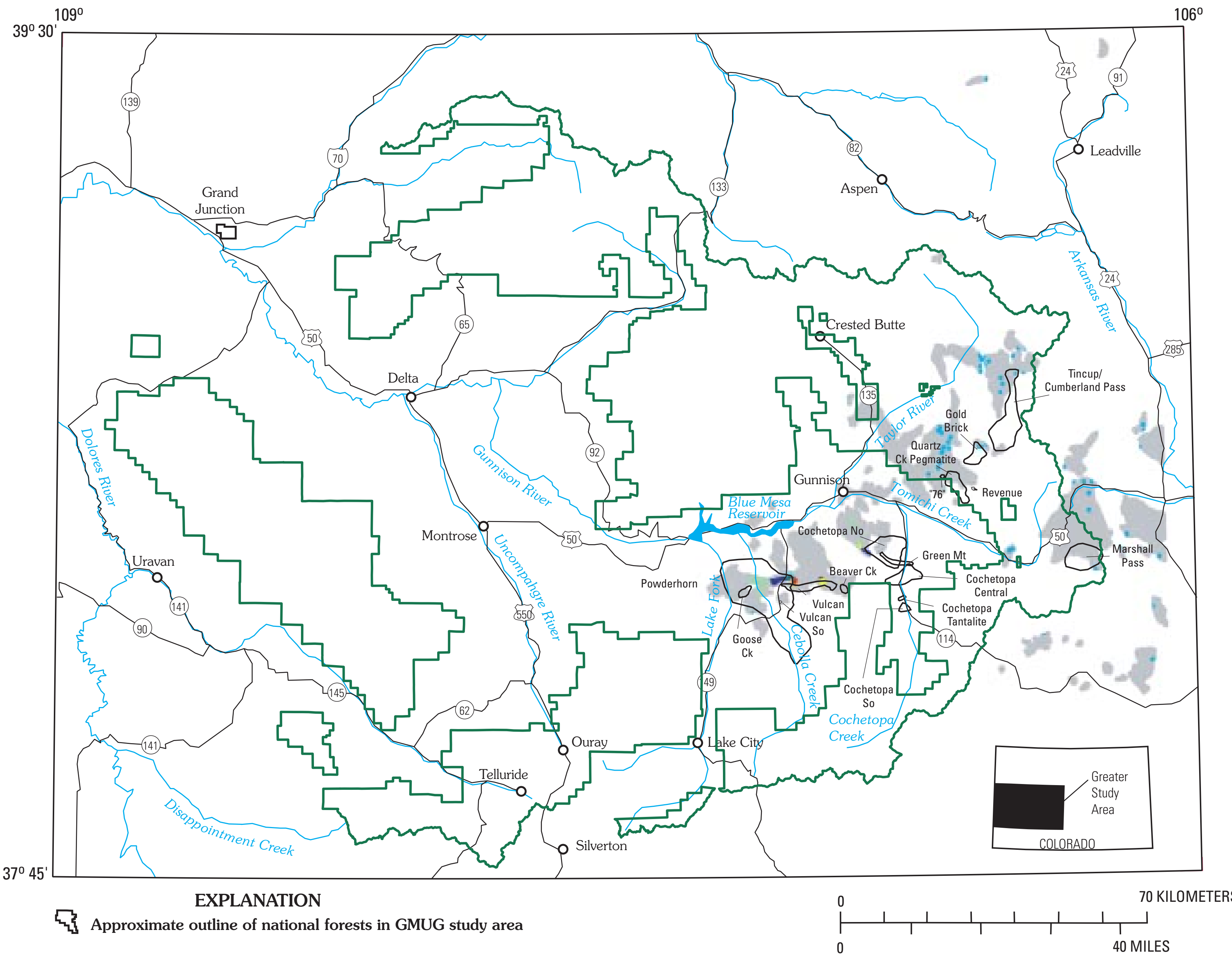

Figure I3 (above and following page). GMUG greater study area, showing favorable tracts for hosting Kuroko-type VMS copper-zinc±gold deposits.

EXPLANATION

Criterion 2—Area underlain by either felsic or bimodal metavolcanic rocks

Criterion 3—Mineralized area known to contain Kuroko-type VMS mines or prospects

Criterion 4—NURE stream-sediment sample site with anomalous concentrations of copper and (or) zinc

Criterion 5—Area within 1 km of a Kuroko-type VMS mine or prospect

Criteria 2, 3, and 5—Area within 1 km buffer of a Kuroko-type VMS mine or prospect and within a mineralized area containing Kuroko-type VMS mines or prospects

Criteria 2, 4, and 5—Area containing a NURE stream-sediment sample with anomalous concentrations of copper and (or) zinc and within 1 km of a Kuroko-type VMS mine or prospect

Criteria 2, 3, 4, and 5—Area within mineralized area known to contain Kuroko-type VMS mines or prospects, adjacent to NURE stream-sediment sample site with anomalous concentrations of copper and (or) zinc, and within 1 km of a Kuroko-type VMS mine or prospect

of known Kuroko-type VMS mineralization to determine the feasibility of undiscovered mineral resources.

Undiscovered Deposit and Endowment Potential

The undiscovered deposit and endowment potential is assessed using a modified version (Spanski and Bankey, this volume, Chapter F, Appendix F1) of the global grade and tonnage models developed by Singer and Mosier (1986) for Kuroko-type massive sulfide deposits. The modified models are constructed exclusively with data for the Precambrian age deposits in the global model to produce a suite of models that are more consistent with the Proterozoic age setting that is present in the study area. The Precambrian model has a median deposit size of 1.2 million t (metric tons) of ore as opposed to 1.5 million t in the global model. The proportions of deposits that contain recoverable copper, zinc, and silver are similar at 100, 75, and 66 percent respectively. However, the Precambrian deposits are only half as likely to contain recoverable lead, 26 percent versus 43 percent in the global model, and approximately 62 percent of the Precambrian deposits contain extractable quantities of gold, versus 56 percent in the global model. The median grades for the Precambrian grade models are 1.3 percent copper, 2.6 percent zinc, 0.42 percent lead, and 23 and 0.59 g/t for silver and gold, respectively. No examples of deposits from Colorado are in the models; however, an unpaired t-test of the production data available for deposits in the Grape Creek and Cebolla districts (Long and others, 1998) shows that the lead, zinc, and silver grades and size (ore tonnages) of these deposits are not inconsistent with those in the Precambrian models. The gold and copper grades are, however, anomalous, being high in gold and low in copper. An assessment panel (Day, Spanski, Bankey, Wilson, and Smith) estimated the numbers of undiscovered deposits to be 0,0,0,1,1 at the 90th, 50th, 10th, 5th, and 1st levels of confidence respectively (see table I2). The estimates suggest that the panel believe the probability of the presence of additional Kuroko-type deposits, with grades and tonnages similar to those of deposits in the Precambrian model, to be very low. The estimate of one deposit at the 5 and 1 percent confidence levels does, however, indicate that the panel recognized a small yet measurable potential that one additional deposit occurs somewhere within a kilometer of the surface within the bounds of the permissive and favorable tract areas. The latter is an acknowledgment of the fact that the majority of the exploration and development activity occurred in the first half of the 1900's and was confined to shallow depths. Inasmuch as Kuroko-type VMS deposits are often clustered, the panel saw a potential for deposits at depth that the exploration methods used in the early 1900's would not have revealed.

The commodity and ore endowments resulting from the Mark3 simulations are summarized in table I2. The results show that within the permissive and favorable tract areas for Kuroko-type VMS deposits there is a 92.9 percent probability that no additional deposits are likely to be present and a 7.1 percent probability of one deposit; a no-deposit scenario is nearly 13 times more likely than a one-deposit scenario.

Table I2. Summary of results of resource endowment potential assessment for undiscovered Kuroko-type volcanic massive sulfide deposits within GMUG greater study area.

Mark3 inputs—Undiscovered deposit estimates:

Estimation confidence	90%	50%	10%	5%	1%
Deposits	0	0	0	1	1

Mark3 outputs—Deposit occurrence probability:

Number of deposits	0	1
Probability of occurrence	92.9%	7.1%

Resource endowment estimates (minimums):

Resource	Probability			Mean
	90%	50%	10%	(probability)
Copper	0	0	0	5,100 (4.9%)
Gold	0	0	0	0.54 (2.6%)
Silver	0	0	0	18 (3%)
Lead	0	0	0	720 (1.5%)
Zinc	0	0	0	13,000 (3.7%)
Ore	0	0	0	370,000 (4.9%)

Endowments given in metric tons.

On the basis of these probabilities, the Mark3 simulation indicates that at the 90, 50, 10 percent probability levels the endowments of ore, copper, zinc, lead, silver, and gold that might be present in undiscovered deposits would be zero. The mean endowment values are averages for all scenarios run and include the no-deposit and one-deposit simulations. The variation in reported probabilities of mean endowments for the five commodities is largely due to the fact that in the grade and tonnage models not all the metals are recovered from every deposit. For example, copper is present in every deposit in the model; however, only 26 percent of the deposits in the model have reported lead grades. Therefore in three out of every four scenarios where a deposit is assumed to be present, no lead endowment will be calculated. The effect on the simulation results is to reduce the probability of the existence of lead and its mean. This effect is best seen in the endowment frequency plots, figure I4.

A more meaningful understanding of the economic importance of the Kuroko-type VMS deposit endowment potential can be gained by looking at the endowment frequency plots (Chapter F, Appendix F1). As in the past, Kuroko-type VMS deposits in the study area will likely be valued for their gold content with other commodities considered as byproducts. The endowment frequency plot for gold endowment (Chapter F, Appendix F1) indicates only a 4.2 percent (100 minus 95.8 percent probability of no endowment) likelihood of the occurrence of a gold endowment, and that its size would range between 240 g and 310 t. The probability that a gold endowment equal to or greater than the mean of 0.54 t could occur is only 2.6 percent. Although these are not encouraging scenarios, the 5 g/t gold grade reported for the Cebolla district (Long and others, 1998) would place it in the 99th percentile (Chapter F, Appendix F1) in terms of the gold grade for Precambrian Kuroko-type VMS deposits. If this high gold content is indicative of VMS mineralization in the study area, then the simulation results are open to some reinterpretation. It could indicate that the local VMS deposits are abnormally enriched in gold, and that the 66 percent of deposits with gold reported may also be low and may under-represent the deposit population in the study area. As a result, the very low endowment threshold of 240 g of gold would be increased significantly, as would the upper limit on the endowment range. The 4.2 percent probability of the existence of a gold endowment would increase to approach 7.1 percent. These subtle differences give reason to believe that a rising gold market could renew exploration interest which would target the favorable Kuroko-deposit VMS tract areas. In addition to being of possible interest for future exploration, these deposits are of concern from an environmental standpoint. Although the median size is a relatively modest 1.2 million t, these deposits are sulfide-rich systems and are capable of generating large volumes of acid effluents when exposed to surface conditions during exploration or development.

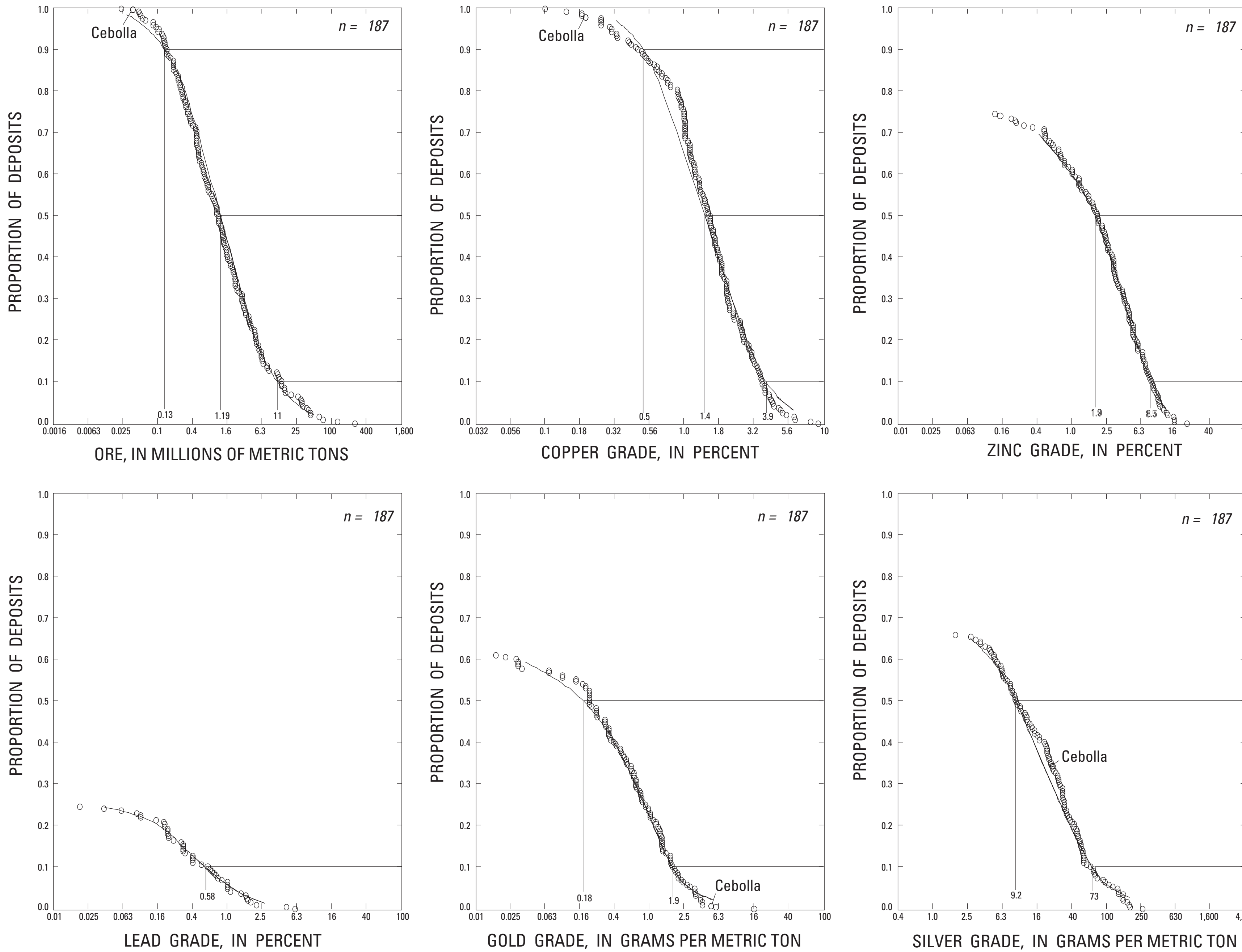

Figure I4. Grade and tonnage models for 187 Precambrian Kuroko-type massive sulfide deposits (modified from Singer, 1986). Cebolla deposit occurs in GMUG greater study area.

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Mineral Resource Assessment for Polymetallic Vein Deposits

By Anna B. Wilson, J. Thomas Nash, Gregory T. Spanski, Viki Bankey, and Steven M. Smith

Chapter J of

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Mineral Resource Assessment for Polymetallic Vein Deposits

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Abstract

Polymetallic veins, rich in copper, lead, and zinc, with smaller but economically important amounts of silver or gold, form from rising, hydrothermal solutions. Location of the veins is determined by local structural features. Known polymetallic vein deposits containing silver, gold, lead, zinc, and copper were locally important producers in two areas of the GMUG National Forest and in areas adjacent to the GMUG Forests. Vein deposits in the San Juan area are generally large and related to Tertiary volcanic rocks, whereas deposits in the northeastern area are mostly smaller and occur in Paleozoic and Proterozoic rocks. Approximately 6,880 square miles of the GMUG Forest study area, located within 10 kilometers of known or inferred shallow subvolcanic Tertiary intrusions, is classified as "permissive" for the occurrence of undiscovered polymetallic vein deposits. Of this "permissive" area, 2,973 square miles in the vicinity of Ruby and Elk Mountains, Dorchester and Forest Hill, Tincup/Cumberland Pass, Gold Brick, and Whitepine, Bondholder, Lake City, Henson Creek, Cimarron, Carson, San Juan, Ouray, and Wilson Peaks mineralized areas are also classified as "favorable." The favorable areas are within 3 kilometers of a known polymetallic replacement or polymetallic vein occurrence or mineralized area known or inferred to host those types of deposits, are within 500 meters of a stream-sediment or rock sample containing anomalous levels of copper, lead, zinc, or detectable silver or gold, and are within 10 kilometers of a caldera or caldera-related structure. Because mining these deposits involved development of several related types of deposits, grade and tonnage records of only polymetallic veins were not available. Therefore, a quantitative assessment was not performed.

Introduction

Veins containing silver, gold, lead, zinc, and copper in a quartz-carbonate gangue have been mined or explored at many places in the GMUG study area (fig. K1). Economically, silver was the most important metal, although some veins were rich in gold, and locally base metals added value. Except close to the surface in the weathering zone, the dominant minerals are sulfides such as galena (PbS), sphalerite (ZnS), chalcopyrite ($CuFeS_2$), arsenopyrite (FeAsS), and pyrite (FeS_2). Most of the silver is contained in the galena, but it also occurs in minerals such as tetrahedrite ($((Cu,Fe,Ag)_{12}(Sb,As)_4S_{13})$), enargite ($Cu_3AsS_4$), and silver sulfosalts (such as stephanite, pyrargyrite, polybasite, proustite, and pearceite). Gold occurs in its native state and locally in tellurides (such as hessite, calaverite, petzite, krennerite, and sylvanite). Electrum (native gold containing more than 20 percent silver) is reported in only one mine (Golden Fleece, Lake City mineralized area) in the GMUG Forests, but in several in the Silverton area.

Economic geologists classify these vein deposits in many ways (Cox and Singer, 1986; Guilbert and Park, 1986; Panteleyev, 1988), but the unifying features are the vein geometry and polymetallic composition, hence the term polymetallic vein (PMV) deposit. We recognize that the broad definition used here encompasses many deposit types used by others, and also that the vein portion of the deposit commonly grades outward into disseminated or replacement types of ores. For instance, in the large Idarado mine, veins tended to be rich in quartz-adularia-gold at high elevations, but they became increasingly rich in chalcopyrite and galena at depth, graded laterally into a replacement zone where the vein crossed the Telluride Conglomerate, and formed skarn-type ore in deeper limestone beds (Mayor and Fisher, 1993). For simplicity, we will include all these kinds of mineralization styles in one descriptive model in this report.

Genetic Model for Polymetallic Veins

Veins rich in copper, lead, and zinc, and carrying smaller but economically important amounts of silver or gold, form from rising, hydrothermal solutions with a temperature of about 250° to 350° C. Vein features are generally those of the "epithermal" class of deposits, but some deeper vein portions may be better characterized by the archaic term "mesothermal" of Lindgren (1933). Several of the deposits in and near the study area have been studied in some detail in the past 25 years to increase understanding of ore-forming processes. (See, for example, Casadevall and Ohmoto, 1977; Nash, 1975; Slack, 1980; Fisher, 1990; Krasowski, 1976; Rosenlund, 1984; Jefferson, 1985; Herald, 1981; Neff, 1988; Earley, 1987.) Geometry of the veins is determined chiefly by the structural framework of faults and local brittle character of host rocks; non-brittle or reactive rocks such as shale and limestone commonly host replacement zones adjacent to the source vein.

Geochronologic studies (Lipman and others, 1976; Bove and others, 2000) demonstrate that the veins formed a million or more years after the host rocks, and in some places they are contemporaneous with small intrusive bodies. Measured ages for minerals associated with ore, and ages inferred from geologic relations, are in the range of 30 to 5 Ma. Ages as old as early Tertiary are likely in the eastern part of the study area, and in theory, we are not aware of any reason to rule out even older times of formation.

Stable isotope studies demonstrate that sulfur is derived from igneous rocks, but water is probably derived from both magmatic and near-surface sources (Casadevall and Ohmoto, 1977; Taylor, 1997; Ohmoto and Goldhaber, 1997). In places, fluid inclusions indicate that the hydrothermal fluids boiled (Nash, 1975). This process marks the uppermost levels (the upper depth limit) of ore formation, but for the large veins as at Sunnyside and Idarado, boiling is not indicated (Nash, 1975). Mineral textures and vein fabrics suggest that the larger vein systems formed deeper than typical hot springs type deposits (currently important sources of gold and silver in Nevada). Determining the source of heat and metals for these deposits is difficult, although clear answers to this seemingly academic question would greatly improve the spatial analysis of where the deposits could be expected.

Polymetallic vein deposits form as part of complexly zoned subvolcanic systems (Silberman and Berger, 1985). The zoning is helpful to specialists during exploration, but also is confusing. The top of the system, which in many places is in volcanic lavas and tuffs, is very different in chemical and mineralogical composition from the deeper part 2,000 to 3,000 ft (about 600–900 m) below. In some parts of the western United States, mining has shown that veins of this type extend down into the plutonic rocks that were related to the source. The top may be rich in gold and associated with fine-grained silica and adularia, whereas the deeper parts have more copper and lead sulfide minerals, often with tungsten and bismuth; alteration products are sericite, epidote, and other minerals reminiscent of parts of porphyry copper systems (Guilbert and Park, 1986). Vertical variability of composition and ore grade complicates classification of small prospects and our interpretation of descriptions of deposits in reports: we must consider whether the prospect is the top of a larger deposit at depth, the bottom of a mostly eroded deposit, or some other type of deposit. Vertical relief in the San Juan Mountains can be of help in this evaluation, and also in the practical aspects of mining, but other parts of the study area lacking much relief do not have this benefit.

Description of Mining Areas Containing Known Polymetallic Veins

Polymetallic vein deposits are prominent in two regions within the GMUG restricted study area: in the south extending from the Wilson Peaks to the Bondholder mineralized areas and in the northeast extending from the Ruby to the Whitepine (also known as Tomichi) mineralized areas (fig. J1). The southern area generally hosts larger deposits that are related to Tertiary volcanic rocks. Deposits in the northeastern area are mostly smaller, and most occur in Paleozoic and Proterozoic rocks. Understanding the geologic setting, character, and mode of origin of known polymetallic vein deposits allows us to formulate critical criteria that can help identify additional areas with potential to host similar deposits.

The western San Juan Mountains between Silverton and Telluride contain some of the best endowed veins in the study area. Here, deposits were mined underground with hundreds of miles of interconnected tunnels. Years of detailed work by many geologists (for example, Burbank, 1930, 1933, 1951; Burbank and Luedke, 1969; Kelley, 1946; Luedke and Burbank, 1981), underground and on the surface, document a regional fracture pattern that radiates out from the elliptical structure of the Silverton caldera margin. Major preexisting graben structures (Eureka graben) appear to control ore distribution within the caldera. Aided by miles of exposure in mines, geologists recognized that the deposits extend downward for thousands of feet, in fact far below the deepest levels of mining, which were generally defined by the elevation of deep tunnels that served as haulages for ore and drains for water. Deep drilling at Idarado (Mayor and Fisher, 1993) intersected skarn-like ore 1,000 to about 3,000 feet below the mined veins, but this ore has not been pursued because of the expense of mining at those depths (ore would have to be lifted, and water pumped). Some of the vein deposits were in pre-Tertiary sedimentary rocks, and those were, in general, less productive. The Telluride Conglomerate, at the base of the volcanic section, contains reactive clasts of limestone that host replacement ores adjacent to larger veins.

Ore in the San Juan Mountains area was mined from small shafts prior to 1900. In later years, consolidation of mining properties permitted large mine complexes to be developed. Ore was transported to mills through long tunnels at elevations below treeline that were sheltered from avalanches and severe winter conditions. A combination of depressed metal prices and high underground mining costs forced almost all of the mines and mills in the western San Juan Mountains to close by the mid-1980’s. (The Sunnyside mine, south of the study area, remained open until 1991.) Total production from the Idarado mine was almost 24 million short tons as of 1976 (Mayor, 1978), and from the Camp Bird purportedly about 13 million short tons (USGS, unpub. data).

Elsewhere in the study area, polymetallic vein deposits were generally much smaller in size. The volcanic-hosted veins near Lake City produced some extremely rich ore in the

1880's and '90's valued at more than $10 million at the time of mining (Irving and Bancroft, 1911), but production in the 20th century was less than 1 million tons. The Lake City area never came close to the production of the nearby Eureka, Red Mountain (West), and Telluride areas (all in the San Juan mineralized area; see Wilson and Spanski, this volume, Chapter E).

Vein deposits in the northeastern part of the study area are commonly somewhat different from the classic San Juan type. The area is on the west flank of the Sawatch uplift and contains Tertiary intrusive rocks (primarily granodiorite), Paleozoic carbonate and clastic rocks, and mines known (or suspected) to have produced ore from polymetallic vein type ore bodies. These veins differ from the San Juan type in that they have more milky "bull" quartz and a relationship to early to middle Tertiary granitic stocks that appear not to have generated an extensive volcanic edifice. Even the most productive mines in veins in sedimentary host rocks in the Ruby mineralized area near Crested Butte produced well under a million tons of ore. The veins mined in the Gold Brick and Tincup/Cumberland Pass mineralized areas were locally important, but relative to veins in the San Juan area were at least an order of magnitude less productive. (See Crawford and Worcester, 1916; Vanderwilt, 1947; Fisher, 1990; Henderson, 1926, among others.)

Application of the Deposit Model for a Mineral Resource Assessment of Polymetallic Vein Deposits

The criteria listed in table J1 are those used in this reconnaissance mineral resource assessment to define "permissive" and "favorable" mineral deposit potential tracts for undiscovered polymetallic vein deposits. The criteria are based on the genetic model presented herein and the data available for the GMUG study area. The applicable regional databases available for this GIS-based assessment include digital geologic map data (Day and others, 1999), mine and prospect locations (Wilson and others, 2000), outlines of mineralized areas (Wilson and Spanski, this volume, Chapter E), regional NURE stream sediment geochemical data (S.M. Smith, unpub. data, 2001), a map of intrusions based on aeromagnetic survey data interpretation (Bankey and others, this volume, Chapter D), and maps showing detailed age and composition of intrusions (Bove and others, 2000; D.J. Bove and others, unpub. data, 2001).

In this chapter, GMUG restricted study area refers only to GMUG National Forests and the lands they roughly surround from Grand Junction to the area east of Gunnison (fig. J1). It also includes the western slope in the Uravan area, but the restricted study area does not include lands in adjacent National Forests: White River, San Isabel, Rio Grande, or San Juan, even though they are within the "greater study area" boundary. Any resource potential indicated outside of this restricted study area is based on incomplete data, especially for mines, prospects, and mineralized areas. Many more areas in the adjacent lands, including national forests, may be permissive, or even favorable. For instance, Aspen and Leadville, both large productive districts, contain polymetallic vein and polymetallic replacement deposits, yet neither is shown in figure J3. The square miles indicated as permissive and favorable are therefore minimums for the entire "greater study area."

The polymetallic vein deposit model used for assessment purposes in the restricted study area is a highly generalized model that embraces at least five deposit models described in Cox and Singer (1986). Although individual examples of hot-spring gold-silver (Berger, 1986), polymetallic vein (Cox, 1986), Creede epithermal vein (Mosier and others, 1986), polymetallic replacement (Morris, 1986), and base- and precious-metal skarn deposits can be cited, for the most part these deposit types commonly occur spatially intermingled. As a consequence of this clustering or nesting of deposit types,

Table J1. Delineation criteria for polymetallic vein deposits in GMUG restricted study area.

Diagnostic criterion for permissive tract delineation
1. Presence of mapped shallow, subvolcanic Tertiary intrusions or geophysical evidence for them. We include a 10 km buffer because known deposits occur approximately this far outward from intrusive centers.
Diagnostic criteria for favorable tract delineation
2. Proximity to known or suspected polymetallic deposits, both vein and replacement. We use a buffer of 3 km to allow space for undiscovered deposits or deposits that are known but not in our database of deposits.
3. Within 3 km of a mineralized area known or inferred to host polymetallic vein or polymetallic replacement deposits.
4. Geochemically anomalous concentrations of copper, lead, zinc, or detectable silver or gold. This geochemical association is the same as discussed for polymetallic replacement deposits. The buffer used is 500 m. Other elements, such as bismuth, cadmium, molybdenum, arsenic, antimony, or tellurium, may be useful in theory, but available information is either nonexistent or inconsistent.
5. Proximity to calderas and caldera-related structures; we include a buffer of 10 km inside and outside calderas to cover caldera-related structures that are known to control ore deposits.
6. Permissive terrane (see criterion 1) minus the areas underlain by Quaternary sediments or young Tertiary basalts.

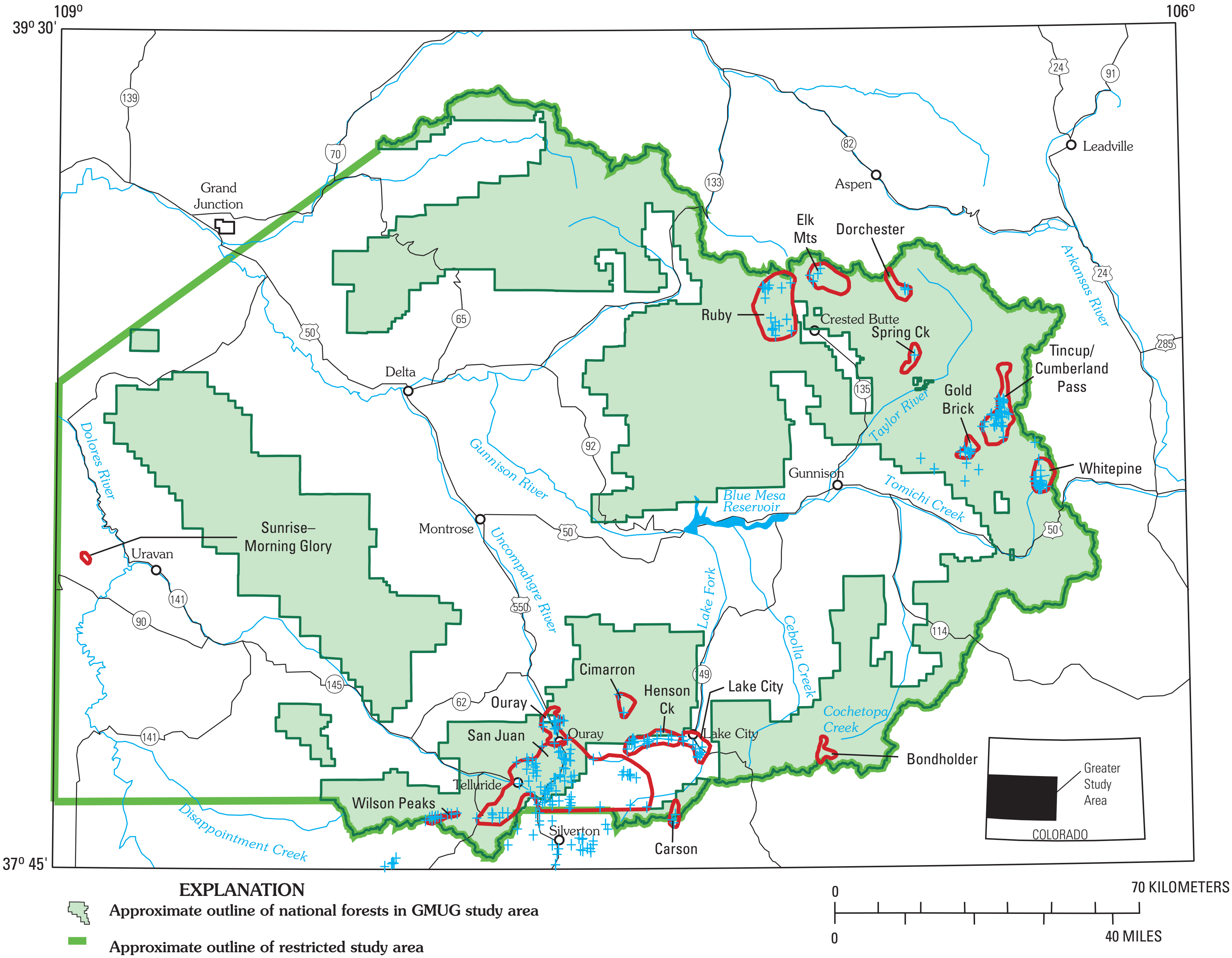


Figure J1. GMUG restricted study area, showing locations of polymetallic vein or polymetallic replacement deposits (plus signs) and the mineralized areas adjacent to or containing them (red outlines).

early mining, particularly where production was significant, required development of several types of deposits. These occurrences are now identified in terms of what is believed to have been the dominant deposit type present. However, for making subjective estimations of numbers of remaining deposits, this type of count is inadequate. The prominence of subordinate deposit types is under-represented, and the size and grade characteristics of the various deposit types involved, reflected in production records, cannot be properly modeled. Historically, production was reported for mills and might reflect the output from a single large mine or from several mines of varying size. In addition, production was in many cases further consolidated and reported by county. To reconstruct the size and grades of the mines by deposit types or to obtain an accurate count of the numbers of deposits of each deposit type that have so far been identified is virtually impossible. Given this situation, the general polymetallic vein model was adopted for the current assessment.

The set of delineation criteria outlined in table J1 is by no means exhaustive. It is limited by the availability of supporting data sets that are both fairly complete and geographically comprehensive at 1:250,000 scale. Additional criteria could have been considered for tract assessment if the digital databases had been more complete. Examples of other data that could have been used to classify and evaluate the mineral resource potential of the area include:

- occurrence of small veins or prospects containing minerals such as stibnite or manganese oxides, or pathfinder elements such as mercury;
- distribution of hydrothermal alteration minerals, such as chlorite, sericite, quartz, with or without pyrite or barite;
- anomalous concentrations of copper, tungsten, gold, arsenic, antimony, bismuth, barium, manganese, iron, or magnesium in bedrock, altered rock, or stream-sediment samples;
- presence of structural features, such as faults or zones of extensional tectonic activity;
- presence of small porphyritic dikes and stocks and associated zones of hydrothermal alteration and breccia pipes;
- presence of Cretaceous or Tertiary age porphyry (model 17, Cox and Singer, 1986), skarn (18b, c, d, Cox and Singer, 1986), or evidence of polymetallic replacement mineralization;
- detailed aeroradiometric maps showing Th/U ratios of less than 4:1 suggesting that uranium depletion may have resulted from hydrothermal activity;
- local ground electromagnetic surveys with sufficient detail to map veins containing high concentrations of sulfide minerals; and
- detailed maps of calderas and related structures located outside the study area that may have an influence inside the study area, such as the Mount Aetna caldera (potentially influencing the Tincup/Cumberland Pass and Whitepine areas), or locations of nonresurgent calderas, such as the Cochetopa Park caldera (which does not appear to be associated with Tertiary intrusions or mineralization).

Permissive Tracts

In the GMUG greater study area, 6,880 mi^2 is classified "permissive" for the occurrence of polymetallic vein deposits (fig. J2; table J2). Polymetallic vein deposits are known to form in rocks of many ages (Precambrian to Tertiary) and compositions. The fundamental requirement is that the host rock be brittle enough to break and stay open, thus allowing a vein to fill open space. Even this broad rule is violated: veins also occur locally in more ductile rocks like shales, and change to more diffuse replacement zones in reactive carbonate rocks. Therefore, there are few geologic restraints on where these veins might form. Veins could be concealed under Quaternary sedimentary deposits, so even these sediments are included in the permissive tracts. Because of the generally accepted association with shallow, subvolcanic intrusions, we include a general stipulation that those rocks, or geophysical evidence for them, be present within 10 km.

Favorable Tracts

In the GMUG greater study area, 2,973 mi^2 is classified "favorable" for the occurrence of polymetallic vein deposits (fig. J3). Some of this area is outside the restricted study area, and this value should be considered a minimum for the "greater study area" for reasons mentioned in the "Application

Table J2. Polymetallic vein tracts in the GMUG restricted study area.

Tract No.[a]	Tract name	Delineation criteria
P1	Permissive for polymetallic veins	1
F1	Ruby and Elk Mountains	2, 3, 4, 6
F2	Dorchester and Forest Hill	2, 3, 5, 6
F3	Tincup/Cumberland Pass, Gold Brick, and Whitepine	2, 3, 4, 6
F4	Bondholder	2, 6
F5	San Juan area	2, 3, 4, 5, 6
	Unnamed	variable

[a]P, permissive tract; F, favorable tract.

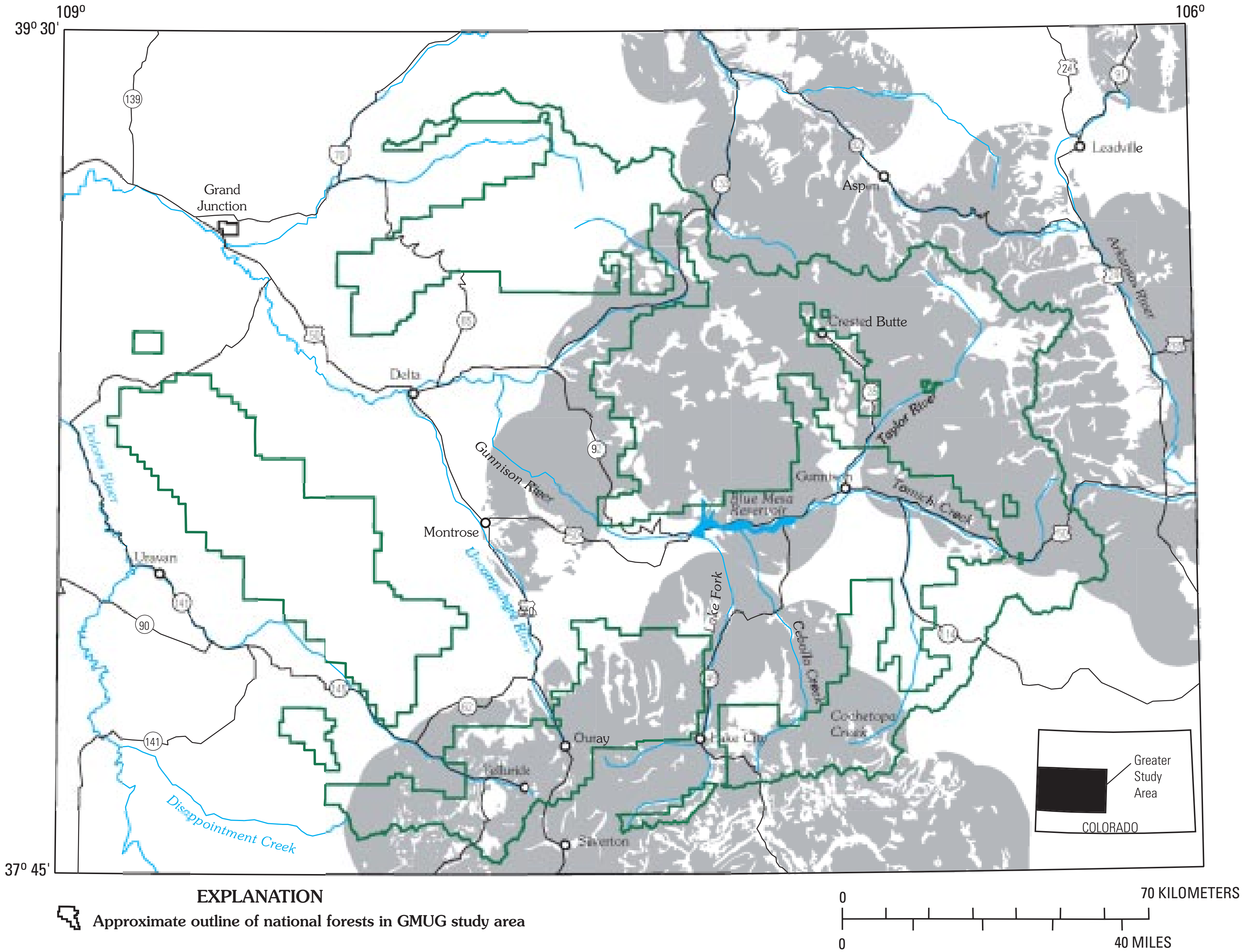


Figure J2. GMUG greater study area, showing permissive tracts (shaded) for polymetallic vein deposits.

of the Deposit Model for Mineral Resource Assessment of Polymetallic Vein Deposits" section. These "favorable" lands represent about 43 percent of the "permissive" tract. Most of the favorable lands are in five well-defined areas, discussed later. The critical criteria used for delineating regions "favorable" for hosting polymetallic vein type deposits appear in table J1. These criteria are more restrictive than those used to delineate the permissive terrain. Increased importance is placed on the presence of evidence that mineralization has occurred, on anomalous geochemistry, and on proximity to caldera structures.

Analysis of the known deposits suggests five additional geologic and geochemical criteria for spatial modeling of favorable areas: proximity (3 km) to areas of known or suspected polymetallic vein or polymetallic replacement deposits; proximity (3 km) to individual polymetallic vein or replacement deposits; geochemically anomalous copper, lead, zinc, or detectable silver or gold (500 m); proximity (10 km) to calderas or caldera-related structures; and omitting areas underlain by young Tertiary basalts and Quaternary sediments. These are mostly empirical criteria and are consistent with the genetic model described earlier. Most of the genetic criteria such as isotopic values or fluid inclusion numbers are either not available for much of the area or are not amenable to spatial modeling. Proximity to faults was studied and modeled, but deleted as a favorable criterion. Proximity to faults alone was considered insufficient evidence to classify the ground as favorable, and elsewhere the ground may already be included using other criteria.

To be considered favorable for polymetallic veins (fig. J3), an area must have been classified as permissive (fig. J2) and meet at least one additional criterion (table J1). Areas meeting at least three criteria are clustered in the northeastern and southern parts of the study area. In the northeastern part of the study area these include (F1) Ruby and Elk Mountains, (F2) Dorchester and Forest Hill, and (F3) Tincup/Cumberland Pass, Gold Brick, and Whitepine mineralized areas. In the southern part of the study area they include (F4) Bondholder, and (F5) Lake City, Henson Creek, Cimarron, Carson, San Juan, Ouray, and Wilson Peaks mineralized areas (fig. J3).

The Ruby and Elk Mountains tract (fig. J3, area F1) contains known polymetallic vein deposits that appear to be related to Tertiary plutons. Most of the veins are hosted in Cretaceous Mesaverde Formation consisting of interbedded sandstone, shale, and coal, or in Ohio Creek Member of the Mesaverde Formation and Tertiary Wasatch Formation consisting of conglomerates, sandstones, and shales. Veins related to the Afley, Augusta, and Mt. Owen stocks are weakly mineralized (Ellis, 1983, p. 9). Most of the mineralization is attributed to the younger felsite plugs related to the Mount Emmons porphyry molybdenum deposit. Mineralogically, the veins carry sulfides, such as galena and sphalerite, the primary sources of silver, as well as pyrite, minor chalcopyrite, and possibly tetrahedrite. Farther from the intrusions, the veins may contain native and ruby silver, and arsenopyrite.

According to Ellis (1983), mining began in 1874 from silver-rich base-metal veins such as the Forest Queen, Ruby Chief, Ruby King, and Bullion King. Several of these mines produced intermittently until the early 1900's. In the 1950's–1960's mining resumed at the Keystone, Micawber (Standard), and Daisy mines. After this, the emphasis shifted to molybdenum discoveries in Redwell (the Mount Emmons deposit) and Red Lady Basins. Little production information is available. Ellis (1983) credited the area with at least 24,000 oz gold, 5.2 million oz silver, 6.6 million lb copper, 30.9 million lb lead, and 55.2 million lb zinc between 1901 and 1969.

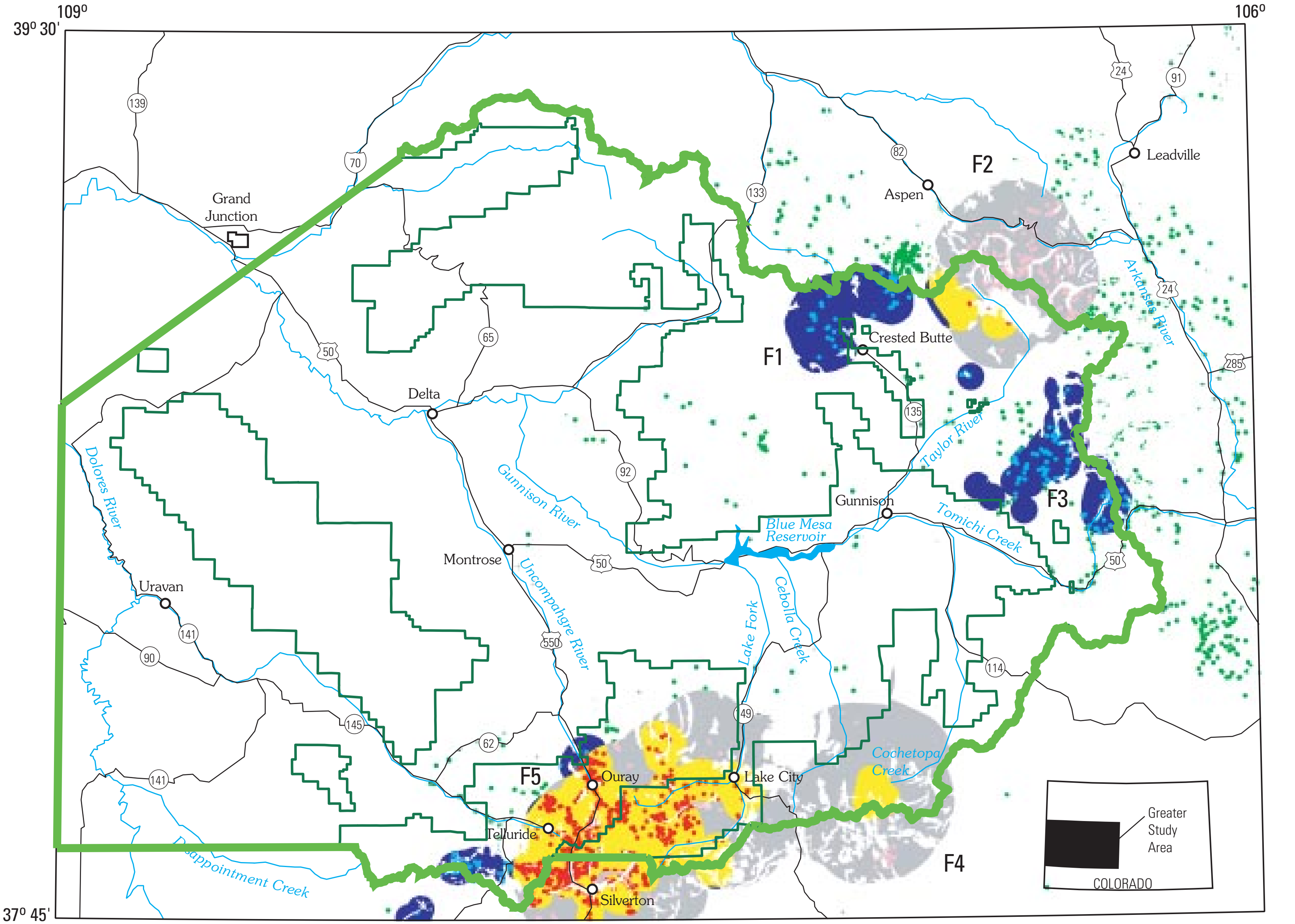
These areas meet criteria 1, 3, 6, and locally, 2 and 4 (tables J1 and J2). Additional, similarly small polymetallic vein deposits are likely to be present in the vicinity or as extensions of known deposits.

Little is known about the deposits in the Dorchester and Forest Hill mineralized areas (fig. J3, area F2) (Garrett, 1950; Prather, 1964; Slebir, 1957). None of the deposits in these areas is classified as a polymetallic vein deposit, yet because these deposits are intimately associated with polymetallic replacement deposits, at least some of the deposits are likely to fit the category. These deposits are on the flank of the Grizzly Peak caldera and may be associated with that structure. This caldera is older than the calderas of the San Juan volcanic field (Day and Bove, this volume, Chapter B). The combination of a mineralized area suspected of containing polymetallic vein or replacement deposits (criteria 2 and 3) and a high density of anomalous geochemical values (criterion 4) within 10 km of the Grizzly Peak caldera (criterion 6) places this tract in the favorable category.

Tincup/Cumberland Pass and Whitepine mineralized areas (fig. J3, area F3) are noted more for their polymetallic replacement than vein deposits. Reactive carbonate rocks were favored for replacement ore zones adjacent to veins (faults), as discussed for the polymetallic replacement deposits (Wilson and others, this volume, Chapter K). However, because the two deposit types are closely related both spatially and genetically, and many of the deposit descriptions (Dings and Robinson, 1957; Worcester, 1919; Trammel, 1961; Rosenlund, 1984; Goddard, 1936; Hill, 1909) mention veins, they are considered together. Additional small polymetallic vein deposits are likely to be present in the vicinity or as extensions of known deposits.

Deposits in the Gold Brick district are fissure-vein deposits (Rugg, 1956; Crawford and Worcester, 1916, p. 80). Locally, deposits hosted by veins in schist and gneiss are widened up to a foot and a half by replacement. Much of the ore consists of sulfide minerals, but there is also a concentration of oxidized ores. Galena appears to have been the primary ore mineral containing gold and silver. In addition, similar small polymetallic vein deposits are likely to be present in the vicinity or as extensions of known deposits.

These three mineralized areas, Tincup/Cumberland Pass, Whitepine, and Gold Brick, combined (fig. J3, area F3) have at least three characteristics favorable for the presence of polymetallic vein deposits. Appropriate intrusions and



EXPLANATION

Approximate outline of national forests in GMUG study area

Approximate outline of area assessed for polymetallic vein deposits

0 70 KILOMETERS

0 40 MILES

Figure J3 (above and following page). GMUG greater study area, showing favorable tracts for polymetallic vein deposits. F1, Ruby and Elk Mountains; F2, Dorchester and Forest Hill; F3, Tincup/Cumberland Pass and Whitepine; F4, Bondholder; F5, San Juan Mountains tracts. Descriptions in text.

EXPLANATION

Criterion 2 or 3 or both—Within 3 km of a deposit or mineralized area containing polymetallic vein (PMV) or polymetallic replacement (PMR) deposits

Criterion 4—Within 500 m of anomalous geochemical sample

Criteria 2 or 3 or both, and 4—Within 3 km of a deposit or mineralized area containing polymetallic vein (PMV) or polymetallic replacement (PMR) deposits and within 500 m of anomalous geochemical sample

Criterion 5—Within 10 km of a caldera boundary

Criteria 2 or 3 or both, and 5—Within 3 km of a deposit or mineralized area containing polymetallic vein (PMV) or polymetallic replacement (PMR) deposits and within 10 km of a caldera boundary

Criteria 4 and 5—Within 500 m of anomalous geochemical sample and within 10 km of a caldera boundary

Criteria 2 or 3 or both, and 4 and 5—Within 3 km of a deposit or mineralized area containing polymetallic vein (PMV) or polymetallic replacement (PMR) deposits and within 500 m of anomalous geochemical sample and within 10 km of a caldera boundary

host rocks are present (criteria 1 and 6), as well as known polymetallic vein deposits (criterion 2) or mineralized areas containing polymetallic vein or replacement deposits (criterion 3). Locally, the mineralized tract may contain geochemically anomalous areas (criterion 4).

The small veins in the Bondholder district (fig. J3, area F4) are somewhat enigmatic. This district has seen minimal production. Only a study by Steven and Bieniewski (1977) mentioned the mines in the area and concluded that the area has low economic potential “because of the small size of the veins and the erratic distribution of valuable metals along them” (p. 33). There are very few geochemical anomalies, but this could be due to insufficient sample density in the databases used for this national forest assessment. The presence of a mineralized area (criterion 2) within a caldera (criterion 6), places this tract in the favorable area.

The San Juan Mountains tract (fig. J3, area F5) contains the Wilson Peaks, San Juan, Ouray, Cimarron, Henson Creek, Lake City, and Carson mineralized areas (fig. J1). This tract contains a slightly different type of polymetallic vein from the rest of the study area, the most striking distinction being their relatively large size. Some of the San Juan Mountains area veins contain millions of tons of ore. All but the veins on the periphery, in Wilson Peaks and Ouray areas, almost certainly have a genetic link to the caldera-related structures (criterion 5). However, radiometric age determinations show that the ores are significantly younger than the caldera events and probably synchronous with younger shallow plugs that were intruded along caldera structures (Lipman and others, 1976; Bove and others, 2000).

By 1945, this area produced $345 million worth of ore, nearly 44 percent of it in gold (summarized from Burbank, in Vanderwilt, 1947, p. 404–405). About 7 million oz of gold accounted for about $150 million (gold was valued at approximately $20.67 per oz until 1934). Silver accounted for 30 percent of the value, lead for 16 percent, and copper and zinc 5 percent each. As of the mid 1970's, the Idarado and Camp Bird mines alone had produced more than 37 million tons of ore.

This tract is classified as favorable because it contains the appropriate host rocks (criteria 1 and 6), contains mineralized areas with polymetallic vein or replacement deposits (criterion 3) or individual deposits (criterion 2), is within 10 km of a caldera (criterion 5), and has many geochemical anomalies (criterion 4).

Undiscovered Deposit and Endowment Potential

Estimation of the probable numbers of additional deposits and simulation of the potential mineral resource endowment that could be associated with those deposits requires that grade and tonnage models for those deposit types be available. In the absence of such models for the polymetallic vein deposit type used, no quantitative assessment was conducted. In its deliberations, however, the USGS assessment panel (Wilson, Spanski, Bankey, Nash, D.A. Lindsey, Smith, and W.C. Day) believed that a secondary, nonquantifiable potential is associated with polymetallic vein type mineralization in the study area. That potential is associated with the probable existence of smaller undiscovered ore bodies that, in the past, would have been developed as a mine or as an extension to a mine. The panel believed that the potential is highest for these ore bodies in areas adjacent to, or directly beneath, the areas of currently known polymetallic vein occurrences. Their numbers, size, and endowment characteristics cannot be estimated because size and grade models are not available. In today's economic and environmental climate, large mining companies are not likely to be interested in sporadic occurrences of this nature; however, these smaller occurrences might be attractive development targets for smaller entrepreneurial groups.

Discussion

What is the outlook for exploration and mining of polymetallic vein deposits in the next 10 or 20 years? From a geological standpoint, we can say with confidence that large tonnages of polymetallic mineralized rock exist in the study area both in former mining areas and as undiscovered deposits. The vital question is not one of geology but of economics. Economic factors are complex, and we are not experts in this field, but we would consider the following as impediments to future mining: (1) lack of a mining infrastructure, including mills and mining expertise; (2) depressed prices for silver and other metals in recent years, with few signs of recovery; and (3) societal resistance to mining and fear of environmental pollution from mining.

Some deposits were mined with high profits in the 1880's, but the mines were closed during the silver crash of the 1890's and never reopened. Many of these mining operations had, in fact, taken out the richest ore; and probably insufficient high quality ore remained to allow mining during periods of higher silver prices in the 20th century. Exploration has been intense, if not exhaustive, in the study area, reducing the likelihood of future discoveries of bonanza-type ores. Most of the production from polymetallic vein deposits has been from large mines since 1920, when changes in milling technology and the advent of selective floatation allowed profitable mining of "low grade" ores. The new technology allowed zinc, which formerly drew a smelter penalty and was considered a contaminant, to be recovered for profit (Burbank and Luedke, 1964). Future changes in mining and milling technology are possible, of course, but are not expected to be enough to offset the economic advantage of lower cost mining, milling, and smelting in other parts of the world. The paradox here is that for mining of polymetallic vein deposits to produce a significant tonnage, a large mining and milling operation is mandated, and this is most at odds with considerations 1 and 3 in the preceding paragraph. Small-scale mining of local pockets of rich ore may be viable, particularly if the operators can find a way to mill and smelt their ore.

The viability of these mineralized areas, again, is dependent on economic factors rather than geology. Geology is favorable beyond the known deposits, and only detailed studies including drilling can determine if additional deposits exist. We expect that any future discoveries would be within or adjacent to the colored areas in figure J3. However, new geologic information, or new concepts of ore formation, could lead to the discovery of ore outside of the favorable areas shown in figure J3 but within the permissive area shown in figure J2.

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Mineral Resource Assessment for Polymetallic Replacement Deposits

By Anna B. Wilson, Gregory T. Spanski, Viki Bankey, and Steven M. Smith

Chapter K of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

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Mineral Resource Assessment for Polymetallic Replacement Deposits

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Abstract

Polymetallic replacement deposits are hydrothermal, epigenetic accumulations of sulfide minerals in bedded deposits (mantos), massive lenses, pipe-shaped bodies, and associated veins hosted in limestone, dolomite, or other chemically reactive (soluble) rock, adjacent to porphyritic intrusions. In the GMUG study area, polymetallic replacement deposits containing lead, zinc, copper, silver, and manganese were locally important producers in the Tincup/Cumberland Pass, Whitepine, Ouray, and San Juan mineralized areas. Approximately 5,133 square miles of the GMUG Forest study area, located within 10 kilometers of known or inferred Tertiary or Cretaceous felsic intrusive rocks, within 2 kilometers of permeable or chemically reactive sedimentary rocks, or in areas known or inferred to be underlain by Paleozoic sedimentary rocks beneath volcanic rocks, are classified as “permissive” for the occurrence of undiscovered polymetallic replacement deposits. Of this “permissive” area, 1,676 square miles in the vicinity of the Ruby, Elk Mountains, Dorchester, Forest Hill, Spring Creek, Tincup/Cumberland Pass, Gold Brick, Whitepine, Cimarron and Henson Creek, San Juan east, Ouray and San Juan west mineralized areas are also classified as “favorable.” The favorable areas contain known polymetallic replacement or polymetallic vein occurrences, are within 2 kilometers of a known polymetallic replacement-type occurrence, contain known or inferred carbonate rocks, and are within 500 meters of a stream-sediment or rock sample containing anomalous levels of silver, lead, or zinc. The assessment team estimated that the probability of even one undiscovered deposit occurring within the “permissive” and “favorable” tracts for polymetallic replacement deposits fell below the range of estimation confidence; therefore, a quantitative assessment was not performed.

Introduction

Polymetallic replacement deposits have been historically important contributors to the total quantity of lead, zinc, copper, silver, and manganese produced in Colorado, especially in the Leadville, Gilman, Alma, Rico, and Tenmile areas, all outside the GMUG restricted study area (fig. K1). Within the restricted study area, in the Tincup/Cumberland Pass, Whitepine (also known as Tomichi), and Ouray mineralized areas, polymetallic replacement deposits have produced smaller, but locally significant, quantities of ore. Substantial amounts of gold or silver in these smaller deposits compensated for their limited volume and made them commercially attractive.

Most of these deposits have similar physical characteristics and occur in the same geologic environments as deposits included in the descriptive model of polymetallic replacement deposits (Morris, 1986, model 19a). Mosier and others (1986) compiled grade and tonnage data for 52 deposits of this type worldwide. Although none of the Colorado deposits is included in the model, grade and tonnage of the GMUG deposits fit the general distribution of the deposits from all over the world used to develop the model. Had they been included, deposits at Leadville, Gilman, and Alma, all close to the GMUG restricted study area, would rank among the five largest producers in one or more of the five commodities (lead, zinc, copper, silver, and manganese) most frequently recovered from this type of deposit.

Genetic Model for Polymetallic Replacement Deposits

Polymetallic replacement deposits are hydrothermal, epigenetic accumulations of sulfide minerals in bedded deposits (mantos), massive lenses, pipe-shaped bodies, and associated veins hosted in limestone, dolomite, or other chemically reactive (soluble) rock, adjacent to porphyritic calc-alkaline intrusions. Occasionally, deposits are distant from an intrusion. The mineralization and intrusive activity are contemporaneous. Worldwide, replacement deposits may be of any age.

Deposits range from small pods and veins to large, mixed-sulfide, replacement bodies; the shapes are irregular and structurally and stratigraphically controlled. Ore bodies are localized by faults, vertical beds, bedding planes, and breccia zones. Limestones below contacts with shale can be especially productive. Vein or pipe structures serve as feeders and also may contain ore. Base-metal skarns, polymetallic veins, and porphyry copper deposits are genetically and spatially

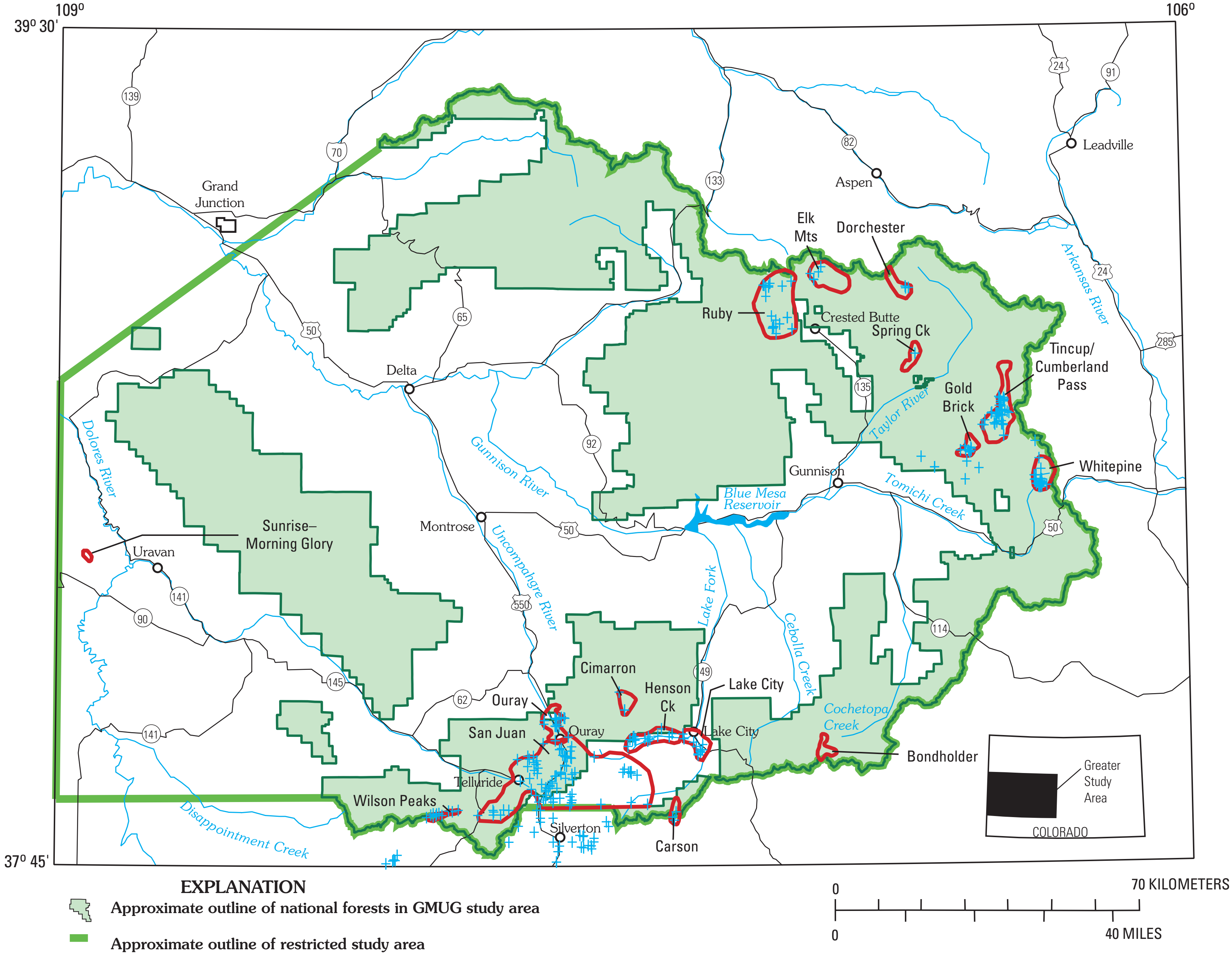


Figure K1. GMUG restricted study area, showing locations of polymetallic vein or polymetallic replacement deposits (plus signs) and the mineralized areas adjacent to or containing them (red outlines).

related to these deposits, and boundaries between these deposit types may be gradational. Many deposits are enriched by supergene processes; some of the deposits have been oxidized and lack sulfide minerals.

Polymetallic replacement deposits commonly contain lead, zinc, copper, and silver sulfide minerals; tungsten, manganese, bismuth, and trace amounts of gold may also occur. Primary ores consist principally of sphalerite and galena; commonly chalcopyrite, silver-bearing tetrahedrite, silver minerals, bismuth minerals, manganese minerals, and gold are present. Secondary oxidized ores typically include cerussite (lead carbonate), smithsonite (zinc carbonate), and cerargyrite (silver chloride). Pyrite (iron sulfide), siderite (iron carbonate), barite (barium sulfate), and quartz are the principal gangue minerals. At district scale, polymetallic replacement deposits may show mineralogical and compositional zonation from Cu-Au (± Bi) nearer the intrusive source, to Pb-Ag, to Zn-Mn at the periphery. Closer to a source intrusion (pluton), polymetallic replacement deposits may grade into skarn deposits.

Alteration may be extensive in the rocks surrounding a deposit. Carbonate rocks may be dolomitized and silicified. Shale and igneous rocks may be chloritized and argillized. Pyrite is locally abundant.

Polymetallic replacement deposits are deposited from aqueous metalliferous fluids separated from an intrusive magma during crystallization. The metals carried in solution are primarily derived from the magma, but some may be derived from the country rock where connate water in convecting cells leaches metals and mixes with magmatically derived fluids. Replacement is most efficient at high temperatures but typically occurs in a range of 200°–400°C. Limestones and permeable calcareous sedimentary rocks are most likely to host ore. Polymetallic replacement deposits are predominantly hosted by carbonates (limestone and dolostone); some are hosted in sandstone, evaporite (gypsum), and calcareous shale, and a few in permeable zones in volcanic rocks.

The precise location of a deposit is the result of a complex mix of physical, chemical and structural interactions. Replacement occurs in situ (in place): the host is replaced by ore, particle by particle (volume for volume), preserving most aspects of the structure of the host rock.

Mosier and others (1986) prepared grade and tonnage models based on data for 52 areas where production from polymetallic replacement ore deposits predominated. However, historically reported production for the mines in these areas was aggregated and the models therefore characterize deposits that are district-size. Available data are insufficient to characterize the individual ore bodies or closely spaced clusters of ore bodies that would more properly fit a mine-based definition of a deposit. The models are also biased, because districts generating less than 100,000 t (metric tons)[1] of ore were not included, and in several cases the ore values in the model were calculated from production and estimates of commodity grades. Given these limitations, the models characterize a population of district-size deposits that ranges in ore tonnage from 0.1 to 69 million t of ore, averaging 5.6 million t; average commodity grades are 8.1 percent lead, 6.3 percent zinc, 0.28 percent copper, and 260 g (grams) of silver and 1.4 g of gold per metric ton.

Description of the Areas Containing Known Polymetallic Replacement Deposits

Several mineralized areas in the GMUG restricted study area contain examples of deposits that fit the descriptive polymetallic replacement model (Morris, 1986). An understanding of the geologic setting, character, and mode of origin of known polymetallic replacement deposits allows us to formulate criteria that can be used to identify additional areas with the potential to host these types of deposits.

The northeastern part of the GMUG restricted study area, extending from Tincup/Cumberland Pass to Whitepine mineralized areas, is on the west flank of the Sawatch uplift. This area contains Tertiary intrusive rocks, primarily granodiorite, Paleozoic carbonate rocks, and mines known (or suspected) to have produced ore from polymetallic replacement ore bodies. Presence of polymetallic base-metal vein deposits in this same area further attests to base-metal-rich hydrothermal mineralization in the area. Most replacement deposits in the area are hosted in limestone and dolomite of the Manitou Dolomite, Dyer Dolomite (Chaffee Group), and Leadville Limestone; the larger occurrences are bedded replacement (blanket) deposits or irregular deposits along premineral faults and fractures (Dings and Robinson, 1957). Locally, they grade into one another and the contact between ore and wall rock is very irregular.

In the Tincup/Cumberland Pass area, bedded replacement deposits (Gold Cup, Silver Cup, Tincup, Robert E. Lee, Drew, El Capitan, and West Gold Hill mines) were locally important producers of silver and lead (Dings and Robinson, 1957). Most of the ore was mined along the contact of a gray limestone and overlying dolomite, within and stratigraphically about 150 ft below the top of the Leadville Limestone.[2] The largest of these ore bodies, a fairly continuous mineralized body, extends about 1,000 ft along the strike of the beds and down dip for 800 ft in the Gold Cup mine. Some important replacement deposits are clearly related to premineral faults (Dings and Robinson, 1957). Ore in the Maid of Athens, Citizen, and Ben Franklin mines (Tincup/Cumberland Pass area) probably is in the sedimentary beds near or adjacent to the Athens fault.

[1]Models are based on metric units for grade (grams) and tonnage (metric tons or megagrams).

[2]These data are given in the units originally measured and published. To convert feet to meters, multiply by 0.3048.

In the Whitepine area, the principal ore bodies are in the upper part of the Leadville Limestone at or near the contact with the overlying Belden Formation (Erie and Eureka-Nest Egg mines). Some important replacement deposits are clearly related to premineral faults (Dings and Robinson, 1957). Most such deposits are small lenses or pods, but ore shoots in the Akron mine in the sedimentary rocks (primarily Manitou Dolomite) along the west side of the Star fault are as much as 300 ft long, 50 ft wide, and 8 ft thick (Dings and Robinson, 1957).

The southern part of the GMUG study area, from Ouray to Ophir (fig. K1), contains intrusive and sedimentary rocks known to be favorable host rocks for replacement deposits at Rico and in the Idarado mine. Favorable units include calcareous strata (such as Lower Mississippian Leadville Limestone and Middle and Upper Pennsylvanian Hermosa Group) where they occur below known vein deposits (as in the Idarado mine) and peripheral to Tertiary stocks emplaced along the ring fracture zone of the Silverton caldera. These strata are about 3,000–4,000 ft below the elevation of Red Mountain Pass. Polymetallic base-metal vein deposits occurring near the surface in Tertiary volcanic rocks are a strong indication that base-metal-rich fluids passed upward through the underlying favorable host rocks along structurally controlled channelways. Deep drilling from within the Idarado mine (Mayor and Fisher, 1993) tested about 3,000 ft of Paleozoic strata and late Proterozoic rocks, intersecting Pb-Zn-Cu mineralized calc-silicate skarn zones in calcareous rocks. The holes did not encounter the probable Tertiary intrusion responsible for the high-temperature alteration and mineralization.

Classic examples of polymetallic replacement mineralization are found in mines such as the American Nettie, Mineral Farm, and Wanakah in the Ouray mineralized area, and the Idarado, Saratoga, Baltic, Portland, and Crown Point in the San Juan mineralized area. Many of these deposits are in limestone units that are not exposed at the surface, such as the manto or channel deposits in Leadville Limestone and Molas Formations at the Mineral Farm mine (Burbank, 1940, p. 205–206, 238; King and Allsman, 1950, p. 51). Host-rock permeability and structure play secondary roles in controlling localization of deposits. Permeable, bedded channel deposits in Dakota Sandstone (metamorphosed to quartzite) localized ore at the American Nettie mine (Burbank, 1940, p. 205–206, 223–225, 229; King and Allsman, 1950, p. 50–51). Deposits in the upper Dakota zone on the east side of the Uncompahgre Valley and 2,000–4,000 ft north of the Laramide-age Blowout intrusive center are localized in minor folds or terrace-like warps superimposed on the generally north-northeast-dipping regional host.

Minor iron and manganese replacement deposits rich in magnetite occur in limestone and dolomite beds at or near contacts with intrusive rocks. In the Tincup/Cumberland Pass area, the Cumberland mine produced iron ore from a layer of limestone in the Belden Formation between a quartz diorite porphyry body and the Tincup porphyry (Dings and Robinson, 1957). In the Whitepine area, the Iron King mine occurs in metamorphosed limy beds of the Belden Formation at the north end of the Morning Glim fault, where the fault is cut off by the Mount Princeton batholith (Dings and Robinson, 1957).

Application of the Deposit Model for a Mineral Resource Assessment of Polymetallic Replacement Deposits

The criteria listed in table K1 are those used in this reconnaissance mineral resource assessment to define “permissive” and “favorable” mineral deposit potential tracts for undiscovered polymetallic replacement deposits. The criteria are based on the descriptive model (Morris, 1986), grade and tonnage models (Mosier and others, 1986), and data available for the GMUG study area. The applicable regional databases available for this GIS-based assessment include the digital geologic map data (Day and others, 1999), mines and prospect locations (Wilson and others, 2000), outlines of mineralized areas (Wilson and others, 2000), regional NURE stream-sediment geochemical data (Smith, 2000), a map of igneous intrusions based on interpretation of aeromagnetic survey data (Bankey and others, this volume, Chapter D), and detailed maps showing age and composition of intrusions (Day and Bove, this volume, Chapter B, and D.J. Bove, unpub. data, 2000).

In this chapter, GMUG restricted study area refers only to GMUG National Forests and the land they roughly surround from Grand Junction to the area east of Gunnison (fig. K1). It also includes the western slope in the Uravan area, but the restricted study area does not include lands in adjacent National Forests—White River, San Isabel, Rio Grande, or San Juan—even though they are within the “greater study area” boundary. Any favorable resource potential indicated outside of this restricted study area is based on incomplete data, especially for mines, prospects, and mineralized areas. Many more areas in the adjacent lands, including national forests, may be permissive, or even favorable. For instance, Aspen and Leadville, both large productive districts, contain polymetallic vein and polymetallic replacement deposits, yet neither is shown in figure K3. The square miles indicated as permissive and favorable are, therefore, minimums for the entire “greater study area.”

The delineation criteria in table K1 are not exhaustive; they are limited by the availability of supporting data sets that are both fairly complete and geographically comprehensive at 1:250,000 scale. Additional criteria could have been considered for tract assessment if the digital databases had been more complete. Examples of other criteria that could have been used to classify and evaluate the mineral resource potential are the following:

- occurrence of manganese oxide minerals in veins or disseminated in carbonate rocks;
- distribution of zones of silicification or dolomitization in limestone, with accompanying pyrite or barite;

Table K1. Delineation criteria for polymetallic replacement deposits in GMUG study area.

Diagnostic criteria for permissive tract delineation
1. Located within a 10-km-wide zone peripheral to known or inferred Tertiary or Cretaceous felsic intrusive (plutonic) rocks; qualifying units include being within 10 km of units Tui, Tmi, Tsi, Tiy, Tio, Ti, or TKi of Day and others (1999), and other Tertiary intrusive units identified on smaller scale maps (D.J. Bove, unpub. data, 2000), and inferred intrusions as interpreted from aeromagnetic survey data (Bankey and others, this volume, Chapter D). (Intrusion contact is buffered 1 km into the intrusion, except for the inferred intrusions, which are not buffered, to accommodate contact mislocation errors in 1:250,000-scale mapping.)
2. Presence of permeable or chemically reactive sedimentary rock (2 km external buffer on surface contacts).
A. Paleozoic units containing Ignacio, Manitou, and Fremont Formations; Chaffee Group; Dyer, Elbert, Ouray, Leadville, Molas, Belden, and Minturn Formations; Hermosa Group; Eagle Valley and Rico Formations (including map units MꞒli, MꞒr, OꞒr, MOr, MDr, ℙhu, ℙee, ℙe, ℙh, ℙmb, ℙb, ℙm, Pℙm, PℙRm (from Day and others, 1999)).
B. Mesozoic and Cenozoic units: includes map units JTRmd, KJde, KJdw, KJdj, KJdm, Jme, Jwe, Jmw, Jmwe, Kdb, Kbc, Kd, Kml, Kmu, Km, Kmvl, Kmvu, Kmv, Tsbt, Tkec (from Day and others, 1999).
3. Location in areas known or inferred to be underlain by Paleozoic sedimentary rocks beneath volcanic rocks in the San Juan Mountains.
Diagnostic criteria for favorable tract delineation (in addition to 1–3)
4. Presence of a mineralized area known to host polymetallic replacement or polymetallic vein deposits or occurrences.
5. Within 2 km of a known polymetallic replacement occurrence.
6. Known or inferred presence of carbonate rocks exhibiting a high affinity for polymetallic replacement mineralization within 1 km of the surface exposure (units from Day and others, 1999).
A. Paleozoic units containing Ordovician Manitou Dolomite or Fremont Dolomite; Devonian Ouray Limestone or Elbert Formation; Devonian-Mississippian Dyer Dolomite of the Chaffee Group; Mississippian Leadville Limestone; Pennsylvanian Hermosa, Minturn, or Belden Formations; and Pennsylvanian-Permian Rico Formation (MꞒli, MꞒr, OꞒr, MOr, MDr, Doe, ℙhu, ℙh, ℙmb, ℙb, ℙm, PDre, Pℙr, Ml).
B. Mesozoic and Cenozoic units containing Middle Jurassic Wanakah Formation or Eocene Telluride Conglomerate (JTRmd, Jwe, Jmw, Jmwe, KJdw, TKec, Tsbt).
7. Within 500 m of a stream-sediment or rock sample site containing anomalous levels of silver, lead, or zinc (Ag>1 ppm, Pb>100 ppm, Zn>250 ppm).

• presence of jasperoid or calc-silicate alteration of carbonate rocks or argillic-propylitic alteration of igneous rocks;
• anomalous concentrations of copper, tungsten, gold, arsenic, antimony, bismuth, barium, manganese, iron, or magnesium in bedrock, altered rock, or stream-sediment samples;
• presence of lithologic shale-limestone unit interfaces;
• presence of major structural features, such as major faults and zones of extensional tectonic activity;
• presence of small porphyritic dikes and stocks;
• presence of Cretaceous or Tertiary age porphyry (model 17), skarn (18b, c, d), or polymetallic vein (22c) mineralization;
• detailed aeroradiometric maps showing Th/U ratios of less than 4:1, suggesting uranium depletion may have resulted from hydrothermal activity;
• local ground electromagnetic surveys.

Permissive Tracts

In the GMUG greater study area, 5,133 mi^2 is classified "permissive" for the occurrence of polymetallic replacement deposits (fig. K2; Spanski and Bankey, this volume, Chapter F, table F1). These areas are within 10 km of known or inferred felsic Cretaceous or Tertiary plutons and are underlain by Paleozoic, Mesozoic, or Cenozoic sedimentary rock units that contain permeable and chemically reactive lithologic units (table K1, criterion 2). Exposures of plutonic rocks, with a 1 km internal buffer, are not considered permissive for replacement deposits.

In most of the eastern part of the permissive tract in the GMUG restricted study area, the plutons and Paleozoic and Mesozoic carbonate rocks are exposed at the surface. In most of the central part of the GMUG area, the plutons are inferred (buried) based on interpretations of geophysical data. In the San Juan Mountains, roughly west of long 107°30′, carbonate-bearing sedimentary rocks may be present locally, within 1 km of the surface beneath the volcanic rocks.

Favorable Tracts

In the GMUG study area, 1,676 mi^2 is classified "favorable" for the occurrence of polymetallic replacement deposits (fig. K3). These lands represent about 33 percent of the "permissive" tract. The criteria used for delineating regions "favorable" for hosting polymetallic replacement deposits are listed in table K1. These criteria are more restrictive than those used to delineate the "permissive" terrain. Increased importance is placed on the presence of sedimentary rock units having a substantial carbonate component and on evidence that mineralization has occurred.

In order to be considered favorable, an area had to display evidence of mineralization. Because polymetallic vein and

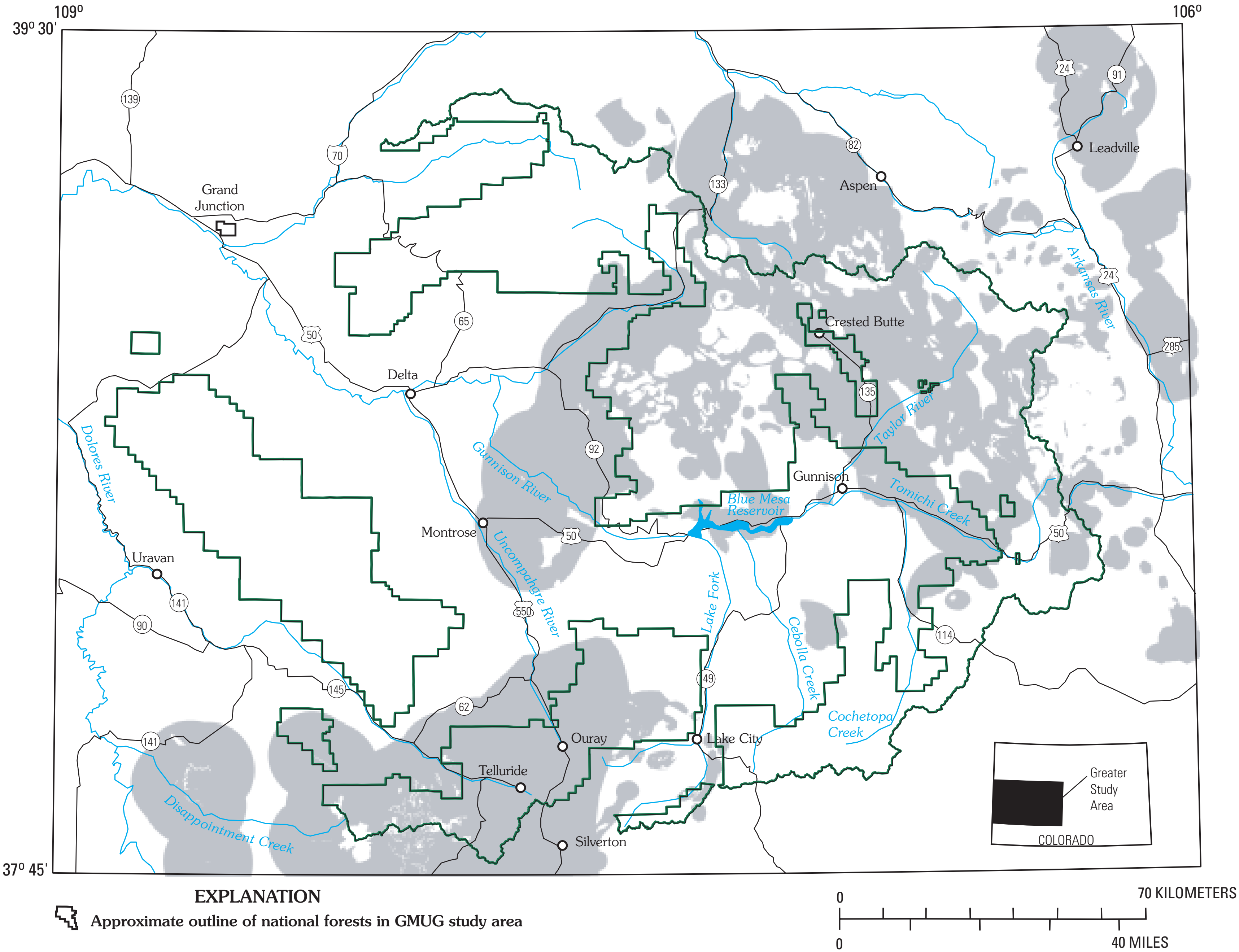
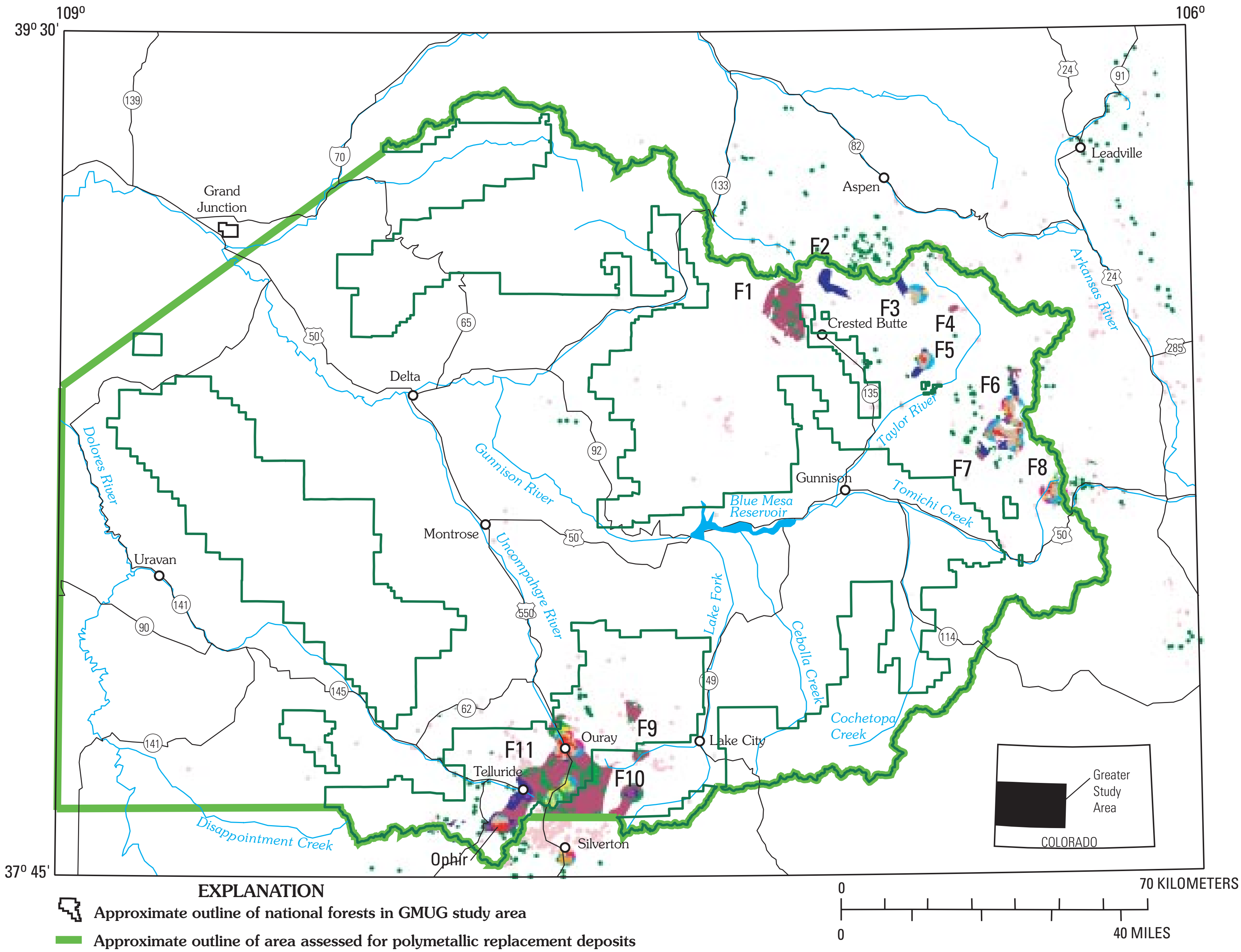


Figure K2. GMUG greater study area, showing permissive tracts (shaded) for polymetallic replacement deposits.


109°
106°
39° 30'
37° 45'
Grand Junction
Delta
Montrose
Uravan
Aspen
Leadville
Crested Butte
Gunnison
Ouray
Telluride
Lake City
Silverton
Ophir
F1
F2
F3
F4
F5
F6
F7
F8
F9
F10
F11
Dolores River
Gunnison River
Uncompahgre River
Taylor River
Tomichi Creek
Arkansas River
Blue Mesa Reservoir
Lake Fork
Cebolla Creek
Cochetopa Creek
Disappointment Creek
139
70
65
50
92
133
82
135
24
91
285
141
90
145
62
550
149
114
Greater Study Area
COLORADO
EXPLANATION
Approximate outline of national forests in GMUG study area
Approximate outline of area assessed for polymetallic replacement deposits
0
70 KILOMETERS
0
40 MILES

EXPLANATION

Criterion 3—Mineralized area containing known polymetallic replacement (PMR) deposits

Criteria 3 + 5—Mineralized area containing PMR deposits + carbonate host rock (Criterion 5)

Criterion 4—Within 2 km of known PMR deposit

Criteria 3 + 4—Mineralized area containing PMR deposits + within 2 km of known PMR deposit

Criteria 3 + 5—Mineralized area containing PMR deposits + carbonate host rock

Criteria 3 + 4 + 5—Mineralized area containing PMR deposits + within 2 km of known PMR deposit + carbonate host rock

Criterion 6—Within 500 m of elevated Ag, Pb, or Zn value (buffered geochemistry)

Criteria 3 + 6—Mineralized area containing PMR deposits + buffered geochemistry

Criteria 5 + 6—Carbonate host rock + buffered geochemistry

Criteria 3 + 5 + 6—Mineralized area containing PMR deposits + carbonate host rock + buffered geochemistry

Criteria 4 + 6—Within 2 km of known PMR deposit + buffered geochemistry

Criteria 3 + 4 + 6—Mineralized area containing PMR deposits + within 2 km of known PMR deposit + buffered geochemistry

Criteria 4 + 5 + 6—Within 2 km of PMR deposit + carbonate host rock + buffered geochemistry

Criteria 3 + 4 + 5 + 6—Mineralized area containing PMR deposits + within 2 km of known PMR deposit + carbonate host rock + buffered geochemistry

Figure K3 (above and previous page). GMUG greater study area, showing favorable tracts for polymetallic replacement deposits. F1, Ruby; F2, Elk Mountains; F3, Dorchester; F4, Forest Hill; F5, Spring Creek; F6, Tincup/Cumberland Pass; F7, Gold Brick; F8, Whitepine; F9, Cimarron and Henson Creek; F10, eastern part of San Juan; F11, Ouray and western part of San Juan tracts. Descriptions in text.

polymetallic replacement deposits are so closely related, any area with evidence of either type of deposit is considered favorable if it also meets the permissive criteria. The field evidence shows that polymetallic replacement deposits tend to occur in clusters (table K1, criterion 4); therefore, proximity to known examples of polymetallic replacement deposits is given greater importance (criterion 5). Evidence of a known or suspected polymetallic replacement deposit alone is an indication of favorable terrain, especially where detailed geologic information is lacking, possibly owing to the scale of the collected data and mapping. A 2-km buffer was given around each mine or prospect known to be a polymetallic replacement deposit (criterion 5). Criteria 4 and 5 are partially redundant; however, criterion 5 becomes important in capturing polymetallic replacement mineralization that occurs at isolated sites beyond the boundaries of recognized mineralized areas.

Although any rock can host a polymetallic replacement, most deposits occur in carbonate rocks. For this reason we have further restricted the potential host rock units (see criterion 2) to only those with a substantial carbonate component (criterion 6).

NURE stream-sediment geochemical data (Smith, 2000) are useful in identifying areas where anomalous levels of metals are concentrated in these deposits (criterion 7). Anomalous threshold values were determined to be 100 parts per million (ppm) for copper, 250 ppm for zinc, and 1 ppm for silver (see Smith, this volume, Chapter C). Inasmuch as these samples are composites of materials derived from all rocks exposed in a drainage basin, they are subject to the effect of dilution; a 500 m buffer has been applied to each geochemically anomalous site to represent the area of influence for the sample.

Inasmuch as the assessment technique of bitmapping employed herein (Spanski and Bankey, this volume, Chapter F) does not rank areas, no importance is attached to the number of criteria that are met at a given location in terms of classification. An area is classified “favorable” if it is within a “permissive“ tract *and* meets either the conditions of criteria 4 or 5, or any combination of criteria 4 through 7. Criteria 6 and 7 are not used singularly to establish a “favorable” status.

The areas identified as being “favorable” for hosting polymetallic replacement deposits are shown in figure K3 and listed in table K2. (Sunrise/Morning Glory, Wilson Peaks, Carson, Lake City, and Bondholder mineralized areas (fig. K1) are not favorable for polymetallic replacement deposits.) All of the areas identified as being favorable correlate with areas with known mineralization.

Ruby tract (fig. K3, area F1) is a known mineralized area containing polymetallic vein occurrences (criterion 4) and local geochemical anomalies (Ag>1 or Pb>100 or Zn>250 ppm) (criterion 7). Polymetallic replacement occurrences are suspected in some of the many mines and prospects, but none is documented.

Elk Mountains tract (fig. K3, area F2) contains a known mineralized area of polymetallic vein and polymetallic replacement mineralization (criterion 4) coupled with favorable carbonate formations (criterion 5). Polymetallic replacement occurrences are suspected in some of the mines and prospects, but none is documented.

Dorchester tract (fig. K3, area F3), a known mineralized area, contains polymetallic replacement occurrences (criterion 4), known polymetallic replacement occurrences (criterion 5), favorable carbonate formations (criterion 6), and local geochemical anomalies (criterion 7). Little is known about the mineral deposits in the Bull Domingo mine, the most productive mine in the area, nor about the scattered deposits in Star Basin (Garrett, 1950; Cunningham, 1976). They appear to have been mined for silver and lead from replacement ore bodies in limestone adjacent to 33 Ma intrusions of the Italian Mountain Intrusive Suite.

Table K2. Polymetallic replacement tracts in GMUG restricted study area.

Cretaceous-early Tertiary tracts:

Tract No.[a]	Tract name	Delineation criteria
P1	Permissive for polymetallic replacements	1, 2, 3
F1	Ruby	1, 2, 3, 4, 7
F2	Elk Mountains	1, 2, 3, 4, 5
F3	Dorchester	1, 2, 3, 4, 5, 6, 7
F4	Forest Hill	1, 2, 3, 4
F5	Spring Creek	1, 2, 3, 4, 5, 6, 7
F6	Tincup/Cumberland Pass	1, 2, 3, 4, 5, 6, 7
F7	Gold Brick	1, 2, 3, 4, 6, 7
F8	Whitepine	1, 2, 3, 4, 5, 6, 7
F9	Cimarron and Henson Creek	1, 2, 3, 4, 7
F10	San Juan east	1, 2, 3, 4, 6, 7
F11	Ouray and San Juan west	1, 2, 3, 4, 5, 6, 7

[a]P, permissive tract; F, favorable tract.

Forest Hill (fig. K3, area F4), a known mineralized area, contains suspected polymetallic replacement occurrences (criterion 4). The Forest Hill mine, for which the area is named, is inferred, but not known, to be a polymetallic replacement mine; therefore, it is not shown in figure K1.

Spring Creek tract (fig. K3, area F5) overlaps a known mineralized area (fig. K1) containing polymetallic replacement occurrences (including replacement manganese) (criterion 4), known polymetallic replacement occurrence (criterion 5), favorable carbonate formations (criterion 6), and local geochemical anomalies (criterion 7). The Doctor mine reportedly was primarily a lead (cerussite) and zinc (smithsonite) deposit with some copper (Meissner, 1954); manganese was distal to the main occurrence. Sulfides such as galena and sphalerite are rare, and no pyrite was observed.

Tincup/Cumberland Pass tract (fig. K3, area F6) includes a known mineralized area containing polymetallic vein and replacement occurrences (criterion 4), known polymetallic replacement mines (criterion 5), favorable carbonate formations (criterion 6), and local geochemical anomalies (criterion 7). Tincup was well known for its polymetallic replacement occurrences such as the Gold Cup mine (Dings and Robinson, 1957). (See earlier section, "Description of the Areas Containing Known Polymetallic Replacement Deposits.")

Gold Brick tract (fig. K3, area F7) is a known mineralized area containing polymetallic vein occurrences (criterion 4), favorable carbonate formations (criterion 6), and, locally, geochemical anomalies (criterion 7). Additional scattered geochemical anomalies (criterion 7) lie to the west in favorable carbonate formations (criterion 6).

Whitepine tract (fig. K3, area F8), a known mineralized area, contains polymetallic vein and replacement occurrences (criterion 4), known polymetallic replacement mines (criterion 5), favorable carbonate formations (criterion 6), and local geochemical anomalies (criterion 7).

Cimarron and Henson Creek tract (fig. K3, area F9) contains two known mineralized areas (Cimarron and Henson Creek, fig. K1) hosting polymetallic vein occurrences (criterion 4), and, locally, geochemical anomalies (criterion 7). Polymetallic replacement mineralization is suspected in some of the occurrences, but none is documented.

The eastern part of San Juan mineralized area (fig. K3, area F10) contains polymetallic vein and replacement occurrences (criterion 4), favorable carbonate formations (criterion 6), and, locally, geochemical anomalies (criterion 7).

Ouray and western part of San Juan mineralized area tract (fig. K3, area F11) are in a known mineralized area containing polymetallic vein and replacement occurrences (criterion 4), known polymetallic replacement occurrences (criterion 5), favorable carbonate formations (criterion 6), and, locally, geochemical anomalies (criterion 7). At Ophir, the area includes the Crown Point polymetallic replacement deposit, and near Ouray, the Portland, Mineral Farm, Wanakah, and American Nettie deposits, which are at least partly polymetallic replacements.

Undiscovered Deposit and Endowment Potential

The assessment of endowment potential and the probability for the existence of undiscovered polymetallic replacement deposits are based on the grade and tonnage models of Mosier and others (1986). Our examination of the grade and tonnage figures suggests that no significant difference exists between the lead, silver, and gold grades and size distribution of districts in the model population and in seven major replacement districts in Colorado. We estimated that the probability of even one undiscovered deposit occurring within the "permissive" and "favorable" tracts for polymetallic replacement deposits fell below the range of estimation confidence. The determination was strongly influenced by the rather large median size (1.8 million t of ore) and grades (5 percent lead, 3.9 percent zinc, 0.23 percent copper, and 0.75 g gold and 175 g silver per metric ton) that are associated with the district-size deposit model population. Also, areas of favorable terrain large enough to conceal district-size deposits that have not been extensively explored are lacking.

We believe a secondary, nonquantifiable potential is associated with polymetallic replacement mineralization in the study area. That potential is associated with the existence of smaller undiscovered ore bodies that, in the past, as either single or tightly clustered bodies, would have been developed as a mine or an extension to a mine. Potential cannot be quantified because individual mines lack the production records needed to characterize their grades and tonnage. However, we think that the potential is high for the existence of new ore bodies in areas adjacent to or beneath currently known areas of polymetallic replacement mineralization. In today's economic and environmental climate, large mining companies would likely not be interested in occurrences of this nature; however, these smaller occurrences could be attractive development targets for smaller entrepreneurial groups. Some fragmentary production records for mines in the Whitepine (Tomichi) and Monarch districts suggest that ores with silver grades in excess of 2.5 times the model median grade of 175 g/t occurred locally, and ore bodies with gold grades ranging from 17 to 124 g/t were encountered in the Gold Cup mine in the Tincup district (Dings and Robinson, 1957).

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Mineral Resource Assessment for Sediment-Hosted Copper Deposits

By David A. Lindsey, Viki Bankey, Daniel H. Knepper Jr., and Gregory T. Spanski

Chapter L of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

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Mineral Resource Assessment for Sediment-Hosted Copper Deposits

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Abstract

Copper occurs in sedimentary rocks of the salt anticlines of the Paradox Basin, the borders of the Uncompahgre uplift, and the Eagle Basin. Most known occurrences are small, but deposits large enough to produce occur in the salt anticline terrane. All such deposits and occurrences are classified as "sediment-hosted," but they vary considerably in geologic setting, origin, form, and size.

Introduction

Sediment-hosted copper deposits, aggregated in a generic global model by Cox (1986), have been classified into three models: reduced-facies, redbed, and Revett. Each model has different geologic features, grades and tonnages, and anticipated environmental impacts when mined and processed (Lindsey and others, 1995). Deposits of the reduced-facies model are hosted in widespread black-shale formations, are relatively high tonnage, and have been mined mostly underground. Deposits of the redbed model occur in local areas of reduced rocks in redbed sequences, are low-tonnage, and have been mined near the surface by open-pit and small underground operations. Redbed deposits have not been a major source of copper. Deposits of the Revett model (Spanski, 1992), based on deposits restricted to the Mesoproterozoic Revett Formation of the Belt Supergroup of Montana and Idaho, are intermediate in tonnage and have been mined entirely underground.

Although sediment-hosted copper deposits in the assessment area include some typical of the redbed model, the largest deposits are not. The primary difference is that they are structurally controlled. Although these were previously considered as a variant of the redbed model (Lindsey, 1996), they are more fully described here and assigned to a new model, equal in rank to existing sediment-hosted copper models. These structurally controlled deposits share some features of other sediment-hosted models, including the redbed and reduced-facies models, which are commonly associated with salt deposits.

Descriptive and Genetic Models for Sediment-Hosted Copper Deposits

Deposits of the reduced-facies model are found where continental clastic sedimentary rocks are overlain by regionally extensive marine or lacustrine shales or carbonates, rich in organic material, that act as traps for mineral deposition (for example, Johnson, 1976; Ensign and others, 1968). Host rocks may be shale or adjacent limestone, sandstone, or conglomerate. Evaporite deposits overlie, or are believed to have once overlain, copper deposits of the reduced-facies model. Deposits of the redbed model occur in the same geologic setting as do deposits of the reduced-facies model, but they lack regionally extensive reduced strata. In Devonian and later strata, copper commonly replaces local accumulations of fossil plant matter. Redbed copper deposits may occur in rifts or intracratonic basins. Deposits of the Revett model occur in thick beds of reduced (pyritic) quartzite (properly, metasandstone) near pre-ore oxidation-reduction fronts (Hayes, 1990). Ore bodies may be stacked, especially near faults. Copper is not associated with solid organic matter in Revett deposits, but may have been deposited as the result of reactions between a copper-bearing ore fluid and a transient gas reductant generated by decay of organic matter.

Structurally controlled sediment-hosted copper deposits of the Paradox Basin (fig. L1) share some of the characteristics of all three models. Like redbed and Revett deposits, the Paradox deposits are in permeable sandstones, commonly located between impermeable beds. The Paradox deposits consist of veins in faults and disseminated bodies adjacent to faults (Schmidt, 1967; Morrison and Parry, 1986). Some disseminated ore bodies are stacked. As in redbed deposits, but not as in Revett deposits, some ore replaces plant matter. Like reduced-facies and some redbed deposits, but unlike Revett deposits, the Paradox deposits are associated with salt (gypsum and halite). In the Paradox Basin, structurally controlled deposits overlie salt-cored anticlines and diapirs. As in many redbed deposits, supergene minerals such as chalcocite, malachite, and azurite are the principal ore

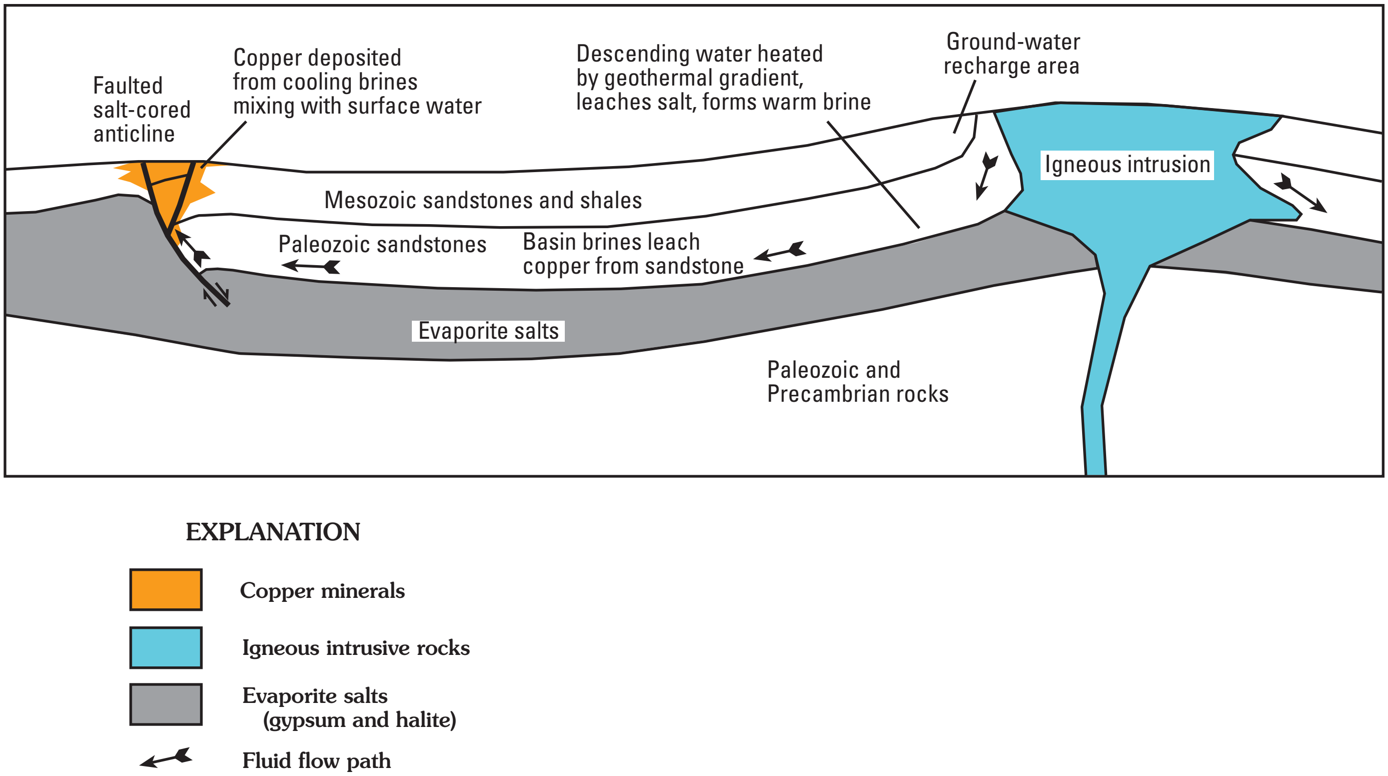


Figure L1. Cross section showing geologic model of structurally controlled sediment-hosted copper deposits in Paradox Basin, Colorado Plateau. Barbs on fault show direction of relative movement. No scale. Modified from Morrison and Parry, 1986.

minerals. The distribution of ore in all models may be controlled by redox reactions, temperature gradients, and solubility of dissolved metal- and metal-complex ions during mixing of ascending basinal brines with descending ground water.

Structurally controlled deposits of the Paradox Basin formed where warm saline basin brines rise through faults and permeable sandstone formations on the flanks and crests of salt anticlines, possibly during Tertiary time (fig. L1) (Morrison and Parry, 1986). Salt, the source of saline brines that leach and transport copper, was deposited in the Pennsylvanian Paradox Formation. Salt diapirs, including salt-cored anticlines, formed from Pennsylvanian to Jurassic time and were reactivated during the Late Cretaceous to Eocene Laramide orogeny. Ground-water recharge areas formed within the uplifted Uncompahgre uplift during the Laramide orogeny from Late Cretaceous to Eocene time (Dickinson and others, 1988) and within the La Sal Mountains, which were formed by intrusion of igneous stocks and laccoliths in Oligocene and early Miocene time (Hunt, 1958; Nelson and others, 1992). Thereafter, ground water entered the Paradox Basin from recharge areas, became saline and warm within the basin, and rose through faults and permeable strata in salt anticlines. The warm saline brines leached copper from source rocks such as redbeds, traveled updip along permeable zones and faults, and deposited copper during mixing with cool, oxidizing surface fluids. Copper deposition by reduction in organic matter is not required by the model, but probably occurred locally. Near-surface oxidation in the weathering zone may further concentrate copper.

Description of the Areas Containing Sediment-Hosted Copper Deposits

In the assessment area, structurally controlled sediment-hosted copper deposits are probably the most important type. The Lisbon mine in Utah and the Cashin mine in Colorado are the most important deposits known to be structurally controlled (Fischer, 1936; Morrison and Parry, 1986). The Lisbon mine produced more than 134,000 t (metric tons) of 1.4 percent copper, and the Cashin mine produced 732,740 lb copper and 363,778 oz silver (Morrison and Parry, 1986). In a report by Summo Minerals Corp. to the U.S. Securities and Exchange Commission (SEC Archives, 1997), production for the Cashin mine is given as 20,670 t of about 4 percent copper and 18.5 oz/ton silver, slightly higher than reported by Morrison and Parry (1986). Production at both mines was from veins and replacements along faults. Exploration by Summo Minerals Corp. in the 1990’s has revealed large lenses of disseminated ore at both mines (Anonymous, 1995). Lenses of disseminated ore are stacked in sandstone beds at more than one stratigraphic level; at the Lisbon mine, disseminated and replacement ore is concentrated in coaly intervals. Ore minerals replace coalified plant fossils and fill voids. Host rocks include permeable sandstone formations of Permian age or younger, especially the Cretaceous Dakota Sandstone and the Jurassic Wingate Sandstone. Veins were also explored and mined at the Cliffdweller, Sunrise, and Copper Rivet mines (Fischer, 1936).

In the mines just listed, copper minerals in structurally controlled deposits include chalcocite, minor amounts of other copper sulfides, and abundant malachite and azurite. Malachite and azurite occur in oxidized zones near the surface. Oxidized zones give way to chalcocite at depth, typically several hundred meters below the surface. Large bodies of disseminated chalcocite ore are of economic interest because solvent extraction and electrowinning can recover copper. No smelting, with attendant environmental problems, is required. Minor gangue minerals include pyrite, iron oxides and hydroxides, and manganese oxides. Silver was an important product of the Cashin mine, and minor amounts of silver are present in some other structurally controlled copper deposits (Fischer, 1936).

In addition to copper and gangue minerals, other indications of mineralizing activity in the structurally controlled environment include bleached zones in sandstone (Conel and Alley, 1984); anomalous quantities of copper, lead, zinc, and silver in rocks, soils, and stream sediments; and copper associated with uranium deposits and anomalously radioactive rock.

Deposits of the redbed model are represented only by small occurrences in the assessment area. They occur in two stratigraphic intervals (Lindsey, 1996): (1) the Upper Triassic Chinle Formation, and (2) the Middle and Upper Pennsylvanian Hermosa Group and Lower Permian Cutler Formation. Copper deposits in Upper Triassic rocks are generally associated with concentrations of organic plant remains (such as logs and leaves) in permeable sandstone. The White Canyon district, Utah, located west of the assessment area in the Upper Triassic Shinarump Member of the Chinle Formation, is the largest representative of the redbed model; it produced 530,000 t at 0.75 percent copper (Finch, 1959). Deposits and occurrences in the Hermosa Group and Cutler Formation are small lenticular bodies in reduced gray sandstone, siltstone, and shale preserved in redbeds. Most host rocks contain organic plant remains, and some contain pyrite. Anomalous concentrations of uranium are commonly present.

Application of the Deposit Model for Mineral Resource Assessment

Structurally controlled sediment-hosted copper deposits are the principal focus of this assessment. Criteria used to identify tracts that have a more-than-negligible probability of hosting structurally controlled copper deposits include the presence of (1) clastic sedimentary rocks containing permeable stratigraphic intervals, (2) salt-cored anticlines, (3) prominent faults near axial zones of salt-cored anticlines, (4) evidence of mineralizing activity commonly associated with Cu-U-V deposit formation, and (5) favorable intervals containing highly permeable sedimentary features, such as channels (table L1).

For identification of tracts, criteria were divided into those that would be useful for identifying permissive tracts

Table L1. Delineation criteria for structurally controlled sediment-hosted copper deposits in GMUG greater study area.

Diagnostic criteria for permissive tract delineation
1. Presence of clastic sedimentary rocks containing permeable stratigraphic intervals (where present in the Pennsylvanian Hermosa Group; Pennsylvanian and Permian Maroon Formation; Permian Cutler Formation; Triassic Shinarump Member of Chinle Formation; Jurassic Glen Canyon Group including Wingate Sandstone, Kayenta Formation, and Navajo Sandstone; Jurassic Entrada Sandstone; Jurassic Salt Wash Member of Morrison Formation; Cretaceous Dakota Sandstone and Mesaverde Group or Formation) known or inferred to occur within 0.2 km of the surface.
2. Presence of anticlines (10 km lateral buffer normal to the fold axis).
Diagnostic criteria for favorable tract delineation
3. Presence of prominent faults near axial zones of anticlines (0.5 km lateral buffer normal to the surface trace of the fault).
4. Evidence of mineralizing activity commonly associated with Cu-U-V deposits.
A. Bleached zones detected by remote sensing survey.
B. Occurrence of mines and prospects with Cu mineralized rock, with or without U and V (10 km lateral buffer to location of mine or prospect).
Other criteria (not used to identify favorable tracts in this assessment)
C. Radiometric (U) anomalies detected by remote sensing surveys.
D. Anomalous Cu, U, and (or) V geochemical signature in rock, soil, and stream sediments.
5. Presence of certain favorable intervals containing highly permeable sedimentary features, for example, stream channels filled with lenses of permeable conglomerate and sandstone containing carbonaceous material, such as fossil logs and other plant matter (includes the Shinarump Member of Chinle Formation and the Salt Wash Member of Morrison Formation) known or inferred to occur within 0.2 km of the surface.

and those useful for identifying favorable tracts; other criteria considered, but not used in tract identification, are also listed (table L1). Permissive tracts (fig. L2) require *both* the presence of permeable clastic sedimentary rocks *and* the presence of anticlines. Ideally, anticlines should be salt-cored, but it was not possible to specify which structures were underlain by evaporite salt and which were not, so *all* anticlines were used to define permissive tracts. Within permissive tracts, favorable tracts were identified by the presence of one or more additional criteria (favorable criteria). Favorable criteria include faults and evidence for the activity of mineralizing fluids. Color coding is used to distinguish the criterion or combination of criteria that apply to each tract (fig. L3). A large portion of the favorable tracts is defined by the presence of faults and a buffer zone placed around each fault; these areas are shown by the color "pink" on the tract map. Other parts of favorable tracts are shown by color codes that represent the presence of bleached strata and copper minerals, either singly or in combination (fig. L3).

Some criteria, although indicative of the presence of mineralized rocks, were not applied because data sets for these criteria were lacking at the scale of assessment. The NURE (National Uranium Resource Evaluation) geochemical data set, for example, is reconnaissance in nature; the spacing of NURE samples was too wide to permit reliable detection of mineralized areas only a few kilometers across. The data of the NURE aeroradioactivity surveys are also widely spaced and better suited for detection of uranium occurrences than for the detection of structurally controlled copper deposits, many of which do not have a radiometric signature.

The bleaching of the host rocks during sedimentary copper mineralization provides an excellent criterion for locating areas of potential mineralization. The bleached host rocks, primarily sandstones, are devoid of the iron oxides that commonly give them their color, and light-colored clay minerals have formed from the alteration of feldspars and the original interstitial clays. The result of this process is primarily the formation of quartz sandstones, with or without a clay matrix, that are highly reflective (high albedo) and appear bright in all parts of the visible spectrum.

Landsat Thematic Mapper (TM) data provide an ideal means for locating exposures of these bright rocks over large regions. Portions of two Landsat scenes were required to cover the Paradox Basin part of the GMUG greater study area (table L2). The data for the two scenes were georeferenced and projected to the common Lambert conformal projection used in the overall study. The scenes were then placed in a digital mosaic and the data for the Paradox Basin extracted.

The data for the visible and near infrared bands of the Paradox Basin data set were used to compute the second principal component for the data. Principal components is a method for identifying the variability in the raster data (Sabins, 1986, p. 262). The first principal component, the major source of variability, is variability caused by topographic factors. The second principal component corresponds to albedo or the overall reflectance of the materials exposed at the Earth's surface in the visible portion of the spectrum. An image of the second principal component was calculated for the Paradox Basin Landsat TM data subset and a threshold was visually established to isolate only the brightest rocks and soils (highest albedos) by increasing the albedo cut-off until areas of known bleached sandstones were included and nearby unbleached sandstones were not. This procedure established that bleached sandstone occurs in 6 percent of the mosaic area in the eastern part of the Paradox Basin.

Bleached sandstones, however, are not the only bright rocks in the eastern part of the Paradox Basin. Carbonate strata and rocks containing abundant gypsum also form very bright natural outcrops in the Paradox Basin and are included in the bright rocks image layer. Nevertheless, by requiring that the bright rocks be sandstones in the structurally controlled copper model, the bright rocks data contribute to the definition of areas favorable for potential deposits.

Permissive Tracts

Four tracts that are considered to be permissive for occurrence of sediment-hosted copper deposits were identified from the distribution of permeable intervals of sandstone and anticlines (table L3; fig. L2). The largest tract (P1) encompasses the salt anticlines of the Salt, Paradox, and Lisbon valleys and the adjacent Uncompahgre uplift, which is a broad regional anticline. Thick intervals of permeable sandstone of Pennsylvanian, Permian, Triassic, Jurassic, and Cretaceous age underlie much of tract P1. Tracts P2 and P3, called "Cretaceous cliffs" for their tendency to form escarpments in the vicinity of Grand Junction, Colo., consist mainly of sandstone in the Cretaceous Mesaverde Group. Tract P4, consisting of the Eagle Basin, Grand Hogback, and mountains to the south, is underlain by Pennsylvanian, Permian, Triassic, Jurassic, and Cretaceous sandstone; the Eagle Basin contains gypsum- and halite-bearing diapirs of the Pennsylvanian Eagle

Table L2. Two Landsat scenes used to map bright rocks in eastern part of Paradox Basin in GMUG greater study area.

Scene ID	LT5035034008722810	LT5036033008616810
Path	35	35
Row	34	33
Date acquired	08/16/87	09/14/86

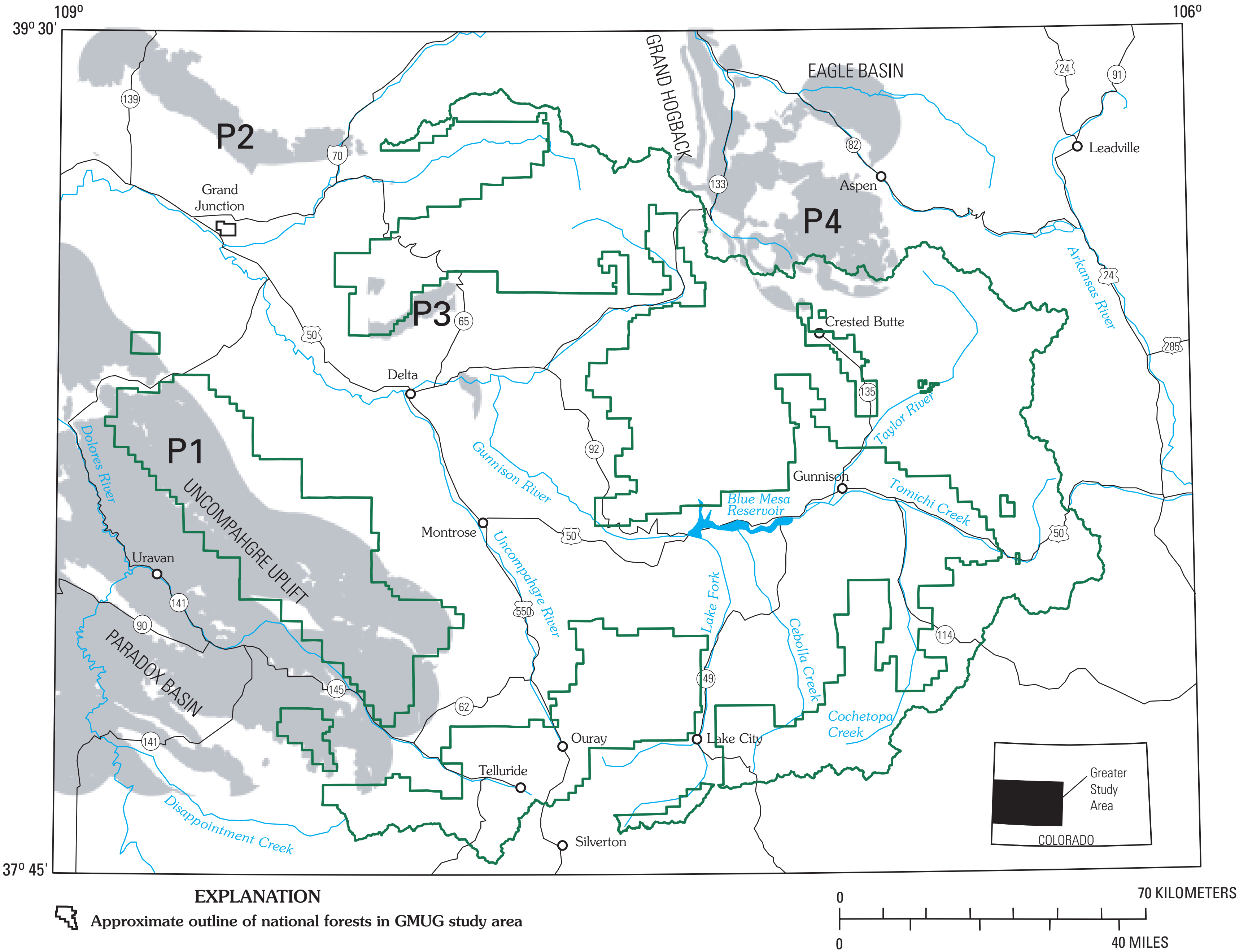


Figure L2. GMUG greater study area, showing permissive tracts (shaded) for structurally controlled sediment-hosted copper deposits. P1, salt anticlines; P2, Cretaceous cliffs 1; P3, Cretaceous cliffs 2; P4, Eagle Basin–Grand Hogback.

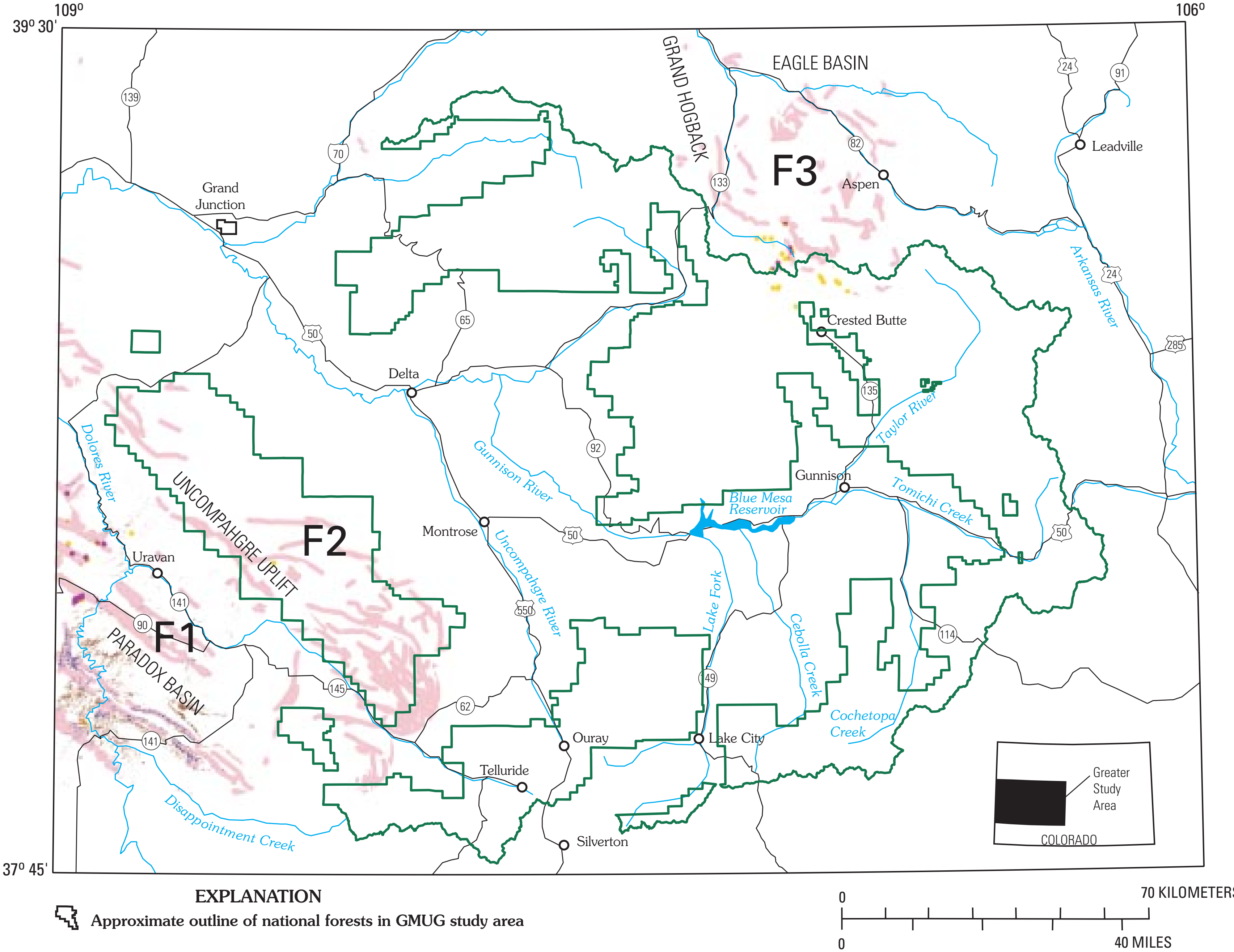
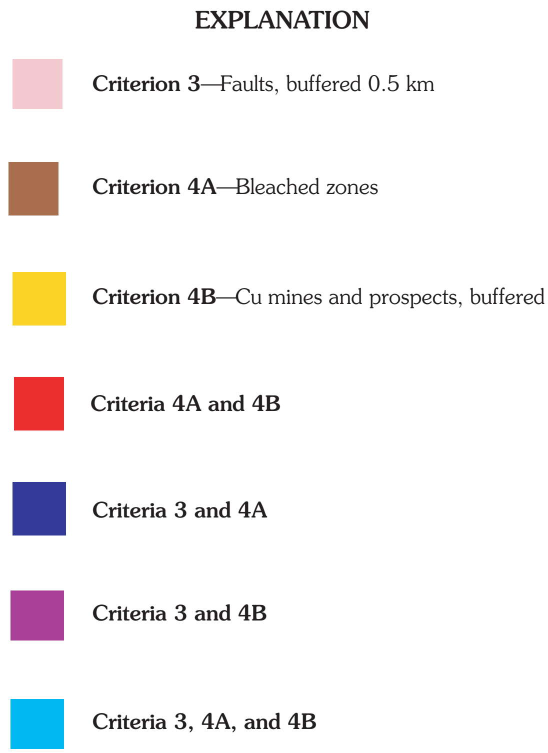


Figure L3 (above and following page). GMUG greater study area, showing areas favorable for sediment-hosted copper deposits. F1, salt anticlines; F2, Uncompahgre uplift; F3, Eagle Basin–Grand Hogback.



Valley Evaporite (Mallory, 1971). The tract also contains large domes formed by intrusion of Tertiary igneous rocks. Since their formation, domes may have provided ground water and hydrostatic pressure for basin brines. As is the case for the Paradox Basin, brines in the Eagle Basin may have leached copper from clastic rocks and deposited copper along faults.

A large part of the assessment area was not included because it failed to include *both* permissive criteria; that is, either permeable clastic sedimentary rocks were present or anticlines could be present, but not both. In addition, the presence of permeable clastic rocks within each stratigraphic interval varies with facies changes across the assessment area, so that permeable clastic rocks within an interval may not be present everywhere. Descriptions of each stratigraphic interval differ somewhat among 1°×2° geologic quadrangle maps within the assessment area, and the identification of permissive areas for this assessment is dependent on the descriptive information from each map. The effects of facies changes and attendant descriptions of map units are evident where tract boundaries (for example, tract P3) are more linear than circular. Such straight boundaries are artifacts of the data source but nevertheless give a general location of the tract.

Favorable Tracts

Within the permissive tracts, three tracts were identified as favorable for the occurrence of sediment-hosted copper deposits (table L3; fig. L3). In addition to the presence of permeable sandstone and anticlinal structures, favorable tracts contain faults and evidence of mineralizing fluids, such as bleached zones, copper-mineralized areas in sedimentary rock, or copper mines and occurrences. Each of these features was assigned numerical values, so that their presence singly or in combination yielded a unique value that identifies which features are present. Areas associated with each numerical value were assigned colors on the map (fig. L3). Tract F1, a series of linear areas oriented parallel to faults, occurs over salt-cored anticlines. In some parts of tract F1, bleached sandstone, copper-mineralized areas, and copper mines record the passage of mineralizing fluids. Tract F1 contains the Cashin mine, where recent exploration has revealed a large mineralized zone; the tract extends west to include the copper mines of Lisbon Valley, Utah, outside the assessment area. Tract F2 is located mostly on the flanks of the Uncompahgre uplift, where bleached areas and faults in sandstone are the principal indicators of a favorable terrane. Tract F3 is located in and near the Eagle Basin, where salt diapirs, copper, and bleached rock are indications of favorable conditions for sediment-hosted copper deposits. Some of the copper occurrences in tract F3 might be of hydrothermal origin, but such information

Table L3. Structurally controlled sediment-hosted copper tracts in GMUG greater study area.

Tract No.[a]	Tract name	Delineation criteria	Tract area (km^2)[b]
P1	Salt anticlines	1 and 2	8,100
P2	Cretaceous cliffs 1	1 and 2	
P3	Cretaceous cliffs 2	1 and 2	
P4	Eagle Basin-Grand Hogback	1 and 2	
F1	Salt anticlines	1, 2, 3, 4A, 4B	2,480
F2	Uncompahgre highland	1, 2, 3, 4A, 4B	
F3	Eagle Basin-Grand Hogback	1, 2, 3, 4A, 4B	

[a]P, permissive tract; F, favorable tract.

[b]Area of permissive tracts includes the area of the favorable tracts lying within.

was not available for this analysis. More research is needed to verify the presence of structurally controlled sediment-hosted copper in the Eagle Basin.

Undiscovered Deposit and Endowment Potential

The resource potential for structurally controlled sediment-hosted copper was not quantitatively assessed. The descriptive and grade and tonnage models used in previous assessments (Ludington and others, 1996) to assess redbed copper deposit potential are not deemed to be appropriate at the scale used in this assessment. Those models embrace a suite of deposits that is intended to characterize the diversity in sediment-hosted copper deposits present in a broad region covering four States. By necessity the models were required to encompass a fairly broad array of ore controls and deposit grades and tonnages. The copper resource potential of structurally controlled copper deposits, however, is largely restricted to deposits that exhibit a mix of characteristics, some common to deposits included in the redbed copper model and some associated with deposits in the reduced-facies copper model. Size and grade data for structurally controlled deposits are insufficient to determine whether the redbed copper deposit grade and tonnage models adequately represent them. The data are also insufficient to produce a new set of grade and tonnage models. The use of the existing redbed copper deposit models would introduce unwarranted uncertainty into the estimates of undiscovered structurally controlled deposits.

Although the magnitude of the resource potential cannot be estimated quantitatively, activity over the last 5 years suggests that structurally controlled sediment-hosted copper mineralization produced deposits that are of commercial interest as a potential source of copper. Exploration drilling in the mid-1990’s identified a reported geologic resource of 11.9 million t (metric tons) of mineralized rock grading 0.496 percent copper occurring in a 2,500-acre area that includes the historic Cashin and Cliffdweller mines (SEC Archives, 1997). During this same period, a deposit containing proven and probable reserves of 31.8 million t of ore grading 0.464 percent copper and containing 147,000 t of recoverable copper was outlined on a 5,900 acre site in the Lisbon Valley 30 km southwest of the Cashin site. Development of the fully permitted Lisbon Valley site is contingent on the currently (2001) depressed market price for copper rebounding to the level of $0.90/lb (SEC Archives, 1997). These examples suggest a viable near-term development potential associated with structurally controlled sediment-hosted copper deposits, which is supported by the environmentally benign character of the extraction and refining methods used to recover metal from these ores. The surface-mined, oxidized ore is treated with acid to put the metal into solution from which the metal is removed by electrowinning. Primary management issues for the near term would be expected to include exploration-related activity and mine site reclamation; development would likely be restricted to areas within the “favorable” tracts.

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Coal Resources and Coal Resource Potential

By R.D. Hettinger, L.N.R. Roberts, and M.A. Kirschbaum

Chapter M of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

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Coal Resources and Coal Resource Potential

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Abstract

Upper Cretaceous strata are known to contain coal in the vicinity of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests, Colorado, and these coal-bearing rocks extend under some areas of the forests. Forest areas are assigned a high, moderate, or low coal resource potential where coal-bearing strata have less than 6,000 feet of overburden. Areas of high potential have nearby outcrop or drill hole data that substantiate the presence of coal. Areas of moderate potential do not have drill hole or outcrop data to substantiate the presence of coal; however, data in adjacent areas indicate that coal is likely to be present. Areas of low potential have no information to substantiate the presence of coal; however, the presence of coal is inferred from regional data. The Uncompahgre National Forest has a low to moderate coal resource potential in areas underlain by the Dakota Sandstone, and it also has a moderate to high coal resource potential in areas underlain by the Fruitland Formation. The Grand Mesa National Forest has a low coal resource potential where it is underlain by the Dakota Sandstone, and it has a high coal resource potential in areas underlain by the Mesaverde Group and Mesaverde Formation. The Gunnison National Forest also has a high coal resource potential in areas underlain by the Mesaverde Group and Mesaverde Formation.

Introduction

Purpose and Scope

Upper Cretaceous rocks in the GMUG greater study area (map area, fig. M1) contain coal-bearing strata that extend under parts of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests, Colorado. The coal-bearing strata are in the Upper Cretaceous Dakota Sandstone, Fruitland Formation, Mesaverde Formation, and Mesaverde Group. Although some of the coal has been mined since the late 1800's, only the West Elk mine is currently operating within the three national forests of this study area (herein called the GMUG forests). The purpose of this chapter is to summarize the coal geology, and assess the coal resource potential for the GMUG forests. We estimate coal resources in the GMUG forest areas underlain by economically significant deposits of coal in the Mesaverde Group and Mesaverde Formation, and this main coal assessment unit is referred to as Area 1 (fig. M1) in this chapter. We also describe less significant deposits of coal that underlie other parts of the GMUG forests.

The areas of high coal resource potential in the Grand Mesa and Gunnison National Forests are contiguous, and they are estimated to have a combined coal resource of about 38 billion short tons, as determined in this study. That tonnage is reported for all beds of coal more than 1 ft thick and having less than 6,000 ft of overburden. This study does not attempt to estimate coal reserves that are the subset of the resource which can be economically produced at the present time. The coal resource is in the regionally extensive Cameo-Fairfield coal group of the Mesaverde Formation and Mesaverde Group. The Cameo-Fairfield has as much as 97 ft of net coal, and individual beds are as much as 30 ft thick. The Grand Mesa and Gunnison National Forests contain an additional 26 billion short tons of non-resource coal that is also in the Cameo-Fairfield coal group at depths greater than 6,000 ft.[1]

The large coal resource reported for the Grand Mesa and Gunnison National Forests must be regarded with caution because the figure does not take into account economic, land-use, environmental, technological, and geologic restrictions that affect the coal's availability and recoverability. The coal would have to be mined using underground methods, and technological and economical constraints generally limit current longwall mining to depths of less than 3,000 ft, beds more than 3.5 ft thick, and strata inclined by less than 12°; additionally, only about 14 ft of coal can be mined even if the bed is of greater thickness (Timothy J. Rohrbacher, U.S.

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[1]Measurements originally made and reported in feet, in miles, in square miles, and in short (2,000-lb) tons are included here in their original units for clarity and to avoid misstatement of precision in conversion. To convert feet to meters, multiply by 0.3048; to convert short tons to metric tons, multiply by 0.91; to convert miles to kilometers, multiply by 1.61; to convert square miles to square kilometers, multiply by 2.6.

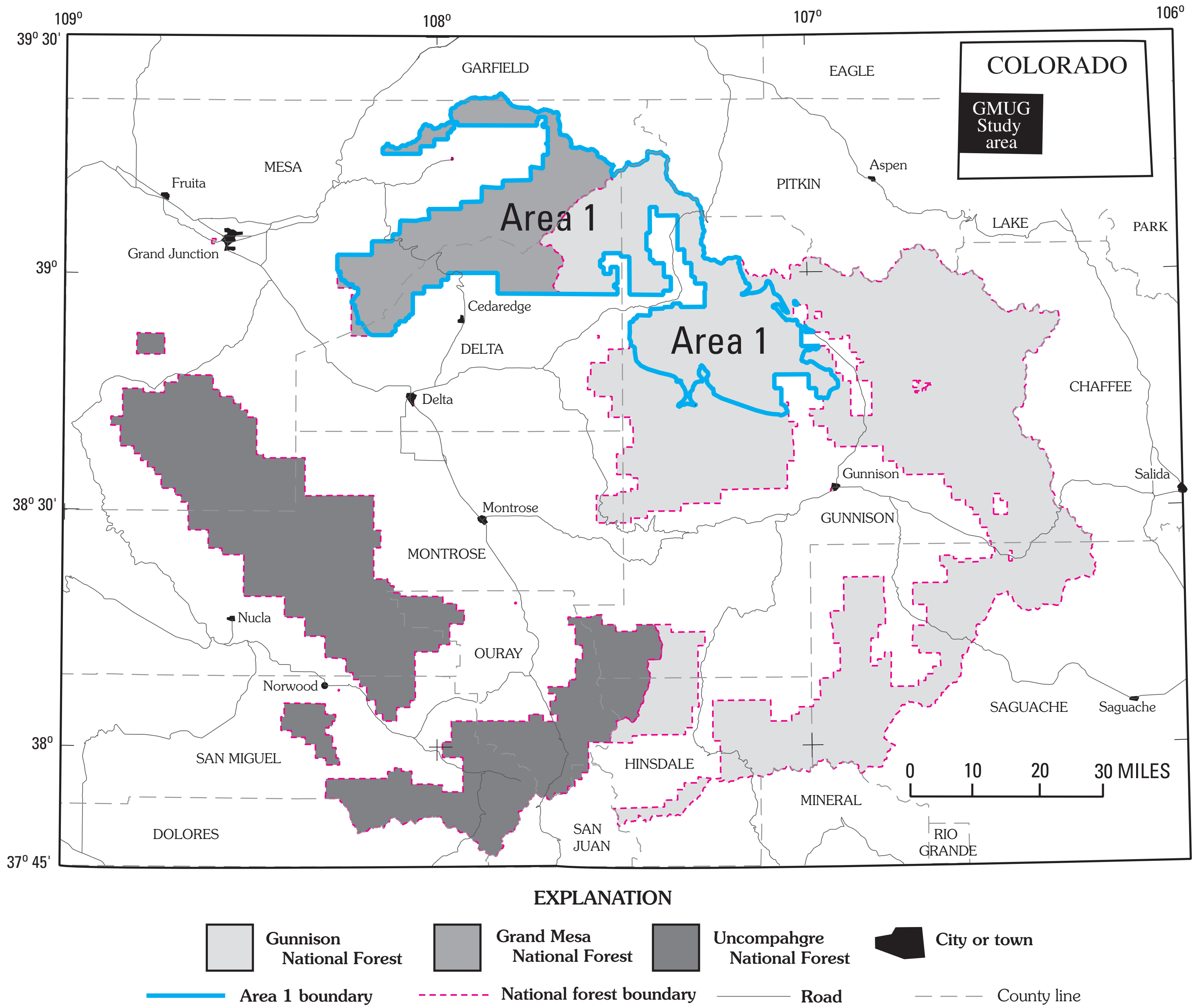


Figure M1. Location of Grand Mesa, Uncompahgre, and Gunnison National Forests, and southern Piceance Basin coal assessment unit (Area 1) within GMUG greater study area. Study area is located in western Colorado (inset) between lat 37°45′ and 39°30′ N. and long 106° and 109° W.

Geological Survey, oral commun., 1996). Only an estimated 37 percent of the coal resource estimated for the Cameo-Fairfield coal group in the Grand Mesa and Gunnison National Forests meets favorable underground mining criteria regarding depth of burial (less than 3,000 ft). Furthermore, only a fraction of that coal could be mined economically because many beds are either less than 3.5 ft thick or more than 14 ft thick and because many localities are steeply inclined. Additional coal would also be restricted from mining because it might be in beds that are discontinuous, left in the ground as pillars for roof support, or bypassed due to mining of adjacent strata.

Location

The greater study area and GMUG forests are located in western Colorado (fig. M1, index) between lat 37°45′ and 39°30′ N. and long 106° and 109° W. (map area, fig. M1). The study area is situated on and adjacent to the northeastern part of the Colorado Plateau, and major structural features include the Sawatch and Uncompahgre uplifts, and the Piceance and Paradox Basins (fig. M2). The Uncompahgre uplift separates the Piceance Basin from the Paradox Basin to the south.

The GMUG forests contain lands located within or adjacent to several coal fields of western Colorado (fig. M3). The coal field boundaries have been variously defined by Landis (1959), Hornbaker and others (1976), and Tremain and others (1996); and the boundaries shown in figure M3 represent a best-fit approximation of their various descriptions. The Grand Mesa National Forest extends across part of the Grand Mesa coal field and lies in close proximity to the Book Cliffs and Somerset coal fields. The northwestern part of the Gunnison National Forest extends across the Carbondale, Crested Butte, and Somerset coal fields. Farther south, parts of the Uncompahgre National Forest lie within the Tongue Mesa coal field and adjacent to the Nucla-Naturita coal field. The geology and resources of each coal field were described in Landis (1959) and are updated annually by the Colorado Geological Survey (for example, Hornbaker and others, 1976; Tremain and others, 1996).

Acknowledgments

We thank Ted Dyman, Tom Judkins, and Brad Van Gosen for their thorough reviews of the manuscript.

Upper Cretaceous and Tertiary Rocks

The GMUG forests are underlain by coal-bearing strata in the Dakota Sandstone, Mesaverde and Fruitland Formations, and Mesaverde Group (table M1). These Upper Cretaceous rocks were deposited in continental and nearshore marine settings along the western margin of the Western Interior seaway. Shoreline positions and depositional systems during the Late Cretaceous are shown in Roberts and Kirschbaum (1995). Although the Dakota Sandstone has a wide distribution throughout the GMUG forests, the Mesaverde Formation and Mesaverde Group are confined to areas where the Gunnison and Grand Mesa National Forests extend across the Piceance Basin, and the Fruitland Formation is confined to an isolated area where the Uncompahgre National Forest extends across the Tongue Mesa coal field (fig. M4).

The Dakota consists of conglomerate, sandstone, mudrock, carbonaceous shale, and coal deposited in alluvial and coastal plain settings during the initial incursion of the Western Interior seaway during the Cenomanian Stage of the Cretaceous Period. The Dakota is about 30–200 ft thick (Young, 1960, his fig. 16) and is overlain by the Mancos Shale. The Mancos consists of about 4,000–5,000 ft of mudrock deposited in an offshore marine environment that persisted from the Cenomanian through Campanian in the study area, when the shoreline was located in Utah.

As the shoreline moved back into the study area during the late Campanian, strata were deposited in a complex system of continental, coastal plain, and shoreface environments. At the Tongue Mesa coal field (fig. M3), about 200 ft of Upper Cretaceous coal-bearing strata is assigned to the Fruitland Formation by Dickinson (1987a, 1987b, 1988) and Hornbaker and others (1976). These rocks are part of a 1,000-ft thick stratigraphic interval that was referred to as the Mesaverde Formation by Landis (1959). In the southern part of the Piceance Basin, about 2,100–5,600 ft of strata has been assigned to the Mesaverde Group and Mesaverde Formation. The Mesaverde has been assigned group status in the Book Cliffs, Grand Hogback, and Carbondale coal fields, but is considered a formation in the Crested Butte and Grand Mesa coal fields. In the Book Cliffs coal field, the Mesaverde Group was divided into (in ascending order) the Castlegate Sandstone, Sego Sandstone, Mount Garfield Formation, and Hunter Canyon Formation (Erdmann, 1934; Fisher and others, 1960). In the Grand Hogback and Carbondale coal fields, the Mesaverde Group was divided into (in ascending order) the Iles and Williams Fork Formations (Collins, 1976). The stratigraphy and nomenclature of the Mesaverde are shown in figure M5; a more detailed discussion of Mesaverde stratigraphy is provided by Johnson (1989) and Hettinger and others (2000).

Depositional systems of continental origin prevailed throughout the study area from the latest part of the Cretaceous Period to the middle part of the Eocene Epoch of the Tertiary Period. The later part of the Tertiary was characterized by basalt flows and intrusions of igneous stocks, dikes, sills, and laccoliths. Volcanic activity was especially prevalent along the southeastern flank of the Piceance Basin and in the San Juan volcanic field (fig. M2).

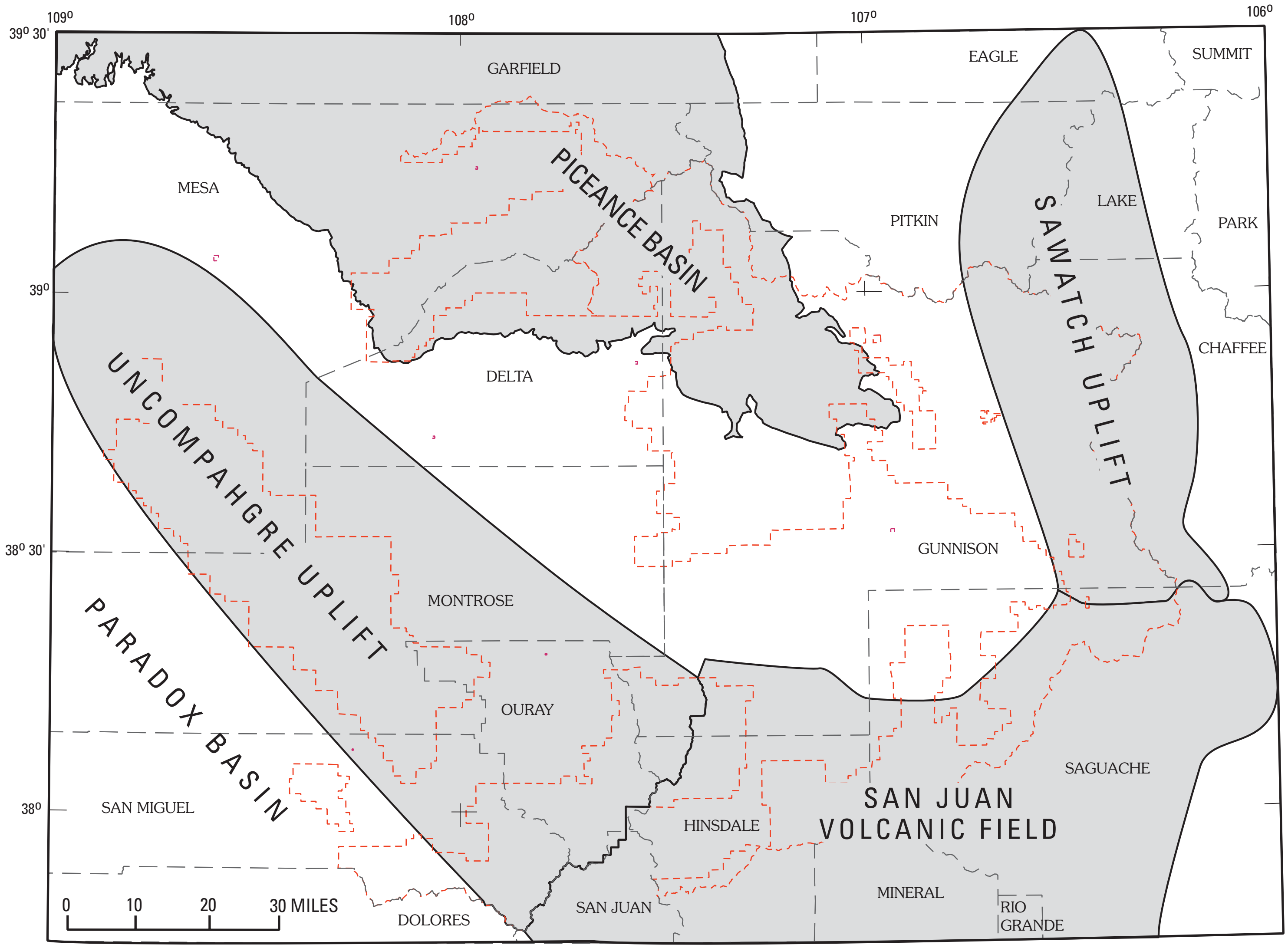
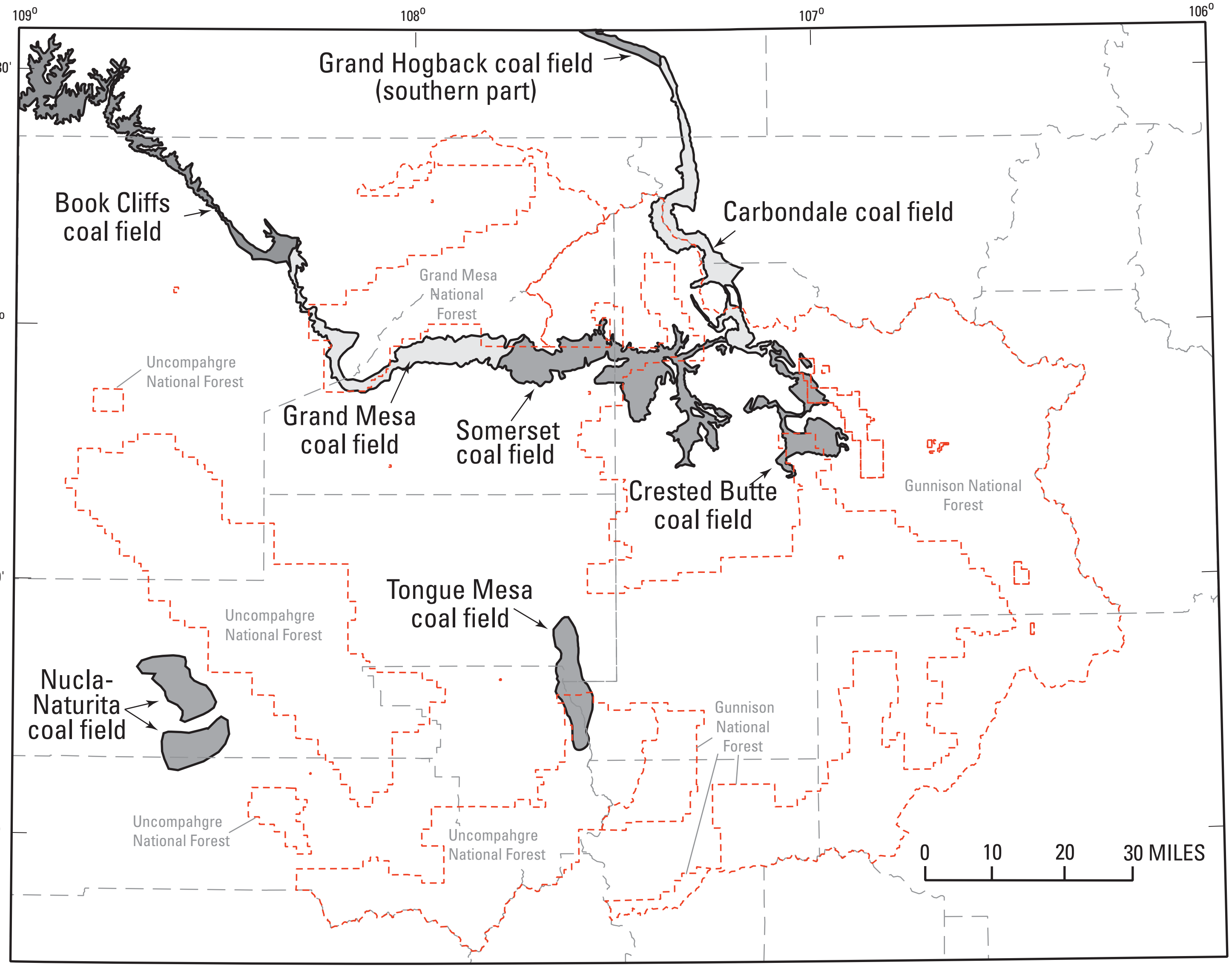


Figure M2. Location of major structural features in GMUG greater study area, and their relationship to Grand Mesa, Uncompahgre, and Gunnison National Forests. GMUG forest boundaries are shown as red dashed lines, and the forests are identified in figure M1.



EXPLANATION

Boundaries of Grand Mesa, Gunnison, and Uncompahgre National Forests

County line

Figure M3. Location of coal fields in GMUG greater study area.

Table M1. Summary of Cretaceous strata in Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests.

Age	Group or Formation	Thickness (ft)	Description
Late Cretaceous	Mesaverde Group and Mesaverde Formation	2,150-5,600	Sandstone, mudrock, carbonaceous shale, and coal. Sandstone is very fine grained to medium grained, and locally coarse grained. Upper part is fine grained to coarse grained and conglomeratic. Lower part intertongues with Mancos Shale. The Mesaverde Group or Mesaverde Formation underlies the Grand Mesa and Gunnison National Forests and is exposed in the Book Cliffs, Carbondale, Crested Butte, Grand Hogback, Grand Mesa, and Somerset coal fields (figs. M3 and M4). In the Book Cliffs coal field, the Mesaverde Group is divided into the Castlegate Sandstone, Sego Sandstone, Mount Garfield Formation, and Hunter Canyon Formation. In the Grand Hogback and Carbondale coal fields, the Mesaverde Group is divided into the Iles and Williams Fork Formations. Coeval strata are assigned to the Mancos Shale and Mesaverde Formation in the Grand Mesa and Crested Butte coal fields. Stratigraphic correlations are shown in figures M5 and M7.
	and		
	Fruitland Formation	200	The Fruitland Formation underlies areas in the Uncompahgre National Forest, and it is exposed in the Tongue Mesa coal field (figs. M3 and M4).
	Mancos Shale	4,000-5,000 (maximum)	Dark-gray shale with minor sandstone and siltstone; includes thin lenses of limestone, sandy limestone, and limy shale. The Mancos intertongues with the lower part of the Mesaverde Group and Mesaverde Formation.
	Dakota Sandstone	30-200	Light-gray and tan, fine- to coarse-grained sandstone or quartzite; minor interbeds of dark-gray shale, shaly sandstone, conglomeratic sandstone, and thin and lenticular beds of coal.

Dakota Sandstone Coal in the Grand Mesa, Gunnison, and Uncompahgre National Forests

Geologic investigations by Young (1960,1973) indicate that the Dakota Sandstone is widely distributed throughout much of the greater study area. It underlies all of the Grand Mesa National Forest and is present within parts of the Uncompahgre and Gunnison National Forests (fig. M4). The Dakota is gently dipping where it is exposed along the flanks of the Uncompahgre uplift; it abuts the San Juan volcanic field to the south and is locally disrupted by Tertiary intrusions in the Gunnison area.

Coal beds in the Dakota are generally thin and discontinuous, and they contain numerous partings of carbonaceous and coaly shale. Beds as thick as 7.7 ft are found locally in the study area, but they also contain many partings (Eakins, 1986). Numerous studies have been conducted to evaluate the coal in the Dakota; the best and most current summary of Dakota coal is by Eakins (1986). Dakota coal is being produced currently at the New Horizon mine in the Nucla-Naturita coal field (fig. M3) and burned at the Nucla power plant. The power plant uses a fluidized-bed combustion process and can therefore burn a lower quality coal than is used at most power plants (Eakins, 1986). The Dakota coals are high-volatile B and C bituminous in apparent rank (Murray, 1981). Coal in the Nucla-Naturita coal field has an ash yield from 6.1 to 12.8 percent and a sulfur content from 0.5 to 1.1 percent on an as-received basis (Murray, 1981). Haines (1978) analyzed 21 coal samples from three beds in the Nucla-Naturita coal field and reported an ash yield of about 11–28 percent and sulfur content of about 0.3–0.7 percent, with calorific values between 7,370 and 11,550 Btu/lb.

Grand Mesa National Forest

The Dakota Sandstone does not crop out within the Grand Mesa National Forest, but it is widespread in the subsurface (fig. M4). Most of the Dakota is buried at depths greater than 4,000 ft, based on its stratigraphic position below younger units within the forest. Dakota coals crop out 6–10 mi south and west of the forest, between the towns of Grand Junction and Delta, Colo. These coals were measured by

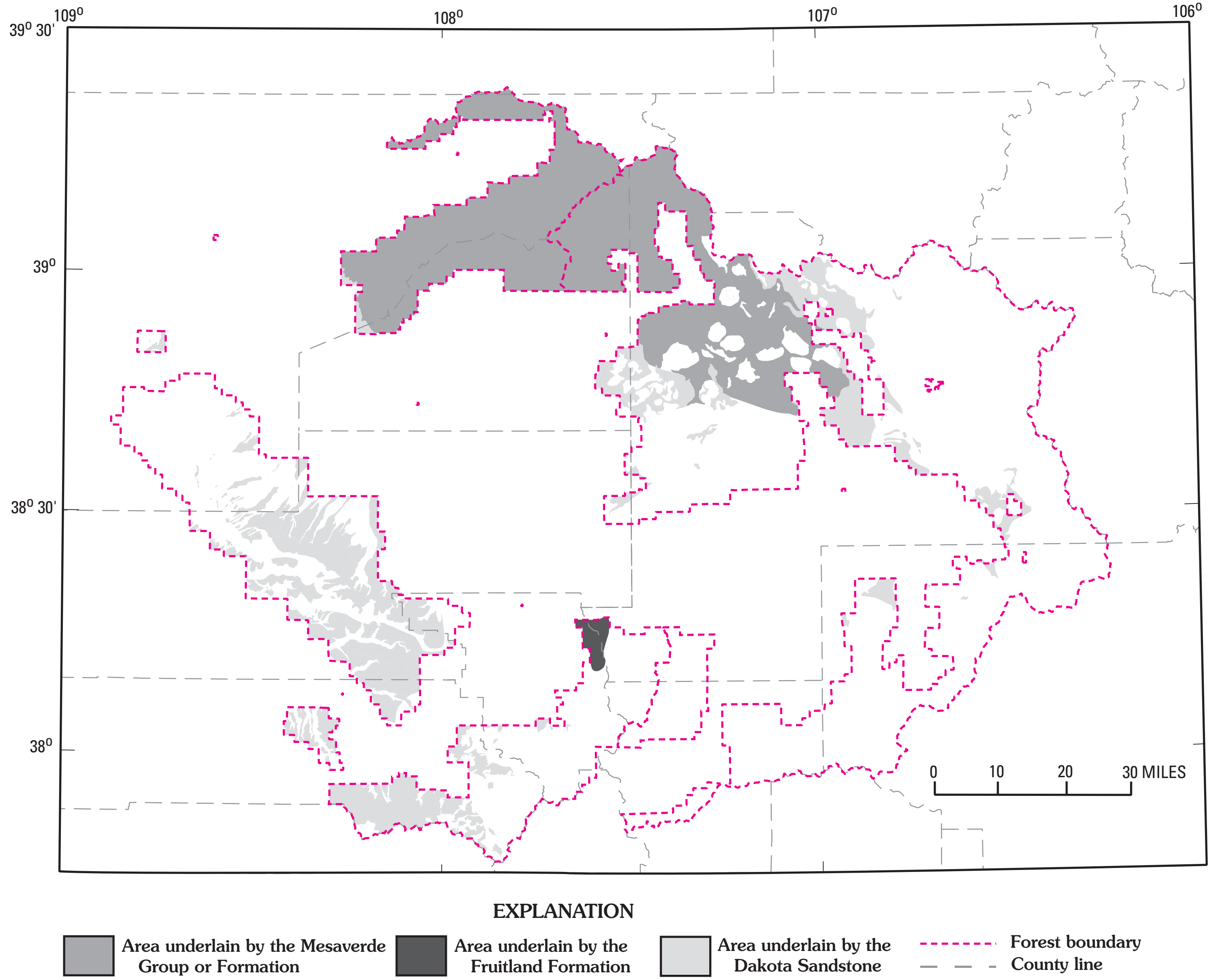


Figure M4. Areas in Grand Mesa, Uncompahgre, and Gunnison National Forests underlain by the Dakota Sandstone, Fruitland Formation, Mesaverde Formation, or Mesaverde Group. Dakota Sandstone also underlies areas covered by the Fruitland and Mesaverde. Tertiary volcanic rocks in Gunnison National Forest might also be underlain by the Dakota Sandstone or Mesaverde Formation. National forests and counties are identified in figure M1.

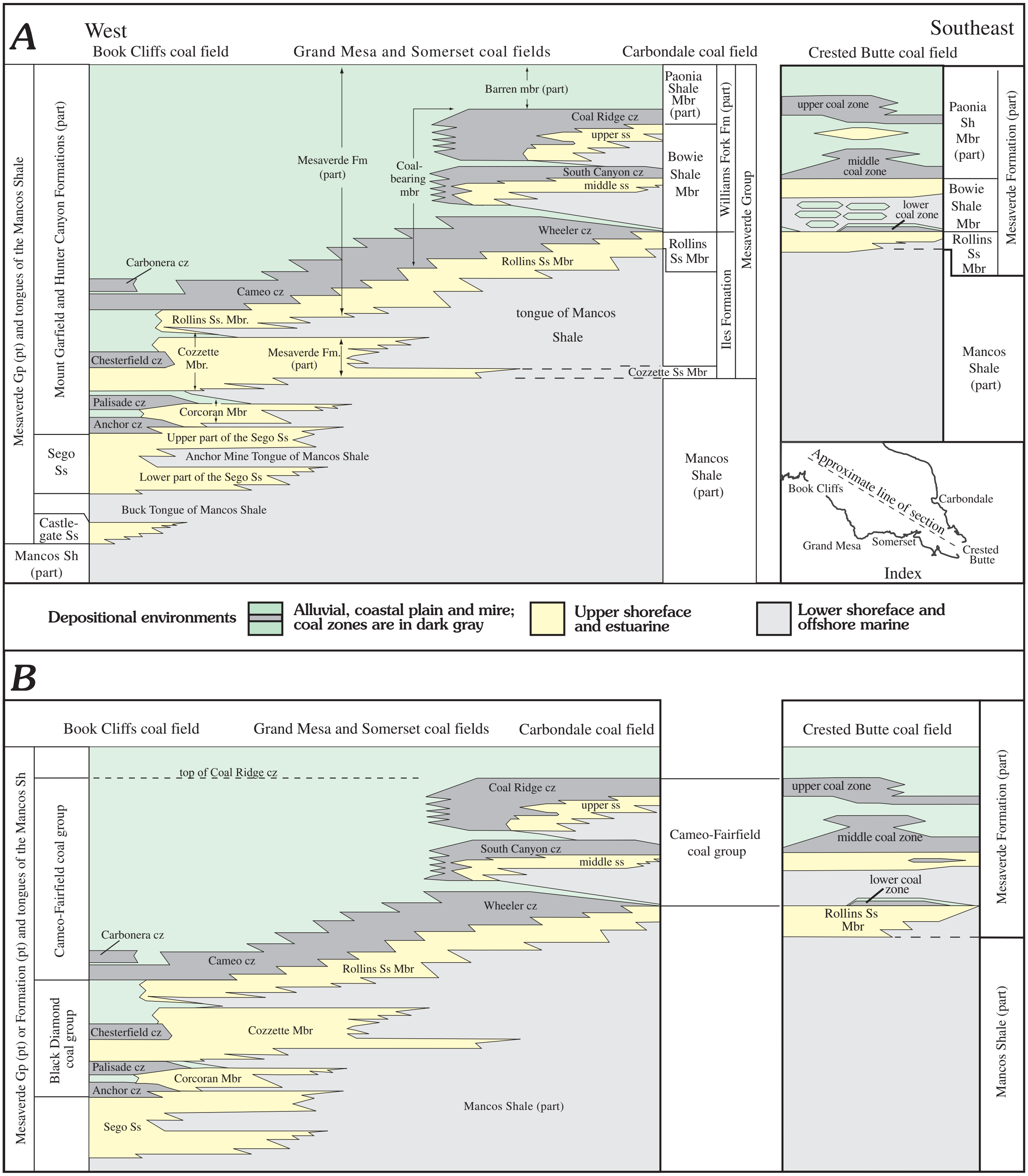


Figure M5. Stratigraphic nomenclature used for the Mesaverde Group and Mesaverde Formation in southern part of Piceance Basin, Colo.; modified from Hettinger and others (2000). *A*, Facies relationships along a line of section that is perpendicular to depositional strike. Index shows line of section in relation to coal fields. *B*, Stratigraphic position and nomenclature used in this report for coal groups and coal zones in the Mesaverde Group and Mesaverde Formation. Line of section is shown in *A*. Ss, ss, sandstone; Mbr, mbr, member; cz, coal zone; Sh, Shale; Gp, Group; Fm, Formation; pt, part.

Woodruff (1912) and Lee (1912). The thickest single bench of coal measured was 20 in. thick; at another locality 6 ft of coal was described within 11 ft of coal-bearing strata (Woodruff, 1912). The poor quality and thin discontinuous nature of the coal precluded development in the area (Woodruff, 1912). The presence of coal within the forest is unknown, but any coal that might be present is likely to be of similar poor quality, quantity, and character.

Gunnison National Forest

Although the Dakota Sandstone is widely distributed in the Gunnison National Forest (fig. M4), data by Gaskill and Godwin (1966a, 1966b), Gaskill and others (1967, 1986, 1987), and Godwin (1968) suggest that the Dakota lacks coal in the eastern and southern parts of the forest. Young (1960, his fig. 6) showed a thin carbonaceous interval within the Dakota at localities east of Delta, Colo., but he did not indicate that this interval contains coal.

Uncompahgre National Forest

The Dakota Sandstone crops out in the Uncompahgre National Forest; however, it is generally poorly exposed, concealed by thick vegetation, or covered by Quaternary landslide deposits. No published reports list precise thicknesses of Dakota coal in the forest; however, a 2.1-ft thick coal bed was measured in the forest about 12 mi northeast of the town of Nucla (fig. M1) (W.W. Boyer, USGS, unpub. data, 1926). Landis (1959) evaluated the Dakota coal as part of a statewide compilation. His generalized maps and descriptions indicate that Dakota coal beds in the forest are likely to be thin, impure, and discontinuous, but that minable reserves might be found locally.

Examples of coal deposits in the Dakota Sandstone are provided from two areas located 5–6 mi outside of the forest. One area is located near the town of Norwood (fig. M1); the other area is less than 5 mi from the town of Nucla in the Nucla-Naturita coal field (figs. M1 and M3). Coal beds in the Norwood area are about 2–11 ft thick including partings (Eakins, 1986). Eleven small mines operated 1–2 mi west of Norwood. The mines worked in beds that were 2.6–5.5 ft thick, and about 25,000 short tons of coal was produced between 1925 and 1979. Coal beds in the Nucla area are reported to be 1.3 to 9.0 ft thick; they contain numerous partings, and they can only be mapped over short distances (Eakins, 1986). Landis (1959) estimated that a 15 mi^2 part of the Nucla-Naturita coal field contained about 114 million short tons of coal. Another small area in the NW¼ sec. 31, T. 47 N., R. 15 W., near the town of Nucla, was estimated to contain about 278,900 short tons of coal (Haines, 1978). Twelve small underground mines and one strip mine operated within 4 mi of Nucla, and they produced more than 2 million short tons of coal between 1915 and 1983 (Eakins, 1986). Currently, the New Horizon strip mine supplies the Nucla Power Plant with coal, and about 400,000 short tons of coal was mined in 1995 (G. Sullivan, written commun., 1997, compiled from Mine Safety and Health Administration data). The New Horizon mine is about 1 mi west of Nucla.

Fruitland Formation Coal in the Uncompahgre National Forest

Approximately 200 ft of coal-bearing strata is present in a small part of the Uncompahgre National Forest at the Tongue Mesa coal field (figs. M3 and M4). The coal-bearing rocks were assigned to the Fruitland Formation by Hornbaker and others (1976) and Dickinson (1987a, 1987b, 1988), and they are part of a 1,000-ft thick interval that was originally thought to be equivalent to the Mesaverde Formation by Landis (1959). Both Landis (1959) and Dickinson (1987a, 1987b, 1988) described the coal-bearing interval as being concealed by heavy vegetation, landslides, talus, and glacial deposits. Coal in the Tongue Mesa coal field is reported to have an ash yield of 6.7–8.4 percent, a sulfur content of 0.5–0.9 percent, and a calorific value of 9,350–10,200 Btu/lb on an as-received basis (Hornbaker and others, 1976). The apparent rank of the coal is subbituminous B (U.S. Bureau of Mines, 1937, p. 110–111) and subbituminous C (Dickinson, 1987a, 1987b, 1988). Some of the coal is reported to be oxidized and bony (Hornbaker and others, 1976).

The geology of the Tongue Mesa coal field was mapped in the vicinity of the Uncompahgre National Forest at a 1:24,000 scale by Dickinson (1987a, 1987b, 1988). Dickinson's maps show the Fruitland cropping out at only a few small and widely spaced localities, and depth to the top of the formation ranges from 0 to 2,500 ft within the forest. The Fruitland contains one laterally extensive coal bed that is about 20–40 ft thick, and three to five coal beds that are about 5–13 ft thick. The beds of coal are gently inclined and disrupted by numerous faults; however, the precise location and displacement of the faults cannot be determined from surface mapping because the area is extensively covered by landslide debris. The faulting and landslide cover have also made the coal resources difficult to assess (Dickinson, 1987a, 1987b). Dickinson stated that the coal-bearing strata were drilled extensively for Federal permits and leases, but the drilling data had not been released at the time of his publications.

Some minor underground mining took place in the Tongue Mesa coal field intermittently between the 1890's and 1940's (Murray, 1981). The Lou Creek, Economy, Tyler, and Kennedy mines operated within the forest in T. 46 N., R. 7 W.; the Lou Creek mined a 40-ft thick bed, and the Economy and Tyler each mined a 30-ft thick bed (Dickinson, 1987a, 1988). Additionally, four small mines operated less than 3 mi from the forest and produced from beds that were 6–23 ft thick (Dickinson, 1987a).

Landis (1959) estimated the 58 mi^2 Tongue Mesa coal field to contain a coal resource of about 2,355 million short tons. Hornbaker and others (1976) thought the resources could be as high as 4,000 million short tons, apparently on the basis of core drilling information available to them. However, the forest lands are only partially within the coal field (fig. M3), and no estimate is available for the portion of this resource that is within the forest.

Mesaverde Group and Mesaverde Formation Coal in the Grand Mesa and Northwestern Part of the Gunnison National Forests (Area 1)

Coal-bearing strata in the Mesaverde Group and Mesaverde Formation underlie approximately 620 mi^2 of the Gunnison National Forest and 520 mi^2 of the Grand Mesa National Forest (fig. M4). These forest lands form a contiguous region that is designated as Area 1 in this report (fig. M1). The coal-bearing Mesaverde Group and Mesaverde Formation extend throughout the subsurface of the Piceance Basin (fig. M2) and are exposed in the Book Cliffs, Carbondale, Crested Butte, Grand Hogback, Grand Mesa, and Somerset coal fields (fig. M3). Numerous mines have produced from these coal fields since the late 1800's, and several mines are currently operating near the southern forest boundaries (see section, "Coal Production"). Some of the coal is also considered to be an important source for natural gas (Johnson, 1989). Because of the ongoing economic interest, the coal resources of Area 1 are evaluated in this report.

Data

The evaluation of Area 1 is based primarily on data and digital files used by Hettinger and others (2000) to describe the geology and estimate coal resources in the southern part of the Piceance Basin, an area included in the USGS National Coal Resource Assessment. The digital files were manipulated in a Geographic Information System (GIS) using ARC/INFO software to report coal resources within various parameters in Area 1. With the exception of files of national forest boundaries, all digital files were prepared in-house or imported from the existing public domain, and they have been made available by Biewick and Mercer (2000). Methods regarding the generation and use of the digital files have been provided by Biewick and Mercer (2000), Hettinger and others (2000), and Roberts and others (2000).

Lithologic and stratigraphic data used to assess coal resources in Area 1 are from 94 drill holes and outcrops located in Area 1 (table M2; fig. M6). Additional data were also used from a much larger data base by Hettinger and others (2000), and those data points are also shown in figure M6. Lithologic interpretations were made using a combination of responses from natural-gamma (gamma ray), density, resistivity, neutron, spontaneous potential, and caliper logs. Coal bed thicknesses were rounded to the nearest foot, and beds less than 1 ft thick were not included in the assessment. Because coal thicknesses were rounded, we used a minimum thickness of 1 ft rather than the 14-in. cutoff for bituminous coal as suggested by Wood and others (1983).

Geologic coverages used to assess Area 1 include (1) a geologic map that shows outcrops of rock units, (2) a structure contour map of the base of each coal resource interval, and (3) isopach maps that show the thickness, net coal, and overburden for each coal resource interval. Outcrops of rock units in Area 1 were obtained from a digital geologic map of Colorado by Green (1992) that was compiled from the 1:500,000-scale geologic map of the State of Colorado by Tweto (1979). Structure contour and isopach maps were prepared using lithologic and stratigraphic information gathered from drill holes and outcrops. These spatial data were gridded using Earth Vision [Dynamics Graphics, Inc.], and the resulting contour lines were then converted into ARC/INFO polygon coverages (Roberts and others, 2000).

Coal Geology

In Area 1, the Mesaverde Group and Mesaverde Formation contain coal within the Black Diamond and Cameo-Fairfield coal groups as referred to by Hettinger and others (2000) (fig. M5). The stratigraphic distribution of Mesaverde coal in Area 1 is demonstrated on cross section *A–A′* (fig. M7). The cross section is oriented nearly perpendicular to shorelines of the Cretaceous Western Interior seaway. The datum used for the cross section is a bentonite bed located stratigraphically near the base of a tongue of Mancos Shale that underlies the Rollins Sandstone Member of the Mount Garfield, Mesaverde, and Iles Formations.

Black Diamond Coal Group

The Black Diamond coal group is located stratigraphically below the Rollins Sandstone Member, and contains (in ascending order) the Anchor, Palisade, and Chesterfield coal zones (fig. M5). Individual beds of coal are generally less than 6 ft thick where they are exposed in the Book Cliffs and Grand Hogback coal fields, and they pinch out southeast of those localities. The Black Diamond coal group underlies Area 1 in Tps. 7, 8, 9 S., Rs. 94, 95, 96 W.; drill hole data show that the coal group lies 3,500–10,500 ft deep and has less than 6 ft of net coal in those areas. Resources were not estimated for the Black Diamond coal group in Area 1 because the coal beds are too thin and too deep to be economically significant.

Cameo-Fairfield Coal Group

The Cameo-Fairfield coal group overlies the Rollins Sandstone Member and contains the thickest and most

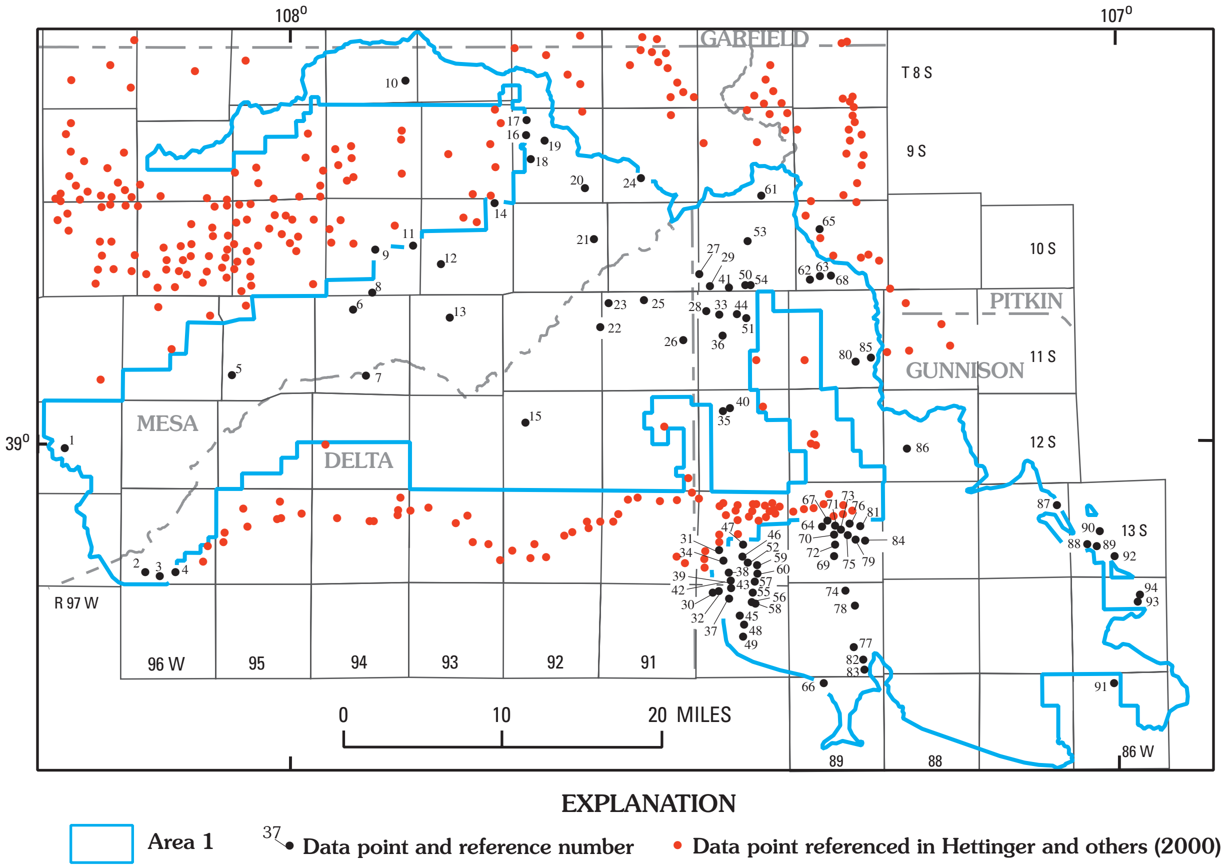


Figure M6. Location of data points used to assess coal resources of Area 1. Area 1 is located where the Mesaverde Formation and Mesaverde Group underlie the Gunnison and Grand Mesa National Forests (figs. M1 and M4). Labeled data points in Area 1, and near its eastern boundary, are referenced in table M2.

extensively mined coals in the Piceance Basin; the coal group is also an important source for natural gas (Johnson, 1989). The coal group is about 1,000 ft thick in the northeastern part of Area 1, and it is less than 200 ft thick in the southwestern and southeastern parts of Area 1. The Cameo-Fairfield extends throughout most of the subsurface of Area 1, and it is exposed near the forest boundaries in the Carbondale, Crested Butte, Grand Mesa, and Somerset coal fields (fig. M3). Exploratory coal drilling in the Grand Mesa and Somerset coal fields has been reported by Eager (1978, 1979), Dunrud (1989a, 1989b), Johnson (1948), and Toenges and others (1949, 1952). Exploratory coal drilling and outcrop measurements in the southern part of the Carbondale coal field have been reported by Collins (1976), Donnell (1962), Dunrud (1989a), Ellis and others (1988), and Kent and Arndt (1980a, 1980b). Coal bed thicknesses in the Crested Butte coal field have been reported in geologic maps by Lee (1912), Gaskill and Godwin (1966a, 1966b), Godwin (1968), and Gaskill and others (1967, 1986). References to coal zones and coal bed thicknesses in those areas are based on our interpretations of their data.

Following the nomenclature of Hettinger and others (2000), the Cameo-Fairfield group contains (in ascending order) the Cameo-Wheeler, South Canyon, and Coal Ridge coal zones in areas located west of long 107°15′ W. (figs. M5, M7; table M1). East of long 107°15′ W., the Cameo-Fairfield group is simply divided into the lower, middle, and upper coal zones (figs. M5, M7, and table M1). Coal zone nomenclature was not extended across long 107°15′ W., owing to structural and stratigraphic complexities, and a paucity of data east of the longitudinal line. Coal-bearing strata in the southern part of the Carbondale and Crested Butte coal fields are poorly exposed, steeply inclined, displaced by numerous faults, and intruded by sills, dikes, and laccoliths. Additionally, coal beds underlie many of the laccoliths.

Net coal in the Cameo-Fairfield coal group ranges from about 50 to 97 ft in a 20- to 30-mi wide belt that extends north to south across the central part of Area 1 (fig. M8). Net coal decreases to less than 50 ft in the remaining parts of Area 1.

Coal distribution in the Cameo-Wheeler, South Canyon, and Coal Ridge coal zones is shown in a series of net coal isopach maps in figures M9, M10, and M11, respectively.

Table M2. Drill hole and outcrop data in Area 1.

[Information is provided for each data point shown in Area 1 in figure M6. Map number (Map No.) refers to the data point in figure M6. Point Identification (ID) is the 10-digit American Petroleum Information (API) number of an oil or gas hole, or the original number of a coal exploration hole or measured section. Type refers to oil and gas hole (O&G); measured section (MS); lithologic log (LL); rotary hole (ROT); rotary and core hole (R/C); undefined (UND). Source refers to the lease operator, well name, data collector, or a U.S. Geological Survey (USGS) or U.S. Bureau of Mines (USBM) publication. The type of publication is an Open-File Report (OF), Bulletin (Bull), Professional Paper (PP), Geologic Quadrangle Map (GQ), or Technical Paper (TP). Latitude and longitude of data point are in decimal degrees. Elevation is measured in feet above sea level to the Earth's surface (or to Kelly bushing of the drill rig) at the data point. The total thickness of coal (Total coal) is provided for the Cameo-Fairfield coal group and includes all coal beds in the group that are more than 1 ft thick. The total thickness of coal and number of coal beds (# beds) are also provided for Cameo-Wheeler, South Canyon, and Coal Ridge coal zones, which are within the Cameo-Fairfield group. Total coal and number of beds includes all coal beds that are more than 1 ft thick. Blank space indicates (1) the coal zones had no coal at the data point, (2) data were not provided (map numbers 31 and 34), or (3) the coal zones were not identified at location of data point (map numbers 86 through 94)]

Data point identification				Data point location						Net coal in Cameo-Fairfield group* (ft)	Cameo-Wheeler coal zone		South Canyon coal zone		Coal Ridge coal zone	
Map No.	Point ID	Type	Source	Long W.	Lat N.	Sec.	Township	Range	Elevation (ft)		Total coal (ft)	# beds	Total coal (ft)	# beds	Total coal (ft)	# beds
1	IP-77-1	ROT	USGS OF 78-540	108.24233	38.99503	21	12 S	97 W	7230	31.0	31	8				
2	IP-77-2A	ROT	USGS OF 78-540	108.14739	38.88108	32	13 S	96 W	8700	15.5	15.5	6				
3	IP-77-3	ROT	USGS OF 78-540	108.13039	38.87767	33	13 S	96 W	8450	15.0	15	5				
4	HK-77-1	ROT	USGS OF 78-540	108.11172	38.88131	34	13 S	96 W	8030	34.5	34.5	9				
5	05-077-05011	O&G	PACIFIC-SMITH 1-C	108.04617	39.06228	30	11 S	95 W	10191	31.0	31	4				
6	05-077-05017	O&G	WESTERN FRNTR-BIG CRK 1	107.90175	39.12242	4	11 S	94 W	9464	39.0	39	10				
7	05-029-05031	O&G	APACHE-MACHELSON 2	107.88661	39.06178	34	11 S	94 W	10133	61.0	61	6				
8	05-077-08188	O&G	EXXON-OLD MAN MTN #1	107.87972	39.13839	33	10 S	94 W	10043	43.0	43	12				
9	05-077-08598	O&G	FUELCO-FEE E-22-10-94-S	107.87486	39.17894	22	10 S	94 W	7929	48.0	48	12				
10	05-077-08043	O&G	MOBIL-BEAR CRK 1-25	107.83967	39.33339	25	8 S	94 W	8430	74.0	55	6	14	6	5	3
11	05-077-07360	O&G	ALPINE OIL-GOVT 1	107.83089	39.18153	24	10 S	94 W	8512	71.0	68	9			3	1
12	05-077-05026	O&G	EL PASO-LEON CRK 1	107.79828	39.16478	29	10 S	93 W	9062	37.0	35	5			2	1
13	05-077-08295	O&G	EXXON-KENNY CREEK #1	107.7875	39.11528	9	11 S	93 W	9577	50.0	50	5				
14	05-077-08395	O&G	BV-CARLTON CURRIER 2-1	107.73472	39.22083	2	10 S	93 W	8052	70.0	57	5	9	4	4	3
15	05-077-05001	O&G	SUNRAY-COLO FED C-1	107.69861	39.01908	8	12 S	92 W	9825	81.0	81	10				
16	05-077-05097	O&G	EL PASO CONOCO GOVT 1	107.69756	39.28253	8	9 S	92 W	7665	89.0	70	3	15	3	4	1
17	05-077-05108	O&G	APACHE CORP-RUSHMORE 1	107.69633	39.29686	5	9 S	92 W	7617	87.0	63	2	18	4	6	2
18	05-077-07352	O&G	NORDON-GOVT 1	107.692	39.261	20	9 S	92 W	7610	66.0	54	7	5	3	7	3
19	05-077-08435	O&G	COORS-USA 1-16 SC	107.67528	39.27861	16	9 S	92 W	7850	91.0	68	4	13	3	10	5
20	05-077-08545	O&G	CELERON PORTER MT FD35-1	107.62722	39.23453	35	9 S	92 W	8267	95.0	55	3	24	8	16	2
21	05-077-08575	O&G	AMOCO-RUTH MTN #1	107.61647	39.18703	13	10 S	92 W	8711	97.0	60	7	21	7	16	5
22	05-029-05000	O&G	UNION-OVERLAND GOV'T 1	107.61003	39.106	13	11 S	92 W	9421	66.0	44	3	14	4	8	2
23	05-029-06001	O&G	PAN AM-USA MARVIN WOLF 1	107.60042	39.12897	6	11 S	91 W	8899	82.0	57	5	25	3		
24	05-077-05074	O&G	MTN STATES-28-1 GOV'T	107.56033	39.24308	28	9 S	91 W	9180	94.0	57	6	35	5	2	1
25	05-029-05083	O&G	VICTOR DRLG-GOVT #1	107.55767	39.13117	4	11 S	91 W	8538	94.0	62	4	27	5	5	1
26	05-029-06069	O&G	AMOCO-ELECTRIC MTN U.#1	107.51167	39.09444	13	11 S	91 W	8216	73.0	32	5	29	5	12	4
27	05-051-06043	O&G	PETRO-FED 1-25-10-91	107.49297	39.15547	25	10 S	91 W	8195	74.0	45	3	27	8	2	1
28	05-051-06008	O&G	RALSTON-PETROLWS 11-90-7	107.48417	39.12028	7	11 S	90 W	8181	74.0	40	6	22	6	12	5
29	05-051-06009	O&G	RALSTON-FED 31	107.47939	39.14411	31	10 S	90 W	7901	73.0	45	3	23	4	5	2
30	LEE-MS-47	MS	USGS BULL 510	107.4775	38.86167	5	14 S	90 W		54.0	27	7	10	1	16	2
31	Not provided															
32	DUN-40	LL	USGS MAP C-115	107.47111	38.86278	5	14 S	90 W	8109	76.0	33	6	29	2	14	2
33	05-051-06024	O&G	PIUTE-COAL BSN10-8-11-90	107.46944	39.11742	8	11 S	90 W	7918	78.0	40	7	27	6	11	4
34	Not provided															
35	05-051-06035	O&G	AMOCO-SUMERSET #2	107.46544	39.02875	8	12 S	90 W	8515	85.0	40	4	29	4	16	3
36	05-051-06007	O&G	RALSTON-PETRLWS 11-90-17	107.46533	39.09867	17	11 S	90 W	8101	55.0	26	8	16	4	13	5
37	DUN-41	LL	USGS MAP C-115	107.46	38.85611	9	14 S	90 W	8256	77.0	32	5	29	2	16	3
38	LH-2-33	R/C	USBM TP 721	107.45947	38.87931	33	13 S	90 W	7504	74.9	27.6	4	34.9	6	9.7	2
39	LH-5-33	R/C	USBM TP 721	107.45758	38.87164	33	13 S	90 W	7636	64.5	25.1	5	28.9	3	6.3	1
40	05-051-06021	O&G	AMOCO-SUMERSET #1	107.45756	39.03128	9	12 S	90 W	8441	87.0	39	4	30	4	18	2
41	05-051-06010	O&G	RALSTON-RALSTON 10-90-32	107.45744	39.14203	32	10 S	90 W	7711		9	2	23	4	6	4
42	LH-1-33	R/C	USBM TP 721	107.45739	38.87164	33	13 S	90 W	7643	73.7	27.7	5	33.3	6	7.3	3
43	LH-3-4	R/C	USBM TP 721	107.45667	38.86558	4	14 S	90 W	7765	50.0	13.6	4	23	4	12.3	4
44	05-051-05007	O&G	POOL-HENDERSON 1	107.4485	39.11806	9	11 S	90 W	7532	35.0	30	6	5	1		
45	DUN-42	LL	USGS MAP C-115	107.44667	38.83944	16	14 S	90 W	7678		20	3	17	2		
46	DUN-52	UND	USGS Map C-115	107.44331	38.89461	28	13 S	90 W	7092	81.0	31	4	34	5	16	4
47	DUN-51	UND	USGS Map C-115	107.44272	38.90539	21	13 S	90 W	6765	71.0	35	4	24	2	12	2
48	DUN-43	LL	USGS MAP C-115	107.4425	38.83167	15	14 S	90 W	8442	79.0	43	3	26	2	10	2
49	DUN-44	LL	USGS MAP C-115	107.4425	38.82056	22	14 S	90 W	8484	78.0	34	3	33	3	11	2
50	05-051-06011	O&G	RALSTON-FED33 (10-90-33)	107.43794	39.14511	33	10 S	90 W	7561	55.0	31	5	16	3	8	4
51	05-051-06013	O&G	RALSTON-HENDRSN 11-90-10	107.43764	39.11386	10	11 S	90 W	7550	31.0	25	8	6	2		
52	DUN-53	UND	USGS Map C-115	107.43675	38.88839	27	13 S	90 W	7597	62.0	21	3	28	4	13	3
53	05-051-06023	O&G	PIUTE-RAGGED MTN FED16-4	107.43533	39.18561	16	10 S	90 W	8238	44.0	34	5	6	2	4	2
54	05-051-06014	O&G	RALSTON-10-90-34-SW	107.43203	39.14431	34	10 S	90 W	7490	51.0	30	4	15	1	6	4
55	DUN-57	LL	USGS MAP C-115	107.43167	38.86	3	14 S	90 W	8292	47.0	13	2	27	3	7	2
56	LH-4-10	R/C	USBM TP 721	107.431	38.854	10	14 S	90 W	8041	46.2	10.9	4	18.6	3	15.1	5
57	DUN-56	LL	USGS MAP C-115	107.42917	38.87139	34	13 S	90 W	8051	77.0	31	6	35	4	11	2
58	DUN-58	LL	USGS MAP C-115	107.42889	38.85167	10	14 S	90 W	8156	62.0	22	5	20	2	20	3
59	DUN-54	UND	USGS Map C-115	107.42544	38.88636	27	13 S	90 W	7955	57.0	18	2	20	2	19	5
60	DUN-55	LL	USGS MAP C-115	107.42539	38.87856	34	13 S	90 W	8114	65.0	18	3	33	3	14	2
61	05-051-06001	O&G	SUNRAY-S.WOLF CRK UNIT 1	107.41792	39.22683	34	9 S	90 W	9170	48.0	30	4	12	4	6	3
62	DUN-76	LL	USGS MAP C-115	107.36131	39.14925	31	10 S	89 W	9060	47.0	21	2	18	2	8	1
63	DUN-78	LL	USGS MAP C-115	107.35	39.15222	32	10 S	89 W	9530	51.0	21	3	24	3	6	1
64	LH-11-9	R/C	USBM B-501	107.34992	38.92189	9	13 S	89 W	6385	18.2	12	4	2.4	1	0	0
65	KENT MS-9	MS	USGS OF 80-709	107.34989	39.19494	17	10 S	89 W		54.1	23.1	3	15	2	16	9
66	Lee-MS-71/69/68	MS	USGS BULL 510	107.34833	38.7775	4	15 S	89 W		56.4	29.2	5	21.2	2	6	1

Table M2. Drill hole and outcrop data in Area 1.—Continued

Data point identification				Data point location						Net coal in Cameo-Fairfield group* (ft)	Cameo-Wheeler coal zone		South Canyon coal zone		Coal Ridge coal zone	
Map No.	Point ID	Type	Source	Long W.	Lat N.	Sec.	Township	Range	Elevation (ft)		Total coal (ft)	# beds	Total coal (ft)	# beds	Total coal (ft)	# beds
67	LH-6-16	R/C	USBM B-501	107.34275	38.9275	16	13 S	89 W	6358	24.4	18.5	4	4.2	2	0	0
68	DUN-79	LL	USGS MAP C-115	107.33717	39.15242	33	10 S	89 W	9640	36.0	19	4	13	2	4	1
69	LH-19-28	R/C	USBM B-501	107.33597	38.89428	28	13 S	89 W	6560	18.2	15.6	3	2.4	1		
70	LH-16-21	R/C	USBM B-501	107.33397	38.91314	21	13 S	89 W	6440	19.0	16	2			0	0
71	LH-9-16	R/C	USBM B-501	107.33381	38.92189	16	13 S	89 W	6400	17.7	16	3			1.5	1
72	LH-18-21	R/C	USBM B-501	107.33353	38.90431	21	13 S	89 W	6500	18.5	14.8	3	3.1	1		
73	LH-14-15	R/C	USBM B-501	107.32722	38.91856	15	13 S	89 W	6534	23.2	17.6	3	1.5	1	2.4	2
74	DUN-68	LL	USGS MAP C-115	107.32167	38.8625	3	14 S	89 W	7236	24.5	13.5	3			11	2
75	LH-15-22	R/C	USBM B-501	107.31953	38.91344	22	13 S	89 W	6650	19.7	18.1	2			0	0
76	LH-20-15	R/C	USBM B-501	107.316	38.924	15	13 S	89 W	7635	21.9	17.2	2	2.6	2	1	1
77	LEE-MS-64	MS	USGS BULL 510	107.31278	38.81083	26	14 S	89 W		40.5	16.1	3	6	1	18.4	3
78	DUN-69	LL	USGS MAP C-115	107.31111	38.84917	11	14 S	89 W	7600	20.0	11	5			9	2
79	LH-17-23	R/C	USBM B-501	107.30906	38.90922	23	13 S	89 W	6740	24.7	18.8	3	2.2	1	0	0
80	ELLIS-MS-129	MS	USGS MAP C-97-B	107.30806	39.07333	26	11 S	89 W		13.0					13	4
81	LH-25-14	R/C	USBM B-501	107.304	38.922	14	13 S	89 W	7540	22.2	15.2	2	5.3	3	0	0
82	DUN-71	LL	USGS MAP C-115	107.30167	38.79861	35	14 S	89 W	8562	20.5	13.5	4	3	1	4	1
83	DUN-72	LL	USGS MAP C-115	107.3	38.78917	35	14 S	89 W	8854	26.0	13	2	5	2	8	3
84	LH-21-23	R/C	USBM B-501	107.29878	38.90811	23	13 S	89 W	6940	18.7	14.7	2	2.1	2	0	0
85	ELLIS-MS-128	MS	USGS MAP C-97-B	107.29	39.07667	25	11 S	89 W		5.0					5	3
86	GASKILL-MS-1	MS	USGS MAP GQ-1604	107.24917	38.99333	29	12 S	88 W		7.1						
87	LEE-MS-125	MS	USGS BULL 510	107.07139	38.93917	12	13 S	87 W		3.0						
88	LEE-MS-123	MS	USGS BULL 510	107.03722	38.90333	20	13 S	86 W		4.0						
89	LEE-MS-122	MS	USGS BULL 510	107.02583	38.90056	29	13 S	86 W		6.0						
90	LEE-MS-127	MS	USGS BULL 510	107.02167	38.91472	20	13 S	86 W		11.0						
91	GASKILL-MS-4	MS	USGS MAP GQ-1604	107.00667	38.775	4	15 S	86 W		14.0						
92	LEE-MS-121	MS	USGS BULL 510	107.00444	38.89139	28	13 S	86 W		10.0						
93	LEE-MS-115	MS	USGS BULL 510	106.97778	38.84972	11	14 S	86 W		26.8						
94	LEE-MS-117	MS	USGS BULL 510	106.97528	38.85611	11	14 S	86 W		23.7						

*Cameo-Fairfield group = Cameo-Fairfield coal group of the Mesaverde Group or Formation. The coal group contains the Cameo-Wheeler, South Canyon, and Coal Ridge coal zones west of long 107° 15′ W.

Data used to construct the maps are identified in table M2 and figure M6.

Cameo-Wheeler Coal Zone (West of Long 107°15′ W.)

The Cameo-Wheeler coal zone (fig. M5) underlies a 925 mi^2 area that includes all parts of Area 1 west of long 107°15′ W. The coal zone overlies the Rollins Sandstone Member and is about 100–400 ft thick. The Cameo-Wheeler coal zone has approximately 5–80 ft of net coal, and net coal exceeds 50 ft throughout the central part of Area 1 (fig. M9). Near the southern boundary of Area 1, in the Grand Mesa and Somerset coal fields, the Cameo-Wheeler has 10–70 ft of net coal in as many as 15 beds that are 1–30 ft thick. Principal coals in the Somerset coal field include the Old King Coal (A) bed, Somerset (B) bed, Bear (C) bed, and Orchard Valley (D) bed (Dunrud, 1989a, 1989b). Near the eastern boundary of Area 1, in the Carbondale coal field, the Cameo-Wheeler contains about 7–27 ft of net coal in one to three beds that are 3–18 ft thick. Principal coal beds in the southern part of the Carbondale field are the Coal Basin A, B (Somerset), and C (Bear) (Dunrud, 1989a; Ellis and others, 1988).

South Canyon Coal Zone (West of Long 107°15′ W.)

The South Canyon coal zone underlies a 530 mi^2 region in Area 1. This coal zone overlies and intertongues with the middle sandstone of the Bowie Shale Member of the Williams Fork Formation (fig. M7). It extends west from long 107°15′ W. and pinches out along a sinuous line that trends about N. 20° W. from sec. 31, T. 12 S., R. 92 W. to sec. 30, T. 8 S., R. 95 W. (fig. M10). The coal zone is 1–200 ft thick and contains 1–30 ft of net coal (fig. M10). Net coal exceeds 20 ft along a 5- to 10-mi wide belt that trends N. 20° W. throughout the central part of Area 1. In the Somerset coal field, the South Canyon has 15–35 ft of net coal in two to five beds that are 1–25 ft thick, and important coal beds include the Oliver (D), D-1, and D-2 beds (Dunrud 1989a). In the southern part of the Carbondale field, at Coal Basin, the South Canyon contains the 3–20 ft thick Dutch Creek coal bed (Collins, 1976; Dunrud, 1989a).

Coal Ridge Coal Zone (West of Long 107°15′ W.)

The Coal Ridge coal zone overlies and intertongues with the upper sandstone in the Bowie Shale Member of the Williams Fork Formation (fig. M7), and the coal zone occupies about the same area as the underlying South Canyon coal zone. The Coal Ridge is 100–400 ft thick near the line of long 107°15′ W., is less than 100 ft thick throughout most of its west half, and pinches out near the same line as the underlying South Canyon coal zone (fig. M11). The Coal Ridge generally has less than 10 ft of net coal, although a small area with about 20 ft of net coal is located near the Somerset coal field (figs. M3 and M11). In the Somerset coal field, the Coal Ridge coal zone contains 10–26 ft of net coal in two to seven beds that are 1–10 ft thick; important beds include the Hawksnest (E) and E-2 (Dunrud, 1989a). In the southern part of the Carbondale coal field, the Coal Ridge coal zone has 2–10 beds of coal that are 1–23 ft thick, and named beds include the Placita, Sunshine, North Rim, and Lake Ridge coal beds (Ellis and others, 1988).

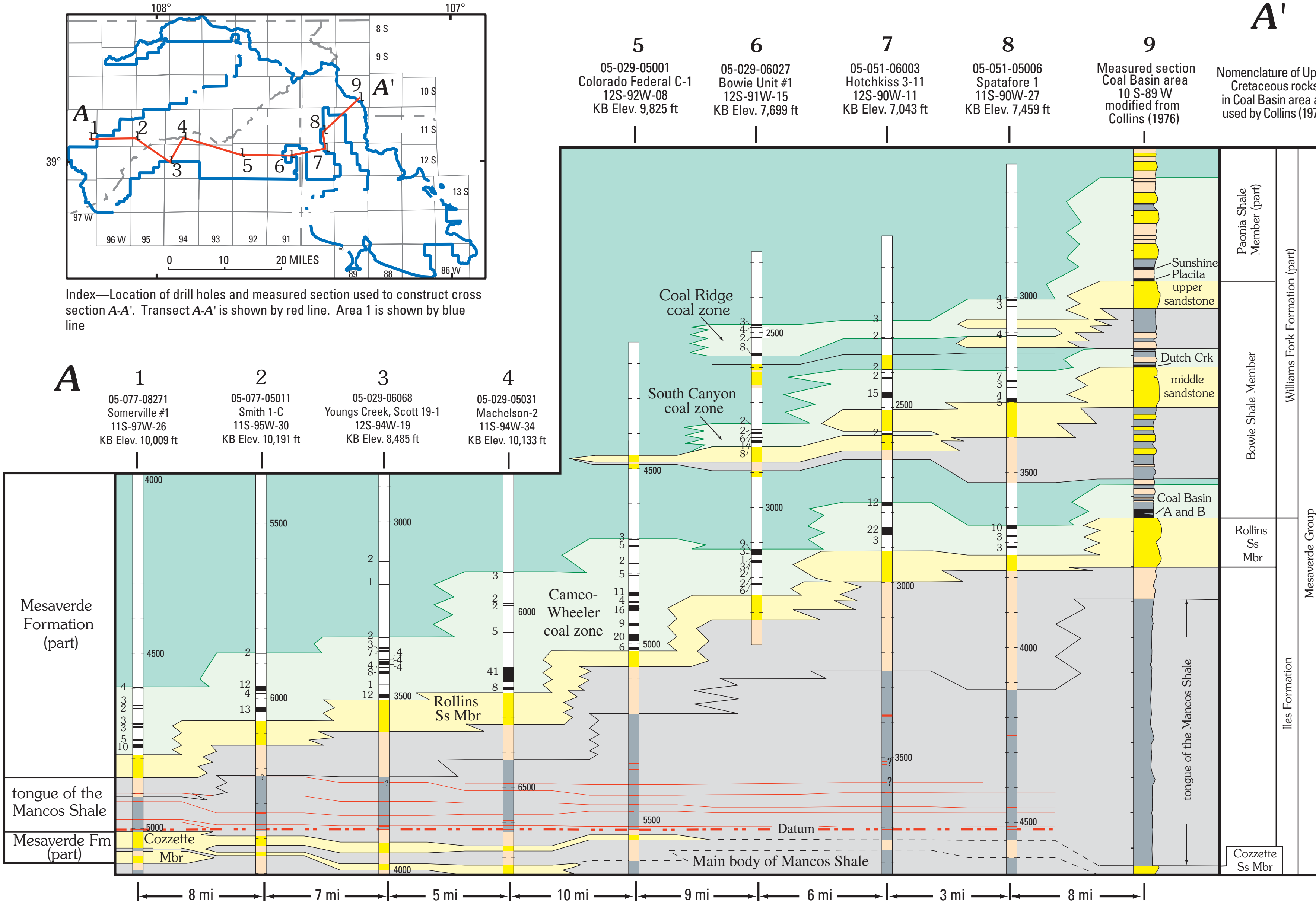


Figure M7 (above and following page). Stratigraphy of continental and marine rocks in the Upper Cretaceous Mesaverde Group and Mesaverde Formation, along cross section *A-A′*, in Area 1. Location of cross section *A-A′* is shown in index.

EXPLANATION

Lithologic and depositional interpretations

Rock type (indicated by color in drill hole column)

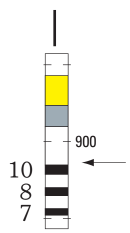
- Sandstone
- Siltstone or interbedded sandstone and mudrock
- Mudrock
- Coal
- **Bentonite**—Queried where uncertain
- **Lithology not interpreted**—Interval does not contain coal

Depositional environments (indicated by background pattern)

- **Coastal plain and alluvial**—Coal zones are light green
- Upper shoreface and estuarine
- Lower shoreface and offshore marine

Drill hole information

2	Drill hole identification number as shown on cross section
05-077-08271	American Petroleum Information (API) number
Somerville #1	Drill hole name
11S-97W-26	Location (township, range, section)
KB Elev. 10009 ft	Drill hole elevation (Kelly bushing)



Columnar section showing selected rock types penetrated by drill hole; down-hole depths are reported in 500 ft intervals on right side of column. Rock types were interpreted from geophysical logs. Thickness of coal (black) is shown in feet on left side of column

Abbreviations

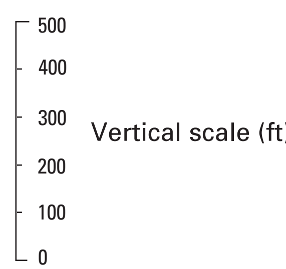
Fm	Formation
Mbr	Member
Ss	Sandstone
Sh	Shale
pt	part

Contacts

- **Facies contact**—Dashed where approximate
- **Facies contact that rises stratigraphically**—Dashed where approximate
- **Datum; dashed where approximate**—Represents a surface of maximum marine transgression
- **Bentonite marker bed**

Scale

4 mi — **Distance between drill holes and measured sections**



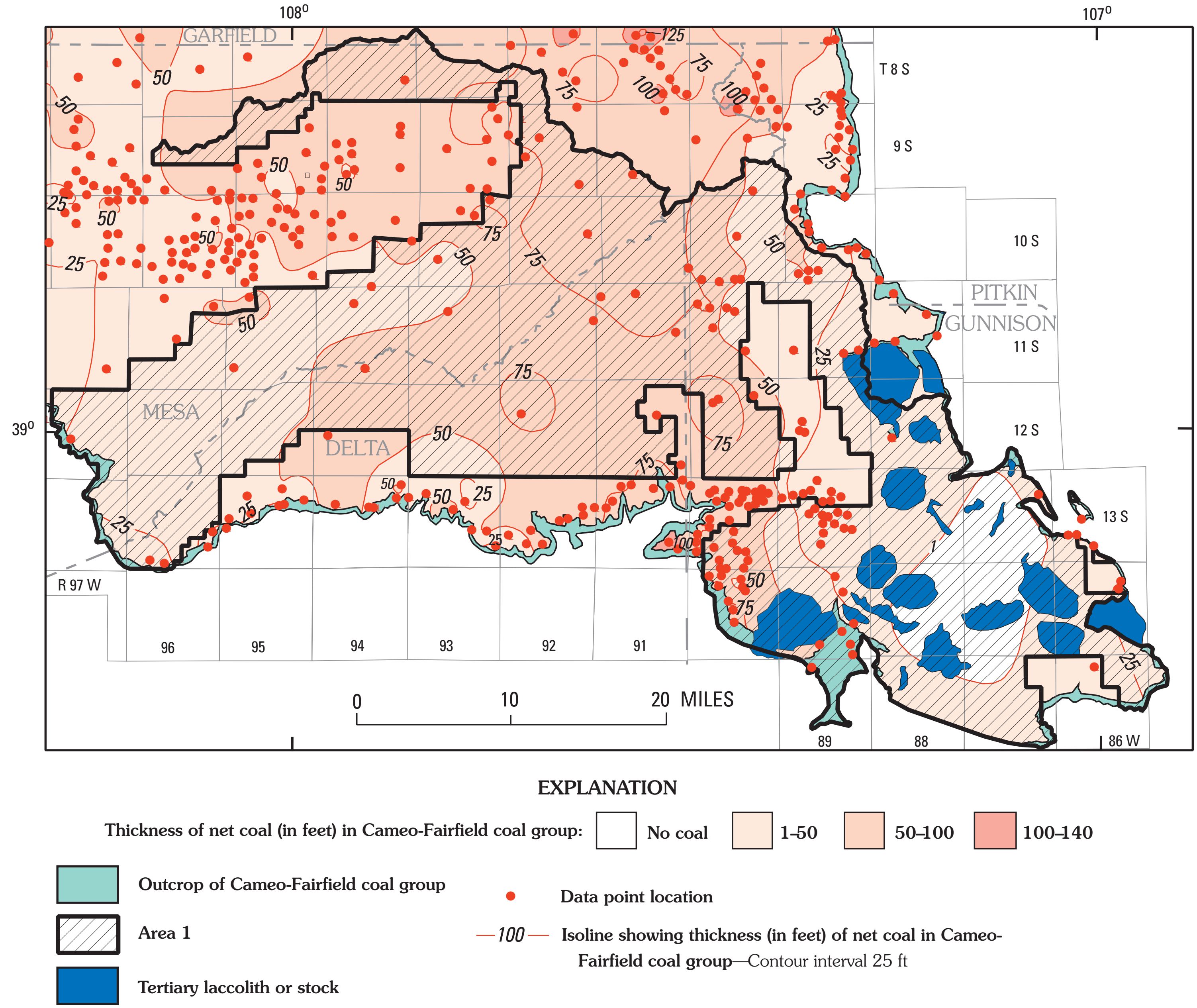
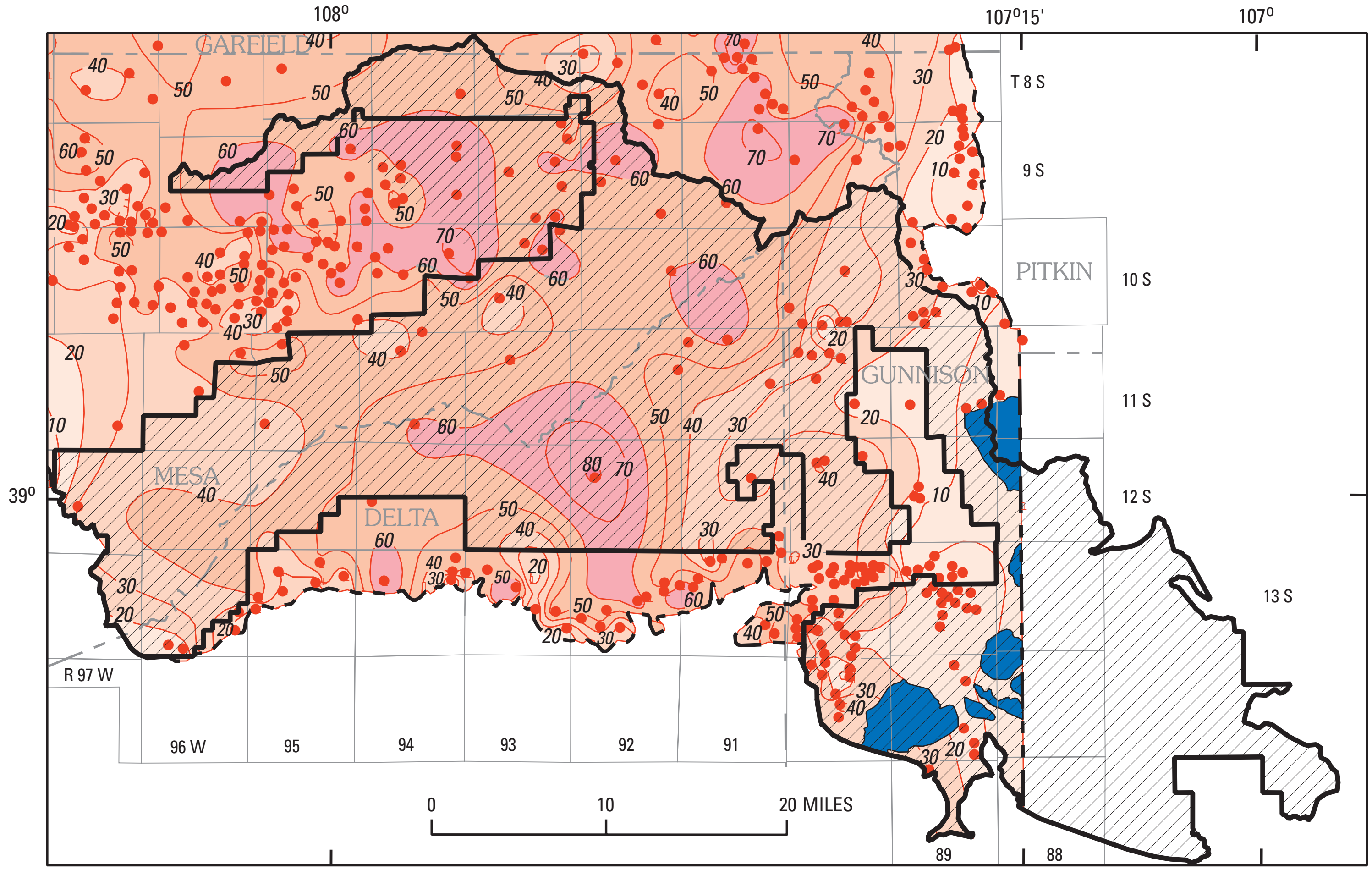


Figure M8. Isopach map of net coal in Cameo-Fairfield coal group in Area 1. Net coal values represent all beds of coal more than 1 ft thick.



EXPLANATION

Range of net coal thickness (in feet): 1–20; 20–40; 40–60; 60–80; 80–90

Boundary of Cameo-Wheeler coal zone

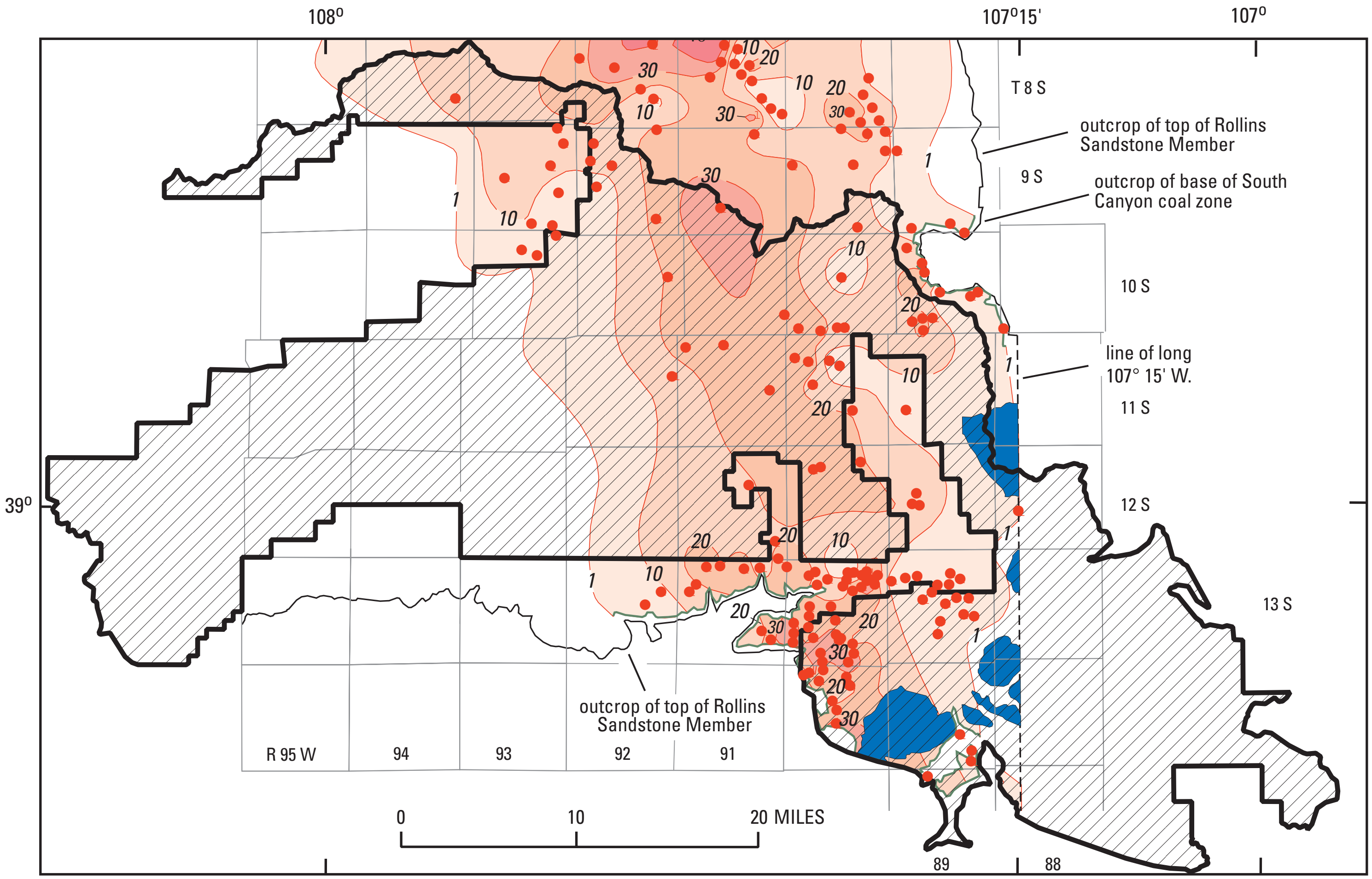
Tertiary laccolith or stock

Area 1

Data point location

40 — Isoline showing net thickness (in feet) of coal beds greater than 1 ft thick in Cameo-Wheeler coal zone—Contour interval 10 ft. Hachured for closed low

Figure M9. Isopach map of net coal in Cameo-Wheeler coal zone in Area 1. Net coal values represent all coal beds more than 1 ft thick. Cameo-Wheeler coal zone is defined only for areas located west of long 107°15′ W.



EXPLANATION

Range of thickness (in feet) of net coal in South Canyon coal zone: No coal; 1–10; 10–20; 20–30; 30–40; 40–50

Tertiary laccolith or stock

Area 1

Outcrop of South Canyon coal zone

Data point location

—10— **Isoline showing thickness of net coal**—Contour interval 10 ft; 1 ft contour also shown

Figure M10. Isopach map of net coal in South Canyon coal zone in Area 1. Net coal values represent all coal beds more than 1 ft thick. South Canyon coal zone is defined only for areas located west of long 107°15′ W.

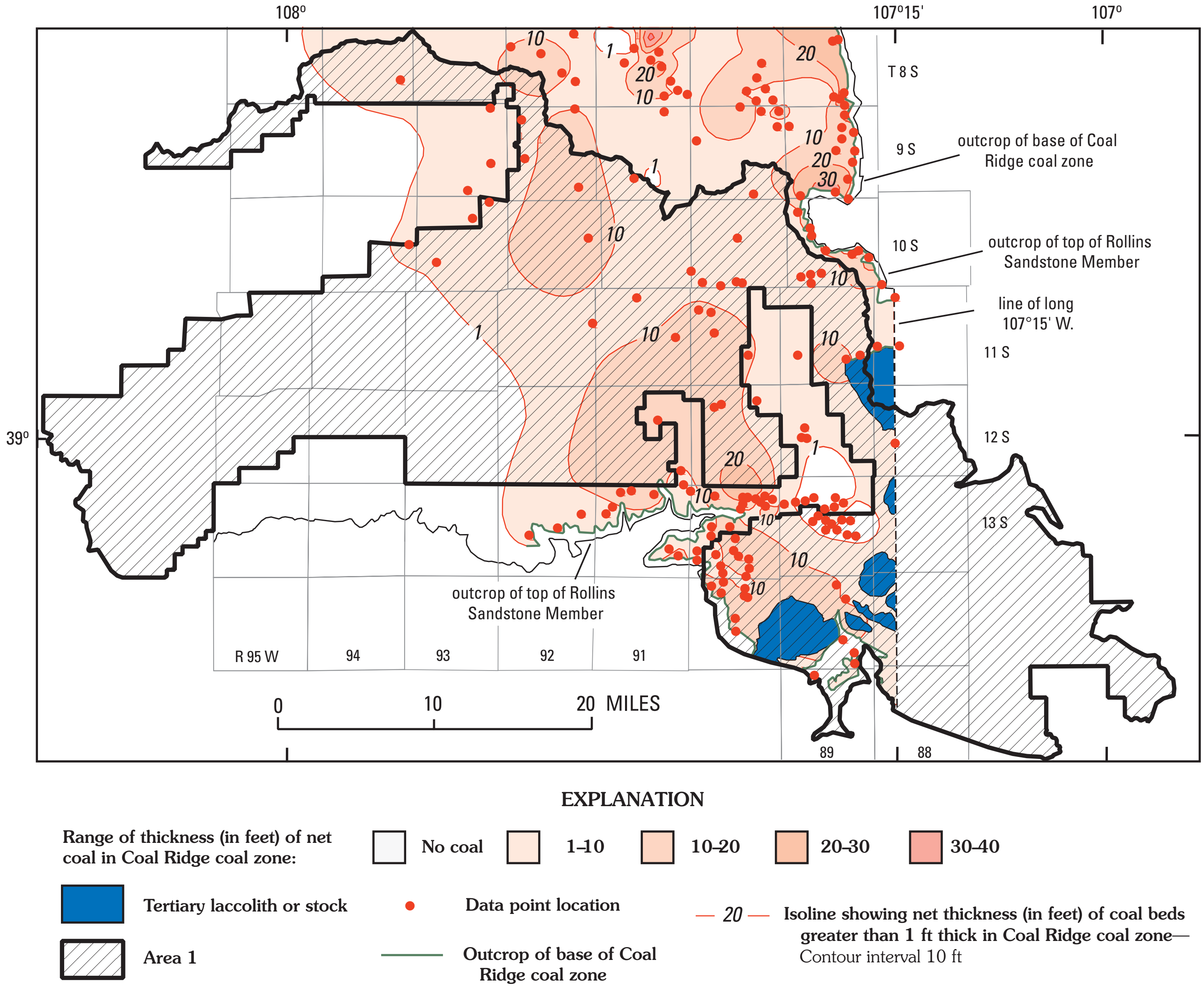


Figure M11. Isopach map of net coal in Coal Ridge coal zone in Area 1. Net coal values represent all coal beds more than 1 ft thick. Coal Ridge coal zone is defined only for areas located west of long 107°15′ W.

Lower, Middle, and Upper Coal Zones (East of Long 107°15′ W.)

East of long 107°15′ W., the Cameo-Fairfield coal group is divided into the lower, middle, and upper coal zones. The collective coal zones have about 1–30 ft of net coal (fig. M12) in one to five beds, and individual beds are 1–25 ft thick.

The lower coal zone overlies a basal marine sandstone that was considered to be equivalent to the Rollins Sandstone Member by Gaskill and Godwin (1966a, 1966b), Godwin (1968), and Gaskill and others (1967, 1986, 1987). The lower coal zone contains only one or two coal beds that were measured locally along outcrops in the Crested Butte coal field. The only important coal in the lower zone is the 0–4.0 ft thick A bed, which is located 7–10 mi south of the town of Crested Butte in the Ohio Creek district (T. 15 S., R. 86 W.) (Gaskill and others, 1987).

The middle coal zone overlies a second marine sandstone that is about 100–200 ft stratigraphically above the Rollins equivalent sandstone. The middle coal zone contains two to six coal beds that range from 1 to 25 ft thick. Included in the middle zone are four beds near the town of Crested Butte; these are bed I (1.5–6.5 ft thick), bed II (5.0–10.0 ft thick), bed III (2.0–25.0 ft thick), and bed IV (0–6.0 ft thick) (Gaskill and others, 1986). Other important beds include the B bed, which is 5.6–8.6 ft thick in the Ohio Creek district, and several unnamed beds that have been mined on Anthracite Mesa in T. 13 S., R. 86 W. (Gaskill and others, 1967).

The upper coal zone is about 300 ft stratigraphically above the Rollins equivalent sandstone, and it contains several lenticular coal beds in the Crested Butte coal field. Important beds include the C bed, which is about 5 to 6 ft thick in the Ohio Creek district, and a 3.5-4.5 ft thick anthracite bed that has been mined 7 mi southwest from the town of Crested Butte (Gaskill and others, 1987).

Coal Quality

The Cameo-Fairfield coal group has an ash yield of 1.9–29.9 percent, a sulfur content of 0.3–3.2 percent, and calorific values of 8,160–15,190 Btu/lb, based on values in the Grand Mesa, Somerset, Carbondale, and Crested Butte coal fields (table M3). The coal has an apparent rank that varies from subbituminous A to anthracite in the southern part of the Piceance Basin (Hornbaker and others, 1976). The coal's apparent rank generally increases to the southeast along the basin's southern and eastern flanks owing to the increase in depth of burial (Johnson, 1989), and it also increases near igneous intrusions owing to local heating (Hornbaker and others, 1976). The apparent rank of coal is subbituminous A to high volatile B bituminous along the basin's southern flank, and high volatile C bituminous to medium volatile bituminous along the basin's eastern flank; some beds have been metamorphosed to semianthracite and anthracite in the Carbondale and Crested Butte coal fields. Coal with coking properties has been identified in the eastern part of the Somerset coal field, the southern part of the Carbondale coal field, and the Crested Butte coal field (Hornbaker and others, 1976; Murray and others, 1977).

Coal Resources

Methods

Coal resources were estimated using the methodology of Wood and others (1983). Coal quantities reported as resources represent, as accurately as data allow, all coal in the ground in beds greater than 1 ft thick and under less than 6,000 ft of overburden. The term "original resource" refers to coal in the ground prior to mining. More deeply buried coal is reported as other occurrences of non-resource coal. This study does not attempt to estimate coal reserves which are that subset of the resource that can be economically produced at the present time. Coal resources were estimated by multiplying the volume of coal by the average density of coal (Wood and others, 1983, p. 36). For this study, we used an average density of 1,800 short tons per acre-ft for bituminous coal.

Coal tonnages were reported within overburden categories of 0–500, 500–1,000, 1,000–2,000, 2,000–3,000, and 3,000–6,000 ft. Overburden was determined by subtracting

Table M3. Ash yield, sulfur content, and calorific values of coal in Cameo-Fairfield coal group in vicinity of Area 1, southern part of the Piceance Basin, Colo.

[Coal field locations are shown in figure M3. Modified from Hettinger and others (2000). Values are based on ranges of proximate and ultimate analyses summarized by Hornbaker and others (1976), Murray and others (1977), and Tremain and others (1996); values in the U.S. Geological Survey USCHEM database provided by R.H. Affolter (written commun., 1998), and include values summarized by Toenges and others (1949, 1952) for the Somerset coal field. Coal from the C.M.C. mine had an ash yield of 23.3 percent and was included in the Book Cliffs coal field by Tremain and others (1996); we included that ash value in the Grand Mesa coal field because the C.M.C mine was located in the Grand Mesa coal field as defined by Landis (1959)]

Coal field	Ash (pct)	Sulfur (pct)	Btu/lb
Grand Mesa	2.1–23.3	0.4–2.2	8,300–13,490
Somerset	2.4–29.9	0.3–3.2	8,160–14,380
Crested Butte	3.2–9.1	0.4–1.9	11,080–14,440
Carbondale	1.9–16.2	0.3–2.1	10,160–15,190

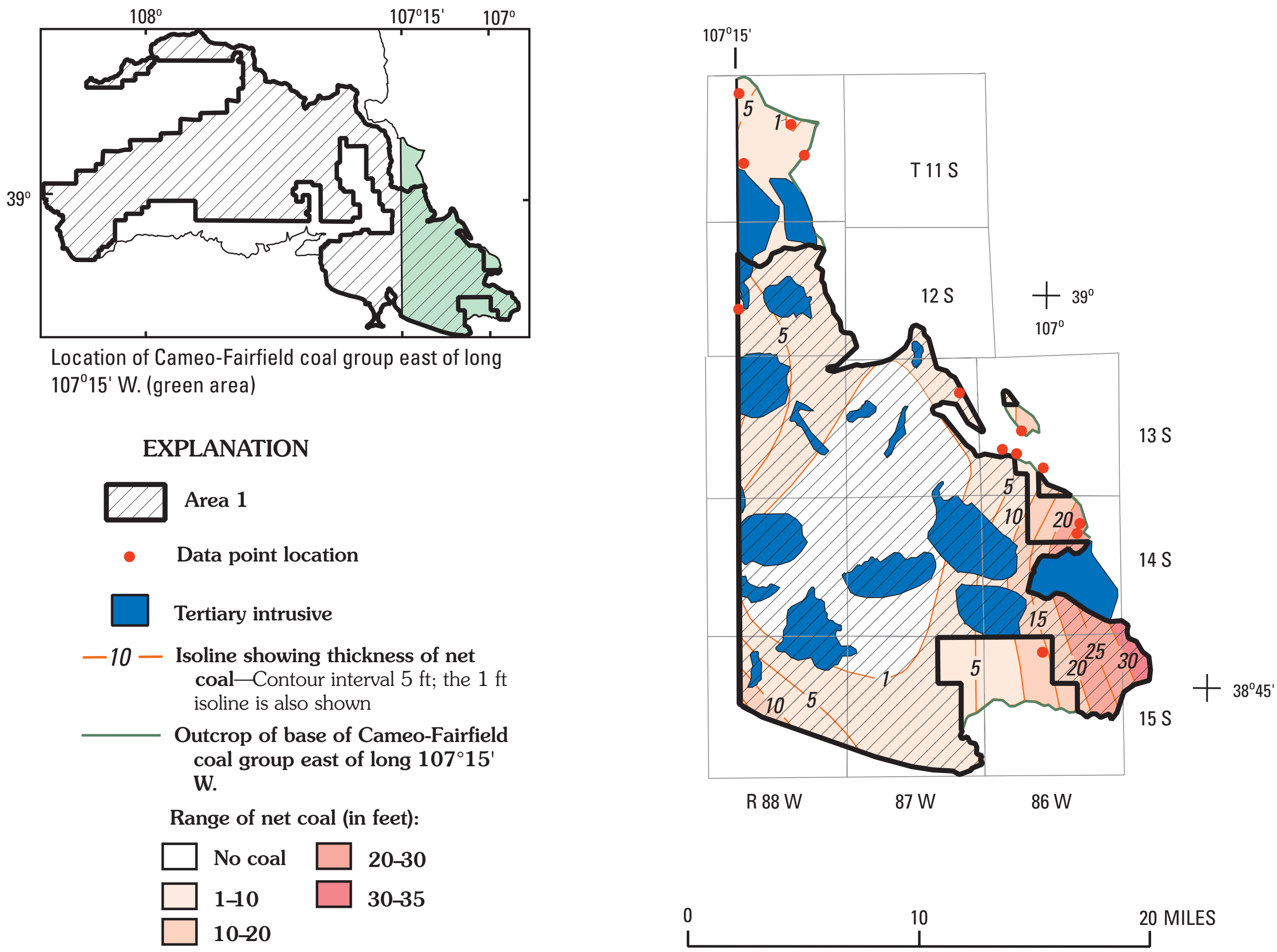


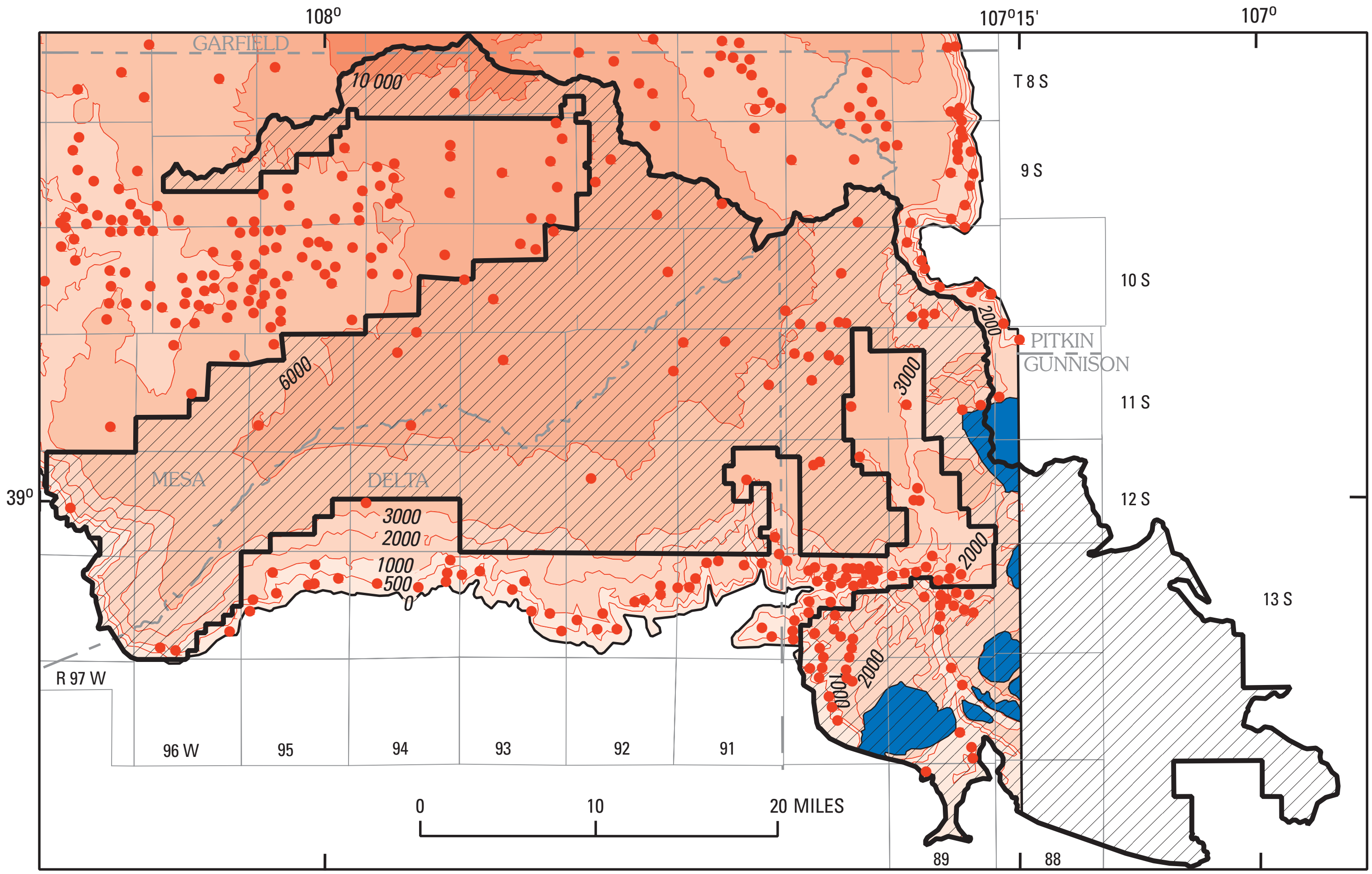
Figure M12. Isopach map of net coal in Cameo-Fairfield coal group east of long 107°15′ W., in Area 1. Net coal values represent all coal beds more than 1 ft thick.

elevations at the base of the specified coal interval from surface elevations; the difference therefore represents the maximum overburden on the specified coal interval. Elevations at the base of the Cameo-Fairfield coal group and Cameo-Wheeler coal zone were determined from a structure contour map of the top of the Rollins Sandstone Member (Hettinger and others, 2000). Similarly, elevations at the base of the South Canyon and Coal Ridge coal zones were determined from structure contour maps that represent the base of those respective coal zones. Maximum overburden thicknesses on the Cameo-Wheeler, South Canyon, and Coal Ridge coal zones are shown in figures M13, M14, and M15, respectively, and the maximum overburden thickness on the base of the Cameo-Fairfield coal group east of long 107°15′ W. is shown in figure M16.

Coal tonnages are also reported by identified and hypothetical reliability categories as defined by Wood and others (1983). Identified resources are located less than 3 mi from a coal measurement (data point), and hypothetical resources are located more than 3 mi from a coal measurement.

Results

Area 1 has an original coal resource of about 38 billion short tons in the Cameo-Fairfield coal group. That resource represents coal beds more than 1 ft thick and under less than 6,000 ft of overburden. The resource figure does not include coal folded over the flanks of laccoliths or buried beneath laccoliths. Approximately 32 percent of the resource is in the Grand Mesa National Forest, and 68 percent of the resource is in the Gunnison National Forest. Area 1 also contains about 34 billion short tons of non-resource coal in the Cameo-Fairfield group that is covered by 6,000–11,500 ft of overburden. Approximately 76 percent of the non-resource coal is in the Grand Mesa National Forest, and 24 percent is in the Gunnison National Forest. Coal tonnages are reported by reliability and overburden categories for each coal zone in the Cameo-Fairfield group where it is located west of long 107°15′ W. (tables M4, M5, and M6, respectively), and tonnages are reported for the entire Cameo-Fairfield coal group where it is located east of long 107°15′ W. (table M7).



EXPLANATION

Range of overburden (in feet): 0–1,000 | 1,000–3,000 | 3,000–6,000 | 6,000–10,000 | >10,000

Tertiary laccolith or stock

Area 1

Data point location

—1000— Isoline showing thickness of overburden—Isolines are labeled at 0, 500, 1,000, 2,000, 3,000, 6,000, and 10,000 ft intervals

Figure M13. Isopach map of overburden on base of Cameo-Wheeler coal zone in Area 1. Cameo-Wheeler coal zone is defined only for areas located west of long 107°15′ W.

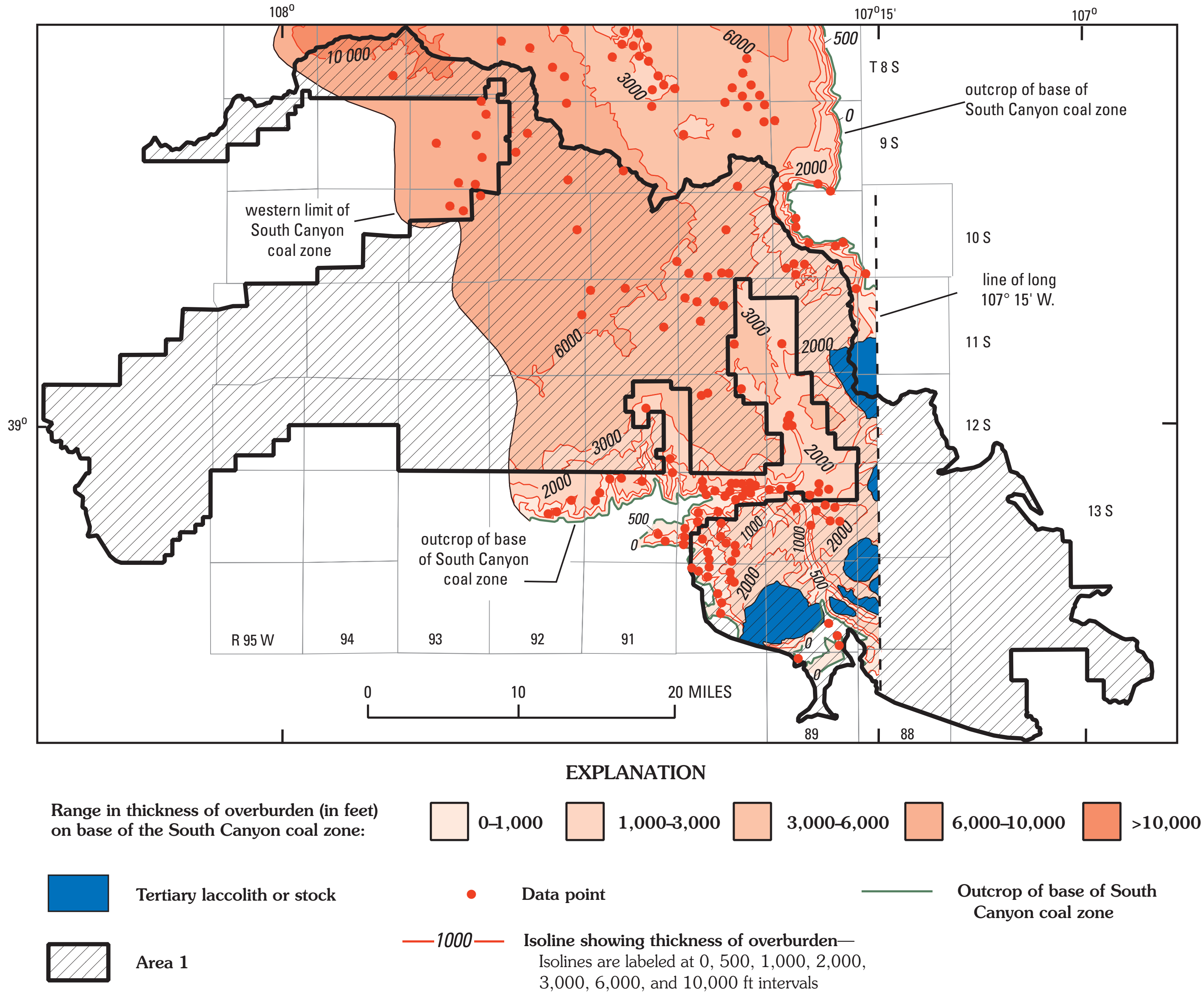


Figure M14. Isopach map of overburden on base of South Canyon coal zone in Area 1. South Canyon coal zone is defined only for areas located west of long 107°15′ W.

Table M4. Original coal resources (*A*) and other occurrences of non-resource coal (*B*) in Cameo-Wheeler coal zone, Area 1.

[Coal tonnages were rounded to two significant figures, and categories that show total tonnage may not equal the sum of the components because of independent rounding]

A. Original coal resources (in millions of short tons) in Cameo-Wheeler coal zone, Area 1.

Forest	Reliability	Overburden (ft)					Total
		0-500	500-1,000	1,000-2,000	2,000-3,000	3,000-6,000	
Grand Mesa	Identified	140	130	420	940	5,500	7,100
	Hypothetical	78	94	290	440	3,900	4,800
Grand Mesa Total		210	220	710	1,400	9,300	12,000
Gunnison	Identified	940	820	2,200	2,600	8,100	15,000
	Hypothetical	80	15	0.058	200	1,800	2,100
Gunnison Total		1,000	830	2,200	2,800	9,900	17,000
Grand Total		1,200	1,100	2,900	4,100	19,000	29,000

B. Other occurrences of non-resource coal (in millions of short tons) in Cameo-Wheeler coal zone at depths greater than 6,000 ft in Area 1.

Forest	Reliability	Overburden (ft)		Total
		6,000-10,000	>10,000	
Grand Mesa	Identified	16,000	790	17,000
	Hypothetical	4,400	450	4,900
Grand Mesa Total		21,000	1,200	22,000
Gunnison	Identified	5,400	0.00	5,400
	Hypothetical	1,300	0.00	1,300
Gunnison Total		6,700	0.00	6,700
Grand Total		27,000	1,200	28,000

Table M5. Original coal resources (*A*) and other occurrences of non-resource coal (*B*) in South Canyon coal zone, Area 1.

[Coal tonnages were rounded to two significant figures, and categories that show total tonnage may not equal the sum of the components because of independent rounding]

A. Original coal resources (in millions of short tons) in the South Canyon coal zone, Area 1.

Forest	Reliability	Overburden (ft)					Total
		0-500	500-1,000	1,000-2,000	2,000-3,000	3,000-6,000	
Grand Mesa	Identified	0.00	0.00	0.00	0.00	0.25	0.25
	Hypothetical	0.00	0.00	0.00	0.47	26	26
Grand Mesa Total		0.00	0.00	0.00	0.47	26	27
Gunnison	Identified	180	350	840	740	2,500	4,600
	Hypothetical	0.2	2.5	20	59	410	490
Gunnison Total		180	350	860	790	2,900	5,100
Grand Total		180	350	860	790	2,900	5,100

B. Other occurrences of non-resource coal (in millions of short tons) in South Canyon coal zone at depths greater than 6,000 ft in Area 1.

Forest	Reliability	Overburden (ft)		Total
		6,000-10,000	>10,000	
Grand Mesa	Identified	2,000	100	2,100
	Hypothetical	300	48	340
Grand Mesa Total		2,300	150	2,500
Gunnison	Identified	1,100	0.00	1,100
	Hypothetical	170	0.00	170
Gunnison Total		1,300	0.00	1,300
Grand Total		3,600	150	3,800

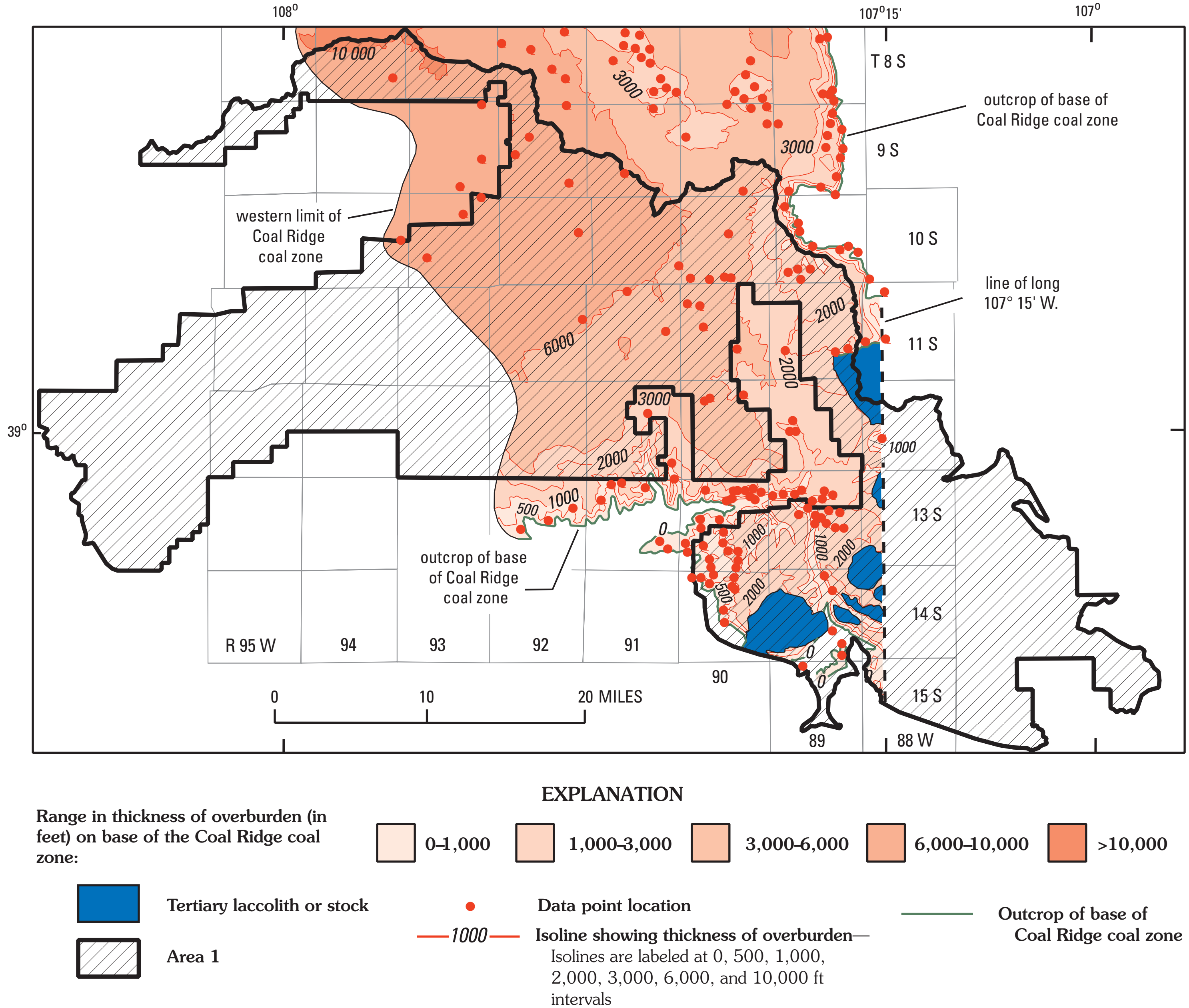


Figure M15. Isopach map of overburden on base of the Coal Ridge coal zone in Area 1. Coal Ridge coal zone is defined only for areas located west of long 107°15′ W.

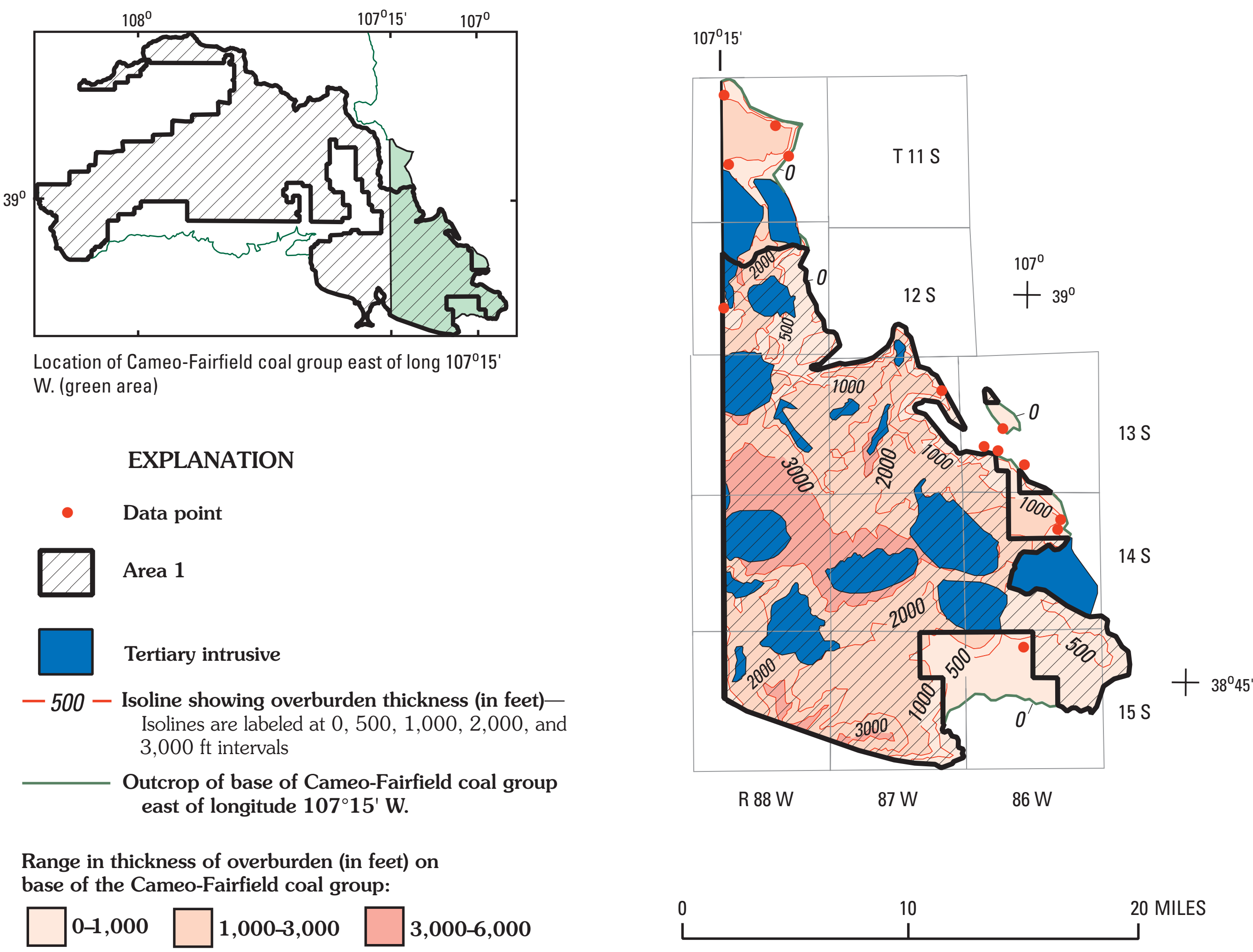


Figure M16. Isopach map of overburden on base of Cameo-Fairfield coal group east of long 107°15′ W., in Area 1.

The large coal resource figure reported for Area 1 must be regarded with caution because it does not reflect economic, land-use, environmental, technological, and geologic restrictions that affect the availability and recoverability of coal. The coal would have to be mined using underground methods, and technological and economical constraints generally limit current longwall mining to (1) depths of less than 3,000 ft, (2) beds more than 3.5 ft thick, and (3) strata inclined by less than 12°; additionally, only about 14 ft of coal can be mined even if the bed is of greater thickness (Timothy J. Rohrbacher, oral commun., 1996). These overburden and bed thickness limits are supported by a summary of 81 longwalls operating in the United States by 30 companies (Merritt and Fiscor, 1995, p. 32–38). Only an estimated 14 billion short tons of coal in Area 1 meets favorable underground mining criteria regarding depth of burial (less than 3,000 ft), and only a fraction of that coal could be mined economically because many beds are either less than 3.5 ft thick or more than 14 ft thick, and because many localities in the vicinity of the Crested Butte and Carbondale coal fields are steeply inclined. Additional coal would also be restricted from mining because it might be in beds that are discontinuous, left in the ground as pillars for roof support, or bypassed due to mining of adjacent strata.

Cameo-Wheeler Coal Zone

The Cameo-Wheeler zone has an original coal resource of 29 billion short tons in Area 1 (table M4*A*). The resource is distributed across 560 mi^2 where the coal is covered by less than 6,000 ft of overburden (fig. M13). Approximately 9.3 billion short tons is under less than 3,000 ft of overburden, and 5.2 billion short tons is under less than 2,000 ft of overburden. The Cameo-Wheeler contains an additional 28 billion short tons of non-resource coal in Area 1 (table M4*B*). The non-resource coal is covered by 6,000–11,500 ft of overburden.

South Canyon Coal Zone

The South Canyon zone has an original coal resource of approximately 5.1 billion short tons in Area 1 (table M5A). The resource is distributed across a 320 mi^2 area where the

Table M6. Original coal resources (*A*) and other occurrences of non-resource coal (*B*) in Coal Ridge coal zone, Area 1.

[Coal tonnages were rounded to two significant figures, and categories that show total tonnage may not equal the sum of the components because of independent rounding]

A. Original coal resources (in millions of short tons) in Coal Ridge coal zone, Area 1.

Forest	Reliability	Overburden (ft)					Total
		0-500	500-1,000	1,000-2,000	2,000-3,000	3,000-6,000	
Grand Mesa	Identified	0.00	0.00	0.00	0.27	0.00	0.27
	Hypothetical	0.00	0.00	0.18	5.8	27	33
Grand Mesa Total		0.00	0.00	0.18	6.1	27	34
Gunnison	Identified	170	230	670	540	1,400	3,000
	Hypothetical	0.96	0.82	0.22	38	330	370
Gunnison Total		170	230	670	580	1,700	3,300
Grand Total		170	230	670	580	1,700	3,400

B. Other occurrences of non-resource coal (in millions of short tons) in Coal Ridge coal zone at depths greater than 6,000 ft in Area 1.

Forest	Reliability	Overburden (ft)		Total
		6,000-10,000	>10,000	
Grand Mesa	Identified	1,200	20	1,200
	Hypothetical	300	11	310
Grand Mesa Total		1,500	31	1,500
Gunnison	Identified	230	0.00	230
	Hypothetical	32	0.00	32
Gunnison Total		260	0.00	260
Grand Total		1,700	31	1,800

Table M7. Original coal resources in Cameo-Fairfield coal group located east of long 107°15′ W., Area 1.

[All of these coal resources are within the Gunnison National Forest. Coal tonnages were rounded to two significant figures, and categories that show total tonnage may not equal the sum of the components because of independent rounding]

Reliability	Overburden (ft)					Total
	0–500	500–1,000	1,000–2,000	2,000–3,000	3,000–6,000	
Identified	160	160	63	51	2.6	440
Hypothetical	160	64	160	100	57	540
Grand Total	320	220	220	150	60	980

coal is covered by less than 6,000 ft of overburden (fig. M14). Approximately 2.1 billion short tons is under less than 3,000 ft of overburden, and 1.4 billion short tons is under less than 2,000 ft of overburden. The South Canyon contains an additional 3.8 billion short tons of non-resource coal in Area 1. The non-resource coal is covered by 6,000–11,200 ft of overburden (table M5B).

Coal Ridge Coal Zone

The Coal Ridge coal zone has an original coal resource of approximately 3.4 billion short tons in Area 1 (table M6*A*). The resource is distributed across 360 mi^2 where the coal is covered by less than 6,000 ft of overburden (fig. M15). Approximately 1.7 billion short tons is under less than 3,000 ft of overburden, and 1.1 billion short tons is under less than 2,000 ft of overburden. The Coal Ridge contains an additional 1.8 billion short tons of non-resource coal in Area 1. The non-resource coal is covered by 6,000–11,000 ft of overburden (table M6*B*).

Coal Resources of the Cameo-Fairfield Coal Group East of Long 107°15′ W.

Area 1 has an original resource of 980 million short tons of coal in the Cameo-Fairfield coal group where it is located east of long 107°15′ W. (table M7). The resource is distributed across 220 mi^2 and is in the lower, middle, and upper coal zones. This resource figure is tenuous because of the complex geology and paucity of coal measurements in the area. Additionally, the resource figure does not include coal that is folded over the flanks of laccoliths or that is buried beneath laccoliths in the region. Maximum overburden on the Cameo-Fairfield coal group east of long 107°15′ W. is shown in figure M16. Approximately 910 million short tons of coal is under less than 3,000 ft of overburden, and 760 million short tons is under less than 2,000 ft of overburden.

Coal Production

About 150 million short tons of coal has been mined since the late 1800's from the Cameo-Fairfield coal group in the Carbondale (southern part), Crested Butte, Grand Mesa (eastern part), and Somerset coal fields. About 99 million short tons was mined in Gunnison County, 30 million tons was mined in Pitkin County, and 21 short million tons was mined in Delta County (Eakins and Coates, 1998). The coal was produced from about 60 mines; the mine areas are shown in figure M17. Mining activity prior to 1977 was compiled by Murray and others (1977), and mining activity from January 1977 to December 1997 was summarized by Hettinger and others (2000). About 83 million short tons has been extracted from 21 mines that operated at various times between January 1977 and December 1997. Only four mines were producing coal at the end of 1997; all four mines are in the Somerset coal field, and they are the Bowie No. 1 (Orchard Valley mine), Bowie No. 2 mine, Sanborn Creek, and West Elk (Mt. Gunnison) mines. In 1997, the Sanborn Creek and West Elk (Mt. Gunnison) mines produced 1.6 million and 5.6 million short tons of coal, respectively.

About 19 mines have produced coal from the Grand Mesa and Gunnison National Forests (fig. M17), and most of the mines are located in the Crested Butte and Somerset coal fields. We did not attempt to determine production from the Grand Mesa and Gunnison National Forests because production records generally reflect operations conducted within and adjacent to the forest lands. Coal production data by Gaskill and others (1986, 1987) show that none of the coal mines in the Crested Butte coal field have operated since the 1950's. Only the West Elk mine in the Somerset coal field was operating within the Gunnison National Forest at the time of this publication.

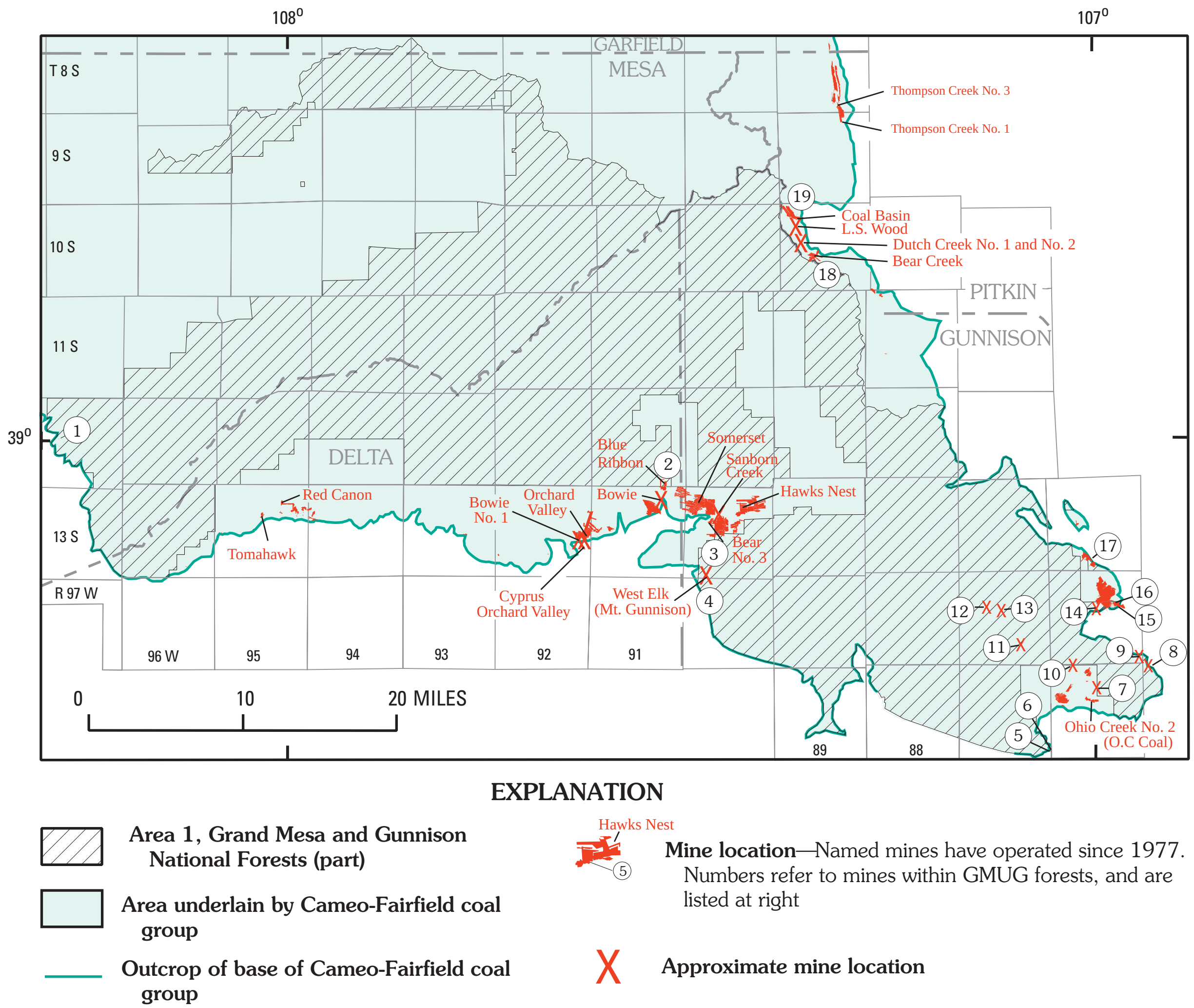
Summary of Coal Resource Potential in the Grand Mesa, Uncompahgre, and Gunnison National Forests

The three GMUG forests are considered to have coal resource potential in areas where underlying strata (1) are likely to have accumulated in a coal-forming environment, and (2) the potential coal-bearing rocks are less than 6,000 ft deep (fig. M18). As summarized in this report, coal-bearing strata are either known or are likely to be in the Dakota Formation, Fruitland Formation, Mesaverde Formation, or Mesaverde Group. Areas of high coal resource potential have nearby outcrop or drill hole data that substantiate the presence of coal. Areas of moderate coal resource potential do not have drill hole or outcrop data to substantiate the presence of coal; however, data in adjacent areas indicate that coal is likely to be present. Areas of low coal resource potential have no information to substantiate the presence of coal; however, the presence of coal is inferred from regional data.

Coal Resource Potential of the Dakota Sandstone in the Grand Mesa and Uncompahgre National Forests

There are two problems in trying to determine the coal resource potential of the Dakota Sandstone. The first problem is that few data are available for Dakota coal in the GMUG forests. The presence of coal in the Dakota must therefore be inferred from adjacent areas where the Dakota has been described. The second problem is that the Dakota Sandstone and underlying Jurassic strata have been mapped as a single unit at many localities in the Gunnison and Uncompahgre National Forests, and presence of the Dakota is not certain in those areas. Based on published geologic maps, the Dakota is definitely present where mapped separately from the underlying Burro Canyon Formation, and it is likely to be present below areas where younger sedimentary rocks have been mapped at the surface.

The GMUG forests have either a moderate, low, or no resource potential for coal in the Dakota Sandstone (fig. M18*A*). The Uncompahgre National Forest has a low to moderate coal resource potential in areas underlain by the Dakota Sandstone. Although few data are available to substantiate the presence of coal in the forest, the occurrence of minable coals outside of the forest (near the towns of Nucla and Norwood) indicates that isolated deposits of minable coal might also be in the forest. The Dakota Sandstone has a low coal resource potential in a small part of the Grand Mesa National Forest. The Dakota is 5,000 and 6,000 ft deep in that area, and its low resource potential is based on outcrop data that show the Dakota to contain a few thin coal beds about 10 mi outside the forest along the Gunnison River. Any Dakota coal that might be present in the Grand Mesa National Forest would not have current mining potential because it is at depths that exceed the physical or economic limits of present-day mining techniques. The Dakota Sandstone has no coal resource potential in the remaining part of the Grand Mesa National Forest because it is more than 6,000 ft deep. Available data indicate that the Dakota does not contain coal where it is exposed in the vicinity of the Gunnison National Forest, and therefore this forest is not considered to have resource potential for Dakota coal.



MAP NUMBER AND NAME OF MINE

1 Kannah Creek
2 Blue Ribbon
3 Bear No. 3
4 West Elk (Mt. Gunnison)
5 Castle Rock

6 Hinkle
7 K-D (Kozy Draw); S.L. Staples & Son
8 Comstock
9 Robinson (Kochevar)
10 Richardson; Richardson Coal Co.; Mt. Carbon Anthracite Coal Co.; Gomer Dollard and Weaver Brothers

11 Mt. Carbon Anthracite Coal Co., Ohio Creek-Anthracite Coal Co., and W. Hinds
12 Ruby-Anthracite (Floresta No. 1); Caledonia Fuel Co., Union Pacific Coal Co., and Colorado Fuel and Iron Co.
13 Unknown
14 Wheatstone
15 Verzuh

16 Crested Butte, Bulkley No. 1 and 2, and Porter
17 Peanut, Elk Mountain, and Horace
18 Bear Creek
19 Coal Basin

Mines that have produced coal from the GMUG forests. Mines are located by numbers shown on map.

Figure M17. Location of coal mines that have produced from Cameo-Fairfield coal group in vicinity of Area 1. Mines that have produced coal since 1977 are named in red type. Mines that became inactive prior to 1977 are not named. Mines that have operated within the forest are shown in list.

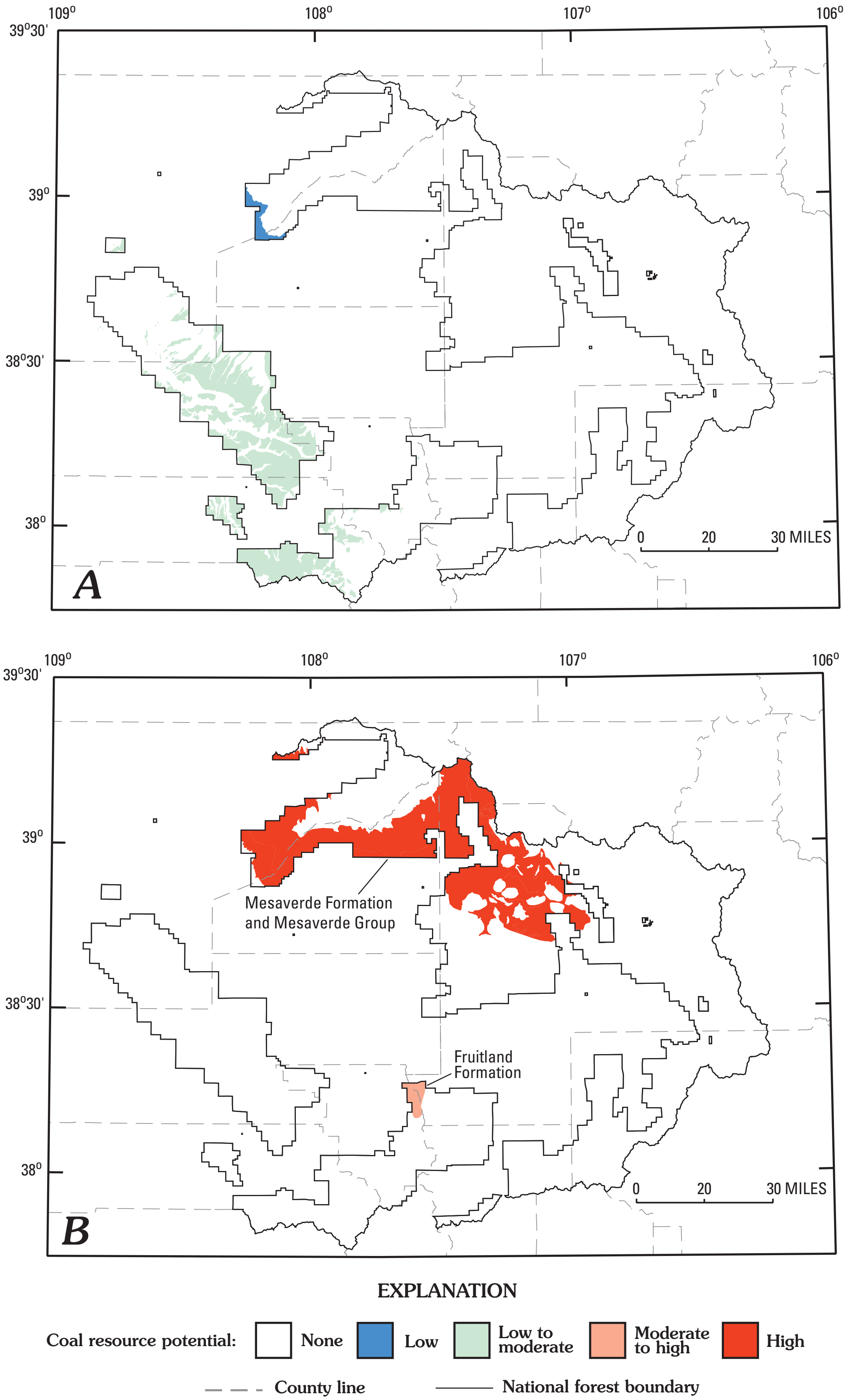

109°
108°
107°
106°
39°30'
39°
38°30'
38°
0
20
30 MILES
A
B
Mesaverde Formation
and Mesaverde Group
Fruitland
Formation
EXPLANATION
Coal resource potential:
None
Low
Low to moderate
Moderate to high
High
County line
National forest boundary

Figure M18 (previous page). Coal resource potential in Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests. GMUG forests are identified in figure M1. *A*, Coal resource potential for GMUG forest areas underlain by the Dakota Sandstone. *B*, Coal resource potential for GMUG forest areas underlain by the Fruitland Formation, Mesaverde Formation, or Mesaverde Group. GMUG forest areas intruded by volcanic rock were not assessed.

Coal Resource Potential of the Fruitland Formation in the Uncompahgre National Forest

The Uncompahgre National Forest has a moderate to high resource potential for coal where it is underlain by the Fruitland Formation in the Tongue Mesa coal field (fig. M18*B*). The area is given a high resource potential because it is known to contain thick beds of subbituminous coal; the area is also assigned a moderate resource potential because coal bed continuity could not be determined, owing to poor exposure and structural complexities. Coal beds were mined locally in the Tongue Mesa coal field between the 1890’s and 1940’s (Dickinson, 1987a, 1987b, 1988), and there has been some interest to develop the coal since that time (Hornbaker and others, 1976; Dickinson, 1987a, 1987b, 1988). Although the area has a moderate to high resource potential, Hornbaker and others (1976) thought that the coal in the Tongue Mesa area could not compete with better coal in the Somerset field.

Coal Resource Potential of the Mesaverde Group and Mesaverde Formation in the Grand Mesa and Gunnison National Forests

The Grand Mesa and Gunnison National Forests have a high coal resource potential where the Cameo-Fairfield coal group is at depths of less than 6,000 ft (fig. M18*B*). This regionally extensive coal group is in the Mesaverde Group and Mesaverde Formation; it contains as much as 97 ft of net coal, and has individual coal beds as thick as 30 ft within the forest areas. Cameo-Fairfield coal has been mined at several coal fields located in and adjacent to the forests. About 150 million short tons has been produced since the late 1800’s, and the West Elk mine is currently operating in the Gunnison National Forest.

The area of high coal resource potential in the Grand Mesa and Gunnison National Forests (fig. M18*B*) is estimated to contain about 38 billion short tons of coal in the Cameo-Fairfield coal group, as determined for Area 1 in this study. This large resource figure does not represent minable reserves, which are a subset of the resource that could be economically produced at the present time. Coal in the Cameo-Fairfield would have to be mined using underground methods, and technological and geologic restrictions preclude much of the resource from being economically mined. For example, only 37 percent of the coal resource is at depths (less than 3,000 ft) favorable for longwall mining. Some coal would be precluded from mining because the beds are too thin, thick, or steeply inclined. Additional coal would also be restricted from mining because the beds might be discontinuous, left in the ground as pillars for roof support, or bypassed due to mining of adjacent strata.

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Potential Aggregate Resources

By Daniel H. Knepper Jr., and Viki Bankey

Chapter N of

Resource Potential and Geology of the Grand Mesa, Uncompahgre, and Gunnison (GMUG) National Forests and Vicinity, Colorado

Edited by Viki Bankey

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By Daniel H. Knepper, Jr., and Viki Bankey

Abstract

This chapter presents the results of potential aggregate resources that are suitable for use in asphaltic and Portland cement concrete, evaluating both the exposed bedrock and the unconsolidated sedimentary deposits. A limited assessment of landslide hazards for Mancos Shale, Brushy Basin Member of the Morrison Formation, Wasatch Formation, and sedimentary deposits identified as landslide-produced is also included herein.

Introduction

Almost any rock or unconsolidated deposit can be used by the construction industry for some purpose, such as back fill or road base. However, the specifications for aggregate used in asphaltic concrete or Portland cement concrete are extremely high and rigid, and the material used for aggregate must pass specific tests of the American Society for Testing and Materials (2000). The consequences of the rigid ASTM tests are that even in a region rich with fresh, exposed bedrock and sand and gravel deposits such as western Colorado, the amount of potential concrete aggregate may be substantially less than might be presumed.

Because aggregate that meets specifications for concrete applications is also useful for most other construction applications, this study deals exclusively with the assessment of potential aggregate sources that are suitable for use in asphaltic and Portland cement concrete.

Aggregate Sources

Two primary sources of potential concrete aggregate exist: bedrock and gravel. Both boulders and large cobblestones from bedrock or gravel can be crushed to form appropriately sized aggregate particles. In fact, aggregate for use in asphaltic concrete must be composed of particles that have all fractured surfaces. Crushed stone is the major source of natural aggregate in the eastern United States, and it is becoming more and more important in the West as available supplies of alluvial sand and gravel are depleted or otherwise preempted by urbanization and other alternative land uses. Appropriately sized gravel particles obtained by screening and washing of alluvial gravel deposits are preferred for use in Portland cement concrete, but crushed stone can be used as well.

Both the exposed bedrock and the unconsolidated sedimentary deposits in the GMUG greater study area were evaluated for potential suitability as a natural aggregate resource, and maps were prepared showing the distribution of these potential resources (figs. N1, N2).

Evaluating and Modeling Potential Aggregate Resources

There is no substitute for a geologist standing on an outcrop for evaluating the physical and chemical properties of a rock unit or gravel deposit for its potential as a natural aggregate resource. Nevertheless, a great deal about the quality of a potential resource can be inferred from the lithology and age of the deposit alone (Langer and Knepper, 1998). For example, lithologic units composed primarily of shale, siltstone, salt or gypsum, or friable sandstone most likely do not have the hardness and durability required for high-quality aggregate. Similarly, pebbles, boulders, and cobbles in gravel deposits of Tertiary age in the GMUG greater study area are commonly highly weathered and crumble under a minimum of stress. Silicic volcanic and shallow intrusive rocks, although having excellent physical properties for natural aggregate, are highly likely to contain microcrystalline quartz (cristobalite, tridymite) that reacts adversely with the alkali in Portland cement and significantly weakens the resulting concrete. Langer and Knepper (1998) presented a more complete description of the common rock types that in many places provide suitable natural aggregate. Their report also described the general physical and specific deleterious chemical properties of common rocks

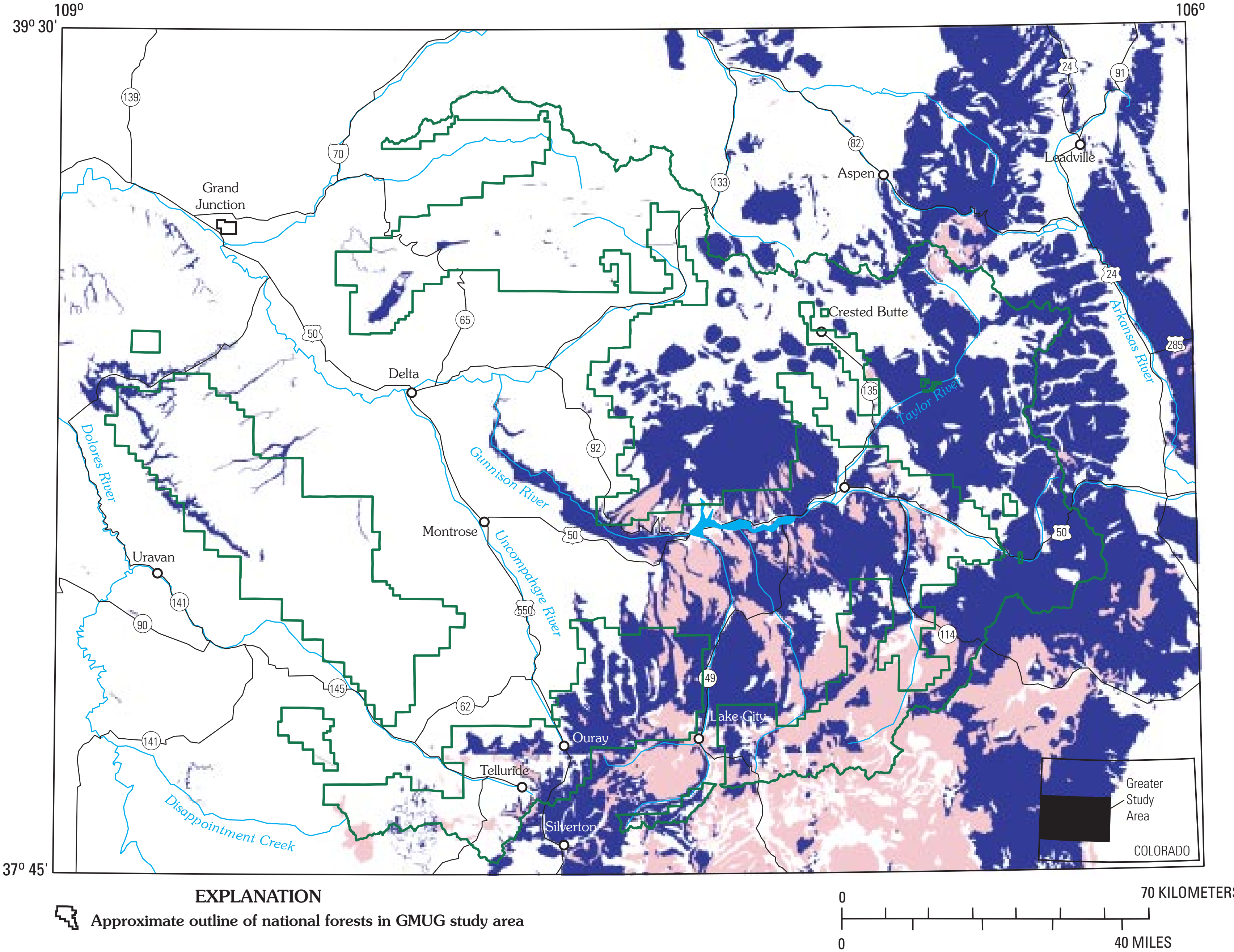

Figure N1. GMUG greater study area, showing quality and location of bedrock aggregate resources. Pink, satisfactory, deleterious; blue, satisfactory, innocuous.

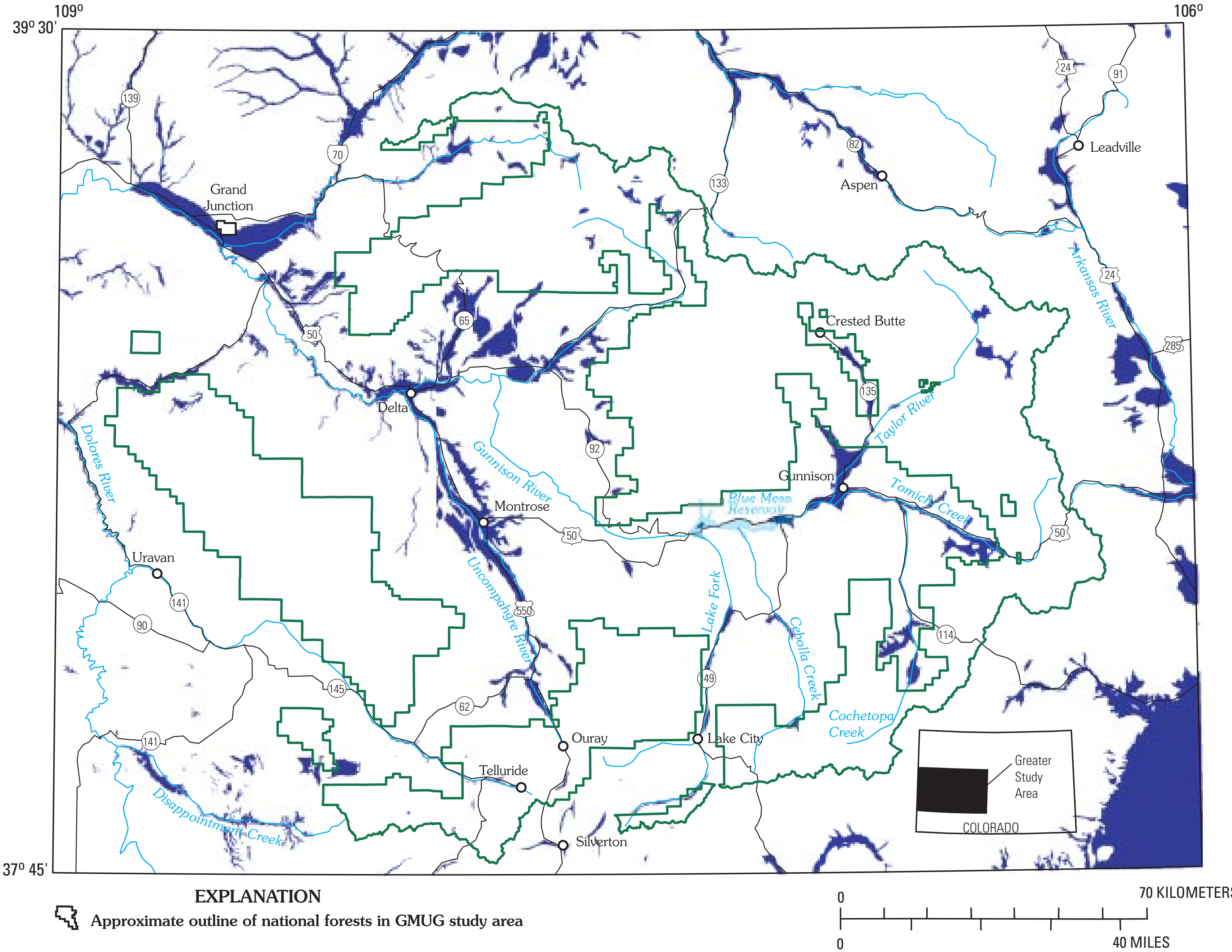

Figure N2. GMUG greater study area, showing quality and location of unconsolidated aggregate resources. Blue, satisfactory, innocuous.

and minerals that should be considered in evaluating potential natural aggregate resources.

Using the lithologic and mineralogic criteria of Langer and Knepper (1998), each of the map units on the geologic map of the GMUG greater study area (Day and others, 1999) was rated for its physical and chemical properties as a potential natural aggregate source, drawing heavily on a previous rating of each map unit on the geologic map of Colorado (Knepper and others, 1999). Physical properties were rated either satisfactory, fair, poor, or unsuitable. Based on the ratings of the lithologic units, a simple model was constructed to identify potential sources of natural aggregate in the GMUG greater study area.

Figure N1 shows the results for bedrock, where pink areas show potential aggregate sources that are satisfactory and deleterious, and blue areas show potential aggregate sources that are satisfactory and innocuous. Figure N2 shows similar results for unconsolidated material. No areas fit the satisfactory and deleterious category; blue areas show potential aggregate sources that are satisfactory and innocuous. Table N1 lists areas of modeled results, in square miles.

Limited Assessment of Landslide Hazards for Four Geologic Units

At the request of the USDA Forest Service, a limited assessment of landslide hazards was generated by calculating slope from topographic data and combining it with the geologic data set (Day and others, 1999). The four geologic units selected for this limited assessment were Mancos Shale, Brushy Basin Member of the Morrison Formation, Wasatch Formation, and sedimentary deposits identified as landslide-produced. These were chosen because they are known to cause landslide problems in the study area.

Figure N3 shows the results of the limited assessment of landslide hazards. A combination of color and intensity is used to display information about geologic unit and slope. Mancos Shale is shown in shades of red/pink, Brushy Basin Member in shades of blue, Wasatch Formation in green, and landslide sediments in yellow/gold. Darker colors indicate steeper slopes, ranging from 15° to 20° for light colors, from 20° to 25° for medium colors, and greater than 25° for darkest colors.

Table N1. Areas calculated for bedrock and unconsolidated material for potential aggregate sources.

[Total area includes all public and private lands; forest area includes only area within the Grand Mesa, Uncompahgre, and Gunnison National Forests; BLM area includes only area managed by the Bureau of Land Management. Areas rounded to the nearest whole number]

	Total area (mi^2)	Forest area (mi^2)	BLM area (mi^2)
GMUG study area, no model	19,800	4,868	5,092
Bedrock—satisfactory, deleterious	1,450	335	347
Bedrock—satisfactory, innocuous	4,681	1,636	736
Unconsolidated—satisfactory, deleterious	0	0	0
Unconsolidated—satisfactory, innocuous	1,313	38	146

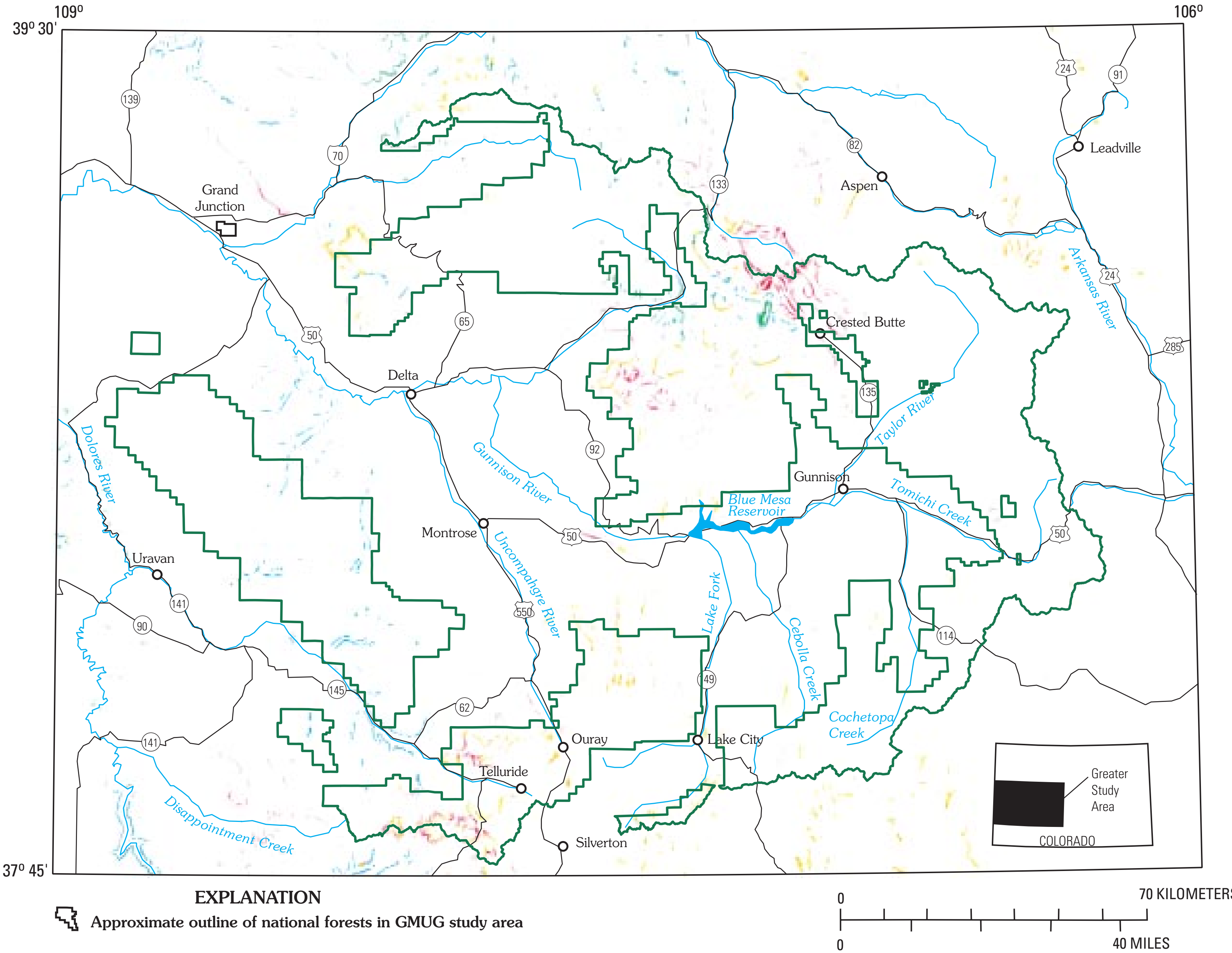

Figure N3. GMUG greater study area, showing some potential areas of landslide risk. Red/pink, Mancos Shale; yellow/gold, landslide sediments; blue, Brushy Basin Member of Morrison Formation; green, Wasatch Formation. Darker values of the same color indicate steeper slopes.

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