USGS
science for a changing world

Mineral Resource Potential and Geology of the Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest, Colorado

U.S. Geological Survey Professional Paper 1610

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

Mineral Resource Potential and Geology of the Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest, Colorado

Edited by Viki Bankey, Sandra J. Soulliere, *and* Margo I. Toth
U.S. Geological Survey

With a section on Salable Minerals

By John S. Dersch
U.S. Forest Service

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1610

Supersedes U.S. Geological Survey Open-File Report 96-82

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 2000

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

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

Library of Congress Cataloging-in-Publication Data

Mineral resource potential and geology of the Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest, Colorado / edited by Viki Bankey, Sandra J. Soulliere, Margo I. Toth ; with a section on Salable Minerals by John S. Dersch.
p. cm. — (U.S. Geological Survey professional paper ; 1610)
Includes bibliographical references.
1. Mines and mineral resources—Colorado—Arapaho National Forest.
2. Geology—Colorado—Arapaho National Forest. I. Bankey, Viki. II. Soulliere, Sandra J. III. Toth, Margo I. IV. Series.

TN24.C6 M56 2000
553′.09788′65—dc21

99-056293
CIP

CONTENTS

PLATE

[Plate is in pocket]

FIGURES

TABLES

Mineral Resource Potential and Geology of the Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest, Colorado

Edited by Viki Bankey, Sandra J. Soulliere, *and* Margo I. Toth

With a section on SALABLE MINERALS

By John S. Dersch
U.S. Forest Service

SUMMARY

The assessment of the mineral resource potential of the Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest, Colorado (referred to as "the Forest" in this report) was made to assist the U.S. Forest Service in fulfilling the requirements of Title 36, Chapter 2, part 219.22, Code of Federal Regulations, and to supply resource information so that the mineral resources of the Forest can be considered along with other resources in land-use planning. The Middle Park Ranger District of the Arapaho National Forest is included in this report on the Routt National Forest because the two areas are administered by the staff of the Routt National Forest and are included in a single planning document.

This report discusses the potential for as yet undiscovered mineral and energy resources within the Forest. All available information regarding mineral deposits or occurrences and energy resources, as of June 1994, was assembled to assess the mineral and energy potential. Geological maps were compiled at a scale of 1:250,000 (plate 1). Mineral and energy potential maps were also created for deposit types within the Forest.

Although most of the Forest is north of the productive Colorado Mineral Belt, the Forest has a history of mineral exploration and some mining development. The molybdenum mine at Henderson is located just outside the southeastern boundary of the Forest, and the Northgate district, in the northeastern part of the Forest, was an important producer of fluorspar. Deposits of gold, silver, lead, zinc, copper, fluorspar, uranium, and vanadium have been exploited from mines and prospects within the Forest. Some production of the industrial minerals mica, vermiculite, crushed and lightweight aggregate, and sand and gravel has also occurred. Coal beds and oil and gas reservoirs have been identified within and adjacent to the Forest, and geothermal waters from hot springs in the area have been used for recreational purposes.

CHARACTER AND GEOLOGIC SETTING

The Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest cover about 1.2 million acres in north-central Colorado. Seven mountain ranges and parts of six counties are within the Forest. The Forest consists primarily of forested land at higher elevations separated by rolling hills, sage-covered valleys, and broad meadows. Elevations range from about 6,800 ft at Mad Creek to more than 12,900 ft at Clark Peak in the Medicine Bow Mountains. Within the Forest, the Continental Divide trends north-south through the Park Range, turns east-west to follow the crestline of the Rabbit Ears Range, and then turns southward toward the Vasquez Mountains in the southern part of the Forest. North- and east-flowing streams drain into the Platte River, and south- and west-flowing streams drain into the Colorado River.

The geology of the Forest varies considerably in age and character; rocks range in age from nearly 2-billion-year-old granitic and mafic intrusive and metamorphic rocks to modern stream gravels (see geologic time chart in Appendix 1). In the northwestern part of the Forest, the Elkhead Mountains contain Upper Cretaceous through Tertiary sedimentary rocks crosscut by Upper Tertiary intrusions, dikes, and sills. Within this area, the Miocene Hahns Peak stock has particular importance because ore has been mined from the surrounding breccia (Gale, 1906; Vanderwilt, 1947). Small patches of volcanic lava flows and breccias also overlie the sedimentary rocks locally.

The central part of the Forest consists of a north-trending belt of mountains that includes the southern part of the Sierra Madre Mountains, the Park Range, and the northern part of the Gore Range. The core of these ranges is made up of Proterozoic metamorphic and granitic rocks, whereas the flanks of the ranges are composed of Paleozoic sedimentary rocks. The Sierra Madre Mountains and the Park Range consist of Proterozoic gneisses, amphibolite, migmatite, and younger mafic and granitic plutons. The northern Gore Range consists mainly of Proterozoic granite with isolated outcrops of Paleozoic sedimentary rocks.

The northeastern part of the Forest is in the Medicine Bow Mountains, and the rocks are mainly Proterozoic granite and hornblende gneisses. Just outside the Forest boundary in this area, the Independence Mountain thrust fault separates Paleozoic and Tertiary sedimentary rocks from the Proterozoic rocks. At the southern extension of the range, the Never Summer Mountains consist of Proterozoic biotite gneiss and migmatite intruded by shallow-level Tertiary stocks and dikes. Tertiary sedimentary rocks are exposed west of the Never Summer thrust fault.

West of the Never Summer Mountains, the Rabbit Ears Range separates the North Park Basin from the Middle Park Basin. In the Rabbit Ears Range, Tertiary sedimentary and volcanic rocks are intruded by small Tertiary intermediate-composition porphyries.

The southeastern part of the Forest includes parts of the Williams Fork and Vasquez Mountains. These ranges are primarily Proterozoic granitic rocks and gneisses with Tertiary sedimentary rocks exposed in the valley between the ranges. Faulting is prevalent in this area and cuts across all rock types. The Williams Fork thrust fault at the western boundary of the Forest juxtaposes Proterozoic granite and gneiss over Cretaceous sedimentary rocks.

MINERAL RESOURCES

In this report, mineral resource information is given in terms of mineral deposit types and their geologic settings. Mineral deposit types are defined by geologic characteristics of known deposits that may occur within or near the Forest. Each deposit type may be represented by a known mine or mining district. For the discussion that follows, each mineral deposit type has been assigned a letter designation (A, B, or C, etc.) for distinction on figures and tables within the text. Definitions of terms used in the assessment of potential are summarized in Appendix 2. All available information was assembled and analyzed according to the procedures outlined by Shawe (1981) and Taylor and Steven (1983). This study is based primarily on information from published sources but also includes unpublished data from previous studies.

The Forest contains several mines and mining districts and includes part of the productive Colorado Mineral Belt. No major quantities of metallic minerals have been produced from mines within the Forest (Neubert, 1994). Minor production occurred from the late 1800's though the early 1970's, and exploration for metals continues today. Areas within the Forest displaying substantial evidence of metallic mineralization, but only minor production, include the Hahns Peak, Pearl, Teller, and La Plata-Dailey mining districts, the Greenville mine area, and the Parkview and Poison Ridge intrusive centers (Neubert, 1994).

Three areas within or adjacent to the Forest have records of major production. The Northgate district, an important fluorite producer, is in the northeastern part of the Forest. This area was the second largest producer of fluorite in Colorado and accounted for approximately 32 percent of the total fluorspar production in Colorado before it closed in the early 1970's (Brady, 1975). To the southwest of Northgate, the Crystal district also produced fluorite until the 1970's. The Henderson mine, located just outside the southeastern part of the Forest, was a major producer of molybdenum.

ENERGY RESOURCES

Areas in the Forest underlain by Paleozoic through Tertiary sedimentary rocks have been explored intermittently for oil and gas since 1928. Three oil fields have been discovered in the Elkhead Mountains and Flat Tops area. Although no coal production has been recorded from the Forest, major mines operate near the Forest, and parts of two major coal fields extend into the Forest. Geothermal springs are known in the town of Steamboat Springs and several miles to the north at Strawberry Park Hot Springs.

UNDISCOVERED MINERAL AND ENERGY RESOURCES

Mineral and energy resources are classified into three types: locatable, leasable, and salable. Tables 1 and 2 summarize the mineral potential for each area. Figure 1 shows areas of potential for all locatable minerals, and figure 2 shows areas of potential for all leasable minerals.

LOCATABLE MINERALS

Locatable minerals include most metals and industrial minerals categorized by the General Mining Law of 1872. Ten principal types of deposits of locatable minerals were considered in this assessment and are listed below and in tables 1 and 2. Each summary of the deposit type includes a brief description of the geologic setting and associated metals, and the location of principal areas favorable to host these resources. Each deposit type is assigned a letter designation for distinction on figures and tables within this report.

A. *Stockwork molybdenum.*—Formed in the upper parts of granite bodies and in adjacent country rock; deposits are valuable mainly for molybdenum but also contain tungsten, tin, and bismuth. The area around Hahns Peak and a small area in the Never Summer Mountains have high potential for molybdenum in small stockwork deposits. An elongate area in the southeastern part of the Forest, near the Henderson mine, has moderate potential for undiscovered small stockwork deposits of molybdenum.

B. *Porphyry copper-molybdenum.*—Formed in shattered portions of granitic intrusions and surrounding country rock; deposits contain copper and molybdenum with byproduct gold, tungsten, and tin, and traces of silver, lead, and zinc. Two small areas in the Rabbit Ears Range have high potential for stockwork copper-molybdenum deposits. A large east-west-trending area, consisting of several shallow plutons, along the crest of the Rabbit Ears Range has moderate potential for stockwork copper-molybdenum.

C. *Polymetallic veins*.—Related to Proterozoic(?), Laramide, and Tertiary igneous activity; deposits contain lead, zinc, silver, copper, and gold with minor molybdenum, tin, tungsten, bismuth, and antimony. Major areas favorable for this deposit type include the Williams Fork Mountains area, the northern part of the Park Range, and the Never Summer Mountains in the eastern part of the Forest.

D. *Massive sulfides.*—Deposited in volcanic and sedimentary rocks in a marine environment during Proterozoic time; later metamorphism converted the volcanic and sedimentary rocks to amphibolite, calc-silicate, and felsic gneisses. These deposits contain lead, zinc, silver, copper,

Table 1. Resource potential of lands in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado, classified according to type of deposit.

[The Routt National Forest and Middle Park Ranger District of the Arapaho National Forest contain a total of about 2,028 mi^2. Figures in columns under each category of resource potential are in mi^2 and are rounded to the nearest mi^2. Letters preceding the deposit type reference the deposit type as discussed in the text]

Type of deposit	Resource potential: High	Resource potential: Moderate
Locatable resources		
A. Stockwork molybdenum	14	59
B. Porphyry copper-molybdenum	1	79
C. Polymetallic vein	159	5
D. Massive sulfides	123	364
E. Fluorspar veins	51	0
F. Vein uranium	1	6
G. Sandstone uranium-vanadium	7	32
H. Placer gold	5	6
I. Platinum group elements in ultramafic rocks	1	0
J. U-Th-REE in pegmatites	4	2
Total Locatable Resources	366	547
Leasable resources		
K. Coal	--	--
L. Conventional and subthrust oil and gas	0	1,120
M. Coal-bed methane	0	225
N. Basin-centered gas	0	0
O. Oil in fractured shales	0	188
Total Leasable Resources	0	1,622

Table 2. Description of areas of locatable and leasable resources in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

[Level of resource potential and certainty explained in Appendix 2. Areas of potential are shown on figures 16-25, 36, and 38-41 and plate 1. --do-- indicates the entry is the same as the one above it]

Map area	Resource potential	Commodities
Stockwork molybdenum		
A1	H/C	Mo, Cu, Pb, Zn, Ag, Au
A2	H/C	Mo, Cu, Pb, Zn, Ag, Sn, Nb
A3	M/C	Mo, Cu, Pb, Zn, Ag, Sn, Au
Porphyry copper-molybdenum		
B1	M/C	Cu, Mo, Pb, Zn, Ag, Au
B2	H/C	Cu, Mo, Pb, Zn, Ag
B3	H/C	Cu, Mo, Pb, Zn, Ag, Au, As
Polymetallic veins		
C1	H/C	Ag, Au, Cu, Pb, Zn
C2	H/C	Pb, Zn, Ag, Mo
C3	M/B	Cu, Pb, Mo, Ag, W
C4	H/C	Cu, Pb, An, Mo, As, Cd, Sb
C5	M/B	Ag, As, V Zn, Co, Sn, W
C6	H/C	Cu
C7	H/C	Cu, Mo, Pb, As, Ag, W, Zn, Sn
Massive sulfides		
D1	H/C	Cu, Pb, Zn
D2	M/B	--do--
D3	H/C	--do--
Fluorspar veins		
E1	H/C	F
E2	H/C	--do--
E3	H/C	--do--
Vein uranium		
F1	M/B	U
F2	H/C	--do--
Sandstone uranium-vanadium		
G1	M/C	U, V
G2	H/C	--do--
G3	M/B	--do--
G4	H/C	--do--
Placer gold		
H1	M/C	Au
H2	H/B	--do--
H3	H/C	--do--
H4	H/C	--do--
H5	H/C	--do--
H6	M/B	--do---

Table 2. Description of areas of locatable and leasable resources in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado—*Continued*.

[Level of resource potential and certainty explained in Appendix 2. Areas of potential are shown on figures 16–25, 36, and 38–41 and plate 1. --do-- indicates the entry is the same as the one above it]

Map area	Resource potential	Commodities
	Sandstone uranium-vanadium	
G1	M/C	U, V
G2	H/C	--do--
G3	M/B	--do--
G4	H/C	--do--
	Placer gold	
H1	M/C	Au
H2	H/B	--do--
H3	H/C	--do--
H4	H/C	--do--
H5	H/C	--do--
H6	M/B	--do---
H7	M/B	--do---
	Platinum group elements in ultramafic rocks	
I1	H/C	Pt, Pd
I2	H/C	--do--
	U-Th-REE in pegmatites	
J1	M/C	U, Th, REE
J2	H/C	--do--
J3	H/C	--do--
J4	M/B	--do--
J5	H/C	--do--
	Coal	
K1	H/B	Coal
K2	M/B	--do--
K3	L/C	--do--
	Conventional and subthrust gas accumulations	
L1	M/B	Gas
L2	M/B	--do--
L3	M/B	--do--
L4	L/C	--do--
L5	L/B	--do--
L6	L/B	--do--
	Coal-bed methane	
M1	M/C	Coal-bed methane
M2	L/D	--do--
	Basin-centered gas	
N1	L/C	Gas
	Oil in fractured shales	
O1	M/D	Oil
O2	M/D	--do--
O3	L/C	--do--

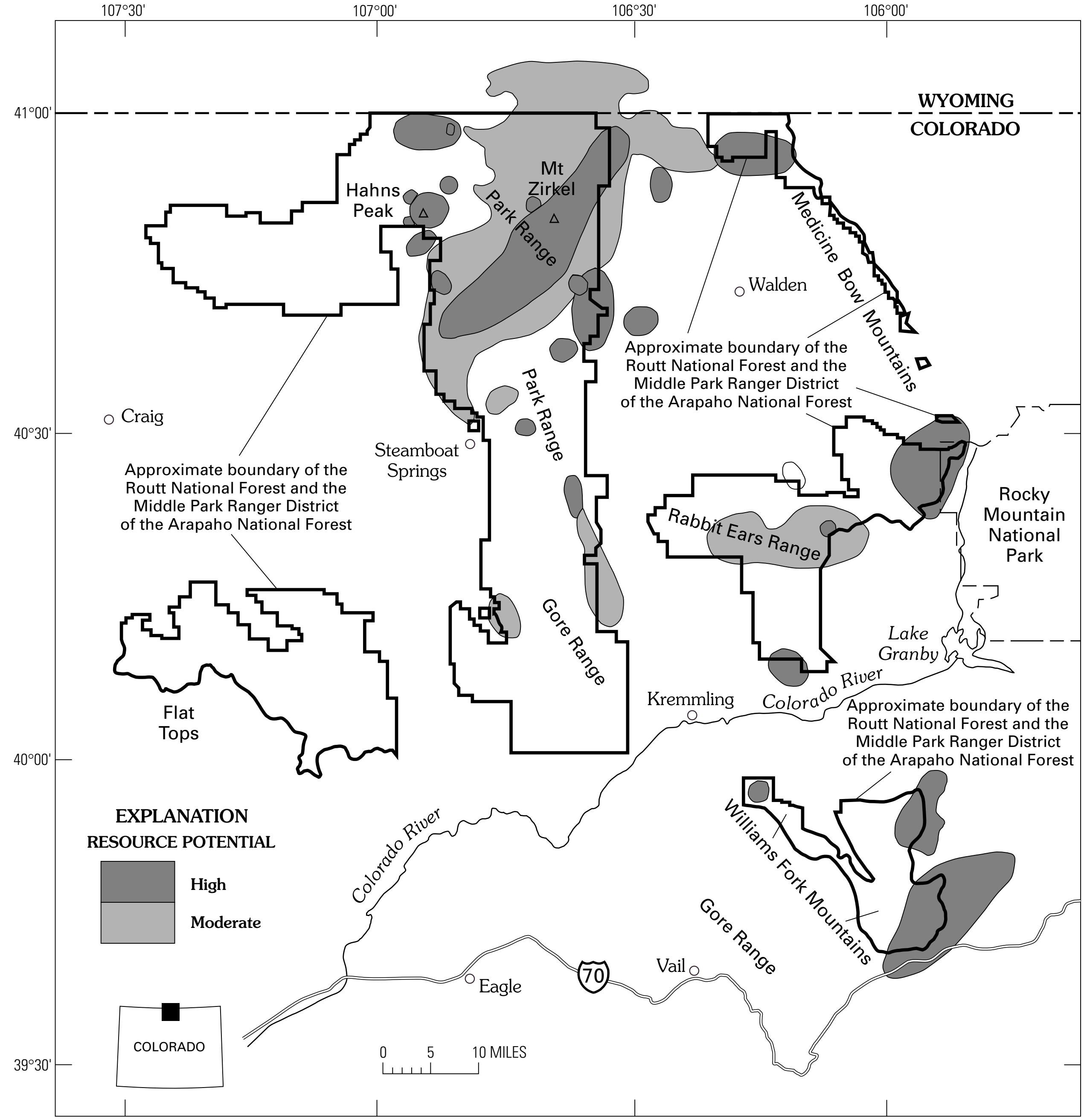


Figure 1. Map summarizing potential for undiscovered locatable minerals in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Where areas of potential overlap, only the highest degree of potential is shown.

and gold. A large northeast-trending zone in the northern part of the Park Range has high potential for massive sulfide deposits associated with calc-silicate and amphibolite host rocks. A large area of moderate resource potential encloses this high potential area. In the southeastern part of the Forest, a medium-sized area has high potential for massive sulfides; this area has several mines and prospects containing copper, lead, and zinc.

E. *Fluorspar veins.*—Formed from hot solutions associated with igneous intrusions; deposits contain fluorspar and minor amounts of barite. Three areas within the Forest have high potential for vein fluorspar: the northern part of the Forest, near the Northgate deposits; the Crystal mining district, on the eastern side of the Park Range; and the Delaney Butte area east of the Forest in North Park.

F. *Vein uranium.*—Formed from hot solutions associated with igneous intrusions; deposits contain uranium and other trace elements. A small area in the southeastern part of the Forest near Jones Pass has high potential for uranium in veins associated with fractures in granitic rock. On the

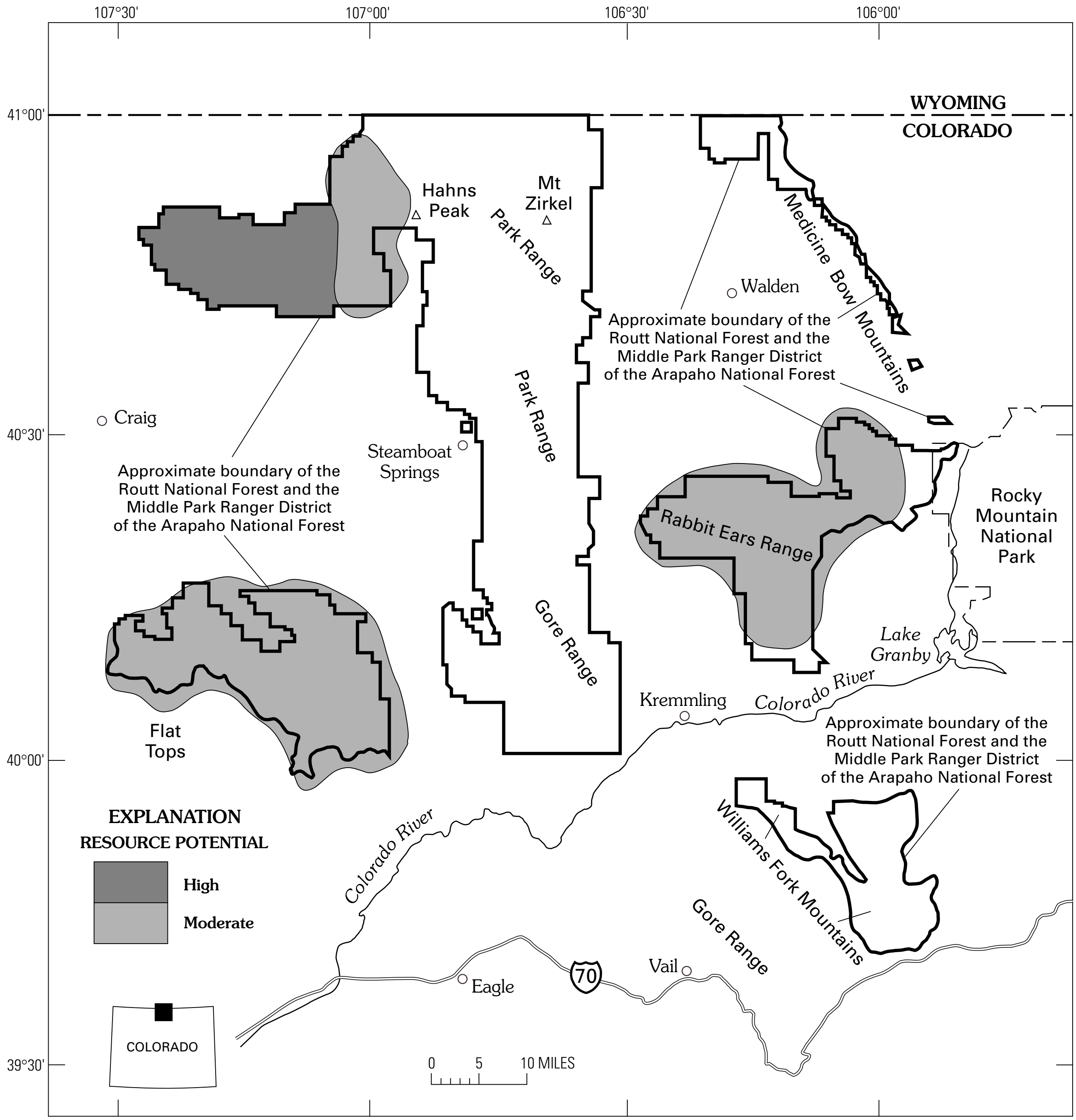


Figure 2. Map summarizing potential for leasable minerals in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Where areas of potential overlap, only the highest degree of potential is shown.

southwest side of the Gore Range, near Morrison Creek, a small area has moderate potential for vein uranium associated with granitic rock.

G. *Sandstone uranium-vanadium.*—Formed during diagenesis of sandstone units; deposits contain uranium, vanadium, and minor amounts of copper. Two areas have high potential for sandstone-hosted uranium and vanadium: a north-south-trending elongate area near Rabbit Ears Pass and the Troublesome mining district northeast of Kremmling. Two small areas have moderate potential for sandstone-hosted uranium and vanadium: along Norris Creek on the east side of the Park Range and a north-south-trending elongate area near Rabbit Ears Pass.

H. *Placer gold.*—Deposited in streams or slope washes that traversed or eroded gold-bearing rock; deposits contain gold and minor quantities of silver. Three small areas near Hahns Peak have high potential for gold in placer deposits, and one small area has moderate resource potential. On Independence Mountain, just outside the Forest east of Mt. Zirkel, one area has moderate potential and one area has high resource potential for small placer deposits. An area north of the Rabbit Ears Range on the Forest boundary has moderate potential for gold.

I. *Platinum-group elements in ultramafic rocks.*—Formed from gravity settling and convection processes in intrusive basaltic magmas. Near Elkhorn Mountain in the northernmost part of the Park Range, a small area within the Elkhorn complex has high potential for platinum-group elements; a small area between Bear and Lone Pine Creeks on the east side of the Park Range also has high potential for platinum-group elements.

J. *U-Th-REE in pegmatites*.—Formed from crystallization of minerals from residual melts of granitic bodies. Three areas have high potential and two areas have moderate potential for U, Th, and REE (rare earth elements) in pegmatites. These areas occur within the north-central part of the Forest in granitic rocks of the Park Range.

LEASABLE MINERALS

The first major change in the Mining Law of 1872 came with the passage of the Mineral Leasing Act of 1920. The 1920 Act placed the following minerals under the leasing law: oil, gas, coal, oil shale, sodium, potassium, phosphate, native asphalt, bituminous rock, and sulfur. Geothermal energy was added to the list of leasable minerals by the Geothermal Steam Act of 1970. The principal leasable minerals in the Forest are listed below, and areas favorable for resources are briefly described. Hot springs are present in the town of Steamboat Springs and about 8 mi to the north at Strawberry Park Hot Springs. The extent of these springs has been outlined in previous studies, and there is no potential for undiscovered springs in the remaining parts of the Forest.

K. *Coal*.—Formed from the decomposition and alteration of organic remains in deltaic environments. One area in the northwestern part of the Forest has high potential for coal. An area of moderate potential is in the southwestern part of the Forest in the Flat Tops, and an area of low potential is in the eastern part of the Forest in the Rabbit Ears Range.

L. *Conventional oil and gas.*—Formed in near-shore and coastal-plain environments from the decay of hydrocarbons in source rocks. Three large areas in the Forest have moderate potential, and five large areas have low potential for further conventional discoveries of oil and gas.

M. *Coal-bed methane*.—Generated during the maturation process of coal. One small area in the northwest part of the Forest in the Elkhead Mountains has moderate potential, and one small area in the southwest part of the Forest in the Flat Tops has low resource potential for coal-bed methane accumulations.

N. *Basin-centered gas.*—Formed in near-shore and coastal-plain environments from the decay of hydrocarbons in source rocks. A small area in the western part of the Elkhead Mountains has low resource potential for basin-centered gas.

O. *Fractured shale-oil accumulations.*—Formed in near-shore and coastal-plain environments from the decay of hydrocarbons in source rocks. Shale is both the source rock and the reservoir rock; oil can be produced where shale is thermally mature and fractured. Three areas in the western part of the Forest have moderate potential for fractured shale-oil accumulations, and one large area in the eastern part of the Forest has low potential.

SALABLE MINERALS

Salable minerals, as defined in the Materials Act of 1947, include petrified wood, sand, dimension stone, gravel, pumice, cinders, perlite, and some clay. Salable minerals in the Forest include crushed aggregate, dimension stone, sand, and gravel.

Crushed aggregate.—Numerous sources of crushed aggregate are present in the Forest in the Elkhead Mountains, the Park and Medicine Bow Ranges, and the Flat Tops. Aggregate includes sandstone, volcanic rock, granite, basalt, landslide material, and glacial drift. Uses are roadway building, concrete, railroad ballast, rip rap, and fill.

Dimension stone.—Some decorative dimension stone is produced locally in the Forest in the Park Range, Elkhead Mountains, and Flat Tops. Moss- or lichen-covered granite and sandstone are used for interior or exterior facing in homes or buildings.

Sand and gravel.—Numerous deposits of sand and gravel are located along the Elk and Colorado Rivers and their major tributaries within the Forest. Uses include concrete work and products, fill material, plastering sands, and snow and ice control.

QUANTITATIVE ASSESSMENT OF METALLIC RESOURCES USING GRADE-TONNAGE MODELS

At the request of the U.S. Forest Service, the U.S. Geological Survey has provided subjective probabilistic estimates of undiscovered mineral resources that might exist within the Forest. Based on the geology, geophysics, geochemistry, and production records of known deposits in the Forest, deposit types were defined and compared to other similar deposits worldwide. The number of undiscovered deposits of median size on the grade-tonnage curve likely to be present in the Forest was estimated at the 90th, 50th, 19th, 5th, and 1st percentiles; the first percentile is the likelihood of occurrence with a 1 percent probability. Using the computer program MARK3, tonnages for undiscovered deposits in the Forest were estimated from known tonnages and grades of deposits worldwide. Estimates do not consider any of the economics involved in extracting the metals.

Only three mineral deposit types have sufficient grade and tonnage information for assessment using MARK3: massive sulfide deposits, porphyry copper-molybdenum deposits, and placer gold deposits. All remaining deposits known in the Forest lack sufficient data for the quantitative assessment.

For massive sulfide deposits, the number of undiscovered deposits was estimated to be 0, 0, 1, 1, and 2 at the 90th, 50th, 10th, 5th, and 1st percentiles, respectively (estimates for the remaining deposits are presented in the same order of percentiles). Estimates of mean metal content in undiscovered massive sulfide deposits in the Forest are: 3,200 tons of copper, 1,900 tons of zinc, 180 tons of lead, 0.05 tons of gold, and 2.9 tons of silver in 48,000 tons of total ore. For porphyry copper-molybdenum deposits, the number of undiscovered deposits was estimated to be 0, 0, 1, 1, and 2. Estimated mean metal contents are 109,000 tons copper, 1,600 tons molybdenum, 2.6 tons gold, and 17 tons silver in a total of 20,000,000 tons of ore. For placer gold, the number of undiscovered deposits was estimated at 0, 0, 1, 1, and 1. Estimated mean metal content is 0.6 tons of gold and 0.003 tons of silver in 3,900,000 tons of ore.

INTRODUCTION

This report presents an assessment of the mineral and energy potential of the Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest, referred to as "the Forest" in this report. The Middle Park Ranger District of the Arapaho National Forest is included in this report because the two areas are administered by the staff of the Routt National Forest and are included in a single planning document. The Middle Park Ranger District is east of the Routt National Forest and includes parts of the Gore and Rabbit Ears Ranges and the Williams Fork and Vasquez Mountains. For simplicity, only figure 3 distinguishes the Middle Park Ranger District; in all other plates and figures, the district is included within the Forest boundary.

This mineral resource assessment was produced to assist the U.S. 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 in land-use planning. This report addresses the potential for undiscovered mineral and energy resources in the Forest and is based upon information available as of May 1994. The identified, or known, mineral and energy resources of the Forest were studied by the U.S. Bureau of Mines (Neubert, 1994).

"Ton," as used in this report, indicates "metric ton" unless specified otherwise.

GEOGRAPHIC SETTING

The Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest cover approximately 1.2 million acres in north-central Colorado. Parts of six counties are within the Forest: Routt, Jackson, Grand, Moffat, Rio Blanco, and Garfield. Five separate parcels comprise the Forest (fig. 3) and consist of primarily forested land at higher elevations separated by rolling hills and valleys of brush and meadows. The largest parcel borders Wyoming and includes the Elkhead Mountains and the Park and Gore Ranges. Small scattered parcels along the crest of the Medicine Bow Mountains comprise the northeastern part of the Forest. The central parcel borders Rocky Mountain National Park and includes the Rabbit Ears Range and part of the Never Summer Mountains. The two southern parcels share borders with the White River National Forest: the southwestern parcel includes part of the Flat Tops Primitive Area and the southeastern parcel includes the Williams Fork and Vasquez Mountains.

The Continental Divide lies within the Forest along the crests of the Park and Rabbit Ears Ranges and forms part of the Forest boundary in the Never Summer and Vasquez Mountains. Elevation in the Forest ranges from about 6,800 ft at Mad Creek to more than 12,900 ft at Clark Peak in the Medicine Bow Mountains. The Forest also partially encloses two topographic basins, North Park and Middle Park, located along the eastern slopes of the Park and Gore Ranges. The Rabbit Ears Range divides the mostly flat-lying, sage-covered North Park from the hills and valleys of Middle Park.

Most of the tributaries that drain the Forest flow into the Colorado River, with the exception of the tributaries that drain into North Park and flow into the North Platte River. Numerous alpine lakes dot the topography, particularly in the Mount Zirkel Wilderness Area—and Steamboat Lake and Lake Catamount are located just outside the Forest (pl. 1). Access to the Forest is provided by several improved and unimproved roads from U.S. Highway 40 and State Highways 9, 125, and 131. The major communities near the Forest are Steamboat Springs, Walden, Kremmling, Craig, and Yampa.

METHODS FOR IDENTIFYING FAVORABLE AREAS FOR UNDISCOVERED MINERAL RESOURCES

Mineral and energy resources include three categories: locatable resources, leasable resources, and salable resources. Areas favorable for the occurrence of locatable and leasable resources are summarized on figures 1 and 2. Areas within the Forest that were rated as favorable for specific types of as yet undiscovered resources are similar

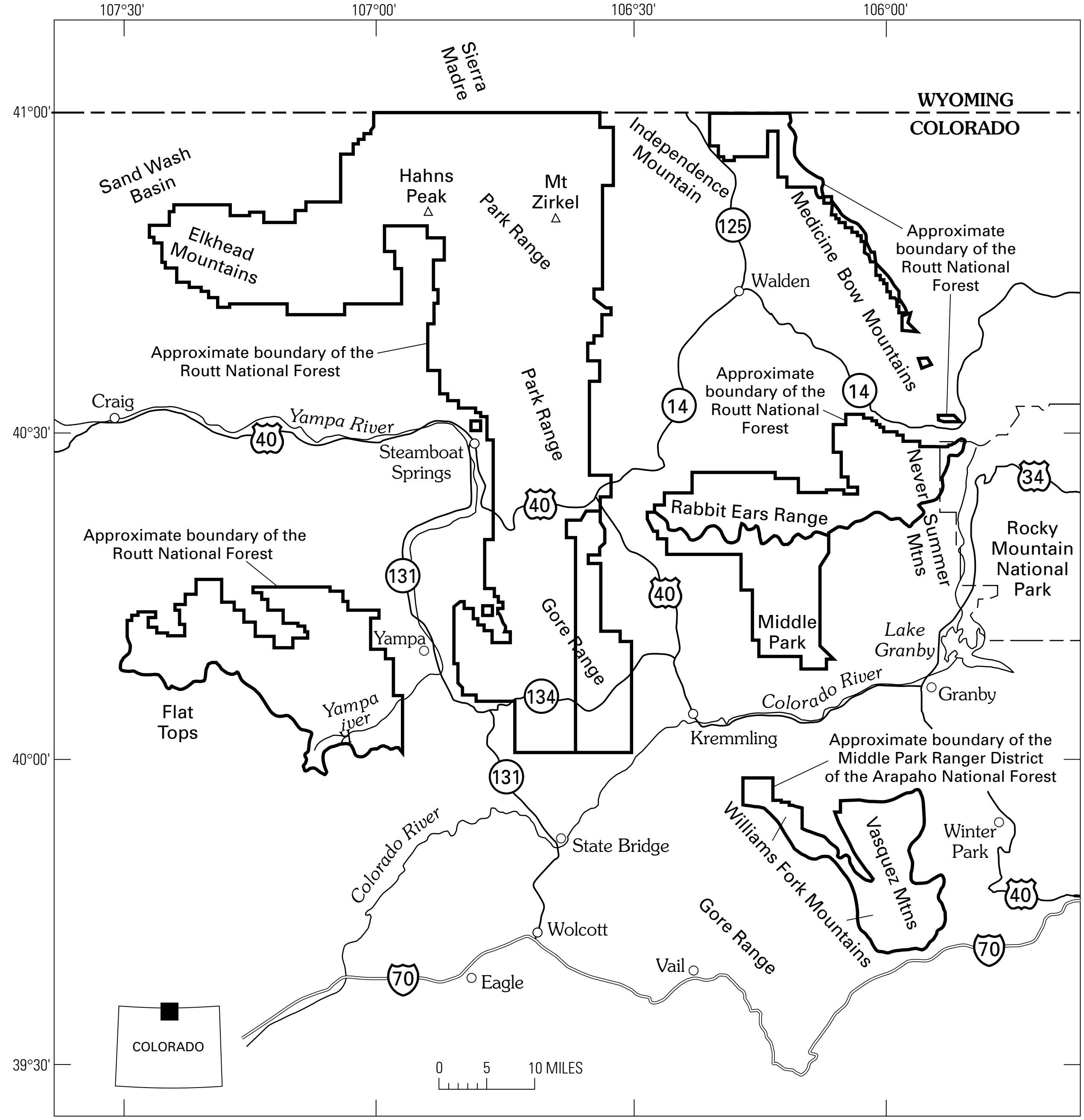


Figure 3. Index map showing the location of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

to those that host productive deposits elsewhere in the Forest or in other parts of the United States.

Mineral and energy resources are specified in terms of deposit types and their geologic settings. Deposit types are based on geologic characteristics of known deposits within or near the Forest. Most of the mineral deposit types are exposed in mines or prospects. The boundaries of favorable areas are based on a combination of geologic, geochemical, and geophysical criteria. A letter designation (A, B, C, etc.) is used to represent the deposit type in the text, on figures, and on the plates. Definition of terms used in this assessment of mineral potential for each deposit type are summarized in Appendix 2.

All available information was assembled and analyzed according to the procedures outlined by Shawe (1981) and Taylor and Steven (1983). Mineral and energy resource potential information is presented in detail on plate 1 and is summarized on figures 1 and 2. This study is based primarily on published literature but includes unpublished data from studies in progress.

PREVIOUS ASSESSMENTS

Parts of the Forest have been previously assessed for mineral and energy resources by the U.S. Geological Survey. These areas include the Flat Tops Primitive Area, the Mount Zirkel Wilderness, the Williams Fork Roadless Area, the Service Creek Roadless Area, and the Never Summer, Rawah, and Vasquez Peak Wilderness Study Areas (fig. 4). In addition, a small Bureau of Land Management Wilderness Study Area that adjoins the Forest (Platte River Adjacent Wilderness Study Area) was also studied (fig. 4) (Dickerson and McDonnel, 1989). Published reports describe the geology and evaluate the mineral potential of each area. References for each report are shown in table 3.

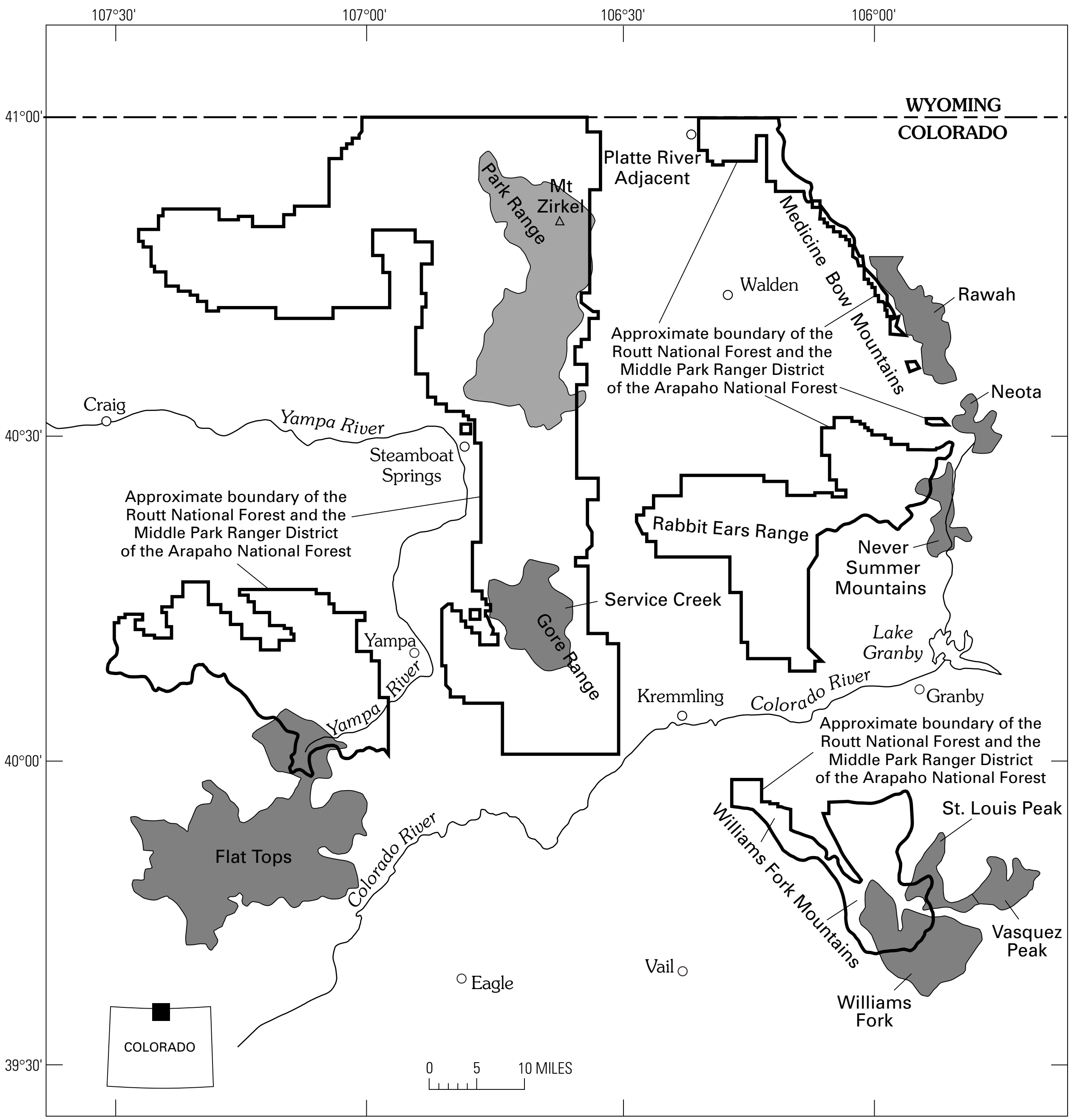


Figure 4. Index map of studied public lands in or adjacent to the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

ACKNOWLEDGMENTS

Several individuals contributed data and assistance to this study. George Snyder provided valuable information on the geology of north-central Colorado and this manuscript benefited greatly from his input. Rusty Dersch of the U.S. Forest Service provided information regarding Forest boundaries and salable minerals. Anna Wilson lent assistance in digitizing areas of potential.

Table 3. Previous studies that cover parts of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

[NURE, National Uranium Resource Evaluation]

Study Area	Reference
Flat Tops Primitive Area	Mallory and others (1966)
Williams Fork Roadless Area.	Theobald and others (1985); Barton (1985b)
St. Louis Peak Roadless Area	Theobald and others (1985); Barton (1985a)
Vasquez Peak Wilderness Study Area	Theobald and others (1985); Barton (1985c)
Mt. Zirkel Wilderness Study Area	Snyder and others (1981); Snyder (1987b)
Service Creek Roadless Area	Schmidt and others (1984)
Rawah Wilderness Study Area	Motooka and others (1979); Pearson and others (1982)
Neota-Flat Tops Wilderness Study Areas	Pearson and others (1981)
Never Summer Wilderness Study Area	Pearson and others (1981)
Craig 1° × 2° NURE	Bolivar and others (1979); Craig and others (1982)
Rawlins 1° × 2° NURE	Weaver and others (1978)
Cheyenne 1° × 2° NURE	Trexler (1978)
Greeley 1° × 2° NURE	Bolivar and others (1978); Youngquist and others (1981)
Denver 1° × 2° NURE	Bolivar and others (1978); Shettel and others (1981)
Leadville 1° × 2° NURE	Planner and others (1981)
Craig 1° × 2° and Rawlins 1° × 2° detailed NURE	Shannon and others (1981)
Hahns Peak and Pearl districts	Allen (1982)

GEOLOGY

By Margo I. Toth *and* Sandra J. Soulliere

The geology of the Forest was compiled at a scale of 1:250,000 from published geologic maps. Most of the geology was modified from the Craig 1°×2° quadrangle (Tweto, 1976), but parts of the Denver (Bryant and others, 1981), Leadville (Tweto and others, 1978), and Greeley (Braddock and Cole, 1978) 1°×2° quadrangles were also used. Detailed geology is given in other publications (Snyder, 1980a, 1980b, 1980c and 1980d; Braddock and Cole, 1990).

GEOLOGIC HISTORY

The geologic history of the Forest encompasses almost 2 billion years and is characterized by complex structural and rock-forming events. Excellent papers by Tweto (1980), Wallace (1990), De Voto (1990), and Reed and others (1993) describe the geologic setting and tectonic history of Colorado. Hedge and others (1986) describe the Proterozoic era of the Rocky Mountain region, and Tweto (1987) describes the nomenclature of Proterozoic rocks in Colorado. Much of the following discussion is drawn from these sources.

Within the area of the Forest, the oldest rocks are Early Proterozoic. Volcanic and sedimentary formations were accreted onto the margin of the Archean Wyoming craton and metamorphosed to gneiss, schist, and migmatite at about 1.7 Ga (billion years ago). During Early Proterozoic (1.7 Ga) and Middle Proterozoic (1.4 Ga) time, these rocks were intruded by large granitic plutons. Within the Forest, Proterozoic rocks make up the core of most of the major mountain ranges (plate 1). The Proterozoic rocks are cross-cut by well-defined, northeast-trending faults and shear zones of the Colorado lineament, which was initially formed in the Proterozoic (Warner, 1978) and was later reactivated. The northern margin of this lineament, known as the Mullen Creek–Nash Fork shear zone, traverses southeastern Wyoming.

The next major geologic event occurred during early and middle Paleozoic time when a thick sequence of marine and nonmarine sediments was deposited upon the Proterozoic rocks (Berg, 1960). In late Paleozoic time, two elements of the Ancestral Rocky Mountains, the Uncompahgre highland and the Ancestral Front Range, were formed. The Ancestral Front Range occupied much of the area currently encompassed by the Forest. Parts of the Ancestral Rocky Mountains may have attained altitudes of as much as 5,000 to 10,000 feet above sea level (Mallory, 1971). Uplift of the Ancestral Rockies caused older sedimentary rocks to be eroded, and in places the Proterozoic basement was partially exposed. Sedimentary rocks were deposited in a large basin that formed between the Uncompahgre and Front Range and also locally on newly exposed Proterozoic basement rocks.

During Mesozoic time, mountain-building decreased and inland seas covered the area, depositing marine and nonmarine sediments. Clastic sediments were deposited in early Mesozoic time as erosion of the highlands continued. Continental, marginal-marine, and complex intertonguing marine and nonmarine sediments were deposited throughout the rest of the Mesozoic.

The final exit of the sea marked the beginning of the Laramide orogeny, which produced most of the present primary mountain ranges in central Colorado. During this orogeny, plutonic rocks were emplaced along a northeast-trending zone in central Colorado coincident with major Proterozoic structures. Streams eroded older sedimentary rocks, and these deposits accumulated in structural basins formed during Late Cretaceous and Tertiary time.

During late Cenozoic time, crustal extension associated with formation of the Rio Grande rift to the south caused development of the present basins and ranges. Extension was accompanied by intrusion of a wide variety of granitic rocks 28 to 23 Ma, by eruption of volcanic rocks 33 to 30 Ma, and by intrusion and eruption of rhyolite and basalt 20 Ma to 7.6 Ma.

A major period of glaciation began in the area of the Forest about 500,000 years ago and recurred as recently as 12,000 years ago. During the height of glaciation, ice almost totally covered the higher ranges, and the valleys were filled with glaciers. The modern alpine topography, with deep U-shaped valleys that is seen today, is largely a product of glacial erosion.

DESCRIPTION OF ROCK UNITS

PROTEROZOIC ROCKS

The most widespread rocks in the Forest are Proterozoic metamorphic and plutonic rocks, exposed in the core of most of the major mountain ranges. The rocks fall into five lithologic groups and are of two ages: 1.7 Ga and 1.4 Ga.

Two of the groups of metamorphic rocks occur in the Forest: hornblende gneiss, amphibolite, and calc-silicate gneiss (Xfh, plate 1), and biotite gneiss and migmatite (Xb, plate 1). These rocks are typically metamorphosed to upper amphibolite or sillimanite facies and are structurally and stratigraphically complex. Hornblende gneiss, amphibolite, and calc-silicate gneiss are dominant in the northern part of the Forest in the Park Range. Smaller amounts are present in the Medicine Bow Mountains, Never Summer Mountains, and in the southeastern part of the Forest in and near the Vasquez Mountains. Before metamorphism, the hornblende gneiss and amphibolite rocks were probably mafic lava flows, near-surface intrusions, or layers of basaltic ash that were deposited in seawater; the carbonate-rich layers and calc-silicate gneisses likely were carbonate sediments. Biotite gneiss and migmatite rocks crop out in small isolated areas in the Park Range and Gore Range, in large parts of the Never Summer Mountains, and as a large, continuous body in the southeastern part of the Forest in the Williams Fork Range and Vasquez Mountains. Before metamorphism, the gneiss and migmatite probably were marine deposits of graywacke, shale, and felsic volcanic rocks.

The Routt and Berthoud Plutonic Suites make up the remaining Proterozoic rocks in the Forest. Rocks of the Routt Plutonic Suite are 1.7 Ga in age and consist of a mafic and a granitic suite of plutons; rocks forming the Berthoud Plutonic Suite are 1.4 Ga in age and consist solely of granitic plutons.

The 1.7-Ga mafic plutons in the northern part of the Park Range (Xm, plate 1) are small, homogeneous, and consist of biotite-hornblende quartz diorite. The largest, the Elkhorn Mountain pluton, extends from the northwestern part of the Park Range across the Wyoming border. The mafic plutons grade into 1.7-Ga granitic rocks, but elsewhere, angular inclusions of mafic plutons occur in granitic rocks, indicating that they are distinctly older than the granite (Snyder, 1987b).

The 1.7-Ga granitic rocks include foliated quartz monzonite and granodiorite rocks (Xg, plate 1) of the Rawah and Boulder Creek batholiths (Tweto, 1987). The largest continuous outcrop of these rocks is found in the core of the Gore Range, but significant amounts also occur in the northern Park Range closely associated with calc-silicate gneisses, in the Medicine Bow Mountains, and in the southeastern part of the Forest in the Williams Fork Mountains. The granitic plutons are generally concordant with the enclosing gneisses and contain biotite and (or) hornblende. The bodies were intruded during and immediately following folding and metamorphism of the gneiss and migmatite complex.

The 1.4-Ga intrusive rocks are composed of massive to gneissic-biotite granite, quartz monzonite, and granodiorite (Yg, plate 1). These bodies have the following occurrences: large continuous bodies of the Sherman batholith in the Medicine Bow Mountains; one northeast-elongate, continuous body of the Mt. Ethel pluton in the central part of the Gore Range; and fault slivers of the Silver Plume batholith in the Williams Fork Mountains. Contacts with the country rock range from sharp to diffuse. Rocks from these units lack metamorphic foliation, and most are discordant with the enclosing gneisses. This plutonic event was largely anorogenic.

PALEOZOIC ROCKS

Lower Paleozoic rocks in the Forest (plate 1) include the following sedimentary units: Leadville Limestone (Lower Mississippian), Gilman Sandstone (Mississippian or Devonian), Dyer Dolomite (Mississippian? and Devonian), Parting Sandstone (Devonian), and the Sawatch Quartzite (Upper Cambrian). The units are only present as isolated outcrops on the southwestern flank of the Gore Range. The maximum combined thickness of the lower Paleozoic rocks is less than 350 ft.

Middle and upper Paleozoic rocks in the Forest include the State Bridge Formation (Lower Triassic to Lower Permian), Goose Egg Formation (Permian), Satanka Shale (Permian), Maroon Formation (Lower Permian to Middle Pennsylvanian), Weber Sandstone (Lower Permian to Middle Pennsylvanian), the Eagle Valley Evaporite (Middle and Upper Pennsylvanian), and the Minturn Formation (Middle Pennsylvanian). These formations contain conglomerate, sandstone, mudstone, shale, gypsum, anhydrite, and minor amounts of limestone. Many of the formations are characteristically maroon or red. These formations either pinch out or are truncated against the western flank of the Gore Range; only small, isolated outcrops are present in the Forest.

MESOZOIC ROCKS

Mesozoic rocks in the Forest include the following sedimentary units: Lance Formation (Upper Cretaceous), Fox Hills Sandstone (Upper Cretaceous), Lewis Shale (Upper Cretaceous), Mesaverde Group (Upper Cretaceous), Pierre Shale (Upper Cretaceous), Mancos Shale (Upper Cretaceous), Colorado Group (Upper Cretaceous), Dakota Sandstone (Upper and Lower Cretaceous), Morrison Formation (Upper Jurassic), Curtis Formation (Middle Jurassic), Sundance Formation (Middle Jurassic), Entrada Sandstone (Middle Jurassic), Nugget Sandstone (Lower Jurassic), Glen Canyon Sandstone (Lower Jurassic), Chinle Formation (Triassic), and the Chugwater Group (Triassic), (Ku, Ju, and TrPu, plate 1). The lower of these units consists dominantly of sandstone and conglomerate; shale becomes more prevalent in the upper part of the section. Mesozoic rocks crop out in small, elongate, north-trending areas along the flanks of the Gore and Park Ranges. Extensive outcrops of Cretaceous rocks are found west of the Gore Range in the Flat Tops, but only the Mancos Shale crops out within the Forest.

MIDDLE TERTIARY ROCKS

Middle Tertiary rocks are moderately widespread in the Forest except in the Park and Gore Ranges. Four groups crop out in the Forest: (1) Oligocene Rabbit Ears volcanic rocks, (2) Oligocene and late Miocene calc-alkaline hypabyssal intrusive rocks, (3) late Miocene compositionally diverse intrusive and extrusive rocks, and (4) Miocene basalt and basaltic andesite flows.

The oldest of the Tertiary igneous rocks in the Forest are those of the Rabbit Ears volcanic field, which extends southward from the crest of the Rabbit Ears Range into Middle Park (Tv, plate 1). The Rabbit Ears volcanic rocks were erupted 30–33 Ma ago (Izett, 1966; Naeser and others, 1973). The volcanic rocks range in thickness from 0–100 ft in the southern areas to as much as 800 ft thick in the northern outcrop area. The Rabbit Ears volcanic rocks consist of a complex interlayered sequence of breccias, lahars, tuffs, and a few thin, discontinuous trachyandesite and trachybasalt lava flows; the tuffs are generally rhyolitic and are slightly welded to nonwelded. Fragments in breccia vary widely in color and texture and range in composition from silicic to intermediate. Fragments in the south are less than 2 ft in diameter. In the north, blocks as much as 5 ft in diameter are common, suggesting a northern source area. Trachyandesite lava flows are interlayered in the upper part of the sequence, whereas trachybasalt lavas have been found only at the base.

Most of the Oligocene and late Miocene hypabyssal intrusive rocks in the Forest crop out in an east-west-trending belt in the Rabbit Ears Range that extends from Baker Mountain in the western Rabbit Ears Range to the Never Summer Mountains (Ti, plate 1). Two other occurrences of these intrusive rocks are in or near the Forest: a medium-sized pluton at the southern end of the Gore Range and the small Red Mountain plug (associated with molybdenum), just outside the southeastern boundary of the Forest (pl. 1). The rocks range in age from 22.7 to 28.8 Ma (Izett, 1966; Naeser and others, 1973), although most of them are Oligocene in age (older than 24 Ma). Compositions range from dacite to rhyolite. Most of the intrusive rocks are fine to medium grained and are strongly porphyritic in texture.

Compositionally diverse late Miocene rocks crop out in two fairly limited areas: west of the Park Range in the Elkhead Mountains and high in the Park Range in the area around Walton Peak and Rabbit Ears Pass (To, plate 1). Most of the rocks in the Elkhead Mountains are 7.6 to 11.5 Ma and occur as hypabyssal stocks, sills, and dikes. Intrusive rocks in the Elkhead Mountains range in composition from basalt to rhyodacite and include alkalic varieties of these compositions; the more felsic rocks are concentrated in the central area around Hahns Peak. Near Walton Peak and Rabbit Ears Pass, a large area of trachybasaltic volcanic rocks (Tv, plate 1) is intruded by small, intermediate-composition porphyries. One porphyry just west of Rabbit Ears Pass area has an age of 17.0 Ma (Snyder, 1980b); the trachybasalt flows were erupted between 17 and 20 Ma.

Miocene basaltic and basaltic andesite flows are located in the southwestern part of the Forest, predominantly in the area of the Flat Tops (Tb, plate 1). The basalts are part of a bimodal assemblage that includes small rhyolitic dikes and flows on the eastern side of the Flat Tops. The basaltic rocks are dense, black, and alkalic and form flows 5 to 200 ft thick; they include interbedded tuffs and volcanic conglomerates.

LATE CRETACEOUS AND TERTIARY ROCKS

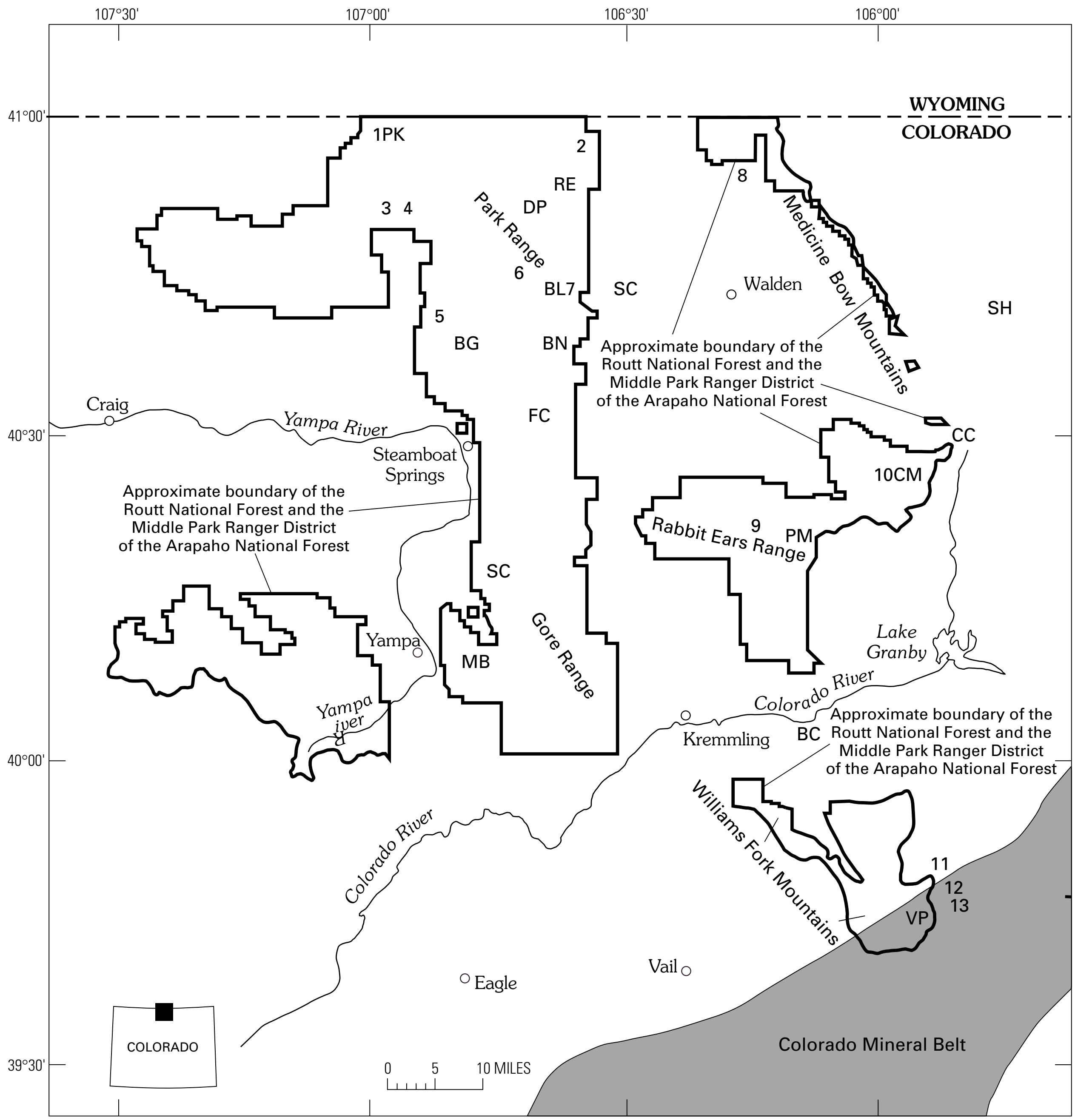
Late Cretaceous and Tertiary rocks in the Forest include the following Formations: Middle Park Formation (Paleocene and late Cretaceous?), Wasatch Formation (Eocene and Paleocene), Coalmont Formation (Eocene and Paleocene), Fort Union Formation (Paleocene), White River Formation (Oligocene), Troublesome Formation (Miocene and Oligocene), Browns Park Formation (Miocene), and North Park Formation (Miocene) (Tks, plate 1). These units were deposited in local structural basins and small grabens that formed during Tertiary time. The rocks consist of claystone, siltstone, limestone, sandstone, and conglomerate; locally they contain beds of volcanic ash. Extensive outcrops are present to the west of the Park Range in the Sand Wash Basin and east of the Park and Gore Ranges in North and Middle Parks.

QUATERNARY AND PLIOCENE(?) UNCONSOLIDATED DEPOSITS

Holocene alluvium in drainages and fans across the Forest consists of gravel, sand, and silt. Extensive landslides of Holocene and Pleistocene age occurred along the east side of the Gore Range and in the Elkhead Mountains. The landslide deposits consist of shaly material with variable amounts of boulders of sandstone and basalt. Pleistocene glacial till and outwash in the Gore Range consist of boulders, gravel, and sandy deposits. Pliocene(?) gravel deposits are found on Gravel Mountain in the eastern part of the study area near the Continental Divide.

COLORADO MINERAL BELT

In Colorado, most of the important hydrothermal mineral deposits are part of an elongate zone known as the Colorado Mineral Belt (Tweto and Sims, 1963) (fig. 5), which extends from the San Juan Mountains in southwestern



EXPLANATION

Mining districts		Mineralized areas	
1	Elkhorn Mountain	BC	Beaver Creek
2	Pearl	BG	Big Creek
3	Hahns Peak	BL	Bear Creek–Lone Pine Creek
4	Farwell Mountain	BN	Beaver Creek–Norris Creek
5	Greenville	CC	Cam Claims
6	Upper and lower Slavonia	CM	Mt. Cumulus
7	Crystal	DP	Diamond Park
8	Northgate	FC	Fish Creek Reservoir
9	Poison Ridge	MB	Morrison Creek–Beaver Creek
10	Teller	PK	Peak 9731
11	La Plata	PM	Parkview Mtn
12	Dailey	SC	Service Creek
13	Henderson-Urad	SH	Spencer Heights
		VP	Vasquez Peak

Figure 5. Index map showing mining districts and mineralized areas within or adjacent to the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

Colorado to the eastern margin of the Front Range, northwest of Denver. The belt contains a large number of mineral deposits associated with numerous felsic to intermediate intrusive and volcanic rocks of Late Cretaceous to late Tertiary age. The Colorado Mineral Belt cuts across both pre-Cretaceous structural trends and the present north-south topographic grain of the southern Rocky Mountains. Only the southeastern part of the Forest falls within the Colorado Mineral Belt.

STRUCTURAL GEOLOGY

Rocks in the Forest have a complex structure that reflect events in Proterozoic, Paleozoic, early Mesozoic, and late or post-Miocene time. Many of the major structures were affected by recurrent movements and intrusion of Proterozoic and Tertiary plutons.

Three major systems of Proterozoic faults and shear zones are recognized in the Forest (pl. 1) (Tweto, 1980). A fault system trending north-northwest is widespread; some elements of this system originated before the emplacement of the 1.7-Ga plutons, but other elements postdate emplacement of the 1.4-Ga granitic plutons. The Gore fault on the west side of the Gore Range is typical of these structures (pl. 1).

A system trending northeast is expressed mainly by strongly developed shear zones that cut across the trend of major mountain ranges. This system was active principally during and following intrusion of the 1.4-Ga granitic suite, although it may have originated earlier (Tweto, 1980). The shear zone in the northern Park Range between Soda Creek and North Fork Fish Creek is one of the most well developed of these zones in the Forest (pl. 1). Rocks in these zones are typically ground or “mylonitized” into very fine grained rocks.

The third system of faults is an east-west-trending fault system that parallels major lithologic contacts in basement rock; this system is only present in the northernmost part of the Forest close to the Wyoming border. To the north of the Forest in Wyoming, a similar structure called the Mullen Creek–Nash Fork shear zone separates Archean basement rocks north of the zone from Early Proterozoic rocks south of the zone. The shear zone is interpreted as a collision boundary between the Archean craton to the north and Proterozoic island-arc terrane to the south (Hills and Houston, 1979).

Uplift of the Ancestral Rocky Mountains reactivated Proterozoic structures, such as the Gore fault, and formed new faults. The Gore fault bounded the western side of the Ancestral Front Range; aprons of coarse arkosic sediment were deposited next to the fault in the central Colorado trough.

Tectonic uplift, folding, and faulting were also associated with the Laramide orogeny in latest Cretaceous time. Several of the major Laramide uplifts occupy the sites of late Paleozoic uplifts. The Medicine Bow, Park, and Gore Ranges occupy the site of the late Paleozoic Front Range highland (Tweto, 1980). Most of the uplifts were formed by reactivation of late Paleozoic and Proterozoic faults, but new faults were also formed, such as the Williams Fork Range thrust fault (pl. 1) . The thrust faults were originally interpreted to be near-surface expressions of steep faults formed by vertical forces (Tweto, 1980), but recent research indicates that many thrust faults flatten beneath mountain uplifts and were formed by horizontal forces (Erslev and Rogers, 1993). Large, deep structural basins formed concurrently with the Laramide uplifts, and sediments deposited in the basins are a principal record of the Laramide orogeny. North Park, Middle Park, and Sand Wash Basin are examples of these basins (pl. 1).

Laramide tectonism waned in the Eocene and was replaced by erosion, sedimentation, uplift, local folding, and normal faulting related to crustal extension. Block faulting reactivated many Laramide and Proterozoic faults, renewing uplift of many of the mountain ranges. Several faults of late Miocene age occur along the western side of the Park Range. The Steamboat Springs fault has as much as 900 ft of movement (Izett, 1975). Extension formed the north-northwest-trending Rio Grande rift zone, which may extend as far north as Wyoming (Tweto, 1979).

GEOCHEMISTRY

By Steven M. Smith

GEOCHEMICAL SURVEYS

Geochemical data used in the assessment of the Forest were obtained primarily from samples collected and analyzed for previous mineral assessments. Sample data are in the U.S. Geological Survey National Geochemical Database (described by Hoffman and Marsh, 1994). These data were derived from USGS analyses of 1,701 rock, 2,460 stream-sediment, and 475 heavy-mineral-concentrate samples, taken for previous resource assessments of Wilderness Areas (table 3), and National Uranium Resource Evaluation (NURE) project analyses of 3,256 stream-sediment samples taken for uranium resource assessments of 1°×2° quadrangles (table 3). Data for another 206 stream-sediment samples from the Hahns Peak and Pearl mining districts (Allen, 1982) also were added; altogether, 8,098 samples are represented. The NURE data were combined from the Cheyenne, Craig, Denver, Greeley, Leadville, and Rawlins 1°×2° quadrangle reconnaissance studies and from detailed follow-up studies in the Craig and Rawlins 1°×2° quadrangles (table 3). Published data were included from USGS mineral resource assessments of the Flat Tops Primitive Area, the St. Louis Peak, Service Creek, and Williams Fork Roadless Areas, the Neota–Flat Top, Never Summer, Mt. Zirkel, Rawah, and Vasquez Peak Forest Service Wilderness Study Areas (table 3). Unpublished data were included from analyses performed in support of USGS geologic mapping throughout the region.

METHOD OF STUDY

The data contain analytical values for 62 different elements, although no single sample was analyzed for all of these elements. Eighteen elements commonly associated with mineral deposits were selected for primary use in this study: antimony, arsenic, bismuth, cadmium, chromium, cobalt, copper, gold, lead, mercury, molybdenum, nickel, silver, tin, tungsten, uranium, vanadium, and zinc.

The use of three separate sample media, analyzed by various techniques at different laboratories, precluded simply combining raw data into one interpretable database. For each sample medium, data were separated by project (table 3) and analytical method, and were divided into five classes; low background, high background, slightly anomalous, moderately anomalous, and highly anomalous. The four threshold values (table 4) between these five classes were determined by examining data frequency histograms in conjunction with crustal-abundance data (Parker, 1967; Fortescue, 1992), spatial distribution patterns, multielement correlations, and geology. In most cases, the four threshold values were the same or similar for samples from projects analyzed by the same laboratory and method. Exceptions are noted in table 4.

Data that fall within each class were assigned a "weight" value from 0 to 4—low background (0), high background (1), slightly anomalous (2), moderately anomalous (3), and highly anomalous (4). A new data set, composed of the assigned weight values for each element and sample medium, was created. Point-plot maps were made from the new data set for all 18 elements. Areas containing samples with "weight" values of 2, 3, or 4 were identified as geochemically anomalous. This method allowed interpretations to be made from geochemical maps that simultaneously displayed all available element data. Multielement suite maps also were created by plotting the sums of selected element weights. These maps were used to distinguish geochemically anomalous areas that have mineral potential from areas that have anomalies unrelated to mineral deposits.

Most of the samples containing elevated concentrations of base and precious metals and related elements are associated with known mining districts and mineral deposits. The following section describes geochemical anomalies within and proximal to the Forest. Most descriptions are given with respect to areas of known deposits; other anomalies are referenced to local prominent geographic features. The general locations of the anomalous areas are shown on figure 3, and mining districts are shown on figure 5; more detailed location information is on plate 1.

Table 4. Threshold values used to divide concentration ranges of elements in different sample media into five classes: low background, high background, slightly anomalous, moderately anomalous, and highly anomalous.

[Values in parts per million. (a), threshold of high background class (lowest high background value); (b), threshold of slightly anomalous class (lowest slightly anomalous value); (c), threshold of moderately anomalous class (lowest moderately anomalous value): (d), threshold of highly anomalous class (lowest highly anomalous value); n.a., not analyzed; --, unused classes below the lower detection limits of the analytical method; aa, threshold values for additional analyses by atomic absorption spectroscopy]

Element	NURE stream-sediment samples				USGS stream-sediment samples				Other stream-sediment samples[1]				Heavy-mineral-concentrate samples				Rock samples			
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
Ag	--	--	2	10	0.5	1	5	10	0.5	1	5	10	--	2	3	50	0.5	5	50	500
As	12	20	30	50	10	20	30	40		n.a.			--	140	200	1000	--	140	200	1000
Au	--	--	0.04	0.5	--	--	0.02	0.5		n.a.			--	--	--	50	--	--	7	10
													0.03	0.05	0.5	2 aa	0.01	0.02	0.2	1 aa
Bi		n.a.			--	--	--	--		n.a.			--	14	20	100	--	--	10	100
Cd	--	--	5	7	--	--	--	--		n.a.			--	--	--	--	--	--	20	100
Co[2]	16	25	50	75	30	50	70	100	12	18	30	70	50	100	300	700	20	50	100	1000
Cr[2]	100	200	300	800	200	500	1000	5000	40	70	100	500	200	500	1000	5000	100	500	1000	5000
Cu	40	60	100	500	40	60	100	500	40	60	100	500	30	50	100	500	50	100	1000	10000
Hg		n.a.				n.a.				n.a.				n.a.			0.1	0.2	0.5	2
Mo[3]	--	--	--	4	3	5	10	20		n.a.			10	50	100	500	2	15	50	200
Ni	35	65	100	500	70	100	200	500	30	70	100	500	30	70	200	700	70	200	1000	5000
Pb[2]	20	35	100	200	35	55	100	200	20	35	100	200	200	500	1000	2000	50	100	700	10000
Sb	--	2	4	9	--	--	--	--		n.a.			--	--	140	200	--	70	100	150
Sn	--	10	16	30	--	10	16	30		n.a.			20	50	100	300	7	10	20	70
U	7	15	30	60		n.a.				n.a.				n.a.			5	30	50	500
V	120	160	250	400	200	300	500	700		n.a.			200	500	700	1000	150	300	500	1000
W	--	15	20	40	--	--	30	50		n.a.			70	150	500	1000	35	50	500	1000
Zn	150	175	250	500	90	150	250	500	90	150	250	500	--	300	700	2000	75	200	1000	10000

1 Stream-sediment samples from Allen (1982)

2 Co, Cr, and Pb thresholds used for USGS stream-sediment samples from the Service Creek Roadless Area are 50-70-100-150 (Co); 300-700-1000-5000 (Cr); and 100-150-200-300 (Pb).

3 Mo thresholds used for USGS stream-sediment samples from the Rawah and Never Summer Wilderness Areas are 3-7-15-20.

RESULTS

HAHNS PEAK MINING DISTRICT

Samples from the Hahns Peak mining district (fig. 5) and surrounding gold placers contained anomalous concentrations of antimony, arsenic, lead, molybdenum, silver, and zinc (for locations, see Snyder and others, 1981). Silver and arsenic were found at highly anomalous concentrations in stream-sediment samples; zinc, lead, molybdenum, and antimony also were determined to be moderately anomalous in at least one sample. One rock sample had moderately anomalous concentrations of arsenic and antimony. The anomalies are probably related to disseminated silver-lead-zinc mineral deposits associated with the Tertiary Hahns Peak porphyry stock (Young and Segerstrom, 1973).

CAM CLAIMS AREA

Samples from this area in the Never Summer Mountains contained anomalous concentrations of arsenic, bismuth, molybdenum, and zinc (for locations, see Pearson and others, 1981). One stream-sediment sample contained 500 parts per million (ppm) zinc, which is considered highly anomalous. Two rock samples contained anomalous concentrations of arsenic and molybdenum; bismuth and zinc also were found at moderately anomalous concentrations in rock samples. The Cam claims are in exposed mineralized Proterozoic gneiss.

HENDERSON-URAD MOLYBDENUM AREA

Highly anomalous concentrations of lead, tin, tungsten, and zinc and moderately anomalous concentrations of gold and copper are in stream-sediment samples around the Henderson and Urad molybdenum deposits (fig. 5) (for locations, see Theobald and others, 1985; Barton, 1985c). Each of the stream-sediment samples contained zinc in concentrations greater than 1,000 ppm and are among the highest stream-sediment zinc values in the study area. These deposits are classic examples of Climax-type molybdenum porphyry deposits (White and others, 1981).

MT. CUMULUS

Stream-sediment and rock samples collected on the west side of Mt. Cumulus in the Never Summer Mountains contained elevated concentrations of arsenic, bismuth, lead, molybdenum, tin, silver, and zinc (for locations, see Pearson and others, 1981). Zinc concentrations were anomalously high in most of the stream-sediment samples, and one rock sample contained greater than 1 percent Zn. Stream-sediment samples were characterized by an association of moderately to highly anomalous concentrations of zinc, lead, molybdenum, and tin plus slightly anomalous silver. Geochemically anomalous rock samples were distinguished by zinc-cadmium-lead, tin-arsenic, molybdenum-arsenic, or lead-silver-bismuth associations. The anomalies in the area are thought to be associated with the Tertiary Mt. Cumulus stock.

VASQUEZ PEAK MOLYBDENUM ANOMALOUS AREA

The area of the Vasquez Mountains (fig. 3) is characterized by high background concentrations of molybdenum and tin in rock and stream-sediment samples with moderately to highly anomalous concentrations of arsenic, bismuth, gold, lead, molybdenum, silver, and tin (for locations, see Theobald and others, 1985; Barton, 1985c). Slightly to moderately anomalous concentrations of molybdenum are in several rock and heavy-mineral-concentrate samples. One rock contained an anomalous concentration of tin, and several heavy-mineral-concentrates contained moderately to highly anomalous tin. Slightly anomalous concentrations of lead were determined in rock and heavy-mineral-concentrate samples. Arsenic was highly anomalous in two rock samples. Several heavy-mineral concentrates contained moderately to highly anomalous concentrations of silver, gold, or bismuth. One concentrate sample contained the highest gold and silver values (300 ppm Au and 200 ppm Ag) in samples from the Forest. A single stream-sediment sample in the same area contained 0.48 ppm gold. The anomalies are probably associated with a Tertiary stock in Proterozoic granite.

BEAR CREEK–LONE PINE CREEK ANOMALOUS AREA

Three rock samples in this area on the northeast side of the Park Range contained anomalous concentrations of cobalt, copper, nickel, and chromium (for locations, see Snyder and others, 1981). Another rock had anomalous concentrations of bismuth, copper, chromium, and silver. These anomalies are associated with an exposure of Proterozoic peridotite.

ELKHORN MINE AREA

The anomaly at the Elkhorn mine just south of the Wyoming border in the Park Range (Elkhorn Mountain mining district; fig. 5) is characterized by elevated concentrations of silver, gold, cadmium, copper, mercury, lead, antimony, and zinc in six rock samples (for locations, see Snyder and others, 1981). The analyzed rocks contained as much as 500 ppm cadmium, 3,000 ppm silver, 1,000 ppm antimony, 1 percent copper, 1 percent lead, and 20 percent zinc. Several stream-sediment samples have been collected in the Elkhorn mine area; none of these samples contained anomalous metal concentrations. The anomalies are associated with mineralized pods and veins in Proterozoic gabbro in the vicinity of the Elkhorn mine.

RED CANYON–CRYSTAL MINING DISTRICT

Ten rock samples from the Red Canyon–Crystal district (fig. 5) have moderately to highly anomalous concentrations of arsenic, molybdenum, and mercury (for locations, see Snyder and others, 1981) . These anomalies are probably related to fault zones in Proterozoic granite that have been prospected for fluorite and uranium.

SPRING CLAIMS AREA

Two spring-sediment samples collected for the National Uranium Resource Evaluation program east of the Park Range in North Park contained highly anomalous concentrations of uranium, including the maximum value (385 ppm U) in the Forest geochemical database (for locations, see Bolivar and others, 1979; Craig and others, 1982). The Spring claims cover an area with uranium enrichment in peat.

DIAMOND PARK AREA

Geochemical samples from the Diamond Park area in the northern part of the Park Range contained anomalous concentrations of bismuth, copper, lead, molybdenum, silver, and tungsten (for locations, see Snyder and others, 1981). Bismuth, copper, lead, and molybdenum values were moderately to highly anomalous in rock samples. Silver and tungsten were anomalous in rock and stream-sediment samples. Known deposits in the area consist of small mineralized quartz veins associated with fault zones in Proterozoic gneiss.

BEAVER CREEK AREA (FARWELL MOUNTAIN MINING DISTRICT)

Geochemical samples from the Beaver Creek area of the Farwell Mountain mining district just east of Hahns Peak contained elevated concentrations of arsenic, bismuth, copper, gold, lead, molybdenum, tin, tungsten, silver, and zinc (for locations, see Snyder and others, 1981). Rock samples were characterized by moderately to highly anomalous concentrations of copper, bismuth, tin, molybdenum, gold, silver, and tungsten, and low concentrations of lead and zinc. Several stream-sediment samples were characterized by anomalous zinc, lead, and silver concentrations. Molybdenum was also anomalous in two stream-sediment samples. The anomalies are probably associated with mineralized Proterozoic pegmatite, schist, and gneiss.

DAILEY (ATLANTIC) MINING DISTRICT

Geochemical anomalies of copper, lead, molybdenum, silver, tin, and zinc are in the Dailey mining district (fig. 5) (for locations, see Theobald and others, 1985; Barton, 1985c). Rock samples contained weakly anomalous concentrations of molybdenum, lead, and silver, and isolated moderately anomalous concentrations of lead, tin, and zinc. One heavy-mineral-concentrate sample was highly anomalous in copper, tin, and zinc and moderately anomalous in silver, molybdenum, and lead. Other heavy-mineral-concentrate samples contained moderate to high single-element anomalies of silver, copper, lead, or zinc. These geochemical anomalies are associated with mineralized shears and faults in Middle Proterozoic Silver Plume Granite.

KING SOLOMON MINE AREA (FARWELL MOUNTAIN MINING DISTRICT)

Three rock samples from the King Solomon mine area just east of Hahns Peak contained moderately to highly anomalous concentrations of copper, bismuth, zinc, lead, and silver (for locations, see Snyder and others, 1981). One stream-sediment sample also contained anomalous silver. The King Solomon mine exposes mineralized Proterozoic gneiss.

LA PLATA MINING DISTRICT

Highly anomalous concentrations of antimony, arsenic, cadmium, copper, lead, molybdenum, silver, tin, and zinc are in several rock samples from this district (fig. 5) (for locations, see Theobald and others, 1985; Barton, 1985b). Three rocks contained 1 to 1.5 percent lead, five rocks had greater than 1 percent zinc, five rocks had 1 percent or greater arsenic, and two rocks contained high silver (1,000 and 1,500 ppm Ag). Heavy-mineral-concentrate samples collected in this area have slightly to moderately anomalous concentrations of copper, molybdenum, and tin. The anomalies are associated with mineralized faults and shear zones in Middle Proterozoic Silver Plume Granite.

TELLER MINING DISTRICT

Numerous geochemical anomalies are in the Teller mining district (fig. 5) (for locations, see Pearson and others, 1981). Elements with elevated concentrations include antimony, arsenic, cadmium, copper, gold, lead, molybdenum, silver, tin, and zinc. Silver was present in moderately to highly anomalous concentrations in rock and stream-sediment samples. The district also contains moderately to highly anomalous molybdenum in rock saples; one sample contained greater than 2,000 ppm. Analyses of five rocks showed arsenic concentrations that were greater than 10 percent. Two rock samples contained greater than 500 ppm cadmium. Concentrations of antimony range as high as 1,500 ppm in rock samples. Lead was highly anomalous in several rock samples (four determinations were greater than 1.5 percent) and in stream-sediment samples. Six rock samples contained zinc in quantities from 1 to 12 percent; several stream-sediment samples were also highly anomalous in zinc. Gold, copper, and tin were at anomalous concentrations in rock samples. Most stream-sediment samples from the district contained anomalous concentrations of silver, lead, and zinc; scattered stream-sediment samples also contained anomalous concentrations of arsenic, cobalt, copper, and molybdenum. The Teller district mines and prospects were excavated in mineralized fracture zones and veins in Proterozoic granite and schist. Silver was probably the primary target of exploration (Pearson and others, 1981).

RED ELEPHANT MOUNTAIN AREA

One rock sample collected from this area in the northeast part of the Park Range near Mt. Zirkel contained anomalous concentrations of bismuth, copper, gold, lead, and silver (for locations, see Snyder and others, 1981). None of the stream-sediment samples from this area were anomalous in metals. The anomalous rock came from a mineralized zone in steeply dipping layered gneiss (Patten, 1987).

BEAVER CREEK–NORRIS CREEK AREA

Anomalous concentrations of molybdenum and uranium were determined in stream-sediment samples from this area on the east side of the Park Range (for locations, see Snyder and others, 1981). No rock samples with anomalous metals were analyzed from the area. The anomalies are probably associated with local uranium enrichment in the Upper Jurassic Morrison Formation.

BEAVER CREEK AREA

Elevated uranium and molybdenum concentrations were found in rocks from the Beaver Creek area southeast of Kremmling (for locations, see Snyder and others, 1981). The maximum uranium value of the entire data set was at this location (1180 ppm U). Four other rock samples from this area contained anomalous concentrations of uranium.

Molybdenum was found at moderately to highly anomalous concentrations in five rock samples. The anomalies are probably associated with exposures of uranium-enriched Upper Cretaceous(?) and Paleocene Middle Park Formation.

SPENCER HEIGHTS AREA

Rock samples from the Spencer Heights area east of the Forest in the Cache la Poudre contained highly anomalous concentrations of uranium, as much as 872 ppm (for locations, see Pearson and others, 1981). The anomaly is associated with uranium mineralization in a broad shear zone and pegmatite dikes cutting granitic gneiss.

GREENVILLE MINE AREA

Several geochemical samples from the Greenville mine and vicinity (Greenville mining district; fig. 5) contained elevated concentrations of antimony, bismuth, cadmium, copper, lead, silver, tin, tungsten, and zinc (for locations, see Snyder and others, 1981). Copper, lead, and zinc were each in rock samples at concentrations greater than 10 percent. Moderately and highly anomalous concentrations of silver, bismuth, cadmium, antimony, and tin were in selected rock samples. A few rocks contained anomalous concentrations of gold, and almost every rock contained molybdenum in slightly anomalous concentrations. Thirteen stream-sediment samples were collected by Snyder (1987a) downstream from the Greenville mine. At a distance of about 1 km downstream from the mine, the concentrations of copper, lead, and silver in these samples dropped from highly anomalous to low background levels; zinc was still slightly anomalous 2 km downstream. This suggests, at least within the Park Range, that stream-sediment anomalies are locally derived. The anomalies at the Greenville mine are associated with a metamorphosed massive sulfide deposit (Snyder, 1987a).

LOWER SLAVONIA MINING DISTRICT

This area in the headwaters of Gilpin Creek in the Park Range contains geochemical anomalies of antimony, bismuth, cadmium, copper, gold, lead, silver, tin, and zinc (for locations, see Snyder and others, 1981). Rock samples contained highly anomalous concentrations of each of these elements. Only one stream-sediment sample from the area had anomalous copper concentrations.

UPPER SLAVONIA MINING DISTRICT

The Upper Slavonia mining district in the headwaters of Gilpin Creek in the Park Range contains enriched concentrations of antimony, bismuth, cadmium, copper, gold, lead, mercury, molybdenum, silver, tin, and zinc (for locations, see Snyder and others, 1981). Rock samples contained anomalously high values for many of these elements; greater than 500 ppm cadmium, 2 percent copper, 1.5 percent lead, 19 percent zinc, and greater than 10 ppm mercury. Three stream-sediment samples had anomalous concentrations of copper, lead, or zinc.

PEARL MINING DISTRICT

Geochemical samples from the Pearl mining district (fig. 5), and the associated mineralized area on Independence Mountain, contained anomalous concentrations of bismuth, cadmium, copper, gold, lead, mercury, silver, tin, tungsten, and zinc (for locations, see Snyder and others, 1981). Most of the rock samples from the area were highly anomalous in copper, lead, zinc, silver, gold, and bismuth. A few rock samples were moderately or highly anomalous in cadmium, mercury, or tungsten. Stream-sediment samples were slightly to moderately anomalous in zinc and silver, with a few samples having slightly anomalous concentrations of copper, lead, and tungsten.

POISON RIDGE AREA (A.O. PORPHYRY COPPER DEPOSIT)

No geochemical samples from the Poison Ridge area (Poison Ridge mining district; fig. 5) were in the database. Kinney and others (1968) report anomalous molybdenum, lead, and copper in rock samples as well as very anomalous concentrations of copper, lead, zinc, and molybdenum in stream-sediment samples. The anomalies are related to the A.O. porphyry copper deposit, associated with a Tertiary quartz latite porphyry stock. Karimpour (1982) reported that rock samples from exploration drill holes contained anomalous concentrations of copper (as much as 4,400 ppm), molybdenum (140 ppm), gold (0.45 ppm), silver (2.74 ppm), and tungsten (10 ppm).

PEAK 9731–ELKHORN COMPLEX AREA

This area near the Wyoming border in the Park Range contains anomalous concentrations of cobalt, chromium, and nickel (for locations, see Snyder and others, 1981). Rock and stream-sediment samples show the same geochemical signature of anomalous chromium and cobalt associated with slightly anomalous nickel. The anomaly is associated with gabbros and peridotite in the Elkhorn igneous complex.

BIG CREEK AREA

A weak geochemical anomaly of slightly elevated concentrations of antimony, arsenic, cadmium, copper, gold, mercury, tungsten, vanadium, and zinc was found in the Big Creek area on the western side of the Park Range (for locations, see Snyder and others, 1981). Two rock samples have anomalous concentrations of vanadium, cadmium, and zinc. Stream-sediment samples were characterized by slightly anomalous concentrations of arsenic, gold, copper, mercury, antimony, tungsten, and zinc. The anomalies are probably related to massive sulfide mineralization in Proterozoic schist and layered gneiss.

CONTINENTAL DIVIDE–FISH CREEK RESERVOIR ANOMALOUS AREA

A single rock sample collected on or near the Continental Divide west of Fish Creek Reservoir contained highly anomalous concentrations of gold, cobalt, molybdenum, and vanadium; moderately anomalous concentrations of silver and arsenic; and slightly anomalous concentrations of copper and nickel (for locations, see Snyder and others, 1981). No additional information about the source of this mineralized sample or the type of rock analyzed is available in the database.

MORRISON CREEK–BEAVER CREEK ANOMALOUS AREA

Two stream-sediment samples from the vicinity of Morrison and Beaver Creeks, (8 mi west of Yampa, Colo.) contained highly anomalous concentrations of silver, arsenic, vanadium, and zinc with moderately anomalous concentrations of cobalt, tin, and tungsten (for locations, see Schmidt and others, 1984). The concentration of silver here is one of the highest values for the Forest study area (69 ppm). No sources for these anomalies are known.

OTHER OCCURRENCES

Silver.—The maximum silver value (79 ppm) in the stream-sediment data set was in a NURE sample from the Service Creek drainage within the Service Creek Roadless Area. Two more samples in the Silver Creek drainage, within the Service Creek Roadless Area, contained anomalous silver values. The source of these anomalies is not known. Three NURE stream-sediment samples with anomalous concentrations of silver were collected on the northeast flank of Independence Mountain, west of State Highway 125 and the Forest boundary. Possibly, silver may have come from the conglomerates on the crest of Independence Mountain, which may also have been the source for gold placers on the southwest flank (Hail, 1965).

Arsenic.—Two stream-sediment samples with anomalous arsenic values were collected in the Pagoda Peak–Sand

Peak area northwest of the Flat Tops Primitive Area. No sources for the anomalies are known.

Bismuth.—One rock sample, from the north side of Buffalo Mountain in the Soda Creek drainage basin, contained anomalous concentrations of bismuth, copper, and mercury. The source of the metal anomaly is unknown. Several claims and prospects in this area are assumed to have been located for uranium exploration (Snyder, 1987a).

Cadmium.—Localities of stream-sediment samples with slightly anomalous values of cadmium are scattered widely throughout the Forest. Almost none of these localities coincide with areas of known mineral deposits or with localities containing anomalous cadmium in rock samples. The anomalous stream-sediment samples were analyzed by the same laboratory and method. The anomalous cadmium sample distribution pattern and the lack of correlation with known cadmium occurrences suggests that these anomalies are random and possibly due to analytical variation near the lower determination limit of the analytical method.

Cobalt.—A broad cobalt anomaly in NURE stream-sediment samples occurs in the Flat Tops Primitive Area. These samples are associated with Tertiary basalt flows that cover the area (Tweto, 1976; Tweto and others, 1978). A similar cobalt anomaly is associated with exposures of the Proterozoic Elkhorn igneous complex in the northern part of the Forest. Mafic rock types, including the basalts in the Flat Tops Primitive Area and the gabbro and peridotite sequences in the Proterozoic Elkhorn igneous complex, are commonly enriched in cobalt, chromium, nickel, and vanadium. A cobalt anomaly over exposures of these rock types may not be related to unusual or economic concentrations of cobalt or associated elements but merely represents high background levels of cobalt. Several rock samples in the area of Simpson Mountain between Service Creek and Silver Creek within the Service Creek Roadless Area contained slightly anomalous concentrations of cobalt. The source of these anomalies is not known.

Chromium.—The distribution of elevated chromium in stream-sediment samples is similar to that of cobalt, nickel, and vanadium and correlates with exposures of Tertiary basalt in the Flat Tops Primitive Area and exposures of the Elkhorn complex. Chromium values also were slightly to moderately anomalous in rock samples in the Simpson Mountain area. These anomalous chromium values are attributed to high background in mafic rocks.

Copper.—One rock sample with a highly anomalous copper concentration and a moderately anomalous mercury concentration was collected from the vicinity of the Continental Divide just west of Round Mountain near the southern boundary of the Mt. Zirkel Wilderness. The source of these anomalies is not known. Another rock sample, collected on the north side of Buffalo Mountain in the Soda Creek drainage basin contained anomalous concentrations of copper, bismuth, and mercury. The source of the anomalous rock is unknown. Another rock sample with anomalous copper concentration was collected from the Kelly Lake area just west of the Rawah Wilderness. Pearson and others (1982) describe an outcrop of copper-bearing rock at this locality. Copper Ridge, just north of Steamboat Springs, is the source of an additional rock sample with anomalous copper.

Gold.—The maximum value for gold in the stream-sediment data set (7.42 ppm Au) was determined in a sample from the drainage basin just south of Threemile Creek on the northeast flank of Independence Mountain. The source of this gold is probably the same conglomerates thought to be responsible for the placers on the southwest side of Independence Mountain (Hail, 1965). Another stream-sediment sample that contained a highly anomalous concentration of gold (1.06 ppm) was collected outside of the Forest in the Soda Creek drainage basin, 1 mi north of Steamboat Springs. The source of this gold is not known. Two stream-sediment samples from the northeast flank of Bear Mountain and just outside the Mt. Zirkel Wilderness contained anomalous gold values. The source for these samples may be mineralized rock similar to that in the Upper Slavonia district just west of the Continental Divide. Two stream-sediment samples, collected southwest of Rand and in the Willow Creek drainage basin just north of the Forest boundary, contained anomalous concentrations of gold. The source of this gold is probably in the upper Willow Creek drainage basin and may lie within the Forest.

Lead.—A cluster of anomalous lead concentrations in heavy-mineral-concentrate samples was found in the headwaters of Keyser Creek within the St. Louis Peak Roadless Area. These samples were also anomalous in tungsten and zinc. Theobald and others (1985) suggests that these anomalies are associated with small massive sulfide deposits.

Mercury.—One rock sample from the Continental Divide, just west of Round Mountain, contained moderately anomalous concentrations of mercury and copper. A group of four rock samples from the north side of Buffalo Mountain in the Soda Creek drainage basin contained slightly to moderately anomalous concentrations of mercury. One of these samples was also anomalous for copper. The sources of these anomalies are unknown.

Molybdenum.—The entire southern half of the Rawah Wilderness contains slightly to moderately anomalous concentrations of molybdenum in stream-sediment samples. Pearson and others (1982) suggested that the Proterozoic granites in the Wilderness Area contained elevated concentrations of molybdenum. Four stream-sediment samples with anomalous concentrations of molybdenum were collected in the Silver Creek drainage basin within the Service Creek Roadless Area. No source is known for these anomalies. One rock sample in the Northgate fluorite mining district (fig. 5) was highly anomalous in molybdenum. Similar molybdenum enrichment was associated with the fluorite deposits in the Red Canyon–Crystal mining district (fig. 5).

Nickel.—Almost every stream-sediment or rock sample with elevated nickel concentrations collected in the Forest region is associated with the common mafic rock geochemical signature of cobalt-nickel-chromium-vanadium. The Tertiary basalts in the Flat Tops Primitive Area and the Elkhorn complex are delineated by anomalous nickel concentrations in stream-sediment samples. The Simpson Mountain area also has slightly anomalous nickel concentrations in rock samples.

Tin.—A number of stream-sediment samples collected in Big and Little Red Parks northwest of Hahns Peak (fig. 5) contained anomalous tin values. The Fish Creek area west of Steamboat Springs contains three stream-sediment sample localities and one rock sample locality with anomalous tin. Several rock samples and two stream-sediments samples that were collected in the Service Creek Roadless Area between Service Creek and Silver Creek contained anomalous concentrations of tin. No sources are known for these anomalies.

Uranium.—Five rock samples collected along the west side of lower Troublesome Creek contained anomalous concentrations of uranium and molybdenum. These rocks, from the upper Oligocene and Miocene Troublesome Formation of Middle Park, may reflect sandstone-hosted uranium enrichment. One stream-sediment sample containing anomalous concentrations of uranium and zinc was in the Agua Fria area. The uranium is associated with a pegmatite in Proterozoic quartz monzonite (Snyder, 1987a). One rock sample, containing 896 ppm uranium, was collected just north of U.S. Highway 40 before the descent into the Harrison Creek drainage. This anomaly is unrelated to known sources. A stream-sediment sample in the Service Creek drainage also contained anomalous concentrations of uranium without a known source.

Vanadium.—The distribution of vanadium is similar to that of cobalt, chromium, and nickel as discussed above. In addition to slight enrichment in rock samples near Simpson Mountain, nearby stream-sediment samples in Silver Creek contained anomalous concentrations of vanadium. Several rocks in the Byers Peak region of the St. Louis Peak Roadless Area contained anomalous concentrations of vanadium. The sources of these anomalies are not known.

Tungsten.—Heavy-mineral-concentrate samples collected from the upper Keyser Creek drainage basin were anomalous in tungsten, lead, and zinc. Small massive sulfide deposits may be responsible for the anomaly (Theobald and others, 1985). Several stream-sediment samples from the Rawah Wilderness Area were highly anomalous in tungsten. This same region is also high in molybdenum. The elevated tungsten and molybdenum values may be related to the granitic terrain.

Zinc.—Anomalous zinc was associated with anomalous lead and tungsten in heavy-mineral-concentrate samples collected from the Keyser Creek region.

GEOPHYSICAL STUDIES

By Viki Bankey *and* James A. Pitkin

PREVIOUS STUDIES

Geophysical studies were made of six Forest Service Wilderness Study Areas within or adjacent to the Forest: the Mt. Zirkel Wilderness and northern Park Range vicinity (Daniels, 1987); the Rawah Wilderness (Pearson and others, 1982); the Comanche–Big South, Neota–Flat Top, and Never Summer Wilderness Study Areas (Pearson and others, 1981); the Indian Peaks Wilderness Study Area (Pearson and U.S. Bureau of Mines, 1980); the Gore Range–Eagle's Nest Wilderness (Tweto and others, 1970); and the Vasquez Peak Wilderness and vicinity (Moss and Abrams, 1985). Other geophysical studies in the area were made by Behrendt and others (1969) and Johnson and others (1984). Figure 6 shows areas included in these published reports that provide both maps and interpretations of geophysical anomalies.

Three sets of geophysical data, comprising gravity, aeromagnetic, and radiometric maps, were compiled from previous studies (figs. 7 and 8) and interpreted for the area of the Forest.

GRAVITY DATA

The complete Bouguer gravity anomaly map (fig. 8) was produced using edited gravity data from 4,200 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 UTM projection having a central meridian of longitude 107°W. and a base latitude of 39°. These data were gridded at a spacing of 1.2 mi (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 on shallower, more local anomalies, a derivative gravity map (fig. 9) was calculated from the Bouguer gravity grid using the computer program FFTFIL (Hildenbrand, 1983) to remove or filter anomaly wavelengths longer than about 42 mi (70 km). The filter was selected to eliminate 100 percent of the wavelengths greater than 48 mi (80 km), to pass 100 percent of the wavelengths less than 36 mi (60 km), and to pass a linear percentage of the wavelengths between these values. This "high-pass" derivative map emphasizes anomalies produced by shallow sources and suppresses longer wavelength anomalies that are related to deep sources.

The horizontal gradient of the gravity field was calculated using the method of Cordell and Grauch (1985), which results in high gradient values where the gravity field changes intensity over short distances across the map. The maximum gradient trends are plotted on the high-pass gravity map (fig. 9) as dashed white, somewhat discontinuous lines. These sinuous lines of maximum gradient commonly follow geologic boundaries resulting from measurable density contrasts. The method best reflects the surface projection of vertical boundaries between shallow units; boundaries dipping less than 90° will be offset from the maximum gradient (Blakely and Simpson, 1986). These inaccuracies are less apparent at regional scales (Grauch and Cordell, 1987).

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 limits 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.

AEROMAGNETIC DATA

Figure 7 is a reference map for previous aeromagnetic surveys showing location, flight-line spacing and direction, and original flight elevation of surveys. A magnetic anomaly map of the Forest (fig. 10) was produced from

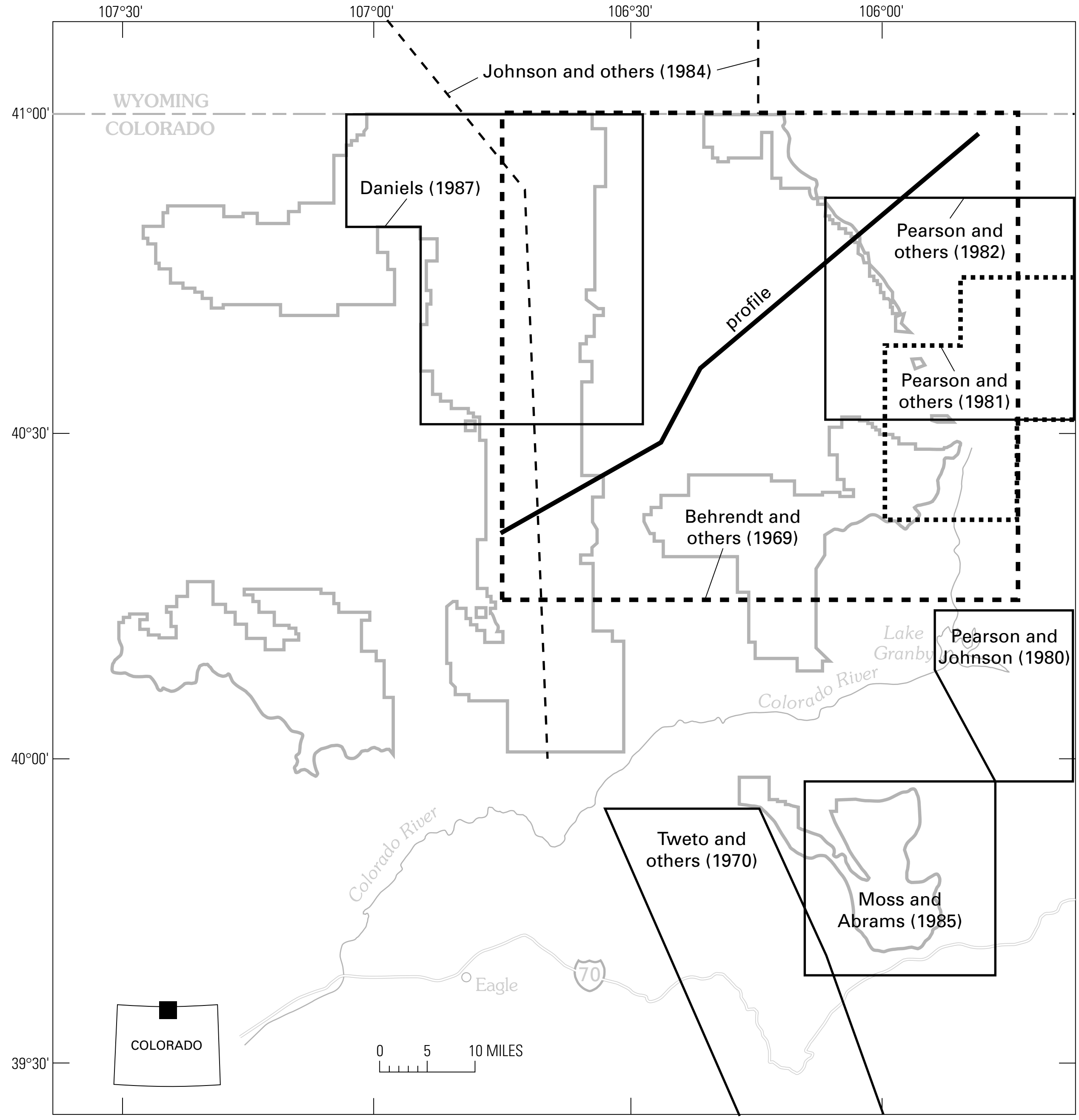
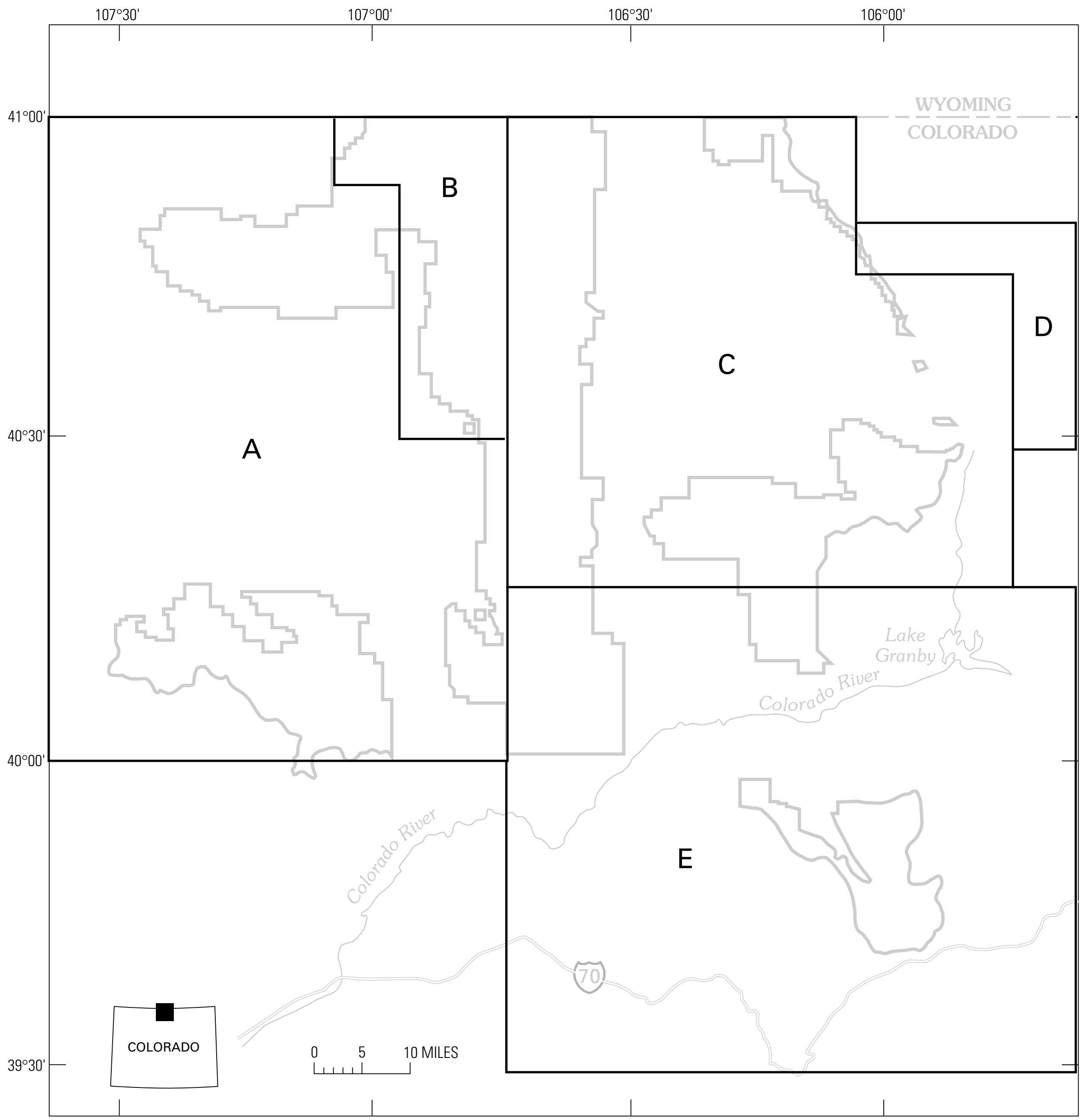


Figure 6. Map showing areas of previous geophysical studies. See References Cited section of this report for complete citations.

these surveys. Data from these surveys were projected using a UTM projection having a central meridian of longitude 107°W. and a base latitude of 39°N. The data were initially gridded at a spacing of 1/3 to 1/4 the flight-line spacing, then were regridded to 1 km. The Definitive International Geomagnetic Reference Field (DGRF), updated to the date and elevation of each survey, was removed before merging, using a program by Sweeney (1990). The total-intensity magnetic anomaly map (fig. 10) shows regional magnetic anomalies; for more detail, refer to the original magnetic maps referenced in figure 7 that are plotted at a larger scale.

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 and metamorphic rocks contain enough magnetic minerals to



EXPLANATION

Letter on map	Elevation (ft)	Line spacing (mi)	Dir.	Survey area	Year flown	Reference
A	400 a.t.	3 mi	E-W	Craig NURE	1978	LKB Resources (1979)
B	12,000 bar.	2 mi	N-S	North Park west	1972	USGS (1978)
C	13,000 bar.	2 mi	E-W	North Park central	1965	USGS (1978)
D	400 a.t.	1 mi	N-S	Front Range NURE	1977	Geometrics (1979a, 1979b)
E	14,000 bar.	1 mi	E-W	Wolcott-Boulder	1967	USGS (1968)

[Line spacing refers to distance between flight lines; Dir. refers to the direction the survey was flown; Elevation refers to the elevation of the survey flown, either at constant barometric elevation (bar.) or constant clearance above terrain (a.t.)]

Figure 7. Map showing location of aeromagnetic surveys used to compile aeromagnetic map.

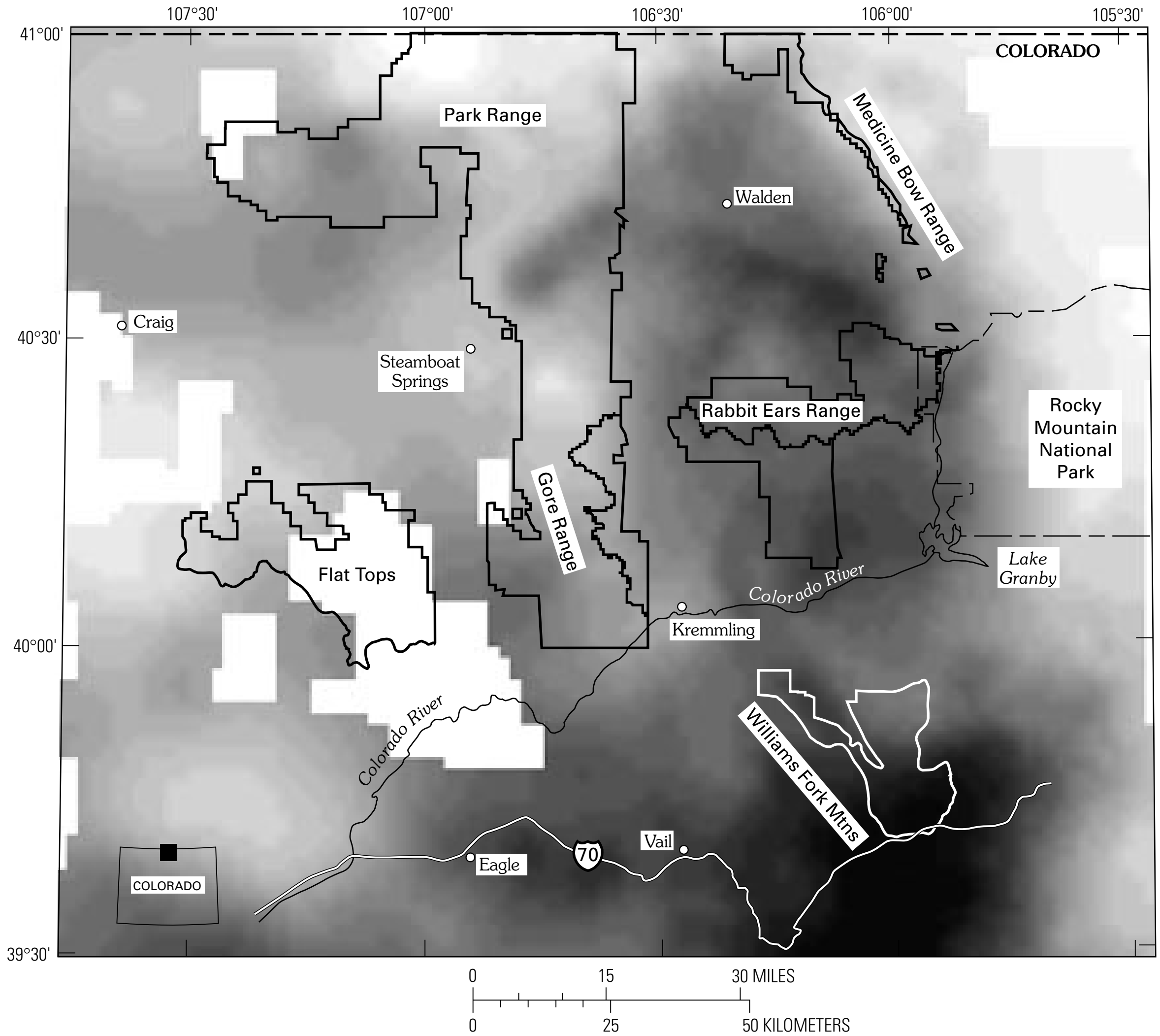


Figure 8. Complete-Bouguer gravity anomaly map of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Darker grays indicate lower gravity values; lighter grays indicate higher gravity values. White blocks show large areas of no data.

generate magnetic anomalies, whereas sedimentary rocks are commonly nonmagnetic.

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 northern side of a magnetic high. In some cases, 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. Another 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-intensity 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 on the White River uplift. Reversals in older intrusive rocks (such as Proterozoic rocks) may no longer cause a magnetic low because the magnetization of the rocks tends to decay over time and eventually will align itself with the direction of the present-day Earth's magnetic field.

Aeromagnetic anomaly maps are important tools in mapping surficial and buried igneous rocks. Aeromagnetic data can be used to locate and estimate depths to igneous intrusions that may be related to possible mineral deposits. Rings of magnetic highs with central or reentrant lows may indicate porphyry systems in which hydrothermal alteration has destroyed preexisting magnetic minerals.

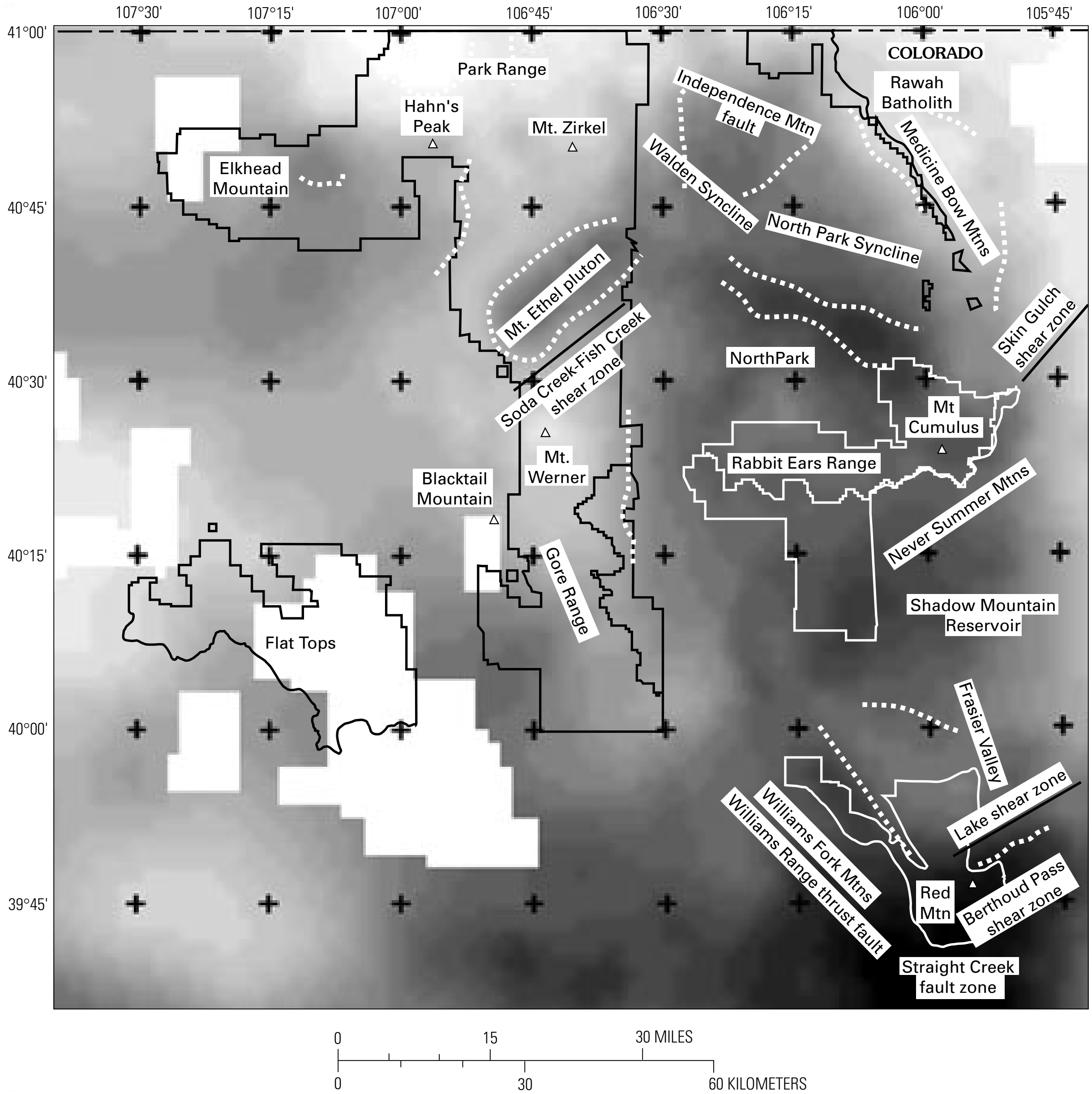


Figure 9. High-pass filtered Bouguer gravity anomaly map of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Darker grays indicate lower gravity values; lighter grays indicate higher gravity values. Dashed white lines trace high gravity gradients (see text). White blocks show large areas of no data.

Local magnetic highs may exist where hydrothermal alteration or contact metamorphism has created secondary magnetic minerals, as for example in a magnetite-bearing ore body.

Aeromagnetic anomaly maps have some limitations in locating mineral deposits. Some of the known mineral deposits in the Forest have no distinctive aeromagnetic expression—the Henderson molybdenum deposit is one example. 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.

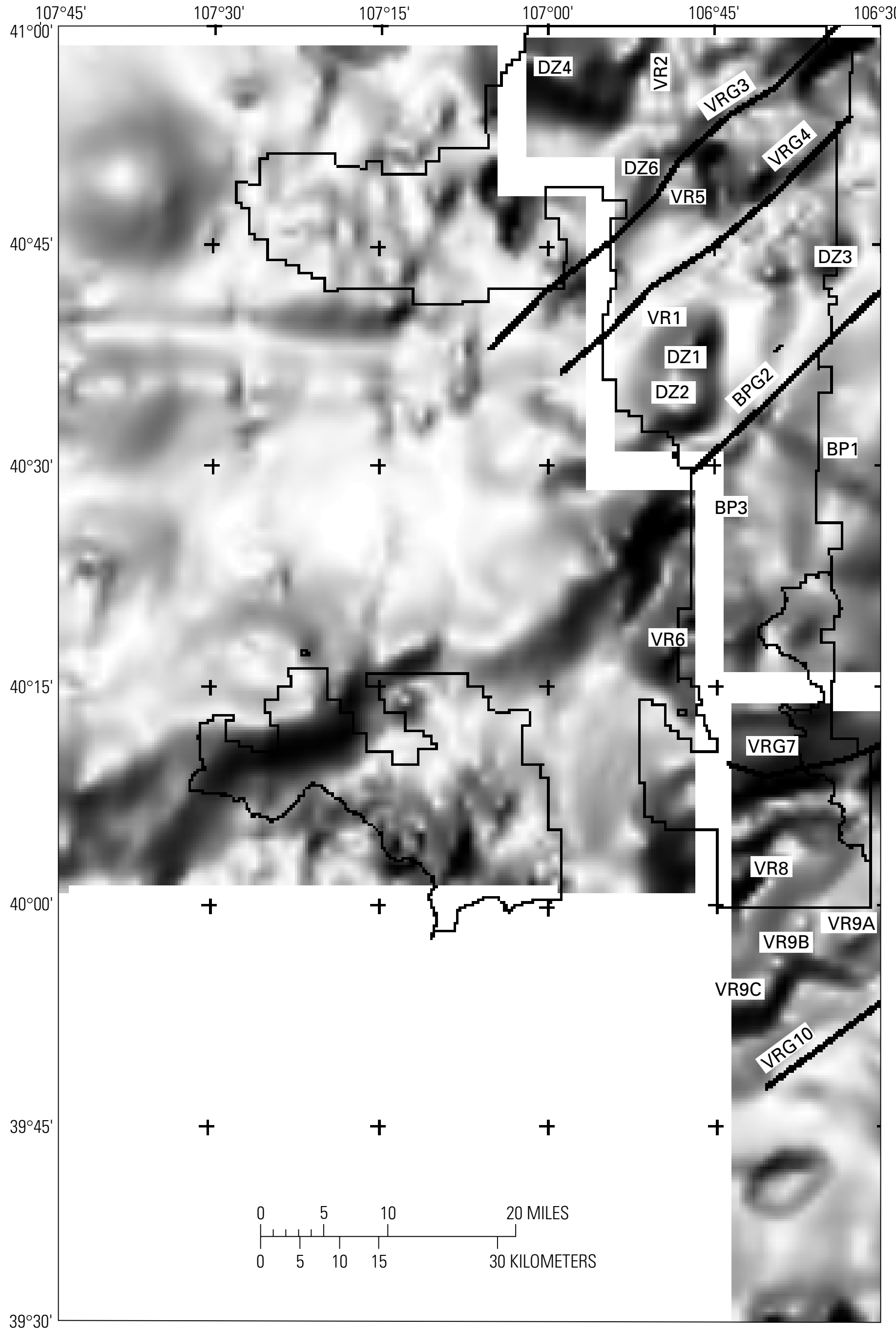
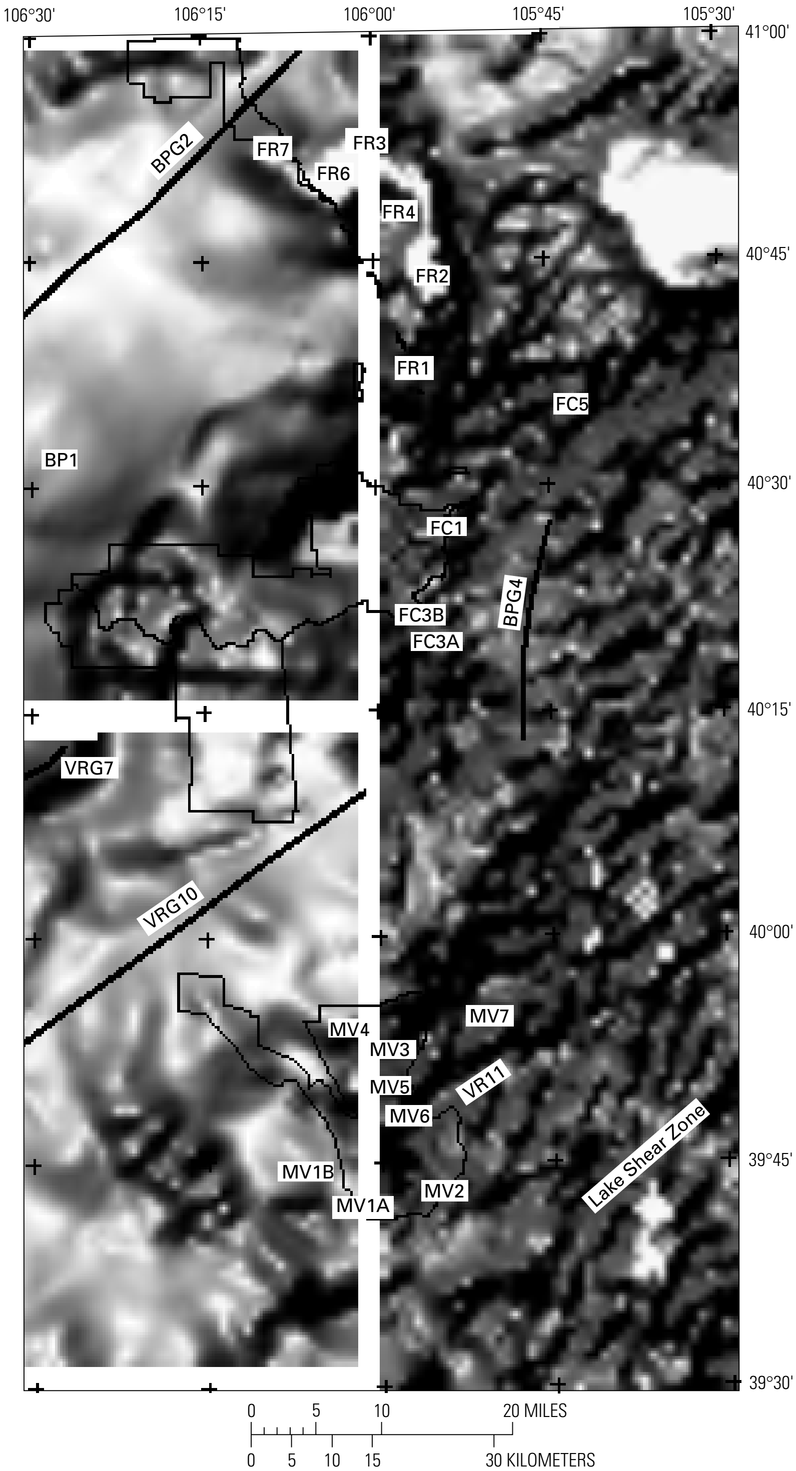


Figure 10 (above and facing page). Residual shaded-relief magnetic anomaly map of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Sun angle is 80 degrees, sun direction from the northwest. Magnetic anomalies are identified in text.

PHYSICAL PROPERTIES OF ROCKS

Earlier studies in the Forest and vicinity that provide measurements of density and susceptibility of various rock types are summarized in table 5.

Proterozoic rocks in and near the Forest have a wide range of measured magnetic susceptibilities and densities. The Proterozoic granitoid and gabbroic rocks are generally the most magnetic (Moss and Abrams, 1985); Proterozoic metamorphic rocks are generally moderately magnetic,



although Proterozoic metasediments may be relatively nonmagnetic (Daniels, 1987). Proterozoic migmatites and biotite gneisses appear to be more magnetic than granites in some parts of the Gore Range in the southern part of the Forest (Daniels, 1987).

In and near the Forest, amphibolites and gabbros are the densest of the common Proterozoic rocks, whereas some granites and felsic metamorphic rocks have lower densities (Behrendt and others, 1969; Moss and Abrams, 1985). As a group, the Proterozoic rocks are significantly denser than Tertiary intrusive rocks (Case, 1967; Behrendt and others, 1969; Brinkworth, 1973; Moss and Abrams, 1985). Oligocene intrusives are among the least dense rocks in the study area (Moss and Abrams, 1985).

Table 5. Average susceptibility and density values for rocks in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest and vicinity, Colorado.

[n.a. not available]

Rock type	Number of samples	Susceptibility (cgs units)	Density (g/cm^3)
Daniels, 1987 (Mt. Zirkel area)			
1.8-Ga gabbro and mafic intrusions	8	1.8×10^{-3}	n.a.
1.7-Ga quartz monzonite - Buffalo Mtn.	2	1.8×10^{-3}	n.a.
1.7-Ga quartz monzonite - other	9	0.1×10^{-3}	n.a.
1.4-Ga quartz monzonite - Marguerite	2	4.1×10^{-3}	n.a.
1.4-Ga quartz monzonite - other	3	0.46×10^{-3}	n.a.
Proterozoic pelitic schists - chloritized	1	8.6×10^{-3}	n.a.
Proterozoic pelitic schists	3	0.02×10^{-3}	n.a.
Proterozoic gedrite gneiss	1	6.2×10^{-3}	n.a.
Proterozoic hornblende gneiss	2	0.65×10^{-3}	n.a.
Proterozoic metasedimentary and metavolcanic rocks, undifferentiated	12	0.33×10^{-3}	n.a.
Tertiary Browns Park Formation, altered	4	0.024×10^{-3}	n.a.
Tertiary Browns Park Formation, altered	4	0.114×10^{-3}	n.a.
Tertiary intrusives, olivine-bearing	4	2.68×10^{-3}	n.a.
Tertiary intrusives	6	0.732×10^{-3}	n.a.
Moss and Abrams, 1985 (Vasquez Peak and vicinity)			
Tertiary intrusive rocks			
rhyolite (altered)	n.a.	0.35×10^{-3}	2.38
quartz monzonite	n.a.	0.5×10^{-3}	n.a.
unaltered average	n.a.	n.a.	2.62
Cretaceous sedimentary rocks			
Pierre Shale	n.a.	nonmagnetic	2.61
Dakota Sandstone	n.a.	nonmagnetic	2.52
Niobrara Formation	n.a.	nonmagnetic	2.66
Proterozoic intrusive rocks			
Silver Plume Granite	n.a.	0.6×10^{-3}	2.67
Boulder Creek Granodiorite	n.a.	1.2×10^{-3}	2.66
gabbro	n.a.	10.3×10^{-3}	3.03
Proterozoic metamorphic rocks			
hornblende gneiss	n.a.	1.6×10^{-3}	2.89
biotite gneiss	n.a.	0.5×10^{-3}	2.74
sillimanite gneiss	n.a.	0.9×10^{-3}	2.76
amphibolite and calc-silicate gneiss	n.a.	1.0×10^{-3}	2.80
Case, 1967 (Colorado Mineral Belt)			
Proterozoic granitic rocks	35	n.a.	2.65
Proterozoic metamorphic rocks	46	n.a.	2.79
Tertiary porphyritic rocks	64	n.a.	2.65
Tweto and Case, 1972 (Leadville 30-minute quadrangle)			
Proterozoic rocks	n.a.	0.32×10^{-3}–4.5×10^{-3}	2.75
Paleozoic sandstones and quartzites	n.a.	0	2.63
Paleozoic dolomites and limestones	n.a.	0	2.80
Paleozoic, upper (undifferentiated)	n.a.	0	2.50
Cretaceous and Tertiary intrusive rocks	n.a.	0.46×10^{-3}–2.67×10^{-3}	2.63

Table 5. Average susceptibility and density values for rocks in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest and vicinity, Colorado—*Continued.*

[n.a. not available]

Rock type	Number of samples	Susceptibility (cgs units)	Density (g/cm^3)
Isaacson and Smithson, 1976 (Sawatch Range, Elk and West Elk Mountains)			
Proterozoic rocks	36	n.a.	2.71
Tertiary granitic rocks	27	n.a.	2.63
Campbell and Wallace, 1986 (Holy Cross Wilderness Area and vicinity)			
Proterozoic intrusive rocks	n.a.	0.68×10^{-3}	n.a.
Proterozoic metamorphic rocks	n.a.	0.3×10^{-3}	n.a.
Proterozoic granites	n.a.	0.5×10^{-3}	n.a.
Cretaceous-Tertiary intrusive rocks	n.a.	0.58×10^{-3}	n.a.
Behrendt and others, 1969 (Park Range, North Park); Plouff, 1961 (Roberts Tunnel)			
Proterozoic metamorphic rocks	n.a.	n.a.	2.84
Proterozoic granitic rocks	n.a.	n.a.	2.64
Mesozoic sedimentary rocks	n.a.	n.a.	2.60
Cenozoic sedimentary rocks	n.a.	n.a.	2.40

Density measurements of Mesozoic and Tertiary sedimentary rocks to the west and southwest in the central Colorado Plateau (Plouff, 1961) vary from 2.3 to 2.6 grams/cubic centimeter (g/cm^3). Mesozoic and Tertiary rocks in the study area are lithologically similar (Behrendt and others, 1969) and may have similar densities. The few available measurements of magnetic susceptibility of these rocks indicate that they are virtually nonmagnetic.

Some Tertiary plutons are magnetic and produce conspicuous positive anomalies (Moss and Abrams, 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).

No measurements of remanent magnetizations for the rocks in the Forest and vicinity are available. Pearson and U.S. Bureau of Mines (1980) suggest that the mid-Proterozoic Silver Plume granite may be reversely magnetized, but the amount of remanence is unknown. On the magnetic anomaly map (fig. 10), the Silver Plume granite appears less magnetic than surrounding rocks where it crops out in the study area.

INTERPRETATIONS OF GRAVITY AND MAGNETIC DATA

REGIONAL FEATURES

Regional northeast-trending magnetic and gravity highs, lows, and gradients occur across the study area and beyond and have been noted previously. The northeast-trending grain in a regional aeromagnetic map of the area has been interpreted as part of a Proterozoic zone or belt of en echelon shears 200 mi wide that extends from the Grand Canyon to south of the Black Hills (Zietz and others, 1969). Pratt and Zietz (1973) interpreted the alignment of magnetic anomalies from Rangely, Colo., to 6 mi south of Julesburg, Colo., as a major basement structural discontinuity that may have controlled the location of the Tertiary volcanic centers of the Rabbit Ears Range and Never Summer Mountains. Prodehl and Lipman (1989) recognized that the dominant structural grain of Proterozoic rocks parallels accretion boundaries, primarily the Mullen Creek–Nash Fork zone of continental suturing of Archean and Proterozoic crust in southeastern Wyoming. Major Proterozoic shear zones, such as the Soda Creek–Fish Creek, Homestake, Berthoud Pass, and Idaho Springs–Ralston shear zones, parallel this trend. These northeast-trending zones 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 the area between the Mullen Creek–Nash Fork shear zone at its northern boundary and the Homestake shear zone—an area about 100 mi wide that covers the entire Forest study area. Warner postulates that this zone, which he named the Colorado lineament, can be traced from the Grand Canyon to Lake Superior and probably ceased as a wrench-fault system about 1,700 m.y. ago. Regardless of the 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 preexisting conduits for later intrusions and possible mineralizing fluids.

Zietz and others (1969) also notes an east-west trend in the aeromagnetic data, especially in the western part of the State, that includes the east-west-trending Independence Mountain fault (within the Forest) and Proterozoic fold axes in the Front Range (east of the Forest).

Tweto (1987) has postulated that the Rawah batholith encompasses a much larger area than is mapped in the Medicine Bow Mountains. He has included outcropping granitic rocks in the Gore and Park Ranges as part of this batholith and cites boreholes that penetrated similar rock in North Park and southwest of the Park Range as evidence of continuity beneath cover. Rock composition within this batholith varies from granite, quartz diorite, and quartz monzonite, with numerous inclusions of more mafic igneous rocks. This variation in rock composition results in varying shapes and intensities of magnetic anomalies.

The southernmost part of the study area lies on the northern 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. This 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 Colorado Mineral 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). Because this gravity low does not continue northward into the Forest, we can predict that mineralization of the type associated with the low-density batholith and the related Colorado Mineral Belt will not be present in the study area.

For the purposes of discussing local geophysical features, the Forest is divided into five areas: the Park and Gore Ranges, including the Mt. Zirkel Wilderness Area; the Medicine Bow Mountains; the Rabbit Ears and Never Summer Mountains; the Williams Fork Mountains, including the Vasquez Wilderness Area; and the Flat Tops (fig. 4). Geophysical anomalies show poor correlation with mapped rocks in the northwestern part of the Forest near the Elkhead Mountains, and this area is not included in detailed interpretation. Magnetic anomaly numbers on figure 10 have been assigned as shown in table 6.

PARK AND GORE RANGES AND THE MT. ZIRKEL WILDERNESS AREA

Behrendt and others (1969) conducted a geophysical study of the North Park Basin and surrounding mountains using gravity, aeromagnetic, and seismic data. Their discussion of gravity and magnetic anomalies in the Park Range and Medicine Bow Mountains is summarized here and augmented with more detailed or current interpretation where appropriate.

Gravity anomalies arise in this area from contrasts between Proterozoic metamorphic and plutonic rocks, and between Cenozoic sedimentary and older sedimentary rocks. The Independence Mountain thrust sheet north of North Park is associated with a gravity high that increases northward to the Wyoming border. This gravity high is bifurcated by a north-south-trending gravity low (fig. 9) that may indicate a sedimentary basin below the thrust plate or may be caused by low-density igneous rocks. Gravity lows caused by low-density basin-fill are at the deepest parts of the North Park syncline and the Walden syncline, outside the Forest.

Table 6. References for magnetic anomaly prefixes in figure 10.

Prefix	Author	Area	Reference
DZ	Daniels	Mt. Zirkel Wilderness	Daniels (1987)
BP	Behrendt	North Park and vicinity	Behrendt and others (1969)
FR	Flanagan	Rawah Wilderness	Pearson and others (1982)
FC	Flanagan	Comanche	Pearson and others (1982)
MV	Moss	Vasquez Peak	Moss and Abrams (1985)
VR	Bankey	Routt National Forest	This report

High-pass filtering of the Bouguer gravity data (fig. 9) shows a northeastern continuation of the Mt. Ethel pluton gravity low beyond the mapped extent of the pluton. Magnetization contrasts are not associated with this pluton. The gravity low encompasses the Walden syncline, reaches lower values just southwest of the Medicine Bow range-front fault, and continues across the northernmost Medicine Bow Mountains where granitic rocks are mapped. A gravity model of the Mt. Ethel pluton shows a granitic body with a density contrast of 0.2 g/cm^3 between the granite and surrounding rocks (Behrendt and others, 1969). Although low gravity values in North Park partially result from a syncline filled with low-density rocks, the trend and extent of the gravity low and correlation with magnetic gradients seem to confirm Behrendt and others' conclusion that buried granitic rocks are a contributing cause of this broad gravity low.

Behrendt and others (1969) concluded that positive magnetic anomalies in the Park Range and Medicine Bow Mountains are caused by Proterozoic rocks of varying composition, some having estimated magnetite content of as much as 1 percent. From geophysical evidence, they inferred the presence of high-density gneisses and schists, but later geologic mapping shows intermixing of unmetamorphosed igneous rocks (quartz monzonites and diorites) with crystalline metavolcanic and metasedimentary rocks (Snyder 1980a, 1980b, 1980c, 1980d). Because the magnetic variation within these units may be greater than the variation between units, determination of rock type based on magnetic mapping is not possible in this area.

A northeast-trending magnetic high (BP1; fig. 10, table 6) extends from the eastern Park Range, North Park, and the Medicine Bow Mountains. Behrendt and others (1969) modeled two gravity and magnetic profiles along this magnetic feature. Magnetic models show a complex basement terrane composed of blocks of varying amounts of mafic material, consistent with Tweto's (1987) hypothesis that the Rahwah batholith underlies this region and trends northeast-southwest. Gravity modeling suggests that rocks in the Medicine Bow Mountains have higher densities (2.90 g/cm^3) than rocks in the Park Range (2.80 g/cm^3). The maximum thickness of the sediment fill in North Park is 3.2 mi (5.3 km), and vertical uplift is at least 4.0 mi (6.7 km) for the Medicine Bow Mountains and 3.8 mi (6.4 km) for the Park Range, relative to North Park.

North-south gravity profiles through the Park Range and Medicine Bow Mountains by Johnson and others (1984) show that the Proterozoic island-arc crust south of the Mullen Creek–Nash Fork shear zone is thicker than the Archean Wyoming cratonic crust north of the zone, in agreement with recent seismic studies (Mooney, 1991). A density of 2.85 g/cm^3 for pelitic schists and gneisses (Johnson and others, 1984) is equivalent to high-density schists and gneisses of assumed density of 2.90 g/cm^3 (Behrendt and others, 1969). South of lat 40°30'N., a gravity high is attributed to both pelitic schist and gneiss and a body of Tertiary volcanic rocks having a density of 2.90 g/cm^3 (Johnson and others, 1984). The volcanic rocks do not appear magnetic on figure 10. Johnson and others (1984) suggest that the density of the Mt. Ethel granite may be 2.65 g/cm^3. The granite body is bounded on the south by the northeast-trending Soda Creek–Fish Creek mylonitic shear zone (Snyder, 1980b), a recurrently reactivated zone of movement that controlled the emplacement of the pluton (Tweto, 1987).

MT. ZIRKEL AND NORTHERN PARK RANGE

In the northern Park Range, magnetic anomalies that appear shallow (using anomaly size and intensity) may be caused by Proterozoic granites and metamorphic rocks, which are associated with polymetallic veins, or they may indicate areas of Tertiary intrusive rocks such as the Hahn's Peak intrusion, which are associated with disseminated silver-lead-zinc mineral deposits (fig. 16). Tertiary intrusions in proximity to Mt. Ethel batholithic rocks are also linked elsewhere in the Forest to fluorspar veins. Other evidence, such as geochemical anomalies, must be used to determine the significance of positive magnetic anomalies in this area.

Daniels (1987) interpreted aeromagnetic anomaly data for the Mt. Zirkel Wilderness Area and vicinity, and his work is summarized here with additional comments where applicable. Anomalies DZ1-DZ6, shown on figure 10, can be modelled as buried or exposed Proterozoic rocks, but Daniels (1987) also suggested that they could be caused by subsurface Tertiary intrusions, indicating a higher mineral potential in areas of magnetic highs. However, anomaly DZ4 is not a likely Tertiary intrusion as reinterpreted here.

Positive anomaly DZ4 (fig. 10) is attributed to the highly magnetic Elkhorn gabbro and the anomaly continues west and southwest of the exposed pluton, indicating a buried extension about equal to its exposed mass. A small positive anomaly northeast of magnetic high DZ4 is associated with ultramafic rocks where there is a high potential for platinum-group elements (see fig. 24). A large gravity high is also associated with this gabbro. High-pass filtering of the gravity data prepared for this report (fig. 9) shows this positive gravity anomaly to be centered on the outcrop, with positive values continuing northwest into Wyoming and southwest as a positive gravity ridge. Although small outcrops of Xm rocks are found near magnetic anomalies DZ3 and DZ6, the main gravity and magnetic anomalies do not continue eastward in the Forest, and we conclude that this mafic body does not have a significant eastward buried extent.

Positive magnetic anomalies DZ1 and DZ2 are located on the western edge of the Mount Ethel pluton (fig. 10). The grain size and composition at the western edge of the pluton changes from medium-grained biotite granite and quartz monzonite to a swarm of coarse-grained pink aplite and leucogranite porphyry dikes (Snyder, 1987b), but this compositional change in itself would not account for positive magnetic anomalies. Quartz monzonite porphyry or more mafic granodioritic rocks are likely sources of anomalies DZ1, DZ2, and perhaps DZ3 (Daniels, 1987), whose model across anomalies DZ1 and DZ2 suggests a burial depth of nearly 0.6 mi (1 km) to the top of each intrusion. No gravity anomalies are associated with magnetic anomalies DZ1-DZ3 (fig. 9).

Positive magnetic anomaly DZ5, at Big Agnes Mountain near Mt. Zirkel (fig. 10), has a source modeled below 1 mi (1.5 km) (Daniels, 1987). Felsic gneiss, pelitic schist, and granite, with small intrusions of pegmatite and ultramafic rock exposed at the surface cannot account for anomaly DZ5; thus, an ultramafic source at depth is required. A gravity high associated with magnetic anomaly DZ5 supports the presence of a more mafic, dense body at depth.

Positive magnetic anomalies DZ6 and VR5 are located at and southeast of Farwell Mountain (fig. 10). These anomalies have gravity highs associated with them, which suggests a different source than anomalies DZ1–DZ3. Gabbro crops out just east of anomaly DZ6. The lack of physical correlation between the gabbro outcrop and the anomaly might be explained by destruction of magnetite by mineralization in the nearby Farwell Mountain mining district.

Positive magnetic anomalies form a northeast-trending ridge, VR1, north of and parallel to the Mount Ethel pluton (fig. 10). A gravity high correlates with this ridge. Massive sulfide deposits are associated with the eastern and western parts of the ridge; and the ridge of high magnetic and gravity values, coupled with the preferred northeast direction of the anomalies, indicates the possible extent of such deposits. The actual source of the anomalies is undetermined: either a structural high or a variation in rock type could account for this feature.

A north-south-trending ridge of magnetic highs (VR2) is associated with rocks on the upper plate of a thrust mapped just east of the Elkhorn gabbro, in an area of outcropping quartz monzonite and nonmagnetic metavolcanics (fig. 10). Throughout the northern Park Range, correlation of magnetic anomalies with Proterozoic igneous rocks is variable: some positive and negative magnetic anomalies reflect variations in the magnetization of quartz monzonites and granitic rocks, whereas other magnetic anomalies may indicate small buried intrusions of unknown composition. Without other confirming evidence of intrusions that may be associated with mineral deposits, magnetically anomalous areas such as this ridge must be regarded as suggestive of intrusions but cannot be confirmed. In this case, a north-south-trending gravity low correlates with the magnetic ridge, a pattern that elsewhere resembles anomalies caused by magnetic Tertiary intrusions, which are frequently less dense than Proterozoic rocks. Behrendt and others (1969) attributed this gravity low to a sedimentary basin below the thrust plate, but granitic rocks also have low densities and could cause the gravity low.

The horizontal gradient of the magnetic field was calculated, and this gradient map shows two northeast-trending magnetic gradients that cross the northern part of the Forest: VRG3 extends from Glen Eden in the southwest to the northeastern corner of the Forest, and VRG4 parallels VRG3 across the Park Range and approximately 15 mi south. These gradients encompass a magnetically low area that includes the Elk River valley (and thus is partially topographically controlled) and continues northeastward to include the Independence thrust sheet. These trends could reflect unmapped shear zones or structural grains in Proterozoic rocks.

SOUTHERN PARK RANGE AND GORE RANGE

Magnetic gradient BPG2 follows the southern boundary of the Mount Ethel pluton and is associated with the Soda Creek–Fish Creek shear zone (fig. 10). South of the gradient, magnetic low BP3 is located just east of Mt. Werner. This low is not topographically related and has no associated gravity expression. Gneissic rocks (Xfh) mapped in the area correlate poorly with the low, because the rocks are widespread elsewhere over the Park Range with no corresponding intense low. Tweto (1987) has inferred from borehole data that a northeast-trending wedge of largely metasedimentary rock (Xb) underlies this area. The range of rock types within this Xb unit (biotite gneiss, migmatite, marble, and calc-silicate rocks) vary widely in susceptibility ranges, and presumably a non-mafic type predominates in this area. Another possible source is a buried, reversely magnetized, mafic intrusion of similar density to Proterozoic diorite or monzonite (but not Mt. Ethel pluton-type rocks, which are less dense). Precambrian basement north of this zone is primarily felsic and hornblendic gneiss (Xfh), whereas south of the zone basement is granitic rock of the Routt Plutonic Suite (Tweto, 1987).

Two small, northeast-trending positive anomalies (labeled VR6, fig. 10) at and northeast of Blacktail Mountain are superimposed upon generally high magnetic values of Proterozoic granitic rocks. The limited aerial extent and sharp gradients of anomalies VR6 suggest shallow sources, possibly intrusions. One of the anomalies is associated with a mapped Tertiary basalt; however, other similar outcrops of basalt have no related positive magnetic anomalies. Alternatively, anomalies VR6 could indicate more highly magnetic areas of Proterozoic rocks.

In the Gore Range, an abrupt east-west gradient (VRG7) separates high magnetic values to the north from lower magnetic values to the south (fig. 10). Negative magnetic anomaly VR8 is part of a northeast-trending, magnetically low zone that continues through the Rabbit Ears Range and the Never Summer Range (including anomaly FC4), where its southern boundary is associated with the Skin Gulch shear zone. It is part of a major magnetic feature that crosses the Routt National Forest study area and beyond, traversing the Flat Tops, following the northwest border of the Rabbit Ears Range, cutting through Cameron Pass–Specimen Mountain, and continuing across the northern part of the Front Range along the Cache la Poudre River to Fort Collins. This magnetic zone is more than 120 mi (200 km) long and between 12 mi (20 km) and 30 mi (50 km) wide. This zone is a major basement discontinuity and, as previously mentioned (Pratt and Zietz, 1973; Brinkworth, 1973), may have controlled emplacement of the Tertiary volcanic rocks in the Rabbit Ears Range and elsewhere along its length. A northeast-trending gradient, VRG10, follows the southern boundary of this zone of weakly magnetic rocks.

Positive magnetic anomalies VR9A-VR9C are shallow, local features that fall within the larger zone of magnetic low values (fig. 10). Anomaly VR9B correlates with mapped Tertiary mafic intrusive rocks, which are the likely sources of all three of these positive magnetic anomalies. A positive gravity anomaly on the high-pass filtered map (fig. 9) correlates with this area of magnetic anomalies, reflecting the denser mafic rocks found here.

MEDICINE BOW MOUNTAINS AND RAWAH WILDERNESS AREA

Clusters of magnetic highs in the southern Medicine Bow Mountains are similar in pattern and trend to magnetic highs to the southeast in the Front Range (Pearson and others, 1982). These magnetic highs are separated by a northeast-trending, deep magnetic low described earlier that here follows major faults in the Medicine Bow Mountains.

The magnetic highs in the Medicine Bow Mountains are intensified where magnetic rocks are in high topographic relief, but analysis of the topography (Pearson and others, 1982) demonstrates that many anomalies are not solely caused by topographic changes. The dominant granitic rocks of the Rawah batholith are moderately magnetic, based on measurements of similar-age granites (table 5) and on the generally high magnetic values here, but the intensity of the associated magnetic field appears to vary locally. Localized magnetic highs (FR1, FR2, FR3, FR6, and FR7, on fig. 10) may arise from more mafic rocks at a depth of a few kilometers, enhanced by clusters of shallower inclusions.

A northeast-trending magnetic low (FR4) is postulated (Pearson and others, 1981) as the result of a combination of weakly magnetic inclusions, oxidation of magnetite along faults, and a topographic low. Magnetic low FR4 (fig. 10) is centered on mapped polymetallic vein deposits of Cu and Ag and has been used to help define the favorable terrane for polymetallic veins in this area, on the assumption that it may be associated with either a buried intrusion of low magnetization or with hydrothermal alteration that destroyed magnetic material.

A north-south-trending magnetic low, FR5, parallels the Laramie River valley but lies east of and above the valley floor (fig. 10). This anomaly, located 1 mi west of a mapped reverse fault, is interpreted as a wedge of Phanerozoic sedimentary rock beneath Proterozoic crystalline rocks thrust over it (Pearson and others, 1982).

RABBIT EARS RANGE AND NEVER SUMMER MOUNTAINS

The section of the Forest that includes the Rabbit Ears Range and Never Summer Mountains lies within the broad, northwest-trending magnetic low described in the section on the Gore Range. Within this broad area of low magnetic values, short-wavelength magnetic highs in the Rabbit Ears Range correlate with both volcanic and intrusive rocks. Magnetic highs of similar extent and amplitude along the Continental Divide show that intrusive rocks are also shallowly buried beneath Cenozoic sedimentary rocks. Mapped volcanic rocks south of the Divide and in the Never Summer Mountains do not have associated magnetic anomalies, due in part to topographic effects of lower elevations in this area. Gravity values are poorly correlated to mapped rock units, including the exposed volcanic rocks.

The lack of gravity expression and the reduced amplitudes of magnetic anomalies in the Never Summer Mountains indicate shallow depth to the bases of the source bodies of the magnetic anomalies as a result of the thin Never Summer thrust plate overlying a structural trough of low-density sedimentary rocks (Behrendt and others, 1969). North-south gradients in the magnetic data (anomaly BPG4) and gravity data, with increasing values to the east, suggest that the Never Summer Mountains are separated from the Front Range by a north-trending fault that parallels the Laramie River fault (FR5) to the north.

COMANCHE-NEOTA-NEVER SUMMER STUDY AREAS

Pearson and others (1981) studied gravity and magnetic data of the Comanche–Big South, Neota–Flat Top, and Never Summer Wilderness Study Areas (fig. 4), and his work is reviewed here.

Positive magnetic anomaly FC1 (fig. 10) is caused by the Tertiary Mount Richthofen granodiorite, bounded on the south by the Mt. Cumulus rhyolite-porphyry stock. The Mount Richthofen stock generates no gravity anomaly, whereas a prominent gravity low where Mt. Cumulus rocks crop out is evident on the gravity map (fig. 9) and shows a buried east-west extension of the Mt. Cumulus stock. The Teller mining district of polymetallic veins is associated with the western flank of the gravity low, and a Climax-type molybdenum occurrence is associated with the gravity minimum. Positive magnetic anomalies FC3A and FC3B are located south and north respectively of the Mt. Cumulus stock, suggesting that the stock is nonmagnetic or is reversely magnetized. A regional gravity map (Pearson and others, 1981), which was made using a slightly different method of anomaly filtering than that used to create figure 9, shows local gravity lows at Mt. Cumulus, at Jack Creek, and west of Specimen Mountain. These anomalies may reflect shallow plutons that are connected at depth. The aeromagnetic data used for this report (fig. 10) are of higher quality than those used by Flanagan, and they reveal a greater number of shallow magnetic highs and lows on the Never Summer thrust plate that may be associated with unexposed Tertiary intrusions and possible mineralization.

Negative magnetic anomaly FC2, east of and parallel to positive magnetic anomaly FC1 (fig. 10), is thought to be a southward continuation of the Laramie River fault marked by anomaly FR5 to the north. This discontinuous north-south anomaly can be traced as far south as Shadow Mountain Reservoir.

A northeast-trending magnetic low reaches its lowest values at FC4 (fig. 10). This magnetic low was described earlier in the sections on the Gore Range and the Rabbit Ears Range. This low has been interpreted as the result of destruction of magnetic minerals along fault zones (Pearson and others, 1981), which may account for a small part of the magnetic low, but the extent and intensity is much larger than expected if due solely to alteration.

Local positive anomaly FC5 is within the regional magnetic low. The source is not exposed but may be a small intrusive Tertiary(?) plug, a local area of more magnetic facies of Proterozoic(?) granite, or a dike swarm of unknown age.

WILLIAMS FORK MOUNTAINS, VASQUEZ PEAK, AND ST. LOUIS PEAK AREAS

Moss and Abrams (1985) studied the gravity and magnetic fields of the Williams Fork Roadless Area, in the southeasternmost part of the Forest (fig. 3), and the Vasquez Peak Wilderness Study Area and St. Louis Peak Roadless Area northeast of the Williams Fork Roadless Area. Rocks exposed in this area include Proterozoic intrusive and metamorphic rocks. Measurements of rock properties (table 5) show that the Proterozoic Silver Plume granite is less dense and less magnetic than the metasedimentary gneisses and schists.

Moss and Abrams (1985) selected six small areas of low gravity values and magnetic highs or lows that might indicate either buried Oligocene stocks or varying magnetic mineral content of Proterozoic intrusive or metamorphic rocks. Positive magnetic anomalies MV1A and MV1B (fig. 10) may reflect more mafic rocks within a sequence of Proterozoic metasedimentary rocks. Anomalies MV3 and MV4 are associated with Proterozoic gabbro outcrops. Positive magnetic anomalies MV5 and MV6 may arise from Boulder Creek Granodiorite. Magnetic high MV8 was interpreted by Brinkworth (1973) as caused by an early Tertiary intrusive; Brinkworth attributes a similar buried intrusive to magnetic high MV2.

An east-northeast-trending gravity low on the gravity map (fig. 9) is bounded by the Lake shear zone on the northwest and the Straight Creek fault zone on the southeast. The gravity low marks the presumed exposed and buried extent of the Silver Plume batholith. The gravity high northwest of this low is associated with denser, more mafic metamorphic rocks.

Two deep, northeast-trending magnetic lows dominate the magnetic anomaly map in the Williams Fork region. The northernmost of the two (labelled MV7, fig. 10) follows St. Louis Creek. The southernmost magnetic low (VR11) crosses topography and roughly correlates with the northern part of the Silver Plume batholith. A northeast-trending positive magnetic ridge separates the two lows, and the St. Louis Lake shear zone corresponds to the magnetic gradient between this positive ridge and magnetic low VR11. This ridge corresponds to a gravity gradient that Moss and Abrams (1985) postulated was the contact between Silver Plume Granite and metamorphic rocks; however, this does not explain the northern magnetic low. Two possible causes for the northern low are Silver Plume granitic rocks lie beneath St. Louis Creek, or the source is a nonmagnetic phase of Proterozoic rocks unidentified in this area. A gravity low on the high-pass gravity map (fig. 9) correlates with the eastern part of magnetic anomaly MV7, suggesting granite as a source; alternatively this could indicate less-dense sediments filling Frasier Valley.

A northwest-trending gravity low correlates with decreased magnetic values in the northwestern Williams Fork Mountains and suggests a wedge of sedimentary rocks beneath the Williams Fork thrust plate. Magnetic anomalies are continuous and are not offset along the Williams Fork Mountains thrust. The source of these anomalies is probably basement rocks in the shallow footwall.

Tertiary intrusive rocks, not exposed in this area, are believed responsible for base- and precious-metal mineralization, such as the subvolcanic Oligocene stock associated with the Henderson molybdenum deposit southeast of the Forest. Brinkworth (1973) studied the aeromagnetic and gravity maps of the Climax area and the Front Range. Because of the importance of molybdenum in the southern part of the study area, his work comparing the Climax and Red Mountain (Henderson mine) intrusive complexes is included here.

The Oligocene stocks associated with nearby molybdenum deposits have the lowest density of all rocks in the area and may be delineated by gravity lows (Brinkworth, 1973). However, gravity data are sparse in this remote region, and the gravity field near the large Henderson molybdenum deposit a few miles east of the Williams Fork Roadless Area shows only a slight negative deflection in the Bouguer gravity field (fig. 8). High-pass filtering, however, has removed the strong regional gravity low caused by the batholith associated with the Colorado Mineral Belt, and a residual gravity low just east of the Forest boundary attributed to the Silver Plume batholith also correlates with the Henderson mine (fig. 9). Part of this gravity low could be caused by the subsurface Tertiary intrusive associated with mineralization of subvolcanic rhyolite (averaging 2.49 g/cm^3) and altered country rocks. The negative gravity anomaly continues to the northeast and suggests that any related mineralized areas are more probably east or north, outside the Forest.

The Colorado Mineral Belt gravity low encompasses the area of plutons related to molybdenum enrichment, including the Red Mountain stock and other outlying rhyolitic plutons such as the Montezuma, Leavenworth, and Cabin Creek stocks and the Revenue Mountain and Handcart Gulch stocks, south of the Forest (Brinkworth, 1973). All of these stocks have common volcanic origins; they have components associated with separate intrusive events and hydrothermal episodes; and they are located near major Proterozoic shear zones that may have localized igneous activity at preexisting zones of crustal weakness. However, each intrusion is eroded to a different level; Brinkworth (1973) calculated that the Climax stock is 3,000 ft more deeply eroded than the Red Mountain stock. Neither the Climax nor the Red Mountain stocks have much magnetic expression, but the flight lines are at least 0.5 mi away from the stock outcrops.

FLAT TOPS

The magnetic field of the Flat Tops is characterized by several high-frequency, small positive anomalies over some basalt outcrops. These small anomalies are superimposed on long-wavelength, deep-source anomalies that are probably caused by magnetic contrasts within the Proterozoic basement. Insufficient gravity and magnetic data limits further interpretation in the southwestern part of the Forest.

AERIAL GAMMA-RAY RADIOACTIVITY

INTRODUCTION

Aerial gamma-ray radioactivity data for the Forest are from spectrometer surveys flown during the U.S. Department of Energy National Uranium Resource Evaluation (NURE) program (ca. 1974–1983). NURE surveys that include parts of the Forest are those for the Craig (LKB Resources, Inc., 1979), Denver (Geometrics, 1979a), Greeley (Geometrics, 1978), and Leadville (Geometrics, 1979b) 1°×2° quadrangles. Aerial gamma-ray data (aeroradioactivity) from these surveys were used to prepare an aeroradioactivity database for the Forest. Other compilations of NURE data that include the Forest are Phillips and others (1993) and Duval and others (1995).

Aeroradioactivity is the measurement of terrestrial radioactivity with instruments operated in low-flying aircraft. The source of the radioactivity measured is the near-surface rock and soil (to 12-inch depth) where the primary gamma-ray emitting isotopes are from the natural radioelements potassium (K), uranium (U), and thorium (Th). NURE aerial systems were quantitatively calibrated at sites of known radioelement concentrations, permitting quantitative reporting of survey data in percent for K and parts per million (ppm) for U and Th (assuming equilibrium in the respective decay series). The near-surface distribution of K, U, and Th generally reflects bedrock lithology and modifications due to weathering, erosion, transportation, groundwater 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.

Aerial flight-line spacing for the Forest database is 3-mi east-west and 12-mi north-south for the Craig and Leadville 1°×2° quadrangles and 1-mi east-west and 4-mi north-south for the Greeley and Denver 1°×2° quadrangles. A minimum-curvature algorithm (Webring, 1981) was applied to the flight-line data, producing K, U, and Th 1.8-mi-square grids, which comprise the Forest database. Most of the Forest is within the Craig 1°×2° quadrangle, and the bulk of the database is derived from data for that quadrangle; hence the choice of 1.8-mi for grid-cell size. The grids were used to prepare K, U, and Th color and black-and-white maps at 1:250,000 and 1:500,000 scales for use in the assessment and gray-scale maps at 1:1,000,000 scale for inclusion in this report. Grids of the ratios U:Th and K:Th were also prepared.

DISCUSSION

K, U, Th, U:Th, and K:Th aeroradioactivity gray-scale contour maps of the Forest are shown (respectively) in figures 11, 12, 13, 14, and 15. The Forest boundary is shown on each map, and geographic locations shown on the maps are described in the figure captions. Bodies of water, such as Lake Granby and Green Mountain Reservoir, have no measurable aeroradioactivity. However, the grids used to make figures 11–15 were not masked to show areas of no data for lakes and reservoirs, and any discernable gray-scale values for any bodies of water should be ignored.

The near-surface distribution patterns of K, U, and Th as displayed by aeroradioactivity maps are often similar, resulting from common rock-type associations for these

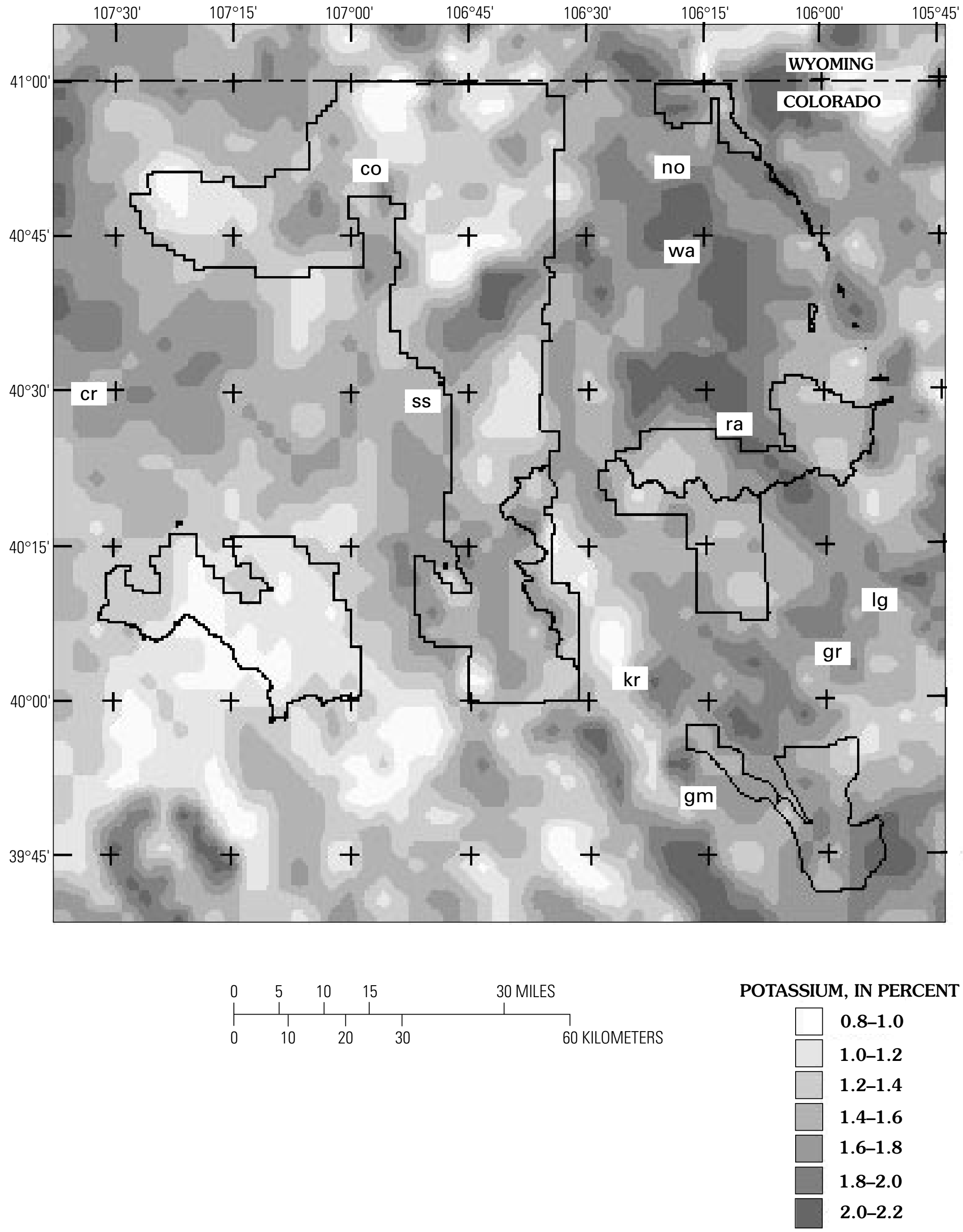


Figure 11. Potassium aeroradioactivity gray-scale contour map of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Values in percent K. Geographic locations: co = Columbine, cr = Craig, gr = Granby, kr = Kremmling, no = Northgate, ra = Rand, ss = Steamboat Springs, wa = Walden.

elements. However, discontinuities in the patterns can reflect significant mineralogic discontinuities, such as the contrasting properties of felsic and mafic igneous rocks. Th generally has a more consistent distribution pattern than K or U, likely resulting from Th being the least mobile of these elements. For this reason, Th is used as the stable denominator in U:Th and K:Th ratios, thereby highlighting subtle variations in U and K distribution. Of particular interest are variations from the 0.25 ratio on figure 14. The ratio for normal crust is 1:4 or, in the case of figure 14, 0.25. Values on figure 14 greater than 0.25 suggest relative enrichment of U, values less than 0.25 suggest relative depletion of U.

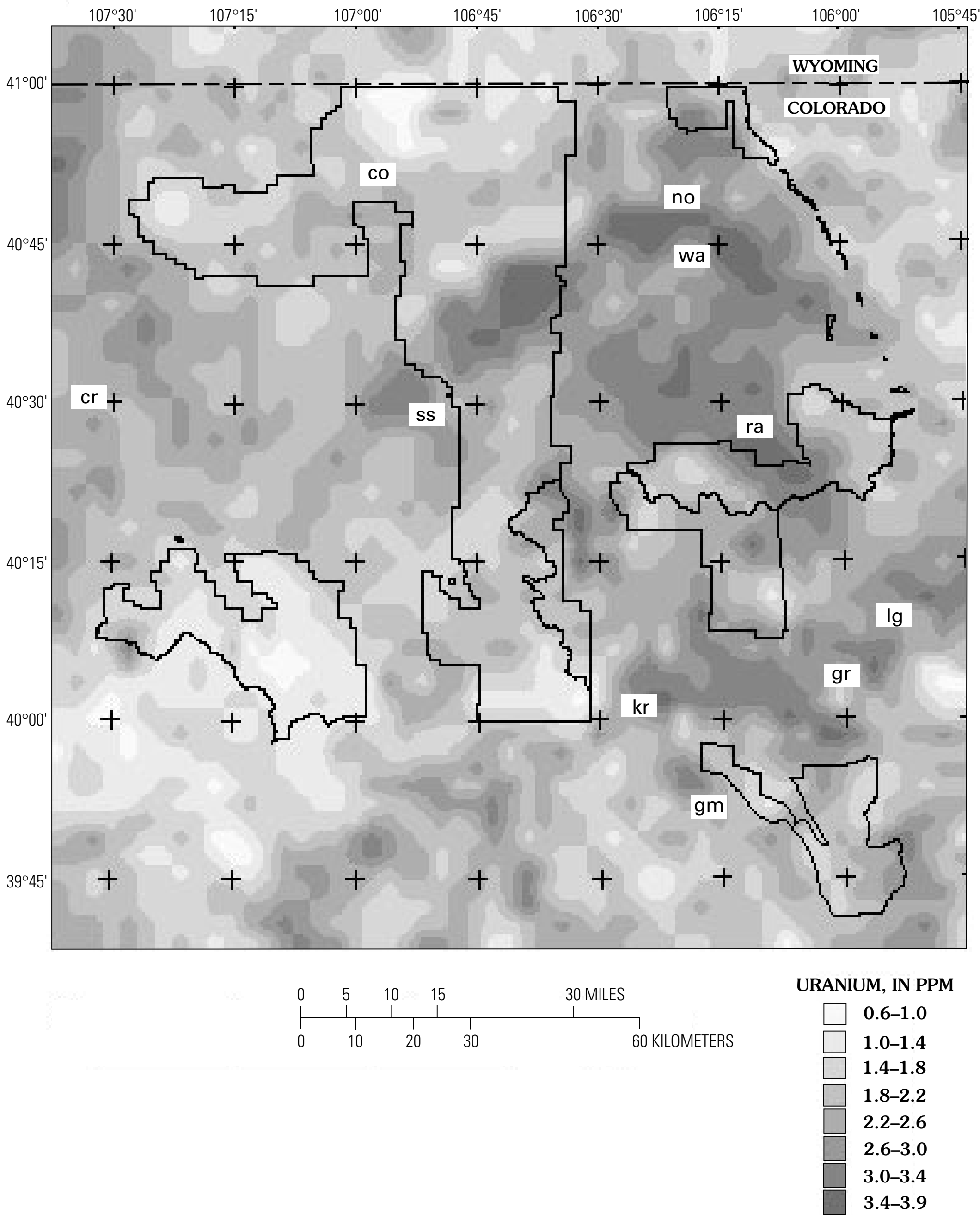


Figure 12. Uranium aeroradioactivity gray-scale contour map of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Values in ppm U. Geographic locations: co = Columbine, cr = Craig, gr = Granby, kr = Kremmling, no = Northgate, ra = Rand, ss = Steamboat Springs, wa = Walden.

INTERPRETATION

Natural radioelement distribution for the Forest, as demonstrated in the grey-scale contour maps (figs. 11–15) has a varied pattern that reflects the diverse geology of the Forest.

Areas of notably higher radioactivity within the Forest include a sizeable area of 1.8 to 2.0 percent K, 2.6 to 3.9 ppm U, and 10 to 13 ppm Th northeast of Steamboat Springs that reflects the presence of 1.4-Ga granite of the Mt. Ethel pluton, a smaller area of 1.8 to 2.0 percent K, 2.6 to 3.0 ppm U, and 11 to 13 ppm Th north of Northgate at the Forest

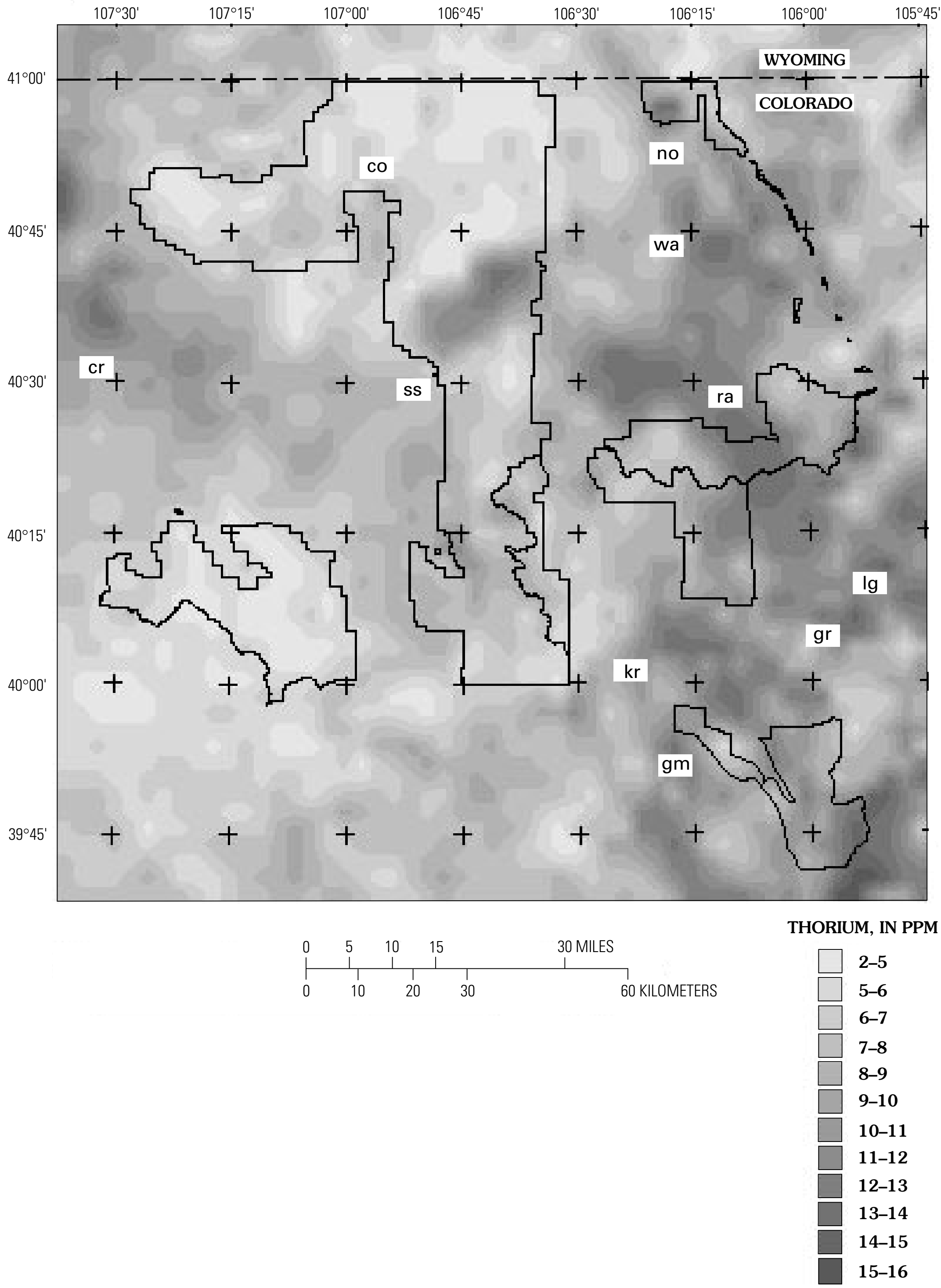


Figure 13. Thorium aeroradioactivity gray-scale contour map of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Values in ppm Th. Geographic locations: co = Columbine, cr = Craig, gr = Granby, kr = Kremmling, no = Northgate, ra = Rand, ss = Steamboat Springs, wa = Walden.

boundary that also relates to 1.4-Ga granite, and an area of 2.0 to 2.2 percent K, 3.4 to 3.9 ppm U, and 11 to 13 ppm Th southeast of Rand where the source rocks are Tertiary arkosic sedimentary rocks of the Coalmont and Middle Park Formations. The area of higher radioactivity that includes the Mt. Ethel pluton extends farther north on the U map compared

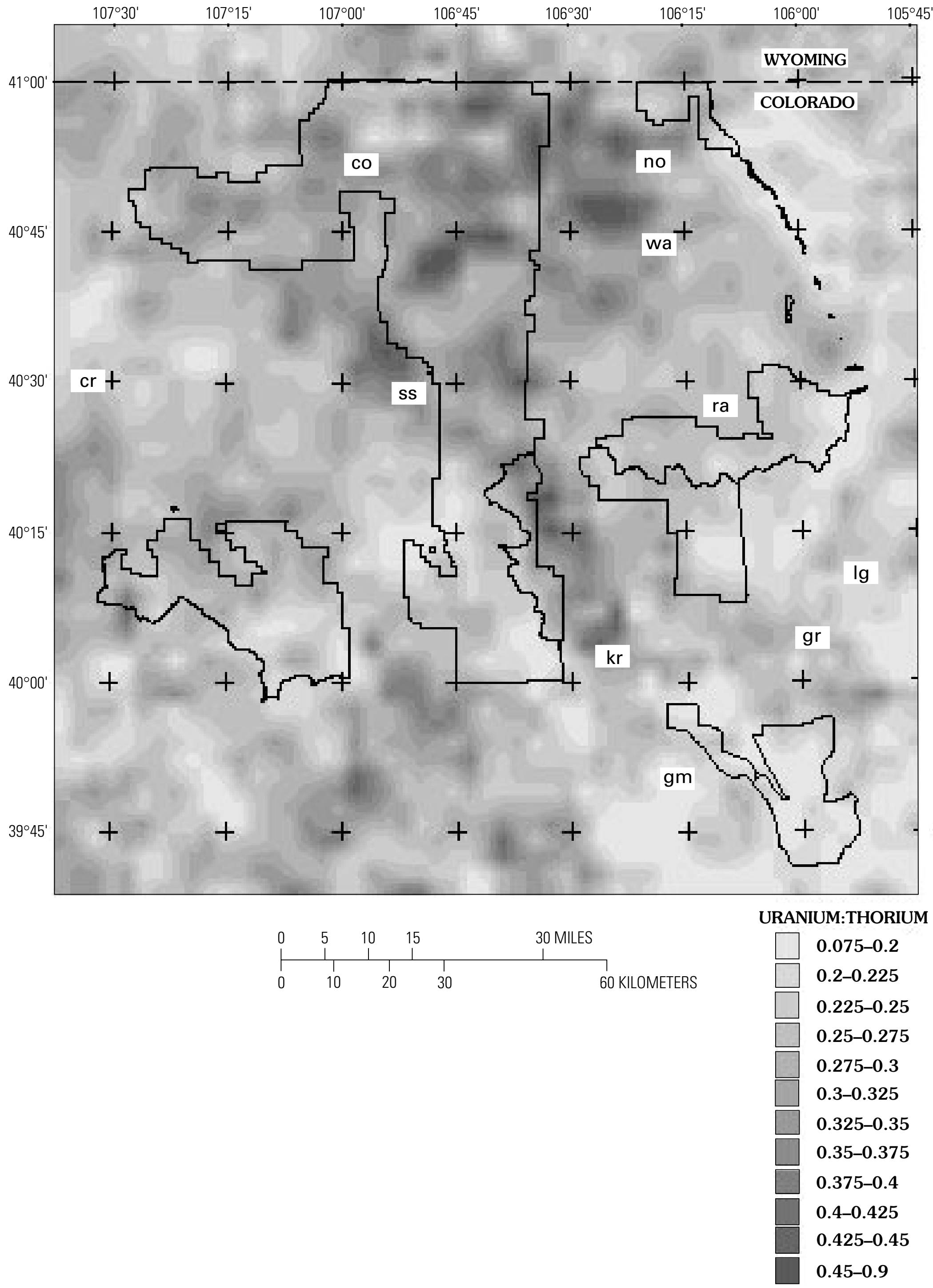


Figure 14. Uranium:thorium aeroradioactivity gray-scale contour map of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Values in ppm U per ppm Th. Geographic locations: co = Columbine, cr = Craig, gr = Granby, kr = Kremmling, no = Northgate, ra = Rand, ss = Steamboat Springs, wa = Walden.

with the same feature on the K and the Th maps, suggesting relatively enhanced U in the adjoining 1.7-Ga metamorphic rocks, a lithologic occurrence substantiated by higher (>0.34) U:Th values. In North Park, between the western and eastern parts of the Forest, the distinct pattern of varied and frequently higher radioactivity (2.0 to 2.4 percent K, 3.0 to 3.9 ppm U,

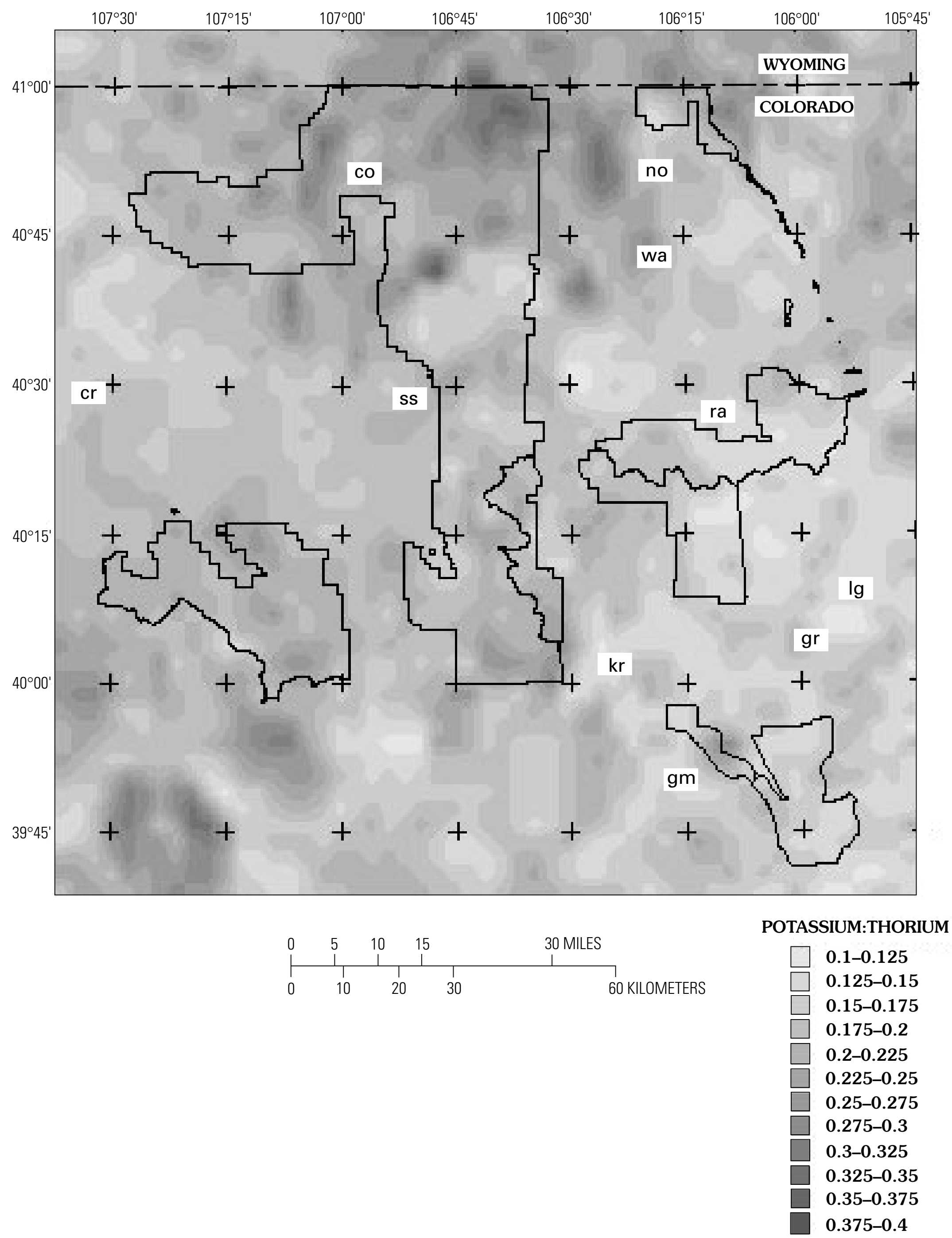


Figure 15. Potassium:thorium aeroradioactivity gray-scale contour map of the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado. Values in K per ppm Th. Geographic locations: co = Columbine, cr = Craig, gr = Granby, kr = Kremmling, no = Northgate, ra = Rand, ss = Steamboat Springs, wa = Walden.

11 to 14 ppm Th) relates mostly to arkosic sedimentary rocks of the Tertiary Coalmont Formation. The U:Th and K:Th ratios for the area between Walden and Rand show relatively mundane patterns indicating relatively similar radioactive lithologies—from west of Rand and Northgate to the Forest boundary, the U:Th (>0.35) and K:Th (>0.30) ratios include strong positive, often non-coincident, features that indicate U- and K-dominant radioactive lithologies.

The radioelement data show a distinct northeast trend that includes the Mt. Ethel pluton, extends past Northgate to the northeast, and extends southwest to include an isolated U high of 3.0 to 3.4 ppm (lat 40°07'N., long 107°28'W.) in Cretaceous sedimentary rocks at the southwest corner of the Forest. Radioelement concentrations for the trend range from low to high, include a variety of rock types, and parallel the strong northeast trend of bedrock outcrops and topography south of the Mt. Ethel pluton. The trend is most pronounced in the U data, but it is also apparent in the K and Th data—coincidence of the three radioelements is demonstrated by lack of expression in the U:Th and K:Th ratios.

In the Forest north of the area of higher concentrations that include the Mt. Ethel pluton, relatively low values of 0.7 to 1.4 percent K, 0.7 to 1.4 ppm U, and 1.5 to 6 ppm Th characterize 1.7-Ga metasedimentary, metavolcanic, and plutonic rocks. This area includes several K-distinctive features, including a zone of 1.6 to 2.0 percent K in metamorphic and plutonic rocks that trends northeast from Round Mountain (lat 40°30'N., long 106°54'W.) through Pearl (lat 40°59'N., long 106°33'W.). North of Columbine, a distinct low of 0.7 to 1.0 percent K, 0.7 to 1.0 ppm U, and 1.5 to 5 ppm Th reflects the low radioelement concentrations of the Elkhorn Gabbro. West of Columbine, the Forest has moderate values of 1.0 to 2.0 percent K and 1.4 to 2.6 ppm U and low values of 1.5 to 7 ppm Th for Cretaceous sedimentary rocks and Tertiary sedimentary, volcaniclastic, and intrusive rocks. Several of the intrusives have distinctive K of 1.4 to 1.8 percent and K:Th of >0.28. In the northwest part of the Forest, in the western Elkhead Mountains west of Columbine, low values of 0.7 to 1.2 percent K, 1.0 to 1.8 ppm U, and 1.5 to 6 ppm Th characterize sedimentary and volcaniclastic rocks.

In the Forest immediately south of the Mt. Ethel pluton, relatively low concentrations of 0.7 to 1.4 percent K and 1.5 to 6 ppm Th and moderate values of 1.4 to 2.6 ppm U for an area of 1.7-Ga metamorphic and plutonic rocks indicate radioactive lithologies similar to those for similar rocks north of the Mt. Ethel pluton. Farther south in the Forest, and including the northern part of the Gore Range, radioelement concentrations are generally moderate to low with some K-distinctive areas for mostly 1.7-Ga granitic rocks. Two 3-element relative highs occur southeast of Steamboat Springs in the Forest in 1.7-Ga granitic rocks, and have possible polymetallic vein deposit significance. One is about 17 mi southeast of Steamboat Springs in the Service Creek drainage at about lat 40°17'N., long 106°40'W., where radioelement concentrations are 1.8 to 2.2 percent K, 2.6 to 3.0 ppm U, 9 to 11 ppm Th, no U:Th expression, and distinct K:Th of <0.18. The other is 20 mi south-southeast of Steamboat Springs between the Morrison and Silver Creek drainages at about lat 40°12'N., long 106°45'W., where concentrations are 1.8 to 2.0 percent K, 2.2 to 2.6 ppm U, 11 to 12 ppm Th, no U:Th expression, and distinct K:Th of <0.18. East and northeast of the Service Creek feature and 15 to 25 mi north-northwest of Kremmling, partly within the Forest, distinct U relative highs of as much as 3.4 ppm and U:Th of >0.35 are suggestive of U deposits in Cretaceous sedimentary rocks.

The southwestern part of the Forest has undistinguished radioelement expression, with mostly low concentrations of 0.7 to 1.2 percent K, 0.7 to 1.8 ppm U, and 1.5 to 7 ppm Th for Cretaceous and Tertiary sedimentary rocks and Tertiary basalt. The previously discussed U high (lat 40°07'N., long 107°28'W.) is just outside the Forest in Cretaceous rocks.

Other occurrences of 1.4-Ga granite include areas where one radioelement is more distinct than the other two, reflecting radioactive lithologic differences between similar rock types. One is a K-distinct (1.8 to 2.2 percent) feature about 12 mi northeast of Northgate, outside the Forest. Another is the Th-distinct (12 to 14 ppm) feature with associated 1.8 to 2.0 percent K and 2.6 to 3.0 ppm U at the southeast corner of the Middle Park Ranger District of the Arapaho National Forest that is related to the Silver Plume batholith and includes the Urad and Henderson Mo orebodies.

That part of the Forest on the east side of North Park has varied radioactivity expression, reflecting source rocks with different radioactive lithologies. At Baker Mountain (not labeled on figs 11–15) about 16 mi east-southeast of Rand and outside of the Forest, a Th-dominant feature (11 to 13 ppm) with coincident K (1.8 to 2.0 percent) and U (2.2 to 3.0 ppm) highs reflects plutonic rocks with potential for Mo porphyry deposits.

Southeast of Kremmling, radioelement data for the Middle Park Ranger District of the Arapaho National Forest has northwest trends reflecting the Williams Range thrust fault. Radioelement concentrations vary appreciably, with the previously discussed Th feature of the 1.4-Ga Silver Plume batholith being the most prominent. A notable feature is an area of >0.20 K:Th east of Green Mountain Reservoir where the source rocks are 1.7-Ga metamorphic and granitic rocks.

ANALYSIS OF RADIOELEMENT DATA BY NURE AERIAL CONTRACTOR

U.S. Department of Energy (DOE) NURE program procedures for each 1°×2° quadrangle included analysis of the aerial survey radioelement data to determine the possibility of U deposit occurrence. The radioelement data (U, K, Th), collected along flight-line profiles, and their ratios (U:K, U:Th, Th:K) were analyzed statistically with surficial geologic data to calculate standard deviations from the mean "per radioelement quantity" per geologic unit. Areas along flight lines that fit statistical (generally at least one standard deviation above the mean for U, U:K, U:Th) and geologic criteria were termed significant anomalies; areas along flight lines that had U, U:K, and U:Th anomalies (generally) at least two deviations above the mean, and had geologic characteristics that were appropriate for U deposits, were termed preferred anomalies. For differences in anomaly definition between quadrangles, the appropriate report (in the DOE GJBX series) should be consulted. K and Th statistics were used to help understand the geology in the vicinity of possible U deposits.

The Craig 1°×2° quadrangle (LKB Resources, Inc., 1979) includes most of the Forest and 2 of 53 preferred U anomalies determined for the quadrangle occur within the Forest. Both are in the northern part of the Forest, in the Park Range. One is about 2 mi east-southeast of Columbine in an area of 1.4 to 1.8 ppm U where it is associated with the Tertiary felsic intrusion of Hahns Peak. The anomaly is of relatively limited dimension and is not apparent in the small-scale radioelement maps of this report. It is in an area of relatively higher U:Th and K:Th because Th is relatively low (1.5 to 5 ppm).

The other preferred anomaly within the Forest is about 13 mi west of Northgate in an area of 2.2 to 2.6 ppm U where the source rock is Proterozoic felsic and hornblendic gneiss. It is in an area of relatively higher U:Th (>0.35) because of low Th (1.5 to 5 ppm); K is low (1.0 to 1.2 percent) and K:Th is moderate and obscure.

As many as 11 preferred U anomalies are near or adjacent to the Forest, none of which are associated with known U occurrences. (In the following text, the U, K and Th features discussed are from the NURE statistical analysis; some are apparent in maps of this report, some are not.) Eight of these anomalies have Cretaceous shale (Mancos primarily) as the source rock; all have good expression in U and its ratios because of slight or no expression in K and Th; locations includes sites northwest of Steamboat Springs, north and south of the southwest part of the Forest, and in several locales in Middle Park along the contact with the Gore Range. The other three anomalies are also well expressed in U and (generally) not in K and in Th and are in the Kremmling-Granby area; one is just northeast of Whitely Peak where the source rock is Tertiary intrusive igneous rock intruded into Pierre Shale; one is in intermediate volcanic rocks of Tertiary age; the third is in the Middle Park Formation.

NURE procedures culminated in evaluation of the favorability of specific 1°×2° quadrangles for the occurrence of U deposits, published in the Department of Energy (DOE) PGJ/F series. Geological, geochemical, geophysical, and mining data were used, although tight deadlines on occasion resulted in aerial gamma-ray survey or geochemical data not being used because of not being available at the time the evaluation was done. The evaluation of the Craig 1°×2° quadrangle utilized both the aerial survey and geochemistry and resulted in one area, which includes part of the Forest, being judged favorable for U deposits. This area includes the approximate western half of the southwest part of the Forest and is described as follows (Craig and others, 1982, p. 1):

> Area D is in the Salt Wash Member of the Morrison Formation (Upper Jurassic) in the southwestern part of the Craig quadrangle and uranium deposits are classed as nonchannel-controlled peneconcordant sandstone-type deposits (subclass 244). The favorable area is essentially a projection of the Meeker mining district based on the regional stratigraphy of the Salt Wash Member and the presence of relatively thick, high-energy sandstone beds containing carbonaceous trash. No airborne radiometric, water or stream-sediment, or drill-hole anomalies support the favorable assignment.

The Salt Wash Member of the Morrison Formation does not crop out in the southwestern part of the Forest—the favorable judgment is based on subsurface stratigraphic extrapolation.

MINERAL RESOURCES—LOCATABLE MINERALS

By Sandra J. Soulliere *and* Margo I. Toth

Locatable minerals include all minerals for which exploration, development, and production are regulated under the Federal General Mining Law of 1872. Most metallic minerals and a large group of nonmetallic or industrial minerals are included in this group. The U.S. Bureau of Mines has identified and described all the known mines and prospects in the Forest, and some of the following is taken from that report (Neubert, 1994).

MINING AND EXPLORATION HISTORY

The earliest known mining in the area occurred in prehistoric times, as evidenced by a quartzite quarry near Rabbit Ears Pass. Archaeologists have recently discovered the remains of a stone-age quarry mined by nomadic tribes for quartzite as early as 8,000 years ago and as late as 500 years ago (Rocky Mountain News, 1993). The remains of nearly 200 quarry pits are found within the Forest at Windy Ridge, about 15 mi southeast of Steamboat Springs.

Modern mining from areas within or near the Forest began in the late 1800's with the discovery of gold placer deposits below Hahns Peak. Major quantities of metallic minerals have not been produced from the Forest (Neubert, 1994). Minor mineral production was recorded between 1860 and the early 1970's from several mines and mining districts within and adjacent to the Forest. These areas include the Elkhorn Mountain, Hahns Peak, Pearl, Crystal, Northgate, Teller, and La Plata-Dailey mining districts, and the Greenville mine area (fig. 5). Areas explored for metallic minerals and areas where mining has occurred but production is unknown include the following: Slavonia, Fish Creek, Blue Ridge, and Slater mining districts, and the Parkview and Poison Ridge intrusive centers in the Rabbit Ears Range. Although exploration for mineral deposits is ongoing, the last major production in the area was recorded in 1973 from fluorite deposits in the Northgate mining district.

The molybdenum mine at Henderson (fig. 5) is located just outside the southeastern boundary of the Forest. The Northgate mining district (fig. 5), the second major fluorite producer in Colorado, includes part of the northeastern Forest. Some of the largest concentrations of mineral deposits in the Rocky Mountain region are just south of the Forest in an area known as the Colorado Mineral Belt. The Colorado Mineral Belt is an elongate zone of hydrothermal mineral deposits that extends from the San Juan Mountains in southwestern Colorado to the Front Range northwest of Denver (Tweto and Sims, 1963). A large concentration of mineral deposits and numerous intrusive and volcanic rocks of late Cretaceous to late Tertiary age characterize the belt. The belt extends into the southeastern part of the Forest (fig. 5).

POTENTIAL FOR UNDISCOVERED MINERAL RESOURCES—LOCATABLE MINERALS

The Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest were evaluated for 10 locatable mineral deposit types (pl. 1, fig. 1). In the following sections, the characteristics of the known deposits in the Forest are briefly summarized, and assessment criteria are established. The assessment criteria were used to evaluate areas within the Forest for the potential for each deposit type. Specific areas within the Forest that met the criteria were delineated and assigned a rating of either moderate or high potential; areas of low potential were not outlined for metallic resources (Gourdarzi, 1984). These ratings refer to the likelihood for the occurrence of a given deposit type. Levels of certainty, labeled A through D, were also assigned to qualify the data; level A indicates the least amount of supporting data and level D the greatest. Definitions and explanations of the mineral resource rating system are in Appendix 2. On figures 1–2, 16–25, and plate 1, areas of high potential are shown in dark gray and areas of moderate potential are shown in light gray. Each mineral deposit type was assigned a letter and number designation to more easily distinguish each type on a map or figure in the report. These letter-number designations are shown on the figures, on plate 1, and have been previously described in the section "Undiscovered Mineral and Energy Resources."

STOCKWORK MOLYBDENUM (A)

COMMODITIES, BY-PRODUCTS, AND TRACE METALS

The commodity is molybdenum; by-products are commonly tungsten, bismuth, and tin.

HOST ROCKS

The deposits are in or associated with Tertiary granitic plutons. Ore may also occur in the country rocks, including Proterozoic crystalline rocks and Paleozoic and Mesozoic sedimentary rocks.

STRUCTURAL CONTROL

Stockwork veins form in fractures produced by the intrusion of a small stock at very shallow crustal levels. The joint pattern may be controlled by joint patterns within the host pluton or by bedding, joints, or faults outside the pluton. Stockwork veins can occur in any brittle rock that can be shattered repeatedly, including the host pluton and favorable country rocks.

AGE

In Colorado, stockwork molybdenum deposits are Oligocene and younger in age.

DEPOSIT DESCRIPTION

Stockwork molybdenum deposits occur in epizonal granitic plutons. Stocks emplaced during multiple phases of intrusion and alteration are the most favorable for hosting stockwork deposits. Favorable plutons have porphyritic textures, associated intrusive breccias and pebble dikes, and commonly have radial dikes. Source rocks have greater than 76 percent SiO_2, high trace amounts of fluorine, rubidium, yttrium, and niobium; and low trace amounts of barium, strontium, and zirconium.

Ore minerals occur in a complex network of stockwork quartz veins, but disseminated flakes of molybdenite are also present in the host granite. Quartz, molybdenite, potassium feldspar, pyrite, fluorite, and phlogopite are the dominant vein minerals; a variety of other minerals may also be present, including topaz, cassiterite, and magnetite. The ore zone occurs above the central igneous complex and also overlaps it; the general morphology of the zone is an inverted bowl. Peripheral veins contain lead, zinc, silver, and gold. Copper may be present but is rare in this type of stockwork system (White and others, 1981).

Wallrocks exhibit pervasive hydrothermal alteration. Assemblages of alteration minerals are zoned outward from potassium feldspar in the system center to quartz-sericite-pyrite and argillic alteration to propylitic assemblages along the outer margins. Oxidized pyrite in the phyllic zone commonly produces a red halo above and around the deposit. Early potassic alteration in intrusions was generated by fluids derived by magmatic processes, and later quartz and sericite formed by mixing with fluids of meteoric origin (Hannah and Stein, 1986).

GEOCHEMICAL SIGNATURE

Stream-sediment samples typically contain anomalous concentrations of molybdenum, lead, tungsten, silver, tin, and gold, although some of these elements are more abundant in peripheral vein systems. Rock samples contain anomalous concentrations of molybdenum, silver, tungsten, bismuth, and fluorine.

GEOPHYSICAL SIGNATURE

Plutons are expected in the area of low gravity of the Colorado Mineral Belt, which is associated with a large, unexposed batholith. Within this area, favorable terrane may be associated with a smaller, residual gravity low in the southeast part of the Forest.

Proterozoic granitic host rocks are often the most magnetic rocks in the Forest and commonly have associated magnetic highs. Tertiary granitic host rocks may or may not be magnetic and are less dense than Proterozoic rocks, especially where extensively altered. Gravity lows, with or without associated magnetic highs, may indicate Tertiary intrusive rock.

Host plutons are notably radioactive because of the elevated concentrations of K, U, and Th that characterize granitic/felsic igneous rocks, and consequently are detectable by radioactivity measurements, dependent on surface exposure.

KNOWN DEPOSITS

There are no known deposits in the Forest. However, a deposit is present at Red Mountain, just outside the southeastern border of the Forest near Berthoud Pass.

ASSESSMENT CRITERIA

1. Presence of a Tertiary, fluorine-rich, high-silica pluton.
2. Multistage igneous activity.
3. Stocks emplaced at very shallow crustal levels in a Tertiary extensional environment.
4. Extensive hydrothermal alteration within and around the stock.
5. Presence of molybdenite in veins and stockwork veinlets and as disseminated flakes.
6. Anomalous molybdenum concentrations in rocks and stream-sediment samples.

ASSESSMENT

Area A1.—A small target area around Hahns Peak in the north-central part of the Forest has high resource potential for molybdenum in stockwork deposits (pl. 1, fig.16), with certainty level C. In this area, a composite laccolithic intrusion of latite and quartz latite is present and includes a central cone-shaped body of intrusive breccia. Hydrothermal alteration consists of early albitization, followed by a later phase of propylitic, argillic, phyllic, and advanced argillic mineral assemblages zoned around the breccia cone sheet (Cascaceli, 1984). Stockwork veins of silica, pyrite, and molybdenite are present, and galena, sphalerite, chalcopyrite occur

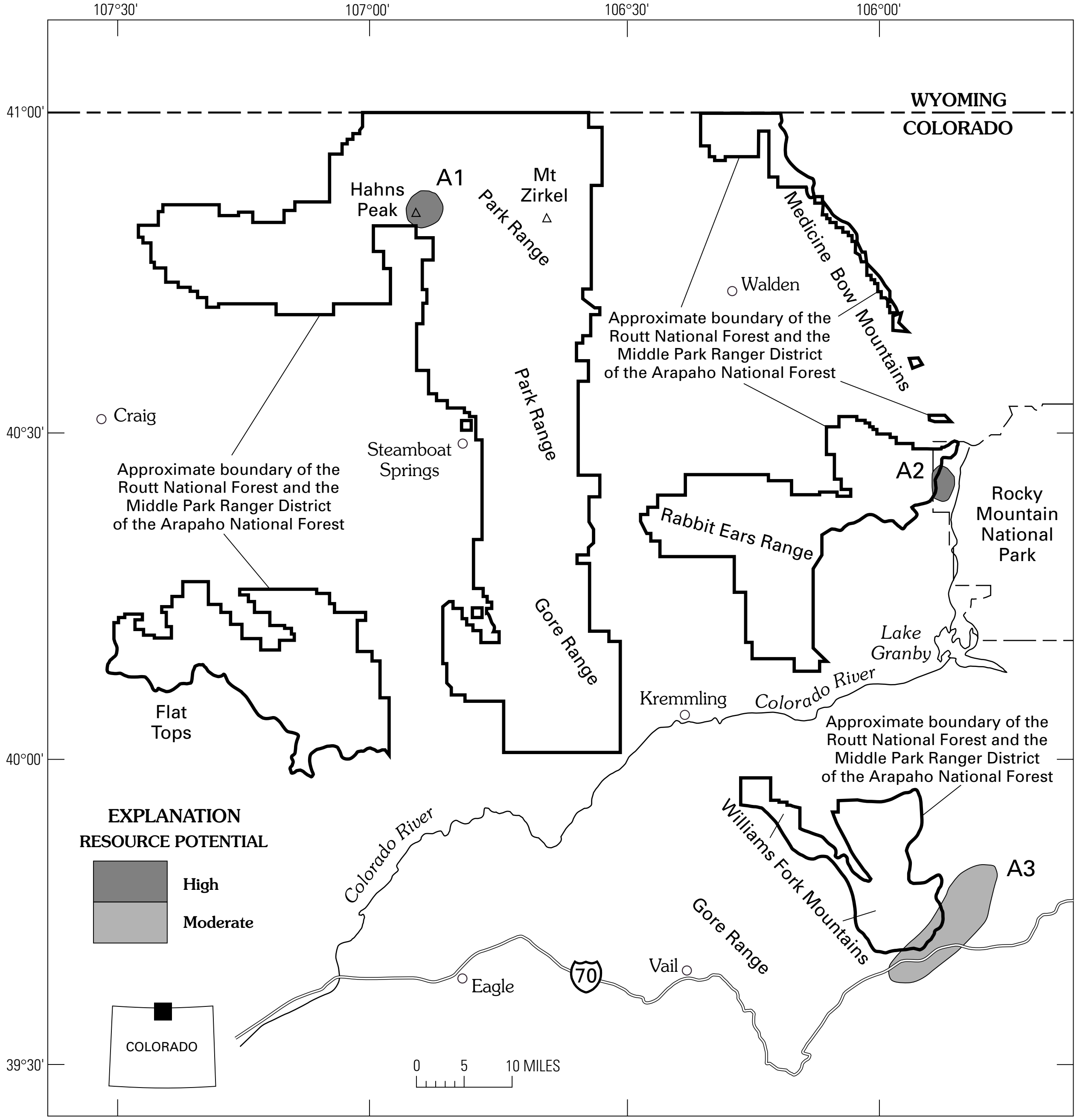


Figure 16. Mineral resource map for stockwork molybdenum deposits (A) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

locally. Minor amounts of auriferous pyrite, argentiferous tetrahedrite, and trace covellite are also locally present.

Area A2.—A small target area in the northeastern part of the Forest in the Never Summer Mountains has high mineral resource potential for molybdenum in stockwork deposits (pl. 1, fig. 16), with certainty level C. Within this area, the Tertiary Mount Cumulus stock has intruded highly fractured Proterozoic igneous and metamorphic rocks and younger sediments. The stock is rhyolitic in composition and contains molybdenite and pyrite in miarolitic cavities and along joints (Pearson and others, 1981). Anomalous concentrations of fluorine, lead, zinc, silver, tin, and niobium are in sediment samples from surrounding drainages. The body occupies a distinctive magnetic high and a gravity low, although the gravity low could be due to the effects of thrusting. The stock has expression in the K, U, and Th aeroradioactivity maps (figs. 11-15), reflecting its rhyolitic composition and probable surface expression. Although no large molybdenum deposits have been found, the unexplored interior of the stock is permissive for a deposit.

Area A3.—In the southeastern part of the Forest, a northeast-trending area has moderate potential for molybdenum in stockwork deposits (pl. 1, fig. 16), with certainty level C. Rock and stream-sediment samples from this area contain anomalous concentrations of molybdenum, lead, zinc, silver, and minor copper, tin, and gold. Pyrite, fluorite, and molybdenite are present in many of the samples (Theobald and others, 1985). The area occurs within the Colorado Mineral Belt and is adjacent to the Henderson mine, a known stockwork molybdenum system with previous metal production. The northeast part of the area has relatively elevated values in the K, U, and especially the Th data (figs. 11–13), and the Henderson mine (outside the Forest) has a distinct Th character.

ECONOMIC SIGNIFICANCE

The United States currently exports molybdenum and has almost half the world's identified resources, most of which occur in deposits of this type (U.S. Bureau of Mines, 1993). Resources of molybdenum are adequate to supply world needs for the foreseeable future.

PORPHYRY COPPER-MOLYBDENUM (B)

COMMODITIES, BY-PRODUCTS, AND TRACE METALS

Commodities are copper and molybdenum; by-products are gold, tungsten, and tin; trace metals include silver, lead, and zinc.

HOST ROCKS

Host rocks include late Cretaceous and Tertiary granitic rocks, Proterozoic crystalline rocks, and some Mesozoic sedimentary rocks.

STRUCTURAL CONTROL

Stockwork veins form in fractures produced by the intrusion of a small stock at very shallow crustal levels. The joint pattern may be controlled by joint patterns within the host pluton or by bedding, joints, or faults outside the pluton. Stockwork veins can occur in any brittle rock that has been shattered repeatedly including the host pluton and favorable country rocks. Favorable plutons occur along intersections of regional fault systems.

AGE

Porphyry copper-molybdenum deposits are late Cretaceous to late Eocene in age.

DEPOSIT DESCRIPTION

Porphyry copper-molybdenum deposits are a combination of disseminations and stockwork veins that occur in the shattered portions of an intrusive and in surrounding country rocks. The upper and outer margins of the intrusive have been shattered from adjustment during cooling or from the high vapor pressure of late mineralizing fluids. Granitic plutons that have multiple phases of intrusion are the most favorable for these types of deposits. Compositions of these plutons range from monzogranite to granite in the Forest. Stocks are most commonly porphyritic; they have radial dikes and associated breccias.

Disseminated ore is most common in the core of the intrusion, and veinlets of ore are dominant toward the outer margins of the intrusive and in the country rock. The richest ore zone occurs where disseminations are still dominant over veinlets (Lowell and Guilbert, 1970). The primary sulfides consist of pyrite, chalcopyrite, bornite, and molybdenite. Other minerals that may be present include sphalerite, galena, gold and silver minerals, wolframite, and cassiterite. A pyrite-rich shell usually occurs just outside of the main ore zone. Erosion and weathering of the metal-bearing portions of the intrusions releases copper, giving rise to a zone of supergene sulfide enrichment. The oxidation of pyrite in the argillic zone commonly produces a large red-colored halo above and around the deposit.

Porphyry copper-molybdenum deposits show pervasive hydrothermal effects that extend into surrounding wall-rocks. Assemblages of alteration minerals exhibit systematic spatial and temporal relationships with respect to one another. Characteristic alteration assemblages are zoned outward from potassium feldspar in the system center to quartz-sericite-pyrite and argillic alteration; propylitic assemblages occur along the outer margins.

GEOCHEMICAL SIGNATURE

The deposits have anomalous concentrations of copper, molybdenum, zinc, lead, silver, and local tungsten, boron, and strontium anomalies. In panned concentrates, tin, tungsten, molybdenum, and fluorine may be present in anomalous concentrations.

GEOPHYSICAL SIGNATURE

Plutons are expected in the gravity low of the Colorado Mineral Belt, which is associated with a large, unexposed batholith. Within this area, favorable terrane may be associated with a smaller, residual gravity low in the southeast part of the Forest.

Proterozoic granitic host rocks are often the most magnetic rocks in the Forest and commonly have associated magnetic highs. Tertiary granitic host rocks may or may not be magnetic and are less dense than Proterozoic rocks, especially where extensively altered. Gravity lows, with or without associated magnetic highs, may indicate Tertiary intrusive rock. Granitic host rocks can be distinctive in aeroradioactivity maps, dependent on surface exposure, because of relatively higher radioelement (K, U, Th) concentrations.

KNOWN DEPOSITS

One known deposit is in the Forest at Poison Ridge in the Rabbit Ears Range. The Poison Ridge deposit has been estimated to contain 51 million tons of rock averaging 0.22 percent copper in the hypogene zone, and 3.3 million tons averaging 0.70 percent copper in the supergene zone (Karimpour, 1982). The Anaconda Company estimated 36–45 million tons averaging 0.15–0.20 percent copper, possibly an additional 90 million tons averaging 0.05 percent copper, and trace amounts of gold for the Poison Ridge deposit (Anaconda Document Collection, file 93304.01, 1981).

ASSESSMENT CRITERIA

1. Presence of a late Cretaceous to Tertiary monzogranite to granite intrusion.
2. Extensive hydrothermal alteration in and around the pluton.
3. Presence of chalcopyrite and molybdenite.
4. Anomalous copper and molybdenum concentrations in rock and stream-sediment samples.

ASSESSMENT

Area B1.—A large east-west-trending area along the crest of the Rabbit Ears Range has moderate resource potential for copper and molybdenum in porphyry copper deposits, (pl. 1, fig. 17), with certainty level C. Several Tertiary hypabyssal plutons crop out within this area, including the one at Poison Ridge that contains identified copper resources. Some of the plutons have alteration pattern assemblages typical of porphyry copper-molybdenum deposits and have anomalous concentrations of copper, lead, zinc, silver, molybdenum, and (or) gold in rocks and stream-sediment samples (Karimpour and Atkinson, 1983; Spicker, 1973). Magnetic data indicate that several plutons of similar size are buried beneath the Rabbit Ears volcanics at the western edge of the area of potential. The plutons are along an east-west trend that is likely to be a Proterozoic lineament and a zone of weakness.

Area B2.—A small target area on Parkview Mountain has high mineral resource potential for copper and molybdenum in copper porphyry deposits (pl. 1, fig. 17), with certainty level C. Parkview Mountain is within the area of moderate potential outlined in B1, but veinlets and disseminations of copper, lead, zinc, silver, and molybdenite are present (Spicker, 1973). Alteration is moderate to intense and consists of locally pervasive quartz-sericite-pyrite with local zones of silica stockworks.

Area B3.—In the headwaters of the Illinois River, a small target area surrounding an intrusive body has high resource potential for copper and molybdenum in porphyry copper deposits (pl. 1, fig. 17), with certainty level C. In this location, a bedded breccia pipe of quartz latite composition contains anomalous concentrations of copper, lead, zinc, gold, silver, molybdenum, and arsenic (Metzger, 1974) Alteration is pervasive and consists of chlorite and sericite. The breccia pipe lies near the intersection of two major linear intrusive trends: the Rabbit Ears intrusives to the west and the intrusives of the Never Summer Range to the north.

ECONOMIC SIGNIFICANCE

The United States currently has almost half the world's identified resources of molybdenum and had a very small (3 percent) import reliance for copper in 1992 (U.S. Bureau of Mines, 1993).

POLYMETALLIC VEINS (C)

COMMODITIES

Commodities include lead, zinc, silver, copper, and gold with minor molybdenum, tin, tungsten, bismuth, and antimony.

HOST ROCKS

Host rocks vary in lithology. Most deposits occur in faults, fractures, or shear zones in Proterozoic igneous and metamorphic rocks. Other host rocks include Tertiary granitic plutons, dikes, and Paleozoic sedimentary rocks. Brittle or easily fractured rocks are particularly susceptible to mineralization.

STRUCTURAL CONTROL

Location of vein deposits is controlled by permeability of host rock. Most deposits are near or adjacent to faults, fractures, fault intersections, and breccia or shear zones although some occur near intrusive contacts.

AGE

Ages of mineralization are late Cretaceous and Tertiary. Host rocks may be of any pre-intrusive age.

DEPOSIT DESCRIPTION

Veins occur in a wide variety of host rocks and are related to late Cretaceous and Tertiary granitic plutons. Vein and vein systems are controlled by the distribution and size of fractures and are commonly modified by movement along fractures both during and after vein filling. Wallrock alteration adjacent to the vein is common, with the most intense alteration a few feet from the vein.

GEOCHEMICAL SIGNATURE

Geochemical anomalies vary with the composition of the individual vein. Lead, zinc, copper, silver, gold, arsenic, antimony, manganese, and barium are most commonly in

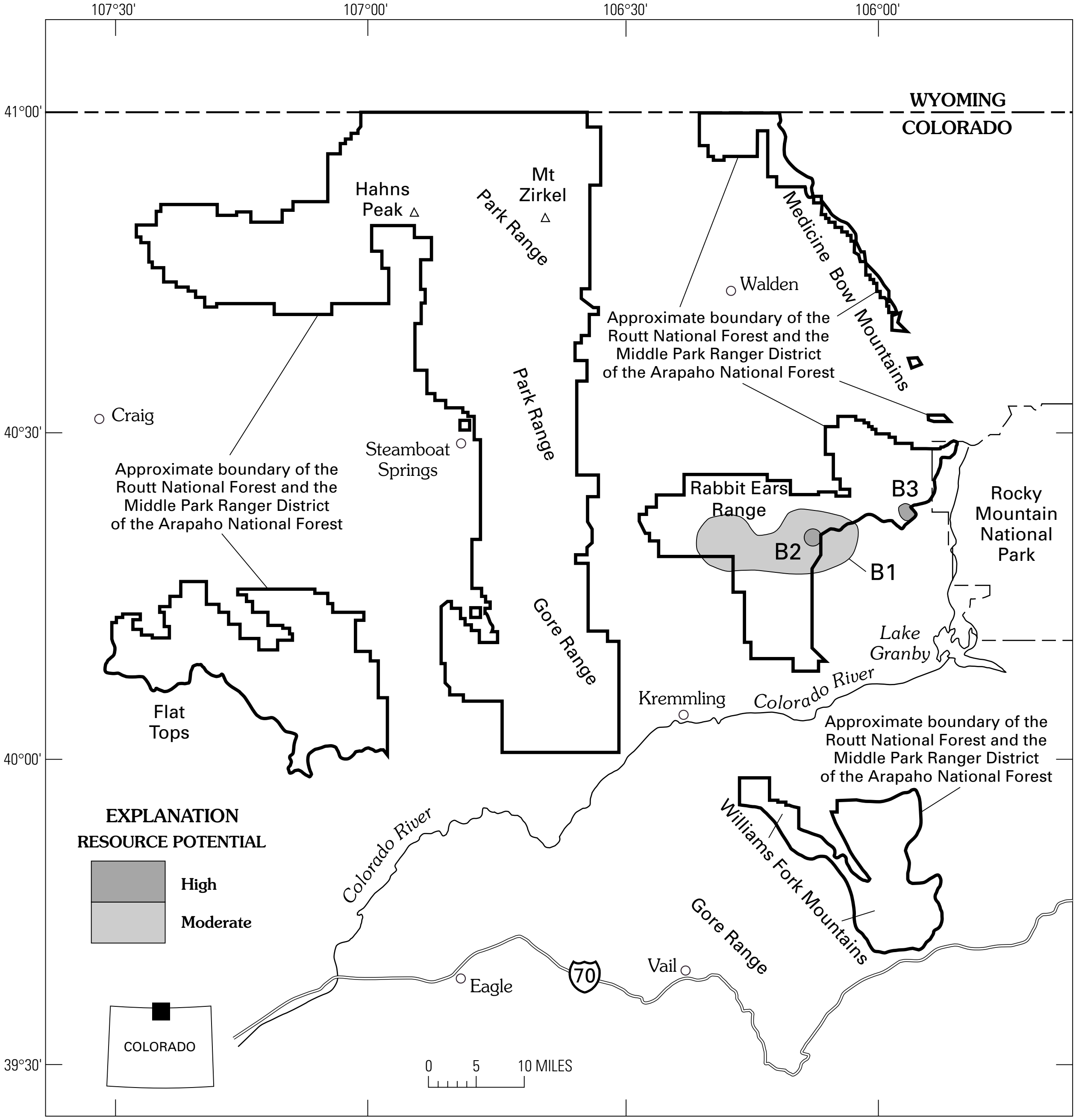


Figure 17. Mineral resource map for stockwork copper-molybdenum deposits (B) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

stream-sediment and rock samples. Element dispersal from individual veins may not be great enough to produce a detectable anomaly in stream-sediment samples.

GEOPHYSICAL SIGNATURE

Most veins are too small to be detected by regional gravity and magnetic surveys. Some intrusives and major structures exhibit prominent anomalies and steep gradient zones in the magnetic- and gravity-anomaly data. Many areas of known veining and wallrock alteration are characterized by magnetic highs; however, delineating these highs requires very detailed geophysical surveys. Electrical resistivity and other site-specific ground surveys are successful at locating veins. However, no such data were available for this assessment. Host rocks can have distinct aeroradioactivity expression, dependent on lithology, surface expression, and detail of aerial survey.

KNOWN DEPOSITS

Known vein deposits include the La Plata mine in the La Plata mining district, the Endomile mine in the Teller district, an area of small claims in the Slater district, the Elkhorn mine in the vicinity of the Encampment district, the Service Creek claims area east of Rabbit Ears Pass, Buffalo Pass and Buffalo Ridge area in the Mt. Zirkel Wilderness, and the Hahns Peak/Farwell Mountain district.

ASSESSMENT CRITERIA

1. Presence of vein deposits in the vicinity.
2. Presence of base or precious metals in rock or stream-sediment samples.
3. Presence of faults, breccia or shear zones, fault intersections, or intrusive contacts.
4. Presence of plutonic or hypabyssal igneous bodies of Late Cretaceous or Tertiary age.

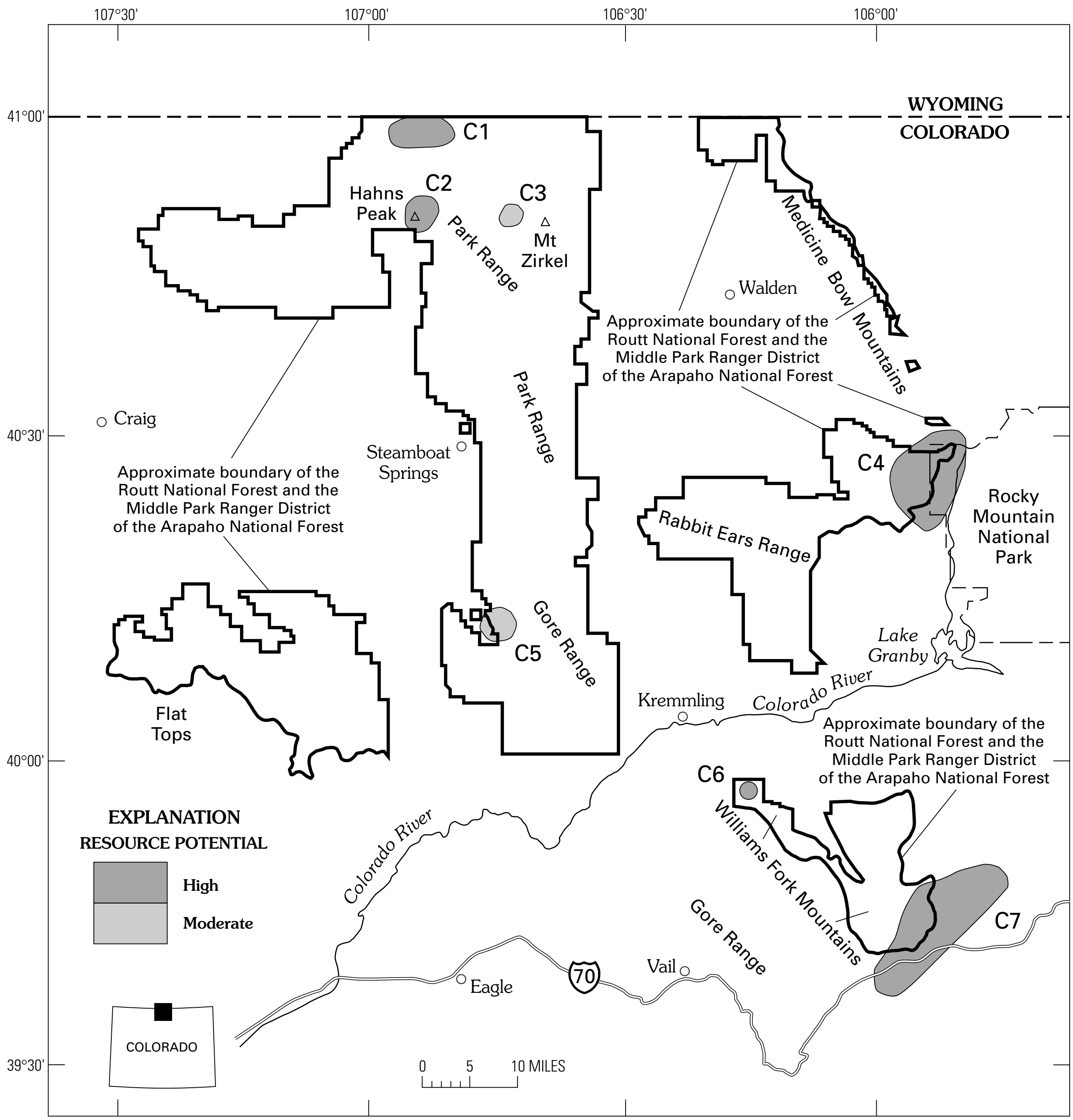


Figure 18. Mineral resource map for polymetallic vein deposits (C) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

ASSESSMENT

Area C1.—In the northwest part of the Forest, the area around Elkhorn Mountain has high mineral resource potential for metals in polymetallic veins (pl. 1, fig. 18), with certainty level C. Within this area, the Elkhorn mine contains elevated amounts of silver, gold, cadmium, copper, mercury, lead, antimony, and zinc in rock samples. Stream-sediment samples from the area did not contain anomalous concentrations of metals. The host rock is the Elkhorn gabbro, and metals are found in pods and veins. The entire area is outlined by a magnetic high. The Elkhorn gabbro is within a sizeable aeroradioactivity low (figs. 11–13), as mafic rocks are relatively deficient in K, U, and Th concentrations.

Area C2.—In the northwest part of the Forest, the area around Farwell Mountain has high mineral resource potential for metals in polymetallic veins (pl. 1, fig. 18), with certainty level C. Several workings in this area include trenches that expose quartz veins and veinlets in gneiss. Rock samples from this area contain anomalous to highly anomalous concentrations of copper, bismuth, tin, molybdenum, gold, silver, and tungsten; lead and zinc are conspicuous for their lack of anomalous values in the rock samples. Stream-sediment samples have anomalous concentrations of lead, zinc, silver, and molybdenum. Host rock is pegmatite, schist, and gneiss.

Area C3.—A small area in the northern part of the Park Range at Diamond Park has moderate mineral resource potential for metals in polymetallic veins (pl. 1, fig. 18), with certainty level B. Rock samples from this area have anomalous concentrations of bismuth, copper, lead, and molybdenum, silver, and tungsten. The metals are found in small quartz veins associated with fault zones in Proterozoic gneiss.

Area C4.—In the northeastern part of the Forest, the Teller mining district and surrounding area has high mineral resource potential for metals in polymetallic veins (pl. 1, fig. 16), with certainty level C. Numerous geochemical anomalies are in this area, including antimony, arsenic, cadmium, copper, gold, lead, molybdenum, silver, tin, and zinc. Silver was present in anomalous to highly anomalous amounts in rock samples (as much as 700 ppm Ag) and in stream-sediment samples. The district also contained anomalous to highly anomalous molybdenum in rock samples; one sample contained greater than 2,000 ppm Mo. Five rocks analyzed contained more than 10 percent arsenic. Two rock samples contained greater than 500 ppm cadmium. As much as 1,500 ppm Sb was found in rock samples. Lead was found to be highly anomalous in several rock samples (four were greater than 1.5 percent Pb) and in stream-sediment samples. Six rock samples contained zinc in quantities from 1 to 12 percent Zn; stream-sediment samples were also highly anomalous in zinc. Gold, copper, and tin were also found at anomalous levels in rock samples. Isolated stream-sediment samples contained anomalous concentrations of arsenic, cobalt, copper, and molybdenum in addition to ubiquitous silver, lead, and zinc. In the Teller district, mines and prospects were located in mineralized fracture zones and veins in Proterozoic granite and schist.

Area C5.—Moderate mineral resource potential for metals in polymetallic veins (pl. 1, fig. 18), with certainty level B, exists in a small area on the southwest side of the Gore Range in and near Morrison Creek. Two stream-sediment samples from this vicinity contain highly anomalous concentrations of silver, arsenic, vanadium, zinc, cobalt, tin, and tungsten. The value for silver (69 ppm) is one of the highest values in the Forest. The host rock in this area is Proterozoic granitic rock. The granite is a distinct, although moderate, feature on the aeroradioactivity maps (figs. 11–13).

Area C6.—At the north end of the Williams Fork Mountains, a small area on Copper Mountain has high mineral resource potential for metals in polymetallic veins (pl. 1, fig. 18), with certainty level C. Host rocks in the area are isolated pegmatites lenses in gneiss. Rock samples from the area have highly anomalous concentrations of copper, but other metals are present only in low concentrations (Neubert, 1994).

Area C7.—In the southeasternmost part of the Forest, a large northeast-trending area at the southern extent of the Williams Fork Mountains has high mineral resource potential for metals in polymetallic veins (pl. 1, fig. 18), with certainty level C. This area encompasses the Atlanta and La Plata mining districts. Rock samples contain anomalous concentrations of molybdenum, lead, arsenic, and silver, and isolated anomalous values of lead, tin, and zinc. Heavy-mineral-concentrate samples have anomalous concentrations of copper, tin, zinc, silver, molybdenum, lead. The area occupies several magnetic lows and is on the edge of the Colorado Mineral Belt (fig. 5). The Straight Creek fault zone extends through the center of the area of potential. Metals are associated with shears and faults in the Proterozoic Silver Plume Granite.

ECONOMIC SIGNIFICANCE

Polymetallic vein deposits have produced copper, lead, and zinc, and the precious metals gold and silver. The United States has a net import reliance of 8 percent lead, 3 percent copper, and 34 percent zinc; gold and silver are currently exported (U.S. Bureau of Mines, 1993). Porphyry copper mines in the Southwestern United States produce the major portion of this metal in the United States, whereas the Midcontinent region produces most of the Nation’s lead and zinc from large replacement deposits. A major change in demand or price for these commodities would be needed to support operation of small mines required to exploit vein deposits, although the presence of silver and gold would certainly enhance the possibility of development. Because veins the Forest are likely to be small, production from them is likely to have only local economic impact.

MASSIVE SULFIDES (D)

COMMODITIES

Commodities include lead, zinc, silver, copper, and gold.

HOST ROCKS

Deposits are found in Proterozoic calc-silicate and hornblende gneiss, amphibolite, and felsic gneiss units. Within the Forest, major areas of these rock types occur west of the Williams Fork thrust fault, within the Never Summer Mountains, northwest of the Independence Mountain thrust fault, and along the Park Range in the largest parcel of the Forest.

STRUCTURAL CONTROL

No regional scale structural control is evident; locally small-scale folds may have concentrated ore. Deposits occur as stratabound layers, pods, or lenses within the host rock; they tend to cluster and follow specific stratigraphic horizons.

AGE

Deposits have the same Proterozoic age as the enclosing host rock.

DEPOSIT DESCRIPTION

The term “massive” refers to the mineralization composed entirely of sulfides and does not carry any size or textural connotation (Sangster, 1972). Principal ore minerals found in these deposits are sphalerite, chalcopyrite, and galena, with minor amounts of silver and gold. Gahnite (zinc spinel), magnetite, and silicates make up the matrix for the sulfide minerals. The sulfides occur in small to large lenses and in laterally extensive zones of disseminated sulfides; all are generally conformable to the layering in the enclosing gneisses and amphibolite. The sulfide ore minerals weather to produce oxide, carbonate, and sulfate minerals.

Although most of the original textures and structures have been destroyed by intense regional metamorphism and deformation, the stratabound deposits are generally considered to be metamorphosed volcanic- or sedimentary-hosted sulfide deposits (Sheridan and others, 1990). In these deposits, the sulfide minerals were syngenetically deposited with felsic and mafic volcanic and sedimentary rocks in a submarine environment. Deposition of the metals probably occurred as the result of exhalative discharge of hydrothermal vents in the sea floor. Later metamorphism converted the volcanic rocks to amphibolite, calc-silicate, and felsic gneisses. It is this later metamorphism, along with deformation, that makes interpretation of the origin of these deposits difficult. Varying interpretations concerning the origin and paleotectonic setting of the deposits in northern Colorado and southern Wyoming have been proposed (Tweto, 1968; Giles, 1976, 1987; Sheridan and others, 1990; Klipfel, 1992). The Forest therefore has potential for several types of massive sulfide deposits. Recent work by Klipfel (1992) concluded that some stratabound sulfide deposits in the northern Park Range were sediment-hosted exhalative (Sedex) deposits related to volcanism that produced nearby Besshi-type and mixed Besshi-Sedex (Broken Hill) type deposits. According to Klipfel, deposition occurred in an ensialic-rift setting rather than an island-arc setting as is currently accepted for this area. The area also may host Kuroko-type (Franklin and others, 1981) volcanogenic massive sulfide deposits.

GEOCHEMICAL SIGNATURE

Geochemical signatures include anomalous concentrations of copper, lead, and zinc in stream-sediment and rock samples.

GEOPHYSICAL SIGNATURE

Magnetic and gravity data are of minimal use in identifying favorable terranes. Magnetite-rich zones can be detected with magnetic surveys, although most zones in this terrane are too small to be detected by regional surveys. Deposits associated with felsic volcanic rocks (Kuroko type) would have an aeroradioactivity signature, dependent on surface expression and detail of aerial survey.

KNOWN DEPOSITS

Several stratabound massive sulfide deposits and related occurrences are within or near the Forest, mainly in the northern Park Range and southern Sierra Madre. Mines in the Pearl district, near the community of Pearl, and the Greenville mine, north of Steamboat Springs, are considered by Sheridan and others (1990) to be examples of stratabound massive sulfide deposits in amphibolite-facies terrane.

ASSESSMENT CRITERIA

1. Presence of Proterozoic gneiss, especially amphibolite and calc-silicate rocks.
2. Presence of geochemical anomalies of base and precious metals.
3. Metals conformable with layers.
4. Island-arc tectonic setting at the time of mineralization.

ASSESSMENT

Area D1.—A large northeast-trending zone in the northern part of the Park Range has high mineral resource potential for massive sulfide deposits (pl. 1, fig. 19), with certainty level C. This area is underlain by favorable calc-silicate and amphibolite host rocks and stream-sediment samples have anomalous concentrations of copper, lead,

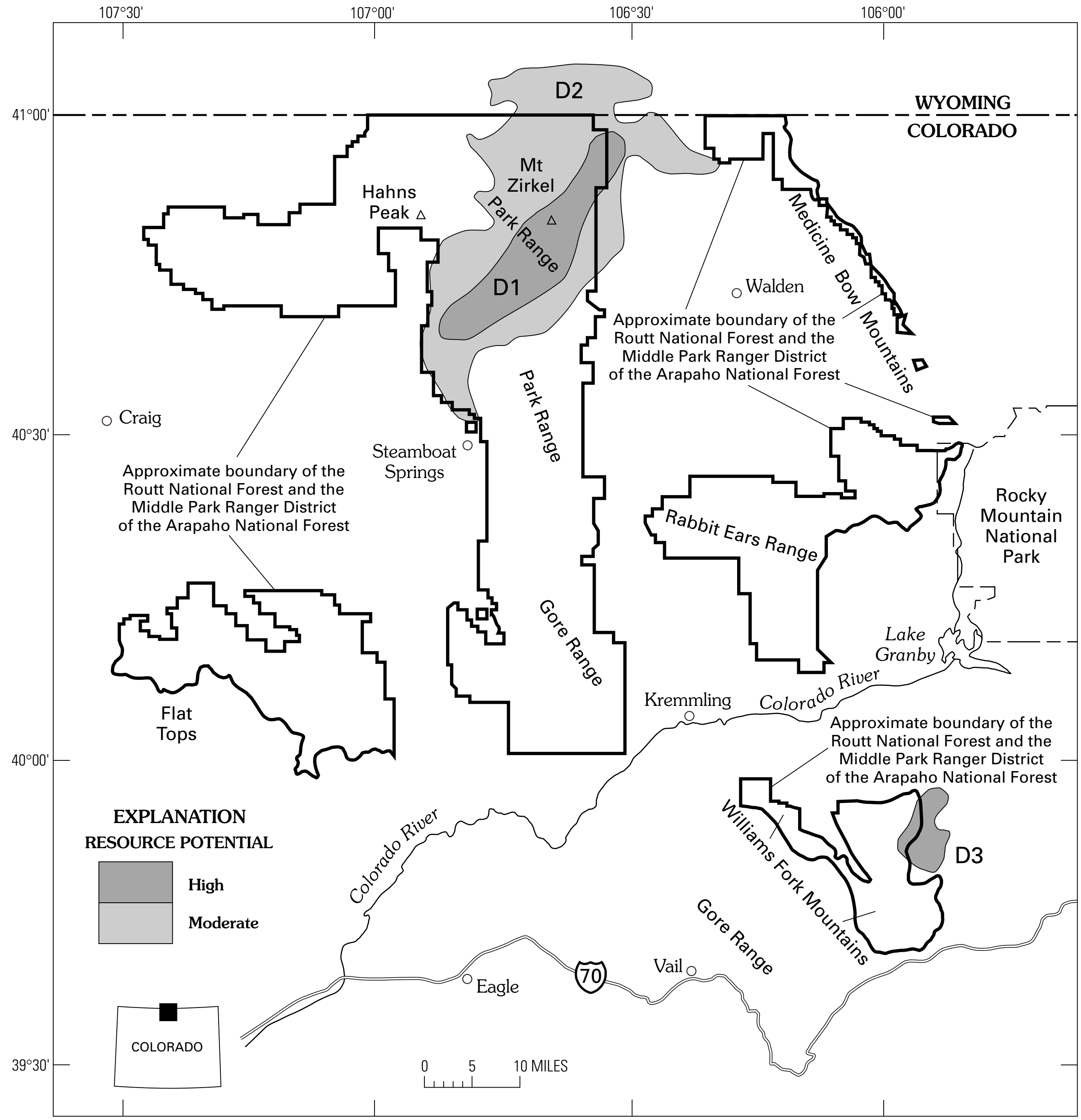


Figure 19. Mineral resource map for stratabound massive sulfide deposits (D) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

and zinc. Several mines and prospects are located in the area, and rock samples contain chalcopyrite, galena, and sphalerite. Anomalous amounts of silver, bismuth, cadmium, antimony, gold, molybdenum, and tin are also present in some rock samples. A ridge of gravity and magnetic high extends from the Greenville mine on the west to the Slavonia mine in the central part of the area. The area of potential was extended farther to the northeast to include the Pearl mine and to account for the general northeast trend of geophysical data.

Area D2.—Enclosing the area of high potential D1, a large area of moderate potential (pl. 1, fig. 19), certainty level B, is defined by outcrop of calc-silicate and amphibolite rock. Isolated stream-sediment samples within this area also contain anomalous concentrations of copper, lead, and zinc.

Area D3.—In the southeast part of the Forest, a medium-sized area has high resource potential for massive sulfides (pl. 1, fig. 17), with certainty level C. This area is underlain by favorable calc-silicate and amphibolite host rocks, and stream-sediment samples have anomalous concentrations of copper, lead, and zinc. Pods and small masses of gossan derived from massive pyrite bodies are common in the calcic metamorphic rocks, and some gossan retain geochemically anomalous amounts of silver, lead, and zinc (Theobald and others, 1985).

ECONOMIC SIGNIFICANCE

The United States has a net import reliance of 8 percent lead, 3 percent copper, and 34 percent zinc; gold and silver are currently exported (U.S. Bureau of Mines, 1993).

FLUORSPAR VEINS (E)

COMMODITY

The commodity is fluorspar.

HOST ROCKS

Dominantly 1.4-Ga Proterozoic granitic rock; lesser amounts of the White River Formation.

STRUCTURAL CONTROL

Deposits are concentrated along Laramide and rift-related late Tertiary(?) extensional faults.

AGE

Deposits are of two ages: Laramide and late Tertiary(?). Only the younger deposits have been productive.

DEPOSIT DESCRIPTION

The following description is from Steven (1960). Fluorite veins and stringers occur along faults in 1.4-Ga granitic rocks. The fluorite consists typically of botryoidal layers that formed as successive encrustations along open fractures or as finely granular aggregates replacing and cementing fault gouge and the White River Formation. The veins contain numerous open spaces ranging from small pores to large cavities as much as 20 ft in width and several hundred feet in diameter. Fluorite is the principal vein material, and fragments of country rock and chalcedony or finely granular quartz constitute the chief impurities. As much as 2 percent fine-grained pyrite is locally disseminated through the fluorspar and adjacent wallrock, although generally it is very sparse. Rounded fragments of wallrocks are in some of the open cavities along the vein. There is a lack of any notable wallrock alteration.

Fluorite was deposited from dilute aqueous solution, predominantly meteoric water, circulating though broken rock. Rounded fragments of wallrocks in open cavities of some veins indicate that movement of the mineralizing solution was sufficient to move and abrade these fragments. Mineral textures of some veins indicate that, locally, mineralization occurred both below and above the water table. The temperature of deposition ranged between 100°C and 150°C.

In the Forest, all veins occur within 1.4-Ga granite of the Mt. Ethel pluton and in Cenozoic sediments overlying the granite. The Mt. Ethel pluton contains interstitial fluorite. Most of the fluorite is magmatic and was deposited as the pluton crystallized, but some has been mobilized after first deposition (Snyder, 1987b). Magmatic fluorite in the Mt. Ethel pluton may have been mobilized and redeposited as veins or breccias during Tertiary time. Alternatively, the source of the fluorite may be a buried intrusion of Tertiary age.

This report only addresses vein fluorite of Tertiary age. Although magmatic fluorite is present in the Mt. Ethel pluton, the potential for undiscovered resources of fluorite of this type of occurrence is low.

GEOPHYSICAL SIGNATURE

Geophysical data may be used to infer the presence of buried plutons that could be the source for the fluorite. Granitic host rocks will be prominent on aeroradioactivity (K, U, Th) maps, dependent on surface expression.

GEOCHEMICAL SIGNATURE

Anomalous concentrations of fluorine in rocks and stream-sediment samples.

KNOWN DEPOSITS

The Northgate mining district is in the northeastern part of the Forest. Most of the production has come from the Fluorspar-Gero-Penbar and Fluorine–Camp Creek vein zones. Since 1922, at least 109,700 tons was produced (Steven, 1960).

ASSESSMENT CRITERIA

1. Presence of late(?) Tertiary, rift-related extensional faults.
2. Presence of 1.4-Ga granitic or other hard rocks in which open fractures can be maintained; presence of extremely permeable rock.
3. Anomalous concentrations of fluorine in rocks.

ASSESSMENT

Area E1.—A large area in the northern part of the Forest has high resource potential for additional deposits of fluorite, with certainty level C (pl. 1, fig. 20). This area encompasses

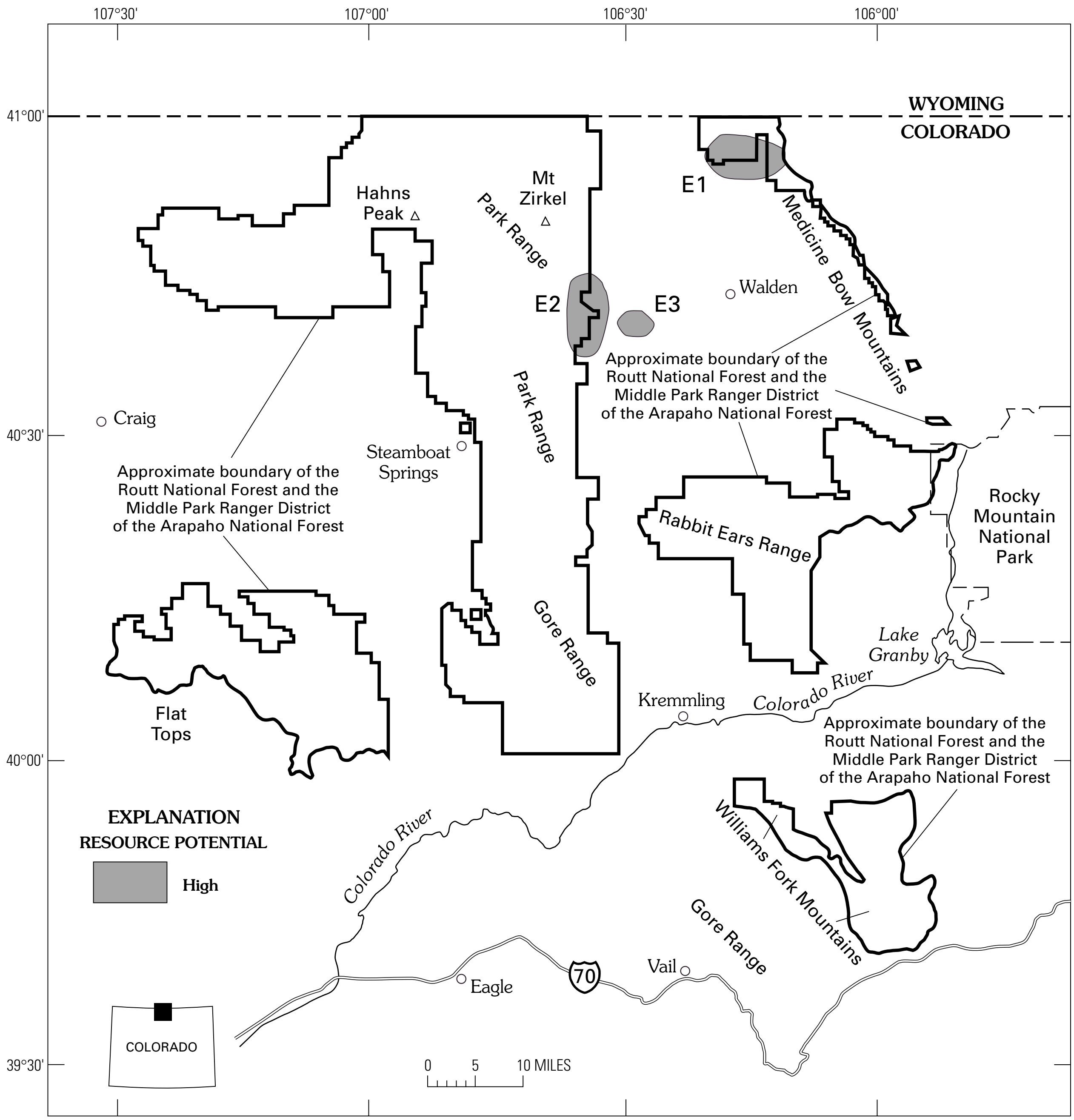


Figure 20. Mineral resource map for fluorspar veins and dissemination deposits (E) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

the Northgate mining district, a past producer of fluorite. In this area, fluorite is present as veins and stringers along faults in 1.4 Ga-granitic rocks and Cenozoic sediments.

Area E2.—On the eastern side of the Park Range, the Crystal district has high resource potential for additional deposits of fluorite, with certainty level C (pl. 1, fig. 20). The district includes rocks of the 1.4-Ga Mt. Ethel pluton, and fluorite is present in fault breccias and veins (Snyder, 1987b). The Crystal district occupies a magnetic and gravity high and may be underlain by a younger pluton that provided the source for the fluorite.

Area E3.—A small area on Delaney Butte east of the Park Range in North Park has high resource potential for fluorite, with certainty level C (pl. 1, fig. 20). Vein fluorite is present in the Proterozoic granite (Snyder, 1987b), an extension of the 1.4-Ga Mt. Ethel pluton.

ECONOMIC SIGNIFICANCE

The United States has a significant reliance upon import sources of fluorspar. In 1992, about 87 percent of the fluorspar was imported (U.S. Bureau of Mines, 1993). Within the United States, deposits in southern Illinois accounted for the majority of production. The Northgate district accounted for about 32 percent of Colorado's production through 1973 and at one point accounted for about 10 percent of the Nation's annual production (Brady, 1975). Production ceased in the Northgate district in the Forest in 1973. Most of the near-surface, easily minable fluorspar at Northgate has been removed, and expensive underground mining would be required to extract the remaining ore (Neubert, 1994).

VEIN URANIUM (F)

COMMODITIES, BY-PRODUCTS, AND TRACE METALS

Uranium deposits, with associated trace amounts of gold, silver, antimony, lead, zinc, and molybdenum occur along fractures and faults in Proterozoic granites.

HOST ROCKS

Host rocks are Proterozoic granitic rock, gneiss, and pegmatite.

STRUCTURAL CONTROL

Deposits occur within or along fractures or breccia zones.

AGE

Probably Late Cretaceous to Tertiary.

DEPOSIT DESCRIPTION

This type of deposit occurs in silicified and brecciated veins along fault zones in 1.7-Ga Proterozoic granitic plutons. Not much is known about the genesis of these deposits.

Opinions have been divided between hydrothermal and supergene mechanisms (Nash and others, 1981), but fluid-inclusion studies seem to suggest hydrothermal processes, with later supergene enrichment. Comparison to similar deposits suggest that the high concentrations of uranium and other metals in the granites probably reflect uranium-enriched supracrustal rocks. This deposit is in contrast to the Schwartzwalder-type of deposit found along the eastern side of the Front Range, where uranium deposits are found solely in Proterozoic metamorphic rocks (Wallace and Karlson, 1985).

GEOCHEMICAL SIGNATURE

A geochemical signature commonly associated with these deposits is uranium, mercury, arsenic, antimony, fluorine, molybdenum, and tungsten.

GEOPHYSICAL SIGNATURE

There is no significant magnetic signature. Gamma-ray spectrometer surveys are appropriate for exploration. Surficial deposits (less than 20 inches deep) would generate anomalies on radiometric maps; deeper deposits may not be evident with this method. Aeroradioactivity (K, U, Th) data will highlight host granites and can locate vein systems, dependent on surface expression and detail of aerial survey.

KNOWN DEPOSITS

The only known occurrence of uranium-bearing veins, the Ray claims, occur about 0.5 mi outside the southeastern boundary of the Forest near Jones Pass, in the Vasquez Mountains. The eastern edge of the Vasquez Peak Wilderness Area was rated as having low potential for uranium in veins in faulted granites (Theobald and others, 1985).

ASSESSMENT CRITERIA

1. Evidence of uranium minerals.
2. Presence of faults, fractures, joints, or shear zones.
3. Presence of quartz veins or silicified faults.
4. Anomalous uranium radioactivity.

ASSESSMENT

Area F1.—On the southwest side of the Gore Range in the vicinity of Morrison Creek, a small area has moderate resource potential for vein uranium (pl. 1, fig. 21), with certainty level B. The host rock in this area is Proterozoic granitic rock. Aeroradioactivity data show moderate values of K, U, and Th (figs. 11–13) and geochemical data indicate a high U/Th value in a few samples. A small magnetic high is also present within the area.

Area F2.—In the southeastern part of the Forest just southwest of Jones Pass, a small area has high resource potential for vein uranium (pl. 1, fig. 21), with certainty level C. The uranium minerals autunite and uranophane are present along with abundant quartz veins in Proterozoic granitic rocks in the area of the Ray claims. Faults, fractures, and joints are abundant and silicified. The area has high aeroradioactivity (K, U, Th) values (figs. 11–13).

ECONOMIC SIGNIFICANCE

The number of producing uranium mines in the United States is relatively small and is likely to remain in this condition for the near future. Exploration and development of any uranium resources in the Forest is unlikely in the foreseeable future due to the depressed state of the uranium industry. Import and export figures for uranium are proprietary (U.S. Bureau of Mines, 1993).

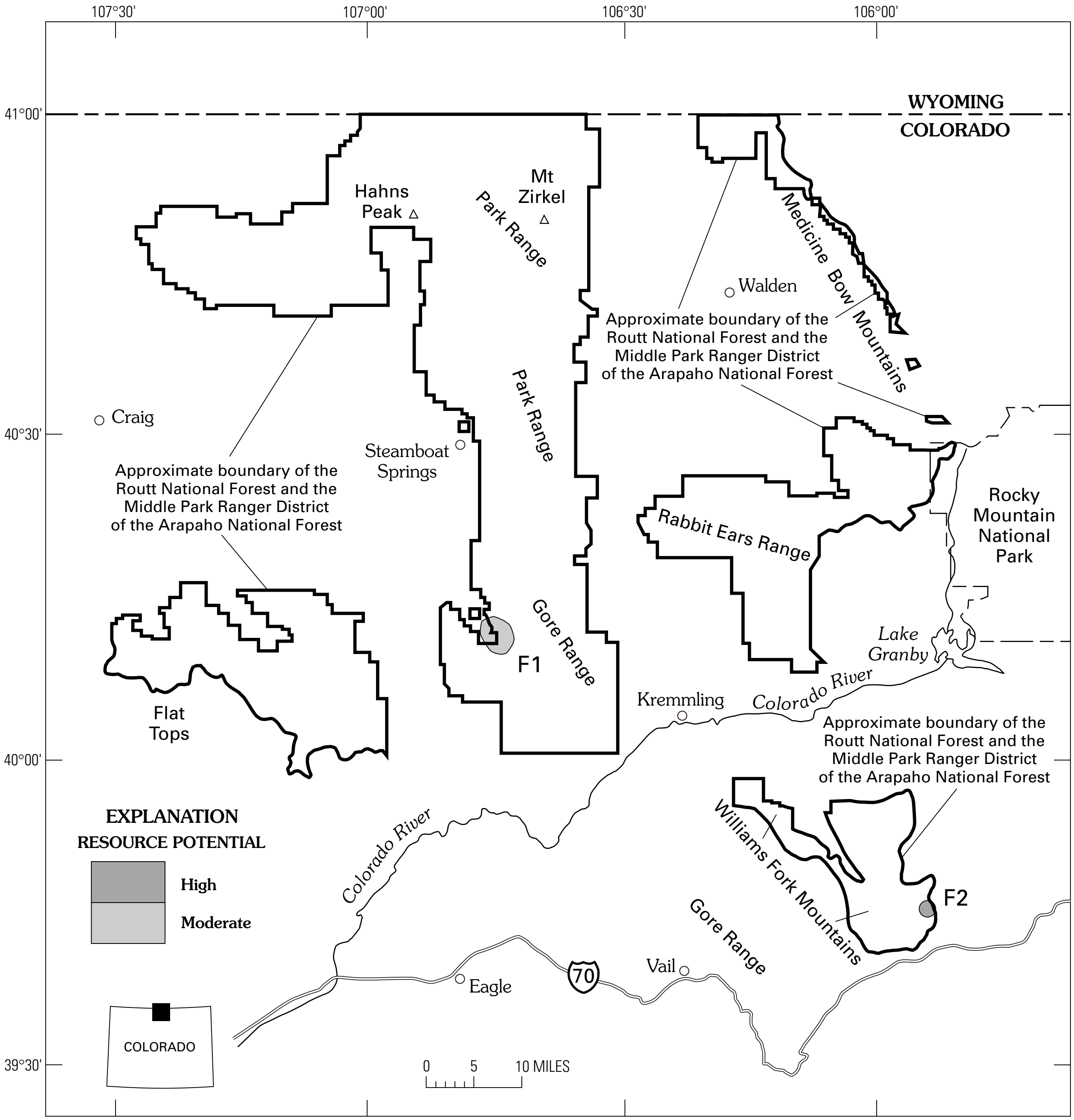


Figure 21. Mineral resource map for vein uranium (F) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

SANDSTONE URANIUM-VANADIUM (G)

COMMODITIES AND BY-PRODUCTS

Commodities are uranium and vanadium with copper by-product.

HOST ROCKS

Host rocks include Paleozoic sedimentary rocks, in particular the Morrison Formation, the Dakota Sandstone, the Troublesome Formation, and the Middle Park Conglomerate.

STRUCTURAL CONTROL

Structural control is variable.

AGE

Mesozoic age.

DEPOSIT DESCRIPTION

Deposits form as microcrystalline uranium oxides, phosphates, carbonates, vanadates, and silicates and are deposited during diagenesis in locally reduced environments in fine- to medium-grained sandstone beds (Turner-Peterson and Fishman, 1986). Some uranium minerals are also deposited during redistribution at the interface between oxidized and reduced areas by ground water. Interbedded shale and mudstone sequences are the source for the ore-related fluids. Fluvial channels, braided-stream deposits, continental basin margins, and stable coastal plains are the most characteristic settings for these deposits.

Deposits are usually massive and tabular in shape and orebodies are nearly concordant with gross sedimentary features of the host sandstone. Deposits may also occur as roll-front bodies that are crescent shaped and discordant to bedding in cross section. Tabular uranium occurs as lenses within reduced sandstone, and roll-front deposits occur at interfaces between oxidized and reduced ground.

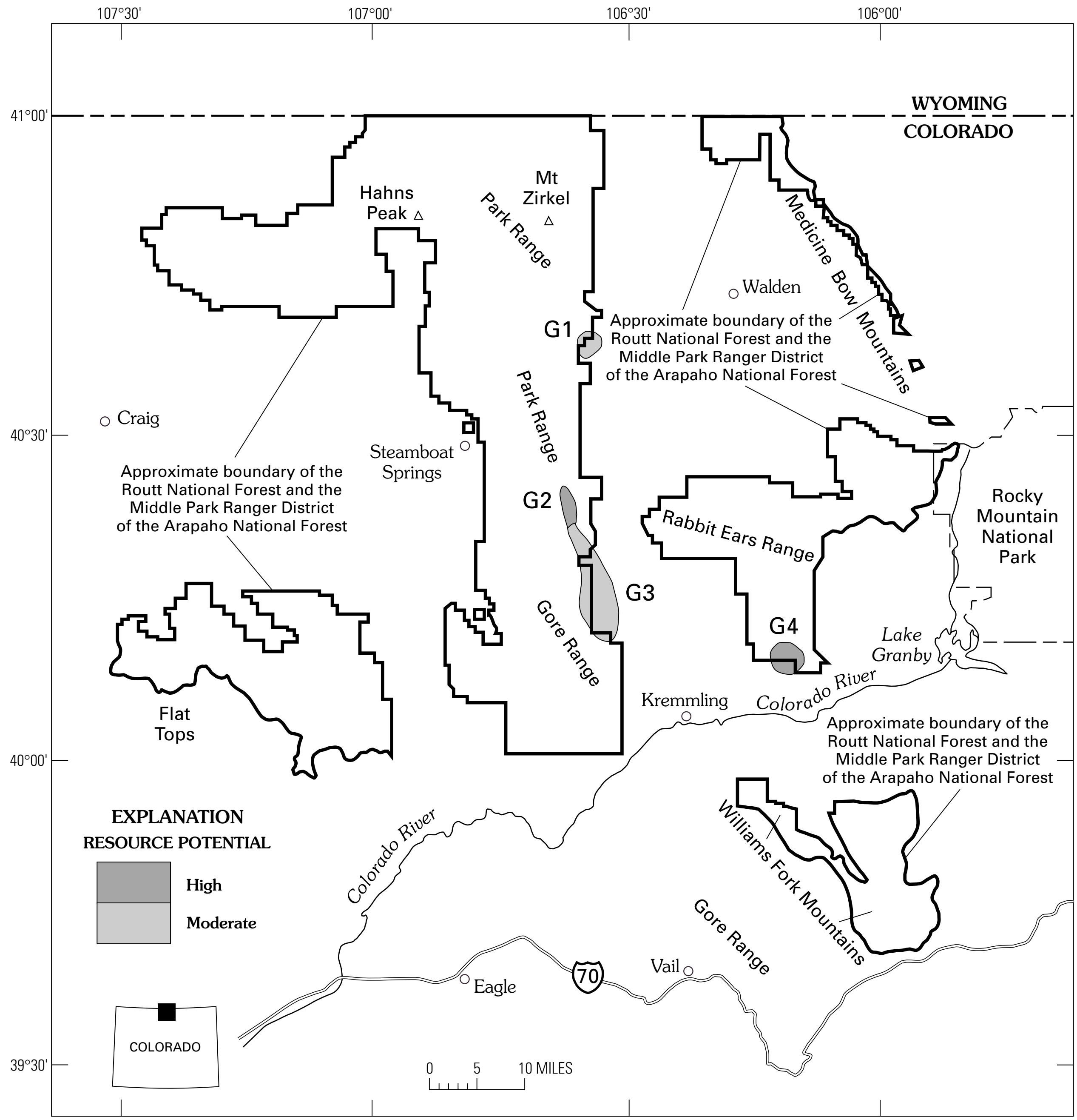


Figure 22. Mineral resource map for sandstone uranium-vanadium deposits (G) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

GEOCHEMICAL SIGNATURE

Uranium, vanadium, molybdenum, selenium, silver, and copper are present in anomalous concentrations.

GEOPHYSICAL SIGNATURE

No expression was recognized in regional aeromagnetic or gravity data. U aeroradioactivity data can be a primary indicator, dependent on surface expression and detail of survey.

KNOWN DEPOSITS

Known deposits occur in the Beaver Creek–Troublesome district near Kremmling, near Norris Creek on the east side of the Mt. Zirkel Wilderness, and at Rabbit Ears Pass.

ASSESSMENT CRITERIA

1. Presence of Morrison Formation, Dakota Sandstone, Troublesome Formation, or Middle Park Conglomerate.
2. Alteration and oxidation of host rocks.
3. Presence of carbonaceous beds or other reductants that cause deposition of uranium.
4. Presence of uranium in favorable units.
5. Anomalous uranium radioactivity, dependent on surface expression

ASSESSMENT

Area G1.—An area on the east side of the Park Range along and near Norris Creek has moderate resource potential for sandstone-hosted uranium and vanadium, with certainty level C (pl. 1, fig. 22). The host rock is the Morrison Formation, and background radioactivity readings are above normal (Snyder, 1987a). No uranium minerals were identified.

Area G2.—A north-south-trending elongate area in the vicinity of Rabbit Ears Pass has high resource potential for sandstone-hosted uranium and vanadium, with certainty level C (pl. 1, fig. 22). Uranium is present mostly as carnotite within the uppermost 25 ft of the Dakota Sandstone; carnotite forms grain coatings, concentrations replacing and surrounding carbonaceous material, and fracture coatings (Malan, 1957).

Area G3.—An elongate area extending south from area G2 has moderate mineral resource potential for sandstone-hosted uranium and vanadium, with certainty level B (pl. 1, fig. 22). This area encompasses the upper portion of the Dakota Sandstone, favorable for uranium in area G2. Geochemical data shows favorable U/Th ratios in this area. U (fig. 12) and U/Th (fig. 14) aeroradioactivity data are relatively anomalous.

Area G4.—The Troublesome district, north of Highway 40 between Kremmling and Hot Sulphur Springs has high mineral resource potential for additional sandstone-hosted uranium and vanadium, with certainty level C (pl. 1, fig. 22). Uranium occurs in the basal portions of the Tertiary Troublesome Formation in sandstone lenses. Carnotite, autunite, schroeckingerite, and unidentified vanadium minerals are present (Malan, 1957). Anomalous radioactivity is present in widely scattered localities.

ECONOMIC SIGNIFICANCE

The number of producing uranium mines in the United States is relatively small and is likely to remain in this condition for the near future. Exploration and development of any uranium resources in the Forest is unlikely in the foreseeable future due to the depressed state of the uranium industry. Import and export figures for uranium are proprietary (U.S. Bureau of Mines, 1993).

PLACER GOLD (H)

COMMODITIES

Gold with minor silver.

HOST ROCKS

Host rocks include modern to Pleistocene-age alluvium in stream sediments, colluvium, or slope-wash deposits; and glacial-fluvial gravels and tills. Placers originate from erosion of veins in Proterozoic and Paleozoic bedrock, although some placers may have been derived from the reworking of paleoplacers, in particular the basal conglomerates of the Dakota Sandstone and the Browns Park Formation.

STRUCTURAL CONTROL

Structure has little influence on the location or deposition of placer deposits. Deposits are usually downstream from known precious-metal lode deposits, mostly related to veins in various rock types. Irregular flow patterns of the streams separated light from heavy components of stream sediment. Gold and other heavier minerals tend to be concentrated on the inside of oxbows and in pools cut into bedrock. Gold is not generally dispersed throughout and constitutes only a small part of the gravels.

AGE

Pliocene(?) or early Pleistocene deposition (Parker, 1961; Parker, 1974).

DEPOSIT DESCRIPTION

Placers are irregularly shaped accumulations of heavy minerals near the bottom of gravel deposits. They range in size from a few feet to a few acres along stream beds or within landslide deposits. Gold is concentrated in ribbons or streaks in individual channels that are normally 180 to 400 ft wide (Parker, 1974). Associated heavy-mineral black sands contain magnetite, chromite, ilmenite, hematite, monazite, pyrite, zircon, garnet, and rutile.

Gold in placer deposits formed in modern alluvium and colluvium and in Pleistocene fluvial sediments. Deposits are found at the base of stream gravels deposited along present-day streams (Willow and Beaver Creeks), in terrace gravels related to these streams, in colluvium or slope-wash deposits (Little Red Park), alluvial fan deposits (Poverty Bar), and in Pleistocene glacial-fluvial deposits. There are no placer deposits formed strictly by glacial activity; however, glaciation can modify or destroy previously formed placer deposits (Parker, 1974). The placers in the Forest have been worked almost exclusively for gold, although the Bear Paw claims along the South Fork of the Michigan River were staked to test for platinum-group elements. No platinum-group elements have been found at this location.

GEOCHEMICAL SIGNATURE

Anomalous concentrations of gold, silver, and locally bismuth are present.

GEOPHYSICAL SIGNATURE

Regional geophysical surveys are of little use, but local seismic surveys could be used to determine the thickness of placer gravels. Ground magnetometers could be used to detect magnetite and ilmenite that may be concentrated in the gold placers and to help locate shallowly buried placers. U and Th aeroradioactivity from monazite, zircon, and other radioactive minerals can be an indicator, dependent on surface expression and detail of survey.

KNOWN DEPOSITS

Areas within the Forest that have produced gold from placer deposits include the following: the area along the South Fork of the Michigan River, between the confluence of Porcupine Creek and the west boundary of the Never Summer Wilderness, which has been intermittently claimed (Bear-Paw group claims) for gold and PGE (Neubert, 1994); gravels along Beaver Creek, Ways Gulch and Deep Creek (between 8,000 and 8,500 ft elevation) in the Hahns Peak mining district (Parker, 1974); the Willow Creek Canyon area; hill-slope placers at Little Red Park, north of Hahns Peak (Parker, 1974); on Sawmill Creek, southwest of Walden; and the Independence Mountain placer (Parker, 1974, p. 31). Poverty Bar, on the east side of Deep Creek just west of the village of Hahns Peak, was the most productive placer in the Hahns Peak district. Total production from placer deposits in the Hahns Peak district has been estimated to be from $500,000 (Parker, 1974) to $2,200,000 (Lakes, 1909).

ASSESSMENT CRITERIA

1. Presence of alluvial or colluvial deposits downstream from known precious-metal deposits.
2. Presence of alluvial or colluvial gravels.
3. Anomalous concentrations of base and precious metals in panned-concentrate samples.

ASSESSMENT

Area H1.—A small area on the north slope of Hahns Peak in Little Red Park was mined for placer deposits (Parker, 1974) and is assigned a moderate resource potential for additional small, undiscovered placer deposits, with a certainty level of C (pl.1, fig. 23). The source of the gold may have been from disseminations in the porphyry at Hahns Peak. The gold at Little Red Park is distinctive for its high silver content (Desborough, 1970).

Area H2.—Poverty Bar, on the south slope of Hahns Peak and west of the village of Hahns Peak, was mined for placer deposits and is assigned a high potential for additional, small undiscovered placer deposits, with a certainty level of B (pl. 1, fig. 23). Most of the placer gold production from the Hahns Peak district came from the Poverty Bar placer (Neubert, 1994), and the source of the gold may also have been from the Hahns Peak porphyry.

Area H3.—A small area south of Hahns Peak, which includes part of the Beaver Creek drainage and Ways Gulch, has been mined for placer deposits. This area is assigned a high resource potential for additional, small, undiscovered placer deposits, with a certainty level of C (pl. 1, fig. 23). During reconnaissance studies in the 1960's, gold was recovered from placers in Ways Gulch (Neubert, 1994), and small localized deposits may still host gold.

Area H4.—The Willow Creek Canyon area was mined for placer deposits but production is unknown (Snyder, 1987a). The area has a high resource potential for additional, small, undiscovered placer deposits, with a certainty level of C (pl. 1, fig. 23). Fine flakes of gold were found in samples collected from placer material on or near bedrock (Snyder, 1987a).

Area H5.—Several drainages along Independence Mountain, just outside the Forest, have produced gold from placer deposits and are included in the small outlined area (pl. 1, fig. 23). This area has a high resource potential for additional undiscovered small placer deposits, with a certainty level of C. Small placer operations were attempted at the head of Threemile Creek, along Placer and Lawrence Draws, and along an unnamed draw between Placer Draw and California Gulch (Hail, 1965, Parker, 1974). The source of the gold is unknown.

Area H6.—A small area south of Threemile Creek, on the northeast slope of Independence Mountain has a moderate resource potential for small placer deposits, with certainty level B (pl. 1, fig. 23). Alluvial material is present in stream drainages and stream-sediment samples from this area contained anomalous concentrations of gold.

Area H7.—A small area just outside the Forest boundary, near Rand, has a moderate resource potential for small

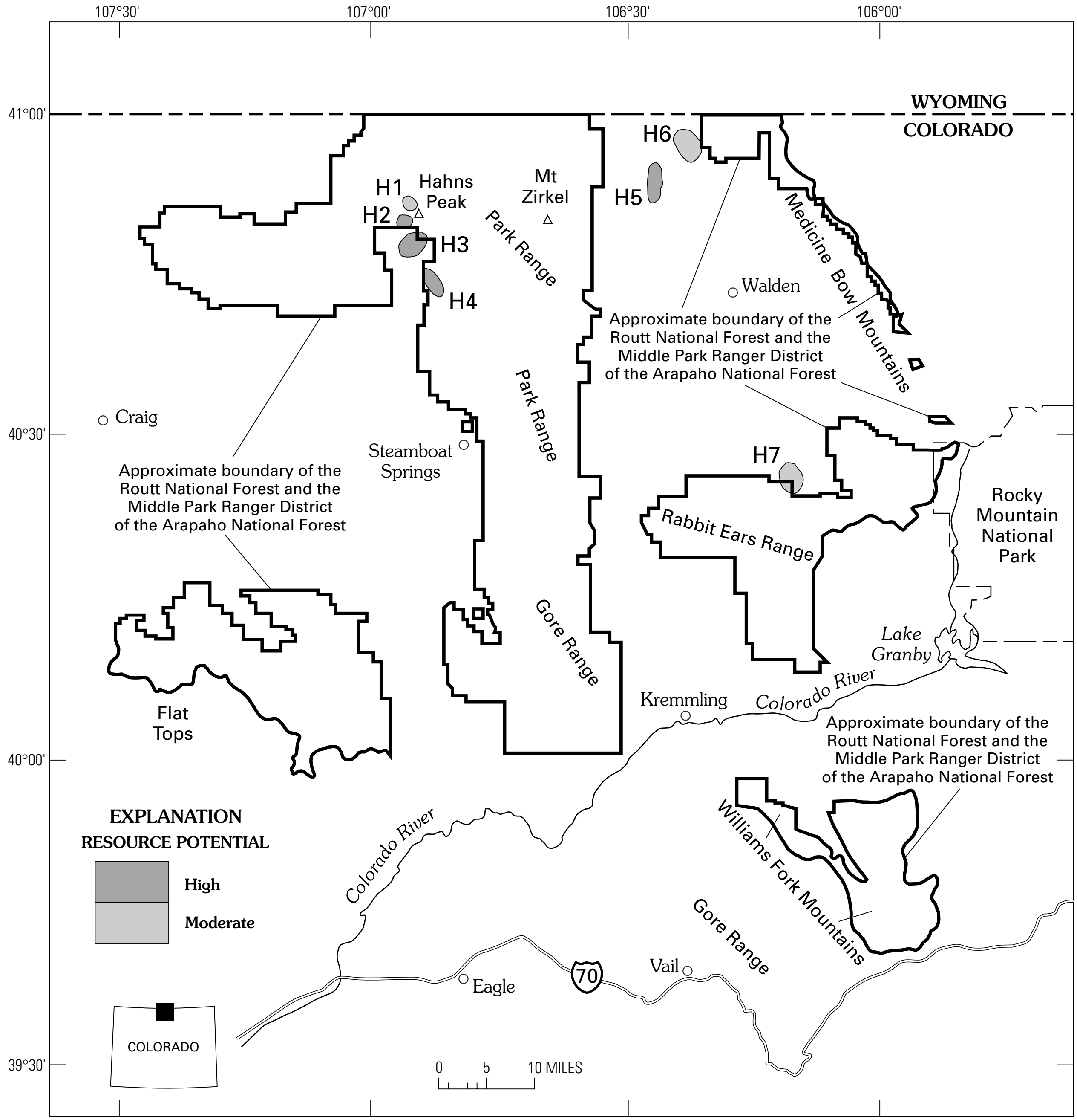


Figure 23. Mineral resource map for placer gold (H) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

placer deposits, with certainty level B (pl. 1, fig. 23). Stream-sediment samples from the area have anomalous concentrations of gold and silver.

ECONOMIC SIGNIFICANCE

Gold is a commodity in high demand. Unlike lode-gold deposits, small placer deposits can usually be worked at a relatively low cost, making them attractive to individuals or small operations. Although most of the known deposits have already been exploited, there is likely to always be an interest in deposits within the Forest. Areas of potential in the Forest are small, have already been well explored, and may only be exploited for recreational panning or mining operations. The United States currently exports gold (U.S. Bureau of Mines, 1993).

PLATINUM-GROUP ELEMENTS IN ULTRAMAFIC ROCKS (I)

COMMODITIES, BY-PRODUCTS, AND TRACE METALS

The commodities are the platinum-group elements (PGE): osmium, iridium, ruthenium, rhenium, platinum, and palladium. Other associated metals include chromium, nickel, and cobalt.

HOST ROCKS

Host rock for these types of deposits is altered peridotite.

STRUCTURAL CONTROL

None.

AGE

Early Proterozoic.

DEPOSIT DESCRIPTION

In the Forest, platinum-group minerals, and associated chromium, cobalt, and nickel, occur in pods and layers in ultramafic rocks (Snyder, 1987a). These layers form from gravity settling and convection processes in intrusive basaltic magmas. Early-formed crystals in these magmas settle to the bottom of the magma chamber, forming continuous layers and pods of minerals. These bodies generally range in composition from peridotite (olivine and pyroxene) at the base, through gabbro (olivine, pyroxene, and plagioclase), to anorthosite (mostly plagioclase) at the top; not all compositions are always present. PGE minerals, and chromium, cobalt, and nickel-bearing minerals crystallize from the melt in the early stages and accumulate in the lower portions of these bodies in the peridotite layers. Platinum-group elements occur as sulfide, arsenide, and sulfide-arsenide minerals, commonly closely associated with copper-sulfide minerals. The precipitation of sulfide minerals from a silicate melt is the most important phenomena in localizing and concentrating PGE; the mechanisms of this process are poorly understood.

GEOPHYSICAL SIGNATURE

Ultramafic plutons are commonly associated with magnetic and gravity highs and unusually low K, U, and Th radioactivity.

GEOCHEMICAL SIGNATURE

Elevated concentrations of cobalt, chromium, and nickel are the most common. Silver, gold, cadmium, copper, mercury, lead, antimony, and zinc are also present.

KNOWN DEPOSITS

There are no known deposits in the Forest. However, about 16 mi due north of the northeasternmost part of the Forest in Wyoming, the New Rambler mine operated from 1900 to 1918 and produced more than 6,000 tons of Cu, Ag, Au, Pt, and Pd ore (McCallum and Orback, 1968).

ASSESSMENT CRITERIA

1. Presence of peridotite.
2. Anomalous concentrations of PGE, Co, Cr, Ni, and (or) Cu, Au, and Ag in soils, rocks, or heavy-mineral-concentrate samples.

ASSESSMENT

Area I1.—Near Elkhorn Mountain in the northernmost part of the Park Range a small area of peridotite within the Elkhorn gabbro complex has high potential for PGE, with certainty level C (pl. 1, fig. 24). The peridotite is a volumetrically minor part of the gabbro mass, but is well-exposed on Peak 9,731 on the Continental Divide. Rock samples from this area contain anomalous concentrations of platinum and palladium; one sample contains as much 0.03 ppm platinum plus palladium (Snyder, 1987a).

Area I2.—A small area between Bear Creek and Lone Pine Creek on the east side of the Park Range has high potential for PGE elements, with certainty level C (pl. 1, fig. 24). This locality contains a long, linear peridotite intrusive. Rock samples from this area contain anomalous concentrations of platinum and palladium (Snyder, 1987a); one sample contained as much as 0.048 ppm platinum plus palladium.

ECONOMIC SIGNIFICANCE

The United States has a net import reliance of 94 percent for the platinum-group metals (U.S. Bureau of Mines, 1993). The only mining of PGE ore in the United States in 1992 was in Montana at the Stillwater complex. World resources are estimated at 100 million kilograms; United States resources are estimated at 9 million kilograms. Any deposits within the Forest are likely to be small and of little economic import.

U-TH-REE IN PEGMATITES (J)

COMMODITIES

The commodities are uranium, thorium, and the rare-earth elements (REE).

HOST ROCKS

Pegmatites in Proterozoic granitic rocks.

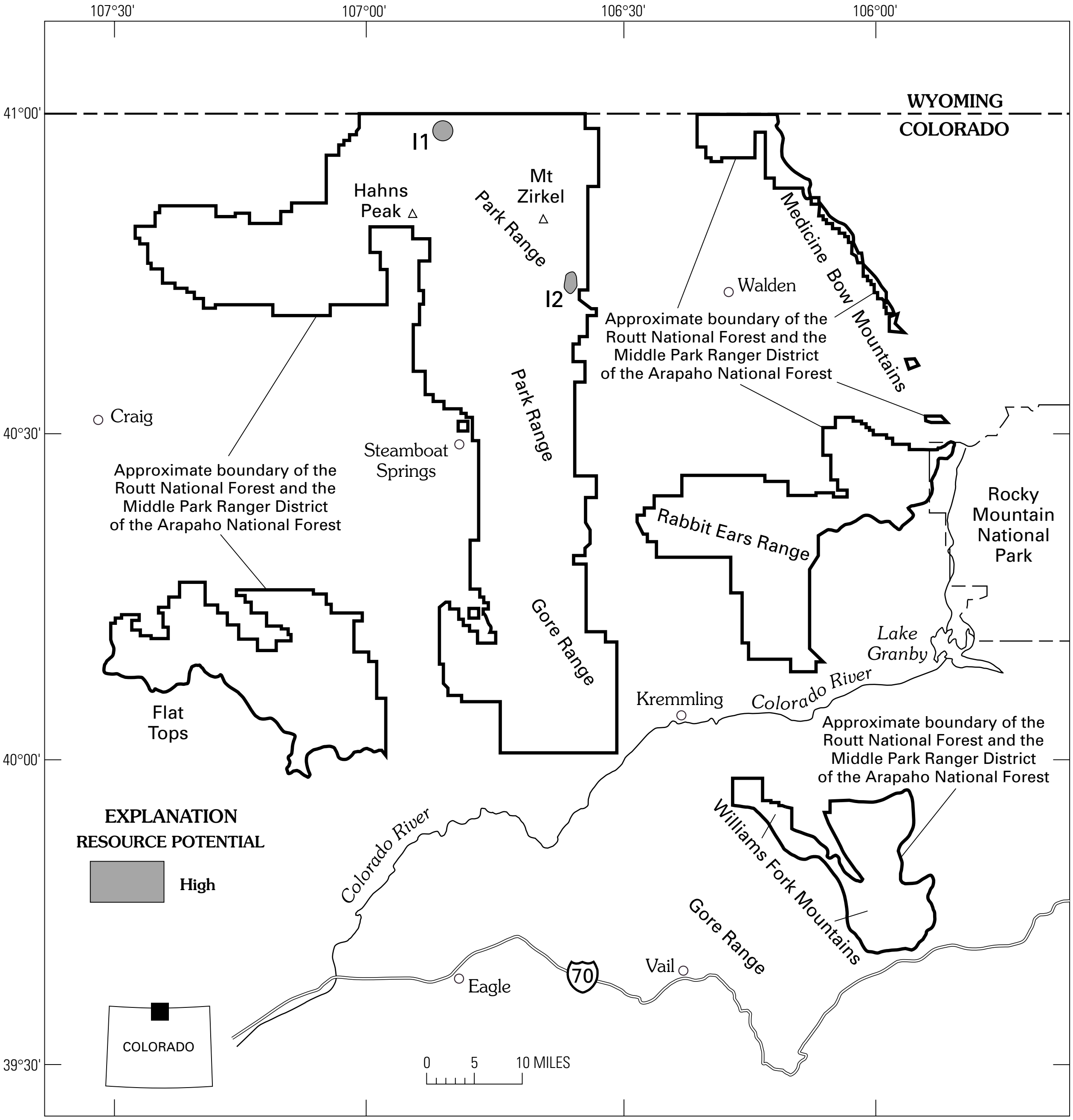


Figure 24. Mineral resource map for PGE in ultramafic rocks (I) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

STRUCTURAL CONTROL

U, Th, and REE minerals occur within pegmatites. There is no structural control except for pegmatites that are emplaced in fault zones.

AGE

U-Th-REE pegmatites are of two ages: 1.4 Ga and 1.7 Ga. The younger pegmatites contain more U-Th-REE than do the older ones, with a few rare exceptions.

DEPOSIT DESCRIPTION

U-Th-REE minerals occur in pegmatites within granitic rocks. Pegmatites contain the minerals that crystallized from the residual melt of a slowly cooling, deeply buried granitic magma body. This residual melt is commonly enriched in gaseous constituents such as H_2O, P, Cl, F, and S as well as the rare-earth elements, U, and Th.

Reported radioactive minerals include uraninite, zircon, xenotime, allanite, fergusonite, euxentie, carnotite, black chalcedony or dark-purple fluorite, as well as secondary alteration products such as autunite, uranophane, or gummite (Snyder, 1987a).

GEOPHYSICAL SIGNATURE

U and Th aeroradioactivity will be anomalous, depending on surface expression and detail of the survey.

GEOCHEMICAL SIGNATURE

Anomalous concentrations of U, Th, or REE in rocks and stream-sediment samples.

KNOWN DEPOSITS

There are no known deposits within the Forest.

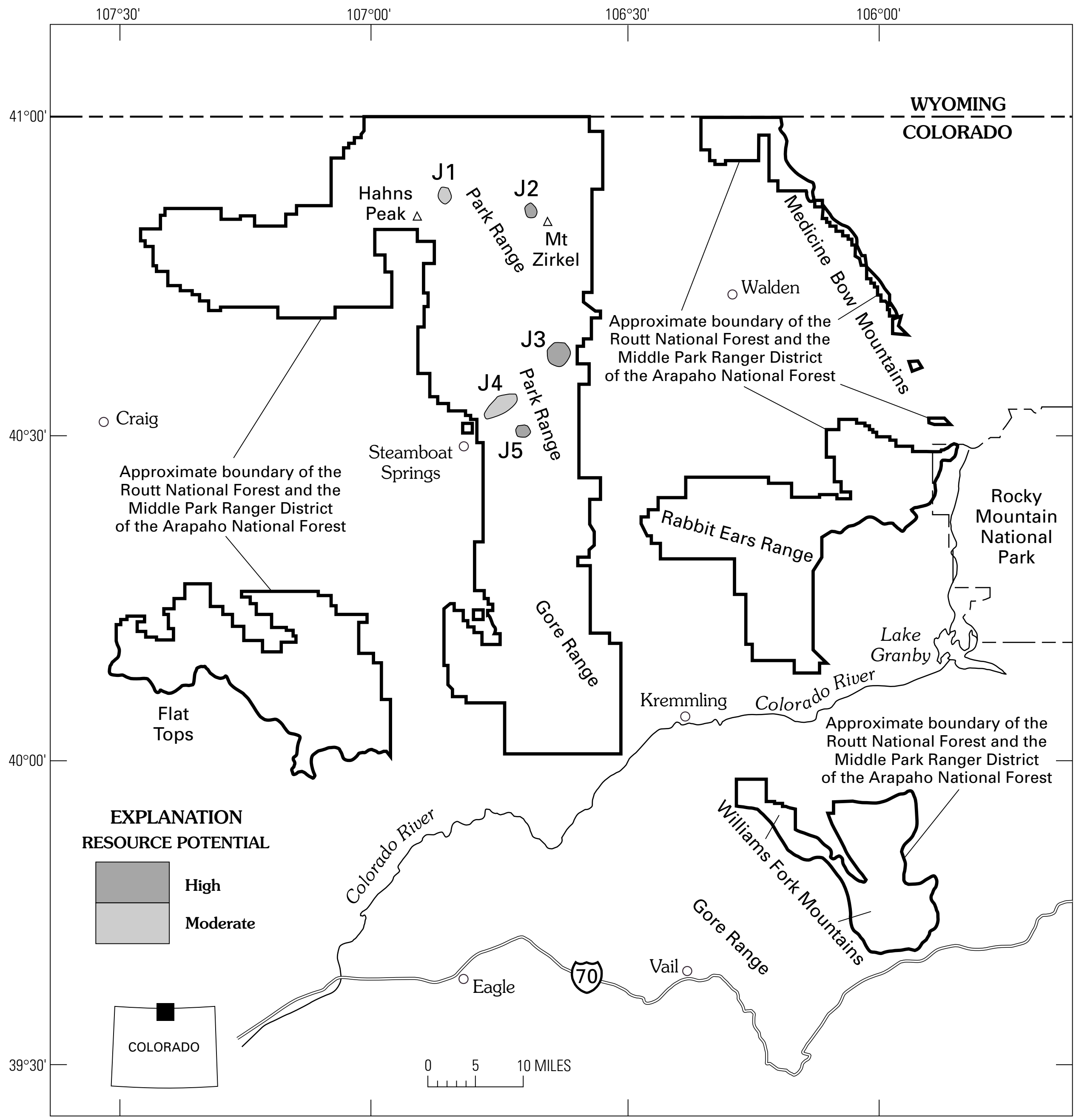


Figure 25. Mineral resource map for U-Th-REE (J) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

ASSESSMENT CRITERIA

1. Presence of pegmatites
2. Anomalous concentrations of U, Th, or REE in rocks or stream-sediment samples
3. Anomalous uranium and thorium radioactivity

ASSESSMENT

Six areas have moderate or high resource potential for U, Th, and REE in pegmatites. All of these areas fall within the north-central part of the Forest in the granitic rocks of the Park Range. The following information is from Snyder (1987a).

Area J1.—A small area on Farwell Mountain has moderate resource potential for U, Th, and REE in pegmatites, with certainty level B (pl. 1, fig. 25). Samples of pegmatites in this area contained as much as 18.5 ppm thorium and 12.4 ppm uranium. Pegmatite muscovite has a reported K-Ar age of 1.9 Ga (Segerstrom and Young, 1972).

Area J2.—Pegmatites in Mica Basin have high resource potential for U, Th, and REE, with certainty level C (pl. 1, fig. 25). A few large specimens of uraninite or euxenite are reported from a mica-beryl pit in pegmatite. One sample from the area assayed 86 percent uranium.

Area J3.—Pegmatites around Agua Fria Lake have high mineral resource potential for U, Th, and REE, with certainty level C (pl. 1, fig. 25). Samples from this area contain greater than 20 percent rare-earth elements and yttrium, as much as 15,000 ppm Th, and 7,000 ppm uranium. The area is within the prominent U and Th aeroradioactivity high (figs. 12 and 13) of the Mt. Ethel pluton.

Area J4.—An elongate zone along the Soda Creek shear zone has moderate potential for U, Th, and REE, with certainty level B (pl. 1, fig. 25). Several samples from the area contain elevated values of uranium and thorium, ranging from 6.1 to 16.9 ppm and 12.6 to 34.4, ppm respectively. The area is within the prominent U and Th aeroradioactivity high (figs. 12 and 13) of the Mt. Ethel pluton.

Area J5.—In the North Fork of Fish Creek, a northeast-trending area has high resource potential for U, Th, and REE in pegmatites, with certainty level C (pl. 1, fig. 25). Samples from this area contained 3,000–7,000 ppm uranium (Beroni and McKeown, 1952; Beroni and Derzay, 1955). Beroni and McKeown (1952) reported uranium analyses of nine samples from the area (20–540 ppm) and constructed an isoradioactivity map showing pod-shaped radioactive zones 1 to 20 ft in length. The Fair-U claims encompass much of this area. The area is within the prominent U and Th aeroradioactivity high (figs. 12 and 13) of the Mt. Ethel pluton.

ECONOMIC SIGNIFICANCE

The uranium market in the United States is relatively depressed and is likely to remain in this condition for the near future. Import and export figures are proprietary (U.S. Bureau of Mines, 1993). Import data for thorium is not available, but large deposits of thorium occur elsewhere in the United States in beach and stream placers, veins, and carbonatites. The United States exported rare-earth metals in 1992 but, previous to that, had a net import reliance of 25 percent (U.S. Bureau of Mines, 1993). Total undiscovered resources of rare earths are believed to be very large relative to expected demands.

MINOR OCCURRENCES

Industrial mica.—Mica Basin, on the northeast side of Big Agnes Mountain in the Mt. Zirkel Wilderness, was the site of many recorded mining claims in the late 1940's (Snyder, 1987a). Many pegmatites, associated with gneiss and schist, in this area contain large mica crystals of muscovite and biotite. The mica crystals contain parting planes that make the material scrap grade (Snyder, 1987a). There is no recorded production of mica from this area or from other sites in the Forest. Although pegmatites are fairly common in the Forest, most do not contain minable quantities of mica or other commercially important minerals.

Uranium in wetlands.—Wetlands have the capacity for extracting metals, particularly uranium, from ground and surface waters containing only very dilute concentrations of metals (Owen and others, 1992). Plutonic and volcanic rocks of the Forest may contain uranium concentrations high enough to feed into local wetlands. Uranium oxides dissolve readily in the oxidizing, carbonate-bearing waters characteristic of most surface waters and near-surface ground waters, and they precipitate when these waters encounter reductants in the subsurface (Owen and others, 1992). Organic-rich sediments found in wetlands act as reductants and may concentrate uranium locally.

Wetland uranium normally does not have associated detectable gamma-ray radioactivity because (1) about 500,000 years are needed for uranium to decay and produce sufficient gamma-ray-emitting daughters to result in measurable gamma-ray anomalies, and (2) the water present can absorb most gamma-rays emitted by uranium daughter products.

Owen and others (1992) sampled wetland areas within the Forest and found that uranium concentrations ranged between 2.4 and 62 ppm and are considered to be weakly to moderately enriched. Twenty-two samples were collected from wetlands in and adjacent to the Mt. Zirkel Wilderness.

At the Spring claims, about 11 mi west of Walden, uranium-bearing peat beds in the vicinity of uranium-bearing springs have been reported (Malan, 1957). The claims are located on the lower eastern slope of Sheep Mountain, about a mile outside the Forest boundary. Uranium-bearing meteoric waters reportedly issue from flat-lying clay, alluvium, and peat. The peat beds provide a reducing environment that effectively precipitates uranium from the mineralized meteoric waters. The peat beds appear to be a local feature; no uranium-bearing peat beds have been mined at this location.

The only uranium deposit in the United States that is mined from surficial wetlands is on the north fork of Flodelle Creek in northeastern Washington (Johnson and others, 1987). No production has been recorded from wetlands or peat bogs within the Forest.

MINERAL RESOURCES—LEASEABLE MINERALS

The Mineral Leasing Act of 1920 amended the General Mining Law of 1872 and set up regulations requiring prospect permits and leases to control the exploration, development, and production of specified minerals. The Mineral Leasing Act placed the following under the leasing law: oil, gas, coal, oil shale, sodium, potassium, phosphate, native asphalt, bitumen, and bituminous rock. Geothermal energy was added to the list of leaseable minerals by the Geothermal Steam Act of 1970.

Known occurrences of leaseable minerals were studied by the U.S. Bureau of Mines and are described in Neubert (1994). The potential for undiscovered deposits of these minerals is addressed in the following sections of this report. Areas within the Forest were assigned a rating of no, low, moderate, or high potential for the occurrence of undiscovered deposits. Levels of certainty, labeled A through D, were also assigned to qualify the data—level A indicates the least amount of supporting data and level D the greatest. Definitions and explanations of the mineral resource rating system may be found in Appendix 2. On figures 2 and 36, figures 38–41, and plate 1, areas of high potential are shown in dark gray and areas of moderate potential are shown in light gray. For ease in reading the plate, areas of low potential are only shown on the page-size figures and, in these cases, are shown in gray. Coal, oil, gas, coal-bed methane, and geothermal resources have been identified within or adjacent to the Forest. No potash, sodium, asphalt, or phosphate resources are known in the Forest.

COAL GEOLOGY AND RESOURCES

By Laura N. Robinson Roberts *and* Carol L. Molnia

INTRODUCTION

This chapter in part reviews the coal geology of the Forest as described in previous studies and presents new resource estimates for coal in the northwest part of the Forest (Area 1, fig. 26) based on information obtained from wells drilled since earlier resource estimates were made (Bass and others, 1955; Landis, 1959). A summary of coal resources compiled from previous work for areas in and adjacent to the Forest is given in Neubert (1994). A new estimate of total hypothetical coal resources of Area 1 under less than 3,000 feet of overburden is about 3.5 billion short tons (table 7). The resource estimates provided in this report are highly speculative, and a great deal of additional information is required to increase the reliability of these figures. No information is available for the vast majority of the area supposedly underlain by coal; major assumptions are made in terms of continuity of coal-bearing intervals, both in terms of stratigraphic and structural setting.

The Forest covers portions of several counties in the northwestern part of Colorado. Because the Forest consists of isolated parcels, number designations are assigned to its different parts for ease of reference (fig. 26). Area 1, the main area of emphasis for this chapter, is where new hypothetical coal resources were estimated. It is in the northwestern part of the Forest and includes the Elkhead Mountains. Area 2 is the central part of the Forest and includes parts of the Park and Gore Ranges; Area 3 is the southwestern part of the Forest and includes the Beaver, Dunkley and Little Flat Tops; Area 4 is the narrow northwest-southeast-trending Medicine Bow Mountains in the northeastern part of the Forest; Area 5 is the east-central part of the Forest and includes the Rabbit Ears Range; and Area 6 is in the southeastern part of the Forest and includes the Williams Fork Mountains.

Parts of two major coal regions extend into the Forest (U.S. Geolgical Survey and Colorado Geological Survey, 1977). The Green River region extends into Area 1 from Wyoming and from points west in Colorado (fig. 26) and also extends into the northwestern corner of Area 3. Virtually all of the coals mined to date in the Colorado part of the Green River region have come from the Yampa coal field, which is Colorado's greatest producer of coal (Keystone Coal Industry Manual, 1993). More than 13 million short tons of coal were produced during 1990 from the Mesaverde Group. Most of the coal is burned at electric generating plants in Craig and Hayden; however, several million short tons are shipped annually by railroad to power plants as far away as Texas and Nebraska. Although major mines are currently operating in the Yampa coal field, no coal production has been recorded from within the bounds of the Forest. The most recent discussion of the history of coal mining activity in the Yampa coal field is given by Neubert (1994).

The North Park region covers most of Area 5 (fig. 26). The North Park and Middle Park coal fields of this region are separated by the generally east-west-trending Rabbit Ears Range. The North Park coal field contains significant coal

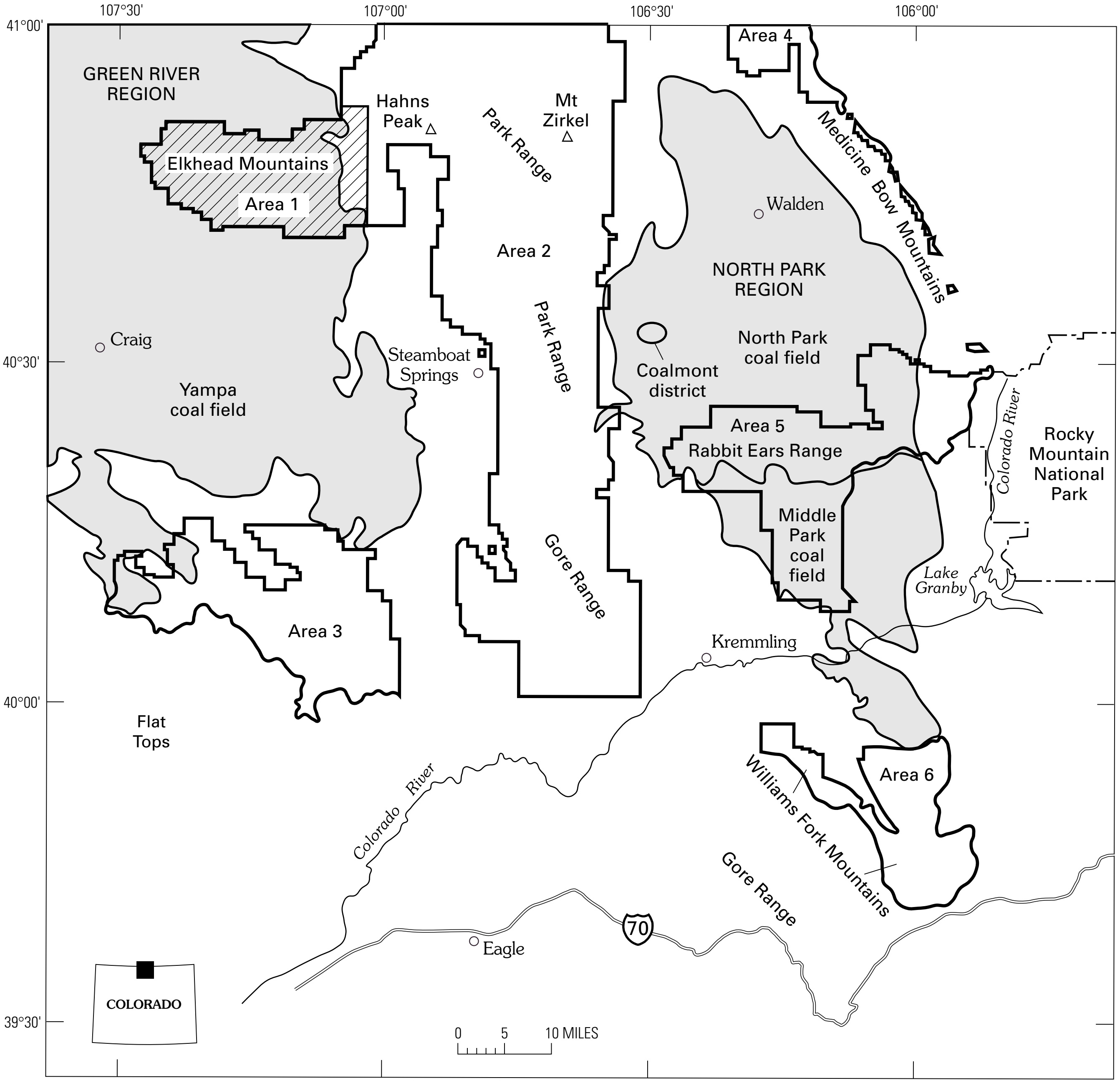


Figure 26. Index map of coal fields in and adjacent to the Routt National Forest. Forest areas are bounded by heavy line. Note number designations for the five areas of the Forest discussed in the text. Shaded pattern represents named coal regions and fields (U.S. Geological Survey and Colorado Geological Survey, 1977). In this report, new resource estimates are presented for Area 1 (cross-hatched area).

resources in the Paleocene Coalmont Formation in the Coalmont district (fig. 26) (Erdmann, 1941); however, minable beds probably do not extend into Area 5. The Middle Park coal field contains rocks equivalent to the coal-bearing Coalmont Formation in the North Park coal field (the Middle Park Formation), but lack of data precludes a resource estimate in this area. Published geologic maps that cover Area 5 of the Forest include Izett (1968); Izett and Barclay (1973); Hail (1968); Kinney (1970); and Kinney and Hail (1970).

AREA 1

Area 1 occupies the southeastern part of the northwest-southeast-trending Sand Wash Basin (fig. 27). Structure contours drawn on the top and base of the Williams Fork Formation in the eastern Sand Wash Basin indicate that strata dip generally less than 2° to the west (Tyler and Tremain, 1993), except at the eastern margin of the basin where Bass and others (1955) measured dips of as much as 23° in rocks

Table 7. Estimated hypothetical coal resources of Area 1 (in millions of short tons) according to overburden category.

[In millions of short tons, values rounded to two significant figures]

	Overburden thickness categories					
Formation	**0-1,000 ft**	**1-2,000 ft**	**2-3,000 ft**	**Total 0-3,000 ft**	**Total 3-6,000 ft**	**Total 0-6,000 ft**
Subbituminous- beds 2.5 ft thick and greater						
Fort Union	71	120	290	480	120	600
Lance (base)	340	230	250	820	860	1,700
subtotal	410	350	540	1,300	980	2,300
Bituminous- beds 1.2 ft thick and greater						
Williams Fork	540	290	610	1,400	2,700	4,100
Iles	350	190	220	760	1,900	2,600
subtotal	890	480	830	2,200	4,600	6,700
Total	**1,300**	**830**	**1,400**	**3,500**	**5,600**	**9,000**

of the Mesaverde Group in the southeastern part of Area 1. Figure 28 shows the surface distribution of Upper Cretaceous and Tertiary rocks and a generalized cross section of those rocks from northwest to southeast across Area 1.

Upper Cretaceous coal-bearing strata include the Iles and Williams Fork Formations of the Mesaverde Group, and the Lance Formation (fig. 29). Reports that discuss the distribution, stratigraphy, and depositional environments of these formations in and near Area 1 include Fenneman and Gail (1906), Bass and others (1955), Sharps (1962), Bader (1983), Irwin (1986), Siepman (1986), Honey and Hettinger (1989), Roehler and Hansen (1989), and Hamilton (1993).

The Iles Formation is about 1,600 ft thick and consists of interbedded light-brown, light-gray and white sandstone, gray sandy mudstone, gray shale and coal (Bass and others, 1955). The contact between the Iles and Williams Fork is the top of the fine-grained, massive, 100-ft-thick Trout Creek Sandstone Member (fig. 30). This member, which can be traced for many miles across the eastern Sand Wash Basin, was deposited in a nearshore marine environment. Strata of the Williams Fork Formation are about 1,200 ft thick and are similar to the those of the Iles Formation, including interbedded sandstone, mudstone, and coal.

The youngest coal-bearing formation of Cretaceous age is the Lance (fig. 29), which is about 1,200 ft thick and consists of continental deposits, including interbedded fine-grained sandstone, gray mudstone, and a few coal beds. In a study of Upper Cretaceous and lower Tertiary stratigraphy in the Sand Wash Basin, Honey and Hettinger (1989) placed the regional Cretaceous-Tertiary unconformity within a thick coarse-grained sandstone unit (their "unnamed Cretaceous and Tertiary sandstone unit"), based on pollen dates. This unit is distinguishable on electric logs of the few wells that penetrate it within or adjacent to the Forest (fig. 31). However, for this report, and for convenience, the Lance-Fort Union (Cretaceous-Tertiary) contact is placed at the top of this unit.

The Tertiary coal-bearing unit, the Paleocene Fort Union Formation (fig. 29), is about 1,000 ft thick and is composed chiefly of brown and gray sandstone and gray mudstone of fluvial origin and coal. Information on the Fort Union Formation in this area can be found in Bass and others (1955), Beaumont (1979), Bader (1983), Irwin (1986), Honey and Hettinger (1989), and Tyler and McMurry (1993).

METHODS USED TO ESTIMATE COAL RESOURCES

Area 1 is the only area where coal resources were estimated for this study. Figures 32–35 show locations of drill holes and measured sections used in resource estimates in Area 1; tables 8 and 9 list sources of these data. The new coal resources for Area 1 are here classified as "hypothetical" (refer to Appendix 3). Hypothetical resources are defined by Wood and others (1983) as tonnage estimates (1) for regions where tonnage estimates are based on knowledge of the geologic character of coal (for example, thickness trends based on knowledge of depositional environments), and (2) for areas beyond a radius of 3 mi from a point of measurement (for example, drill hole or outcrop). Although

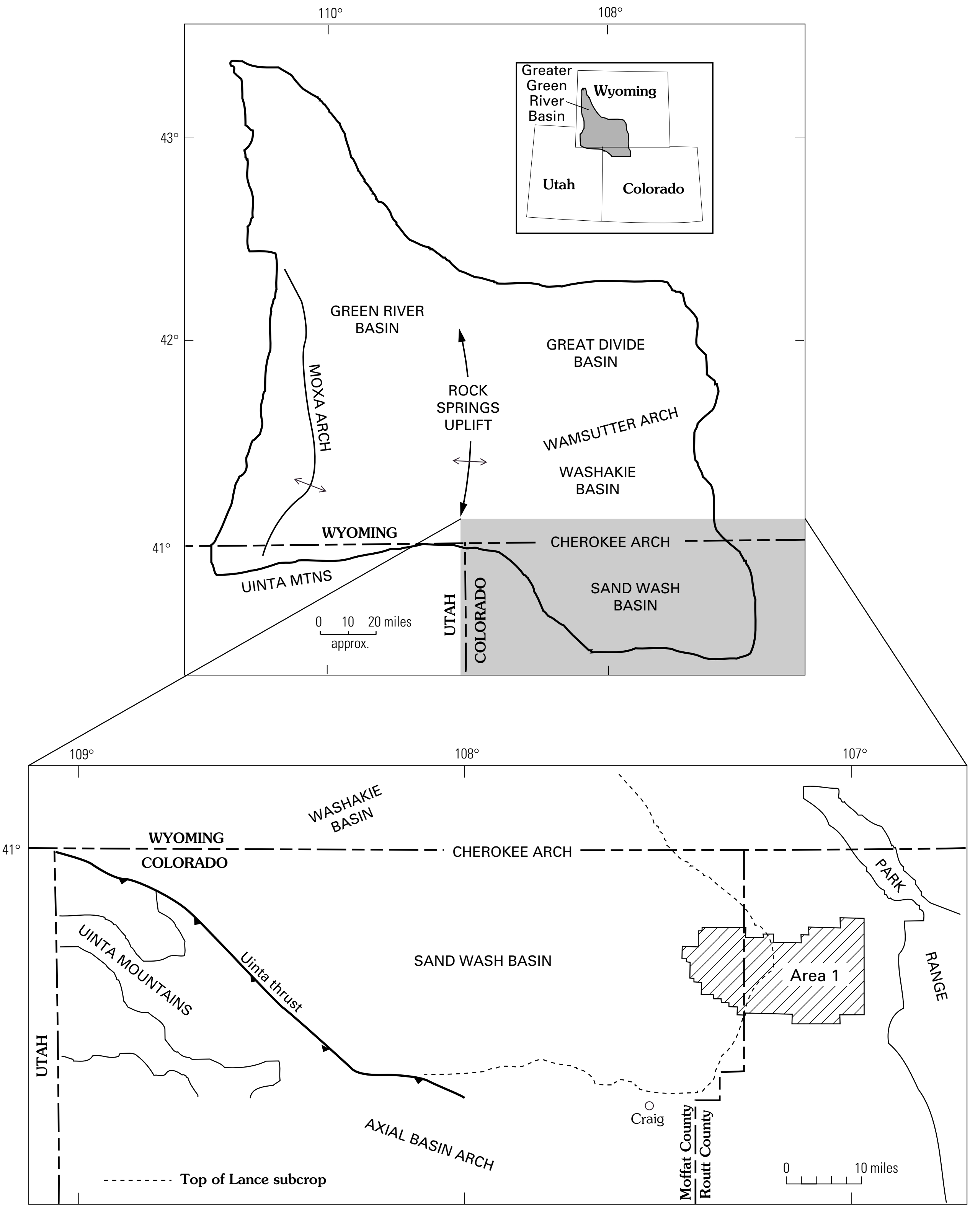


Figure 27. Structural setting of Area 1 in the southeastern part of the Sand Wash Basin of the Greater Green River Basin. Sawteeth on upper plate of thrust fault.

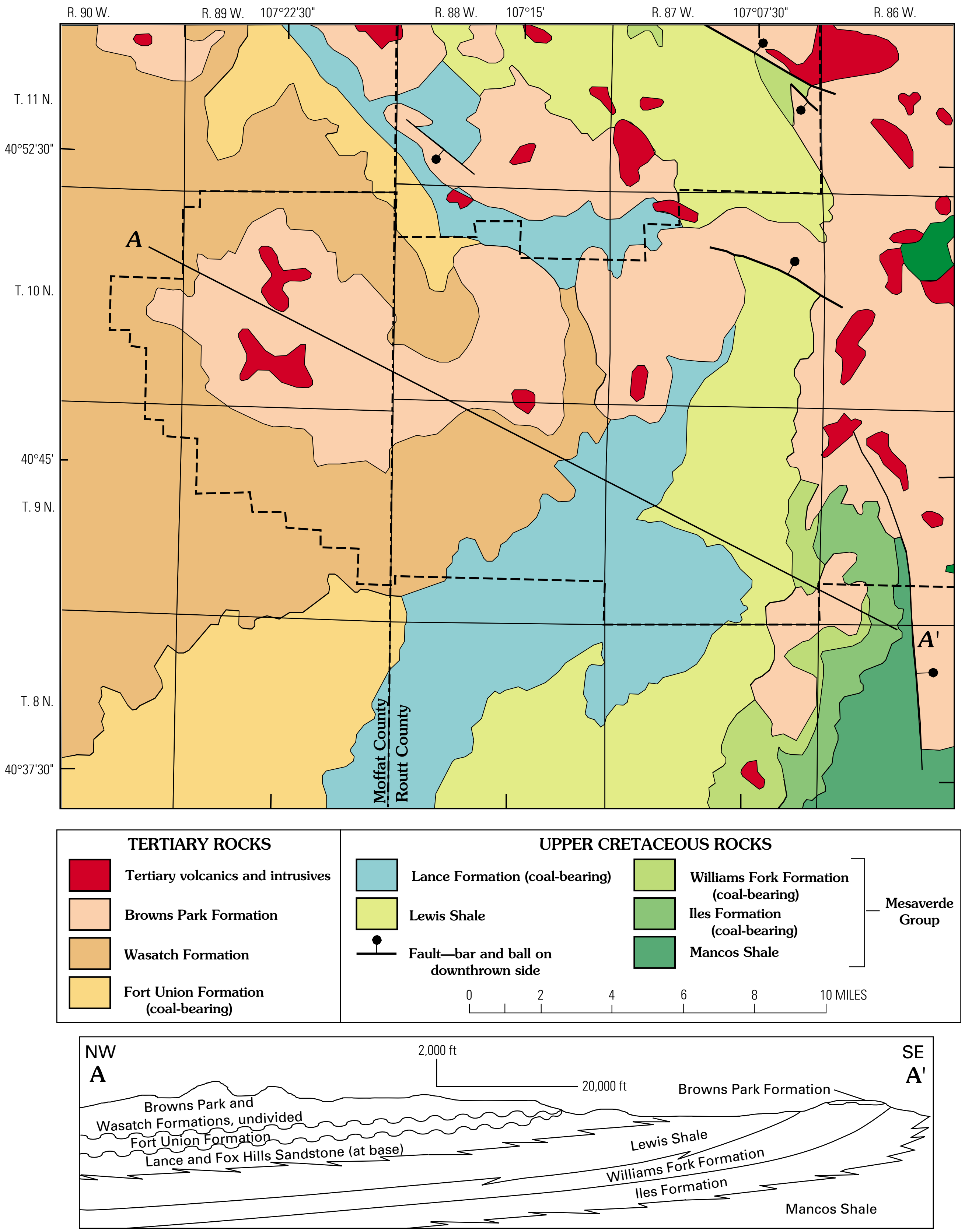


Figure 28. Generalized geologic map showing Upper Cretaceous sedimentary rocks and Tertiary sedimentary, volcanic, and intrusive rocks in and near Area 1. (Modified from Tweto, 1976). Generalized cross section A-A' of Upper Cretaceous through Tertiary sedimentary rocks in Area 1. An unconformity lies at the base of the Wasatch and Fort Union Formations. See figure 26 for location of Area 1.

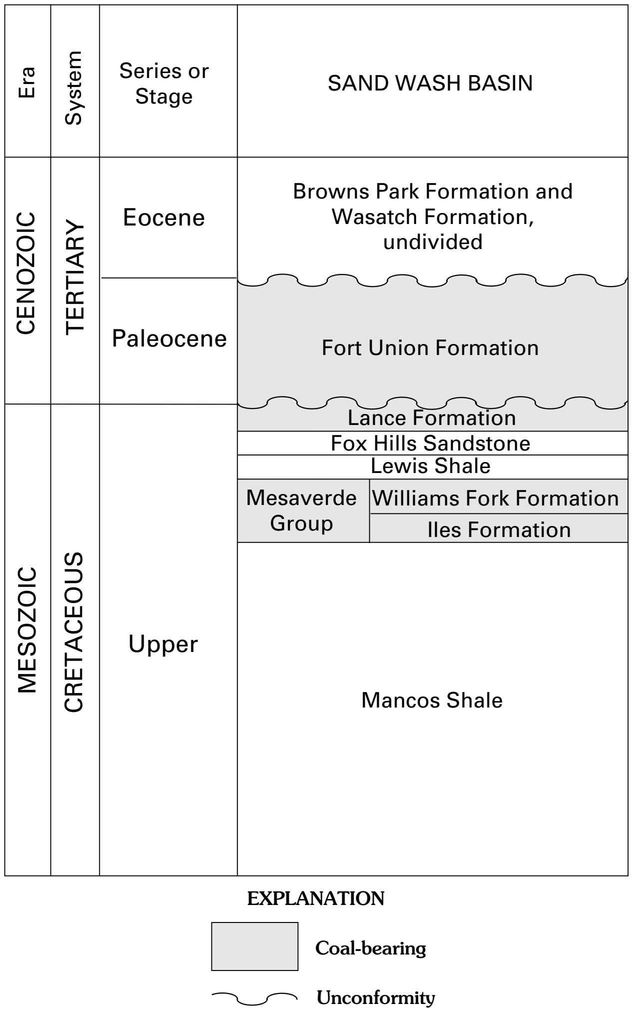


Figure 29. Stratigraphic units in and near Area 1, in the eastern part of the Sand Wash Basin.

points of measurement exist within the Forest that would make it possible to estimate resources for categories of higher reliability (measured, indicated, and inferred categories; see Wood and others, 1983), it is impractical to separate out these categories because there are so few points of measurement and because they are so widely scattered.

By definition, hypothetical coal resources include coal beds to a depth of 6,000 ft that are 1.2 ft or more thick for bituminous coal and 2.5 ft or more thick for subbituminous coal. For this report, the approach used to estimate hypothetical resources within the Forest is a modification of the "extrapolated coal zone method" described in Wood and others (1983). It is a modification because, for these estimates, the entire coal-bearing formation takes the place of "coal zone."

Resource estimates were calculated and reported for coal in each of the formations of interest: Iles, Willliams Fork, Lance, and Fort Union Formations. Tonnage estimates were derived by multiplying a weighted average thickness value of cumulative coal in the formation by the area underlain by the formation. The weighted average thickness values and the areas were calculated with the aid of the Interactive Surface Modeling (ISM) computer program developed by Dynamic Graphics, Incorporated. Because the Mesaverde Group coals are bituminous in rank, coal beds thinner than 1.2 feet are excluded from resource consideration in that Group, and because Fort Union and Lance coals are subbituminous in rank, coal beds thinner than 2.5 feet are similarly excluded in those formations (Wood and others, 1983).

MESAVERDE GROUP COALS

Three different groups of coal beds occur in the Mesaverde Group (Bass and others, 1955; Fenneman and Gale, 1906). It is possible to identify these coal groups, in a general way, in well logs examined for this study. The stratigraphic position of these coal groups are shown on figure 30. The lower coal group consists of coal beds of the Iles Formation. The middle coal group consists of coal beds between the base of the Williams Fork Formation and the Twentymile Sandstone Member. The upper coal group consists of coal beds above the Twentymile Sandstone and the top of the Williams Fork Formation.

Wells drilled on the Forest that penetrated the lower coal group (Iles Formation coals) are 1–4 (fig. 32). The thickest single bed in this group within the Forest is 5 ft thick, and the average is about 3 ft. These thicknesses are consistent with those Iles Formation coal beds that are exposed within and adjacent to the Forest boundary in T. 9 N., R. 86 W. (Bass and others, 1955) (fig. 32; table 9). Total cumulative coal thickness, determined from the available data, for this group within the Forest ranges from 22 to 37 ft. The number of coal beds greater than 1.2 ft thick ranges from 7 to 12. The isopach map (fig. 32A) shows distribution and trends of coal thickness, and the overburden map (fig. 32B) shows the depth to the top of the Iles Formation.

The Iles Formation (includes coal of the "lower coal group" of Bass and others, 1955) contains an estimated 2.7 billion short tons of bituminous coal under less than 6,000 ft of overburden in beds greater than 1.2 feet thick (table 7). This total represents about 29 percent of the total of the four formations. However, more than 70 percent of Iles Formation coal in Area 1 is deeper than 3,000 ft. Near the eastern margin of the basin, where the Iles Formation is exposed at the surface, the dip of the strata containing coal is as much as 23° (Bass and others, 1955); therefore, there is only a narrow areal distribution of shallow coal (fig. 32B) away from which the overburden rapidly thickens to the west.

The middle coal group (near the base of the Williams Fork Formation) contains the thickest and most extensive coal beds of the three groups (fig. 33). The Wadge coal bed, which is currently mined in the eastern part of the Yampa coal field, is in the lower part of this group. Within the Forest, wells that were drilled through these coals are 1, 2

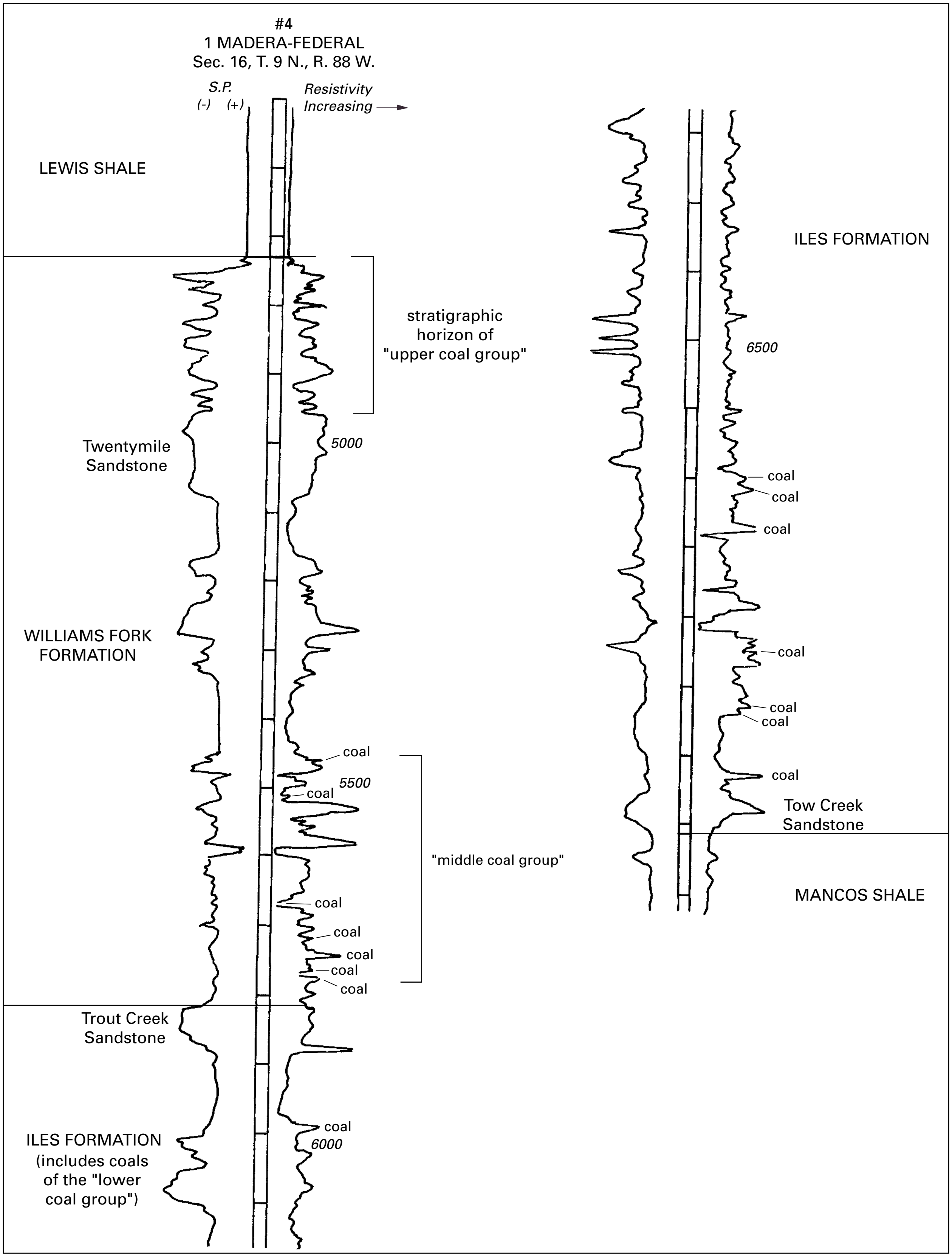


Figure 30. Spontaneous potential (S.P.) and resisitivity log signatures of Upper Cretaceous stratigraphic units in Area 1, showing the "lower coal group" of the Iles Formation and the "middle coal group" and "upper coal group" of the Williams Fork Formation (terminology of Bass and others, 1955). In addition to these logs, gamma ray and sonic logs were used to identify coal beds. Log depths are in feet.

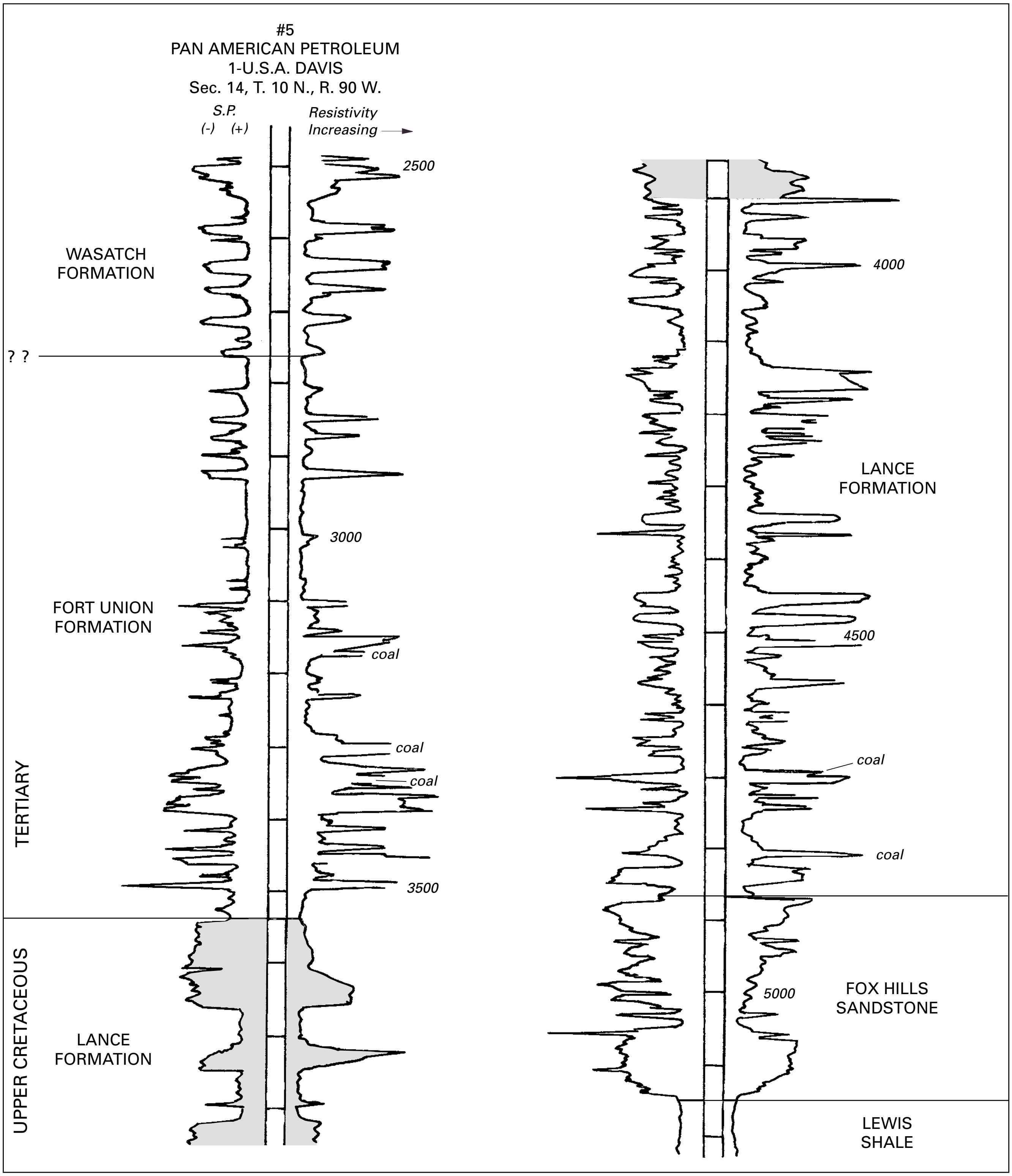
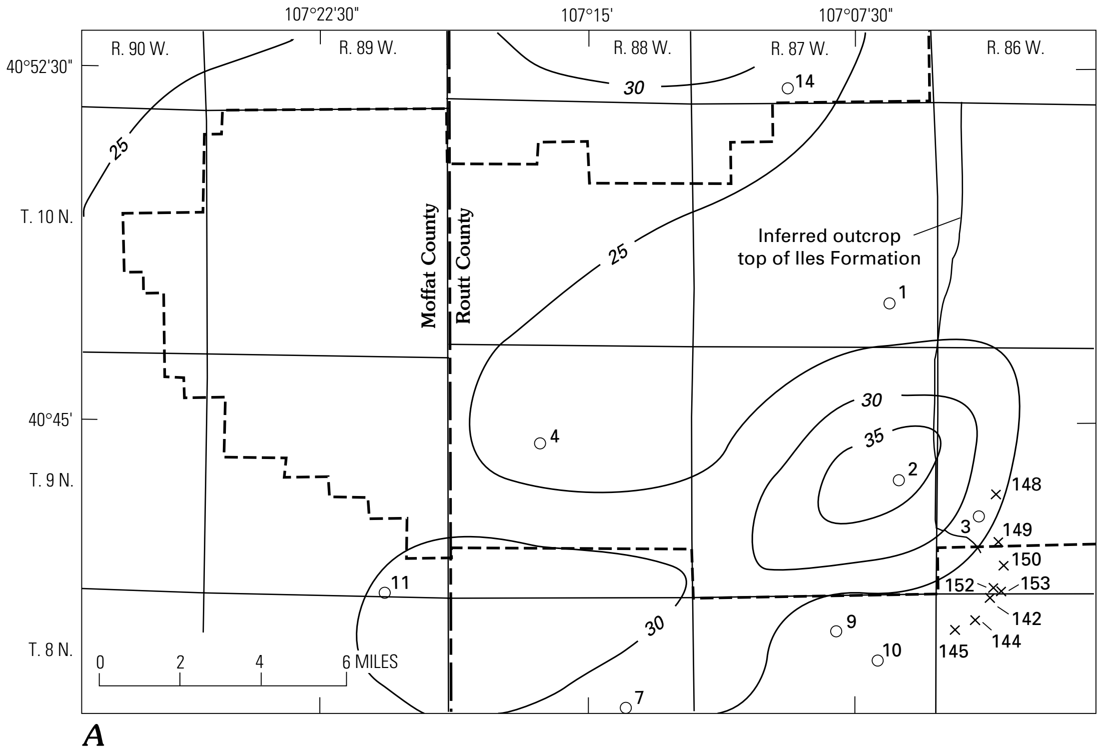


Figure 31. Spontaneous potential (S.P.) and resistivity log signatures of Upper Cretaceous and Tertiary stratigraphic units in Area 1, showing coal beds in the Lance Formation and in the Fort Union Formation. Shaded interval is the "unnamed Cretaceous-Tertiary sandstone unit" of Honey and Hettinger (1989). In addition to these logs, gamma ray and sonic logs were used to identify coal beds. Log depths are in feet.



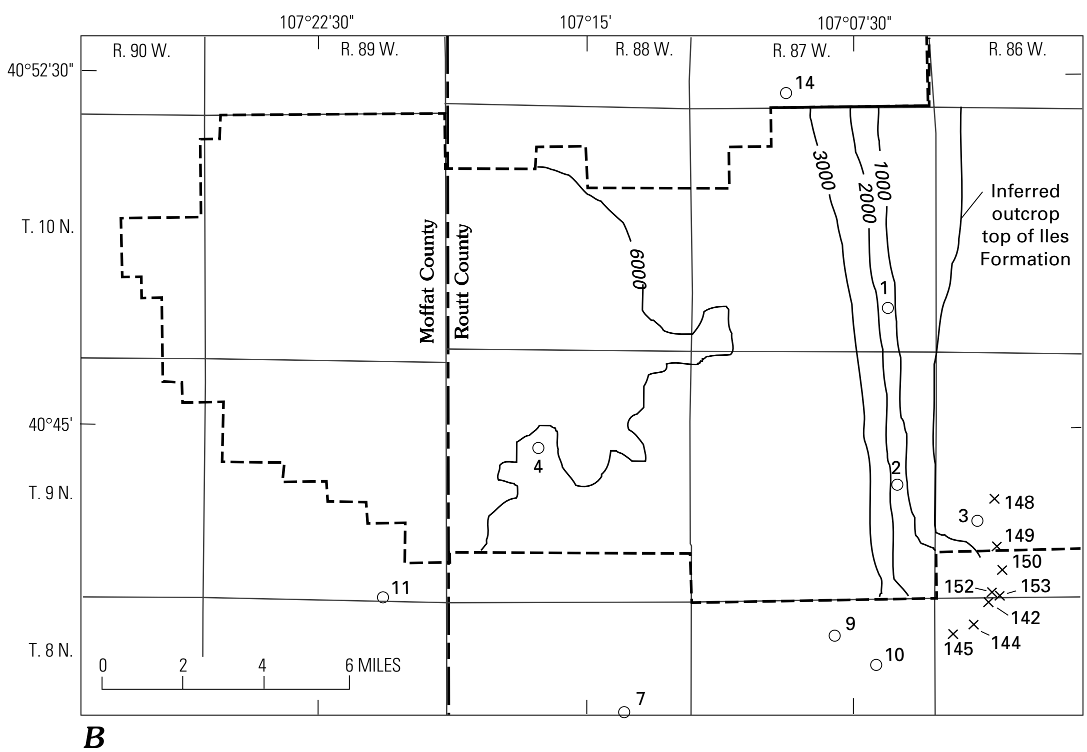


Figure 32. *A,* Isopach map of cumulative coal in the Iles Formation in and near Area 1, including coals of the lower coal group (terminology of Bass and others, 1955). Thickness values are in feet. *B*, Isopach map of overburden; datum is top of Iles Formation in Area 1. Thickness values are in feet. Drill holes represented by (○) and number, measured outcrop sections by (×) and number. See table 8 for location of drill holes; see table 9 for the location, thickness, and source data for measured sections.

Table 8. Location data for drill holes shown in figures 32-35.

Well ID	Ground elev (ft)	T. (N.)	R. (W.)	Sec.	Quarter	Well Name	Owner
1	8533	10	87	26	ne se se	1 Grizzly-Federal	Sun Expl & Production
2	8380	9	87	24	sw nw nw	4-24 California-Federal	Buckhorn Petroleum
3	8800	9	86	29	nw nw nw	1-29 Chevron Federal	Chevron U.S.A.
4	7831	9	88	16	se nw	1 Madera-Federal	Gulf Oil
5	8729	10	90	14	se sw	1 USA-Davis	Pan American Petroleum
7	6852	8	88	14	nw ne sw	1-14 Murphy Ranch-Govt	Chambers Jerry
8	7307	10	90	28	sw sw	1 Welba Peak Unit	Belco Petroleum
9	8427	8	87	3	nw sw se	1-3 Hayden Public Library	Dome Petroleum
10	9040	8	87	11	nw nw se	1-11 Hayden Public Library	Dome Petroleum
11	6999	9	89	35	c se sw	1 Federal	Murfin Sutton
12	7090	9	89	19	se sw se	1-19 E. Van Tassel	Conoco Inc.
13	7958	9	90	3	ne se ne	3-9-90 Villard	Anadarko Production
14	8351	11	87	33	c ne sw	1-B Colo-Federal	Sunray Mid-Continent
15	7714	9	90	23	se nw nw	1 Federal Belco	Occidental Petroleum
16	8150	10	90	26	se se sw	1 Villard	Midwest Oil
17	7886	10	90	27	sw sw ne	A-1 Black Mountain	Anadarko Production

Table 9. Location and coal thickness data of measured outcrop sections (Bass and others, 1955) shown on figures 32-35.

Meas sec. ID	T. (N.)	R.(W)	Sec.	Coal bed thickness (ft)	Number of beds (if more than 1)
Iles Formation, lower coal group					
i148	9	86	20	5.0	
i149	9	86	29	2.5	
i150	9	86	32	4.7	
i152	9	86	32	3.5	
i153	9	86	32	4.8	
i142	8	86	5	3.1	
i144	8	86	6	3.0	
i145	8	86	6	4.6	2
Williams Fork Formation, middle and upper coal group					
w221	9	87	24	3.5	
w151	9	86	32	3.5	
w146	8	86	6	4.7	2
w143	8	86	6	7.7	
Lance Formation coal					
L220	9	87	19	6.5	
L260	9	88	24	2.8	
L261	9	88	25	5.3	2
L262	9	88	26	3.7	
L222	9	87	26	21.2	4
L201	8	87	7	4.0	
Fort Union coal					
F343	8	89	2	4.5	

and 4 (fig. 33). The thickness of individual beds within the group ranges from 2 to 22 ft, and total cumulative thickness for the group reaches a maximum of 40 ft. Coal-bed thicknesses as thick as 7.7 ft were measured on the steeply dipping outcrops in and adjacent to the Forest boundary (table 8).

The stratigraphic horizon where the upper coal group is expected to occur was logged in hole 4 within the Forest; no coal beds were discernible from that log. This is also the case for holes 14 and 11, just northeast and southwest of the Forest boundary, respectively (fig. 33). However, holes 7 and 9, outside the Forest boundary to the southeast, do show coal beds at this horizon. Unfortunately, no data for this zone was recorded in the other wells drilled within the Forest (holes 1 and 2) because the logged interval started below the coal zone. The cumulative thickness of both coal zones in the Williams Fork Formation is represented on the isopach map (fig. 33A).

The Williams Fork Formation (includes coal of the “middle” and “upper coal group” of Bass and others, 1955) contains almost half of all the coal within this part of the Forest. An estimated 4.1 billion short tons of bituminous coal may occur within 6,000 ft of the surface in beds 1.2 ft thick or greater (table 7). However, of this total, over 65 percent of the coal is deeper than 3,000 ft. The isopach map of overburden (fig. 33*B*) shows that relatively shallow coals may exist along the eastern margin of the basin but only in a narrow strip. Overburden increases dramatically in a short distance to the west as the strata dip steeply toward the basin axis. It should be noted that two of the three drill holes within the Forest that contain data on Williams Fork coals were logged starting below the upper coal zone, so they do not have data for the horizon that might include these coal beds. For this reason, the isopachs (fig. 33*B*) may represent a minimum cumulative thickness of coal along the eastern edge of Area 1.

Most of the coal of the Mesaverde Group is high-volatile C bituminous in apparent rank but ranges from sub-bituminous B to high-volatile B bituminous (Bass and others, 1955; Landis, 1959; Khalsa and Ladwig, 1981; Boreck and others, 1981). Coal in the extreme eastern edge of the Yampa coal field is locally metamorphosed to anthracite by igneous intrusions (Bass and others, 1955). For analyses of 21 coal samples from the Yampa coal field, the as-received sulfur values range from 0.4 to 0.9 percent; ash yields range from 4.0 to 20.0 percent, with a geometric mean of 8.1 percent; and calorific values range from 9,870 to 12,010 Btu/lb, with a geometric mean of 11,130 Btu/lb (Khalsa and Ladwig, 1981).

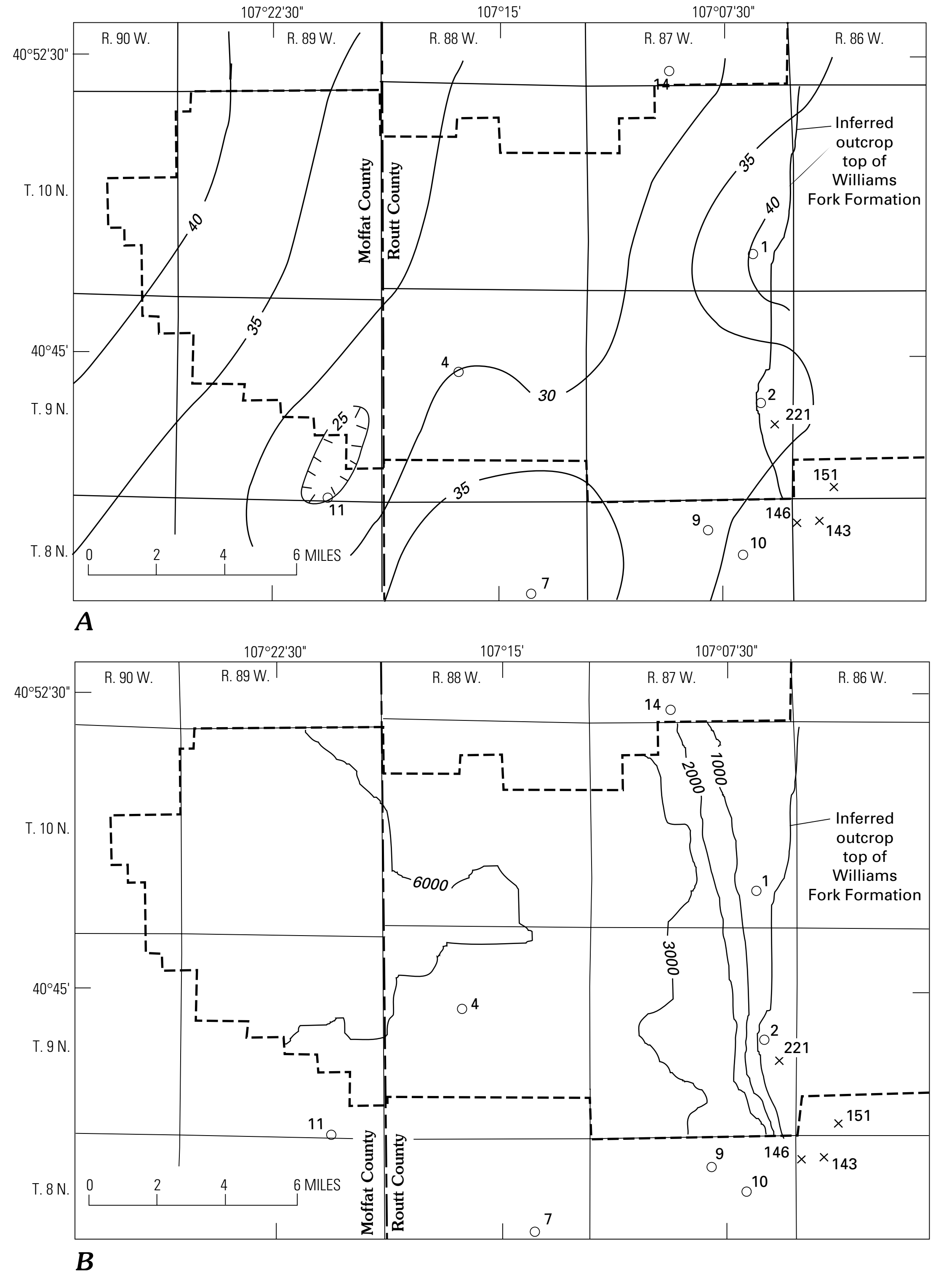


Figure 33. *A,* Isopach map of cumulative coal in the Williams Fork Formation in and near Area 1, including coals of the middle coal group and of the upper coal group (terminology of Bass and others, 1955). Thickness values are in feet. Hachures indicate area of local thinning. *B,* Isopach map of overburden; datum is top of Williams Fork Formation in Area 1. Thickness values are in feet. Drill holes represented by (○) and number, measured outcrop sections by (×) and number. See table 8 for location of drill holes; see table 9 for the location, thickness, and source data for measured sections.

The Mesaverde Group coals (Iles and Williams Fork Formations) have high coal resource potential with certainty level C (K1, fig. 36). This qualitative assessment is based on the proximity of known coal resources (Yampa coal field) and the known distribution, thickness, depth, quantity and quality of coal in these strata. Although Mesaverde Group coal underlies most of Area 1, most of it is buried too deeply to be considered an economic resource.

LANCE FORMATION COALS

Only holes 4 and 5 provide data for Lance coals within the Forest, but several holes outside the Forest added control points for cumulative coal thickness and overburden isopachs (fig. 34). The majority of and the thickest coal beds of the Lance Formation occur within less than 200 ft of the base of the formation (fig. 31). Within the Forest, the thickest coal bed encountered in drill holes is 6 ft thick, but most of the beds are 3–4 ft thick. Lance Formation coal beds are typically thin, lenticular, and difficult to trace for any distance. On the outcrop in sec. 26, T. 9 N., R. 87 W., a cumulative thickness of 21.2 ft of coal in 4 beds near the base of the Lance was measured in an interval of 75 ft (table 9).

The Lance Formation contains an estimated total of more than 1.7 billion short tons of subbituminous coal in beds 2.5 feet thick or greater and under less than 6,000 ft of overburden (table 7). This total represents about 18 percent of the total of the four formations. About 50 percent of the Lance coal is deeper than 3,000 ft. In contrast to the method used for the other formations to determine overburden thickness, structure contours were drawn on the base of the Lance rather than on the top. Because the Lance is about 1,200 ft thick, and because most of the Lance coals occur near the base of the formation, it is a better representation of overburden thickness (fig. 34*B*).

In the early 1920's Lance coal was obtained from small wagon mines northeast of Craig and in T. 7 N., R. 90 W. and T. 6 N., R. 89 W. (Bass and others, 1955). Lance coal is of subbituminous B and C apparent rank (Murray, 1980) and has a calorific value, as mined, of about 9,700 Btu/lb (Bass and others, 1955). On an as-received basis, average sulfur content and ash yields for 6 mine and outcrop samples in the Yampa coal field are 0.5 and 4.8 percent, respectively (Bass and others, 1955).

Based on the available information, the Lance Formation in Area 1 has a high potential for coal resources, with certainty level B (K1, fig. 36). Although coal in this formation underlies most of Area 1, much of it is is thin and lenticular in nature and buried too deeply to be considered an economic resource.

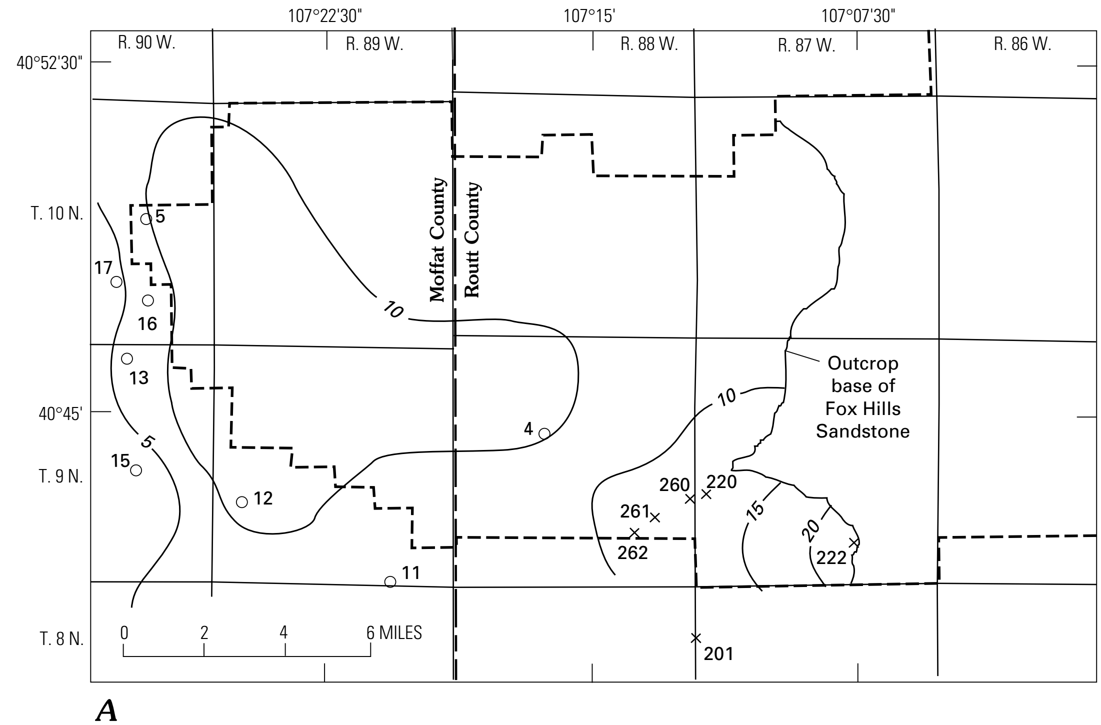
FORT UNION FORMATION COALS

There is almost no information about the Fort Union Formation as it occurs within the Forest boundary. The Fort Union is exposed only in a small area in T.10 N., R. 88 W. and is otherwise completely covered by younger sediments of the Wasatch and Browns Park Formations (fig. 28). Drill hole 5 (fig. 35) is the only drill hole within the Forest that provides data on this unit, but, as with the Lance Formation, wells to the west and south of the boundary provide control for maps that is necessary to make projections into the area with no data. Several studies of Fort Union stratigraphy in the Sand Wash Basin include isopach maps of cumulative thickness of coal in the Fort Union Formation (Boreck and others, 1981; Tyler and McMurry, 1993; Beaumont, 1979; Honey and Hettinger, 1989). Isopachs were projected into the Forest area based on these previous interpretations; cumulative thickness of coal in the Fort Union Formation appears to be thinning to the east toward the basin margin (fig. 35*A*). Almost all of the coal beds occur in the lower part of the Fort Union Formation. Coal beds range in thickness from less than 3 ft to a maximum of 17 ft, with an average thickness of about 5 ft.

The Fort Union Formation contains an estimated total of about 600 million short tons of subbituminous coal under less than 6,000 ft of overburden in beds 2.5 feet thick or greater (table 7). About 20 percent of this total is deeper than 3,000 ft. The Fort Union Formation coal resource tonnage represents only seven percent of the total of the four formations. Seventy-one million short tons are estimated to lie within 1,000 feet of the surface. This may be a very high estimate. The isopach trends (fig. 35*A*, 35*B*) indicate that the coal and overburden are thinning toward the east; therefore, it is possible that the Fort Union Formation is barren of coal where it comes within mining distance of the surface. It is not known how much of the Fort Union Formation may have been removed by erosion prior to deposition of the overlying Wasatch Formation. More information is needed to understand which geologic controls may have affected this resource.

Fort Union coals range from subbituminous B or C in apparent rank in outcrops along the southern, eastern, and northwestern margins of the basin to probably high-volatile A bituminous in the deeper parts of the Sand Wash Basin (Murray, 1980; Scott, 1993). There are no analyses of Fort Union coal in Forest Area 1, but analyses of five samples nearby in Routt and Moffat Counties (of uncertain reliability due to thin overburden and probable weathering) indicate that, on an as-received basis, ash yields are about 5 percent and sulfur values are about 0.3 percent, with a calorific value of about 9,850 Btu/lb (Bass and others, 1955, their table 9).

Fort Union Formation coals have high coal resource potential, with certainty level B (K1, fig. 36). The geologic characteristics of Fort Union coal beds indicate that their cumulative thickness tends to thin to less than 5 ft thick toward the east in Area 1 as they approach mining depth.



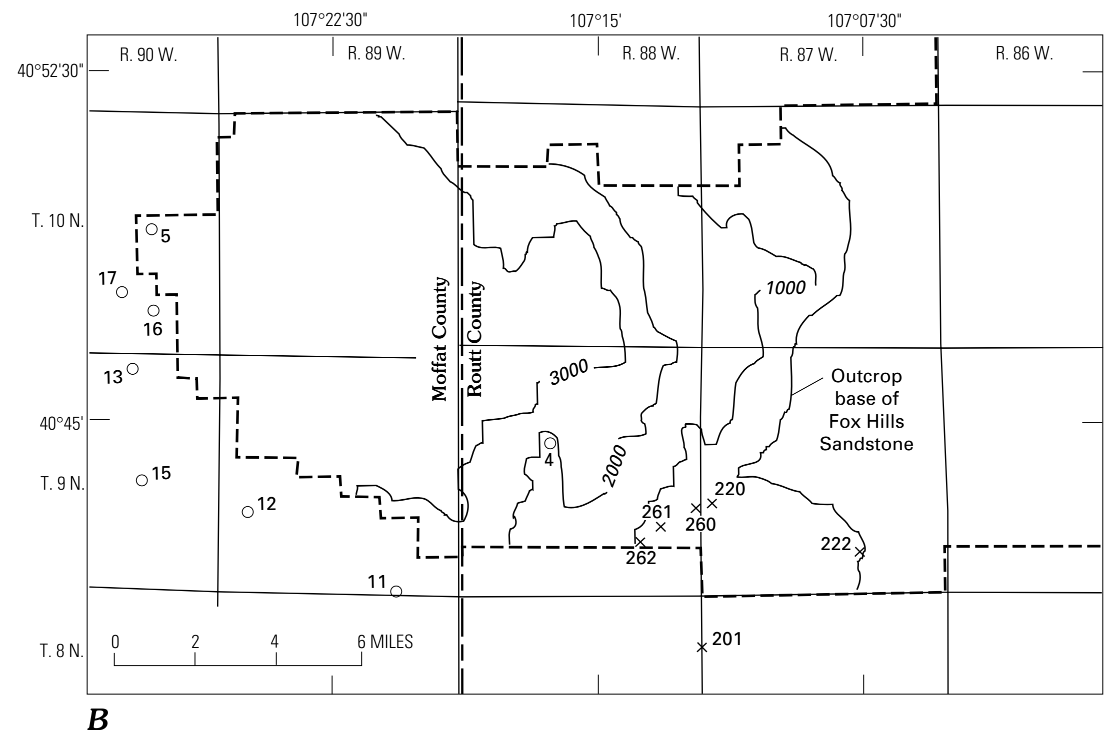


Figure 34. *A*, Isopach map of cumulative coal in the Lance Formation, in and near Area 1. Thickness values are in feet. *B*, Isopach map of overburden; datum is base of Lance Formation (top of Fox Hills Sandstone) in Area 1. Thickness values are in feet. Drill holes represented by (○) and number, measured outcrop sections by (×) and number. See table 8 for location of drill holes; see table 9 for the location, thickness, and source data for measured sections.

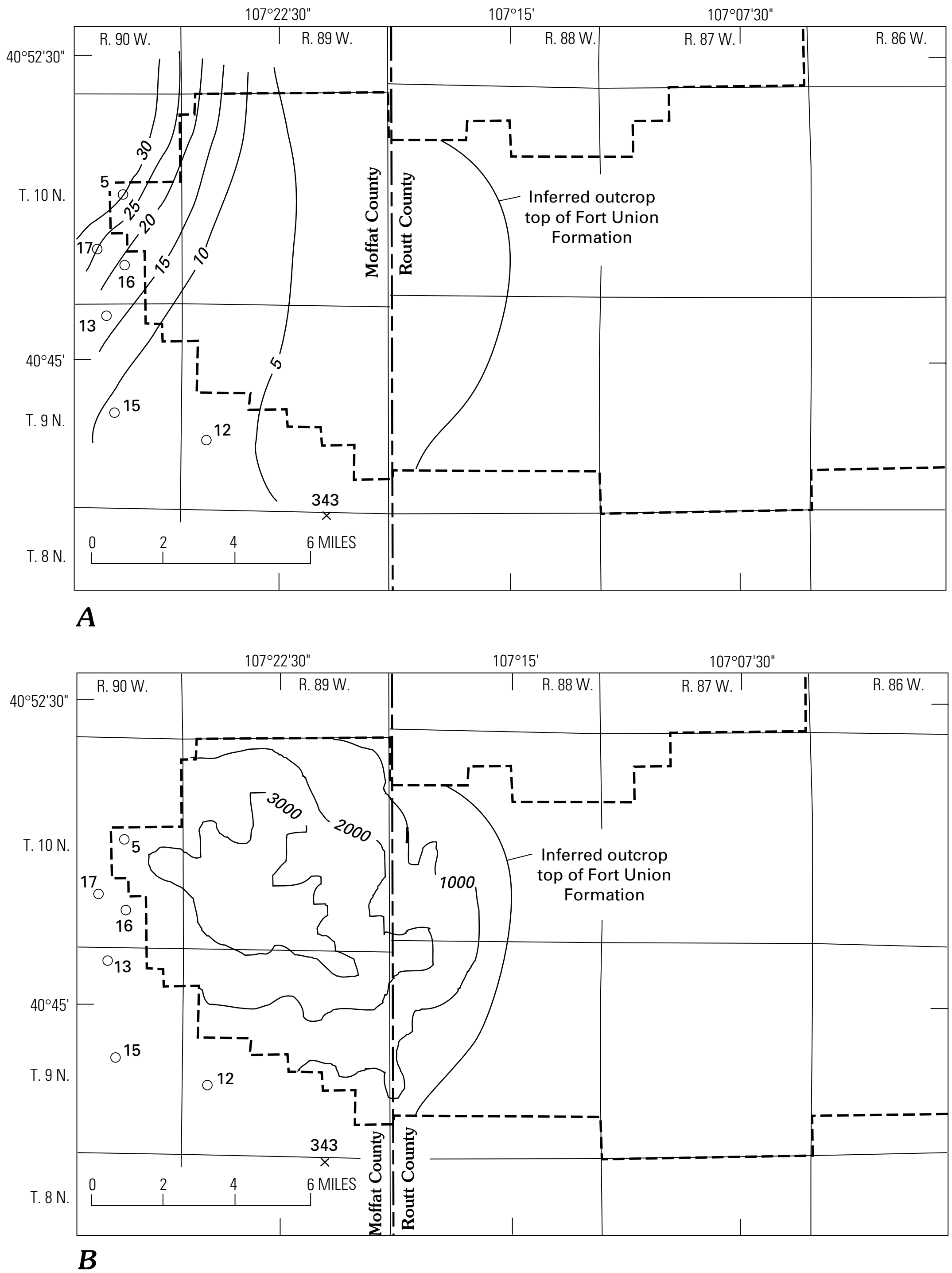


Figure 35. *A*, sopach map of cumulative coal in the Fort Union Formation, in and near Area 1. Thickness values are in feet. *B*, Isopach map of overburden; datum is top of Fort Union Formation in Area 1. Thickness values are in feet. Drill holes represented by (○) and number, measured outcrop sections by (×) and number. See table 8 for location of drill holes; see table 9 for the location, thickness, and source data for measured sections.

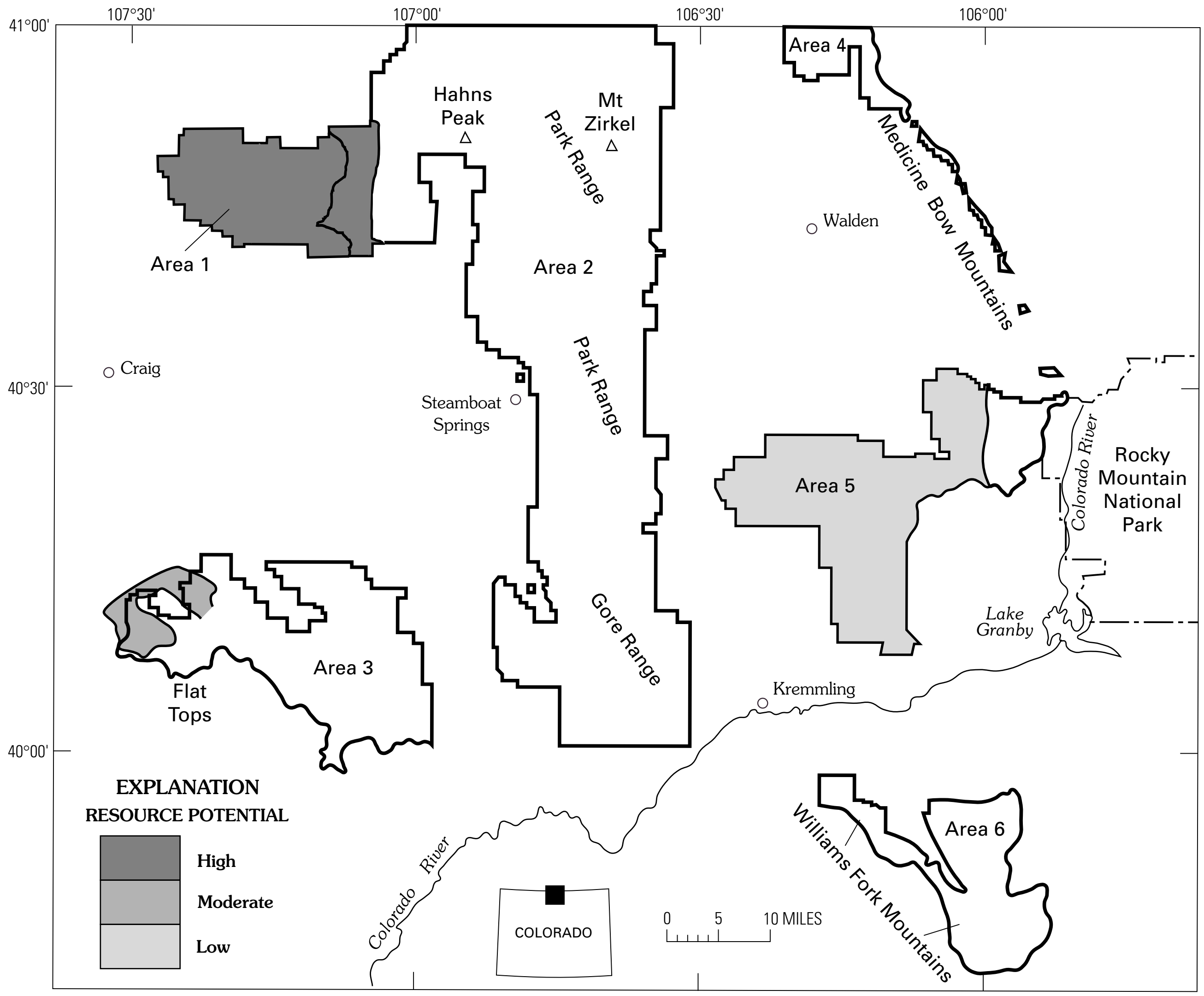


Figure 36. Map showing coal resource potential of areas underlain by coal-bearing Upper Cretaceous and Tertiary stratigraphic units in and adjacent to the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

LIMITATION OF DATA

It is clear on the maps (figs. 32–35) that drill-hole and outcrop data are sparse at best. Of the 16 wells used for this study, only five are within the Forest boundary, and, of those five, only one (hole 4) provides data for three of the four coal-bearing formations. The other holes provide complete data for only one or two of the coal-bearing formations. Therefore, these estimates of coal resources are highly speculative.

The contacts between the Wasatch and the Fort Union and between the Fort Union and the Lance Formations are difficult to distinguish in well logs because these strata are fluvial deposits mapped on the surface using characteristics that do not appear in subsurface geophysical logs, such as color and fairly subtle differences in grain size. Also, picking a contact between the marine and marginal marine units (i.e., Mancos/Iles, Williams Fork/Lewis, and Lewis/Fox Hills) is somewhat arbitrary because these units intertongue. However, stratigraphic correlations of the coal-bearing formations across the study area must be attempted in order to assign coal zones to the correct formation and in order to assign a contact between formations for the purpose of constructing structure contour maps. Documented stratigraphic information (Boreck and others, 1981; Bader, 1983; Honey and Hettinger, 1989) was extrapolated into the Forest from south and west of the study area.

The cumulative coal thickness of the formations also had to be projected across the area with sparse data from areas where documented coal-thickness information exists.

Measurements of coal at the outcrop were generally used to delineate the distribution of the coal and as a minimum thickness value for the isopachs. Outcrop measurements are considered minimum values because they usually only represent a single coal bed in the formation, whereas the isopachs represent cumulative coal thickness in the entire formation. For the Iles and Williams Fork Formations (figs. 32*A*, 33*A*), general isopach trends were drawn based on the estimated orientation of the shoreline that was present at the time of deposition of the peat that formed the coal (Lillegraven and Ostresh, 1990; Hamilton, 1993; Cobban and others, 1994). Isopach trends for the Lance and Fort Union Formation coals (figs. 34*A*, 35*A*) were extrapolated into the Forest from trends determined in previous studies from data to the west of the Forest (Boreck and others, 1981; Tyler and McMurry, 1993; Beaumont, 1979).

Isopach maps of overburden (depths to the top of the Iles, Willliams Fork, and Fort Union Formations; depth to the base of the Lance Formation) were constructed by subtracting the elevation above sea level of the top or base of the coal-bearing formation from the elevation of the ground surface. It must be stressed that the overburden isopachs on the top of the Iles, Williams Fork, and Fort Union Formations (figs. 32*B*, 33*B*, 35*B*) are absolute minimums because coal beds in these formations commonly are near the base of the formation. Therefore, the overburden thickness to the stratigraphically highest coal in these formations is actually greater than appears on the maps. Owing to the thickness of the formations, this difference could be as much as 1,000 ft. The thickness of overburden to the base of the Lance Formation (fig. 34*B*) was used because the coals are all within 200 ft of the base of the formation. Therefore the overburden thickness on the highest coal is actually less than appears on the map.

POTENTIAL FOR OTHER UNDISCOVERED COAL RESOURCES

AREAS 2, 4, AND 6

These areas have no coal resource potential based on the presence of predominantly crystalline rocks and on the lack of coal-bearing rocks, with certainty level D (fig. 36).

AREA 3

The Iles Formation is the only coal-bearing formation in Area 3 and it occurs only in the northwestern part; all younger coal-bearing rocks are eroded (Sharps, 1962). The Iles Formation has moderate resource potential for coal, with certainty level B (K2, fig. 36). Although much of the coal is burned along the outcrop, Sharps (1962) did report a coal bed 3.5 ft thick in this area.

AREA 5

Resource potential for coal in the Coalmont and Middle Park Formations is largely unknown because of the lack of sufficient data; however, the potential is probably low, with certainty level C (K3, fig. 36). Published geologic maps of Area 5 did not report the occurrence of coal in these formations. Although operating coal mines are located north of this area, the geologic characteristics of the coal-bearing units indicate that the coal beds thin and pinch out southward in the direction of Area 5.

OIL, GAS, AND COAL-BED METHANE RESOURCES

By Craig J. Wandrey, Ben E. Law, Charles W. Spencer, *and* Charles E. Barker

INTRODUCTION

More than half the area within Routt National Forest and the Middle Park Ranger District of the Arapaho National Forest is underlain by Proterozoic metamorphic and igneous rocks of the Park, Gore, Rabbit Ears, Front Range, and the Never Summer Mountains (plate 1)—this area has no potential for oil and gas production except beneath the Independence and Williams Fork thrusts. The remaining lands of the Forest where Paleozoic through Tertiary sedimentary rocks occur have been intermittently explored for oil and gas since 1928. This activity resulted in the discovery of one oil field in the Elkhead Mountains and two oil fields in the Flat Tops areas of the Forest (fig. 37). These fields are the California Park field, discovered in 1983 and abandoned in 1984; the Pinnacle field, discovered in 1956 (presently shut-in); and the Scott Hill field, with three producing wells.

In the following discussion, the potential of conventional and unconventional hydrocarbon accumulations are independently discussed. Conventional hydrocarbon accumulations are discrete oil and gas deposits that occur in structural, stratigraphic, and combination traps. In contrast, unconventional hydrocarbon accumulations are regionally extensive and cut across structural and stratigraphic boundaries. They also lack down-dip water contacts. Unconventional accumulations in this region include basin-centered gas, coal-bed methane, and oil in fractured shale. Most of the discussion regarding reservoirs and source rocks applies to most of northwest Colorado, or the North Park and Middle Park Basins.

CONVENTIONAL HYDROCARBON ACCUMULATIONS

Reservoirs.—The principal conventional reservoirs on the Forest lands include the Middle Pennsylvanian Minturn

Formation; the Permian and Pennsylvanian Weber Sandstone and associated formations, the Upper Triassic Shinarump Sandstone and Moenkopi Formation; the Middle Jurassic Entrada Sandstone and Upper Jurassic Morrison Formation; the Lower Cretaceous Dakota and Lakota Sandstones; and the Upper Cretaceous Frontier Formation, Nobrara Formation, Morapos Sandstone Member of the Mancos Shale, Pierre Shale, Mesaverde Group including the Almond Formation, and the Lewis Shale. Tertiary reservoir rocks are absent through most of the area and, where present, are not considered to have any potential. Porosity in the principal conventional reservoirs ranges from less than 10 to 20 percent and permeability ranges from less than 0.1 to 300 millidarcies (mD). Reservoir thickness ranges from 8 to 65 ft. Drilling depths to these reservoirs range from less than 1,000 to 10,000 ft.

Source rocks and geochemistry.—Possible hydrocarbon source rocks include the Middle Pennsylvanian Belden Shale (Nuccio and Schenk, 1986; Waechter and Johnson, 1986), the Permian Phosphoria Formation, the Upper Cretaceous Mowry Shale (Fillmore, 1986), Niobrara Shale, Mancos Shale, Pierre Shale, and Lewis Shale. In addition, the coal beds contained in the Upper Cretaceous Mesaverde Group are likely sources of gas. The Belden Shale may be thermally overmature west of the Gore and Park Ranges and is absent from the stratigraphic section east of the ranges. The Phosphoria and Cretaceous rocks are mature to undermature with respect to hydrocarbon generation. The Paleozoic reservoirs may contain oil with sulfur and sour gas. Mesozoic oil is low sulfur and the gas is sweet. Produced water may vary from salty at depths of more than 5,000 ft and fresh at depths less than 2,000 ft.

Timing of generation and migration.—The present-day levels of thermal maturity were probably achieved during Oligocene time. Most structural traps were most likely formed during the Laramide orogeny; however, some traps could have formed as early as Pennsylvanian time west of the Gore and Park Ranges. Consequently, the temporal relationships between hydrocarbon generation, migration, and development of structural traps were favorable.

Traps and seals.—Although reservoirs such as the Weber, Entrada, Shinarump, Morrison, Dakota, and Frontier Formations potentially have stratigraphic traps, all conventional fields in northwest Colorado and North Park Basin produce from structural traps. Consequently, there is no compelling reason to expect the discovery of significant stratigraphic accumulations. Structural traps could include small, tightly folded anticlines or faulted anticlines. In North and Middle Parks, anticlinal traps produce near the basin margins. The numerous low-permeability shales in Paleozoic and Mesozoic rocks could provide adequate seals.

Exploration status and resource potential.—The area is relatively maturely explored. However, the area is structurally complex and has a long history of structural deformation dating back to Proterozoic time. Some older structures may have been overlooked due to concealment by younger, Tertiary rocks.

The area in the Elkhead Mountains is underlain by Cretaceous and Tertiary sedimentary rock and has moderate potential for gas resources, with certainty level B (L1, fig. 38). A certainty level of B is required because much of the area is covered by Tertiary sedimentary rocks that may conceal older structures in the underlying rock units.

In the Flat Tops area (fig. 37), there are two small accumulations in structural traps; the Pinnacle field, which produced from the Shinarump and Dakota, and the Scott Hill field, which produced from the Weber, Dakota, and Frontier. Untested northwest-trending surface structures in the Flat Tops have moderate potential for gas resources, with certainty level B (L2, fig. 38). Based on the cumulative production from the Pinnacle and Scott Hill fields (less than 150 thousand barrels of oil (MBO)), it is unlikely that new discoveries in this area will exceed 1 million barrels of oil equivalent (MMBOE).

The area from the Rabbit Ears Range south to Corral Peaks between North and Middle Park Basins (L3, fig. 38) is underlain by Cretaceous and Tertiary sedimentary rocks covered and intruded by Tertiary volcanic rocks. The volcanic rocks may conceal structural traps. Immature to marginally mature source rocks in this area have low oil potential, but several test wells have had gas shows. The area has moderate potential for gas resources, with certainty level B. It is unlikely that new discoveries in this area will exceed 6 billion cubic feet (BCF) or 1 million barrels of oil equivalent (MMBOE).

The areas within the Forest on the southwest side of the Gore Range, along the eastern side of the Park Range, and on the northwestern corner of the Williams Fork Mountains (L4, fig. 38) have relatively thin sedimentary sections that are less conducive to gas generation and trapping. These areas have low potential for gas resources, with certainty level C.

SUBTHRUST HYDROCARBON ACCUMULATIONS

Reservoirs.—The most prospective reservoir rocks are the Jurassic Entrada Sandstone and Morrison Formation, and the Cretaceous Dakota and Lakota Sandstones, Frontier Formation, and Niobrara and Pierre Shales. Porosities range from 10 to 20 percent, and permeabilities range from less than 0.1 to 300 mD. Reservoir thicknesses are generally thinner in these basin-margin settings and range from less than 8 ft to 60 ft.

Source rocks.—The Cretaceous Mowry Shale has probably the best source-rock potential (Fillmore, 1986) and has been identified as a primary source rock in the adjacent Greater Green River Basin. Thermal maturities are potentially higher in the subthrust due to increased heating because of greater burial depths.

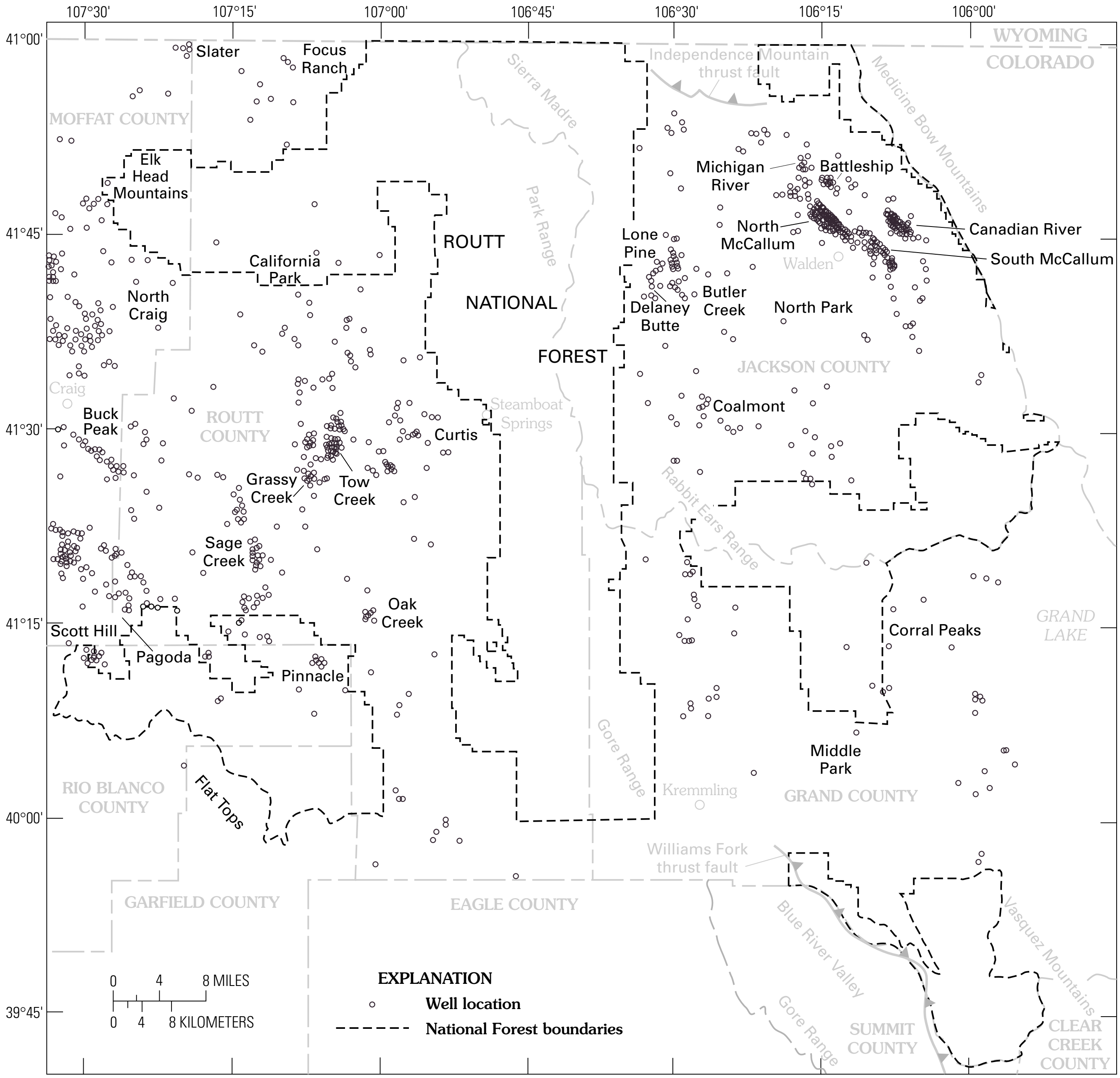


Figure 37. Map showing oil and gas fields in and adjacent to the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

Timing of generation and migration.—Burial histories for North and Middle Park Basins indicate that maximum burial and thermal maturity occurred during Oligocene time (Fillmore, 1986; Maughan, 1988) with migration updip over short distances.

Traps and seals.—Preexisting traps (anticlines and faulted anticlines) may be preserved and enhanced beneath mountain-front thrusts. Proterozoic rocks in the hanging wall of the thrust may also act as a trap in conjunction with an underlying thick, low-permeability shale seal.

Exploration status and resource potential.—Thrust faults having a heave sufficient to create or preserve traps of commercial size are the Independence Mountain thrust, where Proterozoic rocks are thrust south as much as 12 mi over the Paleocene and Eocene Coalmont Formation of North Park (Blackstone, 1977), and the Williams Fork thrust on the east side of the Blue River Valley, where Proterozoic rocks of Williams Fork Mountains are thrust westward over the Pierre Shale. The rocks of the subthrust have not been tested at either the Independence Mountain or Williams Fork thrusts. The potential for finding a 1 MMBOE field under

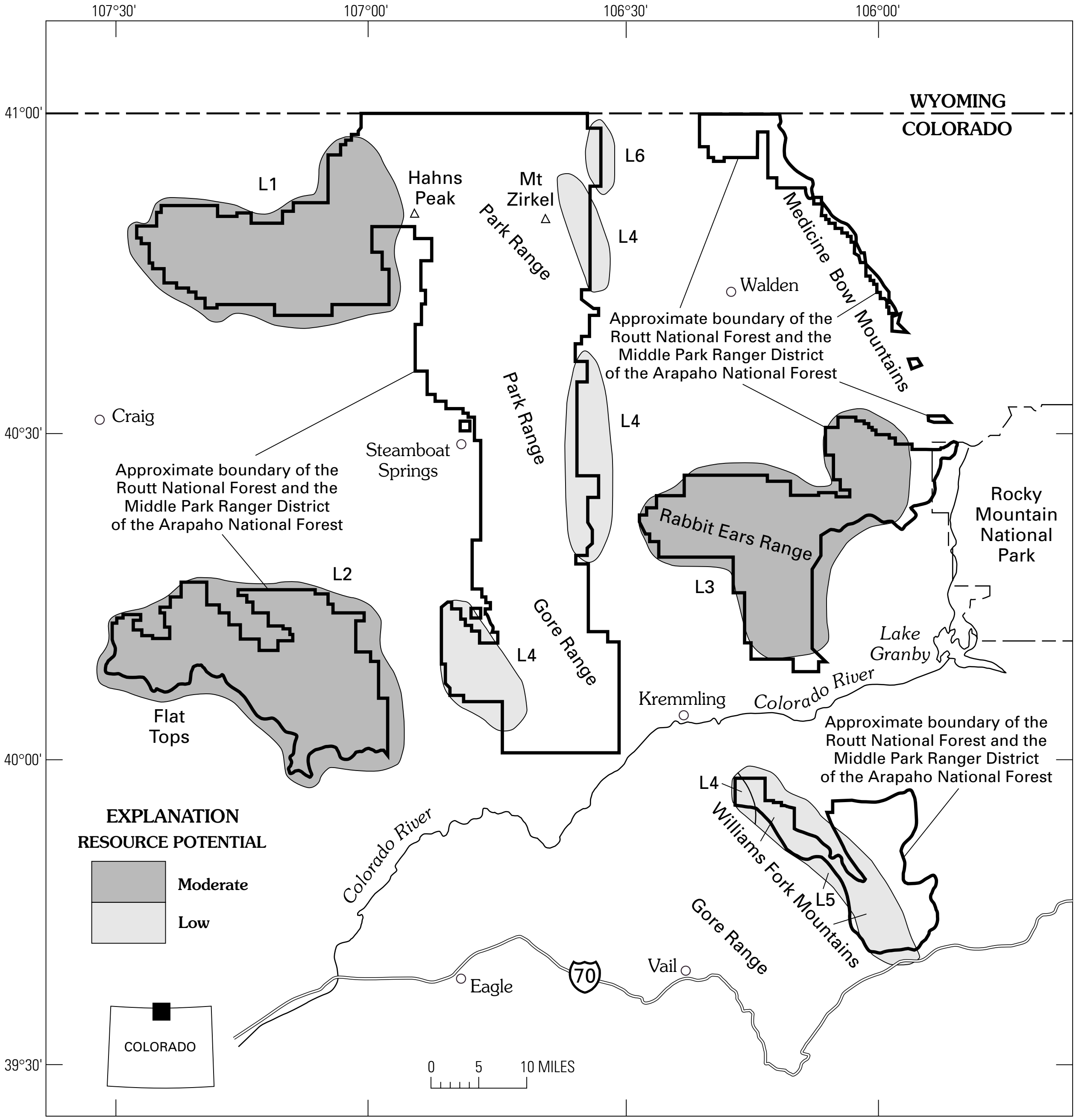


Figure 38. Energy resource map for conventional and subthrust oil and gas accumulations (L) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

the Williams Fork thrust is low, with certainty level B (L5, fig. 38). The potential is also low, with certainty level B (L6, fig. 38) for the Independence Mountain thrust because only a small area of the subthrust extends into the Forest. Resource estimates are based on source-rock potential and volume of potential reservoir rocks within the Forest (subthrust boundaries are highly speculative).

UNCONVENTIONAL HYDROCARBON ACCUMULATIONS

COAL-BED METHANE

The coal-bearing units within the Forest include the Upper Cretaceous Iles, Williams Fork, Almond, and Lance

Formations and the Paleocene Fort Union Formation. Coal beds also occur in the Lower Cretaceous Dakota Sandstone and Upper Cretaceous Frontier Formation; however, the coal beds in these units are so lenticular and thin that they are not considered to have any potential for economic methane production. In order of decreasing coal-bed methane potential, the coal-bearing units are Williams Fork, Almond, Iles, Lance, and Fort Union. The factors considered in this ranking include number of coal beds, cumulative thickness of coal beds, quality of coal, coal rank, and gas content. The principal studies of coal-bed methane resources in the region include those by Boreck and others (1981), McCord (1984), Tremain (1990), Kaiser and others (1993), and Kaiser (1993). Coal-bed methane is sweet (low in sulfur), and water may be fresh to brackish with moderate bicarbonate content.

Coal beds in these Cretaceous and Tertiary rocks were deposited in environments that include fluvial, delta-plain, and back-barrier depositional systems. The thicker and more continuous coal beds in northwest Colorado occur in intervals or zones 100 to 1,200 ft thick. There are as many as 30 coal beds in any single coal zone, but, more commonly, there are four to eight coal beds greater than 2 ft thick. Individual coal beds are as much as 40 ft thick.

Based on analyses of coal beds from the Sand Wash Basin, the rank of coal beds in the various zones ranges from sub-bituminous B to high-volatile bituminous B (0.45–0.75 percent R_o, reflectance in oil). The coal is composed of humic organic matter; vitrinite is the main coal maceral. Cleat development is good and is considered normal for sub-bitumuinous and bituminous coal. The gas content of the coal ranges from 100 to 541 standard cubic feet per short ton (scf/ton), and the gas typically has large amounts of methane with lesser amounts of ethane and heavier hydrocarbons. In some areas of the Sand Wash Basin, coal-bed methane contains carbon dioxide in amounts as high as 25 percent.

In the absence of specific test data, it can be assumed that all coal beds in the Forest contain gas; however, the presence of large amounts of water in coals commonly precludes economic rates of gas production. In areas like the San Juan Basin of New Mexico and Colorado, dewatering programs have been successful, and structural or stratigraphic traps are not necessary for production. However, in other areas, where there are large amounts of water associated with the coal that cannot be economically dewatered, structural traps are necessary for economic rates of gas production (Rice and Law, 1993).

Although no coal-bed methane wells have been drilled in the Forest, regional data from coal-bed methane tests in the Sand Wash Basin indicate the presence of good gas contents, and all of the wells have encountered large volumes of water. In the absence of any conflicting data, the coal-bed methane potential within the Forest is considered low to moderate because of the probable presence of large volumes of water. It is unlikely that there will be any discoveries larger than 6 BCF of gas (1 MMBOE). The area of the Elkhead Mountains has moderate potential for coal-bed methane resources, with certainty level C (M1, fig. 39). A small area outlined by outcrop of the Mesaverde in the northwestern part of the Flat Tops has low resource potential for coal-bed methane resources, with certainty level D (M2, fig. 39). This rating is assigned because of very shallow depths and limited presence of coal-bearing rocks.

BASIN-CENTERED GAS ACCUMULATIONS

Gas in basin-centered accumulations (also referred to as “tight gas reservoirs”) in the Forest include the Lower Cretaceous Dakota Sandstone and Upper Cretaceous Frontier Formation. For the most part, the potential for basin-centered gas accumulations in the Forest is low because the source rocks associated with low-permeability reservoirs in these units are immature to slightly mature. Studies of basin-centered gas accumulations in the Greater Green River Basin of Wyoming, Colorado, and Utah by Law (1984) have indicated that, at present-day depths of at least 8,000 ft and at levels of thermal maturity of 0.8 percent R_o, there is a high probability of encountering basin-centered gas accumulations. For detailed descriptions of basin-centered gas accumulations, see Law and Spencer (1993). The western part of the Elkhead Mountains area has some tight reservoir potential and thus has low potential for gas resources, with certainty level C (N1, fig. 40). It is unlikely that there will be any discoveries within the Forest that will exceed 1 MMBOE. Cretaceous tight reservoirs generally produce sweet gas and they generally do not produce significant amounts of water.

OIL IN FRACTURED SHALES

Fractured shales in the Upper Cretaceous Mancos Shale in northwest Colorado produce oil. The shales (including siltstone, calcareous shale, and limestone) are both the source rock and reservoir rock. Oil production may occur in areas where the shales are thermally mature and fractures are present, such as in areas of maximum flexure along the crests of anticlines and monoclines or in highly faulted areas. Because the production is fracture-related, well productivity is highly variable and unpredictable. The oil is low sulfur, and wells do not produce water. The California Peak field, located in the Elkhead Mountains area of the Forest (fig. 37), is the only fractured shale field in the Forest. This field is very small and produced about 1,748 barrels of oil (BO) and 471 thousand cubic feet of gas (MCFG) through 1991 (Colorado Oil and Gas Conservation Commission, 1992). Examples of fields outside the Forest producing oil from fractured shales include Buck Peak, Grassy Creek, Tow Creek, and Coalmont (fig. 37). The

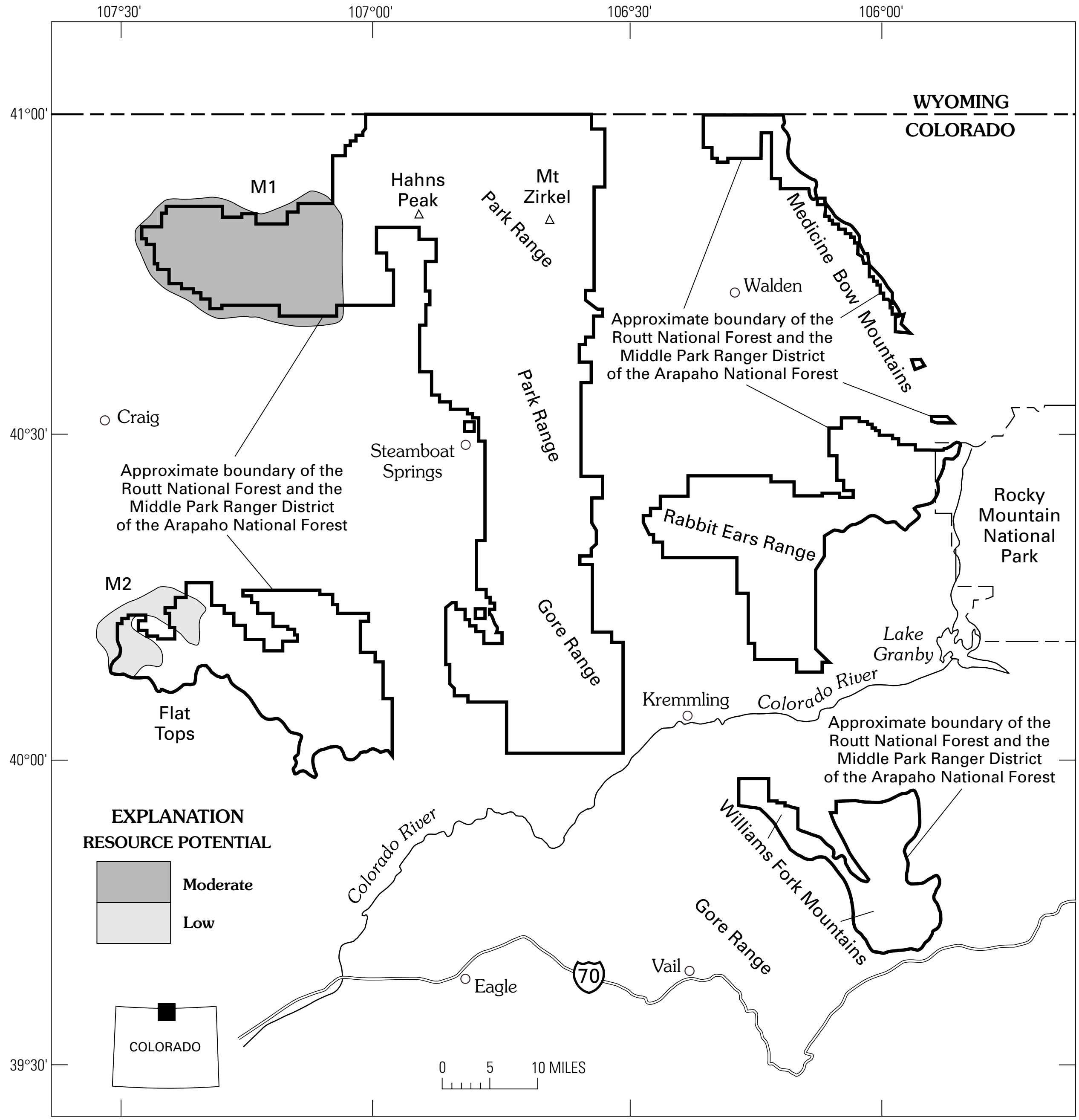


Figure 39. Energy resource map for coal-bed methane gas accumulations (M) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

producing interval in these fields may be as thick as 50 ft. The source rocks are marine shales that contain 1 to 4 percent organic matter. The oil was probably generated in Oligocene time, during maximum burial. The oil is trapped by less brittle, unfractured shale.

The presence of small, tightly folded anticlines and faults in the Elkhead Mountains and Flat Tops areas of the Forest present favorable conditions for the existence of fractured shales. Both of these areas have moderate resource potential for oil, with certainty level D (O1 and O2, fig. 41). Favorable conditions may also exist for the Niobrara Shale in the area of th Rabbit Ears Range and southward into Middle Park (O3, fig. 41); this area has low resource potential for oil, with certainty level C. It is unlikely that any discoveries will exceed 1 MMBO, but future exploration may include the drilling of horizontal and inclined wells that have a better ability to intersect open fractures. Only a few wells have been drilled in northwest Colorado using these methods.

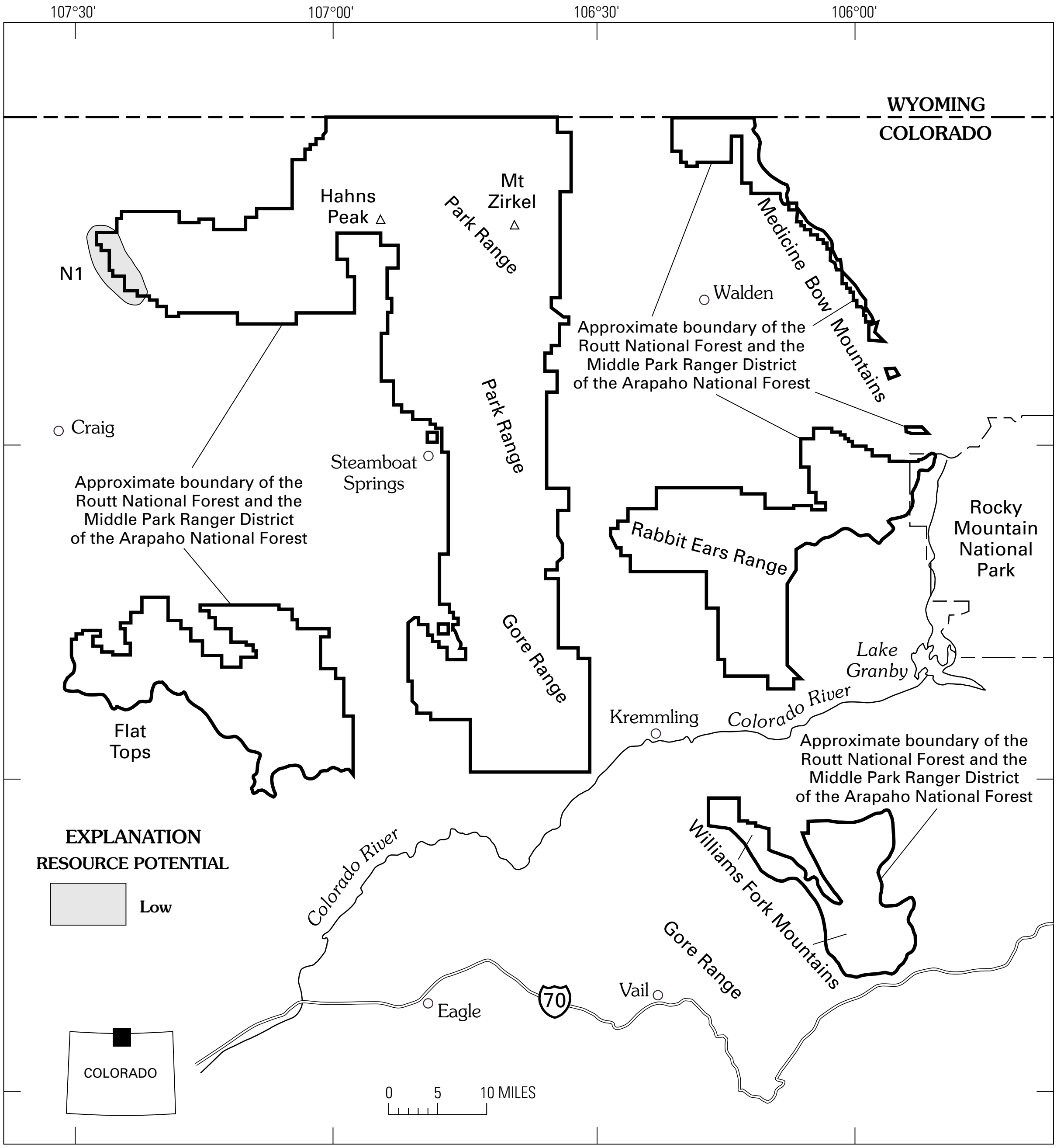


Figure 40. Energy resource map for basin-centered gas accumulations (N) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

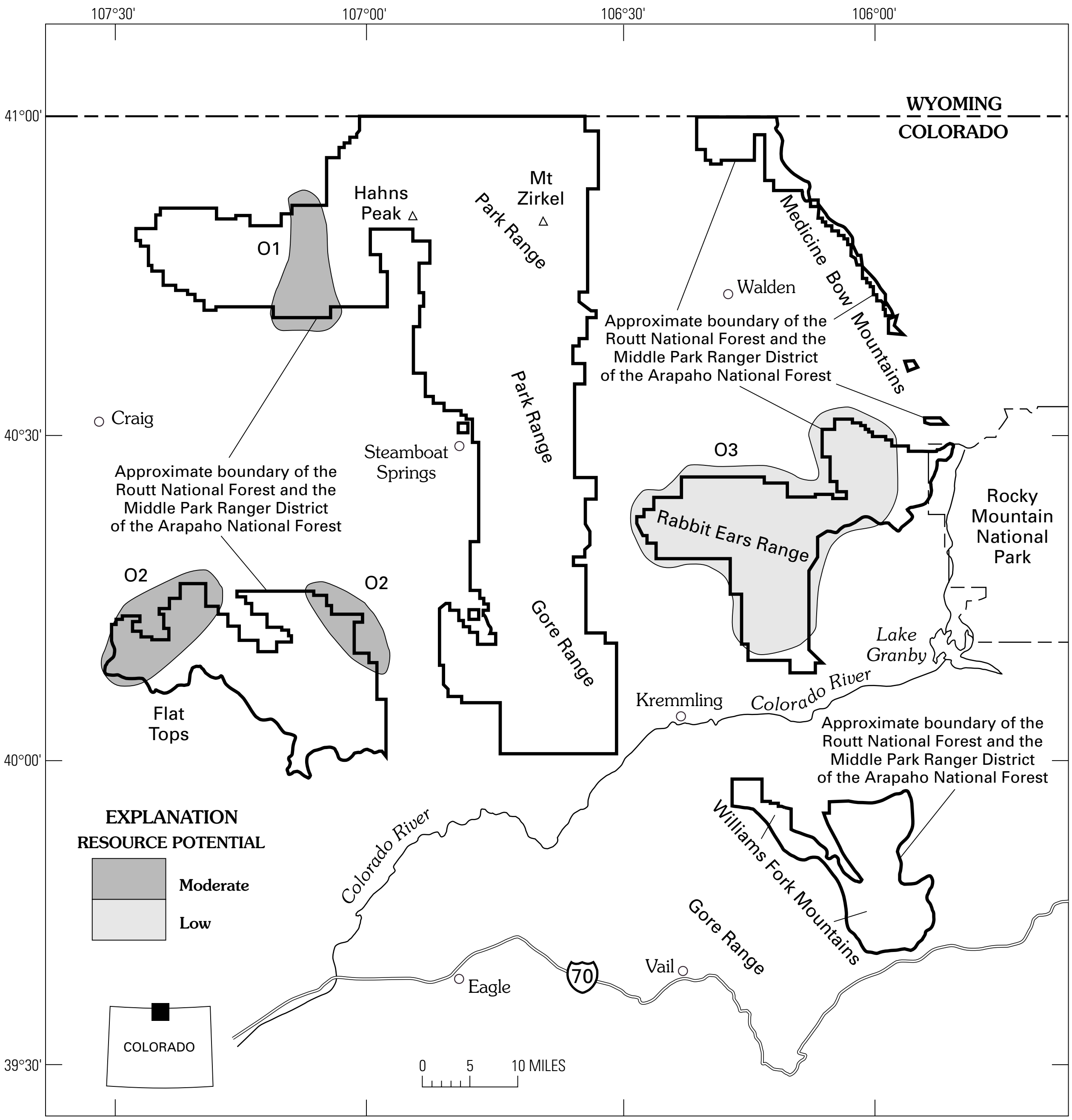


Figure 41. Energy resource map for fractured shale oil accumulations (O) in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest, Colorado.

GEOTHERMAL RESOURCES

By Sandra J. Soulliere

No known geothermal springs are within the Forest. However, several geothermal springs are located near the Forest, including those at Steamboat Springs along the Yampa River, Brand's Ranch artesian well west of Walden, and Routt Hot Springs (also called Strawberry Park Hot Springs) 8 mi north of the town of Steamboat Springs. These thermal springs occur in an area of high regional geothermal gradient in faulted rocks ranging from Proterozoic to Tertiary in age. The presence of hot springs is independent of rock type but is dependent on both structure and the presence of hydrothermal systems. The areal extent of possible hot springs has been estimated for the Steamboat Springs vicinity (Pearl, 1979) and may include land within the Forest.

The town of Steamboat Springs, just outside the Forest boundary, takes its name from one of the several mineral hot springs within the town limits, along the Yampa River. The temperatures of these springs ranges from a low of 68°F to a high of 102°F (Barrett and Pearl, 1978). Heart Spring, located at the southeast end of town, is the only developed spring, and its waters are used in the community pool. Extrapolation from geologic mapping and geophysical studies suggests that these springs are fault controlled (Christopherson, 1979; Pearl, 1979). Pearl and others (1983) estimated that the Steamboat Springs reservoir has an areal extent of 0.52 mi^2.

A group of thermal springs known as the Routt Hot Springs, or Strawberry Park Springs, are located approximately 8 mi north of Steamboat Springs. These springs are used commercially for recreational bathing and are located on private land within the Forest. Five springs in this area discharge water between 124°F and 147°F, at rates of 2 to 50 gallons per minute (Barrett and Pearl, 1978). The springs are fault and fracture controlled and may be part of the Steamboat Springs geothermal system. Pearl and others (1983) estimated that the Routt Hot Springs reservoir has an areal extent of 0.5 to 0.75 mi^2.

Brand's Ranch artesian well, located just west of Walden, was originally an 800-ft-deep oil test hole. Two estimates of the reservoir's extent were made by Pearl (1979). One estimate measured the extent to be limited to 0.36 mi^2 around the well. The other estimate extended the reservoir to include the projected faults south and approximately 1.3 mi north of the well. This system encompasses an area of 1.5 mi^2.

All of the geothermal springs in the vicinity of the Forest have been identified and their extent estimated. Thorough investigations by the Colorado Geological Survey (Barrett and Pearl, 1978; Pearl, 1979; Pearl and others, 1983) have not identified additional geothermal resources near or within the Forest. Therefore, there is no potential for undiscovered geothermal resources within the Forest, with certainty level C.

MINERAL RESOURCES—SALABLE MINERALS

By John S. Dersch, U.S. Forest Service

The Federal Minerals Act of 1947, as amended by the Multiple Surface Use Act of 1955, removed petrified wood, common varieties of sand and gravel, stone, pumice, volcanic cinders (including scoria), and some clay from acquisition by either location or lease. These minerals may be acquired from the U.S. Government only by purchase and are referred to as salable minerals. Several exceptions to the salable category are block pumice, perlite, and forms of dimension stone such as travertine and high-quality marble. Determination that a particular mineral is a salable mineral must be reviewed on case-by-case basis in light of past legal decisions. Salable minerals generally have a low unit value (value per ton); their exploitation is dependent on easy access to transportation, and generally they are used near the production site.

Numerous crushed aggregate sites are within the Forest, some of which are currently active. Needs are met by quarrying bedrock such as sandstone, volcanic rocks, granite, and basalt. Dimension stone needs are met from moss- or lichen-covered granite and sandstones.

Sand and gravel resources are available from most major drainages, landslide deposits, and glacial drift. Uses range from road fill, aggregate for concrete, macadam, mortar, and other purposes. Schwochow (1981) noted nine sand, sand and gravel, rubble, and borrow-material sites within the Forest.

The Forest is included in District 1, a Bureau of Mines designated area for the northwestern counties of Colorado. The sand-and-gravel production in this area for 1992 was 560,000 short tons worth $19,600. The crushed aggregate production in 1991 was 43,000 short tons valued at $144,000.

MINERAL RESOURCE POTENTIAL—SALABLE MINERALS

The mineral resource potential for salable materials is evaluated in this section. Income from the sale of these minerals will vary according to accessibility, unit cost and value, and production. Environmental factors have not been considered in this assessment.

CRUSHED AGGREGATE

Aggregate sources can be found in the Elkhead Mountains, the Park and Medicine Bow Ranges, and the Flat Tops. The Elkhead Mountains consist of a sedimentary rock section intruded by subvolcanic Tertiary igneous rocks. The Park and Medicine Bow Ranges include a granitic rock core intermixed with felsic and hornblende gneisses. The Flat Tops are a northerly dipping sedimentary package partially covered in the south by Tertiary basalts. Glacial drift can be found at higher elevations in the Park Range.

Sandstone.—Sandstone occurs as distinct ridges and caprock in Tertiary, Triassic, and Cretaceous rocks. The Browns Park Formation is a siltstone, claystone, and conglomerate that is flat lying to gently dipping (<10°). It is easily mined, crushed, and sorted by sizes. Uses in the Forest are predominantly roadway construction, but also includes sand and gravel for concrete work. The White River Formation is a tuffaceous siltstone and claystone that is easily crushed and is used for sand and gravel needs or as binder in roadway construction and general building needs. The Wasatch Formation is an arkosic sandstone, mudstone, and conglomerate. These rocks are used for building roadway and may satisfy general building and concrete needs after crushing if sufficient fines are generated during production. The Upper Triassic Chinle and Chugwater Formations are sandstones with intermixed conglomerates, siltstones, mudstones, and shales. All are easily crushed providing a wide range of sizes. Production would exclude the mudstone and shale units. Uses include road building and concrete manufacture.

Volcanic rocks.—Numerous volcanic necks can be found on the northeast corner of the Flat Tops. Numerous Tertiary dikes or sills are found in the Elkhead Mountains east of Bears Ears Mountain. They can both be crushed and used for base materials, particularly roadways and railroad ballast. The necks, dikes, and sills are found as topographically resistant features that can be removed to the ground surface with little visual impact.

Granite.—The Proterozoic granites within the Park Range are crushed for variously sized aggregates that are used in roadway construction, rip rap, and railroad ballast. Sufficient fines are usually produced as binder if needed. Local rock glaciers and talus slopes are a source of material for crushing.

Scoria.—Tertiary basalt flows are found capping sedimentary units on the northeast corner of the Flat Tops. The volume of material is probably limited. These flows can be used for lightweight aggregate and concrete needs.

Landslide material.—These materials, usually consisting of sedimentary rocks, are found at the northern end of the Flat Tops. They can be crushed for general aggregate needs, such as roadway building, railroad ballast, rip rap, and fill.

Glacial drift.—Quaternary glacial drift is found in the Park Range and requires screening only to remove large-sized fragments. The large sizes are easily crushed to usable sizes. Reserves are local and limited. Uses would include roadway building, railroad ballast, rip rap, and fill.

DIMENSION STONE

Some dimension or decorative stone work occurs locally through free use and mineral sale contracts. Moss or lichen-covered granite is used specifically for interior or exterior facing in homes or buildings. In addition to the organic veneer, the color, texture, shape, and crystal size of the granite are important. Hard, resistant sandstone can be cut and trimmed for building facing if the bedding, texture, and colors are pleasing. Most use is local and involves small quantities. Granitic rocks are found in the Park Range, and sandstones can be found in either the Elkhead Mountains or the Flat Tops.

SAND AND GRAVEL

Sand and gravel deposits can be found along the Elk and Colorado Rivers and their major tributaries within the Forest. The deposits must be screened and tested for specific uses. Uses include concrete work and products, fill material, plastering sands, and snow and ice control.

PROBABILISTIC ASSESSMENT OF UNDISCOVERED METALLIC ENDOWMENT USING GRADE–TONNAGE MODELS

By Theresa M. Cookro

INTRODUCTION

Subjective probabilistic estimates of undiscovered deposits and metal endowment are provided by the U.S. Geological Survey for undiscovered mineral deposits and metal endowment within the Forest. The estimates are used to present geologic information in language that can be used by economists and in land-use planning. The probabilistic estimates involve three parts: (1) delineation of areas that are favorable for the types of mineral resources indicated by the geological, geophysical, and geochemical information; (2) subjective estimation of the size and number of undiscovered deposits, which is indicated by historical occurrence and production data and a comparison with grade and tonnage distribution curves of the mineral deposit models; and (3) MARK3 computer program estimation of metal endowment based on grade and tonnage distributions from the known deposits (Singer, 1993; Singer and Cox, 1987; Singer and Ovenshine, 1979; Menzie and Singer, 1990; Root and others, 1992).

Before the assessment could be undertaken, a comprehensive inventory of data from the Forest was compiled. The data included the nature of the existing deposits, their locations, and any available production records (Neubert, 1994). The inventory is used to determine if there are sufficient data to identify the types of mineral deposits that occur within the Forest and to determine whether undiscovered resources could be estimated. The data are combined with geologic, geochemical, and geophysical information to accurately delineate areas within the Forest that are favorable for the occurrence of undiscovered resources.

Although ten types of deposits were identified in the Forest, three grade and tonnage models were used for the prediction of undiscovered deposits: Sierran Kuroko, porphyry copper, and placer gold (Cox and Singer, 1986; Singer, 1992). Estimates for other deposit types were not possible because of insufficient data or the lack of a mineral deposit model in the computer program. The resulting estimates of metal endowment are a useful but imprecise measurement and should not be considered exact. The compilation of production data for individual deposits in the study area and for the deposits used in the grade-tonnage curves is quantitative. Some of the resource estimation methods are subjective, and verification of the results is impossible until the area, in years to come, is thoroughly explored.

Definitions of terms are presented in Appendix 4, and units of measurement are described in Appendix 5.

ASSESSMENT METHOD

DELINEATION OF PERMISSIVE AREAS

For the three-part assessment process, an assessment team was assembled consisting of project geoscientists (S.J. Soulliere, M.I. Toth, V. Bankey, S.M. Smith, J.A. Pitkin, and T.M. Cookro). Compiling geological, geochemical, geophysical and mineral resource data for the Forest was the first step in the assessment process. Deposit types that had characteristics that matched the characteristics defined by individual deposit models were used to determine the probable mineral endowment. Areas were delineated within the Forest as having high or moderate potential for undiscovered mineral resources. These areas predictably may contain a deposit of the type being evaluated. The areas of moderate to high potential correspond to areas where a number of characteristics, geologic, geophysical, geochemical, and structural elements overlap. Areas of mineral potential were considered to extend to a reasonable depth (frequently 0.5 km) depending on the type of deposit and therefore do not always follow map units.

GRADE-TONNAGE MODELS AND ESTIMATION OF UNDISCOVERED DEPOSITS

Mineral deposit models and grade and tonnage curves comprise information from mineral deposits throughout the world that have the specific characteristics found in the definition of each model. Because the models have ore distributions (tonnage and grade) from many deposits of a specific type, they can be applied locally to predict grades and tonnages of undiscovered deposits. Some deposit types cannot be used because not enough background data is available to use the models. The MARK3 computer program can be used to determine undiscovered mineral endowment if the deposit model's grade and tonnage frequency distribution is similar to the distribution of the estimated undiscovered ore deposits in the study area (Orris and Bliss, 1991; Bliss, 1992; Singer, 1992; Menzie and Singer, 1990; Singer and Cox, 1987; Cox and Singer, 1986; Bliss, 1992; Orris and Bliss, 1991). A test for the applicability of the method is whether 80 percent of the expected number of deposits in the Forest lie between the 90th and 10th percentile of the grade and tonnage curves. If not, the estimates cannot be made, and the mineral resource potential cannot be reported in terms of endowment.

After the scientific team delineated areas favorable for the occurrence of mineral deposits, the team's expert judgment was then used to subjectively estimate the number of undiscovered deposits. Economics is not a factor in this determination. The members of the team who estimated the highest or lowest number of unknown deposits were asked to explain their rationale for estimation and a consensus was attained.

The number of undiscovered deposits was estimated at the following levels of probability: 90th, 50th, 10th, 5th, and 1st percentile. A 90th percentile would correspond to 90 percent probability that one or more deposit are present. The least speculative of the five levels of confidence is the 90th percentile. The number of deposits estimated for the 90th percentile is influenced by the number of known deposits of a particular type in the Forest and the extent of past exploration for those known deposits (Singer and Ovenshine, 1979).

A number of factors can be used for the estimates, including the presence and amount of unconsolidated surficial deposits, areas that have a greater number of geologic conditions (surficial or at depth) typical of a particular deposit type, the number of genetically related known deposits in the area, geochemical anomalies, and the presence of favorable alteration zones. The lower the percentile estimate, the more speculative the data. Half of the estimated number of deposits at each confidence level (90 percent, 50 percent, 10 percent, 5 percent , 1 percent) is expected to be larger than the median tonnage for the specific grade and tonnage model (Cox and Singer, 1986; Singer, 1993).

MARK3 COMPUTER PROGRAM

The estimated number of undiscovered deposits for each probability (90 percent, 50 percent, 10 percent, 5 percent, 1 percent) are entered into a Monte Carlo simulator (MARK3) computer program. The MARK3 program randomly selects values from grade and tonnage frequency distributions (created from a database of known deposits in each model) to produce a probability distribution (or probability curve) of the metal tonnages for the expected deposits (Drew and others, 1986; Root and Scott, 1988; Root and others, 1992). The MARK3 selects metal tonnages that would likely be present together in the undiscovered deposits. The selection process consists of 4,999 iterations using a random number generator, and the results are sorted to permit reporting of ore and metal tonnages at the percentiles that were originally estimated (90, 50, 10, 5, and 1).

MARK3 assumes the grade and tonnage distributions are representative of all deposits with similar geologic, geophysical, and geochemical attributes. Grade and tonnage variables are made dependent by treating them as individually normal or jointly bivariate normal (Root and Scott, 1988), even though they are actually independent and not normal. The independent data cannot be used to predict grades and tonnages of deposits with similar attributes. In order to make predictions the data are artificially made dependent by treating the median and mean of the sampling distribution as equal to the median and mean of the grade and tonnage values. The mean and the product of the grade and tonnage values are then set equal to the mean of the metal content. Thus, the two variables, grade and tonnage, are essentially brought into a cumulative distribution function that is jointly bivariate (Drew and others, 1986; Root and Scott, 1988; Root and others, 1992).

CALCULATION OF THE MEAN AND THE MEDIAN

The mean and median are both measures of central tendency. The mean is the arithmetic average of the total estimated tonnage divided by the 4,999 tonnage estimations that were performed. The median is the midpoint of the tonnage distribution. The mean is useful because it is additive, so the mean amount of gold for all expected deposits is the sum of gold means from all of the models (Sierran Kuroko, copper porphyry, and placer gold). The median is not additive, but it is useful because it reflects the shape of the curve of tonnage frequency distributions, or the ranking in a particular set of 4,999 iterations. The mean is strongly influenced by a few large deposits (for example, a world-class deposit) that are in the data sets, whereas the median values are not. The median is a more conservative estimation of undiscovered resources. In our estimations, the mean is a larger number than the median, because grade and tonnage frequency distributions are asymmetric, with a tail toward larger values. A reason for this asymmetry is that the lowest values (grades and tonnages for mineral occurrences) in the frequency distribution are not included because they are small and do not merit extensive exploration. Deposit models realistically cannot contain all mineral-occurrence data because of their subeconomic nature. This grade and tonnage data is rarely recorded in the literature, but it would fall on the lower part of the tonnage frequency distribution curves. Because of the lack of data, each deposit model has a specified minimum cutoff ore grade and minimum deposit size. Hence, the mean is a higher value, and the difference in the mean and median is a measure of the skewness of the curve. It is therefore important to pay attention to both mean and median because together they help to understand the projected metal endowment.

RESULTS

Although several types of deposits were identified in the Forest, it was determined that three deposit types are sufficiently understood to compare them with available deposit models and estimate undiscovered metallic resources. These models are: Sierran Kuroko (massive sulfide) in Singer (1992), porphyry copper in Singer and others (1986), and placer gold in Orris and Bliss (1986). The remaining deposit types in the Forest lack pertinent data for quantitative assessment. The expected amount of contained metal for each metallic commodity associated with the deposit type and the total metric tons of ore are reported in terms of five probability levels (90 percent, 50 percent, 10 percent, 5 percent, 1 percent). The 90th percentile means there is a 90 percent chance that undiscovered deposits will contain at least the reported metric tons of metal and total ore. In order to determine the value of minable undiscovered resources, the results must be subjected to an economic analysis.

MASSIVE SULFIDE OR SIERRAN KUROKO DEPOSITS

The Sierran Kuroko grade and tonnage curves (Singer, 1992, p. 30–32) were modified for this analysis by using the lower half of the curve for the MARK3 simulation because the expected range of grades and tonnages of the undiscovered deposits were comparable to only those grades and tonnages on the lower half of the curve. Eighty percent of the expected number of deposits in the Forest were considered be less than 310,000 metric tons, 1.4 percent copper, 1.3 grams per metric ton gold, and 32 grams per metric ton silver. This is below the midpoint of the curve, so it is more appropriate to use the lower half of the curve. The assessment team estimated that there is a 90 percent chance of no undiscovered deposits, a 50 percent chance of no undiscovered deposits, a 10 percent chance for one deposit, a five percent chance for one deposit, and a 1 percent chance that there are two deposits. These estimates imply a mean of 0.33 undiscovered deposits. The resulting assessment (tables 10 and 11) indicates that there is a 10 percent chance that there are 190,000 total metric tons of undiscovered Sierran Kuroko (massive sulfide) ore in the Forest. From this there could be a production of 4,200 metric tons copper, 6,600 metric tons zinc, 0.14 metric tons of gold, and 8.9 metric tons silver. A five percent chance exists for 250,000 total metric tons of undiscovered ore containing 6,100 metric tons of copper, 13,000 metric tons of zinc, 870 metric tons of lead, 0.33 metric tons of gold, and 21 metric tons of silver (table 11). A one percent chance exists for 360,000 total metric tons of undiscovered ore that would produce 10,000 metric tons of copper, 27,000 metric tons of zinc, 5,000 metric tons of lead, 0.92 metric tons of gold, and 46 metric tons of silver. The median of the total estimated ore and metal content is zero, and the mean is 48,000 metric tons of ore containing, in metric tons, 3,200 copper, 1,900 zinc, 180 lead, 0.05 gold, 2.9 silver. The results of the MARK3 simulation are reported to two significant figures.

PORPHYRY COPPER DEPOSITS

The porphyry copper grade and tonnage curves (Singer and others, 1986, p. 80–81) were modified for this analysis (only the lower half of the curves were used for the MARK3 simulation). As was used for the Sierran Kuroko model, it was also more appropriate to use the lower half of the curve for the MARK 3 simulation because 80 percent of the expected number of deposits in the Forest fell below the midpoint of the curve (or less than 140 million metric tons that contain 56 percent copper). The assessment team estimated a 90 percent chance that there are no porphyry copper deposits, a 50 percent chance that there are no deposits, a 10 percent chance for one deposit, a 5 percent chance for one deposit, and a 1 percent chance of 2 deposits. These estimates imply a mean of 0.33 undiscovered deposits. The results of the simulation (tables 10 and 11) suggest that there is a 10 percent chance that 79,000,000 total metric tons of ore occurs within the Forest, from which there could be a production of 380,000 metric tons of copper, 2,000 metric tons of molybdenum, and 3.2 metric tons of gold. A five percent chance exists for 110,000,000 total metric tons of undiscovered ore containing 590,000 metric tons of copper, 8,900 metric tons of molybdenum, 19 metric tons of gold, and 120 metric tons of silver. And finally, a one percent chance exists for 180,000,000 total metric tons of undiscovered ore that could contain 1,400,000 metric tons of copper, 35,000 metric

Table 10. Mean number of deposits and probability of zero deposits for quantitative estimates.

	Massive Sulfide	Porphyry Copper-Molybdenum	Placer Gold
Expected mean number of deposits	0.33	0.33	0.6
Probability of zero deposits	70%	70%	70%

Table 11. Quantitative estimates of undiscovered resources of massive sulfide, porphyry copper-molybdenum, and placer gold deposits in the Routt National Forest and Middle Park Ranger District of the Arapaho National Forest and vicinity, Colorado.

[Values in metric tons. Percentages in column headings refer to confidence levels for estimates of undiscovered deposits occurring in the Forest]

Metal	90%	50% median	10%	5%	1%	mean
Massive Sulfide						
Number of deposits	0	0	1	1	2	
Total Metric Tons	0	0	190,000	250,000	360,000	48,000
Contained metal for:						
Copper	0	0	4,200	6,100	10,000	3,200
Zinc	0	0	6,600	13,000	27,000	1,900
Lead	0	0	0	870	5,000	180
Gold	0	0	0.14	0.33	0.92	0.05
Silver	0	0	8.9	21	46	2.9
Porphyry Copper-Molybdenum						
Number of deposits	0	0	1	1	2	
Total metric tons	0	0	79,000,000	110,000,000	180,000,000	20,000,000
Contained metal for:						
Copper	0	0	380,000	590,000	1,400,000	109,000
Molybdenum	0	0	2,000	8,900	35,000	1,600
Gold	0	0	3.2	19	57	2.6
Silver	0	0	0	120	410	17
Placer Gold						
Number of deposits	0	0	1	1	1	
Total metric tons	0	0	7,600,000	21,000,000	97,000,000	3,900,000
Contained metal for:						
Gold	0	0	1.0	3.1	13.0	0.6
Silver	0	0	0	0.009	0.59	0.003

tons of molybdenum, 57 metric tons of gold, and 410 metric tons of silver. The median of the estimated total ore and metal content is zero, and the mean is 20,000,000 metric tons of ore that could contain, in metric tons, 109,000 copper, 1,600 molybdenum, 2.6 gold, 17 silver. The results of the MARK3 simulation are reported to two significant figures.

PLACER GOLD DEPOSITS

The placer gold grade and tonnage curves (Yeend, 1986; Orris and Bliss, 1986, p. 263–264) were modified for this analysis. Only the lower half of the curves were used for the MARK3 simulation because the expected deposits were considered small enough that 80 percent of the expected number of deposits in the Forest were below the midpoint of the curve (or less than 1.1 million metric tons of ore containing 0.2 grams per metric ton of gold)(tables 10 and 11). The assessment team estimated a 90 percent chance for no undiscovered placer gold deposits, a 50 percent chance for no deposits, a 10 percent chance for one deposit, a 5 percent chance for one deposit, and a 1 percent chance for one deposit. These estimates imply a mean of 0.6 undiscovered deposits. Silver is reported, even though silver was not historically produced from placers, because it is present in some of the placers and is a resource that may be produced. The results of the simulation (tables 10 and 11) suggest a 10 percent chance that the Forest may have 7,600,000 total metric tons of ore containing one metric ton of gold and no silver. A five percent chance exists for 21,000,000 total metric tons of undiscovered ore containing 3.1 metric tons of gold, and 0.009 metric tons of silver. And finally, a one percent chance exists for 97,000,000 total metric tons of undiscovered ore containing 13 metric tons of gold and 0.59 metric tons of silver. The median of the total estimated placer ore and contained metals is zero, and the mean is 3,900,000 metric tons of ore containing, in metric tons, 0.6 gold and 0.003 silver. The results of the MARK3 simulation are reported to two significant figures.

SUMMARY OF ENVIRONMENTAL STUDIES

By Margo I. Toth, Sandra J. Soulliere, *and* Steven M. Smith

MINES AND MINERALIZED AREAS

Metals in mineral deposits or mineralized areas are commonly contained in sulfide complexes. When oxygen-rich waters react with these sulfide minerals, they often result in highly acidic waters that contain potentially toxic elements such as zinc, copper, cadmium, and arsenic (Plumlee and others, 1993). The presence of carbonate minerals such as calcite can help reduce the acidity and concentrations of some but not all of these metals. Naturally occurring sulfide-rich rocks, underground and open-pit mine workings, and mine waste dumps and tailings can be major sources for acid waters and metals in the environment. The acid waters and toxic metals can adversely affect water quality, aquatic life, wildlife, and agriculture.

Plumlee and others (1993) have shown that different mineral deposit types have characteristic environmental signatures that are a function of geology, geochemical processes, climate, and mining method. The geology or mineral content of a deposit and the geochemical processes that affect the minerals control the acidity and amount of dissolved metals in waters that drain mineralized areas. The local climate and mining methods used affect the rate of acid generation and the extent of dispersion of potentially toxic metal elements. Environmental-geology models, based upon these factors, can be used to predict the likely pre-mining and post-mining environmental signatures associated with a deposit (Plumlee and others, 1993). Such an appraisal can help identify and prioritize the study of existing hazardous mine sites and help predict and plan for the environmental effects of any possible future development.

The major mines and mineralized areas within the Forest are shown in figure 5. Based on geologic and geochemical considerations, only the following mining districts have any significant likelihood of producing high-acid or high-metal waters: Hahns Peak, Pearl district, Greenville mine, Teller district, La Plata-Dailey districts, and Poison Ridge. All of these areas share some or all of the following criteria: extensive alteration, high pyrite content, significant metal concentration, and lack of a carbonate buffer. None of these areas are currently known to produce high-metal or high-acid waters, but only one of these areas, the Greenville mine, was investigated during this study. Studies of waters draining some of the tailings at the Greenville mine showed near-neutral waters and low conductivity, indicating low dissolved solids. Additionally, red iron-oxide precipitates have been reported in streams draining Poison Ridge (Kinney and others, 1968) and the La Plata-Dailey mining districts (R.G. Eppinger, oral commun., 1994). These precipitates are commonly, but not exclusively, found in streams affected by acid drainage from mineralized areas. Further study may be warranted in these areas.

The Colorado Water Quality Control Division (1989) has identified several tributaries of the Yampa River that contain metal concentrations in water that exceed agricultural, water-supply, or aquatic-life standards. The headwaters of two of these tributaries are in the Forest. Elk River, from the South Fork to the Yampa River, has lead concentrations in water that exceed basic standards for aquatic life. The source of this lead was attributed to subsurface mining, although no specific mines or districts were specified as the source. Trout Creek originates on the northeast side of Pyramid Peak and contains cadmium, copper, and mercury above basic aquatic life standards from the Rio Blanco County line to Foidel Creek; below Foidel Creek to the Yampa River, concentrations of copper, iron, mercury, and zinc exceed basic standards for aquatic life, and manganese exceeds the water-supply standard. The source of these metals appears to be coal mines just outside the Forest boundary.

WATER-QUALITY AND ATMOSPHERIC STUDIES

Ongoing work by John Turk of the U.S. Geological Survey (Turk and others, 1992, 1993; Turk and Campbell, 1987) has shown a high acidity in snow in the north-central part of the Forest in the Mt. Zirkel Wilderness. Although the cause has not been identified, the increase may be an effect of coal-fired power plants to the west of the mountain range in Craig and Hayden. The U.S. Forest Service and U.S. Geological Survey have undertaken a study of lichens and mosses to determine whether the coal plants are the sources of pollutants and associated decreasing visibility within the range (Rocky Mountain News, 9/1/94, 9/6/94; Jackson and others, 1996).

REFERENCES CITED

Allen, M.S., 1982, An evaluation of stream sediment and heavy mineral concentrate geochemistry as aids in geologic mapping and mineral exploration in northern Colorado: Kingston, Ontario, Canada, Queen's University M.S. thesis, 243 p. (v. 1) and 222 p. (v. 2).

Bader, J.W., 1983, Section *A-A'*, Subsurface correlations of some Upper Cretaceous and Tertiary rocks from the Cherokee Ridge, Wyoming, to the southeast flank of the Sand Wash Basin, Colorado: U.S. Geological Survey Open-File Report 83-362, 2 sheets.

Barrett, J.K., and Pearl, R.H., 1978, An appraisal of Colorado's geothermal resources: Colorado Geological Survey Bulletin 39, 224 p.

Barton, H.N., 1985a, Geochemical maps showing the distribution and abundance of selected elements in heavy-mineral concentrates derived from stream sediments and ridgetop soils from the upper Keyser Creek basin in the St. Louis Peak Roadless Area, Grand County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1588-H, scale 1:50,000.

———1985b, Geochemical maps showing the distribution and abundance of selected elements in heavy-mineral concentrates from ridgetop soils from the Williams Fork Roadless Area, Clear Creek, Grand, and Summit Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1588-I, scale 1:50,000.

———1985c, Geochemical maps showing the distribution and abundance of selected elements in heavy-mineral concentrates of stream sediments from the Vasquez Peak Wilderness study area and the Williams Fork and St. Louis Peak Roadless Areas, Clear Creek, Grand, and Summit Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1588-G, scale 1:50,000.

Bass, N.W., Eby, J.B. and Campbell, M.R., 1955, Geology and mineral fuels of parts of Routt and Moffat Counties, Colorado: U.S. Geological Survey Bulletin 1027-D, p. 143–250.

Beaumont, E.A., 1979, Depositional environments of Fort Union sediments (Tertiary, northwest Colorado) and their relation to coal: American Association of Petroleum Geologists Bulletin, v. 63, p. 194–217.

Behrendt, J.C., Popenoe, P., and Mattick, R.E., 1969, A geophysical study of North Park–Middle Park Basin, Colorado: Geological Society of America Bulletin, v. 80, p. 1523–1538.

Berg, R.R., 1960, Cambrian and Ordovician history of Colorado, *in* Weimer, R.J., and Haun, J.D., eds., The Geology of Colorado: Denver, Geological Society of America, Rocky Mountain Association of Geologists, and Colorado Scientific Society, p. 10–16.

Beroni, E.P., and Derzay, R.C., 1955, The uranium deposits of the Fish Creek district, Colorado, *in* Guidebook to the Geology of Northwest Colorado: Salt Lake City, Utah, Intermountain Association of Petroleum Geologists, 6th Annual Field Conference, Rocky Mountain Association of Geologists, Annual Field Conference, 1955, p. 123.

Beroni, E.P., and McKeown, F.A., 1952, Reconnaissance for uraniferous rocks in northwestern Colorado, southwestern Wyoming, and northeastern Utah: U.S. Geological Survey Trace Elements Investigations Report TEI-308-A, p. 41.

Blackstone, D.L., 1977, Independence Mountain thrust fault, North Park Basin, Colorado, *in* University of Wyoming Contributions to Geology, v. 16, no. 1, p. 1–16.

Blakely, R.J., and Simpson, R.W., 1986, Approximating edges of source bodies from magnetic or gravity anomalies: Geophysics, v. 51, no. 7, p. 1494–1498.

Bliss, J.D., ed., 1992, Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, 168 p.

Bolivar, S.L., Broxton, D.E., and Olsen, C.E., 1978, Uranium hydrogeochemical and stream sediment reconnaissance of the Denver and Greeley NTMS quadrangles, Colorado: Los Alamos, NM, Los Alamos Scientific Laboratory informal report LA-7177-MS, Grand Junction, CO, U.S. Department of Energy, GJBX-60(78), 138 p.

Bolivar, S.L., Hill, D.E., Sandoval, W., Trujillo, L., Bunker, M.E., Waterbury, G.R., Talcott, C.L., Minor, M.M. and Cheadle, J., III, 1979, Uranium hydrogeochemical and stream sediment reconnaissance of the Craig NTMS quadrangle, Colorado, including concentrations of forty-three additional elements: Los Alamos, NM, Los Alamos Scientific Laboratory informal report LA-7506-MS, Grand Junction, CO, U.S. Department of Energy, GJBX-76(79), 238 p.

Boreck, D.L., Tremain, C.M., Sitowitz, L., and Lorenson, T.D., 1981, The coal bed methane potential of the Sand Wash Basin, Green River coal region, Colorado: Colorado Geological Survey Open-File Report 81-6, 24 p.

Braddock, W.A., and Cole, J.C., 1978, Preliminary geologic map of the Greeley 1°×2° quadrangle, Colorado and Wyoming: U.S. Geological Survey Open-File Report 78-532, scale 1:250,000.

———1990, Geologic map of Rocky Mountain National Park and vicinity, Colorado: U.S. Geological Survey Miscellaneous Investigation Series Map I-1973.

Brady, B.T., 1975, Map showing fluorspar deposits in Colorado: U.S. Geological Survey Mineral Investigations Resource Map MR-70, 10 p.

Brinkworth, G.L., 1973, A geophysical investigation of the Colorado Front Range mineral belt: Boulder, University of Colorado, Ph.D. dissertation, 251 p.

Brobst, D.A., and Pratt, W.P., 1973, Introduction, *in* Brobst, D.A., and Pratt, W.A., eds., United States Mineral Resources: U.S. Geological Survey Professional Paper 820, p. 1–8.

Bryant, B., McGrew, L.W., and Wobus, R.A., 1981, Geologic map of Denver 1°×2° quadrangle, north-central Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1163 (2 sheets), scale 1:250,000.

Campbell, D.L., and Wallace, A.R., 1986, Aeromagnetic map of the Holy Cross Wilderness Area, Eagle, Lake, and Pitkin Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1841-B, scale 1:100,000.

Casaceli, R.J., 1984, The geology and mineral potential of the Hahns Peak intrusive porphyry, Routt County, Colorado: Corvallis, Oregon State University, unpublished M.S. thesis, 223 p.

Case, J.E., 1965, Gravitational evidence for a batholithic mass of low density along a segment of the Colorado Mineral Belt: Geological Society of America Special Paper 82, p. 26.

———1967, Geophysical ore guides along the Colorado Mineral Belt: U.S. Geological Survey Open-File Report 67-039, 13 p.

Christopherson, K.R., 1979, A geophysical study of the Steamboat Springs, Colorado, geothermal systems: Boulder, University of Colorado, M.S. thesis, 107 p.

Cobban, W.A., Merewether, E.A., Fouch, T.D., and Obradovich, J.D., 1994, Some Cretaceous shorelines in the Western Interior of the United States, *in* Caputo, M.V., Peterson, J.A., and Franczyk, K.J., eds., Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists (Society for Sedimentary Geology), p. 393–414.

Colorado Oil and Gas Conservation Commission, 1992, Oil and Gas Statistics for the State of Colorado: Colorado Oil and Gas Conservation Commission.

Colorado Water Quality Control Division, 1989, Colorado nonpoint assessment report, p. 166–173.

Cordell, Lindrith, and Grauch, V.J.S., 1985, Mapping basement magnetization zones from aeromagnetic data in the San Juan Basin, New Mexico, *in* Hintze, W.J., ed., The Utility of Regional Gravity and Magnetic Anomaly Maps: Society of Exploration Geophysics, p. 181–197.

Cox, D.P., Barton, P.B., and Singer, D.A., 1986, Mineral deposit models, *in* Cox, D.P., and Singer, D.A., eds., 1986, Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, p. 1–10.

Cox, D.P., and Singer, D.A., eds., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Craig, L.C., Hail, W.J., Jr., Luft, S.J., Boudette, E.L., and Snyder, G.L., 1982, National Uranium Resource Evaluation, Craig quadrangle, Colorado: U.S. Department of Energy, Grand Junction Office Report PGJ/F-017(82), 106 p., 13 maps, scale 1:500,000.

Crawford, R.D., 1924, A contribution to the igneous geology of central Colorado: American Journal of Science, 5th ser., v. 7, p. 365–388.

Daniels, J.J., 1987, Geophysical appraisal of mineral resources of the Mount Zirkel Wilderness and northern Park Range vicinity, Jackson and Routt Counties, Colorado: U.S. Geological Survey Bulletin 1554-D, p. 217–221.

Desborough, G.A., 1970, Silver depletion indicated by microanalysis of gold from placer occurrences, Western United States: Economic Geology, v. 65, no. 3, p. 304–311.

De Voto, R.H., 1990, Paleozoic stratigraphy, tectonism, thermal history, and basin evolution of central Colorado, *in*, Beaty, D.W., Landis, G.P., and Thompson, T.B., eds., Carbonate-Hosted Sulfide Deposits of the Central Colorado Mineral Belt: Economic Geology Monograph 7, p. 29–44.

Dickerson, R.P., and McDonnell, J.R., Jr., 1989, Mineral resources of the Platte River Adjacent Wilderness Study Area, Jackson County, Colorado: U.S. Geological Survey Open-File Report 89-154, 12 p.

Drew, L.J., Bliss, J.D., Bowen, R.W., Bridges, N.J., Cox, D.P., De Young, J.C., Jr., Houghon, J.C., Ludington, Steve, Menzie, W.D., Page, J.J., Root, D.H., and Singer, D.A., 1986, Quantitative estimation of undiscovered mineral resources: A case study of U.S. Forest Service wilderness tracts in the Pacific mountain system: Economic Geology, v. 81, p. 80–88.

Duval, J.S., Jones, W.J., Riggle, F.R., and Pitkin, J.A., 1995, Potassium, uranium, and thorium aerial gamma-ray maps of the conterminous United States: U.S. Geological Survey Geophysical Investigations Map GP-1010, 3 maps, scale 1:2,500,000, 7 p. text.

Erdmann, C.E., 1941, Preliminary report on the geology of the Coalmont District, Jackson County, Colorado: U.S. Geological Survey Open-File Report 705, 207 p.

Erslev, E.A., and Rogers, J.L., 1993, Basement-cover geometry of Laramide fault-propogation folds: Geological Society of America Special Paper 280, p. 125–146.

Fenneman, N.M., and Gale, H.S., 1906, The Yampa coal field, Routt County, Colorado: U.S. Geological Survey Bulletin 297, 96 p.

Fillmore, B.J., 1986, Stratigraphy and source-rock potential of the Mowry Shale (Lower Cretaceous), North Park, Colorado: Colorado School of Mines, M.S. thesis, 144 p..

Fortescue, J.A.C., 1992, Landscape geochemistry: Retrospect and prospect 1990: Applied Geochemistry, v. 7, p. 1–53.

Franklin, J.M., Sangster, D.M., and Lydon, J.W., 1981, Volcanic-associated massive sulfide deposits: Economic Geology, 75th Anniversay Volume, p. 485–627.

Gale, H.S., 1906, The Hahns Peak gold field, Colorado: U.S. Geological Survey Bulletin 285-H, p. 28–34.

Geometrics, 1978, Aerial gamma ray and magnetic survey, Rock Springs, Rawlins, and Cheyenne quadrangles, Wyoming, and Greeley quadrangle, Colorado: U.S. Department of Energy, Grand Junction Office Report GJBX-17(78), 8 vols.

———1979a, Aerial gamma ray and magnetic survey, Denver and Pueblo quadrangles, Colorado: U.S. Department of Energy, Grand Junction Office Report GJBX-49(79), 8 vols.

———1979b, Aerial gamma ray and magnetic survey, Uncompahgre uplift project, Salina, Utah, Moab, Utah and Colorado, Montrose and Leadville, Colorado, quadrangles: U.S Department of Energy, Grand Junction Office Report GJBX-95(79), 8 vols.

Giles, D.L., 1976, Precambrian mineralization in the southern Rocky Mountain region, *in* Tectonics and Mineral Resources of Southwestern North America: New Mexico Geological Society Special Publication no. 6, p. 127–131.

———1987, Proterozoic framework and metallogeny: Southern Rocky Mountain Province of Colorado and New Mexico [abs]: Geological Society of America Abstracts with Programs, p. 676.

Gourdarzi, G.H., compiler, 1984, Guide to preparation of mineral survey reports on public lands: U.S. Geological Survey Open-File Report 84-0787, p. 7–8.

Grauch, V.J.S., and Cordell, Lindrith, 1987, Limitations of determining density or magnetic boundaries from the horizontal gradient of gravity or pseudogravity data: Geophysics, v. 52, no. 1, p. 118–121.

Hail, W.J., Jr., 1965, Geology of northwestern North Park, Colorado: U.S. Geological Survey Bulletin 1188, 133 p.

———1968, Geology of southwestern North Park, Colorado: U.S. Geological Survey Bulletin 1257, 119 p.

Hamilton, D.S., 1993, Stratigraphy and coal occurrence of the Upper Cretaceous Mesaverde Group, San Wash Basin, *in* Kaiser, W.R., Scott, A.R., Hamilton, D.S., Tyler, R., McMurry, R.G., Zhou, N., and Tremain, C.M., eds., Geologic and Hydrologic Controls on Coal-Bed Methane—Sand Wash Basin, Colorado and Wyoming: Gas Research Institute Topical Report GRI-92/0420, p. 79–106.

Hannah, J.L., and Stein, H.J., 1986, Oxygen isotope compositions of selected Laramide-Tertiary granitoid stocks in the Colorado

Mineral Belt and their bearing on the origin of Climax-type granite-molybdenum systems: Contributions to Mineralogy and Petrology, v. 93, no. 3, p. 347–358.

Hedge, C.E., Houston, R.S., Tweto, Ogden., Peterman, Z.E., Harrison, J.E., and Reid, R.R., 1986, The Precambrian of the Rocky Mountain region, *in*, Harrison, J.E., and Peterman, Z.E., eds., Correlation of Precambrian Rocks of the United States and Mexico: U.S. Geological Survey Professional Paper 1241-D, 17 p.

Hildenbrand, T.G., 1983, FFTFIL—A filtering program based on two-dimensional Fourier analysis on geophysical data: U.S. Geological Survey Open-File Report 83-237, 61 p.

Hills, F.A., and Houston, R.S., 1979, Early Proterozoic tectonics of the central Rocky Mountains, North America: Contributions to Geology, v. 17, p. 89–109

Hoffman, J.D., and Marsh, S.P., 1994, National geochemical data base [abs.], *in* Carter, L.M.H., Toth, M.I., and Day, W.C., eds., USGS Research on Mineral Resources—1994, Part A, Programs and Abstracts: Ninth V.E. McKelvey Forum on Mineral and Energy Resources, U.S. Geological Survey Circular 1103-A, p. 47–48.

Honey, J.G., and Hettinger, R.D., 1989, Cross section showing correlations of Upper Cretaceous Fox Hills Sandstone and Lance Formation, and lower Tertiary Fort Union and Wasatch Formations, southeastern Washakie Basin, Wyoming, and eastern Sand Wash Basin, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1964.

Irwin, C.D., 1986, Upper Cretaceous and Tertiary cross sections, Moffat County, Colorado, *in* Stone, D.S., and Johnson, K.S., eds., New Interpretations of Northwest Colorado Geology: Rocky Mountain Association of Geologists, p. 151–156.

Isaacson, L.B., and Smithson, S.B., 1976, Gravity anomalies and granite emplacement in west-central Colorado: Geological Society of America Bulletin, v. 87, p. 22–28.

Izett, G.A., 1966, Tertiary extrusive volcanic rocks in Middle Park, Grand County, Colorado: U.S. Geological Survey Professional Paper 550-B, p. 42–46.

———1968, Geology of the Hot Sulphur Springs quadrangle, Grand County, Colorado: U.S. Geological Survey Professional Paper 586, 79 p.

———1975, Late Cenozoic sedimentation and deformation in northern Colorado and adjoining areas, *in* Curtis, B.F., ed., Cenozoic History of the Southern Rocky Mountains: Geological Society of America Memoir 144, p. 179–209.

Izett, G.A., and Barclay, C.S.V., 1973, Geologic map of the Kremmling quadrangle, Grand County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-115.

Jackson, L.L., Geiser, L., Blett, T., Gries, C., and Haddow, D., Biogeochemistry of lichens and mosses in and near Mt. Zirkel Wilderness, Routt National Forest, Colorado: U.S. Geological Survey Open-File Report 96-295, 162 p.

Johnson, R.A., Karlstrom, K.E., Smithson, S.B., and Houston, R.S., 1984, Gravity profiles across the Cheyenne belt, a Precambrian crustal suture in southeastern Wyoming: Journal of Geodynamics, v.1, no. 3–5, p. 445–472.

Johnson, S.Y., Otton, J.K., and Macke, D.L., 1987, Geology of the Holocene surficial uranium deposit of the north fork of Flodelle Creek, northeastern Washington: Geological Society of America Bulletin, v. 98, p. 77–85.

Kaiser, W.R., 1993, Abnormal pressure in coal basins of the western United States, *in* Proceedings of the 1993 International Coalbed Methane Symposium, p. 173–186.

Kaiser, W.R., Scott, D.S., Hamilton, D.S., Tyler, R., McMurry, R.G., and Zhou, N., 1993, Geologic and hydrologic controls on coalbed methane: Sand Wash Basin, Colorado and Wyoming: GRI Topical Report GRI-92/0420, 151 p.

Karimpour, M.H., 1982, Petrology, geochemistry, and genesis of the A.O. porphyry copper complex in Jackson and Grand Counties, northwestern Colorado: Boulder, University of Colorado, M.S. thesis, 251 p.

Karimpour, M.H., and Atkinson, W.W., Jr., 1983, Petrogenesis of the A.O. porphyry copper complex in Jackson and Grand Counties, northwestern Colorado: Global Tectonics and Metallogeny, v. 2, p. 15–27.

Keystone Coal Industry Manual, 1993: Chicago, Ill., MacLean-Hunter Publishing Company, 1004 p.

Khalsa, N.S., and Ladwig, L.R., 1981, Colorado Coal Analyses 1976–1979: Colorado Geological Survey Information Series 10, 364 p.

Kinney, D.M., 1970, Preliminary geologic map of the Rand 15' quadrangle, North and Middle Parks, Jackson and Grand Counties, Colorado: U.S. Geological Survey Open-File Report 70-183, 1 sheet.

Kinney, D.M., and Hail, W.J., 1970, Preliminary geologic map of the Hyannis Peak quadrangle, North and Middle Parks, Jackson and Grand Counties, Colorado: U.S. Geological Survey Open-File Report 70-184, 1 sheet.

Kinney, D.M., Izett, G.A., King, R.U., and Taylor, R.B., 1968, The Poison Ridge volcanic center and related mineralization, Grand and Jackson Counties, Colorado: U.S. Geological Survey Circular 594, 8 p.

Klipfel, P.D., 1992, Geology and metallogeny of the southern portion of the Encampment district, Wyoming: Golden, Colorado School of Mines, Ph.D. thesis, T-4080, 244 p.

LKB Resources, Inc., 1979, NURE aerial gamma-ray and magnetic reconnaissance survey, Colorado-Arizona area, Craig NK 13-10 quadrangle: U.S. Department of Energy, Grand Junction Office Report GJBX-153(79), 2 vols., scale 1:500,000.

Lakes, Arthur, 1909, The Hahns Peak mining region, Routt County, Colorado: The Mountain States Mineral Age, July, 1927, p. 10–14.

Landis, E.R., 1959, Coal resources of Colorado, *in* Contributions to Economic Geology: U.S. Geological Survey Bulletin 1072-C, p. 131–232.

Law, B.E., 1984, Relationships of source-rock, thermal maturity, and overpressuring to gas generation and occurrence in low-permeability Upper Cretaceous and lower Tertiary rocks, greater Green River Basin, Wyoming, Colorado, and Utah, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 469–490.

Law, B.E., and Spencer, C.W., 1993, Gas in tight reservoirs—An emerging major source of energy, *in* Howell, D.G. ed., The Future of Energy Gases: U.S. Geological Survey Professional Paper 1570, p. 233–252.

Lillegraven, J.A., and Ostresh, L.M., Jr., 1990, Late Cretaceous (earliest Campanian/Maastrichtian) evolution of western shorelines of the North American Western Interior Seaway in relation to known mammalian faunas, *in* Bown, T.M., and

Rose, K.D., eds., Dawn of the Age of Mammals in the Northern Part of the Rocky Mountain Interior: Geological Society of America Special Paper 243, p. 1–30.

Lovering, T.S., 1935, Geology and ore deposits of the Montezuma quadrangle, Colorado: U.S. Geological Survey Professional Paper 178, 119 p.

Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Economic Geology, v. 65, p. 373–408.

Malan, R.C., 1957, Geology of uranium occurrences in North and Middle Parks, Colorado, *in* Guidebook to the Geology of North and Middle Parks Basin, Colorado: Rocky Mountain Association of Geologists, 11th Annual Field Conference: p. 126–136.

Mallory, W.W., 1971, The Eagle Valley evaporite, northwest Colorado—A regional synthesis: U.S. Geological Survey Bulletin 1311-E, 30 p.

Mallory, W.W., Post, E.V., Ruane, P.J., Lehmbeck, W.L., and Stotelmeyer, R.B., 1966, Mineral resources of the Flat Tops Primitive Area, Colorado: U.S. Geological Survey Bulletin 1230-C, 30 p.

Maughan, E.K., 1988, Geology and petroleum potential, Colorado Park Basin province, north-central Colorado: U.S. Geological Survey Open-File Report 88-450 E, 35 p.

McCallum, M.E., and Orback, C.J., 1968, The New Rambler copper-gold-platinum district, Albany and Carbon Counties, Wyoming: Geological Survey of Wyoming Preliminary Report no. 8, 12 p.

McCord, J.P., 1984, Geologic overview, coal, and coalbed methane resources of the Greater Green River coal region—Wyoming and Colorado, *in* Rightmire, C.T., Eddy, G.E., and Kirr, J.N., eds., Coal-Bed Methane Resources of the United States: American Association of Petroleum Geologists Studies in Geology Series no. 17, p. 271–293.

Menzie, W.D., and D.A. Singer, 1990, A course on mineral resource assessment: Proceedings of the International symposium on Mineral Exploration—The case of artificial intelligence: Tokyo and Tsukuba, Japan, Mining and Materials Processing Institute of Japan, p. 177–188.

Metzger, C.W., 1974, Geology, mineralization, and geochemistry of the upper Illinois River drainage basin, Grand and Jackson Counties, Colorado: Golden, Colorado School of Mines, M.S. thesis, 92 p.

Mooney, W.D., 1991, Continental crustal evolution during the Archean and Proterozoic; evidence from crustal seismology: Geophysical Journal International, v. 104, no. 3, p. 669.

Moss, C.K., and Abrams, Gerda, 1985, Geophysical maps of the Vasquez Peak Wilderness Study Area, and the Williams Fork and St. Louis Peak Roadless Areas, Clear Creek, Grand, and Summit Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1588-D, scale 1:50,000.

Motooka, J.M., Curtis, C.A., McDougal, C.H., Pearson, R.C., and McCallum, M.E., 1979, Geochemical analyses of rocks and stream sediments of the Rawah Wilderness and nearby Wilderness Study Areas, Jackson and Larimer Counties, Colorado: U.S. Geological Survey Open-File Report 79-1502, 79 p.

Murray, D.K., 1980, 1979 Summary of coal resources in Colorado: Colorado Geological Survey Special Publication 13, 24 p.

Naeser, C.W., Izett, G.A., and White, W.H., 1973, Zircon fission-track ages from some middle Tertiary igneous rocks in northwestern Colorado [abs.]: Geological Society of America Abstract with Programs, p. 498.

Nash, J.T., Granger, H.C., and Adams, S.S., 1981, Geology and concepts of genesis of important types of uranium deposits, *in* Skinner, B.J., ed., Economic Geology, 75th Anniversary Volume: El Paso, Texas, Economic Geology Publishing Company, p. 63–116.

Neubert, J.T., 1994, Mineral appraisal of Routt National Forest, Colorado *with a section on* Industrial minerals by J.S. Dersch, U.S. Forest Service: U.S. Bureau of Mines Open-File Report MLA 13-94, 103 p., 2 plates.

Nuccio, V.F., and Schenk, C.J., 1986, Thermal maturity and hydrocarbon source-rock potential of the Eagle Basin, northwestern Colorado, *in* Stone, D.S., ed., New Interpretations of Northwest Colorado Geology: Rocky Mountain Association of Geologists, p. 259–264.

Orris, G.J., and Bliss, J.D., 1986, Grade and tonnage model of placer Au-PGE, *in* Cox, D.P., and Singer, D.A., eds., Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, p. 261–264.

———1991, Grade and tonnage models for industrial mineral deposits: U.S. Geological Survey Open File Report 91-11B. 70 p.

Owen, D.E., Otton, J.K., Hills, F.A., and Schumann, R.R., 1992, Uranium and other elements in Colorado Rocky Mountain wetlands–A reconnaissance study: U.S. Geological Survey Bulletin 1992, 33 p.

Parker, B.H., Jr., 1961, The geology of the gold placers of Colorado: Golden, Colorado School of Mines, Ph.D. dissertation, 578 p.

———1974, Gold placers of Colorado: Quarterly of the Colorado School of Mines, v. 69, no. 4, book 2, 224 p.

Parker, R.L., 1967, Composition of the Earth's crust, chap. D, *in* Fleischer, Michael, ed., Data of Geochemistry, Sixth Edition: U.S. Geological Survey Professional Paper 440-D, p. D1–D19.

Patten, L.L., 1987, Mine appraisal, *in* Snyder, G.L., Patten, L.L., and Daniels, J.J., Mineral Resources of the Mount Zirkel Wilderness and Northern Park Range Vicinity, Jackson and Routt Counties, Colorado: U.S. Geological Survey Bulletin 1554-B, p. 58–107.

Pearl, R.H., 1979, Colorado's hydrothermal resource base—An assessment: Colorado Geological Survey Resource Series 6, 144 p.

Pearl, R.H., Zacharakis, T.G., and Ringrose, C.D., 1983, Geothermal resource assessment of the Steamboat–Routt Hot Springs area, Colorado: Colorado Geological Survey Resource Series 22, 86 p.

Pearson, R.C., and U.S. Bureau of Mines, 1980, Mineral resources of the Indian Peaks Study Area, Boulder and Grand Counties, Colorado, *with a section on* Interpretation of aeromagnetic data by Gordon Johnson: U.S. Geological Survey Bulletin 1463, 109 p.

Pearson, R.C., Braddock, W.A., Flanigan, V.J. and Patten, L.L., 1981, Mineral resources of the Comanche–Big South, Neota–Flat Top, and Never Summer Wilderness Study Areas, north-central Colorado: U.S. Geological Survey Open-File Report 81-578, 73 p.

Pearson, R.C., and Johnson, G., 1980, Mineral resources of the Indian Peaks Study Area, Boulder and Grand Counties, Colorado: U.S. Geological Survey Bulletin 1463, 109 p.

Pearson, R.C., McCallum, M.E., Griswold, M.L., and Patten, L.L., 1982, Mineral resources of the Rawah Wilderness, Larimer County, Colorado, *with a section on* Interpretation of aeromagnetic data by V.J. Flanigan: U.S. Geological Survey Open-File Report 82-376, 27 p.

Phillips, J.D., Duval, J.S., and Ambroziak, R.A., 1993, National geophysical data grids: Gamma-ray, gravity, magnetic, and topographic data for the conterminous United States: U.S. Geological Survey Digital Data Series DDS-9, 1 CD-ROM.

Planner, H.N., Apel, C.T., Fuka, M.A., George, W.E., Hansel, J.M., Hensley, W.K., and Pirtle, June, 1981, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Leadville NTMS quadrangle, Colorado, including concentrations of forty-two additional elements: Los Alamos, NM, Los Alamos Scientific Laboratory informal report LA-8013-MS, Grand Junction, CO, U.S. Department of Energy, GJBX-13(81), 185 p.

Plouff, Donald, 1961, Gravity profile along the Roberts tunnel, Colorado: U.S. Geological Survey Professional Paper 424-C, p. C263–C265.

Plumlee, G.S., Smith, S.M., Toth, M.I., and Marsh, S.P., 1993, Integrated mineral resource and mineral environmental assessments of public lands: Applications for land management and resource planning: U.S. Geological Survey Open-File Report 93-571, 18 p.

Pratt, W.P., and Zietz, Isidore, 1973, Geologic interpretation of Colorado aeromagnetic map, *in* U.S. Geological Survey Research 1973: U.S. Geological Survey Professional Paper 850, p. 50.

Prodehl, Claus, and Lipman, P.W., 1989, Crustal structure of the Rocky Mountain region, *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical Framework of the Continental United States: Geological Society of America Memoir 172, p. 249–284.

Reed, J.C., Bryant, Bruce, and Sims, P.K., 1993, Geology and mineral resources of central Colorado: Colorado School of Mines Quarterly Review, v. 93, no. 1, p. 7–16.

Rice, D.D., Law, B.E., and Clayton, J.L., 1993, Coal-bed gas—An undeveloped resource, *in* Howell, D.G., ed., The Future of Energy Gases: U.S. Geological Survey Professional Paper 1570, p. 389–404.

Rocky Mountain News, November 28, 1993, Evidence of ancient miners abounds on ridge near Steamboat, p. 33A.

———September 1, 1994, Visibility study launched, p. 24A.

———September 6, 1994, Scientists study lichens for signs of pollution, p. 70A.

Roehler, H.W., and Hansen, D.E., 1989, Surface and subsurface correlations showing depositional environments of the Upper Cretaceous Mesaverde Group and associated formations, Cow Creek in southwest Wyoming to Mt. Harris in northwest Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2077.

Root, D.H., and Scott, W.A., 1988, User manual for mineral simulation program: U.S. Geological Survey Open File Report 88-15, 64 p.

Root, D.H., Menzie, W.D., and Scott, W.A., 1992, Computer Monte Carlo simulation in quantitative resource estimation: Journal of Nonrenewable Resources, p. 125–138.

Sangster, D.F., 1972, Precambrian volcanogenic massive sulphide deposits in Canada: A review: Geological Survey of Canada Paper 72-22, 44 p.

Schmidt, P.W., Lovering, T.G., and Kleunder, S.E., 1984, Geologic and mineral resource potential map of the Service Creek Roadless area, Routt County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1639, scale 1:48,000.

Schwochow, S.D., 1981, Inventory of non-metallic mining and processing operations in Colorado: Colorado Geological Survey Map Series 17, scale 1:250,000, 39 p.

Scott, A.R., 1993, Coal rank, gas content, and composition and origin of coalbed gases, Fort Union Formation, Sand Wash Basin, *in* Kaiser, W.R., Scott, A.R., Hamilton, D.S., Tyler, R., McMurry, R.G., Zhou, N., and Tremain, C.M., eds., Geologic and Hydrologic Controls on Coal-Bed Methane—Sand Wash Basin, Colorado and Wyoming: Gas Research Institute Topical Report GRI-92/0420, p. 107–113.

Segerstrom, Kenneth, and Young, E.J., 1972, General geology of the Hahns Peak and Farwell Mountain quadrangles, Routt County, Colorado, *with a discussion of* Triassic and Jurassic rocks, by G.N. Pipiringos: U.S. Geological Survey Bulletin 1349, 63 p.

Shannon, S.S., Jr., Gallimore, D.L., Martell, C.J., Hensley, W.K., Jackson, C.K., and Macdonell, C.J., 1981, Detailed uranium geochemical stream sediment survey data release for the selected portions of the Craig NTMS quadrangle, Colorado, and Rawlins NTMS quadrangle, Wyoming, including concentrations of forty-five additional elements: Los Alamos, NM, Los Alamos Scientific Laboratory informal report LA-8481-MS, Grand Junction, CO, U.S. Department of Energy, GJBX-216(81), 132 p.

Sharps, S.L., 1962, Geology of the Pagoda quadrangle, northwestern Colorado: Boulder, Colo., University of Colorado, Ph.D. thesis, 282 p.

Shawe, D.R., 1981, U.S. Geological Survey workshop on non-fuel mineral resource appraisal of Wilderness and CUSMAP areas: U.S. Geological Survey Circular 845, 18 p.

Sheridan, D.M., Raymond, W.H., Taylor, R.B., and Hasler, J.W., 1990, Metallogenic map of stratabound exhalative and related occurrences in Colorado: U.S. Geological Survey Miscellaneous Investigation Series Map I-1971, scale 1:1,000,000.

Shettel, D.L., Jr., Langfeldt, S.L., Youngquist, C.A., D'Andrea, R.F., Jr., Zinkl, R.J., Garcia, S.R., Hanks, D., George, W.E. and Bolivar, S.L., 1981, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Denver NTMS quadrangle, Colorado: U.S. Department of Energy, Grand Junction, CO, GJBX-263(81), 153 p.

Siepman, B.R., 1986, Facies relationships in Campanian wave-dominated coastal deposits in Sand Wash Basin, *in* Stone, D.S., and Johnson, K.S., eds., New Interpretations of Northwest Colorado Geology: Rocky Mountain Association of Geologists, p. 157–164.

Singer, D.A., 1992, Grade and tonnage model of Sierran Kuroko deposits, U.S. Geological Survey Bulletin 2004, p. 29–32.

———1993, Basic concepts in three-part quantitative assessments of undiscovered resources: Nonrenewable Resources v. 2, no. 2, p. 69–81.

Singer, D.A., and Cox, D.P., 1987, Applications of mineral deposit models to mineral resource assessments: U.S. Geological Survey Yearbook, Fiscal Year 1987, p. 55–57.

Singer, D.A., and Mosier, D.L., 1986, Applications of mineral deposit models to resource assessments: U.S. Geological Survey Yearbook, Fiscal Year 1987 p. 55–57.

Singer, D.A., Mosier, D.L., and Cox, D.P., 1986, Grade and tonnage model of Porphyry Cu, *in* Cox, D.P., and Singer, D.A. eds., Mineral Deposit Models, U.S. Geological Survey Bulletin, 1693, p. 77–81.

Singer, D.A., and Ovenshine, A.T., 1979, Assessing mineral resources in Alaska: American Scientist, v. 67, p. 582–589.

Snyder, G.L., 1980a, Generalized map showing Precambrian rocks and metamorphic facies, keyed to aluminosilicate minerals in meta-shales with excess alumina, northern Park Range, Colorado: U.S. Geological Survey Open-File Report 80-787.

———1980b, Geologic map of the central part of the northern Park Range, Jackson, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1112, scale 1:48,000.

———1980c, Geologic map of the northernmost Gore Range and the southernmost northern Park Range, Grand, Jackson, and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1114.

———1980d, Geologic map of the northernmost Park Range and southernmost Sierra Madre, Jackson and Routt Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1113.

———1987a, Evaluation of surface metallic and nonmetallic resource potential, *in* Snyder, G.L., Patten, L.L., and Daniels, J.J., Mineral Resources of the Mount Zirkel Wilderness and Northern Park Range Vicinity, Jackson and Routt Counties, Colorado: U.S. Geological Survey Bulletin 1554-C, p. 109–213.

———1987b, Geologic appraisal, *in* Snyder, G.L., Patten, L.L., and Daniels, J.J., Mineral Resources of the Mount Zirkel Wilderness and Northern Park Range Vicinity, Jackson and Routt Counties, Colorado: U.S. Geological Survey Bulletin 1554-A, p. 13–55.

Snyder, G.L., Hopkins, R.T., Jr., Domenico, J.A., Frisken, J.G., and Mitchell, J., 1981, Analyses of rock and stream sediment samples from the Mount Zirkel Wilderness and northern Park Range vicinity, Jackson and Routt Counties, Colorado: U.S. Geological Survey Open-File Report 81-186, 85 p.

Spicker, F.A., 1973, The geology, alteration, and mineralization of Parkview Mountain, Grand and Jackson Counties, Colorado: Fort Collins, Colorado State University, M.S. thesis, 96 p.

Steven, T.A., 1960, Geology and fluorspar deposits, Northgate district, Colorado: U.S. Geological Survey Bulletin 1082-F, 422 p.

Sweeney, R.E., 1990, IGRFGRID—A program for creation of a total magnetic field (International Geomagnetic Reference Field) grid representing the Earth's main magnetic field: U.S. Geological Survey Open-File Report 90-45A-B.

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

Taylor, R.B., Stoneman, R.J., and Marsh, S.P., 1984, An assessment of the mineral resource potential of the San Isabel National Forest, south-central Colorado, *with a section on* salable minerals by J.S. Dersch: U.S. Geological Survey Bulletin B-1638, 42 p.

Theobald, P.K., Bielski, A.M., Eppinger, R.G., Moss, C.K., Kreidler, T.J., and Barton, H.N., 1985, Mineral resource potential map of the Vasquez Peak Wilderness Study Area, and the Williams Fork and St. Louis Peak Roadless Areas, Clear Creek, Grand, and Summit Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1588-A, scale 1:50,000.

Tremain, C.M., 1990, Coalbed methane development in Colorado: Colorado Geological Survey, Information Series 32, 35 p.

Trexler, P.K., 1978, Uranium hydrogeochemical and stream sediment reconnaissance of the Cheyenne NTMS quadrangle, Wyoming: Los Alamos, NM, Los Alamos Scientific Laboratory informal report LA-7237-MS, Grand Junction, CO, U.S. Department of Energy, GJBX-106(78), 67 p.

Turk, J.T., and Campbell, D.H., 1987, Estimates of acidification of lakes in the Mt. Zirkel Wilderness Area, Colorado: Water Resources Research, v. 23, p. 1757–1761.

Turk, J.T., Campbell, D.H., Ingersoll, G.P., and Clow, D.A., 1992, Initial findings of synoptic snowpack sampling in the Colorado Rocky Mountains: U.S. Geological Survey Open-File Report 92-645, 6 p.

Turk, J.T., Campbell, D.H., and Spahr, N.E., 1993, Use of chemistry and stable sulfur isotopes to determine sources of trends in sulfate of Colorado lakes: Water, Air and Soil Pollution, v. 67, p. 415–431.

Turner-Peterson, C.E., and Fishman, N.S., 1986, Geologic synthesis and genetic models for uranium mineralization, Grants uranium region, New Mexico, *in*, Turner-Peterson, C.E., and Santos, E.S., eds., A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists Studies in Geology, no. 22.

Tweto, Ogden, 1968, Geologic setting and interrelationships of mineral deposits in the mountain province of Colorado and south-central Wyoming, *in* Ridge, J.D., ed., Ore Deposits of the United States 1933–1967: New York, New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 1, p. 551–558.

———1976, Geologic map of the Craig 1°× 2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-972, scale 1:250,000.

———1979, The Rio Grande rift system in Colorado, *in* Riecker, R.E., ed., Rio Grand Rift: Tectonics and Magmatism: Washington D.C., American Geophysical Union, p. 33–56.

———1980, Summary of Laramide orogeny in Colorado, *in* Kent, H.C., and Porter, K.W., Colorado Geology: Rocky Mountain Association of Geologists, p. 129–134.

———1987, Rock units of the Precambrain basement in Colorado: U.S. Geological Survey Professional Paper 1321-A, 54 p.

Tweto, Ogden, Bryant, Bruce, and Williams, F.E., 1970, Mineral resources of the Gore Range–Eagles Nest Primitive Area and vicinity, Summit and Eagle Counties, Colorado: U.S. Geological Survey Bulletin 1319-C, 127 p.

Tweto, Ogden, and Case, J.E., 1972, Gravity and magnetic features as related to geology in the Leadville 30-minute quadrangle, Colorado: U.S. Geological Survey Professional Paper 726-C, 31 p.

Tweto, Ogden, and Sims, P.K., 1963, Precambrian ancestry of the Colorado Mineral Belt: Geological Society of America Bulletin, v. 74, p. 991–1014.

Tweto, Ogden, Moench, R.H., and Reed, J.C., Jr., 1978, Geologic map of the Leadville 1°×2° quadrangle, northwestern

Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-999, scale 1:250,000.

Tyler, R., and McMurry, R.C., 1993, Stratigraphy and coal occurrence of the Paleocene Fort Union Formation, Sand Wash Basin, *in* Kaiser, W.R., Scott, A.R., Hamilton, D.S., Tyler, R., McMurry, R.G., Zhou, N., and Tremain, C.M., eds., Geologic and Hydrologic Controls on Coal-Bed Methane—Sand Wash Basin, Colorado and Wyoming: Gas Research Institute Topical Report GRI-92/0420, p. 79–106.

Tyler, R., and Tremain, C.M. 1993, Tectonic evolution , stratigraphic setting, and coal fracture patterns of the Sand Wash Basin, *in* Kaiser, W.R., Scott, A.R., Hamilton, D.S., Tyler, R., McMurry, R.G., Zhou, N., and Tremain, C.M., eds., Geologic and Hydrologic Controls on Coal-Bed Methane—Sand Wash Basin, Colorado and Wyoming: Gas Research Institute Topical Report GRI-92/0420, p. 3–19.

U.S. Bureau of Mines, 1993, Mineral Commodity Summaries, 202 p.

U.S. Geological Survey, 1968, Aeromagnetic map of the Wolcott-Boulder area, north-central Colorado: U.S. Geological Survey Open-File Report 68-295, scale 1:125,000.

———1978, Aeromagnetic map of North Park and vicinity, Colorado: U.S. Geological Survey Open-File Report 78-112, scale 1:125,000.

U.S. Geological Survey and Colorado Geological Survey, 1977, Energy resources of Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1039.

Vanderwilt, J.W., 1947, Mineral resources of Colorado: Denver, State of Colorado Mineral Resources Board, 547 p.

Waechter, N.B., and Johnson, W.E., 1986, Pennsylvanian-Permian paleostructure and stratigraphy as interpreted from seismic data in the Piceance Basin, northwest Colorado: Rocky Mountain Association of Geologists, p. 51–64.

Wallace, A.R., 1990, Regional geologic and tectonic setting of the central Colorado Mineral Belt, *in*, Beaty, D.W., Landis, G.P., and Thompson, T.B., eds., Carbonate-Hosted Sulfide Deposits of the Central Colorado Mineral Belt: Economic Geology Monograph 7, p. 19–28.

Wallace A.R., and Karlson, R.C., 1985, The Schwartzwalder uranium deposit, I: Geology and structural controls on mineralization: Economic Geology, v. 80, p. 1842–1857.

Warner, L.A., 1978, The Colorado lineament: A middle Precambrian wrench fault system: Geological Society of America Bulletin, v. 89, p. 161–171.

———1980, The Colorado lineament: Colorado Geology, 1980 Symposium of the Rocky Mountain Association of Geologists, p. 11–21.

Weaver, T.A., Morris, W.A., and Trexler, P.K., 1978, Uranium hydrogeochemical and stream sediment reconnaissance of the Rawlins NTMS quadrangle, Wyoming: Grand Junction, CO, U.S. Department of Energy, GJBX-81(78), 73 p.

Webring, M.W., 1981, MINC—A gridding program based on minimum curvature: U.S. Geological Survey Open-File Report 81-1224, 41 p.

White, W.H., Bookstrom, A.A., Kamilli, R.J., Ganster, M.W., Smith, R.P., Ranta, D.E., and Steininger, R.C., 1981, Character and origin of Climax-type molybdenum deposits, *in* Skinner, B.J., ed., Economic Geology 75th Anniversary Volume: El Paso, Texas, Economic Geology Publishing Company, p. 270–316.

Wood, G.H., Jr., Kehn, T.M., Carter, M.D., and Culbertson, W.C., 1983, Coal resource classification system of the U.S. Geological Survey: U.S. Geological Survey Circular 891, 65 p.

Yeend, W.E., 1986, Descriptive model of placer Au-PGE, *in* Cox, D.P., and Singer, D.A., eds., 1986, Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, p. 261.

Young, E.J., and Segerstrom, Kenneth, 1973, A disseminated silver-lead-zinc sulfide occurrence at Hahns Peak, Routt County, Colorado: U.S. Geological Survey Bulletin 1367, 33 p.

Youngquist, C.A., D'Andrea, R.F., Jr., Zinkl, R.J., Shettel, D.L., Jr., Langfeldt, S.L., Hensley, W.K., Thomas, G.J., Martell, C.J. and Maassen, L.W., 1981, Uranium hydrogeochemical and stream sediment reconnaissance of the Greeley NTMS quadrangle, Colorado: Grand Junction, CO, U.S. Department of Energy, GJBX-265(81).

Zietz, Isidore, Bateman, P.C., Case, J.E., Crittenden, M.D., Jr., Griscom, Andrew, King, E.R., Roberts, R.J., and Lorentzen, G.R., 1969, Aeromagnetic investigation of crustal structure for a strip across the Western United States: Geological Society of America Bulletin, v. 80, p. 1703–1714.

Published in the Central Region, Denver, Colorado
Manuscript approved for publication January 29, 1999
Edited by Richard W. Scott, Jr.
Graphics prepared by authors and Gayle M. Dumonceaux
Photocomposition by Gayle M. Dumonceaux

APPENDIXES

APPENDIX 1—GEOLOGIC TIME CHART

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

EON	ERA	PERIOD		EPOCH	AGE ESTIMATES OF BOUNDARIES (Ma*)
PHANEROZOIC	CENOZOIC	QUATERNARY		Holocene	0.010
				Pleistocene	1.7
		TERTIARY	Neogene subperiod	Pliocene	5
				Miocene	24
			Paleogene subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	MESOZOIC	CRETACEOUS		Late	96
				Early	138
		JURASSIC		Late Middle Early	205
		TRIASSIC		Late Middle Early	240
	PALEOZOIC	PERMIAN		Late Early	290
		CARBONIFEROUS PERIODS	PENNSYLVANIAN	Late Middle Early	330
			MISSISSIPPIAN	Late Early	360
		DEVONIAN		Late Middle Early	410
		SILURIAN		Late Middle Early	435
		ORDOVICIAN		Late Middle Early	500
		CAMBRIAN		Late Middle Early	570†
PROTEROZOIC	LATE PROTEROZOIC				900
	MIDDLE PROTEROZOIC				1,600
	EARLY PROTEROZOIC				2,500
ARCHEAN	LATE ARCHEAN				3,000
	MIDDLE ARCHEAN				3,400
	EARLY ARCHEAN				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.

APPENDIX 2—DEFINITIONS OF LEVELS OF MINERAL RESOURCE POTENTIAL AND CERTAINTY OF ASSESSMENT

DEFINITIONS OF MINERAL RESOURCE POTENTIAL

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

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

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

UNKNOWN mineral resource potential is assigned to areas where information is inadequate to assign low, moderate, or high levels of resource potential.

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

A. Available information is not adequate for determination of the level of mineral resource potential.

B. Available information suggests the level of mineral resource potential.

C. Available information gives a good indication of the level of mineral resource potential.

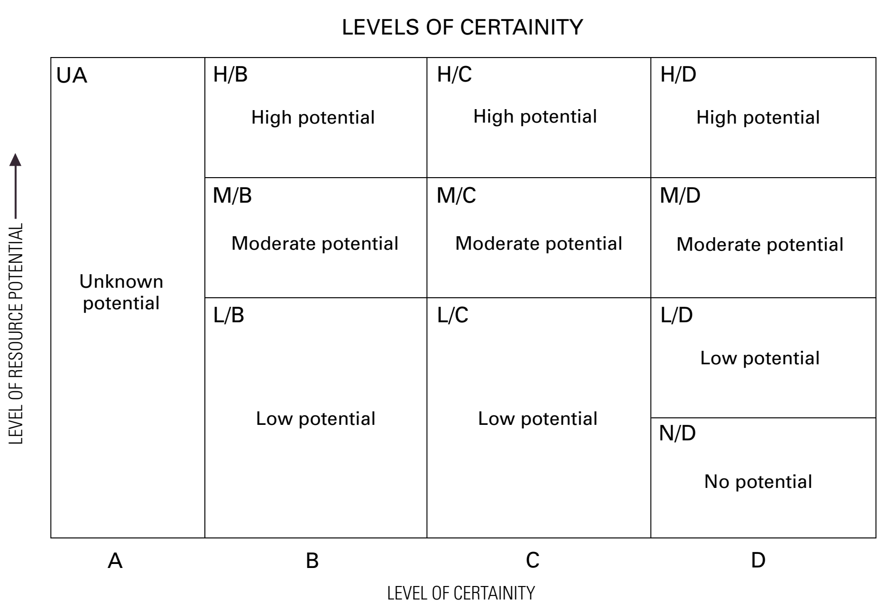
D. Available information clearly defines the level of mineral resource potential.

Abstracted with minor modifications from:

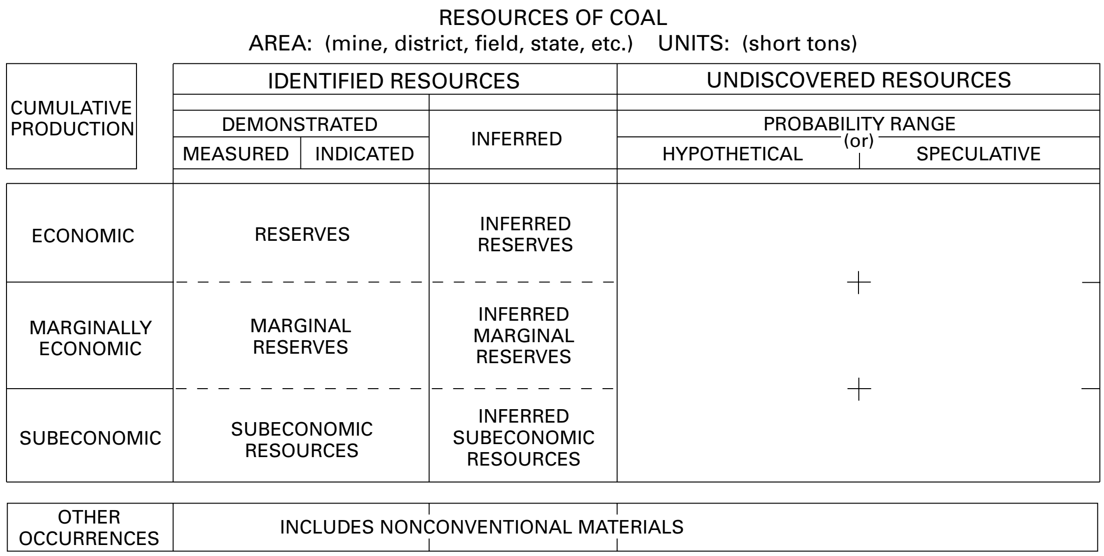
Goudarzi, G.H., compiler, 1984, Guide to preparation of mineral survey reports on public lands: U.S. Geological Survey Open-File Report 84-787, p. 7–8.

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

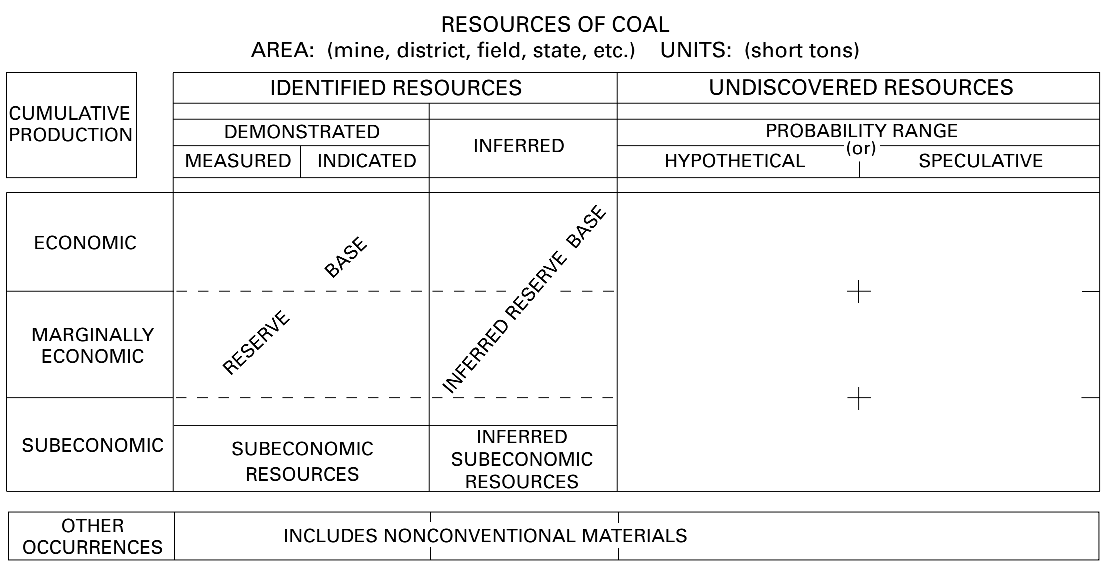
Taylor, R.B., Stoneman, R.J., and Marsh, S.P., 1984, An assessment of the mineral resource potential of the San Isabel National Forest, sout-central Colorado, *with a section on* salable minerals by J.S. Dersch: U.S. Geological Survey Bulletin 1638, p. 40–42.



APPENDIX 3—COAL RESOURCE CLASSIFICATION



A portion of reserves or any resource category may be restricted from extraction by laws or regulations.



A portion of reserves or any resource category may be restricted from extraction by laws or regulations.

APPENDIX 4—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 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 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 circumstances could be considered to have economic potential (Cox and others, 1986).

Mineral occurrence. A concentration of a mineral that is considered valuable 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).

APPENDIX 5—UNITS OF MEASUREMENT

The grade and tonnage curves used in this study contain grades either as grams or percent per metric ton. Thus the estimated amounts of metallic resources within an undiscovered deposit are reported in metric tons of metal. Other units of measurement are noted as they are reported. Conversion factors useful for this report include the following:

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