Mineral Resource Potential and Geology of the White River National Forest and the Dillon Ranger District of the Arapaho National Forest, Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 2035

MENT OF THE
U.S. DEPART
INTERIOR
MARCH 3, 1849

Mineral Resource Potential and Geology of the White River National Forest and the Dillon Ranger District of the Arapaho National Forest, Colorado

By MARGO I. TOTH, ANNA B. WILSON,
THERESA M. COOKRO, VIKI BANKEY,
GREG K. LEE, *and* JAMES E. CASE
U.S. Geological Survey

With a section on SALABLE COMMODITIES

By JOHN S. DERSCH
U.S. Forest Service

U.S. GEOLOGICAL SURVEY BULLETIN 2035

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1993

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For sale by
USGS Map Distribution
Box 25286, Building 810
Denver Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Mineral resource potential and geology of the White River National Forest and the Dillon Ranger District of the Arapaho National Forest, Colorado / by Margo I. Toth ... [et al.] ; with a section on Salable commodities by John S. Dersch.
p. cm. — (U.S. Geological Survey bulletin ; 2035)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:2035
1. Mines and mineral resources—Colorado—White River National Forest. 2. Mines and mineral resources—Colorado—Arapaho National Forest. 3. Geology—Colorado—White River National Forest. 4. Geology—Colorado—Arapaho National Forest. I. Toth, Margo I. II. Dersch, John S. III. Geological Survey (U.S.) IV. Series.
QE75.B9 no. 2035
[TN24.C6]
557.3 s—dc20
[553'.09788]

92–21943
CIP

USGS BULLETIN 2035: SELECTED RESULTS

Undiscovered Metallic Mineral Resources in the White River National Forest and Dillon Ranger District of the Arapaho National Forest ("the Forest")

Quantitative Probabilistic Mineral Resource Assessment by the U.S. Geological Survey (USGS)

This summary highlights the mineral resources of the Forest and is presented to aid land-use planners and other non-scientific personnel.

- This study was undertaken at the request of the U.S. Forest Service. The USGS assessment involved a team of six scientists with expertise in geology, geochemistry, geophysics, mineral deposits, and resource analysis.
- The Forest includes part of the Colorado Mineral Belt, one of the most productive areas of base and precious metals in North America.
- Mining and mineral exploration have played a central role in the history of the Forest since the early 1800's; several world-class mines are either in or adjacent to the Forest, and smaller mines are abundant throughout the Forest.
- More than $15 billion in metals (at current-day prices) has been produced in mining areas adjacent to or within the Forest.
- The last producing mine (Gilman mine) ceased its operations in 1981; current mineral-related activity consists of annual assessment work on unpatented mining claims, prospecting, and small-scale mining.
- Large tracts within the Forest, including Wilderness Areas, have abundant direct and indirect indications of the presence of metallic mineral deposits.
- Fourteen metallic mineral-deposit types were identified in the Forest; of these, stockwork molybdenum, polymetallic vein, polymetallic replacement, and placer gold deposits are the most likely to have undiscovered resources.
- The commodities most likely to occur are molybdenum, zinc, lead, silver, gold, and copper.
- Estimates of the number of undiscovered deposits were made at three probability levels (90, 50, and 10 percent); estimated tonnages were determined by statistical iteration with tonnages and grades of known deposits worldwide.
- Favorable tracts are shown in figure 1 of this report.
- Probabilistic estimates, which do not take into account the cost of recovery, indicate a mean value of $4.05 billion for undiscovered metallic mineral resources in the Forest (shown below).

Probabilistic estimates of gross in-place value (GIPV) of estimated undiscovered mineral deposits for four metallic mineral-deposit types in the Forest, in millions of U.S. dollars.

[Values are calculated using 5-year average metal prices for the years 1986–1991, data from U.S. Bureau of Mines (1992). Prices are not normalized to account for inflation. Estimates DO NOT imply that these resources would be economic to produce. Such a determination would require a complete analysis of both the costs of discovery and engineering feasibility and would require an economic evaluation of production]

Commodity	Probability of GIPV (in percent)			Mean
	90	50	10	GIPV
Molybdenum	0	1,725	9,000	3,225
Zinc	0	21	923	370
Lead	0	29	480	204
Silver	0	16	459	191
Gold	0	1	85	52
Copper	0	0	18	9
			Total	4,050

CONTENTS

PLATES

[Plates are in pocket]

FIGURES

TABLES

MINERAL RESOURCE POTENTIAL AND GEOLOGY OF THE WHITE RIVER NATIONAL FOREST AND THE DILLON RANGER DISTRICT OF THE ARAPAHO NATIONAL FOREST, COLORADO

By MARGO I. TOTH, ANNA B. WILSON, THERESA M. COOKRO, VIKI BANKEY, GREG K. LEE, *and* JAMES E. CASE
U.S. GEOLOGICAL SURVEY

With a section on Salable Commodities

By JOHN S. DERSCH
U.S. FOREST SERVICE

SUMMARY

This summary is presented in a non-technical format for the aid of land-use planners and other non-scientific personnel.

The assessment of the mineral resource potential of the White River National Forest and Dillon 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 Dillon Ranger District of the Arapaho National Forest is included in this report on the White River National Forest because the two areas are administered by the staff of the White River National Forest and are included in a single planning document.

This summary addresses the potential for undiscovered mineral and energy resources in the Forest. Geologic, geochemical, and geophysical data were compiled at a scale of 1:250,000, and, together with all available information on mineral deposits and occurrences, were used in assessing the mineral resource potential of the Forest as of July 1990 (figs. 1–3).

The White River National Forest and Dillon Ranger District of the Arapaho National Forest have a wealth of mineral resources. Mining and mineral exploration have played a central role in the history of this area and are still important. The world-class mine at Gilman is within the boundaries of the Forest, and world-class deposits are present just outside the Forest, in the Leadville mining district and at Climax and Red Mountain. Deposits of gold, silver, lead, zinc, copper, manganese, tungsten, iron, uranium, and vanadium have been exploited within the Forest, and there has been some production of the industrial minerals gypsum, dimension stone, crushed and lightweight aggregate, and sand and gravel. Coal, oil, and gas have been produced in the Forest, and geothermal waters from hot springs have recreational uses. Commercially important exploitation of mineral and energy resources in the future seems assured.

CHARACTER AND GEOLOGIC SETTING

The White River National Forest and the Dillon Ranger District of the Arapaho National Forest encompass about 2.4 million acres in central and northwestern Colorado (fig. 4). Eight distinct mountain ranges and parts or all of 10 counties are within the Forest. The topography in the Forest varies from valleys and plateaus to steep, rugged mountains. Altitude ranges from about 6,000 ft, near the western edge of the Forest, to 14,265 ft, at Castle Peak on the Continental Divide in the southern part of the Forest. The entire Forest is on the western side of the Continental Divide, which forms the eastern boundary of parts of the Forest in many places. Except

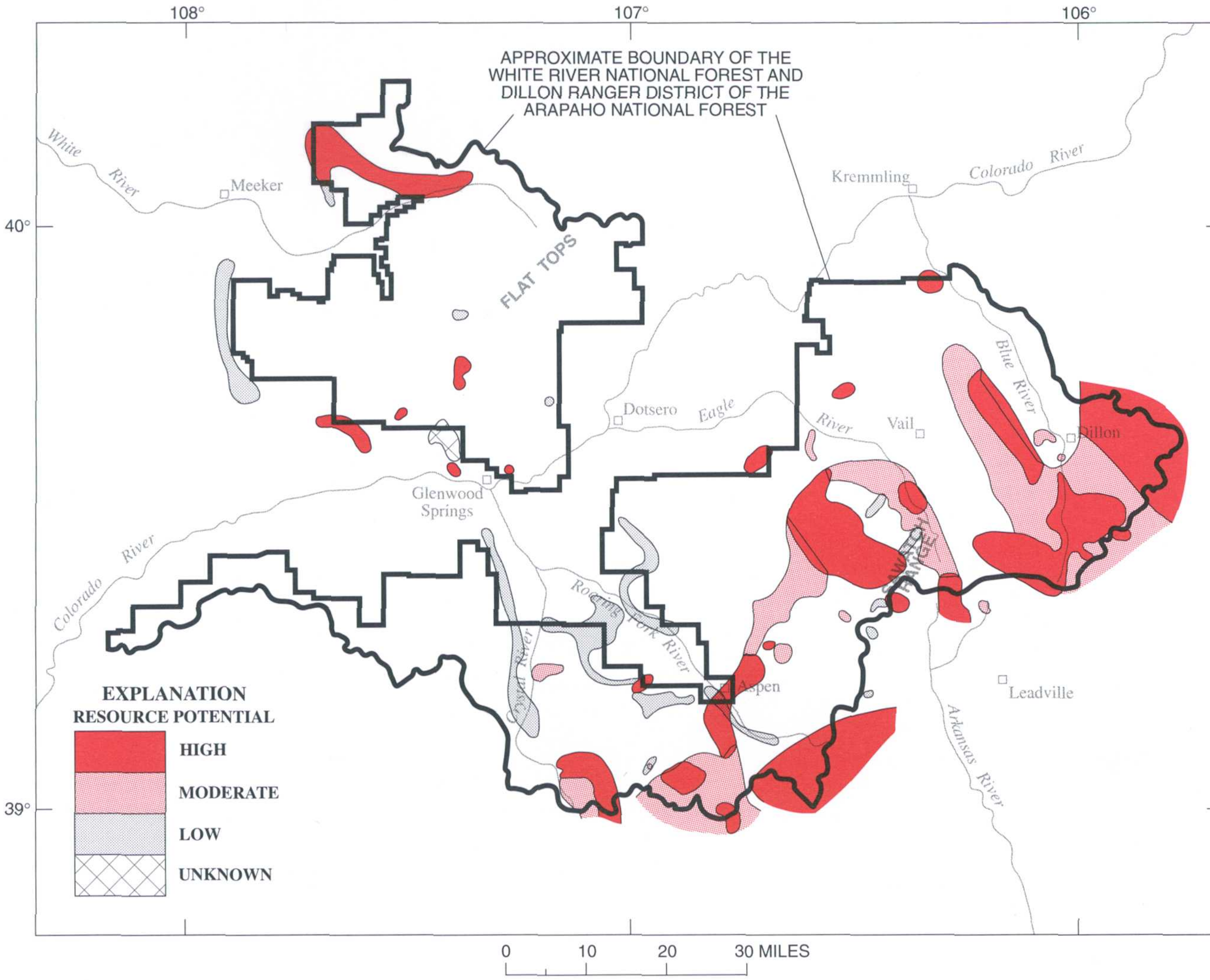


Figure 1. Mineral resource potential map for locatable commodities in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

for some water-diversion projects, the Forest watershed drains into the Colorado River, which flows southwest though central and western Colorado.

The geologic history of the Forest spans nearly 2 billion years. Sedimentary and volcanic rocks accumulated on the southern margin of a landmass, the Wyoming craton, and were metamorphosed at about 1.7 Ga (billion years ago). These metamorphic rocks were intruded by granitic magmas at approximately 1.7 and 1.4 Ga and, together with the granitic plutons, comprise the Proterozoic basement complex (see time chart in Appendix 1).

The next recorded event occurred almost 1 billion years later, in the early and middle Paleozoic. At this time, the basement complex was buried beneath a thick sequence of sediments that were deposited in shallow seaways. Mountain building in the late Paleozoic lifted two highlands as much as 10,000 ft above sea level. During this uplift, all the lower and middle Paleozoic rocks were stripped from the highlands, partially exposing the Proterozoic basement complex, and the Mississippian carbonate rocks that once covered the entire State were severely eroded. The Eagle Basin, a northwest-trending trough, formed between the two highlands, and sediments and evaporites were deposited or precipitated in the basin. Late Paleozoic alluvial fans and dune fields progressively covered these rocks.

Clastic sedimentation continued through the Triassic—erosion continued to strip the highlands, and sediments were deposited in various marginal-marine, stream, and lake environments. Inland seas episodically advanced and retreated across the area, depositing marine and nonmarine sediments during the Jurassic and Cretaceous.

The Laramide orogeny, an episode of mountain building, occurred during the Late Cretaceous. Uplift of the

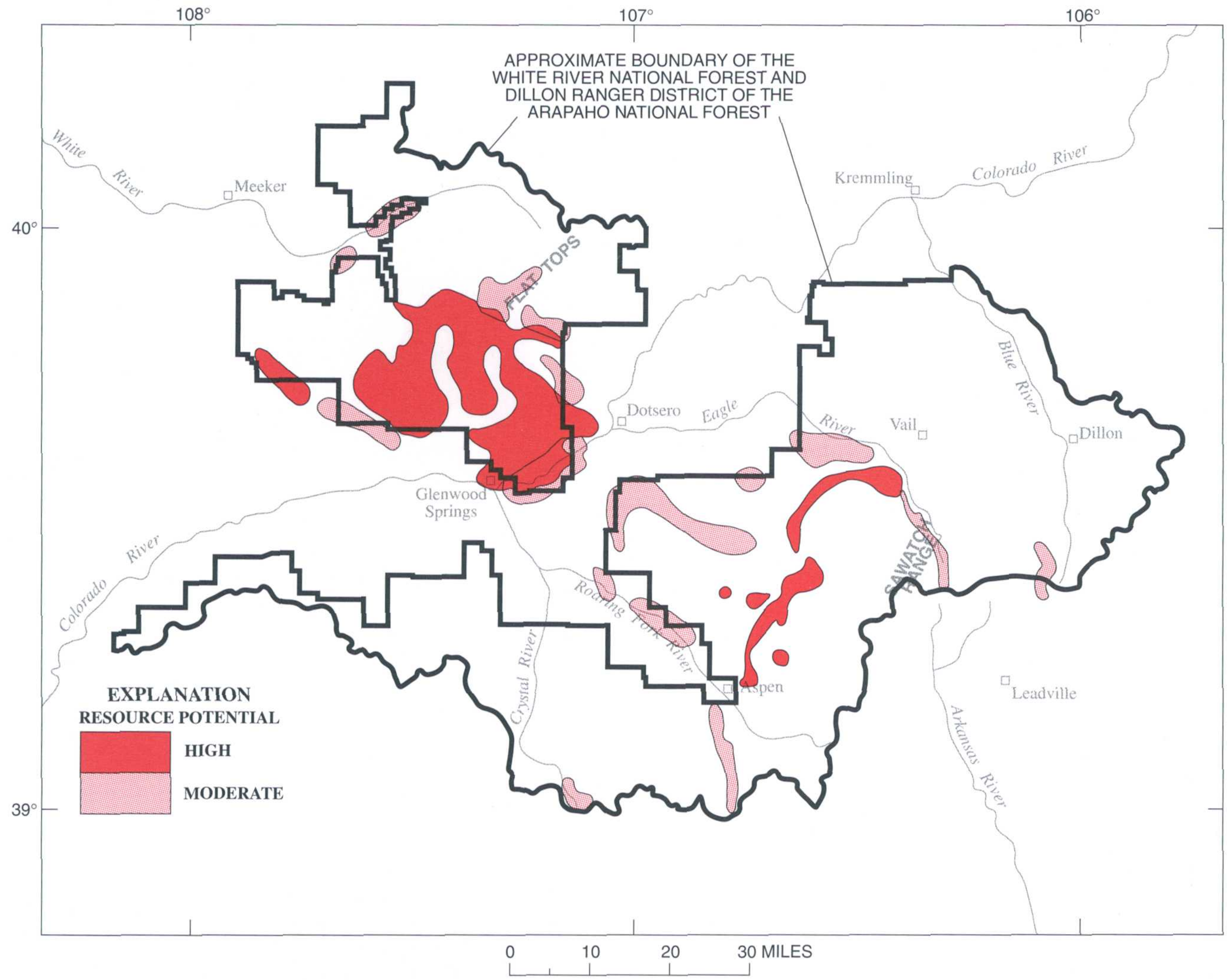


Figure 2. Mineral resource potential map for locatable industrial commodities in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

mountains forced the retreat of the seas, and streams eroded the sedimentary cover rocks and basement complex. Eocene clastic deposits accumulated in structural basins that formed during erosion and in lakes and channels of the fluvial systems that drained the area. Erosion and sedimentation gradually smoothed the mountainous terrane, creating an extensive, relatively flat, erosion surface.

Plutonic rocks were emplaced during the Laramide, from about 74 to 60 Ma (million years ago). The intrusions form a northeast-trending zone across the Forest of small to large granitic bodies in a variety of different shapes and forms. Later magmatism occurred during early Oligocene time, from about 39 to 34 Ma. This suite of rocks was similar to the Laramide granitic rocks but included minor volcanic rocks and was volumetrically more extensive than the Laramide-age granites. These younger intrusive rocks are associated with most of the mineral deposits in the Forest. Smaller amounts of granite were intruded from 29 to 12 Ma, and volcanic activity occurred from 24 to 8 Ma.

A period of climatic cooling resulted in glaciation that continued from about 500,000 years ago, in the Pleistocene, into the Holocene. Glacial erosion gouged into the flat erosion surface, forming the alpine topography observed today, with deep, U-shaped valleys and rugged relief.

MINERAL RESOURCES

Mineral resource potential information is given in terms of mineral-deposit types and their geologic settings. Deposit types are based on geologic characteristics of known deposits within or close to the Forest. Most of the deposit types are represented by type localities at a mine or within mining districts. A letter designation (A, B, C, and so on) is used in the

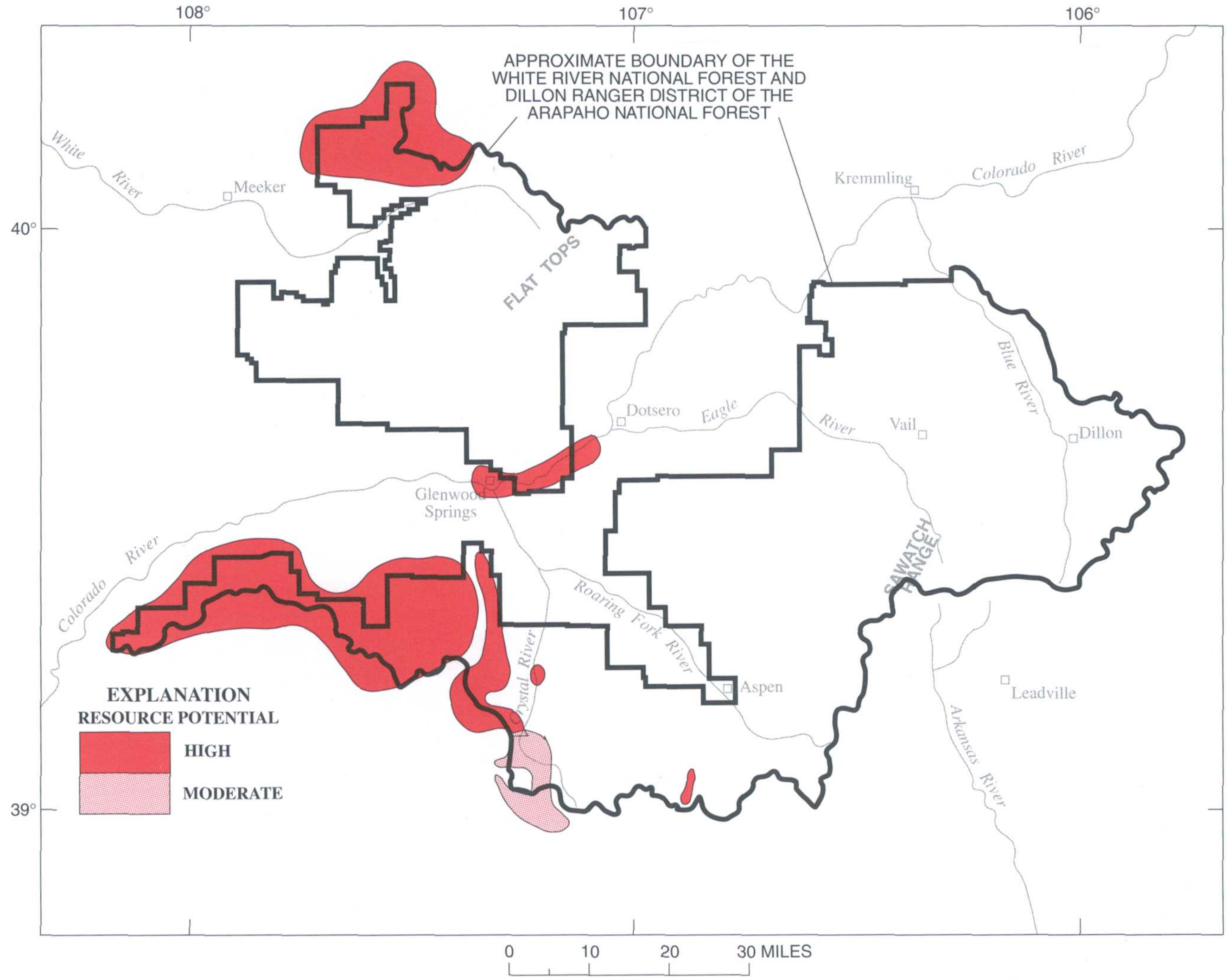


Figure 3. Mineral resource potential map for leasable commodities in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

text and on the various figures and plates to represent each deposit type. Definitions of terms used in the assessment of mineral resource potential for each deposit type are summarized in Appendix 2.

All available information was assembled and analyzed according to procedures outlined by Shawe (1981) and Taylor and Steven (1983). This study is based primarily on information from published literature but includes unpublished data from studies in progress.

The White River National Forest and the Dillon Ranger District of the Arapaho National Forest contain 26 mining districts and mineralized areas. Beginning in 1859, gold placers in the Breckenridge district were the first deposits to be worked. Gold placers were discovered a year later a few miles south of the Forest, at Leadville. These two areas include some of the richest placer deposits in Colorado.

Base- and precious-metal lode or vein deposits were discovered a few years after the gold placers. In the Forest, the first silver vein was discovered in the Montezuma mining district in 1864. In the next decade, lode deposits were discovered throughout the Colorado Mineral Belt (Tweto and Sims, 1963). In 1878, bonanza silver deposits were discovered in the Kokomo-Tenmile district; silver-lead ore was found at Gilman and in the Aspen district the next year. Most of the mining districts and major ore bodies had been discovered by the late 1800's.

The Gilman district, known for its copper and zinc, is the State's largest producer of metals. The Eagle mine consolidated many older mines and workings into a single operating unit in 1918 and was the major producer of metals. Next in overall production of metals within the Forest were the Aspen, Breckenridge, and Kokomo-Tenmile districts,

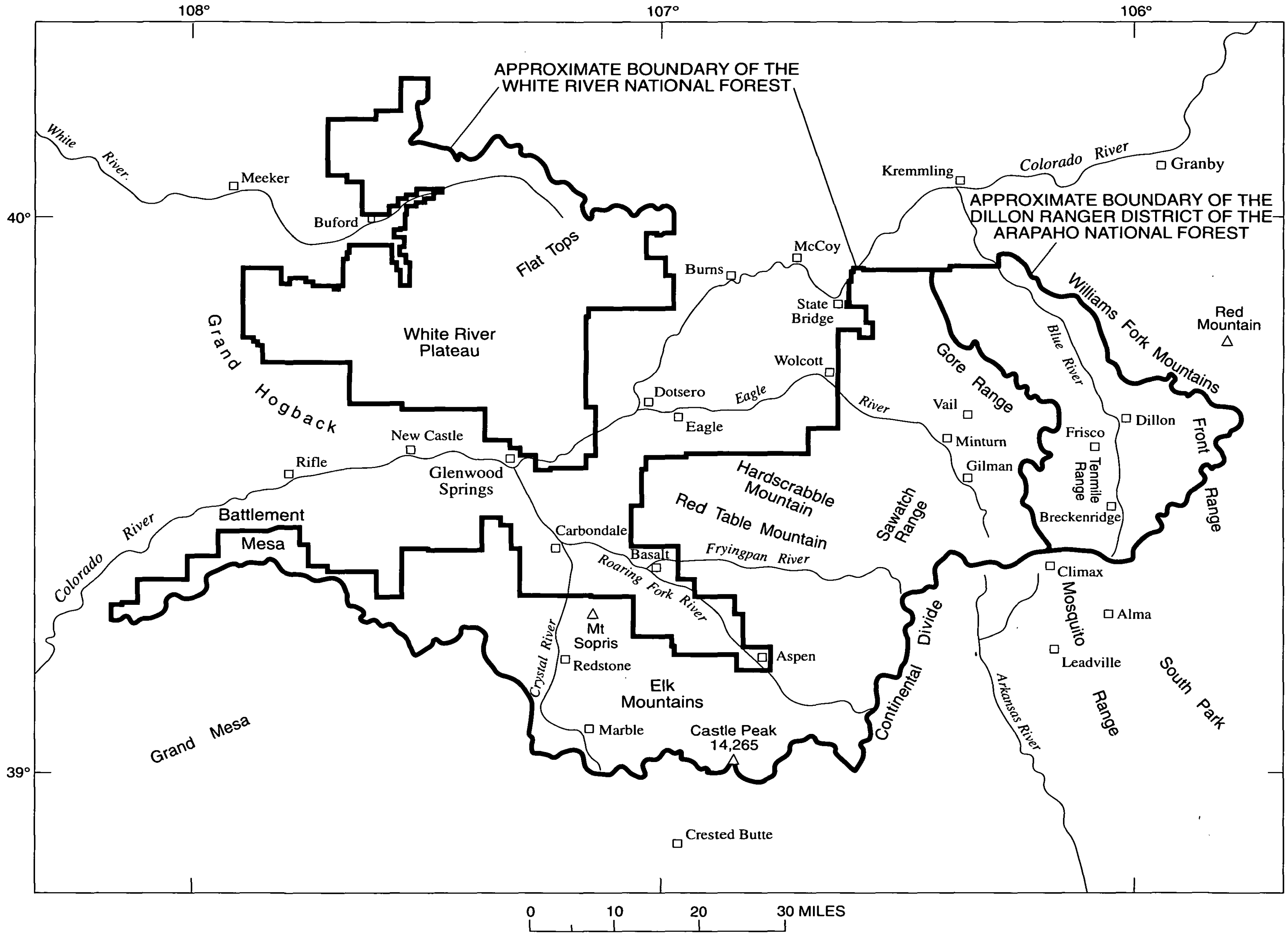


Figure 4. Index map showing the location of the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

Table 1. Resource potential of lands in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado, classified according to type of deposit.

[The White River National Forest and Dillon Ranger District of the Arapaho National Forest contain a total of 3.928 mi^2. Figures in columns under each category of resource potential in mi^2 and rounded to the nearest mi^2. Letters in parentheses preceding the deposit type indicate the deposit type as discussed in the text and listed in the table of contents. --, no area of resource potential for that category of resource potential]

Type of deposit	Mineral resource potential			
	High	Moderate	Low	Unknown
Locatable resources				
(A) Stockwork Mo	1	14	--	--
(B) Stockwork Cu-Mo	11	--	--	--
(C) Skarn	1	1	27	--
(D) Polymetallic replacement	82	111	1	--
(E) Sherman-type Pb-Zn-Ag	7	37	--	--
(F) Polymetallic vein	382	245	--	--
(G) Vein U	1	1	1	--
(H) Vein W	--	18	--	--
(I) Sandstone Cu	2	--	--	--
(J) Sandstone U-V	54	--	44	--
(K) Placer gold	33	6	8	--
(L) Stratabound sulfides	--	--	2	6
(M) Limestone	175	17	--	--
(N) Gypsum	2	85	--	--
Total locatable resources	751	535	83	6
Leasable resources				
(O) Oil and gas	332	--	--	--
(P) Coal	38	33	--	--
(Q) Methane	38	33	--	--
(R) Oil shale	--	52	--	--
(S) Geothermal energy	30	--	--	--
Total leasable resources	438	118	--	--

respectively. Other districts and mines in the Forest had less significance in terms of total production.

The Eagle mine, in the Gilman district, ceased production in 1981. No large-scale mining has taken place in the Forest since that time; current mineral activity consists of annual assessment work on unpatented mining claims, prospecting, and small-scale mining, mostly in the Breckenridge area.

MINERAL RESOURCE POTENTIAL

The assessment of mineral resource potential in this summary is divided into three parts: locatable, leasable, and salable commodities. Table 1 summarizes the total size of areas of high, moderate, low, or unknown resource potential for locatable and leasable commodities, and table 2 summarizes the resource potential of those areas. Figure 1 shows areas of potential for all locatable commodities; figure 2 shows areas of potential for all locatable industrial commodities; and figure 3 shows areas of potential for all leasable commodities. Figures 17–47 show schematic diagrams and the areas of potential for each individual deposit type.

LOCATABLE COMMODITIES

Most metals and industrial minerals are included in the category of "locatable commodities" by the General Mining Law of 1872. The principal types of deposits of locatable commodities considered in this assessment are listed below. In each description, the metals found in each type of deposit and the principal areas of resource potential are briefly summarized. Letter symbols in the list below designate the type of deposit.

A. *Stockwork molybdenum.*—Formed in the carapaces of high-silica granite bodies and in the adjacent country rocks; deposits are valuable mainly for molybdenum, but also contain tungsten, tin, and bismuth. Plutons occur in the southern and eastern parts of the Forest. Two small areas have high resource potential and three small areas have moderate resource potential.

B. *Stockwork copper-molybdenum.*—Formed in granite bodies; deposits are valuable mainly for copper and molybdenum but can also contain gold, tungsten, tin, silver, lead, zinc, and bismuth. Two small areas have high resource potential, and two small areas in the

Table 2. Description of areas of mineral resource potential for locatable and leasable resources in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

[Map areas are shown on figures 17–47 and plates 1–2. The resource potential column shows both resource potential and level of certainty; both are explained in Appendix 2. Deposit sizes are listed in Appendix 3. Size and type of deposit not listed for gas, coal, coalbed methane, or oil-shale deposits or for hot- and warm-water springs. "Do." indicates that the size and type of deposit is the same as the one above it]

Map area	Resource potential	Commodities (byproducts or trace metals)	Size, type of deposit
A1	M/C	Mo	Small, stockworks
A2	H/C	Mo, (Au, Ag, Sn, W)	Do.
A3	H/D	Mo, Cu, (Ag, Au, Bi, Pb, W)	Do.
A4	M/C	Mo, Cu, (Ag, Bi, Pb, Sn, W)	Do.
A5	M/C	Mo	Do.
B1	M/C	Cu, Mo	Small, stockworks
B2	H/C	Cu, Mo	Do.
B3	M/B	Cu, Mo	Do.
B4	H/D	Cu, Mo, (Ag, Pb, Zn)	Do.
C1	L/B	Cu, Fe, Mn, Pb, Zn, W	Small, contact skarn
C2	H/D, L/C	Cu, Mo, Fe	Medium, contact skarn
C3	M/C	Cu, Mo, W	Small, contact skarn
C4	M/C	Cu, Au	Do.
C5	L/C	Cu, Pb, Zn	Do.
D1	L/C	Ag, Cu, Mn, Pb, Zn	Small, replacement
D2	M/C	Ag, Cu, Pb	Do.
D3	H/D, M/C	Ag, Au, Cu, Pb, Zn	Do.
D4	H/D, M/C	Ag, Au, Cu, Pb, Zn	Large, replacement
D5	H/D	Ag, Au, Cu, Pb, Zn	Do.
D6	H/D	Ag, Au, Cu, Pb, Zn	Small, replacement
E1	H/D, M/C	Ag, Zn, Pb, (Cu)	Small, stratabound
F1	H/D	Au	Small, veins
F2	H/D	Ag, Au, Zn, Pb, Cu	Do.
F3	H/D	Ag, Au, Zn, Pb, Cu	Medium, veins
F4	M/C	Ag, Au, Zn, Pb, Cu	Small, veins
F5	H/D	Ag, Au, Zn, Pb, Cu	Large, veins
F6	H/D	Au, Ag, Cu, Pb	Medium, veins
F7	H/D	Au, Ag, Cu, Pb, Zn	Small, veins
F8	H/D	Ag, Au, Mn, Fe, Zn	Medium, veins
F9	H/D	Ag, Au, Cu, Pb, Zn	Small, veins
F10	M/C	Ag, Au, Cu, Pb, Zn	Do.
F11	H/D	Ag, Au, Cu, Pb, Zn	Do.
F12	H/D, M/C	Ag, Au, Cu, Pb, Zn	Do.
F13	H/D	Ag, Au, Cu, Pb, Zn	Large, veins
F14	H/D	Ag, Au, Cu, Pb, Zn	Medium, veins
F15	H/D	Ag, Au, Cu, Pb, Zn	Small, veins

southern part of the Forest have moderate resource potential.

C. *Polymetallic skarn.*—Formed at the contacts between intrusive igneous rocks and chemically reactive host rocks, such as limestone; deposits are valuable mainly for copper, lead, zinc, silver, tungsten, manganese, and iron but may also contain trace amounts of gold. An area of high resource potential occurs south of Aspen,

Table 2. Description of areas of mineral resource potential for locatable and leasable resources in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado—Continued.

[Map areas are shown on figures 17–47 and plates 1–2. The resource potential column shows both resource potential and level of certainty; both are explained in Appendix 2. Deposit sizes are listed in Appendix 3. Size and type of deposit not listed for gas, coal, coalbed methane, or oil-shale deposits or for hot- and warm-water springs. "Do." indicates that the size and type of deposit is the same as the one above it]

Map area	Resource potential	Commodities (byproducts or trace metals)	Size, type of deposit
G1	H/C	U	Small, veins
G2	M/B	U	Do.
G3	L/B	U	Do.
G4	M/B	U	Do.
H1	M/C	W, (Au)	Small, veins
H2	M/C	W, (Zn, Pb, Cu, Ag, Au)	Do.
I1	H/D	Cu, Ag	Small, stratabound
I2	H/C	Cu, Ag, (U, V)	Do.
J1	H/D	U, V	Medium, stratabound
J2	L/C	U, V	Small
J3	H/D	U, V	Do.
J4	H/D	U, V	Do.
K1	M/C	Au	Small, placer
K2	L/C	Au	Do.
K3	M/C	Au	Do.
K4	L/B	Au	Do.
K5	M/C	Au	Do.
K6	M/C	Au	Do.
K7	H/D	Au, (Ag)	Medium, placer
K8	M/C	Au	Small, placer
L1	U/A	Au, Ag, Cu, Pb, Zn	Small, syngenetic, stratiform
L2	L/C	Au, Ag, Cu, Pb, Zn	Do.
L3	L/C	Au, Ag, Cu, Pb, Zn	Do.
L4	L/C	Au, Ag, Cu, Pb, Zn	Do.
L5	U/A	Au, Ag, Cu, Pb, Zn	Do.
L6	U/A	Au, Ag, Cu, Pb, Zn	Do.
M1	H/C	High-calcium limestone	Medium, bedded sedimentary
M2	H/D	High-calcium limestone	Do.
M3	M/C	High-calcium limestone	Do.
M4	M/C	High-calcium limestone	Do.
M5	H/C, M/C	High-calcium limestone	Do.
M6	M/B	High-calcium limestone	Do.
N1	M/B	Gypsum	Small, bedded sedimentary
N2	H/D	Gypsum	Do.

where an iron skarn was once mined. Two small areas of moderate resource potential are in the eastern part of the Forest; two small areas in the southeastern part of the Forest and one small area in the eastern part of the Forest have low mineral resource potential.

D. *Polymetallic replacement.*—Formed by hot solutions traversing limestone and dolomite; deposits contain copper, lead, zinc, silver, and manganese, but many also contain tungsten and gold. The principal area of high resource potential is along the flanks of the

Table 2. Description of areas of mineral resource potential for locatable and leasable resources in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado—Continued.

[Map areas are shown on figures 17–47 and plates 1–2. The resource potential column shows both resource potential and level of certainty; both are explained in Appendix 2. Deposit sizes are listed in Appendix 3. Size and type of deposit not listed for gas, coal, coalbed methane, or oil-shale deposits or for hot- and warm-water springs. "Do." indicates that the size and type of deposit is the same as the one above it]

Map area	Resource potential	Commodities (byproducts or trace metals)	Size, type of deposit
O1	H/D	Gas	
O2	H/D	Gas	
P1	M/C	Coal	
P2	M/C	Coal	
P3	H/D	Coal	
P4	M/B	Coal	
Q1	M/C	Coalbed methane	
Q2	M/C	Coalbed methane	
Q3	H/D	Coalbed methane	
Q4	M/B	Coalbed methane	
R1	M/C	Oil shale	
S1	H/D	Hot- and warm-water springs	
S2	H/D	Hot- and warm-water springs	
S3	H/D	Hot- and warm-water springs	

Sawatch Range, in places where the Leadville Limestone is present. Three other small areas have high resource potential; two have moderate resource potential; and one area has low resource potential. Polymetallic replacement deposits are usually associated with polymetallic vein deposits.

E. *Sherman-type Pb-Zn-Ag.*—Formed by the infilling of solution-collapse structures in the Leadville Limestone; deposits contain lead, zinc, and silver. The outcrop of the Leadville Limestone along the flanks of the Sawatch Range has high resource potential both along the southwestern part of the range and in a small area along the northeastern part of the range; the remaining outcrops of Leadville Limestone have moderate resource potential.

F. *Polymetallic veins.*—Related to Laramide and Tertiary igneous intrusions; deposits contain lead, zinc, copper, silver, gold, and manganese; likely byproducts are tin, antimony, and arsenic. Principal areas of high resource potential are in the Carbonate, Crystal River, Independence, Lincoln Gulch, Fulford, New York Lake, East Lake Creek, Cross Creek, Middle Mountain, Holy Cross City, Gilman, Breckenridge, Montezuma, North Rock Creek, and Green Mountain mining districts; three large areas of moderate resource potential also occur in the southeastern part of the Forest.

G. *Vein uranium.*—Formed from hot solutions associated with igneous intrusions; deposits contain uranium and trace amounts of gold, silver, antimony, lead, zinc, and molybdenum. One small area in the central part of the Sawatch Range has high resource potential; in the eastern part of the Forest, two small areas have moderate resource potential, and one small area has low resource potential.

H. *Vein tungsten.*—Formed from hot solutions in association with igneous intrusions; deposits contain tungsten, gold, silver, and zinc. Two small areas in the eastern part of the Forest have moderate resource potential.

I. *Sandstone copper.*—Formed where copper-rich solutions encountered differing chemical boundaries in sandstone layers; deposits contain copper and uranium, and silver and vanadium byproducts. Two small areas in the Forest have high resource potential: one is a few miles northwest of Aspen, and one is outside of the Forest boundary but in the central part of the Forest area.

J. *Sandstone uranium-vanadium.*—Formed during lithification of sandstone units; deposits contain uranium, vanadium, and trace amounts of copper. Areas of high resource potential include two small areas in the eastern part of Forest, a large area in the northwesternmost part of the Forest, and a small area in the northwestern part of the Forest. An extensive belt along the western margin of the Forest and several smaller areas in the south-central Forest have low resource potential.

K. *Placer gold.*—Deposited by streams that traversed and eroded gold-bearing rock; deposits contain gold and minor quantities of silver and bismuth. One large area near Breckenridge, along the upper Blue River, has high resource potential. Three small areas of moderate resource potential and four areas of low resource potential are in the eastern and southeastern parts of the Forest.

L. *Stratabound sulfides in Proterozoic rocks.*—Formed where gases and (or) fluids from mafic volcanic rocks interacted with sea water to form brines; deposited in volcanic and sedimentary rocks in a submarine environment in Proterozoic time; deposits contain copper, lead, zinc, gold, and silver. Three small areas in the eastern part of the Forest have low resource potential; one area in the western part of the Forest and two small areas in the eastern part have unknown resource potential.

M. *High-calcium limestone.*—Formed in shallow-water marine environments in Mississippian time. Areas on the flanks of the Sawatch Range and south of the Flat Tops that are underlain by the Leadville Limestone have high resource potential. Areas with moderate resource potential are in the southeastern part of the Forest and are underlain by mineralized or altered Leadville Limestone.

N. *Gypsum in evaporite deposits.*—Formed in shallow-water marine environments. An area of high resource potential occurs is in the central part of the Forest where thick and relatively pure beds of evaporite are present; several areas of moderate resource potential occur in the northwestern and central parts of the Forest.

LEASABLE COMMODITIES

Oil and gas, oil shale, potash, sodium, native asphalt, bituminous rock, phosphate, and coal are identified as "leasable commodities" by the Mineral Leasing Act of 1920. The principal types of leasable commodities in the Forest are listed below, and the areas of resource potential are briefly summarized.

O. *Oil and gas.*—Formed in near-shore and coastal-plain environments. Two large areas of high resource potential are along the western margin of the Forest.

P. *Coal.*—Formed in a deltaic system from the decomposition and alteration of organic remains. One area in the southwestern part of the Forest has high resource potential; one area in the northwestern part of the Forest and two areas in the southwestern part of the Forest have moderate resource potential.

Q. *Coalbed methane.*—Generated during the maturation process of coal. One area in the southwestern part of the Forest has high resource potential; one area in the northwestern part of the Forest and two areas in the southwestern part of the Forest have moderate resource potential.

R. *Oil shale.*—Formed in a large, shallow lake and on broad playa fringes. One large area in the southwestern part of the Forest has moderate resource potential.

S. *Geothermal energy.*—Areas of potential consists of thermal springs located along fault zones. One large area near Glenwood Springs has high resource potential, and two smaller areas in the south-central part of the Forest have high resource potential.

SALABLE COMMODITIES

Salable commodities, in general, include petrified wood, common varieties of sand and gravel, stone, pumice, volcanic cinders, and clay. Salable commodities found in the Forest include sand and gravel, dimension stone, crushed and lightweight aggregate, and clay.

Sand and gravel.—Numerous deposits of sand and gravel are located within major drainages in the Forest and are exploited for concrete and structural aggregate materials, road fill, mortar, and other uses. Fifty-three sites that have produced sand and gravel are on Forest land.

Dimension stone.—Sources in the Forest include marble and moss rock. White marble has been mined south of Marble, in Yule Creek, and black marble has been mined south of Aspen, in Conundrum Creek. Numerous moss-rock sites are in the Forest, and the potential resources are essentially unlimited.

Crushed and lightweight aggregate.—Crushed aggregates usable for roadway materials and general construction are derived from limestone, basalt, and granite. Rock quarries are scattered around the Forest in places where topography does not inhibit excavation. Lightweight aggregates include volcanic ash, pumice, and scoria—these materials are scattered around the Forest in limited quantities and contain varying amounts of impurities.

Clay.—Clay resources can be found in the Dakota Sandstone, south of Dillon Reservoir. Where clays have been sampled, they were not of refractory brick quality.

ASSESSMENT OF METAL ENDOWMENT USING GRADE-TONNAGE MODELS

At the request of the U.S. Forest Service, the U.S. Geological Survey has provided a quantitative assessment of the undiscovered mineral resources that might exist in the White River National Forest and Dillon Ranger District of the Arapaho National Forest. Based on the geology, geophysics, and geochemistry of known deposits in the Forest, deposit types were defined and compared to other similar deposits worldwide. The number of undiscovered deposits in the Forest was estimated at the 10th, 50th, and 90th percentiles.

Using a computer program entitled MARK3, tonnages for undiscovered deposits in the Forest were estimated from known tonnages and grades of deposits worldwide. Note that these values do not take into account any of the economics involved in mining the deposits.

Only four deposit types have sufficient grade and tonnage information to assess them using the MARK3 program: stockwork molybdenum, polymetallic replacement, polymetallic vein, and placer gold deposits. All remaining deposits that are known or predicted for the Forest lack sufficient data, or the deposit type is too poorly defined for quantitative assessment.

For stockwork molybdenum deposits, the number of undiscovered deposits was estimated to be 1, 1, and 0 at the 10th, 50th, and 90th percentiles, respectively (estimates for the remaining deposits are presented in the same order of percentiles). A mean of 430,000 tonnes of molybdenum or 220 million tonnes of total ore is suggested for the Forest. For polymetallic replacement deposits, the number of undiscovered deposits was estimated to be 1, 1, and 0. A mean of 220,000 tonnes lead, 250,000 tonnes zinc, 9,800 tonnes copper, 26,041,500 troy ounces of silver, and 99,600 troy ounces of gold is suggested for the Forest; a mean value of 4,100,000 tonnes of total ore may be present. For polymetallic veins, the number of undiscovered deposits was estimated to be 5, 3, and 1. Mean values of 20,400 tonnes lead, 14,000 tonnes zinc, 330 tonnes copper, 8,037,500 troy ounces silver, and 22,800 troy ounces of gold are suggested for polymetallic vein deposits in the Forest; the total amount of ore present has a mean value of 280,000 tonnes. For placer gold, the number of undiscovered deposits was estimated at 2, 1, and 0. A mean value of 7,000 troy ounces of gold and total ore of 330,000 tonnes is suggested for placer gold deposits in the Forest.

INTRODUCTION

This report presents an assessment of the mineral resource potential of the White River National Forest and Dillon Ranger District of the Arapaho National Forest, which are together referred to as "the Forest" in this report. The Dillon Ranger District of the Arapaho National Forest is included in this report with the White River National Forest because the two areas are administered by the staff of the White River National Forest and are included in a single planning document. The Dillon Ranger District is east of the White River National Forest and includes parts of the Williams Fork Mountains, Gore, Tenmile, and Front Ranges (fig. 4). For simplicity, only figure 4 distinguishes or outlines the Dillon Ranger District; in all plates and other figures, the district is included within the Forest boundary.

This mineral resource assessment was undertaken 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 needed for mineral resources to be considered along with other kinds of resources in land-use planning. The identified, or known, resources of the Forest were studied by the U.S. Bureau of Mines (Brown, 1990). This report addresses the potential for undiscovered mineral and energy resources in the Forest and is based upon information available as of July 1990.

GEOGRAPHIC SETTING

The White River National Forest and Dillon Ranger District of the Arapaho National Forest encompass about 2.4 million acres (3,791 square miles) in central and northwestern Colorado (fig. 4). The Forest is in two separate parcels: a southern parcel that is elongate in an east-west direction and a northern, square-shaped parcel. The southern area includes all or part of seven distinct mountain ranges: the Williams Fork Mountains, Front Range, Gore Range, Tenmile Range, Sawatch Range, Elk Mountains, and Battlement Mesa; the northern area encompasses the Flat Tops and White River Plateau. Parts or all of ten counties lie within the Forest: Eagle, Garfield, Gunnison, Lake, Mesa, Moffat, Pitkin, Rio Blanco, Routt, and Summit Counties.

The topography in the Forest varies from valleys and plateaus to steep and rugged mountains. Elevations range from about 6,000 ft, near the western edge of the Forest, to 14,265 ft, at Castle Peak on the Continental Divide in the southern part of the Forest. Six other peaks exceed 14,000 ft, and numerous other peaks exceed 13,000 ft. The entire Forest is on the western side of the Continental Divide, which forms the eastern boundary of parts of the Forest. With the exception of some water-diversion projects, the Forest's watershed drains into the Colorado River. The major tributaries of the Colorado River in the Forest are the Blue River, Eagle River, White River, Fryingpan River, Crystal River, and Roaring Fork.

Interstate Highway 70 traverses east-west through the central part of the Forest. Numerous other State and county highways extend through or to the Forest. Improved and unimproved roads and jeep trails provide access throughout the Forest. The major communities within and near the Forest are Aspen, Breckenridge, Dillon, Frisco, Vail, and Glenwood Springs.

METHOD OF STUDY

The geology of the Forest was compiled from published geologic maps at a scale of 1:250,000. The predominant portion of the geology was taken from the Leadville 1°×2° sheet (Tweto and others, 1978), but parts of the Craig (Tweto, 1976), Denver (Bryant and others, 1981), Grand Junction (Cashion, 1973), and Montrose (Tweto and others, 1976) 1°×2° sheets were also required. Much of the Forest has been mapped only at a reconnaissance level; detail is therefore lacking in some of these areas. In addition, units were combined during reconnaissance mapping and map compilation—this has obscured some important geologic relations. For example, the Leadville Limestone, which is an important ore host throughout the Forest, is combined on the above-mentioned maps with either the underlying Devonian rocks or the entire pre-Leadville Paleozoic section. This lack of detail constrains the precise location of areas of mineral resource potential for the Leadville Limestone.

A simplified geologic map of the Forest was prepared to best illustrate various geologic terranes and was compiled from the above maps by combining units. The purpose was to simplify the map to emphasize the geologic features that were important to mineral resource assessment. The reader is referred to the original maps and the sources that they reference for more detail. Granitic rocks in this report are classified according to Streckeisen and others (1973).

Mineral resource assessments by the U.S. Geological Survey included large parts of the Forest (fig. 5; table 3). The following areas were studied: the Flat Tops Primitive Area, the Gore Range–Eagles Nest Primitive Area and vicinity, the Holy Cross Wilderness, the Maroon Bells–Snowmass Wilderness, the Hunter-Fryingpan Wilderness–Porphyry Mountain Wilderness Study Area, and the Mt. Massive Wilderness. Published reports describe the geology and mineral resource potential of each area. Two small BLM Wilderness Study Areas adjoin the Forest and also have been studied (Soulliere and others, 1985, 1986). References are cited in table 3 and are in the bibliography of this report. A pre-assessment study of the Leadville 1°×2° sheet by Wallace and others (1988) laid much of the groundwork for this report.

Samples from the Forest were sampled and analyzed under the National Uranium Resource Evaluation (NURE) Program (Planner and others, 1981). NURE geochemical data were used to determine the geochemical signatures of areas where U.S. Geological Survey (USGS) data were unavailable.

Geophysical data available for use in the mineral resource assessment studies of the Forest included regional gravity, aeromagnetic, and radiometric data. A complete Bouguer gravity map was produced using edited gravity data from 6,500 stations; the data were collected in past years and extracted from the Defense Mapping Agency gravity data base. These data were gridded at a spacing of 1.2 mi. A derivative gravity map was calculated from the Bouguer gravity grid to emphasize anomalies caused by shallow sources. Aeromagnetic data from a variety of magnetic surveys flown over a 17-year period were compiled on one map. The surveys were flown at line spacings that ranged from 0.5 to 3 mi, either at a constant barometric elevation or at a constant clearance above terrane. Radiometric data for uranium, potassium, and thorium collected as part of the NURE program were also available. In the Leadville 1°×2° quadrangle, which includes much of the Forest, the NURE contractor identified uranium anomalies (Geometrics, 1979), but similar interpretations were not made for potassium and thorium.

Information on mines, prospects, and known resources was taken from the study of identified resources in the Forest by the U.S. Bureau of Mines (Brown, 1990) and supplemented with data from other sources. After consideration of the geology, geochemistry, geophysics, known mineral occurrences, and deposits in the Forest, descriptive models for deposit types that occur in the Forest were established. The same data were then used to establish assessment criteria for undiscovered deposits in the Forest. After the assessment criteria were established, mineral resource potential ratings were assigned to each area within the Forest that had a geologic environment with favorable characteristics for a given deposit type.

In response to a request by the U.S. Forest Service for quantitative assessment data, analyses were made of four of the best defined deposit types in the Forest. Using the MARK3 computer program (Drew and others, 1986; Root and others, in press), estimates were made for total tonnages of undiscovered resources for these deposit types in the Forest.

MINERAL RESOURCE POTENTIAL CLASSIFICATION

Mineral resource potential information is given in terms of mineral-deposit types and their geologic settings. Deposit types are based on geologic characteristics of known and inferred deposits within or close to the Forest. Most of the deposit types are represented by type localities at a mine or within mining districts. A letter designation (A, B, C, and so on) is used in the text and on the various figures and plates to represent each deposit type. Definitions of terms used in the assessment of mineral resource potential for each deposit type are summarized in Appendix 2.

The discussion of mineral resource potential in this report is based on the analysis of geologic terranes defined by particular rock assemblages. Regional structures superimposed on the geologic terranes influenced the location of some of the mineral deposits (fig. 6). An understanding of the nature and distribution of geologic terranes and their structure is necessary for assessment of the mineral resource potential.

All available information was assembled and analyzed according to procedures outlined by Shawe (1981) and Taylor and Steven (1983). Mineral resource potential information is presented in detail on plates 1–2 and is summarized on figures 1–3. This study is based primarily on information from published literature but includes unpublished data from studies in progress.

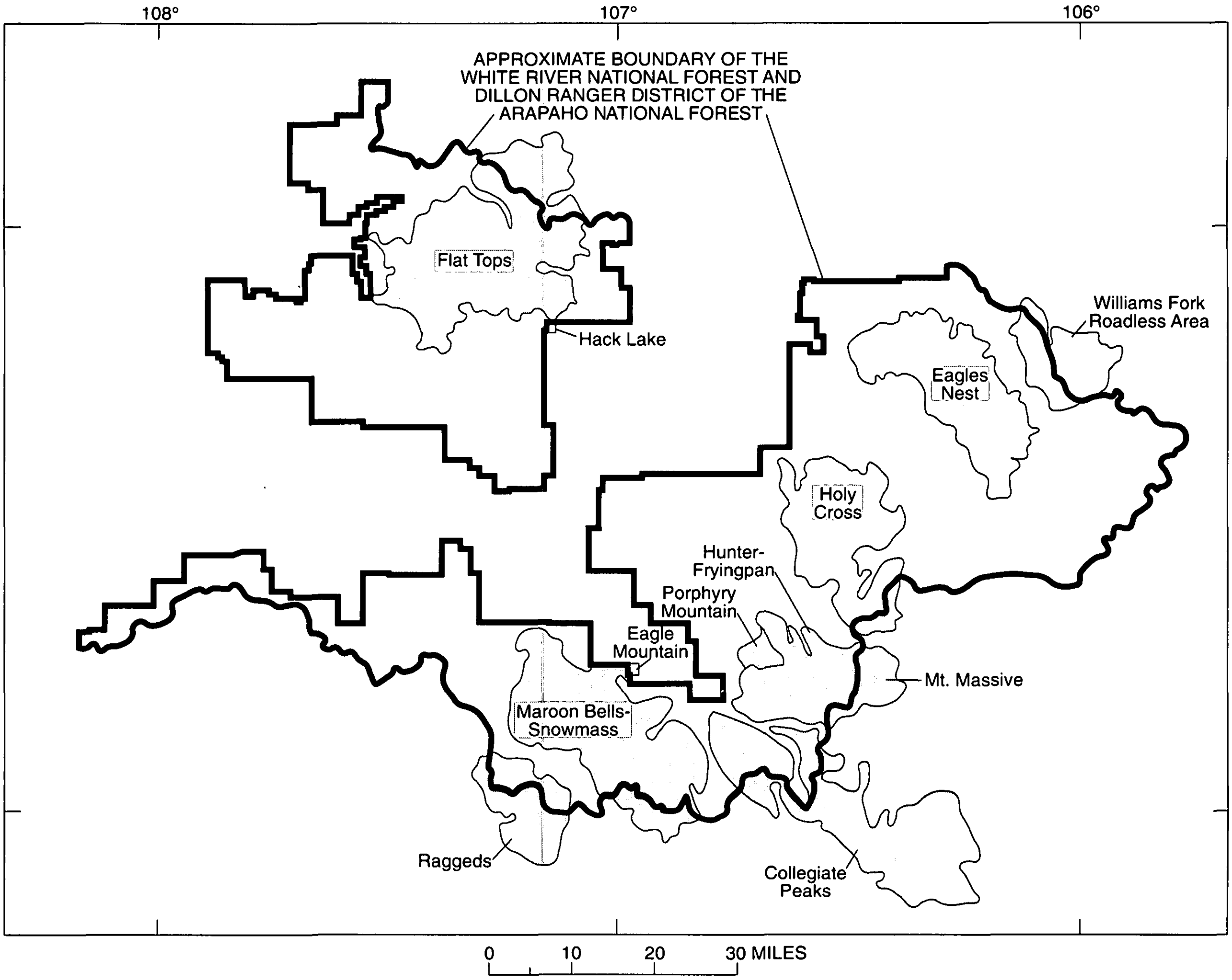


Figure 5. Index map of studied public lands in or adjacent to the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

ACKNOWLEDGMENTS

Many individuals contributed data, ideas, and assistance to this study. Alan Wallace provided valuable information on the geology of central Colorado, and this manuscript has benefitted greatly from his input. Ed LaRock and Donal Maloney were responsible for the digital preparation of the mineral resource potential maps and plates; Donal Maloney also provided valuable assistance in compiling bibliographic information and various other parts of this study. Bill Stephens did the drafting of figures and plates. Gerda Abrams provided gravity data used to make the complete Bouguer gravity map, and her contribution was appreciated. We would like to acknowledge and thank Dick McCammon, Don Singer, Dave Root, and Bill Scott for their help and contribution to the study of undiscovered mineral endowment. Thanks are also due to Greg Spanski for his helpful discussions of grade-tonnage modeling.

GEOLOGY

TECTONIC HISTORY AND STRUCTURE

Excellent discussions of the geologic and tectonic history of the central and northwestern Colorado are summarized in Tweto (1980), Wallace (1990), and Mutschler and others (1987); the following discussion is drawn from these sources.

The geologic history recorded in the Forest spans more than 1.8 billion years, and the major structural and rock-forming events are as follows: Early Proterozoic accretion and metamorphism of volcanic and sedimentary rocks and intrusion of granitic plutons; early to middle Paleozoic deposition of marine and nonmarine sedimentary rocks during repeated epeirogenic (large-scale) movements; late Paleozoic and early Mesozoic erosion and deposition related to the formation of two highlands separated by a narrow basin;

Table 3. Geochemical studies that cover parts of the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado

[NURE, National Uranium Resource Evaluation]

Study Area	Reference
Flat Tops Primitive Area	Mallory and others (1966)
Gore Range–Eagles Nest Primitive Area	Tweto and others (1970)
Holy Cross Wilderness	Wallace and others (1989)
Maroon Bells–Snowmass Wilderness	Freeman and others (1985)
Hunter-Fryingpan Wilderness	Ludington and Ellis (1981)
Porphyry Mountain Wilderness Study Area	Ludington and Ellis (1981)
Raggeds Wilderness	Kness (1984)
Williams Fork Roadless Area	Theobald and others (1983)
Eagle Mountain Wilderness Study Area	Soulliere and others (1985a)
Bull Gulch Wilderness Study Area	Soulliere and others (1986)
Hack Lake Wilderness Study Area	Soulliere and others (1985b)
Leadville 1°x2° NURE	Planner and others (1981)
Grand Junction 1°x2° NURE	Langfeldt and others (1981)
Montrose 1°x2° NURE	Broxton and others (1979)
Denver 1°x2° NURE	Shettel and others (1981)
Craig 1°x2° NURE	Bolivar and others (1979)

Late Cretaceous through early Eocene uplift during the Laramide orogeny, along with volcanism and emplacement of granitic plutons; middle Tertiary tectonic quiescence accompanied by volcanism and emplacement of granite plutons; late Cenozoic magmatism, block faulting activity in an extensional regime and formation of a bimodal suite of basalt and rhyolite and emplacement of related plutons; Pleistocene to Holocene glaciation and erosion.

PROTEROZOIC

The geologic history recorded in the rocks of central Colorado began with Early Proterozoic deposition of volcanic arc and back-arc sedimentary and volcanic rocks on oceanic crust and their accretion to the southern margin of the Archean Wyoming craton. These rocks were metamorphosed to gneiss, schist, and migmatite at about 1.7 Ga. The rocks were intruded by large granitic batholiths during the Early (1.7 Ga) and Middle Proterozoic (1.4 Ga).

The metamorphic rocks have been complexly deformed and now exhibit several sets of superimposed folds. Metamorphism and penetrative deformation occurred prior to and during the emplacement of the 1.7-Ga batholiths, although deformation of the metamorphic rocks predated emplacement of most of the batholithic rocks.

The Proterozoic rocks are crosscut by numerous faults and shear zones that have predominantly north-northwest and northeast trends. Although many of the north-northwest-trending faults initially formed in the Proterozoic, many of them were reactivated during the Phanerozoic. The northeast-trending fault system is typified by the Homestake shear zone in the northern Sawatch Range, as well as similar structures in the Gore and Front Ranges (Tweto and Sims, 1963). The Homestake shear zone both cuts and is cut by 1.4-Ga plutons (Wallace, 1990).

PALEOZOIC

Uplift related to epeirogeny may have begun as early as Cambrian time in central Colorado (Tweto and Lovering, 1977) but was clearly established by Ordovician time (Tweto, 1980). During this time period, sedimentation occurred in response to repeated uplifts and related transgressive-regressive marine and nonmarine cycles. Sediments were deposited in shallow seaways that were episodically bounded by low-relief highlands to the south and east. The Proterozoic basement complex was buried beneath more than 10,000 ft of marine and continental sediments.

Uplift began again in the Late Mississippian and was related to the Ouachita-Marathon orogeny along the southern border of the North American craton (Kluth and Coney, 1981). Two highlands were developed in central Colorado as a result of this uplift: the Ancestral Front Range to the northeast and the Uncompahgre Highland to the southwest. Parts of these uplifts developed into mountain ranges that attained altitudes of as much as 5,000 to 10,000 ft above sea level (Mallory, 1971).

During this late Paleozoic uplift, older sedimentary rocks were eroded from the rising highlands. Mississippian carbonate rocks that probably once covered the entire State were severely and unevenly eroded during this uplift (Tweto,

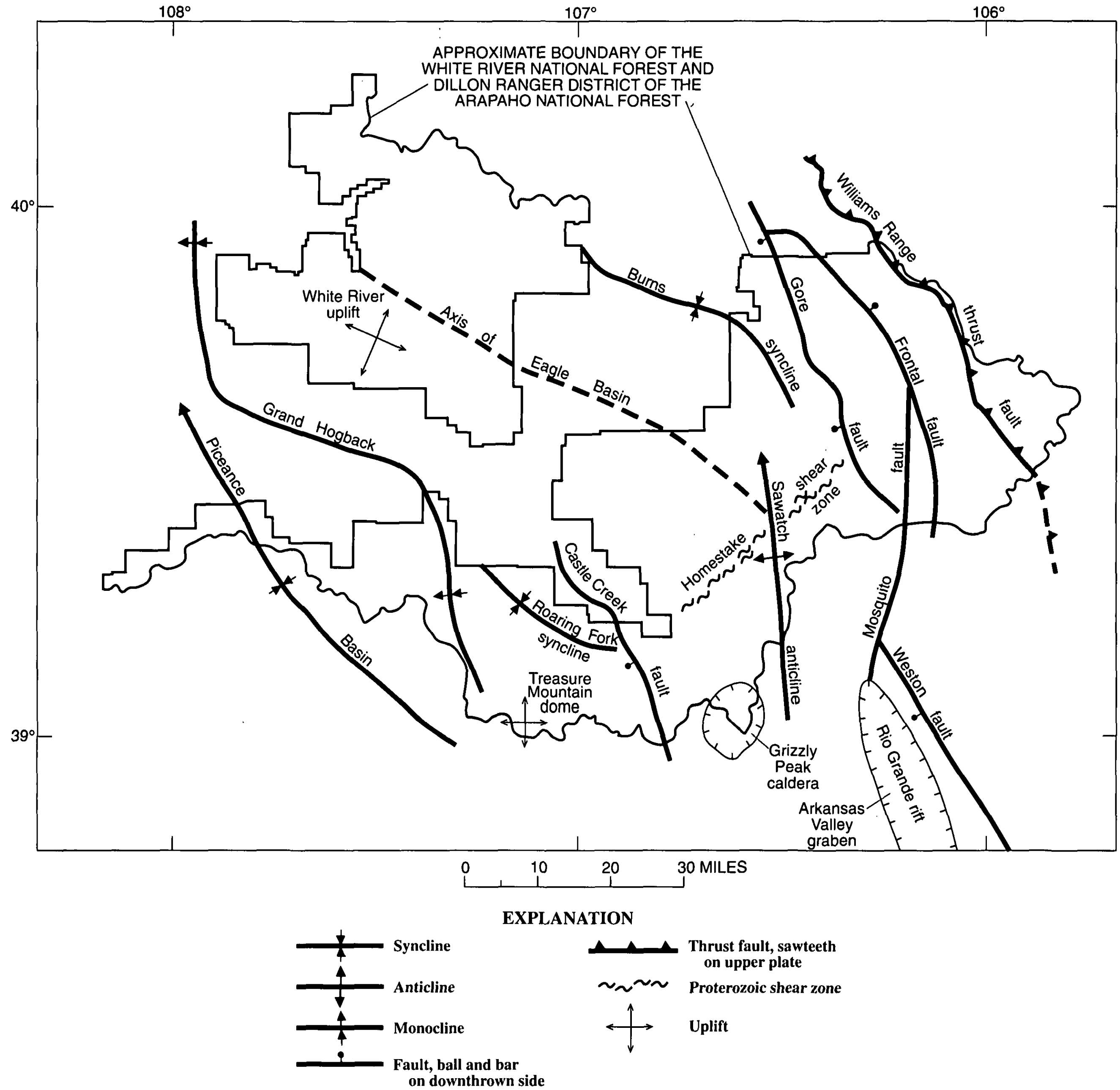


Figure 6. Map showing major structural elements within or close to the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

1980). These carbonate rocks and all earlier Paleozoic rocks were stripped entirely from the late Paleozoic highlands, and the Proterozoic basement complex was partially exhumed.

Clastic sedimentary rocks and evaporites were deposited in the Eagle Basin, a northwest-trending trough that formed between the two highlands. Sediments were also deposited locally on the newly exposed Proterozoic basement. Prograding Pennsylvanian alluvial fans and eolian dune fields progressively covered the sedimentary rocks in the basin. Diapiric flow of the Permian-Pennsylvanian evaporites in the Eagle Basin had a pronounced influence on Permian and younger sedimentation and structure (Tweto, 1977; Freeman, 1971). Some of this diapiric activity has continued into the Quaternary.

MESOZOIC

During the Mesozoic, orogenic activity waned; inland seas episodically covered the area, depositing marine and nonmarine sediments. Clastic sedimentation continued through the Triassic as erosion beveled the highlands and sediments were deposited in various marginal-marine, braided-stream, and lacustrine environments. Jurassic and Cretaceous sedimentary rocks were deposited during several nonmarine and marine cycles related to transgressive and regressive sequences. The Jurassic sedimentary rocks were deposited chiefly in continental and marginal-marine environments, whereas Cretaceous rocks were deposited in complex, intertonguing marine and nonmarine settings.

TERTIARY

The final regression of the Late Cretaceous sea coincided with the beginning of the Laramide orogeny. The Laramide orogeny is associated with horizontal compression, although a large component of vertical displacement (Gries, 1983) has also been noted in some areas of uplift. This orogeny produced most of the present primary mountain ranges in central Colorado. Some of the uplifts were rejuvenations of late Paleozoic uplifts, but some were also newly created. The north-trending Sawatch Range was the first major uplift to develop during the Laramide orogeny; it is an asymmetrical anticline with reverse faults along its western flank (fig. 6). The Gore and Front Ranges began to rise later, reactivating older faults as well as generating new structures, such as the Williams Range thrust fault along the west side of the Williams Fork Mountains (fig. 6).

During the Laramide orogeny, plutonic rocks were emplaced along a northeast-trending zone coincident with the major Proterozoic structures; the Proterozoic structures probably localized magmas as they ascended through the crust. In some places, such as the northern Sawatch Range, small Laramide-age plutons define a northwest trend that may be related to the Laramide orogeny (Wallace and Naeser, 1986).

During Laramide uplift, streams eroded older sedimentary rocks and deeply beveled the Proterozoic crystalline rocks. Eocene clastic deposits accumulated in structural basins that formed during the beveling and in lakes and channels of the fluvial systems that drained the area. Erosion and sedimentation gradually degraded the mountainous terrane until the topography of an extensive late Eocene erosion surface was relatively gentle (Epis and Chapin, 1975).

The White River uplift, a broad elongate dome, and the Grand Hogback monocline (fig. 6) developed in early to middle Eocene time and were the last major Laramide structures to form. The Grand Hogback monocline is a west- to south-dipping monocline that forms the western and southern flanks of the White River uplift.

Middle Tertiary time was marked by a period of relative tectonic quiescence and the early stages of crustal extension. Calc-alkaline granitic rocks were emplaced in a northeast-trending zone across the Forest, and minor amounts of ash-flow tuff were deposited in the southeastern part of the Forest.

Renewed rise of Laramide uplifts and regional crustal extension occurred in the late Cenozoic. Block faulting reactivated many Laramide and Proterozoic faults, renewing uplift of the Sawatch, Gore, Tenmile, and Front Ranges (fig. 4). Extension generated the north-northwest-trending Rio Grande rift zone (fig. 6), a wide belt of continuous grabens extending northward from New Mexico to just south of Leadville and the Forest; the rift crosscuts several of the mountains formed by Laramide uplift. Extensional faulting related to the Rio Grande rift crosscut the east flank of the Sawatch uplift, creating the Mosquito Range and the valley between the Sawatch and Mosquito Ranges, the upper Arkansas Valley graben (figs. 4 and 6) (Tweto, 1977).

Late Cenozoic magmatism, coinciding with renewed uplift and extension, produced a wide variety of granitic rocks, ranging in age from about 29 to 12 Ma, and a bimodal suite of rhyolite and basalt, ranging in age from 24 Ma to 4,150 years. Clastic sediments continued to be deposited in small structural basins during the Miocene and Pliocene.

Significant Neogene (Miocene and Pliocene) deformation did not begin in the Forest until the late Miocene, at about 10 Ma. Renewed doming of the White River uplift began at this time, and orogenic activity continued in the ranges in the eastern part of the Forest. In the Rio Grande rift, horst blocks formed (or continued to form) the Sangre de Cristo and Gore Ranges as late as the early Pliocene (Tweto, 1980). Fault movements, decreasing in displacement, continued into the Pleistocene and, to a minor extent, into the Holocene.

QUATERNARY

A period of Quaternary climatic cooling resulted in glaciation that continued from about 500,000 years ago, in the Pleistocene, into the Holocene. During three glacial maxima, ice almost totally covered the higher ranges and the valleys were filled with glaciers; the modern alpine topography with deep U-shaped valleys is largely a product of glacial erosion. Glacial erosion was also the chief cause of the destruction of the Eocene erosion surface in the higher parts of the mountains.

The only igneous activity in the Quaternary was confined to the eruption of small basalt flows, southeast of the Flat Tops near Dotsero (outside of the Forest) (fig. 4).

COLORADO MINERAL BELT

The White River National Forest and the Dillon Ranger District of the Arapaho National Forest contain 26 mining districts and mineralized areas (fig. 7). Some of the largest concentrations of mineral deposits in the Rocky Mountain region are in the Forest, at Gilman, and adjacent to the Forest, at Climax, Leadville, and Red Mountain (fig. 4). These deposits are part of an elongate zone of hydrothermal mineral deposits, known as the Colorado Mineral Belt (Tweto and Sims, 1963) (fig. 8), which extends from the San Juan

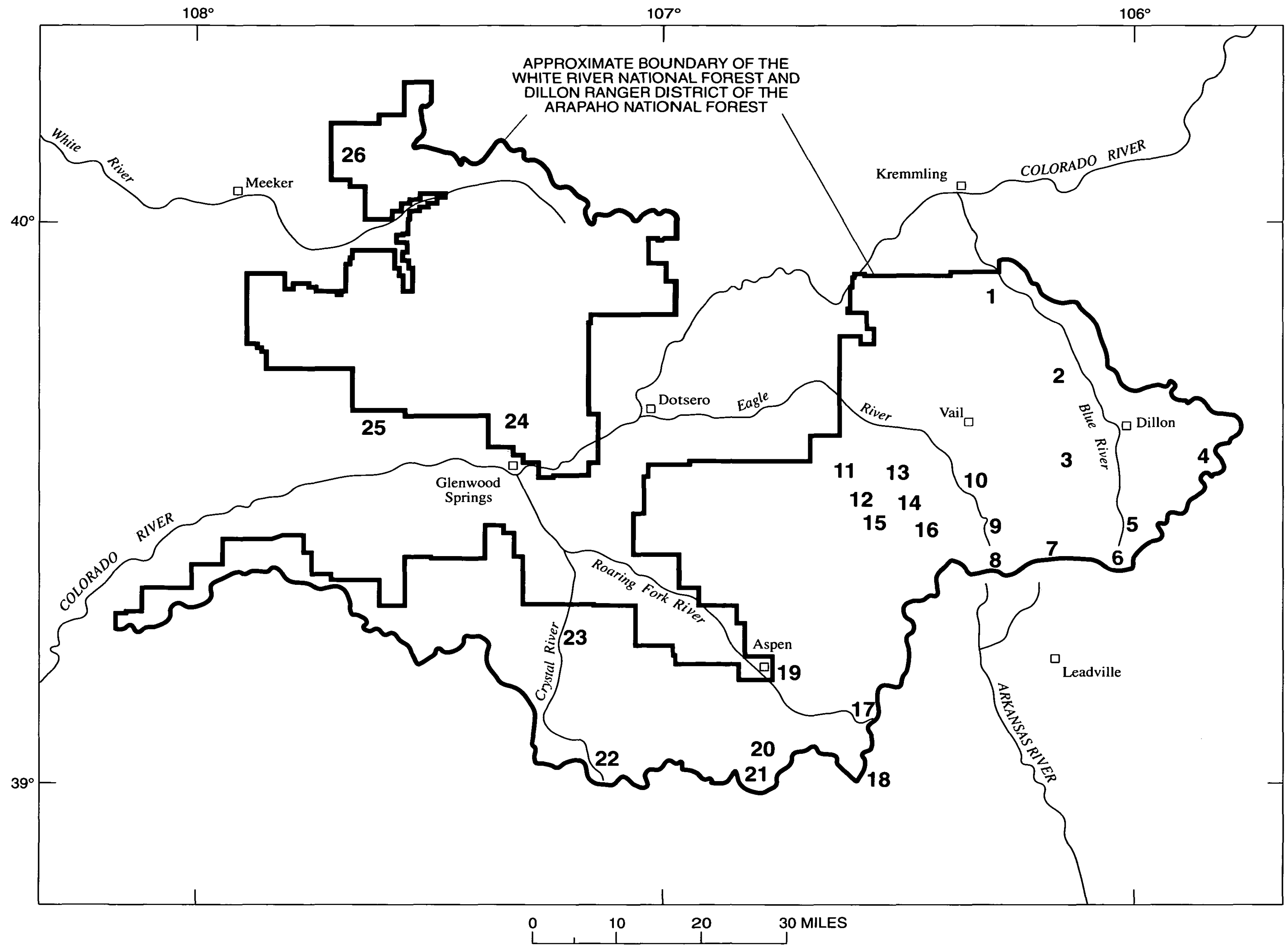


Figure 7. Index map showing mining districts within or close to the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Numbers on map are keyed to mining districts as follows: 1, Green Mountain; 2, North Rock Creek; 3, Frisco; 4, Montezuma; 5, Breckenridge; 6, Upper Blue River; 7, Kokomo-Tenmile; 8, Tennessee Pass; 9, Eagle; 10, Gilman; 11, Fulford; 12, New York Lake; 13, East Lake Creek; 14, East Lake Creek–Cross Creek; 15, Middle Mountain; 16, Holy Cross City–Cross Creek; 17, Independence; 18, Lincoln Gulch; 19, Aspen; 20, Columbia-Ashcroft; 21, Taylor Peak; 22, Crystal River; 23, Spring Butte; 24, Carbonate; 25, Rifle Creek; 26, Uranium Peak. Map modified from Brown (1990).

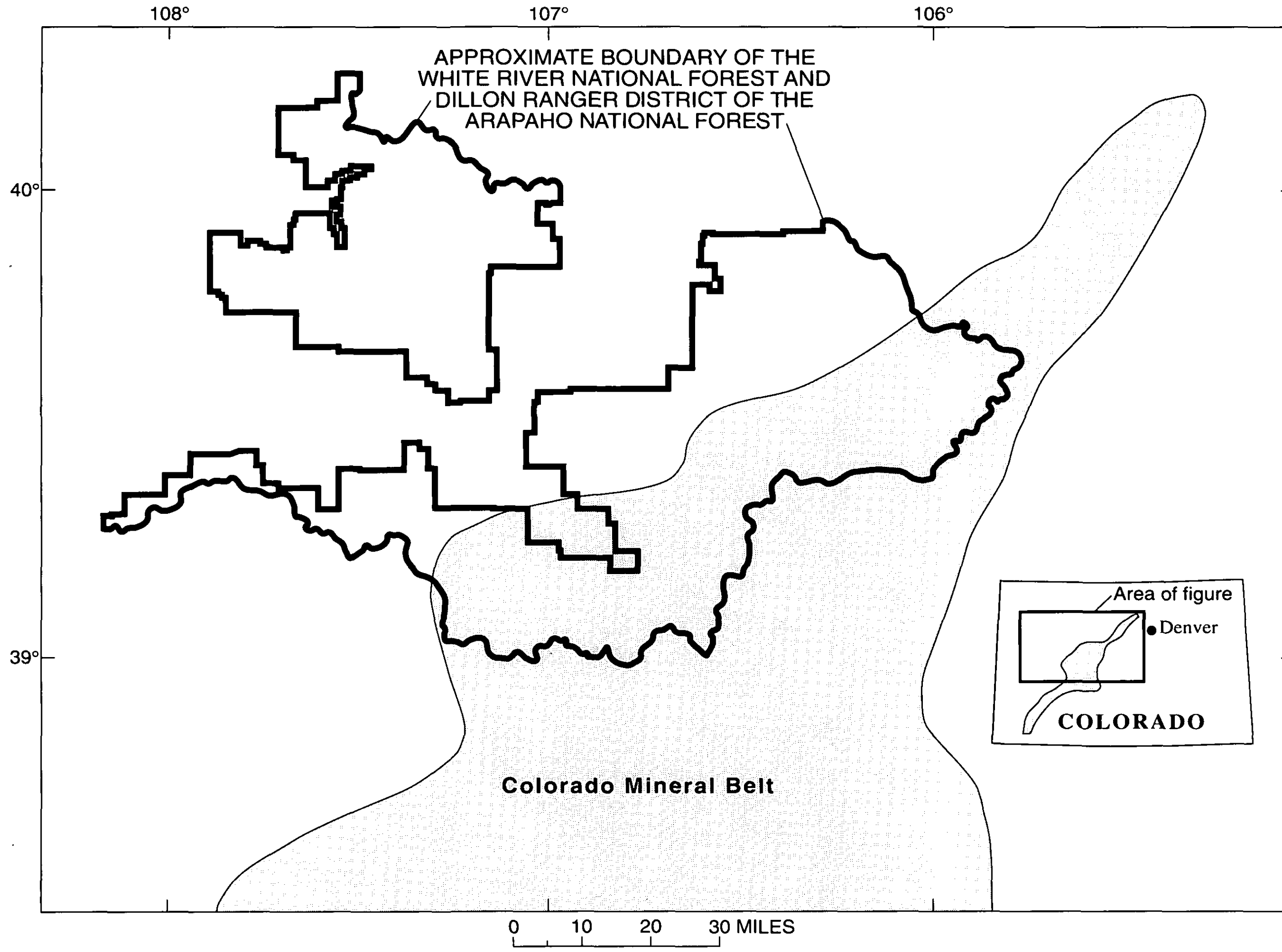


Figure 8. Map of the Colorado Mineral Belt. Modified from Tweto and Sims (1963).

Mountains in southwestern Colorado into the Front Range, north of Denver. The belt is characterized by a large concentration of mineral deposits and numerous felsic to intermediate intrusive and volcanic rocks of Late Cretaceous to late Tertiary age. The Colorado Mineral Belt crosscuts both pre-Cretaceous structural trends and the present north-south topographic grain of the southern Rocky Mountains.

DESCRIPTION OF ROCK UNITS

PROTEROZOIC CRYSTALLINE ROCKS

The metamorphic rocks in the Forest are Proterozoic in age and include biotite gneiss, schist, and migmatite and lesser amounts of calc-silicate and hornblende gneiss. These rocks are typically metamorphosed to upper amphibolite facies and are structurally and stratigraphically complex. The protoliths of the gneiss and schist are interpreted to have been graywacke, shale, and felsic volcanic rocks; the protoliths of the calc-silicate and hornblende gneisses were likely carbonate rocks and intermediate to felsic volcanic rocks and basalt. The metavolcanic rocks have bimodal compositions, and trace-element modeling indicates a mixed mantle-crust source for the felsic volcanics and a mantle source for the basalts (Boardman and Condie, 1986).

Proterozoic plutonic rocks include two suites of granitic rocks, 1.7 and 1.4 Ga in age. The 1.7-Ga intrusive rocks include the Cross Creek Granite in the Gore and northern Sawatch Ranges, the Denny Creek Granodiorite in the central Sawatch Range, and other unnamed granitic to dioritic rocks. The granitic bodies are generally concordant with the enclosing gneisses and most are foliated and contain biotite and (or) hornblende.

The 1.4-Ga intrusive rocks are represented by the peraluminous, multiphase, two-mica St. Kevin Granite and possibly by the age-equivalent Silver Plume Granite. The St. Kevin Granite makes up the core of the Sawatch Range. Rocks from these units lack metamorphic foliation and most are discordant with the enclosing gneisses. This plutonic event was largely anorogenic, and the melts were derived from metasedimentary rocks in the lower crust (Anderson and Thomas, 1985).

Uplift and erosion brought the Proterozoic basement rocks to the surface by the early Paleozoic. A distinctive surface of low relief was developed through erosion—this surface had local relief of about 2–6 ft.

PALEOZOIC SEDIMENTARY ROCKS

The lower Paleozoic rocks include the following: the Sawatch Quartzite (Upper Cambrian), the Peerless Formation (Upper Cambrian), the Dotsero Formation (Upper Cambrian), the Manitou Dolomite (Lower Ordovician), the Harding Sandstone (Middle Ordovician), the Chaffee Group (Upper Devonian and Lower Mississippian), and the Leadville Limestone (Lower Mississippian). The Sawatch Quartzite rests unconformably on Proterozoic basement rocks and commonly shows a very distinctive unconformity. Both the quartzite of the Sawatch and the sandstones and dolomites of the overlying Peerless Formation are widespread units, but they are truncated beneath various unconformities along the Gore Range and near Breckenridge. The Dotsero Formation is only present in the area of the White River Plateau, in the northern part of the Forest, and consists of dolomite, limestone conglomerate, and minor shale. The Manitou contains limestone conglomerate interbedded with calcareous shale and is widespread in the eastern part of the Forest but is absent from Pando and Breckenridge northward. The Harding Sandstone is present only in the western Elk Mountains and along the Eagle River between Minturn and Tennessee Pass. The Chaffee Group contains, from oldest to youngest, the Parting Formation, Dyer Dolomite, and Gilman Sandstone; it is thickest in the area of the White River Plateau and is truncated beneath an unconformity along the west flank of the Gore Range and near Hoosier Pass.

The youngest of these units, the Leadville Limestone, is also referred to as the Leadville Dolomite. In most parts of central Colorado, the carbonate rocks of the Leadville are predominantly or entirely limestone, but from Minturn southeastward through the Leadville mining district and the Mosquito Range, they have been altered to dolomite. East of the Sawatch Range, the belt of dolomite is completely within the Colorado Mineral Belt. The terms Leadville Limestone and Leadville Dolomite are used interchangeably in this report.

The thickness of the Leadville is variable. The formation has a maximum thickness in the Elk Mountains and is truncated to the east along the west flank of the Gore Range and near Hoosier Pass. Karsts formed on the surface of the Leadville as a result of Late Mississippian uplift and erosion—this resulted in the formation of a surface with considerable relief. The dolomite facies of the Leadville is of prime economic interest because it provides the principal host rock for many of the ore deposits in the Forest.

Middle and upper Paleozoic rocks include the Molas and Belden Formations (Lower and Middle Pennsylvanian), Eagle Valley Evaporite (Middle and Upper Pennsylvanian), Minturn (Middle Pennsylvanian) and Gothic Formations (Middle Pennsylvanian), Weber Sandstone (Middle Pennsylvanian to Lower Permian), Maroon (Middle Pennsylvanian to Lower Permian) and the State Bridge Formations (Lower Permian to Lower Triassic). With the exception of the Molas Formation, all of these units are at their thickest in the area of the Eagle Basin and thin eastward to pinch out along the Gore and Sawatch Ranges.

The Molas Formation overlies the Leadville Limestone, except when found in caves that formed in the Leadville and the Dyer Dolomite. In the Forest, the Molas is a mudstone regolith of variable thickness that formed above limestone units. The Belden overlies the Molas and consists of a thick sequence of shale with some argillaceous limestone and increasing amounts of sandstone near the top.

The Eagle Valley Evaporite covers an area of about 50 mi wide by 100 mi long in the central part of the Forest, northwest of the Sawatch Range. The unit consists of gypsum and anhydrite, with lesser amounts of halite and traces of potash salts. It was deposited in a landlocked marine trough between the Uncompahgre and Front Range uplifts. In the central part of the Eagle Basin, the Eagle Valley contains sandstone, shale, siltstone, minor carbonate, and local lenses of gypsum and is referred to as the Eagle Valley Formation.

Overlying and interfingering with the Eagle Valley Evaporite is a sequence of mostly sandstone units that exceed 20,000 ft in thickness. The oldest of these units is the Minturn Formation, which contains beds of sandstone, conglomerate, and shale, with scattered beds and reefs of carbonate rocks. In the western part of the Forest, the Minturn is referred to as the Gothic Formation (Langenheim, 1952). Above the Minturn, the Weber Sandstone is a thin unit that is present only in the westernmost part of the Forest. The Minturn is overlain by the Maroon Formation, which contains characteristically red sandstone, conglomerate, and mudstone. Above the Maroon, the State Bridge Formation contains red-brown siltstone and sandstone and is at its thickest in a local depositional basin in the Hardscrabble Mountain area, south of Eagle.

MESOZOIC SEDIMENTARY ROCKS

Mesozoic rock units include the Chinle Formation (Upper Triassic), Glen Canyon Sandstone (Lower Jurassic), Entrada Sandstone (Middle Jurassic), the Curtis Formation (Middle Jurassic), Morrison Formation (Upper Jurassic), Burro Canyon Formation (Lower Cretaceous), Dakota Sandstone (Lower and Upper Cretaceous), Mancos Shale (Upper Cretaceous), Colorado Group (Upper Cretaceous), Pierre Shale (Upper Cretaceous), and Mesaverde Group (Upper Cretaceous). The Triassic sediments were deposited as orogenic activity waned and inland seas episodically covered the area; sediments were deposited in marginal-marine, braided-stream, and lacustrine environments. The Jurassic and Cretaceous sediments were deposited during nonmarine to marine sedimentary cycles that were separated by uplifts related to the Laramide orogeny. The overall uplift caused a northeastward retreat of the sea and a shift from marine to orogenic continental sedimentation.

Triassic and Jurassic rocks are exposed in the central part of the Forest and at the western edge of the Forest, along the Grand Hogback. The oldest of these sedimentary rocks is the Chinle Formation, which contains red and purple sandstone and siltstone. The Chinle is at its maximum thickness near Brush Creek, south of Eagle, and thins from there in all directions; the formation wedges out along the west side of the Gore Range and in the Elk Mountains. The overlying Glen Canyon and Entrada Sandstones are relatively thin, cross-bedded quartzites. The Entrada is thickest in the northwestern and central parts of the Forest and wedges out southward, in the Aspen area, and eastward, at the Gore Range. The Curtis Formation overlies the Entrada and contains glauconitic sandstone and oolitic limestone. The overlying Morrison Formation contains variegated shale and mudstone, sandstone, and local beds of limestone. The thickness of the Morrison is greatest along the Grand Hogback and Colorado River, near Burns, and thins to the east and southeast.

Cretaceous sedimentary rocks are exposed along the western edge of the Forest, in the vicinity of the Grand Hogback, and in the north-central part of the Forest. Because of the transgressive-regressive nature of these units, most of them are intertonguing. The oldest of these units, the Burro Canyon Formation, contains sandstone and claystone. The overlying Dakota Sandstone consists of sandstone or quartzite with some interbedded dark shale and shaly sandstone. Mancos Shale overlies the Dakota and is the oldest thick sequence of shale in the Cretaceous sequence; it is continuously exposed along the western side of the Forest. The Colorado Group, which is approximately equivalent to the Dakota-to-Mancos sequence, is a relatively thin unit of calcareous shale and marly limestone and is exposed along the northeastern boundary of the Forest, near the Williams Fork thrust. The youngest of the shale units, the Pierre Shale, is comprised of a thick sequence of calcareous, dark-gray, marine shales that crop out along the northern and northwestern parts of the Forest. The Mesaverde Group, in part equivalent to the Pierre, crops out along the Grand Hogback monocline, a prominent fold defining the western and southern margin of the White River uplift. The Mesaverde contains sandstone, shale, and coal beds and crops out along the western border of the Forest.

LATE CRETACEOUS AND EARLY TERTIARY INTRUSIVE ROCKS

Plutonic rocks were emplaced in central Colorado from about 74 to 60 Ma (Mutschler and others, 1987), during the Laramide orogeny, in a northeast-trending zone that is roughly coincident with the Colorado Mineral Belt. The Laramide intrusions form small to large stocks, sills, and dikes in Proterozoic to Cretaceous host rocks. Contacts of the intrusive bodies with the enclosing country rock are sharp and generally discordant. Concordant contacts are present in places, such as those of the stock at Fulford. The igneous rocks are generally granodiorite, monzogranite, and quartz monzonite, but diorite is present in smaller amounts. Biotite is the main varietal mineral, but hornblende is also present in places. The texture of the rocks is fine to medium grained, equigranular to porphyritic. Trace-element and isotopic data indicate that the magmas were derived from partial melting from the lower crust with a possible contribution of mantle material (Stein, 1985).

MIDDLE TERTIARY ROCKS

INTRUSIVE ROCKS

Another period of magmatism took place in a northeast-trending zone across Colorado and the Forest during early Oligocene to Miocene time, from about 40 to 13 Ma. Rocks from 40 to 30 Ma in age consist of generally porphyritic granodiorite, monozogranite, and quartz monzonite in stocks, dikes, sills, and irregular forms. Within the Forest, these rocks were volumetrically more extensive than those of the Laramide orogeny. Trace-element and isotopic data indicate that the magmas were derived from partial melting of the lower crust (Stein, 1985; Obradovich and others, 1969).

Intrusive rocks younger than about 30 Ma range in composition from granodiorite to high-silica granite. These rocks are generally porphyritic, but equigranular varieties are present in some of the larger bodies. Trace-element and isotopic data indicate that these granites were derived from partial melting of the lower crust (Stein, 1985).

VOLCANIC ROCKS

Middle Tertiary volcanic rocks are present at only two locations in the Forest: minor amounts of Oligocene (34 Ma) silicic welded tuffs, andesites, and breccia in the southern part of the Sawatch Range, in the Grizzly Peak caldera south of Independence Pass (Fridrich and Mahood, 1984); and 30-Ma trachytic lavas in the northern part of the Forest, near Green Mountain (Naeser and others, 1973). Sedimentary rocks in basins east of the Sawatch Range also contain volcanic fragments, indicating that some magma chambers reached subvolcanic levels and vented to the surface (Wallace, 1990). Most of the Oligocene volcanoes in the Forest have been deeply eroded.

LATE TERTIARY ROCKS

INTRUSIVE ROCKS

Late Tertiary intrusive rocks are present at Treasure Mountain, in the southwestern part of the Forest. High-Na granite at this location is about 12.5 Ma in age (Obradovich and others, 1969).

BIMODAL VOLCANIC ROCKS

Miocene (24–8 Ma) basaltic flows are in the western part of the Forest, predominantly in the area of the Flat Tops. Just to the east of the Flat Tops, outside of the Forest at Dotsero, basalt flows are as young as 4,150 years. 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 in flows 5–200 ft thick; they include interbedded tuffs and volcanic conglomerates. Trace-element and isotopic data indicate that the basalts were derived predominantly from a mantle source with some crustal mixing (Stein, 1985).

BASIN-FILL DEPOSITS

The Tertiary sedimentary rocks are now found in small, isolated outcrops. They were deposited in limited, local, structural basins and small grabens that formed during Tertiary erosion. These rocks are made up of claystone, siltstone, sandstone, and conglomerate. In the Forest, these units include the Wasatch (Paleocene and Eocene), Green River (Eocene), and Uinta (Eocene) Formations along the western edge of the Forest; the Browns Park (Oligocene and Miocene) and Troublesome (Oligocene and Miocene) Formations along the northeastern edge; and the Dry Union Formation (Miocene and Pliocene) along the eastern and southern edge. The Dry Union has an area of extensive outcrop southeast of the Forest, in the Arkansas Valley. The formations range from 400 to 5,800 ft in thickness.

LATE TERTIARY AND QUATERNARY UNCONSOLIDATED DEPOSITS

Holocene alluvium occurs in drainages and fans across the Forest and consists of gravel, sand, and silt with varying degrees of consolidation. In some places, high-level alluvium is present on ridges and is of Pliocene and Pleistocene(?) age. Landslide deposits are common in the southwestern part of the Forest and are made up of large slump blocks of basalt and glacial material, mudflow, and talus (Pleistocene and Holocene). Glacial deposits formed in Pleistocene time and consist of boulders, gravels, and sandy deposits in streams and moraines.

GEOCHEMISTRY

GEOCHEMICAL SURVEYS

The geochemical contributions to the mineral resource assessment of the White River National Forest and Dillon Ranger District of the Arapaho National Forest were derived from data that include analyses for 2,661 rock, 637 stream-sediment, 820 heavy-mineral-concentrate, and 1,856 National Uranium Resource Evaluation (NURE) stream-sediment samples from the USGS Branch of Geochemistry databases—altogether 5,513 sample are represented. The NURE data were combined from digital copies of analyses listed for the Leadville, Grand Junction, Montrose, Craig, and Denver 1°×2° quadrangles (table 3). Included in the geochemical information produced by the USGS were published and unpublished data previously generated for mineral resource appraisals of the Holy Cross, Mount Massive, Maroon Bells–Snowmass, Hunter-Fryingpan, and Porphyry Mountain Forest Service Wilderness Study Areas, the Gore–Eagles Nest and the Flat Tops Primitive Areas, the Bull Gulch, Eagle Mountain and Hack Lake BLM Wilderness Study Areas, and the Williams Fork Roadless Area (table 3).

METHODS OF STUDY

Analyses for 39 elements were included in the data, and of these, 15 were selected for primary use in the geochemistry contribution to the assessment of resource potential in the study area. These elements are antimony, arsenic, chromium, cobalt, copper, gold, molybdenum, nickel, lead, silver, tin, tungsten, uranium, vanadium, and zinc. The distributions of barium, beryllium, bismuth, boron, chromium, iron, manganese, and thorium were also examined but were determined to be less significant in the evaluation.

To combine the data from different sample media and analytical methods, a series of mathematical operations were performed on the various data sets. In each sample medium, the distributions of the values of every element were first examined to determine whether they were more closely normal or log-normal. Those variables whose distributions were more approximately log-normal were logarithmically transformed.

Next, "standardized" data sets were created from the resultant data by performing the following operations. The mean of each variable was subtracted from each value, and the result was divided by the standard deviation of the variable. This produced new "standard" values that could then be combined from the various data sets. These values, then, represent the number of standard deviations that the original or log-transformed values deviated from means. At locations where more than one sample was collected, the highest values were chosen for the standardized variables. Values between 2 and 3 in the transformed data were considered to represent slightly anomalous concentrations; values of 3 to 5 were treated as moderately anomalous; and values above 5 were considered highly anomalous. Interpretations were derived from graphical displays that could simultaneously include all available data.

These data were spatially interpolated, and contour plots were produced to provide areal representations of anomalous concentrations of various elements in the study area. Point plots of element suites were also generated to give a detailed accounting of the sample-site locations that contributed to the anomalous areas—these plots also provide a view of associations of elements that are thought to be likely constituents of geochemical submodels of various mineral-deposit types.

The concentration thresholds above which elements were determined to be anomalous in the different sample media are listed in table 4. In some cases, both spectrographic and chemical analyses were performed for the same element, and the corresponding threshold values are so noted.

Examination of samples containing elevated concentrations of base and precious metals and related elements revealed that their locations are mostly in the proximity of known mining districts and mineral-deposit occurrences. Following is a description of the anomalies found within the Forest and those found close to the Forest, outside of its boundary. The spatial context of these samples is provided, when applicable, in terms of known areas of deposits; otherwise, the anomalies are geographically referenced. The general locations of most of the known areas are provided in figure 7 and can be seen in greater detail in a paper by Brown (1990).

RESULTS

FRISCO DISTRICT AND MINERALIZED AREA

Anomalies of gold, cobalt, copper, nickel, lead, tin, and zinc were present in this area. Gold, cobalt, lead, nickel, and zinc were found in stream-sediment samples examined during the NURE Program (hereafter referred to as NURE stream-sediment samples) at slightly anomalous concentrations; cobalt and nickel concentrations were also determined to be slightly elevated at two rock-sample locations. Tin was present in highly anomalous concentrations in three NURE stream-sediment samples. Anomalies are most likely related to quartz-sulfide veins in shear zones in Proterozoic migmatite.

MONTEZUMA DISTRICT

Numerous geochemical anomalies were found that were associated with the Montezuma mining district in the eastern part of the Forest. Elements found in elevated concentrations were gold, silver, cobalt, copper, molybdenum, nickel, lead, antimony, tin, tungsten, and zinc. Silver was found in a slightly anomalous amount in a heavy-mineral concentrate, at low and moderately anomalous levels in rock samples, and at moderate and high levels in NURE stream-sediment samples. Gold was present in moderately anomalous concentrations in a NURE stream-sediment sample and at a highly anomalous level in a heavy-mineral concentrate. Cobalt was found to be anomalous at low levels in heavy-mineral-concentrate and rock samples and at moderate levels in rock and NURE stream-sediment samples. Low-level copper anomalies were found in heavy-mineral-concentrate, NURE stream-sediment, and rock samples; moderate-level anomalies were found in NURE stream-sediment and rock samples; and high-level copper anomalies were determined in four NURE stream-sediment samples. One rock sample contained a slightly anomalous concentration of molybdenum; low to moderately anomalous levels were also found in several heavy-mineral concentrates. Low-level nickel anomalies were found in two panned concentrates, in two NURE stream-sediment samples, and at two rock-sample locations. Lead was found at low-anomaly levels in concentrate, stream-sediment, NURE, and rock samples and at moderate levels in rock and NURE stream-sediment samples. Antimony was determined to be present in slightly anomalous concentrations in NURE stream-sediment samples and at moderately and highly anomalous levels in NURE stream-sediment samples and rock samples. A low-level tin anomaly was found in one panned concentrate and in one stream-sediment sample; moderate levels of tin occurred in two NURE stream-sediment samples, and a highly anomalous level was found in one NURE stream-sediment sample and at one rock-sample location. Tungsten was determined at low to moderately anomalous concentrations in 12 heavy-mineral concentrates and at low to highly anomalous levels in 10 NURE steam-sediment samples. Zinc was determined at low and moderate anomaly levels in NURE stream-sediment and rock samples, and six heavy-mineral concentrates associated with the area also showed low-level enrichment.

Anomalies in the Montezuma area are likely related to veins in Proterozoic rocks and in a Tertiary quartz monzonite porphyry stock.

BRECKENRIDGE DISTRICT AND MINERALIZED AREA

Anomalous concentrations of silver, arsenic, gold, cobalt, copper, nickel, lead, antimony, tungsten, and zinc were found in samples associated with this area. One NURE stream-sediment sample contained moderately anomalous amounts of silver. Arsenic was found at low and moderate levels in NURE stream-sediment samples and at moderate and high levels in stream-sediment samples. Gold anomalies were found in five NURE stream-sediment samples at low,

Table 4. Concentration thresholds above which elements were considered anomalous in different sample media.

[Values in parts per million. If both spectrographic and atomic absorption analyses were performed for the same element, both threshold values are noted. S, threshold value for spectrographic analysis; aa, threshold value for atomic absorption analysis; n.a., not available]

Element	Stream-sediment samples	Heavy mineral concentrates	NURE stream-sediment samples	Rock samples
Ag	1	5	5	70
As	500	300	28	100 s 100 aa
Au	10	40 s 3.6 aa	0.19	10 s 0.15 aa
Co	30	100	23.6	50
Cr	150	1,500	158	300
Cu	200	150	87	1,000
Mo	20	50	n.a.	50
Ni	200	200	45	150
Pb	300	1,500	113	2,000
Sb	70	200	4	150 s 2 aa
Sn	15	100	11	15
U	n.a.	n.a.	21.83	966 aa
V	200	1,000	174	500
W	200	150	16	300
Zn	300	700	551	2,000 s 130 aa

moderate, and high levels. One stream-sediment and two NURE stream-sediment samples contained cobalt in slightly anomalous concentrations, and a moderately high value was determined in one stream-sediment sample. Slightly to moderately anomalous amounts of copper, low-level nickel anomalies, low to moderately anomalous amounts of lead, and low- and high-level antimony anomalies were found in NURE stream-sediment samples. A high-level tungsten anomaly was determined in one stream-sediment and three NURE stream-sediment samples. NURE stream-sediment samples also contained slightly to moderately anomalous amounts of zinc.

Geochemical anomalies in the Breckenridge district are related to ore deposits found in veins in monzonite porphyry, quartzite, and shale; stockwork deposits in quartz monzonite; replacement deposits in the Maroon Formation and Dakota Sandstone; and placer deposits.

UPPER BLUE RIVER DISTRICT

Highly anomalous concentrations of silver and tungsten, low to moderately anomalous amounts of lead, and slightly anomalous concentrations of zinc were found in NURE stream-sediment samples in this vicinity. These anomalies are likely related to metallic minerals found in veins in crystalline and sedimentary rocks and replacement deposits in Paleozoic and Mesozoic sedimentary rocks.

KOKOMO-TENMILE DISTRICT

Geochemical anomalies for silver, gold, copper, molybdenum, lead, tin, and zinc were found in this vicinity. Silver was found in slightly anomalous concentrations in one NURE stream-sediment sample, and gold was found at high levels in one rock and one NURE stream-sediment sample. A low-level copper anomaly was found in one NURE stream-sediment sample, and a moderately elevated molybdenum concentration was found in one rock sample. Lead was determined in low to moderately anomalous concentrations in NURE stream-sediment samples, and high tin values were found in rock and NURE stream-sediment samples. Two NURE samples contained low and moderately anomalous levels of zinc. Geochemical anomalies in the Kokomo-Tenmile district are likely related to ore minerals in replacement deposits in the Minturn Formation and, to a minor extent, to veins in crystalline and sedimentary rocks.

TENNESSEE PASS DISTRICT

Three rock-sample locations in this area showed low-level arsenic anomalies, and gold was determined at low and moderately anomalous levels in rocks and at a moderately elevated concentration in a NURE stream-sediment sample. Cobalt anomalies were found at low to moderate levels at three rock-sample sites, and nickel was found in a slightly anomalous concentration in one rock sample. Antimony at low and moderately high levels was found in rock samples; tin at low and moderately anomalous levels was measured in rock and NURE stream-sediment samples, respectively; and tungsten was found in one rock sample at a slightly anomalous level.

The geochemical anomalies in the Tennessee pass area are related to replacement deposits in the Leadville Limestone, veins in Proterozoic rocks, and veins in the Sawatch Quartzite and Minturn Formation.

HOMESTAKE MINE VICINITY

This area, just east of the Forest at the head of the West Tennessee Creek drainage, contains anomalous concentrations of silver, arsenic, gold, copper, nickel, lead, antimony, and zinc. A highly anomalous concentration of silver was found in a stream-sediment sample, and moderate anomalies were found in one heavy-mineral concentrate and at one rock-sample location. Two rock samples were found to contain slightly and moderately anomalous amounts of arsenic. Slightly anomalous amounts of gold, copper, nickel, and low to moderate anomaly levels of lead were also found in rock samples. One rock contained a slightly elevated antimony concentration, and three others contained highly anomalous amounts of antimony. Zinc concentration was measured at moderately high levels in two rock samples and in one heavy-mineral concentrate.

Geochemical anomalies in this area are related to sulfide-bearing hornblende gneiss and amphibolite.

EAGLE PARK MINERALIZED AREA

Arsenic, cobalt, copper, nickel, antimony, tungsten, and zinc were found in anomalous concentrations in this area. Arsenic was measured at low to moderately anomalous levels in rock samples; cobalt was determined at low and highly anomalous concentrations in rock samples and at moderately and highly elevated levels in heavy-mineral-concentrate and stream-sediment samples. Low-level copper anomalies were found in one stream-sediment sample and in one heavy-mineral concentrate. Slightly anomalous concentrations of nickel was determined in two concentrate and in three rock samples, and a moderately anomalous value was determined in one rock sample. Low-, moderate-, and high-level antimony and tungsten anomalies were found in rock samples, and a moderately anomalous amount of zinc was measured in one stream-sediment sample from the area.

Geochemical anomalies are related to small replacement deposits in the Leadville Limestone and adjacent units and to gold-silver deposits in the Sawatch Quartzite.

GILMAN (RED CLIFF, BATTLE MOUNTAIN, BELDEN) DISTRICT

Geochemical samples from the Gilman district contain anomalous concentrations of silver, arsenic, gold, cobalt, copper, lead, antimony, tin, and zinc. Silver and arsenic were determined at slightly to moderately anomalous levels in rock samples, and silver was found in the high range in one NURE stream-sediment sample. A moderately anomalous gold value was found in one rock sample, and slightly elevated cobalt concentrations were also found in one rock and in one NURE stream-sediment sample. Moderately to highly anomalous copper values and low and high lead anomalies were found in NURE stream-sediment samples. A moderate lead anomaly was also determined from one rock sample. Antimony was determined at low- and high-anomaly levels in rock samples and in the moderately anomalous range in one NURE stream-sediment sample. One high tin value was determined from a rock sample, and another high value was determined in a NURE stream-sediment sample collected downstream from the area. Elevated zinc concentrations were found at low levels in stream-sediment and NURE stream-sediment samples, in the moderate range for one NURE stream-sediment and one rock sample, and in the high range for one NURE stream-sediment sample.

The geochemical anomalies in this area are related to carbonate replacement deposits in the Leadville Limestone.

FULFORD DISTRICT–NEW YORK LAKE MINERALIZED AREA

Silver, gold, arsenic, cobalt, copper, molybdenum, nickel, lead, antimony, tin, and zinc were found in anomalously high concentrations in this vicinity. Silver was determined at a slightly anomalous level in one heavy-mineral concentrate, and arsenic concentrations were found to be slightly anomalous in 16 and moderately anomalous in 14 rock samples. Slightly anomalous amounts of gold were found in one heavy-mineral concentrate and in two rocks, and moderately anomalous gold concentrations were found at three rock-sample locations. Slightly to moderately elevated cobalt and copper levels were measured in rock samples, and one heavy-mineral concentrate also contained a slightly anomalous copper concentration. Low-level molybdenum anomalies were determined in two stream-sediment and two rock samples, and nickel was also found in slightly anomalous amounts in four heavy-mineral concentrates and in two rock samples. A slightly elevated lead concentration was measured in one heavy-mineral-concentrate sample, and antimony was found at moderate levels in two rock samples. Two rocks contained slightly anomalous tin amounts, and slightly elevated zinc concentrations occurred in one heavy-mineral concentrate.

The geochemical anomalies in this area are related to veins in Paleozoic sedimentary rocks and Proterozoic basement rocks and to replacement deposits in Cambrian sedimentary rocks. Gold has also been found in this area in quartz-pegmatite veins in Proterozoic migmatite (Brown, 1990).

EAST LAKE CREEK–CROSS CREEK MINERALIZED AREA

This area, in the Holy Cross Wilderness, contains geochemical anomalies for silver, arsenic, gold, cobalt, copper, molybdenum, nickel, lead, antimony, tungsten, and zinc. Four rock samples showed slightly anomalous silver concentrations, and one stream-sediment sample yielded a moderately high value. Low-level arsenic anomalies were determined from four rock-sample sites, and a moderately anomalous value was determined from another. Gold was found in moderately anomalous concentrations in three rock samples and in slightly anomalous concentrations in three heavy-mineral concentrates. One NURE stream-sediment sample contained slightly elevated cobalt concentrations, and a low-level copper anomaly was found in one NURE stream-sediment sample and in one rock; moderately high copper concentrations were determined in rocks from three locations. Heavy-mineral concentrates at 10 sample locations showed slightly elevated nickel concentrations. Lead concentration in rocks ranged from slightly to moderately anomalous at seven locations, and antimony was also found at low to high levels at seven rock-sample sites. Tungsten was measured in the lower anomalous range in one heavy-mineral concentrate and was determined in the high range for one rock sample. Slightly anomalous zinc was found in one heavy-mineral concentrate sample, two stream-sediment samples, and three rock samples; moderately high zinc was determined from two rock-sample locations.

Geochemical anomalies in this area are related to veins in Proterozoic granite, gneiss, and migmatite.

MIDDLE MOUNTAIN MINERALIZED AREA

This area, which has been prospected for a porphyry molybdenum deposit, contains geochemical anomalies for silver, gold, cobalt, copper, molybdenum, nickel, lead, antimony, tin, and tungsten. Low-level silver anomalies were determined from three rock-sample locations, and a low-level gold anomaly was determined in one rock sample. Cobalt was measured at low levels in two stream-sediment and two rock samples, at a moderate level in one rock sample, and at a high level in one stream-sediment sample. Slightly to moderately high copper concentrations were determined from seven stream-sediment samples and four rock locations and was found in the slightly elevated range in one heavy-mineral concentrate. Molybdenum anomalies were found at lower levels in two heavy-mineral concentrates, in five stream sediments, and at nine rock-sample sites; molybdenum was found at moderately high levels in two stream-sediment samples and at nine rock-sample locations; and molybdenum was found at a highly anomalous value in one rock sample. A slightly anomalous nickel concentration was determined in one rock sample, and lead was measured at slightly to moderately high concentrations in four rock samples. One rock sample showed a slightly elevated concentration of antimony, and another contained a moderately high concentration. A low-level tin anomaly was found in one rock sample, and a low-level tungsten anomaly was measured in one NURE stream-sediment and at three rock-sample sites.

Mineralized rock in this area occurs in shear zones, veins, and quartz stockwork in Proterozoic migmatite and granite.

HOLY CROSS CITY DISTRICT–CROSS CREEK MINERALIZED AREA

Numerous anomalies of silver, arsenic, gold, cobalt, copper, molybdenum, nickel, lead, antimony, tin, tungsten, and zinc were found in this area. Slightly to moderately anomalous concentrations of silver were found in sediment, rock, and NURE stream-sediment samples. One rock sample contained moderately anomalous concentrations of arsenic, and gold was determined to be anomalous in the low to moderate ranges in nine heavy-mineral concentrate, two NURE stream-sediment, and eight rock samples; gold was found at highly anomalous levels in one NURE stream-sediment and one rock sample. Cobalt was measured at low-anomalous concentrations in three sediment and six rock samples and at moderately high levels in one rock and one NURE stream-sediment sample. Slightly anomalous concentrations of copper were determined in one heavy-mineral concentrate, four stream-sediment samples, one NURE stream-sediment sample, and four rock samples; moderately high levels were found in one heavy-mineral concentrate and in three rock samples; and one NURE stream-sediment sample had a highly anomalous concentration of copper. Molybdenum in slightly anomalous concentrations was found in one rock sample and in one stream-sediment sample and was determined at a moderately high level in one rock sample. Low-anomaly levels were found for nickel in one NURE stream-sediment and two rock samples. Low to moderate lead anomalies were measured in three rock samples, and a highly anomalous concentration of antimony was found at one rock-sample site. Tin anomalies were found at low levels in one heavy-mineral concentrate, two stream-sediment samples, and one rock sample; they were found at a moderate level in two heavy-mineral concentrates; and they were found at a high level in one NURE stream-sediment sample. One heavy-mineral concentrate contained a slightly anomalous level of tungsten, and one NURE stream-sediment sample contained a highly anomalous level. Zinc was found at low levels in one rock sample and in one heavy-mineral concentrate from Cross Creek, downstream from the mineralized area. A moderately anomalous zinc concentration was also found in another rock sample.

Mineralization in this area occurred in veins and fractures in Proterozoic gneiss, schist, granite, and migmatite, extending from upper West Tennessee Creek to Fulford.

GOLD PARK AND VICINITY NORTH OF HOMESTAKE PEAK

Samples in this area showed anomalous concentrations of silver, copper, lead, antimony, tin, and zinc. Slightly anomalous values of silver, copper, antimony, and tin and moderately high lead, tin, and zinc values were found in rock samples. A moderately anomalous zinc concentration was also measured in one stream-sediment sample. Geochemical anomalies in this area are related to a northwest-trending belt containing abundant Laramide intrusive rocks, veining, and major and minor fracture systems (Wallace and others, 1989).

NEW YORK MOUNTAIN–GOLD DUST PEAK–UPPER EAST LAKE CREEK VICINITY

This area is also part of the northwest-trending zone containing Laramide intrusives and numerous veins, fractures, and shear zones—this area hosts deposits in other known districts and mineralized areas described above (Wallace and others, 1989). Geochemical anomalies include highly elevated silver concentrations in six stream-sediment samples. A slightly anomalous concentration of arsenic was found in one rock sample, and slightly anomalous concentrations of gold were found at two rock-sample locations. Cobalt was measured at low-anomaly levels in two rocks and in one NURE stream-sediment sample. One heavy-mineral concentrate and one rock were found to contain slightly anomalous amounts of copper, and low to moderately anomalous molybdenum levels were found at three rock-sample locations.

TIMBERLINE LAKES

Stream-sediment samples in this vicinity, just outside the Forest in the Holy Cross Wilderness, were determined to contain slightly anomalous concentrations of silver, lead, and zinc. One heavy-mineral concentrate also contained highly anomalous amounts zinc.

Geochemical anomalies are related to deposits in and around a Tertiary rhyodacite to rhyolite intrusive complex with related breccias. The intrusive complex and surrounding Proterozoic rocks are altered to a quartz-sericite-pyrite assemblage (Wallace and others, 1989).

INDEPENDENCE DISTRICT

Silver, gold, arsenic, copper, antimony, tin, and tungsten were found to be associated with the Independence district. Silver anomalies at low and high levels and copper at low and moderate levels were found in NURE stream-sediment samples in the area. Two moderately high gold anomalies were found in NURE stream-sediment samples that were collected downstream from the district, and a rock sample that had a highly anomalous concentration of gold was found in a quartz-vein prospect at Independence Pass. A slightly elevated arsenic value was determined from one stream-sediment sample. A moderately high concentration of copper was determined from one rock sample, and a highly anomalous concentration of antimony was also determined from one rock sample. Weakly and highly anomalous concentrations of tin were found in two stream-sediment samples. A slightly elevated value of tungsten was measured in one heavy-mineral concentrate and in one NURE stream-sediment sample.

Geochemical anomalies in the Independence district are likely related to metal-bearing veins in Proterozoic schist that are associated with a fault system related to the northern part of a ring-fracture zone associated with the Grizzly Peak Caldera.

SOUTH FORK OF THE FRYINGPAN RIVER AND VICINITY

Elevated concentrations of silver, arsenic, molybdenum, lead, tin, and zinc were found in samples from this area. One stream-sediment sample in the upper part of the drainage contained highly anomalous concentrations of silver along with moderately anomalous amounts of lead, tin, and zinc. A moderately anomalous concentration of arsenic was determined in a heavy-mineral concentrate from the same site. Another stream-sediment sample, which was collected from sediment not far downstream, contained a slightly anomalous amount of molybdenum. One rock sample with a slightly anomalous amount of cobalt was collected from the ridge to the west of the drainage.

Although the source of these anomalies is not known, Tertiary dikes and faults are mapped in the vicinity (Tweto and others, 1978)—dikes could possibly account for isolated occurrences. The area is also in close proximity to the Independence district.

FRYINGPAN RIVER DRAINAGE

Isolated anomalies of cobalt, copper, molybdenum, nickel, tin, and zinc were found in this vicinity. One heavy-mineral-concentrate sample in Chapman Gulch contained a slightly elevated concentration of copper, and another had low-level amounts of zinc and moderate amounts of silver. One stream-sediment sample collected south of the inlet of Reudi Reservoir contained moderately anomalous amounts of silver and copper and highly anomalous amounts of molybdenum. Two low-level cobalt, one nickel, and three tin anomalies were from isolated rock-sample locations. Tin was found at a low-anomalous level in one stream-sediment sample from Martin Creek and at a moderately anomalous level in one heavy-mineral concentrate collected from the North Fork of the Fryingpan River. One stream-sediment sample from a northern tributary of the upper part of the Fryingpan River basin (which drains part of the ridge north of Independence Pass) contained a slightly anomalous amount of arsenic. This probably reflects minor metal occurrences, which are common in the small silicic veins associated with fractures in the Proterozoic rocks in the vicinity (Van Loenen and others, 1989).

The Homestake shear zone passes through this area, and geochemical anomalies may be related to associated fracture filling. The scattered and isolated distribution of geochemical anomalies in this area is not suggestive of significant mineral deposits in the vicinity.

LINCOLN GULCH (RUBY) DISTRICT

Anomalies of silver, cobalt, copper, lead, and zinc were found in this area. Highly and moderately anomalous silver values were found in two NURE stream-sediment samples that were collected not far downstream from the district. Cobalt in slightly to moderately anomalous concentrations and copper at moderate and high levels were also found in NURE stream-sediment samples associated with the area. Copper was also determined in a slightly anomalous concentration at one rock-sample location. Lead and zinc occurred in slightly elevated amounts in NURE stream-sediment samples.

The geochemical anomalies in the area are likely related to metal-bearing veins in and near the Lincoln Gulch fault; these veins are mostly in a rhyolite tuff breccia.

ASPEN (ROARING FORK) DISTRICT AND VICINITY

The Aspen district contains anomalous concentrations of silver, gold, cobalt, copper, nickel, lead, antimony, tin, and zinc. High-level silver anomalies were found in three NURE stream-sediment samples, and a moderate-level arsenic anomaly was measured for one rock-sample location. Moderately high amounts of gold were also found in three NURE stream-sediment samples. Two rocks contained slightly elevated concentrations of cobalt, and one rock sample was determined to have a low-level amount of copper. Moderately to highly elevated concentrations of copper were also found in two NURE stream-sediment samples. A low-level amount of nickel was found in one rock sample, and slightly to moderately anomalous lead concentrations were found at four rock-sample sites. Low-, moderate-, and high-level anomalies of lead were also found in six NURE stream-sediment samples. Two NURE stream-sediment samples showed highly anomalous amounts of antimony, and one rock sample contained a slightly elevated concentration. Two stream-sediment samples and two rock samples contained low-level anomalous tin concentrations; one heavy-mineral concentrate and one rock sample had moderately high abundances of tin; and one NURE stream-sediment sample was highly anomalous in tin. Low, moderate, and high zinc concentrations were measured in four rock samples and in five NURE stream-sediment samples.

The Aspen area contains a belt of Tertiary intrusives and ore deposits controlled by Proterozoic shear zones. Geochemical anomalies in this area are related to replacement deposits in the Leadville Limestone and Belden Formation and, to a lesser extent, polymetallic veins.

COLUMBIA-ASHCROFT DISTRICT

The concentrations of silver, gold, cobalt, copper, lead, antimony, tungsten, and zinc were anomalous in samples from this area. Silver concentrations were moderately anomalous in one heavy-mineral concentrate and in one NURE stream-sediment sample. Slightly anomalous amounts of gold was found in one stream-sediment sample and in one NURE stream-sediment sample; a moderately high concentration was determined in another NURE stream-sediment sample. Cobalt and copper concentrations were at slightly elevated levels in stream-sediment and NURE stream-sediment samples. One NURE stream-sediment sample contained low-level amounts of lead; one was determined to have slightly anomalous amounts of antimony; and one contained low-level concentrations of tungsten. Moderately high zinc values were measured in two stream-sediment samples.

Ore deposits in this area are, as in the Aspen district, in the form of replacement deposits and veins. The geochemical anomalies in this area are likely related to these deposits.

HUNTER PEAK (EAST MAROON–CONUNDRUM–CATARACT CREEK) MINERALIZED AREA

Samples from this area contain anomalous concentrations of silver, arsenic, gold, cobalt, copper, molybdenum, antimony, tin, and zinc. Low- to moderate-level concentrations of silver were found in four rock samples and in three stream-sediment samples in the area. One rock sample contained slightly elevated amounts of arsenic. Gold concentrations were in the low range in one stream-sediment sample and in two rock samples; concentration was at a moderate level in one rock sample. The concentration of cobalt was at slightly anomalous levels in one heavy-mineral concentrate and one rock sample, and at moderate levels in one stream-sediment and two rock samples. Two stream-sediment samples and one NURE stream-sediment sample contained slightly elevated amounts of copper, and moderately anomalous amounts were determined from two stream-sediment samples and one rock sample. Molybdenum concentrations spanned the low-, moderate-, and high-anomaly ranges in four stream-sediment samples and for seven rock samples within this area. Antimony concentrations in three rock samples ranged from slightly to moderately anomalous. Low-level anomalies of tin and zinc were found in one rock sample each. Moderate and high anomalies were found for zinc in two stream-sediment samples. Moderately high vanadium concentrations were measured in two stream-sediment samples.

Ore deposits in this area are associated with fractures, shear zones, quartz veins, and sericitic and pyritic alteration in the granodiorite of the White Rock pluton and surrounding hornfels. The geochemical anomalies are likely related to these deposits.

CRYSTAL RIVER (SNOWMASS MOUNTAIN) DISTRICT

Samples from this area contain anomalous concentrations of silver, gold, copper, nickel, lead, and zinc. A slightly anomalous amount of silver was found in one NURE stream-sediment sample, and gold was found in low-level amounts in one heavy-mineral concentrate and in one NURE stream-sediment sample. One NURE stream-sediment sample had a low copper concentration; one had moderate; and one had high. Slightly to moderately anomalous concentrations of lead were found in three NURE stream-sediment samples, two of which also had slightly to moderately anomalous amounts of zinc. Two NURE stream-sediment samples showed slightly elevated concentrations of nickel, one of which also contained slightly anomalous amounts of vanadium. Low-level concentrations of vanadium were also found in another NURE stream-sediment sample. These vanadium anomalies are hosted by the Cretaceous and Jurassic sedimentary rocks in the area (Wallace and others, 1988).

The geochemical anomalies in this area are likely related to metal-bearing veins in faults and fissures in sedimentary rocks along the flank of the Treasure Mountain dome.

SNOWMASS CREEK MINE VICINITY

Samples collected in this area, near the intersection of the Forest boundary with Snowmass Creek, about 8 mi west of Aspen, contained anomalous concentrations of silver, arsenic, cobalt, copper, molybdenum, lead, and zinc. Two rock samples were found to have slight and moderate silver anomalies. Low-level anomalies of arsenic, cobalt, copper, and zinc were also found in rock samples; one moderately high molybdenum concentration was determined from a rock sample. Slightly anomalous copper, lead, and vanadium values were also found in stream-sediment samples. These anomalies are related to ore minerals found along the Snowmass Creek fault zone in the form of sulfide replacement of carbonaceous material (Bryant, 1979).

CARBONATE DISTRICT

One NURE stream-sediment sample in this area contained highly anomalous concentrations of tin, and a slightly elevated amount of tungsten was found in another NURE stream-sediment sample.

Deposits in this district are replacement deposits in carbonate rocks.

RIFLE CREEK DISTRICT

Geochemical sampling density was lower in this area than in other parts of the Forest. However, a slightly anomalous concentration of antimony was found in one rock sample. The concentration of vanadium was detected in one NURE stream-sediment sample at a low-anomalous level.

URANIUM PEAK DISTRICT

Rock samples collected in this area contain moderately to highly anomalous vanadium concentrations, and one of the samples also contained highly anomalous amounts of tin.

OTHER OCCURRENCES

Silver.—One highly anomalous NURE stream-sediment sample was collected from Willow Creek, on the east side of the Gore Range near Silverthorne. This stream drains the Red Peak area, which, like much of the range, contains small veins and shear zones that are likely to exhibit metal anomalies (Tweto and Lovering, 1977). A low-level anomaly was found in a NURE stream-sediment sample in the southwest part of the Forest, in eastern Mesa County near Haystack Mountain, and a moderate anomaly was found near the mouth of West Lake Creek, south of Edwards. Neither of these occurrences is related to any known mining districts (Wallace and others, 1988).

Gold.—A moderate anomaly of unknown origin was found in a NURE stream-sediment sample in upper West Tenmile Creek, near Vail Pass. Two isolated anomalies, one high and one moderate, were found in NURE stream-sediment samples from the upper drainage basin of Buzzard Creek, just outside the Forest in eastern Mesa County in an area covered by continental clastic sedimentary rocks of early Tertiary age (Wallace and others, 1988). A low-level anomaly in a NURE stream-sediment sample collected from Gore Creek may have been derived from the commonly occurring small veins and fractures in the Proterozoic rocks that crop out upstream (Tweto and Lovering, 1977). The origin of another low-level anomaly in a NURE stream-sediment sample from the Middle Creek drainage on the west side of Bald Mountain, north of Vail, is unknown.

Cobalt.—A slightly anomalous concentration of cobalt was found in an isolated NURE stream-sediment sample in the southwestern part of the Forest, near Red Mountain, but nearly all of the anomalous samples not associated with known deposits were concentrated in the northern White River Plateau and Flat Tops Wilderness. These are related to the Tertiary basalt flows that cover that area (Tweto, 1976; Tweto and others, 1978). Seventeen NURE stream-sediment samples and two rock samples had slightly anomalous concentrations of cobalt, and seven other NURE stream-sediment samples in that area contained moderately anomalous concentrations.

Chromium.—Although broadly scattered throughout the Proterozoic terrane in the eastern part of the Forest, anomalies are densely concentrated in the northern White River Plateau and Flat Tops Wilderness and have spatial distribution similar to that of nickel and cobalt. These anomalies are, likewise, strongly associated with the Tertiary basalt flows covering the area. Thirty-seven NURE stream-sediment and two rock samples contained slightly anomalous concentrations of chromium, and seven NURE stream-sediment samples had moderate chromium anomalies in the area.

Copper.—The source of a moderately anomalous concentration in a NURE stream-sediment sample from West Maroon Creek is not known, although mineralized districts are present within several miles of the general area. This vicinity also has frequent human traffic which increases the likelihood of contamination.

Nickel.—One slightly anomalous NURE stream-sediment sample was located in Black Gore Creek, and another came from the upper part of Red Sandstone Creek, on the west side of the Gore Range. This anomaly might be associated with the small mafic dikes that are occasionally found in that area or with the mafic portions of the predominant migmatite. A low-level NURE stream-sediment-sample anomaly also occurs at the Forest boundary, south of Cottonwood Peak, and is associated with a Tertiary basalt flow. A moderately high concentration was found in a NURE stream-sediment sample on East Brush Creek, near Fulford. A heavy-mineral concentrate that was slightly anomalous in nickel was collected from Grouse Creek, near Minturn. A rock sample that had a slightly anomalous concentration of nickel was from the mafic portion of migmatite near the Mount of the Holy Cross. Low and moderately anomalous concentrations were found in three rock samples along the Forest boundary (near Deer Mountain, southwest of the head of the Fryingpan River). Most of the anomalous nickel values were not associated with known deposits. However, most of the samples were densely concentrated in the northern White River Plateau and the Flat Tops Wilderness, where they are associated with Tertiary basalt flows (Tweto, 1976; Tweto and others, 1978). Twenty-eight slightly anomalous and 12 moderately anomalous concentrations were found in NURE stream-sediment samples in that area along with two slightly anomalous concentrations in rock samples (fig. 9).

Tin.—Several, mostly low-level, anomalies that are unrelated to known deposits were scattered throughout the 1.4-Ga granitic terrane that includes the Silver Plume and St. Kevin Granites and equivalents. These scattered, isolated anomalies probably reflect a relatively high background in these rocks —the anomalies probably do not suggest mineralization of any significance.

Uranium.—The known distribution of uranium was based on NURE stream-sediment sampling. Low-level anomalies are scattered broadly in a northeast-trending zone in the southeastern part of the Forest. This zone is predominantly in Proterozoic igneous and metamorphic rocks in the Colorado Mineral Belt. The samples with the highest concentrations (moderately anomalous) are found in the Roaring Fork River, just upstream from Aspen; in Chapman Gulch, southeast of Reudi Reservoir; in Homestake Creek (two samples); in upper West Tenmile Creek, near Vail Pass; in upper Straight Creek; in the North Fork of the Snake River; in Bighorn Creek and upper Slate Creek, in the Gore Range; and in Monte Cristo Creek, a western tributary of the head of the Blue River. It is interesting to note that these higher values occur in locations that can be seen as two sublinear trends. The Roaring Fork, Chapman Gulch, and Homestake Creek anomalies follow the Homestake shear zone quite closely. Moreover, the West Tenmile and Straight Creek sites fall fairly close to a northeastward extension of this trend. The Gore Range, West Tenmile, and Monte Cristo Creek samples, on the other hand, can be envisioned as following a northerly trend subparallel to, and offset to the east of, the Gore fault. Although these rough correlations may be fortuitous, it is not unreasonable to suppose that fracture zones provide increased favorability, if not control, for vein-type uranium occurrences or deposits. No uranium anomalies were found west of Aspen.

Vanadium.—With the exception of NURE stream-sediment samples and the vanadium anomalies already mentioned in association with known mineralized areas, the anomalies in rock, stream-sediment, and heavy-mineral-concentrate samples (nearly all low-level anomalies) were found to be broadly distributed throughout the Holy Cross Wilderness and in the northern part of the Montezuma mining district. Most of the NURE stream-sediment-sample anomalies (mainly low-level anomalies) were in streams draining areas

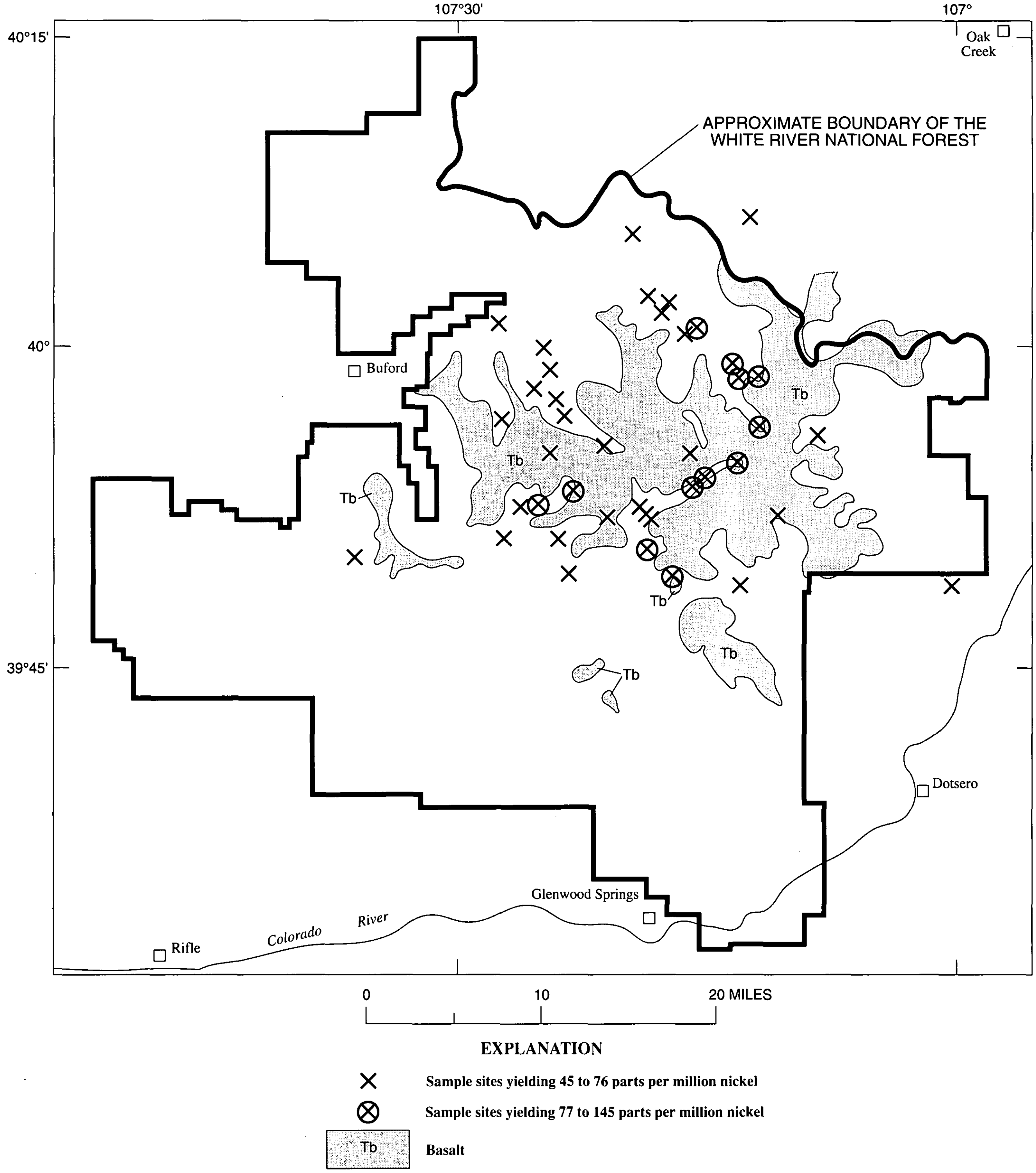


Figure 9. Map showing anomalous nickel concentrations in stream-sediment and rock samples in the western part of the White River National Forest, Colorado.

covered by sedimentary rocks of Paleozoic or younger age (Wallace and others, 1988). Sedimentary rocks of Jurassic and Cretaceous age host low-level anomalies found in NURE stream-sediment samples along the Blue River, north of Green Mountain Reservoir; west of the Gore fault, on Sweetwater Creek; in the Piney River drainage, east of Muddy Creek Pass; east of lower Brush Creek, south of the Eagle River; north of Basalt Mountain, on Cattle Creek; and on East Sopris Creek, southwest of Snowmass (Wallace and others, 1988) (fig. 10). Fifteen NURE stream-sediment samples from the western part of the Forest contained slightly anomalous concentrations of vanadium (fig. 10). These anomalies are associated with a north-trending belt of sedimentary rocks of Cretaceous, Jurassic, and Triassic age that are known to host uranium and vanadium deposits elsewhere in Colorado. Two minor anomalies were found in NURE stream-sediment samples located on Little Rock Creek, near Haystack Mountain in eastern Mesa County, in continental sedimentary rocks of early Tertiary age.

Tungsten.—Isolated, low-level anomalies of unknown origin occurred in two heavy-mineral concentrates from Hamilton and North Acorn Creeks, tributaries of the Blue River on the west side of the Williams Fork Mountains. A slightly anomalous concentration was found in a NURE stream-sediment sample that was located along Black Gore Creek, north of Vail Pass, and another, isolated, low-level anomaly was found in a NURE stream-sediment sample from Meadow Creek, north of New Castle.

Zinc.—A slightly anomalous stream-sediment sample was collected from Last Chance Creek, in the Holy Cross Wilderness, and may be related to the quartz veins and shear zone common in a northwest-trending zone that borders the headwaters of this drainage basin.

GEOPHYSICS

INTRODUCTION TO GEOPHYSICAL DATA SETS

Three sets of geophysical data, which include gravity (fig. 11 and pl. 3), aeromagnetic (pl. 4), and radiometric (figs. 14–16) maps, were compiled and interpreted for the area of the White River National Forest and Dillon Ranger District of the Arapaho National Forest. Published accounts of geoelectric work made for groundwater or engineering purposes in and near the Forest are not complete and were not used for this mineral assessment.

GRAVITY DATA

Anomalies shown on the Bouguer gravity anomaly map (fig. 11 and pl. 3) are caused by the juxtaposition of rocks that have measurable density contrasts and are the result of geological features such as faults, folds, downwarps, intrusions, basin fill, lithologic contacts, or facies changes. Gravity measurements were obtained at single stations, and contoured values were mathematically interpolated between stations; therefore, the number and quality of gravity stations limits the accuracy of anomaly definition. Station spacing is often sparse in mountainous terrain, thus limiting the determination of local structures.

The complete Bouguer gravity anomaly map was produced using edited gravity data collected over the past several decades from 6,500 stations; the data were extracted for this study from the Defense Mapping Agency gravity data base, available from the National Geophysical Data Center, Boulder, Colo. These data were projected using a UTM projection having a central meridian of longitude 105°W. and a base latitude of 0°. 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). The data were contoured at 2 mGal using the CONTOUR computer program by Godson and Webring (1982).

A derivative gravity map (pl. 3) was calculated from the Bouguer gravity grid using the computer program FFTFIL (Hildenbrand, 1983) to remove or filter anomaly wavelengths longer than 30 mi. The filter was selected to eliminated 100 percent of the wavelengths greater than 37.3 mi (60 km), to pass 100 percent of the wavelengths less than 24.9 mi (40 km), and to pass a linear percentage of the wavelengths between these values. This derivative map emphasizes anomalies produced by shallow sources and suppresses the longer wavelength anomalies (wavelengths greater than 30 mi or 50 km) that are related to deep sources (such as regional gradients in the Colorado Plateau, in the White River uplift, and in the Colorado Mineral Belt gravity low). Anomalies from this derivative, high-pass filtered map will be discussed by geophysical province. The horizontal gradient of the gravity field was calculated using the method of Cordell and Grauch (1985). The maximum gradient trends are plotted on the contour maps (fig. 11 and pl. 3) as long, 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).

AEROMAGNETIC DATA

Aeromagnetic anomalies are caused by magnetic differences in rocks that contain measurable amounts of magnetic minerals (magnetite being the most common) and reflect variations in the amount of magnetic material and the shape of the magnetic mass. In general, igneous and metamorphic rocks generate magnetic anomalies, and sedimentary rocks are commonly nonmagnetic. However, exceptions occur, such as the positive anomaly caused by iron-rich sediments of Red Table Mountain or the lack of magnetic anomalies associated with some felsic Tertiary stocks in the Sawatch Range that intrude more magnetic terrain.

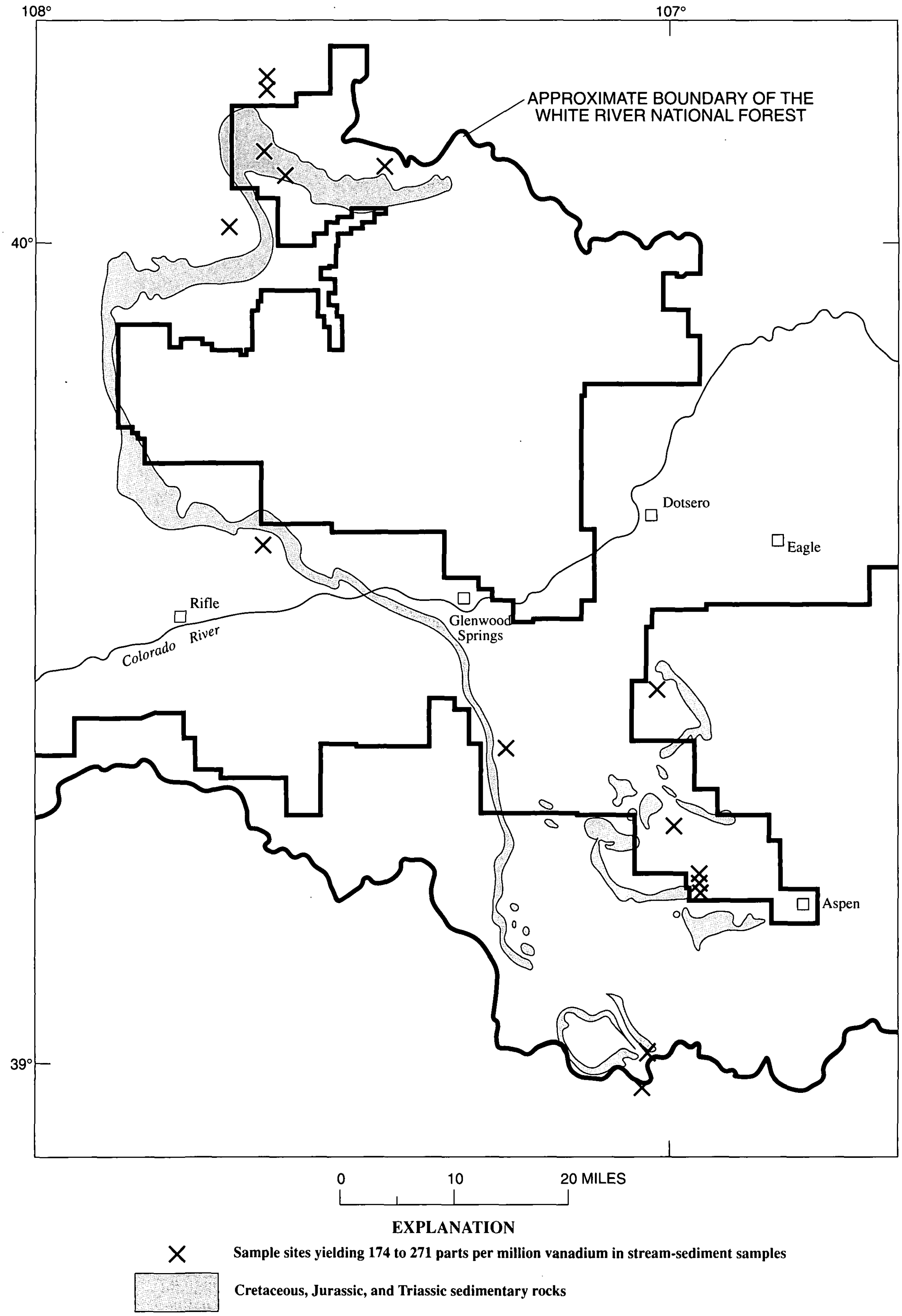


Figure 10. Map showing anomalous vanadium concentrations in stream-sediment samples in the Flat Tops area of the White River National Forest, Colorado.

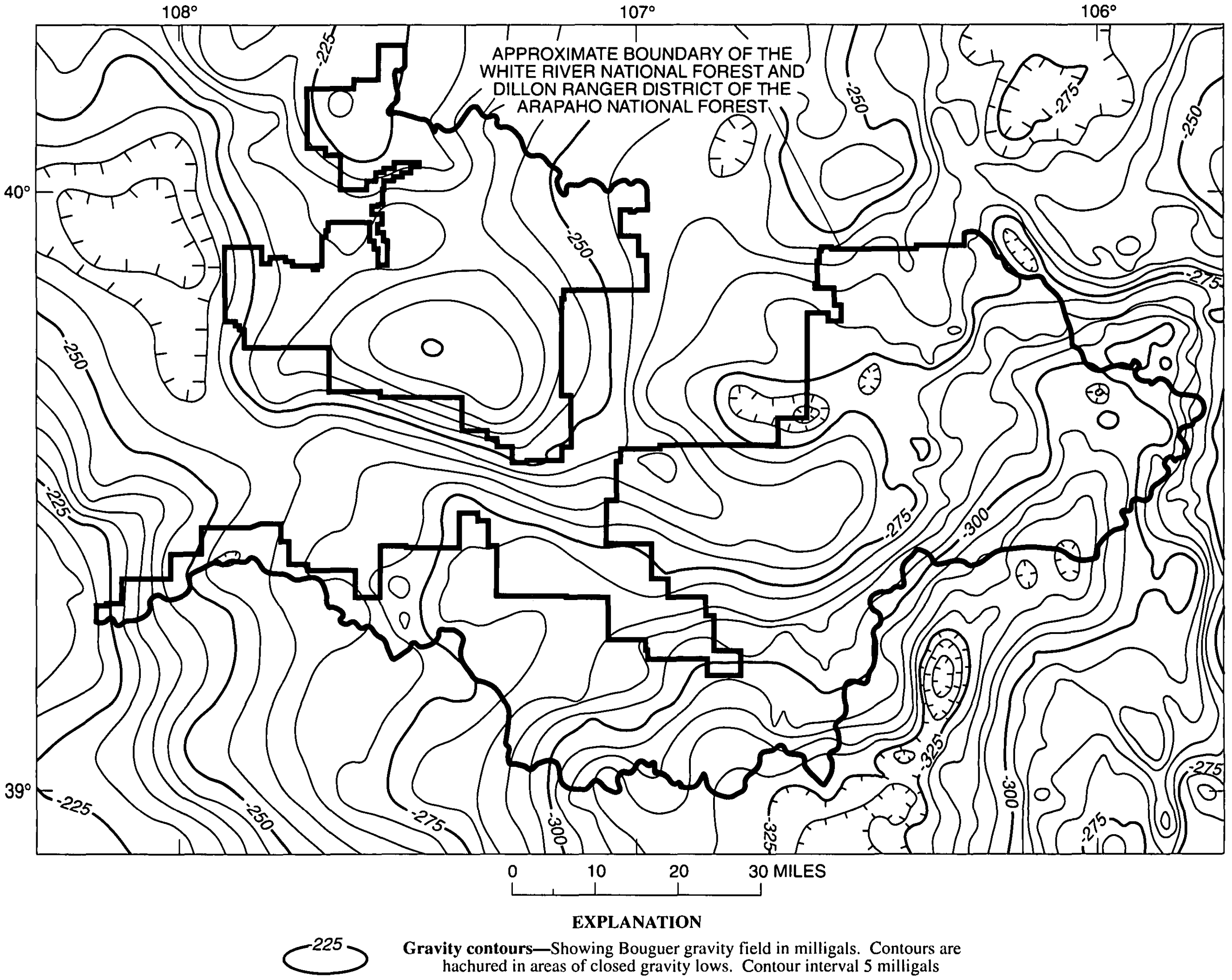
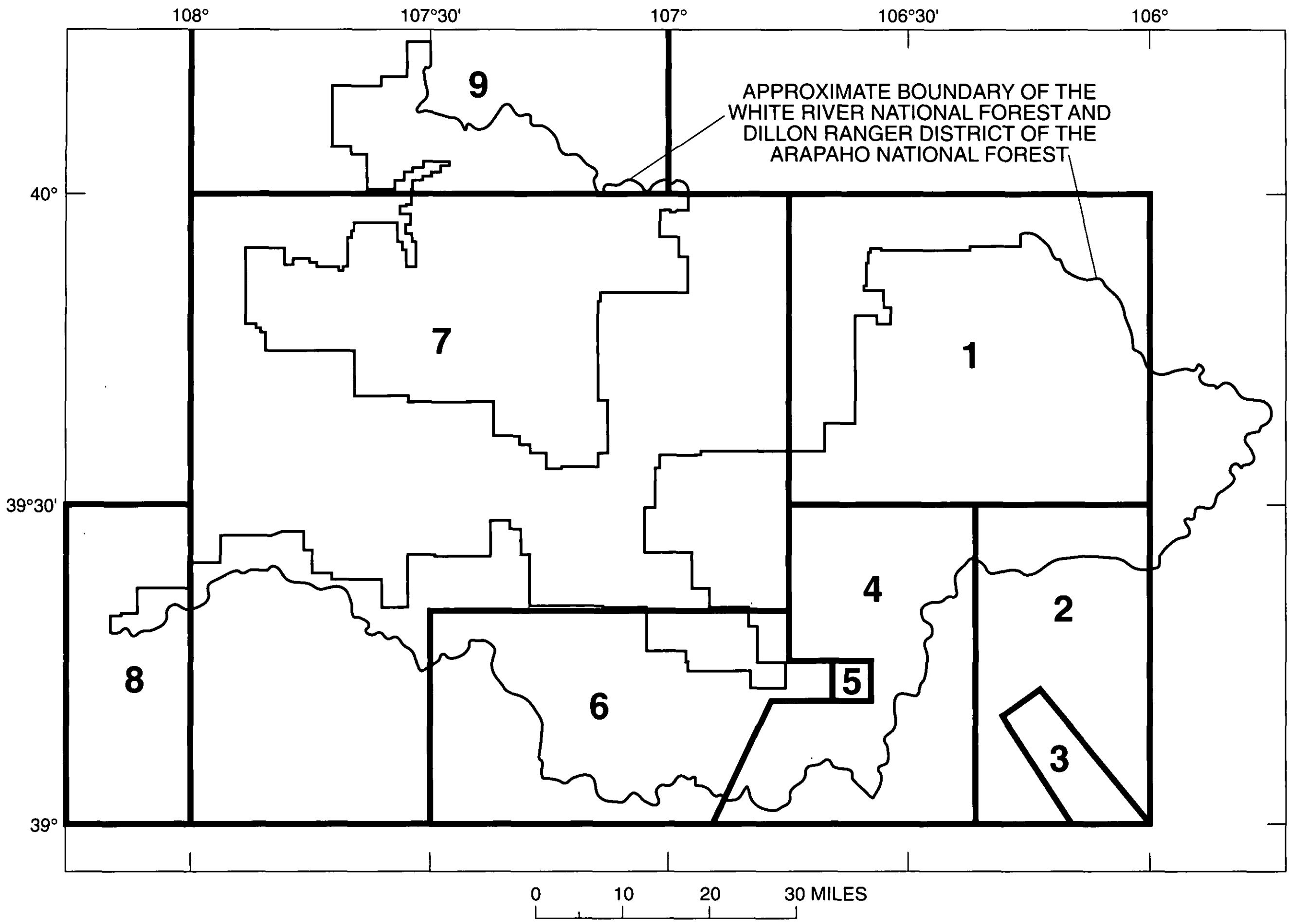


Figure 11. Complete Bouguer gravity anomaly map of the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

Figure 12 is a reference map for aeromagnetic surveys showing location, flight-line spacing and direction, and original flight elevation of surveys that were merged to produce a magnetic anomaly map of the Forest (pl. 4). These data were projected using UTM projection having a central meridian of longitude 105°W. and a base latitude of 0°. The data were gridded at a spacing of 0.3 mi (0.5 km) and contoured at 100 nT (nanoTeslas). The western and northern parts of the Forest are covered by data from NURE surveys that were flown at 3-mi spacing and 400-ft terrain clearance. Using the industry-wide rule of thumb that an airborne survey can detect point sources in a swath on the ground vertically below the aircraft and up to 45° out to each side, we estimate that less than 5 percent of surface sources, and 56 percent of sources at a 4,000-ft depth, were detected by the NURE surveys. Furthermore, the anomaly of a point dipole at 4,000-ft depth has an amplitude that is attenuated by the distance from the measuring instrument (about 0.08 percent as great as it would be if at the surface)—therefore, a point dipole such as this might go undetected. This dipole would be undetected by the older analog surveys that cover the eastern part of the Forest because the pre-digital-era recorders did not have enough dynamic range to record all sources.

The total-intensity magnetic anomaly map (pl. 4) shows regional magnetic anomalies; for more detail, refer to the magnetic maps referenced in figure 12 that are published at a larger scale. The horizontal gradient of the pseudogravity field was calculated using the method of Cordell and Grauch (1985). This method calculates "pseudo" gravity anomalies caused by assumed density contrasts of bodies causing magnetic anomalies; it is used because gravity anomalies are simpler to analyze than magnetic anomalies. Maximum



["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.)]

No. on map	Reference[1]	Spacing (mi)	Dir.	Elevation (ft)	Year flown
1	USGS (1968)	1	E.-W.	14,000 (bar)	1967
2	USGS (1978)	2	E.-W.	14,500 (bar)	1978
3	USGS (1982)	0.5	N. 70° E.	1,000 (a.t.)	1981
4	Godson and others (1985)	0.5	E.-W.	1,000 (a.t.)	1984
5	USGS (1979a)	0.5	N.-S.	1,000 (a.t.)	1978
6	USGS (1979b)	1	E.-W.	14,000 (bar)	1974
7	Geometrics (1979)	3	E.-W.	400 (a.t.)	1978
8	Geodata (1981)	3	E.-W.	400 (a.t.)	1980
9	LKB Resources (1979)	3	E.-W.	400 (a.t.)	1978

[1] See References Cited section of this report for complete citation.

Figure 12. Map showing location of aeromagnetic surveys used to compile aeromagnetic map.

gradient trends of the pseudogravity field are plotted on the contour map (pl. 4) as long, partially discontinuous lines. As described earlier for gravity gradients, these lines often follow geologic boundaries resulting from measurable magnetization contrasts.

RADIOMETRIC DATA

Gamma-ray spectrometer data for the Forest are from airborne surveys from the NURE Program. Measurements detected near-surface (shallower than 20 inches) abundances of the radioelements uranium, potassium, and thorium. The survey was flown by helicopter along east-west lines that were nominally spaced 3 mi apart and draped 400 ft above terrain. Using these specifications, the survey should detect about 5 percent of the gamma-ray point sources exposed at the surface, but it will miss the remaining 95 percent that are between adjacent lines. Because erosion can separate parent and daughter isotopes of U and Th, they are reported as "equivalent" U and Th (eU and eTh, respectively). The contractor-interpreted amounts of K, eU, and eTh were contoured and are shown in figures 14–16. These maps represent flight-line data that are splined and contoured across tracts of unsampled ground between flight lines.

PREVIOUS STUDIES

The White River National Forest is almost completely within the Leadville 1°×2° quadrangle, an area for which a mineral pre-assessment was conducted in 1988. The geophysical compilations made for that report (Wallace and others, 1988) provide some of the information for this report.

Geophysical studies were made for six Forest Service and BLM Wilderness Study Areas within the Forest: the Maroon Bells–Snowmass Wilderness (Campbell, 1985), the Hunter-Fryingpan Wilderness (Campbell, 1981), the Holy Cross Wilderness (Campbell and Wallace, 1986), the Mt. Massive Wilderness (Van Loenen and others, 1989), the Gore Range–Eagle's Nest Wilderness (Tweto and others, 1970), and the Vasquez Peak Wilderness and vicinity (Moss and Abrams, 1985).

Geophysical studies to support mineral resource studies in the Colorado Mineral Belt were made by Case and Tweto (Case, 1965, 1966, 1967; Tweto and Case, 1972). Other geophysical studies include ones by Behrendt and Bajwa (1974) and Isaacson and Smithson (1976). Figure 13 shows areas included in published reports that provide both maps and interpretations of geophysical anomalies.

USING GEOPHYSICS TO DETECT MINERAL OCCURRENCES

GRAVITY ANOMALIES

Gravity stations are usually too widely spaced to define or locate small mineral deposits. Furthermore, density variations caused by a hydrothermal system may not be large, and the geologic setting may often be complex. A detailed gravity survey can fail to detect dense mineralized rock overlain by leached, oxidized, or fractured rock of abnormally low density—a combination resulting in little net gravity expression. On a regional scale, however, gravity can be a useful mapping tool for locating structural breaks and folds and for delineating shallow, buried pediments. Within parts of the Colorado Mineral Belt, gravity measurements have defined broad areas underlain by a low-density composite batholith that is a presumed source of mineralization.

MAGNETIC ANOMALIES

Aeromagnetic data can be used to locate and estimate depths to igneous intrusions that may be related to concealed mineral deposits. Especially intense magnetic lows may indicate intrusions emplaced and solidified during a period of magnetic field reversal; such magnetic lows are associated with some outcrops of Tertiary basaltic rocks on the White River plateau. Older intrusive rocks (such as the Proterozoic rocks) may no longer cause a field-reversal 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 magnetic field of the Earth. Rings of magnetic highs with central or reentrant lows may indicate porphyry systems in which hydrothermal alteration has destroyed preexisting magnetic minerals. Local magnetic highs may exist where hydrothermal alteration or contact metamorphism has created secondary magnetic minerals, as for example in a magnetite-bearing skarn.

All magnetic bodies act as secondary magnets in the Earth's magnetic field and may produce dipole anomalies. In Colorado, polarity effects typically show up as local lows along the northern side of a magnetic high, such as those associated with the Sopris, Snowmass, and White Rock plutons. Sometimes 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 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.

Many of the known mineral deposits in the Colorado Mineral Belt have no distinctive aeromagnetic expression—Climax is one example—suggesting that a lack of magnetic definition does not necessarily downgrade a terrane otherwise deemed favorable for the formation of mineral deposits. Mineral deposits without associated magnetite or pyrrhotite are not expected to create magnetic highs. Deposits may be disconnected from more magnetic roots by subsequent faulting. Other deposits may have lost their early-stage magnetite during subsequent hydrothermal alteration. Tertiary stocks that are less magnetic than the Proterozoic crystalline rocks they intrude create small magnetic lows over the stocks.

RADIOMETRIC ANOMALIES

Near-surface measurements of radioactive intensity and of ratios that are computed from the radioactive elements

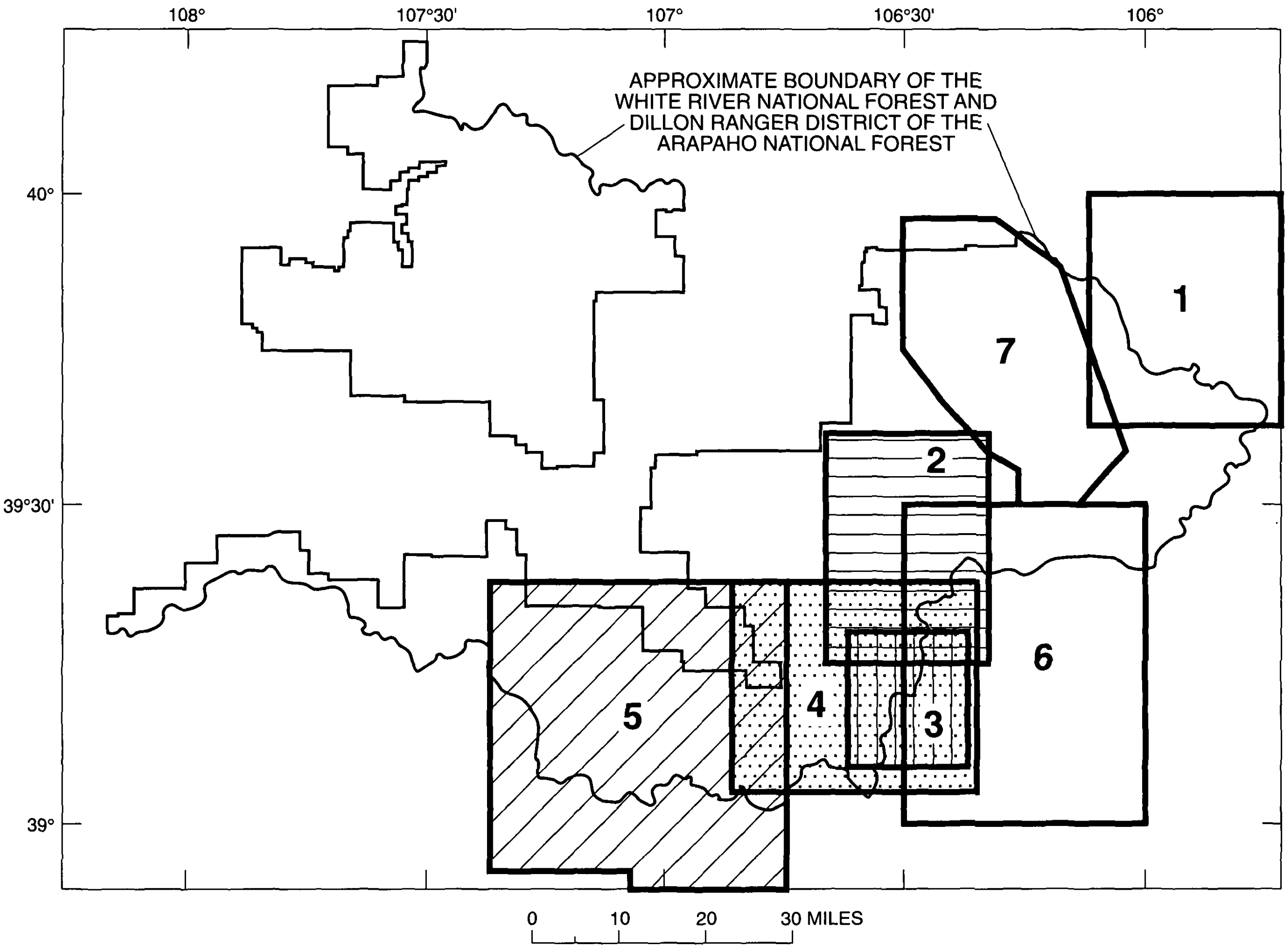


Figure 13. Map showing areas of previous geophysical studies. Numbers on map are keyed to references as follows: 1, Moss and Abrams (1985); 2, Campbell and Wallace (1986); 3, Van Loenen and others (1989); 4, Campbell (1981); 5, Campbell (1985); 6, Tweto and Case (1972); 7, Tweto and others (1970). See References Cited section of this report for complete citations.

uranium, thorium, and potassium can be used to help locate felsic igneous rocks such as granites and rhyolites and certain sedimentary rocks such as uraniferous black shales, immature potassium-rich sandstones, and arkosic rocks. In addition, changes in the ratio of thorium to uranium, which occur naturally in most environments at 4:1, can be used to locate areas of groundwater leaching, high-grade metamorphism, or hydrothermal alteration. Changes in this ratio may be important because uranium may be mobilized in an environment with a high water/rock ratio, whereas thorium migrates less easily. A Th/U ratio greater than 4:1 may indicate uranium depletion, and a Th/U ratio less than 4:1 may indicate uranium enrichment.

PHYSICAL PROPERTIES OF ROCKS

Earlier studies, which provide measurements of density and susceptibility of various rock types, are found in Case (1967), Tweto and Case (1972), Isaacson and Smithson (1976), Campbell (1985), Van Loenen and others (1989), Campbell (1981), Campbell and Wallace (1986), Moss and Abrams (1985), and Brinkworth (1973) and are briefly summarized here and in table 5.

Proterozoic rocks in the Forest have a wide range of measured magnetic susceptibilities and densities. The Proterozoic granitoid rocks are generally the most magnetic; Proterozoic metamorphic rocks are generally moderately magnetic. Proterozoic migmatites and biotite gneisses appear to be more magnetic than granites in some parts of the Sawatch and Gore Ranges.

Amphibolites are the densest of the common Proterozoic rocks, whereas some granites and felsic metamorphic rocks have lower densities. As a group, the Proterozoic rocks are significantly denser than Tertiary intrusive rocks.

The Paleozoic sedimentary rocks have a wide range of densities and are generally nonmagnetic. Their densities range from as low as 2.4 g/cm^3 for porous sandstones and siltstones to 2.85 g/cm^3 for limestones and dolomites. Evaporites of the Eagle Valley region may have densities as

Table 5. Average susceptibility and density values for rocks in the White River National Forest and vicinity, Colorado.

[N.a., not available]

Rock type	Number of samples	Susceptibility (cgs units)	Density (g/cm^3)
Data from Case (1967)			
Precambrian granitic rocks	35	n.a.	2.65
Precambrian metamorphic rocks	46	n.a.	2.79
Tertiary porphyritic rocks	64	n.a.	2.65
Data from Tweto and Case (1972)			
Precambrian rocks	n.a.	$0.32x10^{-3}$–$4.5x10^{-3}$	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-Tertiary intrusive rocks	n.a.	$0.46x10^{-3}$–$2.67x10^{-3}$	2.63
Data from Isaacson and Smithson (1976)			
Precambrian rocks	36	n.a.	2.71
Tertiary granitic rocks	27	n.a.	2.63
Data from Campbell (1985)			
Tertiary granodiorites	11	$1.4x10^{-3}$	2.60
Maroon Formation	6	$0.02x10^{-3}$	2.63
Data from Van Loenen and others (1989)			
Precambrian granitic rocks	n.a.	$0.31x10^{-3}$	n.a.
Precambrian metamorphic rocks	n.a.	$0.16x10^{-3}$	n.a.
Cretaceous-Tertiary dike rocks	n.a.	$0.03x10^{-3}$	n.a.
Data from Campbell (1981)			
Precambrian granites	11	$1.5x10^{-3}$	2.66
Precambrian schists	7	$0.47x10^{-3}$	2.74
Tertiary dike rocks	5	$0.03x10^{-3}$	2.54
Data from Campbell and Wallace (1986)			
Precambrian intrusive rocks	n.a.	$0.68x10^{-3}$	n.a.
Precambrian metamorphic rocks	n.a.	$0.3x10^{-3}$	n.a.
Precambrian granites	n.a.	$0.5x10^{-3}$	n.a.
Cretaceous-Tertiary intrusive rocks	n.a.	$0.58x10^{-3}$	n.a.
Data from Moss and Abrams (1985)			
Tertiary intrusive rocks:			
Rhyolite (altered)	n.a.	$0.35x10^{-3}$	2.38
Quartz monzonite	n.a.	$0.5x10^{-3}$	n.a.
Unaltered average	n.a.	n.a.	2.62
Cretaceous sedimentary rocks:			
Pierre Shale	n.a.	non-magnetic	2.61
Dakota Sandstone	n.a.	non-magnetic	2.52
Niobrara Formation	n.a.	non-magnetic	2.66
Precambrian intrusive rocks:			
Silver Plume Granite	n.a.	$0.6x10^{-3}$	2.67
Boulder Creek Granodiorite	n.a.	$1.2x10^{-3}$	2.66
Gabbro	n.a.	$10.3x10^{-3}$	3.03
Precambrian metamorphic rocks:			
Hornblende gneiss	n.a.	$1.6x10^{-3}$	2.89
Biotite gneiss	n.a.	$0.5x10^{-3}$	2.74
Sillimanite gneiss	n.a.	$0.9x10^{-3}$	2.76
Amphibolite and calc-silicate gneiss	n.a.	$1.0x10^{-3}$	2.80

low as 2.2 g/cm^3, depending on the relative amounts of interstratified clastic and evaporitic material.

The densities of Mesozoic and Tertiary sedimentary rocks in the area vary from 2.3 to 2.5 g/cm^3, based on measurements made on similar rocks to the west and southwest, in the central Colorado Plateau. The few available measurements of magnetic susceptibility indicate that these rocks are virtually nonmagnetic.

Some Tertiary plutons are magnetic and produce conspicuous positive anomalies, 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.

Measured densities of rocks in and surrounding the Leadville 30×30 minute quadrangle, which includes the southeastern part of the Forest, were tabulated by Case (1967). These samples were divided into three major rock types: Proterozoic granites (35 samples), Proterozoic metamorphic rocks (46 samples), and Tertiary porphyries (64 samples). The average density for Proterozoic granites was 2.65 g/cm^3; for Proterozoic metamorphic rocks, 2.79 g/cm^3; and for Tertiary porphyries, 2.65 g/cm^3. The average difference between all Proterozoic rocks (averaging 2.74 g/cm^3) and Tertiary porphyries (2.65 g/cm^3) was 0.09 g/cm^3. This contrast is sufficient to give rise to measurable gravity anomalies where these rock types are juxtaposed.

Measurements of additional rock samples were described in a later report by Tweto and Case (1972), who calculated density values of 2.63 g/cm^3 for Cretaceous and Tertiary porphyries, 2.75 g/cm^3 for Proterozoic granites and metamorphic rocks, 2.63 g/cm^3 for Paleozoic sandstones and quartzites, 2.80 g/cm^3 for Paleozoic dolomites and limestones (giving an average of 2.71 for the latter two rock types), and an assumed density of 2.50 for upper Paleozoic rocks. Susceptibility measurements for the igneous and metamorphic rocks gave generally low values (averaging 0.32×10^{-3} cgs units—a metric unit for susceptibility) for Proterozoic granites, bimodal values for Proterozoic gneisses and schists (ranging from less than 1×10^{-3} to 4.5×10^{-3} cgs units—low to moderately magnetic), and a wide range of values for Cretaceous and Tertiary intrusive rocks (ranging from 0.46×10^{-3} to 2.67×10^{-3} cgs units—low to moderately magnetic). The sedimentary rocks were essentially nonmagnetic.

Isaacson and Smithson (1976) calculated a mean density of 2.63 g/cm^3 for 27 samples of Tertiary granitic rocks and a mean density of 2.71 g/cm^3 for 36 samples of Proterozoic rock.

Campbell's report on the Maroon Bells–Snowmass Wilderness Area (Campbell, 1985) provides density and susceptibility measurements for Tertiary granodiorites (11 samples) and sedimentary and metasedimentary rocks of the Maroon Formation (6 samples). Density values for granodiorites ranged from 2.43 to 2.69 g/cm^3, with an average value of 2.60 g/cm^3; values for Maroon Formation rocks ranged from 2.46 to 2.82 g/cm^3 (a wide range), with an average value of 2.63 g/cm^3. Susceptibility values for granodiorites averaged 1.4×10^{-3} cgs units, and values for the Maroon Formation were essentially nonmagnetic, with an average of 0.02×10^{-3} cgs units.

Campbell made susceptibility measurements for Proterozoic granites, Proterozoic metamorphic rocks, and Cretaceous and Tertiary dike rocks in the Mt. Massive Wilderness (Van Loenen and others, 1989). Although there was a wide range of values for all rock types, in general, the granites were the most magnetic, averaging 0.31×10^{-3} cgs units; the metamorphic rocks were slightly less magnetic, averaging 0.16×10^{-3} cgs units; and the dike rocks were much less magnetic, averaging 0.03×10^{-3} cgs units. Values for individual samples of coarse-grained porphyritic Proterozoic granites were as high as 11.14×10^{-3} cgs units.

In a report on the Hunter-Fryingpan Wilderness, Campbell (1981) provides densities and susceptibilities for Proterozoic granites (11 samples), Proterozoic schists (7 samples), and Tertiary dikes associated with the Grizzly Peak caldera (5 samples). Density values for granites ranged from 2.58 to 2.79 g/cm^3, with an average value of 2.66 g/cm^3; values for schists ranged from 2.63 to 3.20 g/cm^3, and averaged 2.74 g/cm^3; and values for Tertiary dikes ranged from 2.43 to 2.63 g/cm^3, and averaged 2.54 g/cm^3. Susceptibility values averaged 1.5×10^{-3} cgs for granites (from 0.07×10^{-3} to 6×10^{-3} cgs units); values were lower for schists, averaging 0.47×10^{-3} cgs units (ranging from 0.03×10^{-3} to 2×10^{-3} cgs units); and values were very low for Tertiary dikes, averaging 0.03×10^{-3} cgs units (ranging from 0.01×10^{3} to 0.06×10^{-3} cgs units). These susceptibility values differ from the values reported by Case (1967) and Tweto and Case (1972) for Proterozoic granites, which were generally lower than Tertiary units.

In a study of the aeromagnetic map of the Holy Cross Wilderness (Campbell and Wallace, 1986), susceptibilities for rocks from the area were measured as follows: Proterozoic metamorphic rocks averaged 0.3×10^{-3} cgs units, Proterozoic intrusive rocks averaged 0.68×10^{-3} cgs units, Proterozoic granites averaged 0.5×10^{-3} cgs units, and Cretaceous and Tertiary intrusive rocks averaged 0.58×10^{-3} cgs units. Campbell concluded that, in this region, rocks cannot be distinguished solely by susceptibilities but that, in general: (1) Cross Creek Granite has higher susceptibilities than other Proterozoic intrusive rocks, (2) Fulford-type stocks (including Fulford, Gold Dust Peak, upper East Lake Creek, Missouri Creek, and West Tennessee Lakes stocks) have higher susceptibilities than other stocks, and (3) mylonites associated with both shear zones and altered rocks have low susceptibilities.

Moss and Abrams (1985) summarized and augmented density and susceptibility values made by Brinkworth (1973). The number of samples measured was not included in the table by Moss and Abrams (1985); their average values are provided in table 5.

INTERPRETATIONS OF GRAVITY AND MAGNETIC DATA

For the purposes of this discussion, the Forest is divided into six areas: Battlement Mesa; the White River Plateau and Flat Tops Wilderness; the Elk Mountains; the Sawatch Range and Red Table Mountain; Dillon, Montezuma, and Red Mountain; and the Gore Range and Williams Fork Mountains (see fig. 4 for general locations).

BATTLEMENT MESA AREA

The Battlement Mesa area, in the westernmost part of the Forest, is associated with both a broad gravity gradient of 30–40 mGal (milligals) (fig. 11) and a broad magnetic high of 600 nT (pl. 4). The high-pass filtered gravity map (pl. 3) removed the broad gradient that is associated with the Colorado Plateau to the west, and a residual 10-mGal gravity low remains over the mesa. The gravity low and magnetic high are spatially related to the topographic high of the mesa, and the size and amplitudes of these anomalies reflect a presumably deep source. The gravity low may be produced by a thick sequence of low-density Cretaceous and Tertiary rocks. The magnetic data in this area are of poor resolution so that smaller, shallower sources are difficult to discern on the magnetic anomaly map.

East of the mesa, at the Divide Mountain anticline, deflections in contour lines and small anomalies in both the gravity and magnetic maps follow the north-northwest-trending axis of the anticline. Small gravity and magnetic highs along the southern part of the axis may be associated with unmapped dikes like those mapped farther south. Certain small gravity lows may reflect salt bodies below the surface; for example, the low in the eastern part of the area over the Wolf Creek anticline is modeled as a salt pillow (Grout and others, in press). The northern end of the axis of this fold is associated with a broader, low-amplitude magnetic high from a deeper source that could be a small pluton at depth. The high-pass gravity map shows an area of slight positive gravity anomalies that may reflect overthickened Mancos Shale units (Grout and others, in press).

WHITE RIVER PLATEAU AND FLAT TOPS WILDERNESS AREA

The gravity field of the northern part of the Forest (fig. 11) is a broad 25–35-mGal positive anomaly that is associated with the topographic high of the White River uplift, which exposes older, denser rocks. A steepened gradient follows the southern fault that bounds the uplift. An east-west-trending saddle in the gravity data is caused by lower gravity values within this broad high where Tertiary basalt becomes the major rock outcrop. The high-pass gravity map (pl. 3) removes the gravity expression of deep sources, and the resulting gravity field shows the gravity highs shifted toward the south and the amplitude of the lows of the Flat Tops increased.

The magnetic field in this area is characterized by high-frequency, small, positive and negative anomalies over the basalt outcrops, some of which may have formed during periods of reversed magnetization. These small anomalies are superimposed on long-wavelength, deep-source anomalies that are probably caused by magnetic contrasts within the Proterozoic basement.

The southern and southwestern margins of the uplift are flanked by four magnetic highs that are similar in appearance, magnitude, extent, and depth-to-source. Because they are located along the edge of the uplift, they are presumed to be structurally controlled, but the source of these anomalies is unclear. They may be caused by locally exposed Proterozoic rocks, such as those found in the bottom of some canyons in the southern White River uplift.

East and west of the uplift, the magnetic field has little relief. The gravity field of the high-pass map shows gravity lows associated with the Eagle Valley Evaporite, near Gypsum; between Eagle and Edwards; near State Bridge; and at Basalt Mountain. Similar gravity lows without associated outcrops in this region may be related to buried evaporite sources.

ELK MOUNTAINS AREA

The major part of the Elk Mountains area is discussed in detail in the report on the Maroon Bells–Snowmass Wilderness (Campbell, 1985) and is summarized here. The Elk Mountains are within an extensive 30–50-mGal gravity low, called the Colorado Mineral Belt gravity low, that trends northeast across the Forest 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 (Tweto and Case, 1972; Isaacson and Smithson, 1976). A shallow intracrustal origin for the gravity low (which has 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) has been demonstrated by gravity models (Case, 1966; Tweto and Case, 1972; Isaacson and Smithson, 1976). Many of the mapped intrusions in this area are probably apophyses from the top of this massive batholith. Most of the major mining districts, such as Climax and Breckenridge, are within the gravity low, and many are at or near the axis defined by the lowest gravity values.

Positive magnetic anomalies in the Elk Mountains mark outcrops of the Mt. Sopris, Snowmass, White Rock, and Ragged Mountain mid-Tertiary plutons. Models by Campbell (1985) show that the first three plutons are connected at depth to a regional batholith. The Sopris and Snowmass plutons are magnetically simple, but the White Rock pluton has magnetically distinct subunits that may reflect alteration of a relatively large part of the pluton and, hence, may indicate the possible presence of altered and mineralized rocks.

The high-pass gravity field of the Elk Mountains area shows the gravity field with the broad, low-amplitude gradient removed. A gravity high is centered over the Sopris, Snowmass, and White Rock plutons, which are within the area of a mapped upper plate of a thrust fault (Tweto and others, 1978). Southwest of the mapped thrust fault, a large gravity low is associated with granite at Treasure Mountain. This gravity low separates the small gravity high of the Ragged Mountain pluton from the larger gravity high associated with the other three plutons. The relationships at depth between the Ragged Mountain pluton and the other three plutons is not clear.

SAWATCH RANGE AND RED TABLE MOUNTAIN AREA

Magnetic gradients in the northern Sawatch range are a product of fault-generated juxtaposition of rocks with contrasting magnetic susceptibilities. The magnetic data have a parallelism with the Homestake shear zone; the east-northeast-trending metamorphic layering; or with northwest-trending, uplift-related, high-angle faults of Laramide and younger age. Magnetic highs in the Sawatch Range and in the Gore Range to the north are related to magnetite-rich Proterozoic granites and migmatites.

In the Sawatch Range and vicinity, many of the Tertiary intrusive rocks appear to be nonmagnetic and lack distinctive signatures. Many major mining districts are located on the flanks of magnetic highs or lows caused by sources other than Tertiary intrusive rocks.

Reports on Wilderness Study Areas provide detailed descriptions of the geophysical nature of parts of the Sawatch Range; these include the Mt. Massive Wilderness (Van Loenen and others, 1989), the Hunter-Fryingpan Wilderness (Campbell, 1981), and the Holy Cross Wilderness (Campbell and Wallace, 1986) (fig. 5). In addition, some of the southeasternmost parts of the Forest were studied by Tweto and Case (1972). These reports are briefly summarized here.

The mineral-belt gravity low continues northeast across the Mt. Massive Wilderness Area and outlines the underlying batholith. Magnetic anomalies in the area are caused by contrasts in the makeup of bedrock. Magnetic highs in the northern part of the area are associated with magnetic mid-Proterozoic granites. Magnetic lows in the southern part of the area are associated with low to moderately magnetic Early Proterozoic schists and gneisses. Areas with anomalously low magnetism in the extreme southern part of the Mt. Massive Wilderness Area are associated with Cretaceous and Tertiary intrusive rocks. An arcuate, east-west series of magnetic lows, called the "Halfmoon lows" by Campbell (1981), follows Halfmoon Creek and crosses the Continental Divide west of Blue Lake (Van Loenen and others, 1989). Rocks in this area have lower magnetic susceptibility and some appear altered, but it is not clear whether the rocks were originally nonmagnetic, were altered, or both. These magnetic lows may reflect a shallow pluton (Tweto and Case, 1972) associated with the Halfmoon stock.

The high-pass gravity map (pl. 3) shows the resultant gravity field without interference from the large gravity low discussed above. A gravity high is centered in the area of the Halfmoon lows, where the predominant rock is dense biotite gneiss and migmatite.

Immediately west of the Mt. Massive Wilderness, in the Hunter-Fryingpan Wilderness, a gravity gradient marks the rim of the Grizzly Peak caldera, and rocks within this caldera have lower densities (Campbell, 1981). Like the Mt. Massive magnetic field, the Hunter-Fryingpan magnetic field reflects the difference in susceptibilities between granites and schists. Some anomalies may indicate buried sources. Detail of anomalies is best shown by the original map (Campbell, 1981); however, some of the positive anomalies are caused by magnetic rocks in topographic highs, and lower amplitude anomalies appear where these same rocks are in valleys.

To the north, the Holy Cross Wilderness is on a structural dome that is marked by a gravity high on the high-pass gravity map (pl. 3). Campbell and Wallace (1986) identified several magnetic lineaments in two major directions: one set trends north-northwest and is associated with Laramide (Late Cretaceous to Paleocene) and younger features, and one set trends northeast and is associated with Proterozoic features such as the Homestake shear zone. Some of these lineaments may reflect zones of alteration in previously magnetic rocks. The lineaments divide the wilderness into zones having distinct geophysical signatures. The highest magnetic values correspond to outcropping gneisses and schists. Moderately high values are associated with Cross Creek Granite. An area near Homestake Reservoir has both low magnetic and gravity values in an area that includes calc-silicate rocks and other rocks such as the St. Kevin Granite that are generally more magnetic elsewhere. This region may have been subjected to widespread alteration, but no field evidence supports this.

Most Cretaceous and Tertiary stocks in the area are intruded into more magnetic Proterozoic rocks and have either no magnetic expression or generally appear as magnetic lows. The Fulford stock is an exception: it appears as a distinct magnetic high. Other stocks outside the Holy Cross Wilderness, such as the Humbug stock, also generate significant magnetic highs.

The Homestake shear zone is marked by northeast-trending gravity and magnetic gradients. The high-pass gravity map (pl. 3) shows a northeast-trending zone of lows on the downthrown side of a fault along the southern margin of the shear zone from Aspen to Homestake Peak. A continuation of the shear zone, 5 mi west of Dillon, shows a marked truncation of magnetic highs having a northeast trend that follows the mapped part of the shear zone.

A 200-nT, northwest-trending, positive magnetic anomaly that appears as a deep-source anomaly over Red Table Mountain is probably associated with redbed sequences in the sedimentary rocks.

DILLON, MONTEZUMA, AND RED MOUNTAIN AREA

Between the Sawatch Range and the Gore Range is an interesting east-northeast-trending zone of magnetic lows that corresponds to a gravity low in the high-pass gravity map (pl. 3). This zone covers an area from west of Vail to Dillon and crosses many north-northwest-trending topographic and structural features. North and south of this zone, a north-northwest-trending linear zone of magnetic highs is associated with Proterozoic biotite gneisses and migmatites and, to a lesser extent, with Proterozoic granites. Brinkworth (1973) studied the aeromagnetic and gravity maps of the Climax area and the Front Range, and this work is summarized here. East of Dillon, the Montezuma stock (an Oligocene intrusion located at the intersection of the Williams Fork thrust and the southwestern extension of the Berthoud Pass—Loveland Pass Proterozoic shear zone) is associated with a gravity low and a series of magnetic highs. The Montezuma stock has magnetically zoned subunits (Neuerburg, 1971) that represent separate intrusive episodes with associated hydrothermal events, and some parts of the stock are more magnetic than others. Brinkworth (1973) determined that measured susceptibilities of the samples were too low to account for the magnitude of the highest magnetic values; he postulated a local buried sulfide mass to account for the magnetic maxima. Neuerburg (1971) determined that the stock increases in size with depth and is a cupola of a larger batholith.

Brinkworth (1973) suggested that the batholith is defined by a zone of northeast-trending gravity lows (including the Montezuma stock and other outlying rhyolitic plutons such as the Red Mountain, Leavenworth, and Cabin Creek stocks and the Revenue Mountain and Handcart Gulch stocks, east of the Forest). All of these stocks have common volcanic origins; they have subunits associated with separate intrusive events and hydrothermal episodes, and they are located near major Proterozoic shear zones that may have localized igneous activity at pre-existing 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. A more pronounced gravity low at Red Mountain may reflect the greater volume of subvolcanic rhyolite (averaging 2.49 g/cm^3) and more extensive altered country rocks than that at the Climax stock, which has little gravity expression. Neither the Climax nor the Red Mountain stocks have much magnetic expression, but the flight lines were at least 0.5 mi away from the stock outcrops. Brinkworth (1973) proposed that this batholith may be an important source for molybdenum. However, the high-pass gravity map (pl. 3) suggests that this batholith is not northeast-trending: it appears to trend north, and it includes both the Climax and Red Mountain stocks as well as the Montezuma stock. Because buried batholiths play such an important role in the mineralization that occurred in this area, this trend of gravity lows may be significant.

GORE RANGE AND WILLIAMS FORK MOUNTAINS AREA

The Gore Range–Eagle's Nest Wilderness Study Area is northeast of the Holy Cross Wilderness, in the Gore Range (fig. 5). A report by Tweto and Lovering (1977) includes an interpretation of the magnetic field of this area and is summarized here.

The magnetic field is generally high over the Gore Range, and individual anomalies reflect differences in rock types (migmatites, granodiorites, and granites) and local topography. Steep magnetic gradients follow the range-front faults along the east and west sides of the Gore Range. Susceptibilities of the rocks in the area range from more magnetic migmatites, moderately magnetic granodiorites, and less magnetic granites. Most magnetic highs and lows are spatially related to the rock types that crop out across the area: higher values occur over migmatites and, in some places, over granodiorites, and lower values occur over granites. Magnetic highs in the southern Gore Range are associated with migmatites and biotite gneisses, and these highs also seem to be a continuation of the magnetic highs that follow the Homestake shear zone in the Sawatch Range to the southwest. The magnetic map (pl. 4) showed no firm evidence for hidden intrusives.

Moss and Abrams (1985) studied the gravity and magnetic fields of the Williams Fork Roadless Area, in the northeasternmost part of the Forest (fig. 5), and the Vasquez Peak Wilderness Study Area and St. Louis Peak Roadless Area, northeast of the Williams Fork Roadless Area. Brinkworth (1973) showed that Oligocene stocks, associated with nearby molybdenum deposits, have the lowest density of all rocks in this area and that gravity lows may outline the stocks. 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. Moss and Abrams (1985) suggested six small areas that might indicate buried Oligocene stocks. Elsewhere, gravity gradients follow contacts between Silver Plume Granite and denser Proterozoic gneisses.

Magnetic anomalies are continuous along the Williams Range thrust fault. The thrust does not offset the source of these anomalies—the source of these anomalies is, therefore, probably in the lower plate.

INTERPRETATION OF RADIOMETRIC DATA

Radiometric data (uranium, potassium, and thorium) were collected for 1°×2° quadrangles as part of the NURE Program. In the Leadville 1°×2° quadrangle, which contains much of the area of the Forest, the contractor identified 93 statistical uranium anomalies (defined as places along flight lines where raw eU counts were more than two standard deviations above the mean of the entire survey (Geometrics, 1979)). No similar analysis was made for K or Th. The contractor's analysis is summarized below.

Of the 93 anomalies discussed by the contractor, 41 uranium highs are spatially associated with the Wasatch Formation and the Ohio Creek Member of the Hunter Canyon Formation of the Colorado Plateau. Other anomalously high uranium counts were associated with Proterozoic crystalline rocks in the Sawatch and Gore Ranges and are presumed to be associated with fissures in Proterozoic metamorphic rocks. Few of the anomalies were near known uranium occurrences, and they did not correlate well with certain formations that are accepted as uranium-host units. Paleozoic sedimentary rocks host some fracture-controlled radioactive mineral occurrences within "black" or fossiliferous limestones, black shales, or micaceous sandstones (such as the Maroon Formation and a shale unit at the base of the Cambrian Sawatch Quartzite). Mesozoic sedimentary rocks host many stratigraphically controlled radioactive-mineral occurrences within sandstones, channel conglomerates, petroliferous limestones, and various carbonaceous zones, including the Chinle, Navajo, Entrada, Morrison, Mancos, and Dakota units.

Eight uranium mines are within the Leadville 1°×2° quadrangle. Five of these are located near Rifle, and production is from the Entrada Sandstone. One mine is northeast of Aspen, producing from Tertiary veins cutting Proterozoic crystalline rocks. The remaining two mines, which have negligible production from the Chinle and Maroon Formations, are located in the northeast part of the Leadville 1°×2° quadrangle.

The maps in figures 14–16 show high concentrations of eTh (and, to a lesser extent, of eU and K) compared to the granitic intrusive and metamorphic rocks of the Sawatch Range. Many eU highs (fig. 15) are on and are presumed related to Middle Proterozoic rocks. In the absence of geochemical processes that separate the relatively more soluble U from Th, the ratio of eU/eTh in fresh intrusive rocks should be 0.25. The eU/eTh ratio is lower than this (implying uranium depletion) over parts of the Middle Proterozoic units of the Sawatch Range, but higher values (uranium enrichment) are over upper Paleozoic and Mesozoic sedimentary units to the north and west. This suggests that erosional and groundwater processes in the area have moved uranium from primary Middle Proterozoic sources to present-day deposits in sedimentary units of the Eagle and Piceance Basins.

The K map (fig. 16), like those of eU and eTh, shows highs over Middle Proterozoic units, but other K highs fall over Early Proterozoic gneissic rocks, particularly in the Gore, Tenmile, Mosquito, and Sawatch Ranges; the map also shows highs over Phanerozoic rocks in the central and western parts of the map. Tectonic elements (such as faults west of the Gore and Sawatch Ranges, the Homestake shear zone and its extension to the southwest, and the Grand Hogback monocline) are evident on the 1:250,000-scale map (Geometrics, 1979) (empirical leveling of flight lines acts to mute features subparallel to those lines, possibly accounting for the missing east-west parts of the Grand Hogback). Some Tertiary intrusive units cause K highs: the Tertiary basalt flows south of Dotsero might comprise such a unit. Some middle Tertiary intrusive bodies give rise to K highs, but other bodies, such as the Snowmass stock, do not. The broad K highs over sedimentary units of Grand Mesa and the White River Plateau seem to wax and wane without clearly correlating with particular units.

MINERAL RESOURCES—LOCATABLE COMMODITIES

Locatable commodities include all minerals for which exploration, development, and production are regulated under the Federal General Mining Law of 1872. Most metals and industrial minerals are included in this group. Known deposits of locatable minerals, and mining and exploration history, are described by the U.S. Bureau of Mines (Brown, 1990). Below is a brief summary of that report.

MINING AND EXPLORATION HISTORY

The White River National Forest and the Dillon Ranger District of the Arapaho National Forest contain 26 mining districts and mineralized areas (fig. 7). In 1859, gold placers in the Breckenridge district were the first deposits to be worked. Gold placers were discovered a year later a few miles south of the Forest, at Leadville. These two areas include some of the richest placer deposits in Colorado.

Base- and precious-metal lode deposits were discovered a few years after the gold placers were found. In the

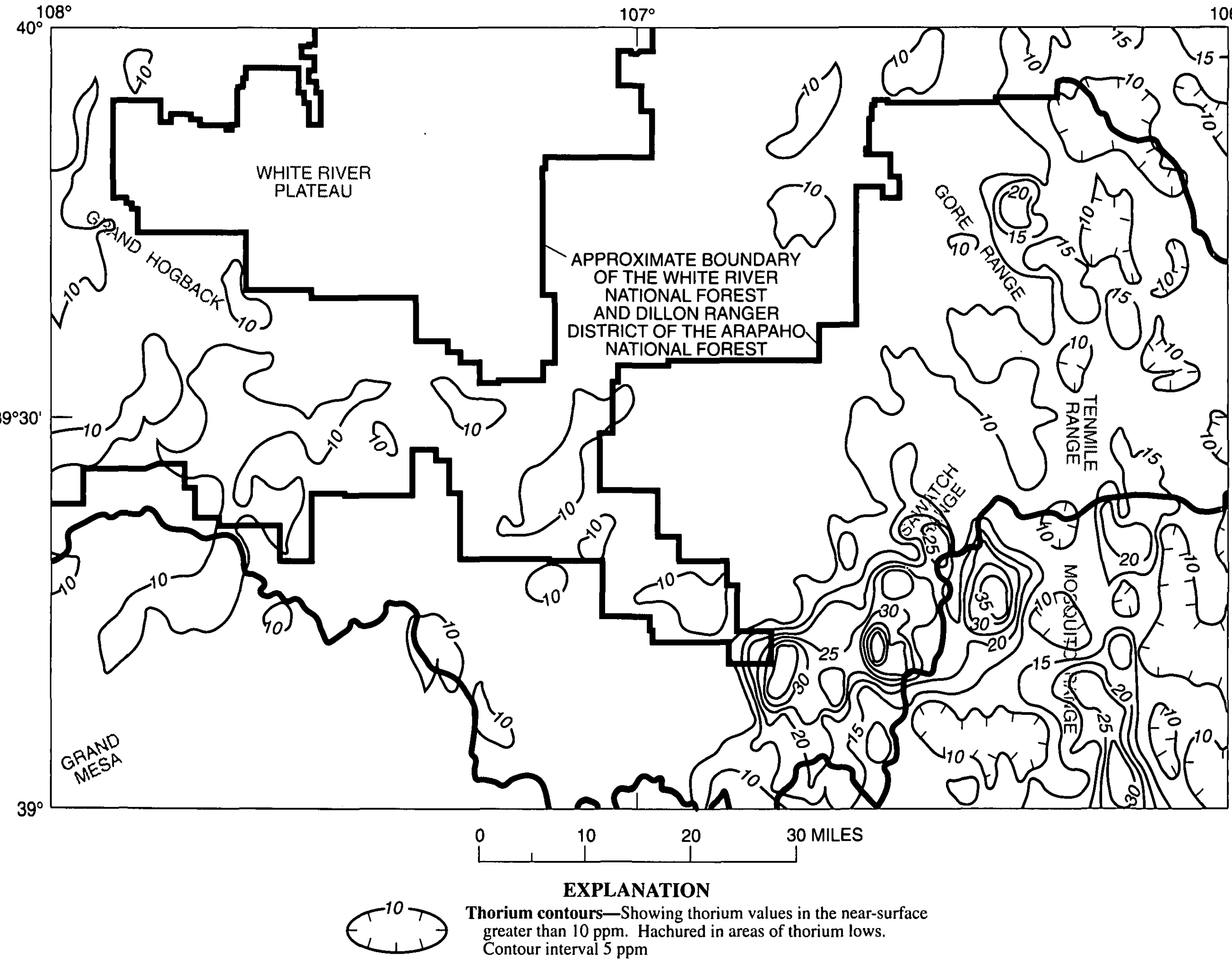


Figure 14. Contour map of thorium (eTh) greater than 10 ppm.

Forest, the first silver vein was discovered in the Montezuma mining district in 1864. During the next decade, lode deposits were discovered throughout the Colorado Mineral Belt, and prospectors founded numerous mining camps. In 1878, bonanza silver deposits were discovered in the Kokomo-Tenmile district. Silver-lead ore was found at Gilman and in the Aspen district the next year. Most of the mining districts and major ore bodies in the Forest had been discovered by the late 1800's.

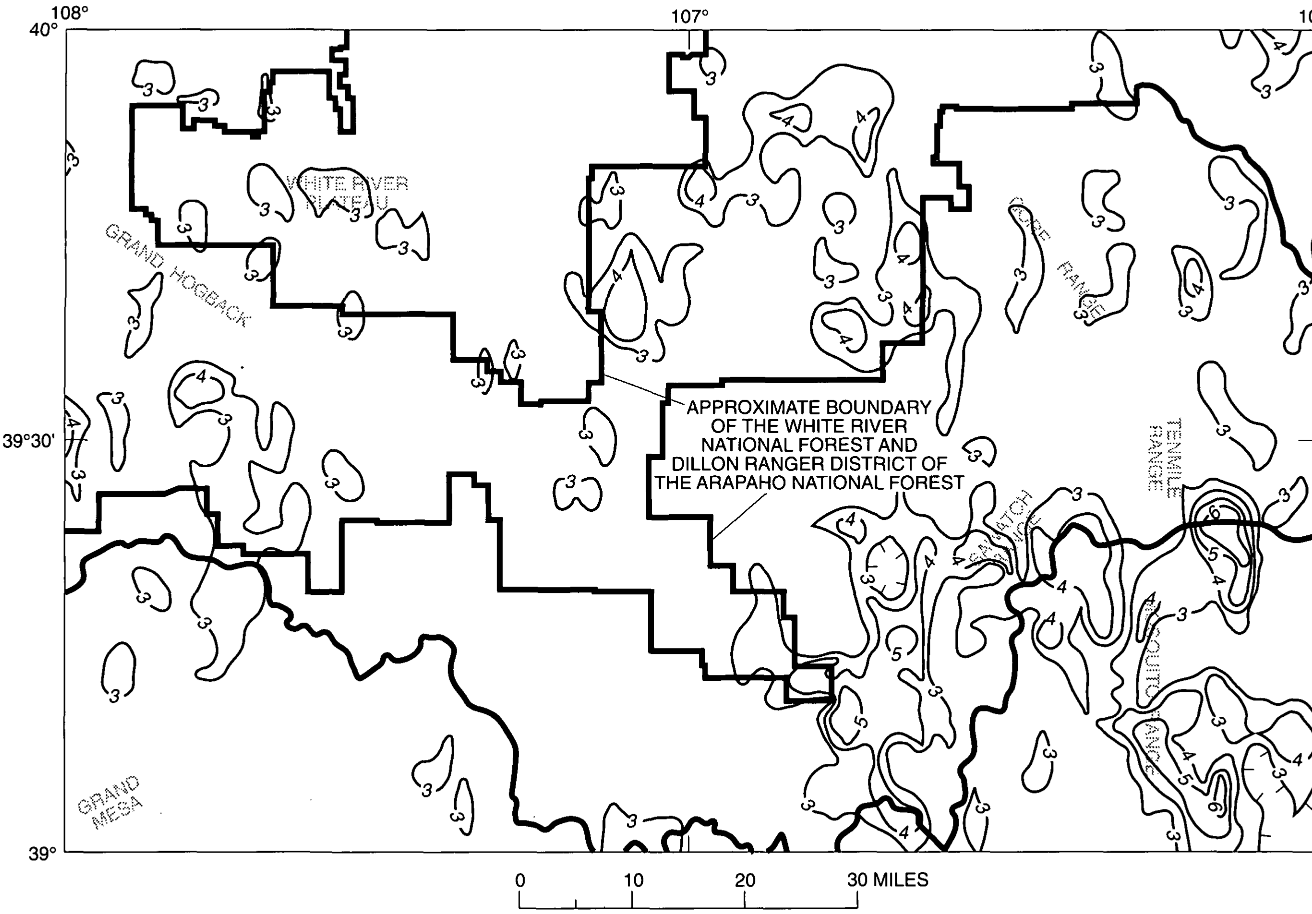
The Gilman district, known for its copper and zinc, is the State's largest producer of metals. The Eagle mine consolidated many older mines and workings into a single operating unit in 1918 and was the major metal producer. Next in overall production in the Forest were the Aspen, Breckenridge, and Kokomo-Tenmile districts, respectively. Other districts and mines in the Forest had less significance in terms of total production.

The Eagle mine, in the Gilman district, ceased production in 1981. No large-scale mining has taken place in the Forest since that time; current mineral activity consists of annual assessment work on unpatented mining claims, prospecting, and small-scale mining. Most of the activity is in the Breckenridge area and consists of reclamation of old placers.

METALS

The White River National Forest and Dillon Ranger District of the Arapaho National Forest have mineral deposits that contain base, precious, and ferrous metals in a variety of different geologic terranes. The deposits formed during several different metallogenic events, including Proterozoic sedimentation, Paleozoic sedimentation and erosion, Cretaceous to Paleocene plutonic activity, Oligocene plutonic and volcanic activity, and Pleistocene to Holocene weathering and erosion. Rock units that host deposits in the Forest and the metals they host are listed in table 6. Deposit models are identified by capital letters in parentheses in the following discussion.

The only known Proterozoic deposits in the Forest are small deposits of stratabound copper, lead, zinc, gold, and



EXPLANATION

Uranium (eU) contours—Showing uranium values in the near-surface greater than 2.0 ppm. Hachured in areas of uranium lows. Contour interval 1 ppm

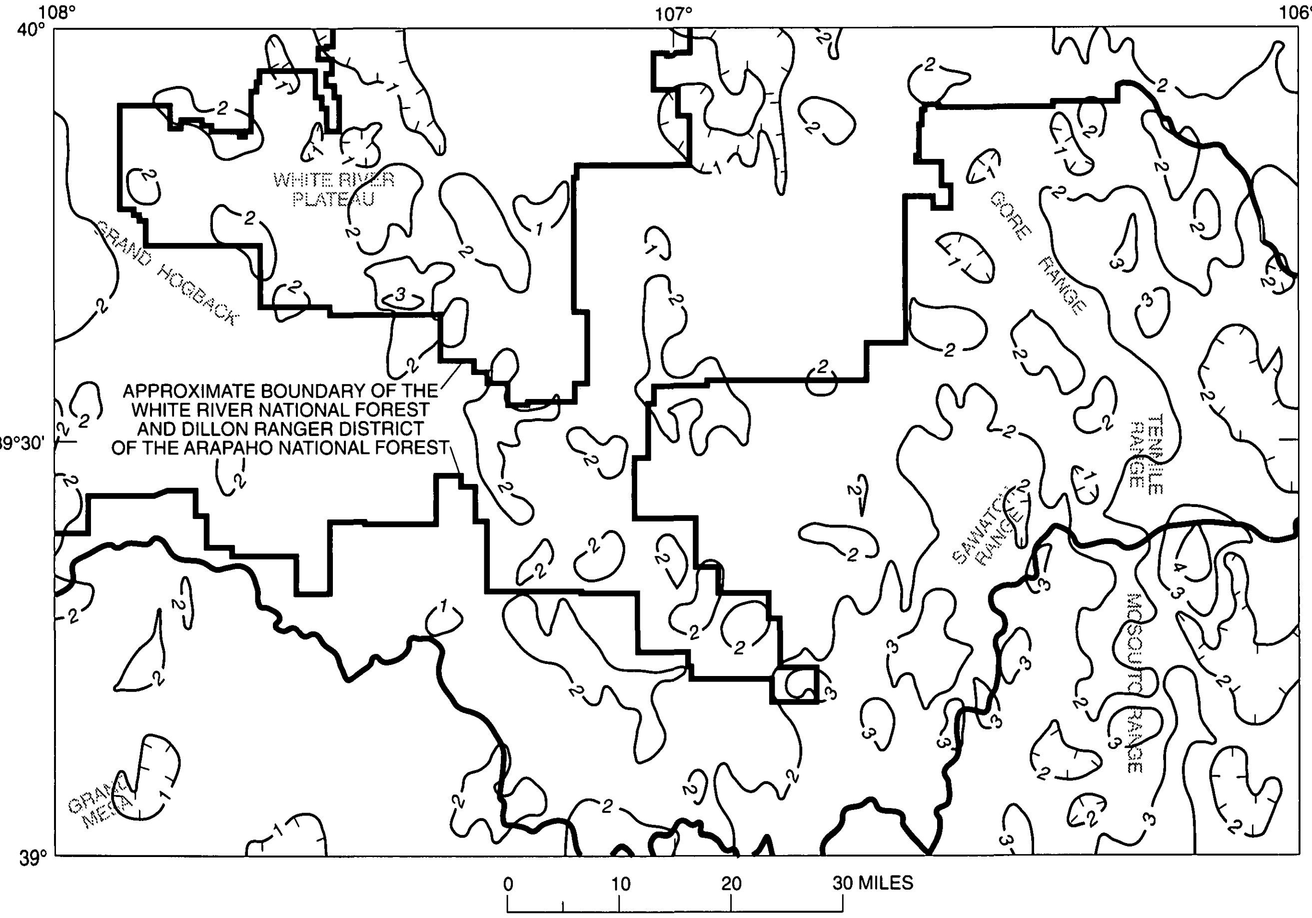
Figure 15. Contour map of uranium (eU) greater than 2.0 ppm.

silver (L). These metals were deposited syngenetically with submarine felsic and mafic volcanic rocks. The volcanic rocks were regionally metamorphosed in the Proterozoic to dominantly amphibolite and calc-silicate gneiss. The deposits tend to cluster spatially and follow specific stratigraphic horizons. No deposits of this type have been found in the Forest, but several areas contain disseminated sulfides in Proterozoic rocks and have associated low-level metal anomalies.

Metallogenesis is not recognized in the Forest again until the late Paleozoic (Late Mississippian to Early Pennsylvanian), when uplift of the Sawatch Range exposed the Mississippian Leadville Limestone to surface weathering. As a result of this weathering and ensuing erosion, a widespread, complex network of caves formed just below the surface of the limestone. Metal-rich brines may have migrated from the adjacent Eagle Basin to be deposited in some of the caves as a major part of the cave filling—this may have formed silver, lead, zinc, and copper deposits (E); some workers, however, argue that these types of deposits formed during the Tertiary from basin brines moving along thermal gradients controlled by igneous intrusions. The overprint of Laramide and Oligocene mineralization has obscured much of the evidence for this late Paleozoic period of mineralization.

In the late Paleozoic and early Mesozoic, thick sequences of sandstone were deposited in the Eagle Basin. Sediment-hosted stratiform copper deposits formed in some of the sandstone units at some localities where the sandstone is interbedded with transgressive marine shale (I). The copper deposits formed early in the diagenetic history of the enclosing sedimentary rocks from brines derived from the sedimentary basin itself. Metals include copper, uranium, vanadium, and silver. One deposit of this type is known in the Forest at Snowmass Creek, but a similar deposit is found several miles outside of the Forest, at Horse Mountain.

As orogenic activity waned and inland seas episodically covered the area, Mesozoic sedimentary rocks were deposited in various marginal-marine, braided-stream, and lacustrine environments. Jurassic and Cretaceous sedimentary rocks were deposited in nonmarine to marine sedimentary cycles. Some of the sandstone units deposited in nonmarine environments contain uranium and vanadium deposits (J).



EXPLANATION

Potassium contours—Showing potassium values in the near-surface greater than 1.5 ppm. Hachured in areas of potassium lows. Contour interval 1 ppm

Figure 16. Contour map of potassium (K) greater than 1.5 ppm.

Uranium and vanadium formed during diagenesis as microcrystalline uranium oxides and silicates; ore formed in localized reducing environments. Some of the uranium oxides were also deposited and redistributed by ground water at the interface between oxidized and reduced ground. Known deposits are northeast of Rifle (in the Rifle district) and in the northwesternmost corner of the study area (in the Uranium Peak mining district).

The Laramide orogeny was characterized by major uplift and magmatic activity throughout Colorado. Magmatic activity continued until recent times; a major pulse of activity occurred in the Oligocene. Hydrothermal systems related to the emplacement of Laramide and Oligocene plutonic bodies generated most of the deposits that are in the Forest today; these deposits include: polymetallic veins (F), replacement deposits (D), polymetallic skarns (C), stockwork copper-molybdenum (B), and stockwork molybdenum (A). Although the ages of the igneous bodies span from Laramide to recent times, most of the ore deposits are Oligocene in age. Laramide deposits are generally small, with the exception of those at Aspen.

Polymetallic vein deposits (F) occur in Proterozoic rocks, Paleozoic and Mesozoic sandstones and shales, and Cenozoic intrusive and volcanic rocks. Faults and shear zones provided avenues for mineralizing solutions. Most of the veins trend northeast—the dominant direction of shearing. Metals in the veins include copper, lead, zinc, silver, gold, and manganese. Veins at certain localities contain uranium (G) or tungsten (H). Ore bodies in veins are typically small, and those that have been mined were mined for precious metals (Romberger, 1980).

Replacement bodies in sedimentary rock (D) were formed where hydrothermal solutions mineralized favorable country rocks, such as limestone or dolomite. Metal-bearing veins in the host and underlying and overlying units are associated with these deposits. Most of the known replacement deposits are distributed along the flanks of the Sawatch uplift, where uplift and erosion has exposed the favorable strata. Examples of these deposits are at Gilman and Aspen.

Polymetallic skarn deposits (C) formed where Laramide or Oligocene magmas intruded favorable country rocks, such as limestone and dolomite, and altered them to a

Table 6. Metallic mineral resource potential for rock units in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

Rock type and age	Associated or potential mineral resources
Unconsolidated Deposits	
Quaternary deposits: Lacustrine, fluvial, eolian, and surficial deposits	Placer Au
Igneous Rocks	
Epizonal granites (Laramide to Tertiary)	Mo, Cu, Au, W, Sn, Bi
Granitic intrusives (Late Cretaceous-Tertiary)	Pb, Zn, Cu, Ag, Au, W, Mn
Felsic dikes and tuffs	Pb, Zn, Cu, Ag, Au, W
Precambrian crystalline rocks (migmatite, igneous and metamorphic rocks)	Pb, Zn, Cu, Ag, Au, Mo, Mn
Sedimentary Rocks	
Dakota Sandstone and Burro Canyon Formation (Cretaceous)	U, V, Cu, Ag
Morrison Formation, Salt Wash Member (Upper Jurassic)	U, V, Cu
Entrada Sandstone (Middle Jurassic)	U, V, Cu
Navajo Sandstone (Lower Jurassic)	U, V, Cu
Glen Canyon Sandstone (Lower Jurassic)	U, V, Cu
Chinle Formation (Upper Triassic)	U, V, Cu, Ag
State Bridge Formation (Lower Triassic to Lower Permian)	U, V, Cu, Ag
Maroon Formation (Lower Permian to Middle Pennsylvanian)	U, V, Cu, Ag
Minturn Formation (Middle Pennsylvanian)	U, V, Cu, Ag
Belden Formation (Middle and Lower Pennsylvanian)	Cu, Pb, Zn, Ag, W
Leadville Limestone (Mississippian)	Pb, Zn, Cu, Ag, Au, W, Mn
Dyer Dolomite (Lower Mississippian and Upper Devonian)	Pb, Zn, Ag
Manitou Dolomite (Lower Ordovician)	Pb, Zn, Ag
Sawatch Quartzite (Upper Cambrian)	Pb, Zn, Cu, Ag, Au

complex assemblage of silicate minerals. Ore bodies associated with the skarns are localized by faults, bedding planes, and breccia zones. Ore minerals include copper, lead, zinc, silver, molybdenum, manganese, tungsten, iron, and trace amounts of gold. Some of the ores in the Breckenridge district may have been produced from skarn. In addition, the iron deposit south of Aspen, at Taylor Peak, is an iron-rich skarn in which magnetite layers were mined for iron.

Stockwork copper-molybdenum systems (B) with associated gold, lead, and zinc were developed in some of the Laramide and Oligocene plutons. The stockworks are located in the upper parts of the intrusive body or in the surrounding country rock above the body. The location of veins are controlled by joint patterns produced by the pluton and (or) bedding, joints, folds, or earlier faults outside of the pluton. No known stockwork copper-molybdenum deposits are in the Forest, but several areas have potential for these kinds of deposits.

Stockwork molybdenum deposits (A) formed after a change in the tectonic regime from compression to extension. These deposits occur in the youngest igneous rocks along the length of the Colorado Mineral Belt. Stockwork molybdenum deposits are associated with small, highly differentiated, complex plutons; small quantities of tungsten, tin, lead, and bismuth are possible byproducts. Although there are no known deposits within the Forest, the world-class Climax deposit lies just outside the southeastern margin of the Forest. Because of the proximity to Climax, the Forest has been heavily prospected for this type of deposit. Several small areas within the Forest have potential for a Climax-type deposit.

No other ore-forming events occurred until Pleistocene time, when placer gold deposits (K) were formed. Placers are commonly close to their mineralized source, and most can be related to veins in Proterozoic or Paleozoic rocks. Gold and other heavy minerals in these mineralized areas were concentrated as weathering residues in soils and eluvium. These minerals were later transported to form a part of placer deposits in streams, terraces, glacial sediments, and erosional debris on slopes. Some placers may be derived, in part, from the reworking of paleoplacers. Weathering and fluvial action formed these deposits in Pleistocene to Holocene time in several different areas within the Forest.

INDUSTRIAL MINERALS

Industrial and nonmetallic minerals are classified as either locatable or salable. Locatable minerals include high-calcium limestone, high-magnesium dolomite, gypsum, vermiculite, pegmatite-hosted nonmetallic minerals, and fluorite—these locatable minerals are discussed in this section and in the section that follows, Mineral Resource Potential—Locatable Commodities. Salable minerals include sand and gravel, dimension stone, pumice, perlite, and clay—these salable minerals are described in the sections on Mineral Resources—Salable Commodities and Mineral Resource Potential—Salable Commodities that appear later in this report.

The White River National Forest and Dillon Ranger District of the Arapaho National Forest contain two types of industrial mineral deposits: high-calcium limestone (M) and gypsum (N). The Leadville Limestone is the host for deposits of high-calcium limestone. The Leadville was deposited in Mississippian time in a shallow-water marine environment by precipitation of calcium carbonate from sea water and by accumulation of organisms rich in calcium carbonate. Although the limestone within the Forest has not been mined, two areas of identified resources have been outlined.

The Eagle Basin, a large northwest-trending basin, formed in central Colorado during Pennsylvanian time. Evaporites were deposited in the basin in an area 50 mi wide by 100 mi long and consisted principally of gypsum and anhydrite (N) with a lesser amount of halite and traces of potash salts. Gypsum was mined in the early 1900's near Ruedi.

MINERAL RESOURCE POTENTIAL—LOCATABLE COMMODITIES

The White River National Forest and the Dillon Ranger District of the Arapaho National Forest were evaluated for 14 locatable mineral-deposit types (pls. 1 and 2, table 2). Table 2 is presented in the text and is reproduced on plates 1 and 2 as an aid in the following discussions of each deposit type. In the following section, the characteristics of known deposits within the Forest are briefly summarized, and assessment criteria are established. Schematic diagrams accompany each model type as an aid for land-use planners and other administrative personnel. The assessment criteria for each deposit type were used to evaluate the Forest for areas of potential for each type of deposit. Ratings of resource potential include ratings of high, moderate, low, and unknown and refer to the likelihood of an occurrence for a specific deposit type. Certainty levels of A, B, C, and D qualify each rating. The letter A indicates the least amount of supportive data for a potential rating and the letter D indicates the most. Definitions and explanations of the level of mineral resource potential are described in Appendix 2, and the size classification for deposits is described in Appendix 3.

Specific areas with mineral resource potential are assigned letter-number designations for ease of description. These letter-number designations are shown on figures 17–47 and plates 1–2. All of the areas of potential for a specific deposit type are given the same letter, starting with A for the first deposit model. The letter is followed by a number which is assigned from left to right across the plate or figure. As an example, an area that has potential for stockwork molybdenum deposits, is labeled with the letter A for the deposit type, followed by a number, such as A1, A2, A3, etc., which is the location identifier. Each letter-number combination indicates a specific geographic area with a defined resource potential and level of certainty for a restricted set of commodities that occur in that deposit type. Areas can have different or identical resource potential and certainty. A letter-number combination can refer to an area with more than one level of potential also. For example, area D4 includes areas of high and moderate resource potential.

On plates 1–2 and figures 17–47, areas of high potential are shown in red; areas of moderate potential are shown in pink; and areas of low potential are shown in a shaded pattern. Areas of unknown potential are shown in a cross-hatched pattern. Certainty ratings are provided in table 2 and in the text.

STOCKWORK MOLYBDENUM (A)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is molybdenum; byproducts are tungsten, bismuth, and tin; trace metals are copper, silver, gold, and lead.

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 will repeatedly shatter; this includes the host pluton and favorable country rocks.

AGE

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

DEPOSIT DESCRIPTION

Stockwork molybdenum deposits occur in epizonal granitic plutons. Stocks showing multiple phases of intrusion and alteration are the most favorable for producing stockwork deposits (fig. 17). These plutons have porphyritic textures, associated intrusive breccias and pebble dikes, and commonly have radial dikes. Source rocks have greater than 76 percent SiO_2 and are high in fluorine, rubidium, yttrium, and niobium and are low in barium, strontium, and zirconium.

Ore minerals occur in a complex network of stockwork quartz veins; 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 wide 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. Although copper occurs in other stockwork molybdenum systems, it is rare in the Climax-type system (White and others, 1981).

Wallrocks exhibit pervasive hydrothermal alteration. Assemblages of alteration minerals exhibit systematic spatial and temporal relationships. Alteration mineral 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. The oxidation of pyrite in the phyllic zone commonly produces a red halo above and around the deposit. Oxygen isotope studies indicate that early potassic alteration in intrusions was generated by fluids derived by magmatic processes and that later quartz and sericite were influenced by 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 the peripheral vein systems. Rock samples contain anomalous concentrations of molybdenum, silver, tungsten, bismuth, and fluorine.

GEOPHYSICAL SIGNATURE

Plutons occur in the gravity low of the Colorado Mineral Belt, which is associated with a large, unexposed batholith. Within this extensive area, favorable terrane may be associated with a smaller, residual gravity low that encompasses an area between Climax and Red Mountain, northeast of the Forest. Local offsets in the gravity field may indicate faults and structural breaks that could have provided paths for mineralizing fluids.

Proterozoic granitic host rocks are often the most magnetic rocks in the region of 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 granitic rock. A Th/U ratio of less than 4:1 suggests uranium depletion that may have resulted from hydrothermal activity.

KNOWN DEPOSITS

The best example of a stockwork molybdenum deposit is the world-class Climax mine, just outside the southeastern border of the Forest.

ASSESSMENT CRITERIA

1. Presence of a Tertiary, fluorine-rich, high-silica pluton.

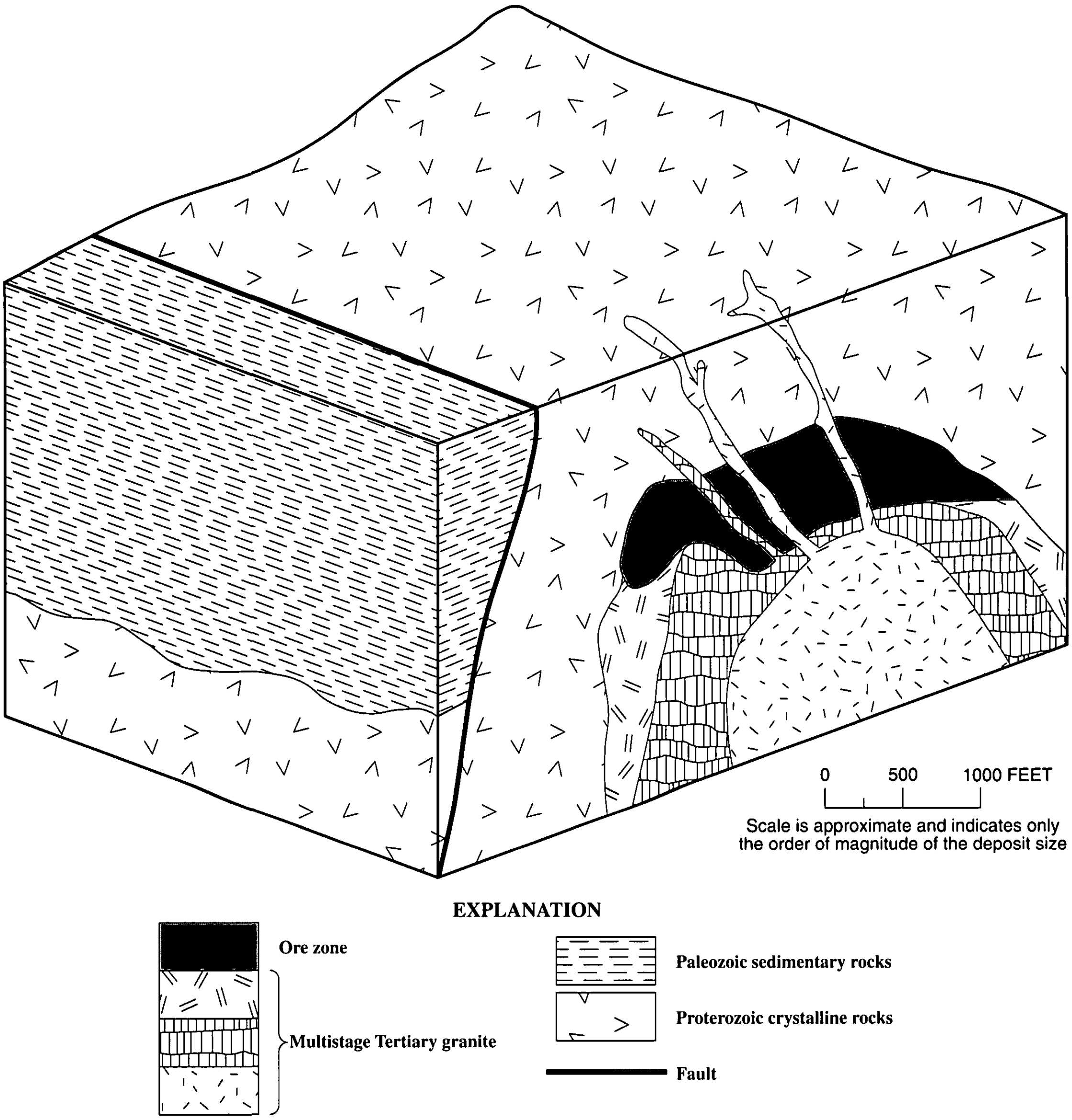


Figure 17. Schematic diagram of stockwork molybdenum deposit (deposit type A).

2. Multistage igneous activity.
3. Occurrence within the gravity low of the Colorado Mineral Belt.
4. Stocks emplaced at very shallow crustal levels in a Tertiary extensional environment.
5. Extensive hydrothermal alteration within and around the stock.
6. Presence of molybdenite in veins and stockwork veinlets and as disseminated flakes.
7. Anomalous molybdenum concentrations in rocks and stream-sediment samples.

ASSESSMENT

Area A1.—The area of Treasure Mountain, in the southwestern part of the Forest has moderate resource potential for molybdenum in small stockwork deposits (pl. 1, fig. 18) with certainty level C (table 2). Treasure Mountain was formed by the intrusion of an epizonal, texturally complex granite pluton (Mutschler, 1970). The pluton contains small, widely separated, quartz-pyrite-sericite-fluorite veins with minor amounts of molybdenite on the crest of the dome (Mutschler, 1976). The pluton occupies both a gravity and magnetic low.

Area A2.—Two small areas on the southeasternmost Forest boundary have high potential for molybdenum in small stockwork deposits (pl. 1, fig. 18) with certainty level C (table 2). These two areas are at West Red Mountain and at the area of the headwaters of Pine and Tellurium Creeks. Both areas are within the confines of the Grizzly Peak caldera, which occupies a well-defined gravity low and has several favorable host lithologies for stockwork

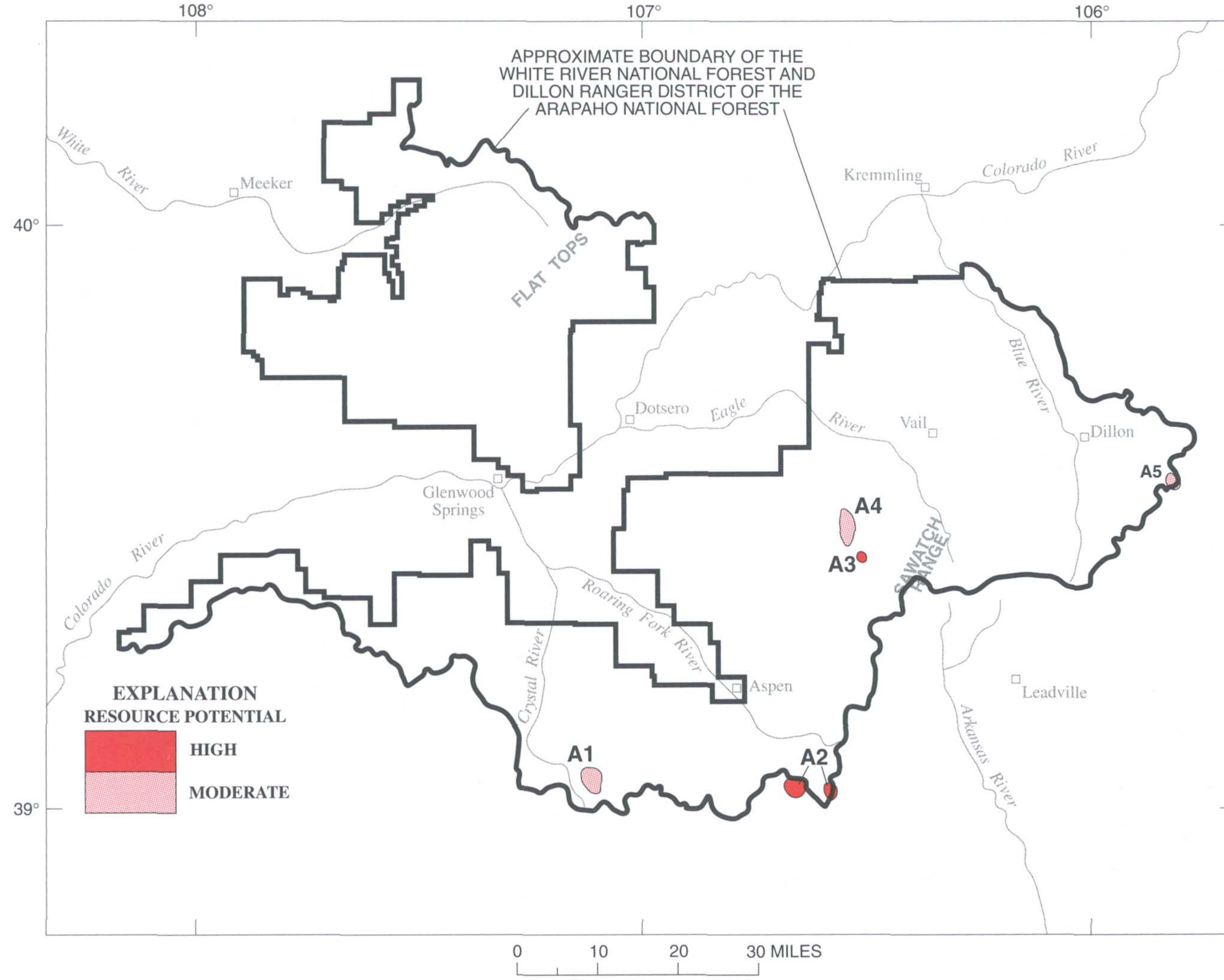


Figure 18. Mineral resource potential map for stockwork molybdenum deposits (A) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

molybdenum, including numerous breccia pipes. The areas of potential have stockwork veins containing quartz and variable amounts of molybdenite; sericitic alteration is prevalent (Cruson, 1973; Baskin, 1987). Slightly anomalous concentrations of gold, silver, tungsten, and tin are also present. The mineralization at West Red Mountain formed in a breccia pipe, and the mineralization at Pine and Tellurium Creeks developed in quartz latite plugs and rhyolite (Cruson, 1973; Baskin, 1987).

Area A3.—An area around Middle Mountain, in the Holy Cross Wilderness, has high resource potential for small stockwork molybdenum deposits (pl. 1, fig. 18) with certainty level D (table 2). Rhyolite dikes having textures similar to those at Climax are present. Quartz-molybdenite veinlets were observed on the surface and were encountered along with pyrite and minor chalcopyrite during exploration drilling (Wallace and others, 1989). Quartz-pyrite-sericite alteration extends more than 2 mi from the dikes. Rock samples have anomalous concentrations of copper, molybdenum, lead, silver, gold, tungsten, and bismuth with a peripheral zone of anomalous lead, copper, and silver concentrations. Stream-sediment samples have anomalous concentrations of copper, molybdenum, and lead; some samples also contain silver and tungsten.

Area A4.—A zone west of East Lake Creek has moderate potential for molybdenum resources in a small stockwork deposit (pl. 1, fig. 18) with certainty level C (table 2). Rocks in this zone have been intensely altered to quartz, pyrite, and sericite, and oxidation has produced a red color. Quartz-molybdenite veins were not observed, but base-metal sulfide veins are abundant (Wallace and others, 1989). Stream-sediment samples contain anomalous concentrations of copper, molybdenum, lead, tungsten, and silver, and rock samples contain anomalous concentrations of copper, molybdenum, lead, silver, tin, and bismuth. Despite the absence of visible molybdenite and an obvious intrusive complex, the alteration, structure, anomalies, and base-metal veins may indicate an unexposed stockwork deposit. The area occupies a magnetic low, which could suggest the presence of a buried pluton.

Area A5.—A small intrusive body a few miles south of the main Montezuma stock is assigned a moderate resource potential for small stockwork molybdenum deposits (pl. 1, fig. 18) with certainty level C (table 2). The stock exhibits phyllic and potassic alteration in a quench-textured porphyry and exhibits stockwork veins of molybdenite (Neuerberg, 1971; Neuerburg and others, 1974). The intrusive complex is also along the Montezuma shear zone, a major northeast-trending structural zone. The Montezuma stock itself occupies both a gravity low and a well-defined magnetic low.

ECONOMIC SIGNIFICANCE

The U.S. currently exports molybdenum and has approximately one-third of the world's identified resources, most of which occur in stockwork deposits. For the last 50 years, the Climax mine, just outside the eastern edge of the Forest, has supplied at least one-half of the world's molybdenum (Govett and Govett, 1976). Although there is an adequate supply of molybdenum to supply the world's needs for a number of years, there will probably be continued exploration interest for molybdenum within the Forest at localities with geologic characteristics like those of the Climax deposit.

STOCKWORK COPPER-MOLYBDENUM (B)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

Commodities are copper and molybdenum; byproducts 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 will repeatedly shatter; this includes the host pluton and favorable country rocks. The plutons occur along intersections of regional fault systems.

AGE

Stockwork copper-molybdenum deposits are Laramide to mid-Tertiary in age.

DEPOSIT DESCRIPTION

Stockwork copper-molybdenum deposits, also called porphyry copper deposits, are a combination of disseminations and stockwork veins that occur in the shattered portions of an intrusive and in the surrounding country rocks (fig. 19). The upper and outer margins of the intrusive become shattered due to adjustments from 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.

Disseminations are most common in the core of the intrusive, and veinlets become dominant towards the outer margins of the intrusive and into 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.

Copper-molybdenum stockwork deposits show pervasive hydrothermal effects that extend into the surrounding wallrocks. 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,

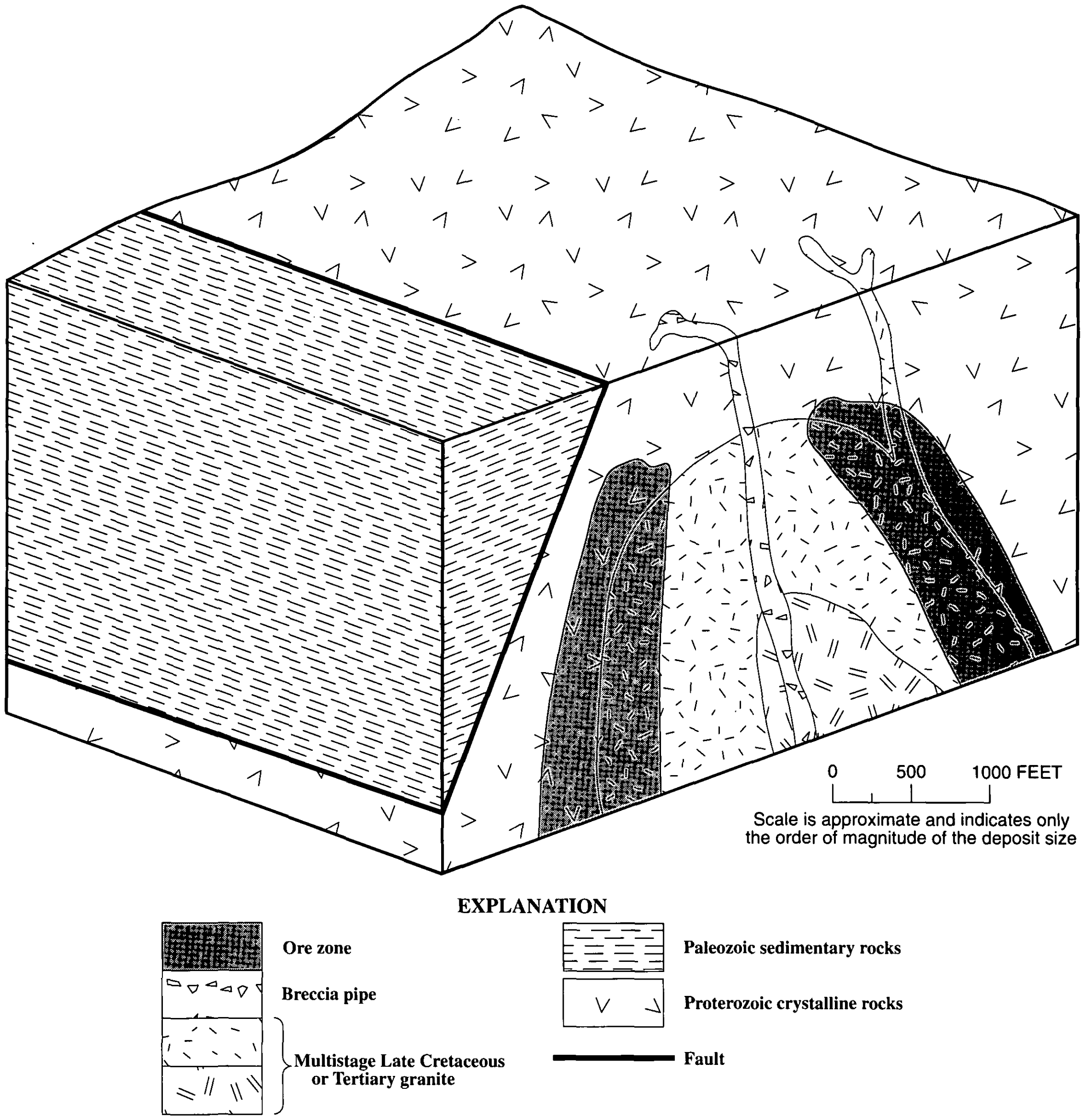


Figure 19. Schematic diagram of stockwork copper-molybdenum deposit (deposit type B).

tungsten, molybdenum, and fluorine may be present in anomalous concentrations.

GEOPHYSICAL SIGNATURE

Plutons occur in the gravity lows of the Colorado Mineral Belt, which is associated with a large, unexposed batholith. Proterozoic granitic host rocks are often the most magnetic rocks in the region of the Forest, and are associated with magnetic highs. Tertiary granitic host rocks, which may or may not be magnetic, are less dense than Proterozoic rocks, especially where extensively altered. Gravity lows, with or without associated magnetic highs, may indicate Tertiary granitic rock. A Th/U ratio of less than 4:1 suggests uranium depletion that may have resulted from hydrothermal activity.

KNOWN DEPOSITS

No known deposits are in the Forest. However, several areas have characteristics favorable for deposits of this type.

ASSESSMENT CRITERIA

1. Presence of a Late Cretaceous to Tertiary monzogranite to granite intrusion.
2. Occurrence within the gravity low of the Colorado Mineral Belt.

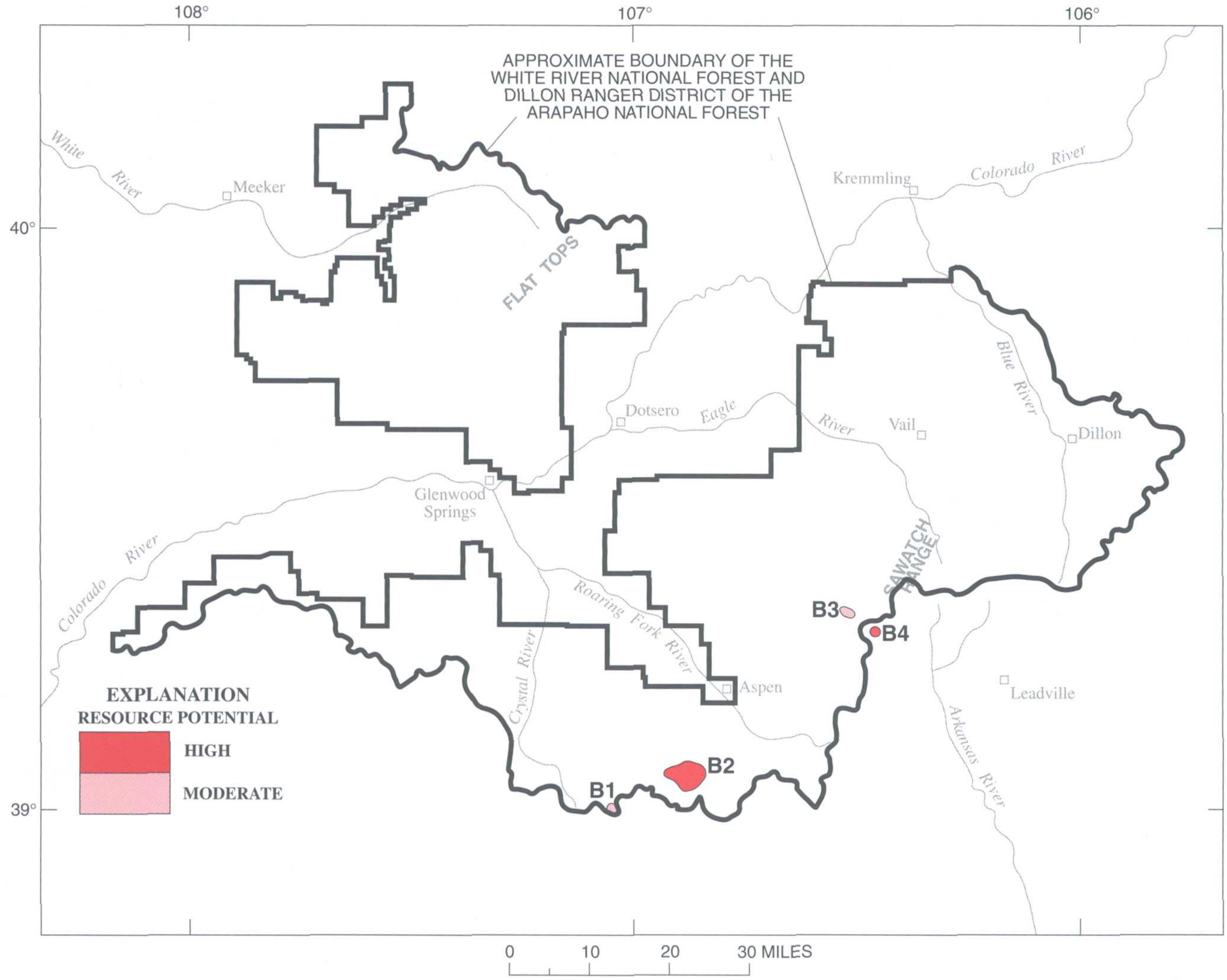


Figure 20. Mineral resource potential map for stockwork copper-molybdenum deposits (B) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

3. Extensive hydrothermal alteration in and around the pluton.
4. Presence of chalcopyrite and molybdenite.
5. Anomalous copper and molybdenum concentrations in rock and stream-sediment samples.

ASSESSMENT

Area B1.—An area around Paradise Pass, in the southwestern part of the Forest, has moderate potential for molybdenum in small stockwork deposits (pl. 1, fig. 20) with certainty level C (table 2). As noted by Mutschler and others (1981) and Pillmore and Leanderson (1983), large portions of the Paradise Pass stock are cut by a stockwork of quartz-sericite-pyrite veins that locally carry molybdenite and chalcopyrite. Pervasive quartz-sericite-pyrite alteration between veinlets is locally developed. A late period of argillic alteration occurred contemporaneously with the base-metal event. The Paradise pluton occupies a gravity high.

Area B2.—An area of the White Rock pluton, in Conundrum, East Maroon, and Cataract Creeks, has high potential for copper and molybdenum in a small stockwork deposit (pl. 1, fig. 20) with certainty level C (table 2). Rock and stream-sediment samples from this area contain anomalous copper and molybdenum concentrations (Miller and Ficklin, 1976; Freeman and others, 1985). Quartz, molybdenite, chalcopyrite, and pyrite are present in veins and shear zones; some molybdenite and chalcopyrite is also present in disseminations (Weisner and Bieniewski, 1984; Freeman and others, 1985). Wallrock alteration consists of quartz-sericite-albite. The area occupies gravity and magnetic lows.

Area B3.—An area in the eastern part of the Forest, between Middle Cunningham Creek and Lyle Lake, has moderate potential for copper and molybdenum resources in a small stockwork deposit (pl. 1, fig. 20) with certainty level B (table 2). Quartz-fluorite-malachite and quartz–specular-hematite–potassium-feldspar veins are common in this area, and many of the rocks have been altered to a quartz-sericite assemblage (Wallace and others, 1989). Only slightly anomalous concentrations of molybdenum were found in stream-sediment samples, and copper, fluorine, and minor molybdenum were detected in rock samples from the area. The area occupies a gravity low and is at the intersection of a major north-northwest-trending magnetic lineament (Campbell and Wallace, 1986).

Area B4.—An area 1 mi west of Timberline Lake, just outside the eastern part of the Forest, has high resource potential for a small stockwork copper-molybdenum deposit (pl. 1, fig. 20) with certainty level D (table 2). Information concerning this deposit is taken from Wallace and others (1989). Rocks at this location range from rhyodacite to rhyolite in composition and have related intrusive breccias. Quartz-molybdenite veinlets were observed at the surface and were also noted during exploratory drilling by industry in 1970. Veins containing base metals are present around the periphery of the complex. The copper/molybdenum ratio of the deposit is greater than 1.0. The intrusive complex and surrounding Proterozoic rocks are altered to a quartz-sericite-pyrite assemblage. Stream-sediment samples contain anomalous amounts of silver, molybdenum, lead, and zinc. No magnetic anomaly is associated with the deposit.

ECONOMIC SIGNIFICANCE

The U.S. currently exports molybdenum and has very minor import reliance (9 percent) for copper (U.S. Bureau of Mines, 1990). Most of the molybdenum production was from the world-class stockwork molybdenum deposits near the Forest, at Climax and at Red Mountain (Henderson mine). Average molybdenum grades at these locations are more than ten times those in average copper-molybdenum deposits. Only a minor amount of copper is produced from stockwork copper-molybdenum deposits.

POLYMETALLIC SKARN (C)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

Commodities include copper, lead, zinc, tungsten, manganese, and iron; trace amounts of gold occur.

HOST ROCKS

Host rocks are carbonate-bearing rocks, mainly pure to impure contact metamorphosed or metasomatized limestone or limey sandstone. Skarns are in direct contact with granodiorite to granite plutons but may extend as far as 0.75 mi from the intrusion. Skarn assemblages are found in limestones of the upper Paleozoic Belden, Maroon, Minturn, and Gothic Formations and in the Cretaceous Niobrara and Jurassic Morrison Formations. Iron skarn is found in limestone of the Belden Formation.

STRUCTURAL CONTROL

Ore minerals occur in skarn bodies adjacent to igneous intrusions. The richest bodies are in carbonate rocks. Ore bodies are localized by faults, bedding planes, and breccia zones. Deposits may be as much as 0.75 mi from the intrusive.

AGE

Both the intrusive bodies and mineralization are Late Cretaceous and Tertiary. Carbonate host rocks may be of any pre-intrusive age, but in the Forest, they are late Paleozoic and Cretaceous.

DEPOSIT DESCRIPTION

Skarns are a type of replacement deposit and form in areas where granitic rocks have intruded highly reactive wallrocks such as limestone (fig. 21). In the Forest, ore deposits in skarn occur as massive replacements, disseminations, podiform bodies, stringers, or fracture fillings; associated polymetallic veins are common. Iron ore is a significant constituent in one of the skarns in the Forest.

Ore minerals include enargite, sphalerite, argentite, tetrahedrite, digenite, scheelite, molybdenite, chalcopyrite, galena, bornite, and magnetite. Skarn mineralogy includes Fe-Mg-Mn-silicate mineral assemblages that may include: diopside-hedenbergite, tremolite-actinolite, grossularite-andradite, wollastonite, idocrase, calcite, epidote, chlorite, and quartz. A variety of minerals may occur in the weathered zones of skarns.

Iron-rich skarn ore is composed of massive magnetite with minor pyrite. Surface exposures have weathered to limonite and hematite, giving a distinctive yellow-orange color to the deposit. Calcite is the most common gangue mineral, but barite, siderite, quartz, and garnet also occur locally.

GEOCHEMICAL SIGNATURE

Anomalous concentrations of tungsten, copper, zinc, manganese, cobalt, berrylium, and arsenic occur in rock and stream-sediment samples.

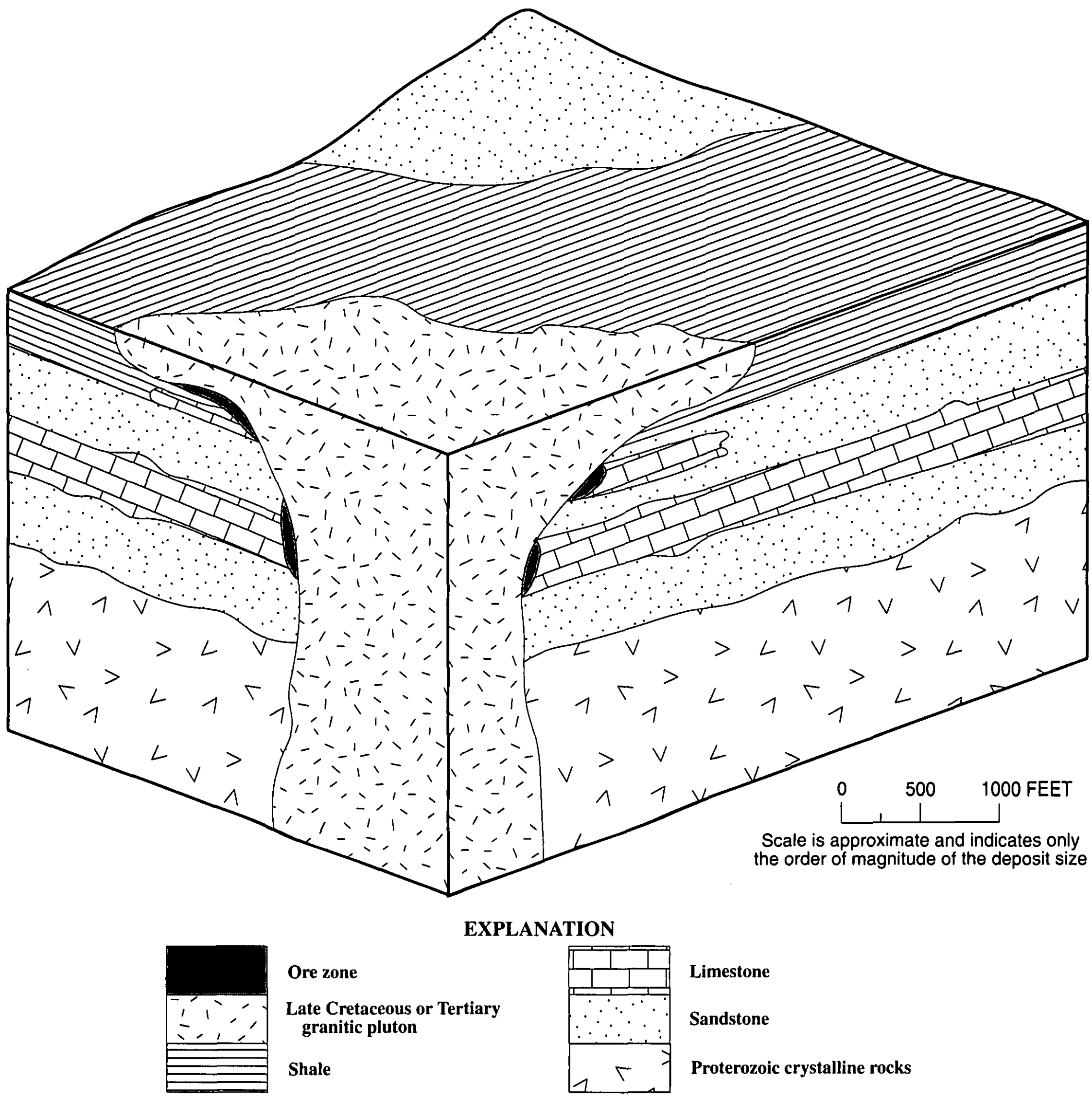


Figure 21. Schematic diagram of polymetallic skarn deposit (deposit type C).

GEOPHYSICAL SIGNATURE

In some places, regional aeromagnetic and gravity data can be used to detect major faults and to locate buried plutons, especially low-density Tertiary intrusions. Magnetite-rich zones show up as local magnetic highs on regional aeromagnetic maps. Contacts between magnetic plutons and nonmagnetic limestone would appear as a magnetic gradient. A Th/U ratio of less than 4:1 suggests uranium depletion that may have resulted from hydrothermal activity.

KNOWN DEPOSITS

In the Breckenridge district, some ore was produced from a skarn deposit in the Niobrara and Morrison Formations (Lovering and Goddard, 1950); the iron deposit south of Aspen, at Taylor Peak (Pitkin County Iron mine), is an iron-rich skarn developed in limestones of the Belden Formation.

ASSESSMENT CRITERIA

1. Intrusive contact with sedimentary or metasedimentary carbonate-bearing strata.
2. Calc-silicate skarn mineral assemblage, accompanied by magnetite and various sulfides.
3. Geochemical anomalies including W, Zn, Cu, Pb, Mn, or Mo.
4. Aeromagnetic anomalies indicating presence of plutons and zones rich in magnetite.
5. Presence of faults, contacts between shale and limestone units, or other major structural features.

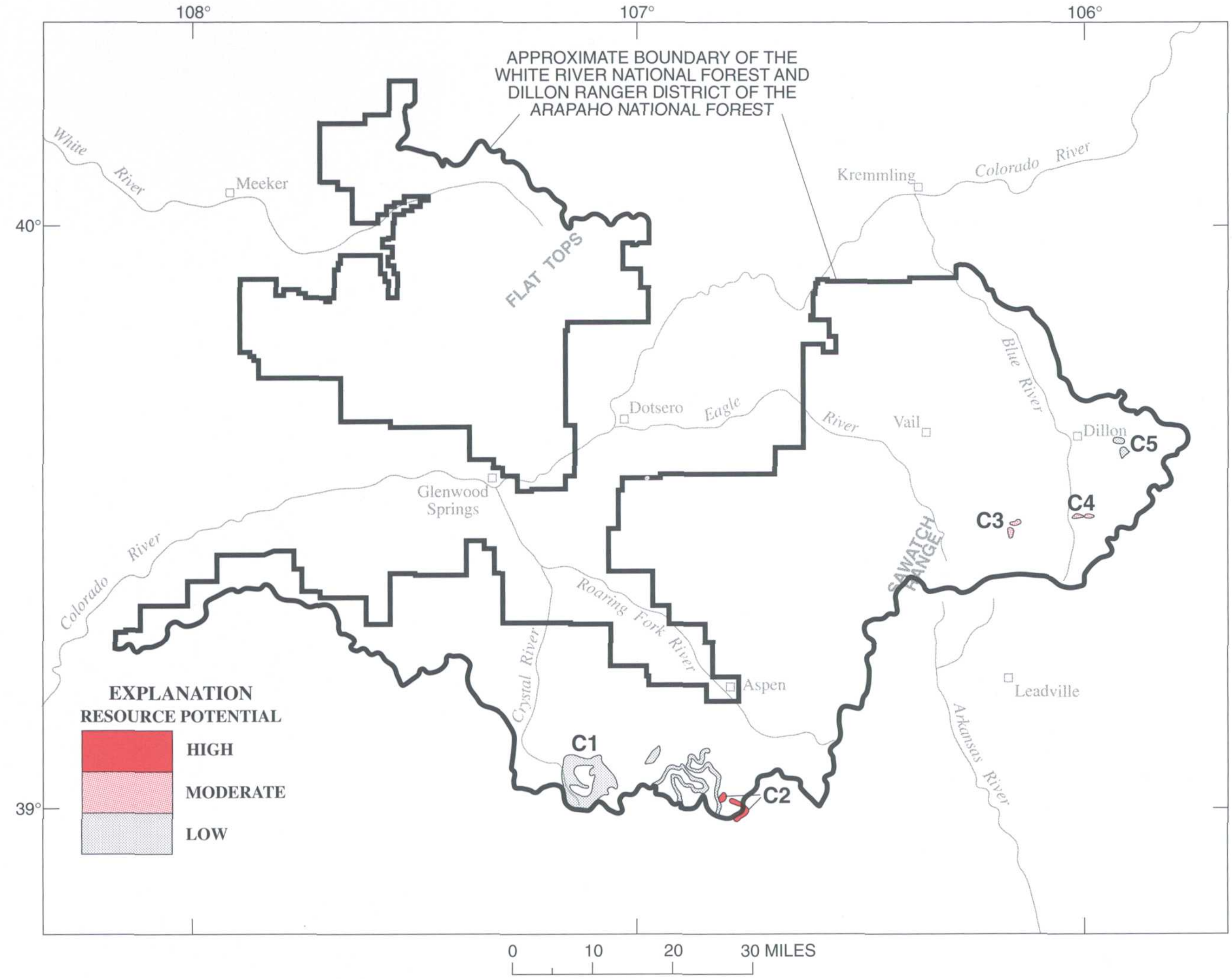


Figure 22. Mineral resource potential map for polymetallic skarn deposits (C) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

ASSESSMENT

Area C1.—In the southwestern part of the Forest, granite of the Treasure Mountain stock is surrounded by an extensive halo of hornblende-hornfels-facies contact-metamorphic rock (Mutschler, 1970, 1976). The metamorphism extends outward from the pluton to the Mancos Shale and includes several limestone-bearing units: the Leadville Limestone, the Chaffee Group, and the Gothic, Maroon, and Belden Formations. Replacement deposits are found in several of these units; however, no skarn assemblages have been noted. For these reasons, the area is assigned a low resource potential for metals in small skarn deposits (pl. 1, fig. 22) with certainty level B (table 2).

Area C2.—A small area in the southern part of the Forest, south of Aspen, has both low and high potential for metals in skarn deposits. Within this area, skarn assemblages are developed in some of the country rock surrounding the White Rock pluton. Metals, however, are not prevalent. Bryant (1979) indicates that the contact aureole for the pluton is a maximum of about 0.6 mi thick. Near Taylor Peak, a skarn deposit formed in limestone of the Belden Formation and has been mined for iron (Pitkin County Iron mine). Pyrite and local copper and molybdenum do, however, occur in quantities as great as several tenths of a percent (Bryant, 1979). The area around the Pitkin County Iron mine has high potential for medium-sized deposits of metals, specifically iron, in additional skarn deposits (pl. 1, fig. 22) with certainty level D (table 2). Remaining areas of low potential (pl. 1, fig. 22) with certainty level C (table 2), are assigned according to information in Bryant (1969, 1979), who delineated areas of metamorphism and (or) sulfide disseminations. Because of the small scale of plate 1, areas of potential are only shown if they are associated with the main body of the White Rock pluton.

Area C3.—Two small areas surrounding Tucker Mountain and Copper Mountain have moderate potential for metals in small skarn deposits (pl. 1, fig. 22) with certainty level C (table 2). As described by Bergendahl and Koschmann (1971), garnet, epidote, chlorite, biotite, and sericite occur throughout this area as aggregates, replacement masses, disseminations, and fissure fillings in sedimentary rocks; calcite, wollastonite, and hornblende were also noted (Koschmann and Wells, 1946). Molybdenite, pyrite, chalcopyrite, magnetite, and specular hematite are disseminated in the alteration zone adjacent to small igneous bodies in limestones of the Maroon and Minturn Formations.

Area C4.—Two small areas south of Prospect Hill, near Breckenridge, have moderate potential for metals in small skarn deposits (pl. 1, fig. 22) with certainty level C (table 2). As described by Lovering and Goddard (1950) and Cocker and Pride (1988), silicates formed in the limey beds of the Niobrara and Morrison Formations. Some of the beds contain appreciable amounts of gold and copper. Ore bodies are usually small, spotty, and irregular and cluster closely around the quartz monzonite porphyry.

Area C5.—Contact metamorphic deposits and minor polymetallic veins occur in two small areas at the west end of the Montezuma stock in carbonate-bearing facies of the Pierre Shale. The shale has been silicified, and garnet, pyrite, quartz, tremolite, and sericite are present. Some ore has been found in thin veins in the altered shale, but no ore of contact-metamorphic origin was observed (Lovering, 1935). Area C5 has low resource potential for metals in small skarn deposits (pl. 1, fig. 22) with certainty level C (table 2).

ECONOMIC SIGNIFICANCE

Some skarn deposits are large and high grade and can contain significant quantities of precious metals, particularly silver. Metals commonly supplied from skarns include copper, lead, zinc, silver, iron, and tungsten. The U.S. imports only 8 percent of its lead, 9 percent of its copper, and 20 percent of its iron. However, the U.S. imports 61 percent of its zinc, 73 percent of its tungsten, and three times more silver than it exports (U.S. Bureau of Mines, 1990). Tungsten is a strategic and critical mineral. No productive skarns are known in the Forest, and only a few small areas have been identified as having any potential. Such deposits in the Forest would have minimal impact on the Nation's mineral supply.

POLYMETALLIC REPLACEMENT (D)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

Commodities are copper, lead, zinc, silver, tungsten, manganese; trace amounts of gold occur.

HOST ROCKS

Host rocks are carbonates, mainly pure to impure dolomite, and minor amounts of quartzite. The main carbonate unit in the Forest is the Leadville Limestone, but deposits also occur in limestones in the Belden, Minturn, and Gothic Formations. The sandstone units in the Forest are the Sawatch Quartzite and Dakota Sandstone. A few replacement deposits also occur in sandstone and siltstone of the Maroon Formation and Eagle Valley Evaporite.

STRUCTURAL CONTROL

Mineralized rock usually occurs adjacent to igneous intrusions, although deposits may also be distant from the intrusive. Ore bodies are localized by faults, vertical beds, bedding planes, and breccia zones. Shale-limestone contacts such as the contact between the Leadville Limestone and Belden Formation are especially productive. Deposits in the Belden are higher grade within the limestone units than within the shale.

AGE

Mineralization age is Late Cretaceous and Tertiary—the same as that of the associated intrusive body. Host rocks may be of any pre-intrusive age. In the Forest, host rocks range in age from Cambrian to Cretaceous.

DEPOSIT DESCRIPTION

Most of the metals produced in the Forest were from polymetallic replacement deposits. These deposits formed where Cretaceous or younger intrusions encountered carbonate or, locally, quartzite units (fig. 23). Deposits range from small pods and veins to large, mixed-sulfide, replacement bodies; the shapes are irregular and structurally controlled. Most of the deposits were enriched by supergene processes. Replacement ore bodies with the largest production are mantos (large sheet-like bodies) extending as much as 4,000 ft laterally, from 50 to 400 ft in width, and from 2 to 150 ft in thickness. The second most productive group of ore bodies are chimney-shaped bodies that occur at the lower ends of the mantos. The oldest replacement-type ore is found within the chimney deposits, and it is believed that the chimney-shaped part of the ore bodies are feeder zones to the mantos.

Primary ores consist principally of sphalerite and galena but locally contain chalcopyrite, silver-bearing tetrahedrite, silver minerals (argentite and digenite), bismuth minerals, manganese, and gold. The principal gangue minerals are

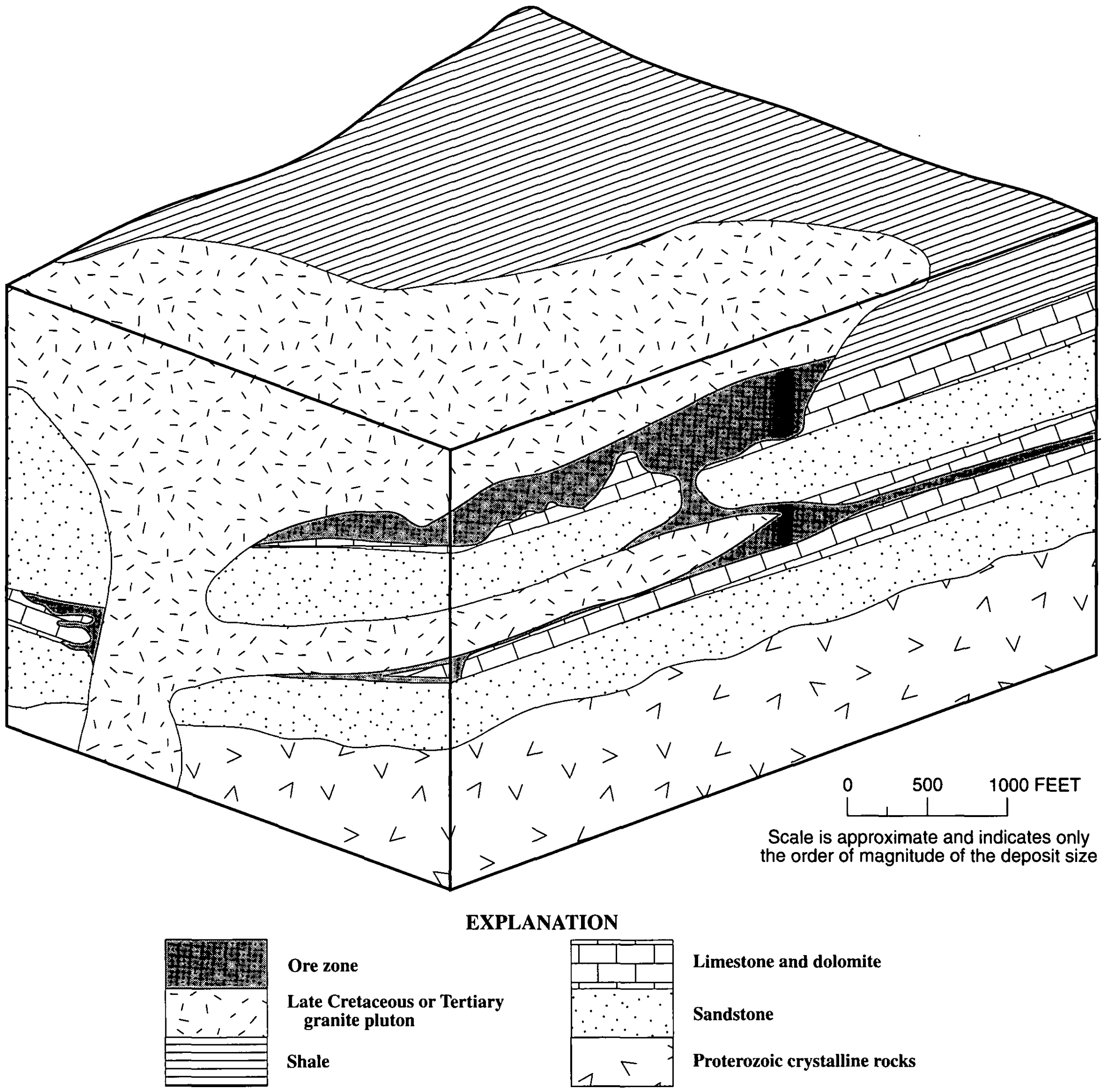


Figure 23. Schematic diagram of polymetallic replacement deposit (deposit type D).

pyrite, siderite, and silica. Secondary oxidized ores typically include cerussite, cerargyrite, and zinc carbonate.

Manganese-oxide minerals occur in epigenetic veins or cavity fillings in limestone, dolomite, or marble associated with the intrusive complex. Minerals include rhodochrosite, calcite, and quartz and varying amounts of rhodonite, barite, fluorite, jasper, ankerite, manganocalcite, pyrite, chalcopyrite, galena, and sphalerite. Ore minerals occur in tabular veins, irregular open-space fillings, lenticular pods, pipes, and chimneys. Manganese replacement deposits were exploited specifically for the iron and steel industry.

GEOCHEMICAL SIGNATURE

Anomalous concentrations of copper, zinc, manganese, gold, silver, tungsten, and arsenic occur in rock and panned-concentrate samples.

GEOPHYSICAL SIGNATURE

In some places, regional aeromagnetic and gravity data can be used to detect major faults controlling or influencing mineralization. These methods could locate buried plutons, especially low-density igneous Tertiary intrusions, that supplied heat, solutions, and metals to form hydrothermal systems. Magnetite-rich zones, caused by hydrothermal enrichment of secondary magnetic material, show up as local magnetic highs on regional aeromagnetic maps. Contacts between magnetic plutons and nonmagnetic limestone would appear as a magnetic gradient. A Th/U ratio of less than 4:1 suggests uranium depletion that may have resulted from hydrothermal activity.

KNOWN DEPOSITS

In the Aspen district, the Aspen and Emma mines (high grade of 200 ounces/short ton silver (Brown, 1990)), the

Little Anny, Spar, Chloride, and Mollie Gibson mines along the Leadville-Belden contact are classic examples. In the Gilman District, the Eagle mine was a major producer; deposits are mostly replacements in the Leadville Limestone. Manganese was also mined at Gilman. In the Kokomo district, the Wilfley-Kimberly, Robinson Consolidated, and the Victory–Lucky Strike mines are excellent examples of replacement deposits in the limestones of the Minturn Formation.

ASSESSMENT CRITERIA

1. Presence of carbonate rocks, particularly the Leadville Limestone, quartzite, or sandstone.
2. Presence of Cretaceous and (or) Tertiary plutons, dikes, or sills.
3. Presence of base and precious metals.
4. Occurrences of manganese oxides in veins or disseminated in carbonate rocks.
5. Geochemical anomalies including Zn, Cu, Pb, Mn, W, Au, Ag, or Mo.
6. Presence of faults, contacts between shale and limestone units, or other major structural features.

ASSESSMENT

Area D1.—A small area in the northwestern part of the Forest has low resource potential for metals in small replacement deposits (pl. 1, fig. 24) with certainty level C (table 2). This area includes the Dade prospect, where workings are in the Leadville Limestone; both lead and silver occurrences have been reported (Mallory and others, 1966; Brown, 1990).

Area D2.—Two small areas along or adjacent to the Crystal River have moderate resource potential for metals in small replacement deposits (pl. 1, fig. 24) with certainty level C (table 2). Within these two areas, replacement deposits formed in the sandstone and siltstone of the Eagle Valley Formation where they were in contact with granitic rocks of the Mt. Sopris pluton. Copper, lead, and silver minerals are present in the M & J claims along Bulldog Creek, and lead minerals occur in the Spring Butte mine on the Crystal River (U.S. Geological Survey, 1990).

Area D3.—An area in southern part of the Forest, around Treasure Mountain, has high and moderate resource potential for metals in small replacement deposits (pl. 1, fig. 24) with certainty levels D and C respectively (table 2). Within this area, replacement deposits formed in carbonate rocks adjacent to fracture zones and vein systems and formed beneath impermeable argillaceous beds that served as barriers to hydrothermal fluids (Mutschler, 1976; Kness, 1984). Replacement deposits are found in Leadville Limestone and in limestones of the Gothic and Belden Formations; production has consisted of copper, lead, zinc, and minor silver and gold. Areas close to known deposits are assigned a high resource potential for metals in replacement deposits with certainty level D, and adjacent areas in carbonate host rocks are assigned a moderate resource potential with certainty level C.

Area D4.—A large U-shaped area around the flanks of the Sawatch anticline has high and moderate potential for metals in large replacement deposits (pl. 1, fig. 24). Within this area, favorable limestones of the Leadville Limestone and Belden Formation are present along with numerous plutonic bodies. Uplift of the Sawatch Range resulted in substantial faulting along the flanks of the Sawatch anticline, providing a favorable structural environment. The Belden-Leadville contact also provided a structural horizon for mineralization. High potential with certainty level D (table 2), is assigned to areas within known mining districts, where ore-forming processes were known to occur. Areas of high potential for replacement deposits include the Aspen and Fulford districts on the west and the Gilman and Tennessee Pass districts on the east. Moderate potential with certainty level C (table 2), is assigned to remaining areas due to the presence of favorable host rocks and geologic similarities to known mineralized areas.

Area D5.—A small area, due east of Tennessee Pass, has high resource potential for metals in large replacement deposits (pl. 1, fig. 24) with certainty level D (table 2). This area is in the Kokomo-Tenmile districts, where replacement deposits are found in limestone members of the Minturn Formation. Favorable characteristics include the presence of favorable host rocks (Maroon Formation) and plutonic bodies, extensive faults, presence of metals, and proximity to a known mining district.

Area D6.—A small area near Breckenridge has high resource potential for metals in small replacement deposits (pl. 1, fig. 24) with certainty level D (table 2). This area is within the Upper Blue River and Breckenridge mining districts. Although vein deposits are the dominant type of deposits within these districts, some subsidiary replacement deposits formed where veins intersected favorable rocks. Favorable characteristics include the presence of favorable host rocks (the Maroon Formation and Dakota Sandstone) and plutonic bodies, extensive faults, known metals, and proximity to a known mining district.

ECONOMIC SIGNIFICANCE

Replacement deposits constitute an important deposit type within the Forest. Deposits may be large and high grade and may contain significant quantities of precious metals, particularly silver. The U.S. imports only 9 percent of its copper and 8 percent of its lead; it imports all its manganese; it imports at least three times more silver than is produced domestically, 61 percent of its zinc, and 73 percent of its tungsten (U.S. Bureau of Mines, 1990). There are no individual world-class mines of this type in Colorado, but within the Forest, production from the Aspen, Gilman, Leadville, and Kokomo-Tenmile districts has been locally significant.

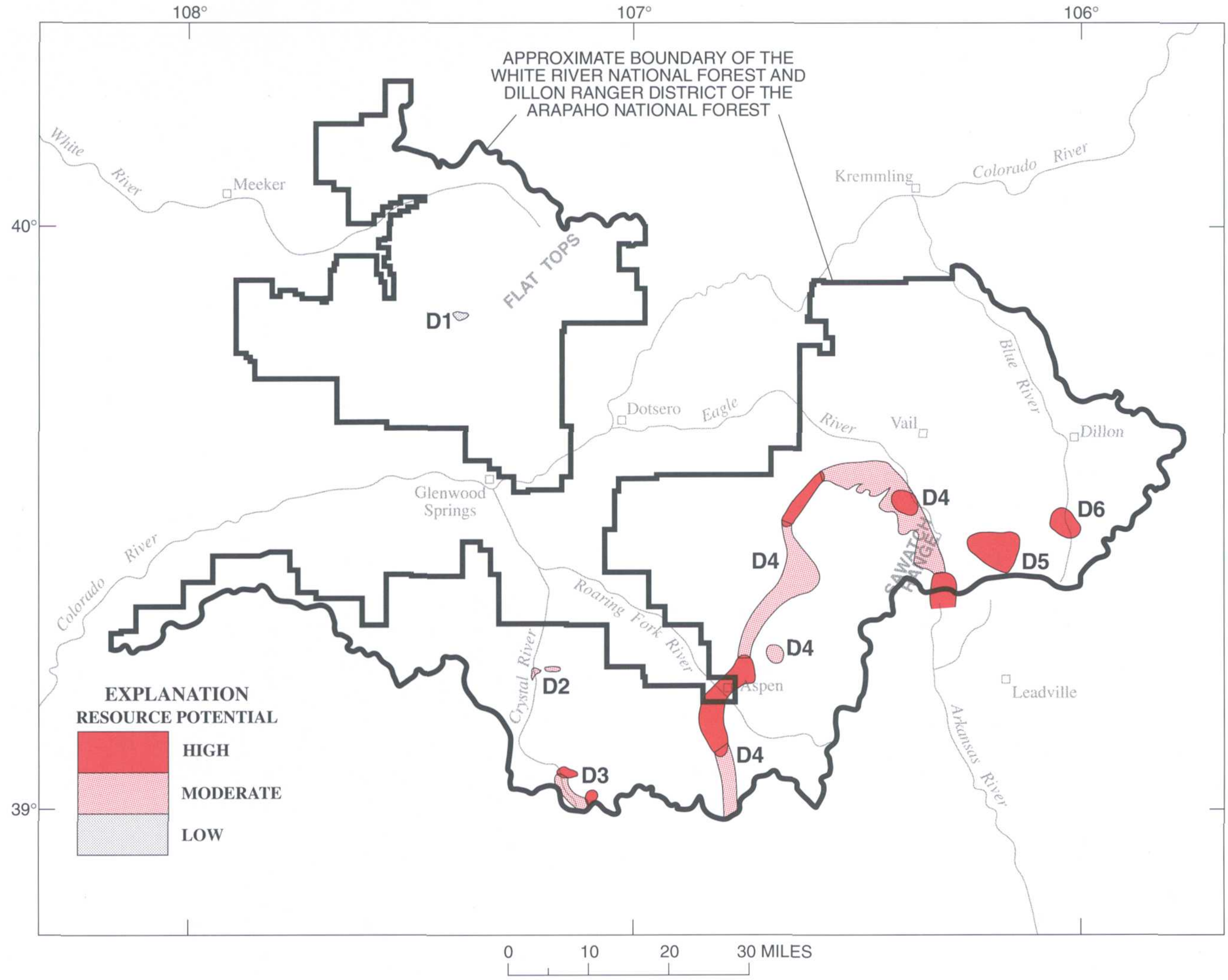


Figure 24. Mineral resource potential map for polymetallic replacement deposits (D) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

Future small discoveries are likely and could help support the local economy, but they will have minimal impact on the Nation's import-export balance.

SHERMAN-TYPE LEAD-ZINC-SILVER (E)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

Commodities include lead, zinc, and silver; copper is a trace metal.

HOST ROCKS

In the Forest, dolomite of the Leadville Limestone is the host rock. The Dyer Dolomite and Manitou Formation are recognized as hosts in areas adjacent to the Forest (Tschauder and others, 1990)—mineralization of these rocks depends on the position of the overlying erosion surface. The most favorable horizons are located within the transition zone between the Red Cliff and Castle Butte Members of the Leadville Limestone (Tschauder and Landis, 1985). Karst deposits have been reported in Aspen and Leadville and as far north as Gilman.

STRUCTURAL CONTROL

Deposits formed in the bottom of caves developed in areas of partial removal and thinning of the Leadville Limestone. A strong northeast trend related to a joint system is common for many of the ore deposits (Tschauder and Landis, 1985). Where paleovalleys were present, ore deposits occur at a significantly lower stratigraphic level, such as in the Dyer Dolomite.

AGE

The age of these deposits is disputed and is either Mississippian (Tschauder and others, 1990) or Tertiary (Johansing and Thompson, 1990).

DEPOSIT DESCRIPTION

The carbonate-hosted ores in central Colorado have been viewed strictly as replacement deposits until relatively recent times. Although Behre (1953) noted the similarity between the deposit at the Sherman mine, just to the east of the Forest, and Mississippi Valley–type deposits (Cox and Singer, 1986), it was not until the 1980's that workers began research to investigate a possible origin for ores that was different than replacement-type deposits (Beaty and others, 1990). The possible genesis of these deposits is being closely examined as this report is being written, so the ratings and interpretations included herein may need to be modified in the future. Within Colorado, these deposits are referred to as "Sherman-type," named after the deposit at the Sherman mine, northeast of Mt. Sherman, just southeast of the Forest in the Mosquito Range.

There are two main schools of thought concerning the origin of Sherman-type deposits. Johansing and Thompson (1990) conclude that Sherman-type deposits formed during the Tertiary as a result of basinal brines moving along thermal gradients controlled by igneous intrusions. Tschauder and others (1990) argue that Sherman-type deposits formed during the Mississippian from regional brines moving under a hydraulic gradient. All of the authors agree that ore in Sherman-type deposits is contained within paleocaves or karsts in the Leadville (fig. 25).

The karsts were filled with iron oxide; carbonate speleothems; stratified dolomitic sand, silt, and clay with associated splatter marks, desiccation cracks, mud drapes, collapse breccia, and angular to rounded grains of silver-rich minerals (Tschauder and others, 1990). Significant amounts of black shale and gray clay from the overlying Belden and Molas Formations are also present in the breccias. Ore occurs as narrow, sinuous bodies that are semi-concordant with bedding; the orebody is commonly elongated in a northeast direction, parallel to the joint system.

Ores are present in the form of open-space fillings. In contrast to replacement deposits, chalcocite or one of the copper sulfosalts is the copper mineral present instead of chalcopyrite, and high concentrations of silver, no tellurides, iron-poor sphalerite, a low amount of pyrite, and significant amounts of barite are characteristic (Beaty and others, 1990; Tschauder and others, 1990). The overprint of Laramide through mid-Tertiary ore deposition that was associated with intrusive centers has obscured much of the evidence for

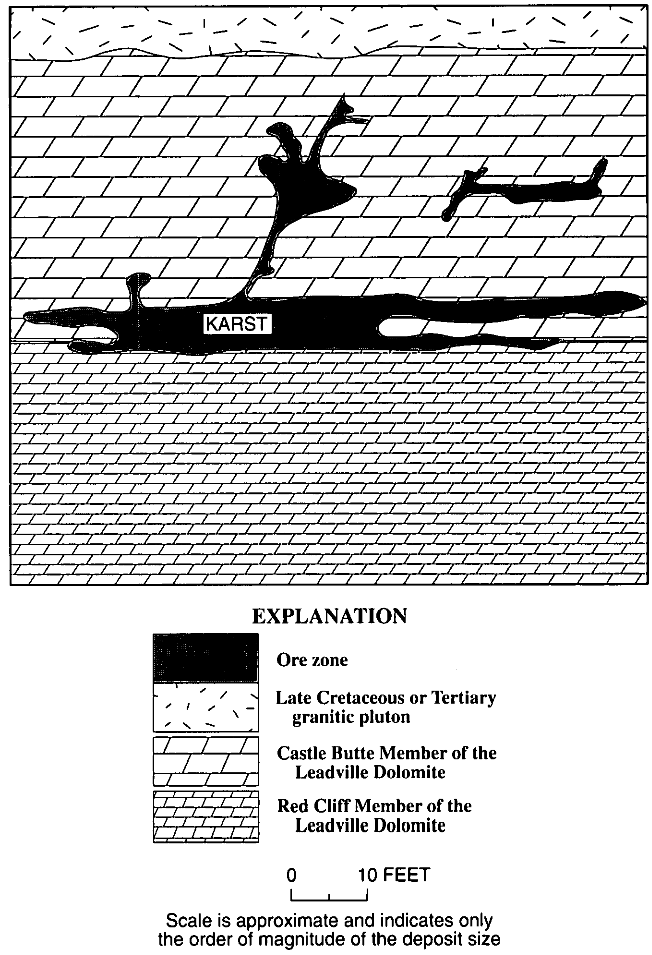


Figure 25. Schematic diagram of Sherman-type lead-zinc-silver deposit (deposit type E). Modified from Johansing and Thompson (1990).

cave-hosted mineralization. In certain places, however, it is clear that porphyries commonly truncate the ore and are, thus, younger. Orebodies were emplaced unrelated to faults or feeder veins.

GEOCHEMISTRY

Anomalous concentrations of Pb, Ag, Zn, and Ba occur in panned-concentrate samples.

GEOPHYSICS

The deposits have no direct geophysical expression.

KNOWN DEPOSITS

Within the Forest, Sherman-type deposits are known from the Wyoming mine, at Gilman; from the Annie Hill, Smuggler, and Park Tunnel mines, at Aspen; and from the Down Under mine, at Lenado (Tschauder and others, 1990).

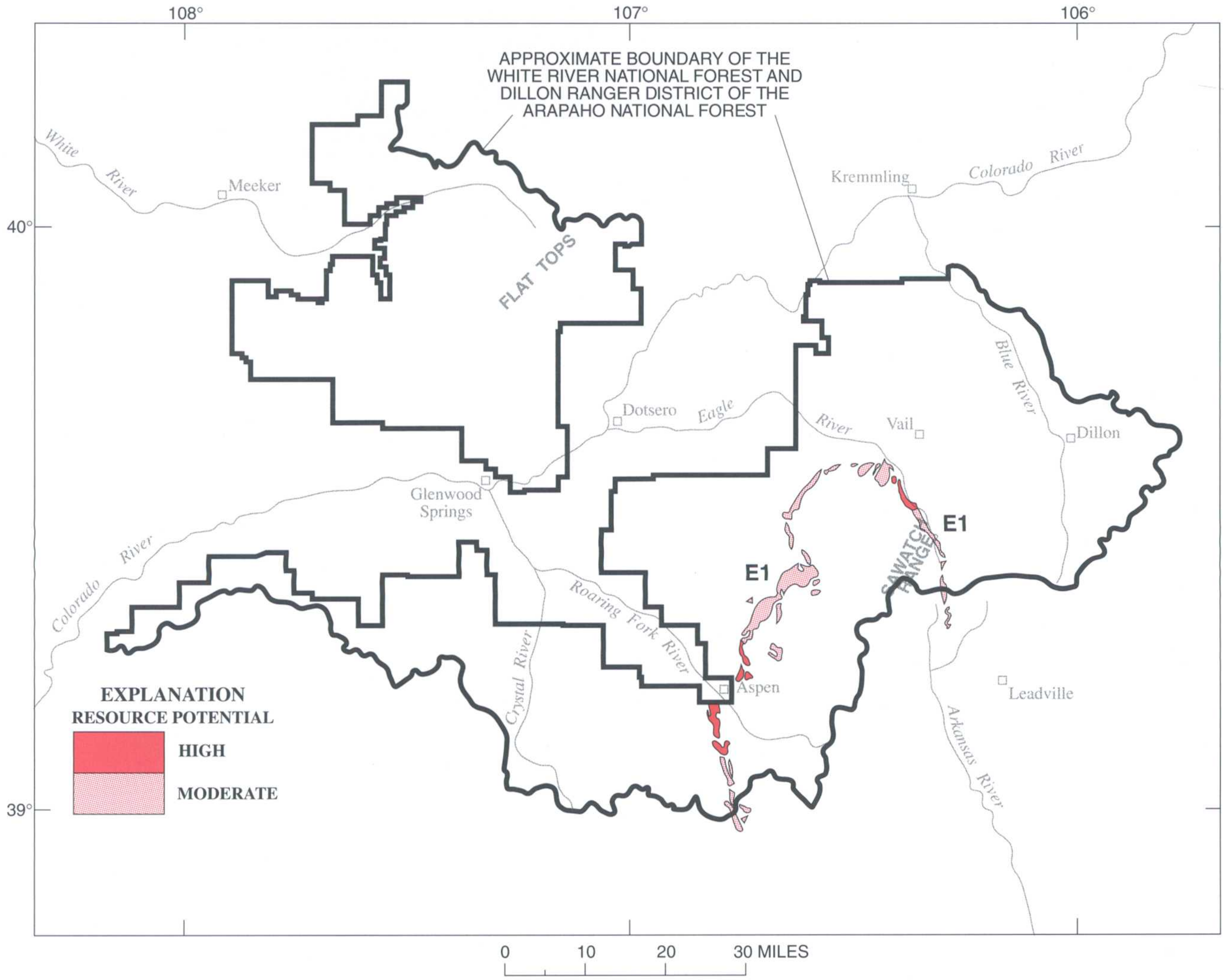


Figure 26. Mineral resource potential map for Sherman-type lead-zinc-silver deposits (E) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

East of the Forest, Sherman-type deposits, including the Sherman mine, have been major sources for silver and lead in the Mosquito Range for over 100 years (Johansing and Thompson, 1990).

ASSESSMENT CRITERIA

1. Presence of dolomites of the Leadville Limestone; the most favorable zone is the transition between the Red Cliff and Castle Butte Members.
2. Presence of solution-erosion features such as solution breccias and other features indicative of cave-fill.
3. Geochemical anomalies, including Pb, Zn, Ag, and Ba.

ASSESSMENT

Area E1.—A large U-shaped area around the flanks of the Sawatch anticline has high and moderate potential for metals in small Sherman-type deposits (pl. 1, fig. 26) with certainty levels D and C, respectively (table 2). The area of potential is outlined by outcrops of the Leadville Limestone. Areas of high potential include those where production has occurred and where evidence of a Sherman-type deposit is present. This includes the area around Aspen, Lenado, and Gilman (Beaty and others, 1985; De Voto, 1983; Tschauder and others, 1990). Areas of moderate potential include areas that have appropriate host rocks, anomalous concentrations of metals in stream-sediment or rock samples, and areas where direct evidence supporting a Sherman-type model (rather than one of simple replacement) is lacking.

ECONOMIC SIGNIFICANCE

Zinc is supplied primarily (61 percent) from large-tonnage foreign sources. A major change in demand or increase in price for this commodity would be needed to support operation of small mines. The U.S. imports 9 percent of its copper and 8 percent of its lead (U.S. Bureau of Mines, 1990). Discovery of silver would certainly enhance the possibility of development. Although the Sherman mine, 12 mi southeast if the Forest, was a large producer, these deposits are uncommon in the Forest. Minor amounts of ore have been produced from these types of deposits at Aspen and Gilman; however, the likelihood of this deposit type supplying large quantities of these metals in the Forest is low.

POLYMETALLIC VEINS (F)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

Commodities include lead, zinc, copper, silver, gold, and manganese; antimony, arsenic, and tin are potential byproducts.

HOST ROCKS

Host rocks vary widely in lithology. The bulk of the deposits occur in shear zones in Proterozoic crystalline rocks, both igneous and metamorphic. Other host rocks include Tertiary-age felsic granitic plutons, dikes, ash-flow tuffs, and Paleozoic and Cretaceous sedimentary rocks. Brittle, easily fractured rocks are particularly susceptible to mineralization.

STRUCTURAL CONTROL

Ores are deposited in areas of high permeability, such as intrusive contacts, faults, fault intersections, and breccia veins and pipes. Shear zones are particularly susceptible to mineralization. Replacement orebodies may form where veins intersect carbonate rocks.

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 (fig. 27). The geometry of the veins and the vein systems is controlled by the distribution and size of fractures, which are commonly modified by movements along the fractures that took place during and after vein filling. The wallrock adjacent to the vein usually shows alteration; the most intense alteration is within a few feet of the vein. The feldspars and ferromagnesian minerals are commonly replaced by the alteration assemblage of quartz, sericite, and minor ankerite. Vein material is commonly iron stained and limonitic, and sulfides often extend into the country rock. Quartz decreases in abundance outward from the vein into the country rock.

Veins range in length from a few inches to as much as a mile and may be as much as 15–20 ft wide and 3,000 ft in vertical extent. Single ore shoots can be as much as 1,000 ft long and 850 ft in vertical extent. Deposits occur as simple to complex, multiphase veins with comb structure, crustification, and colloform textures of quartz with sulfides. Ore is mostly massive, fine- to coarse-grained sulfide, but it is also disseminated in gangue. Major ore minerals include native gold and electrum, sphalerite, chalcopyrite, galena, arsenopyrite, tetrahedrite-tennanite, silver sulfosalts, and argentite.

The highest gold concentrations are generally within the uppermost oxidized portions of veins. Pyrite is abundant and commonly increases with depth, whereas lead and silver decrease with depth. Most veins are oxidized in their upper portions and show enrichment in precious metals. Oxidation can extend as much as 100 ft below the surface, destroying primary minerals and locally increasing the grade of the vein. Manganese is also common in gossan zones and has been prospected in several locations.

GEOCHEMICAL SIGNATURE

Geochemical anomalies vary with the chemistry of the individual vein. Lead, zinc, copper, silver, gold, tungsten, tin, arsenic, antimony, manganese, and barium are most commonly in 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 do exhibit prominent anomalies and steep gradient zones in the magnetic- and gravity-anomaly data (the Homestake shear zone is an example). Many areas of extensive veining and wallrock alteration are characterized by magnetic lows due to destruction of magnetite; however, delineating these lows requires very detailed geophysical surveys.

KNOWN DEPOSITS

Examples of this type of deposit are the Wellington, Country Boy, Sallie Barber, Washington, Dunkin, Puzzle, Ouray, Gold Dust, and Farncomb Hill mines in the Breckenridge mining district and mines in the Kokomo, Upper Blue

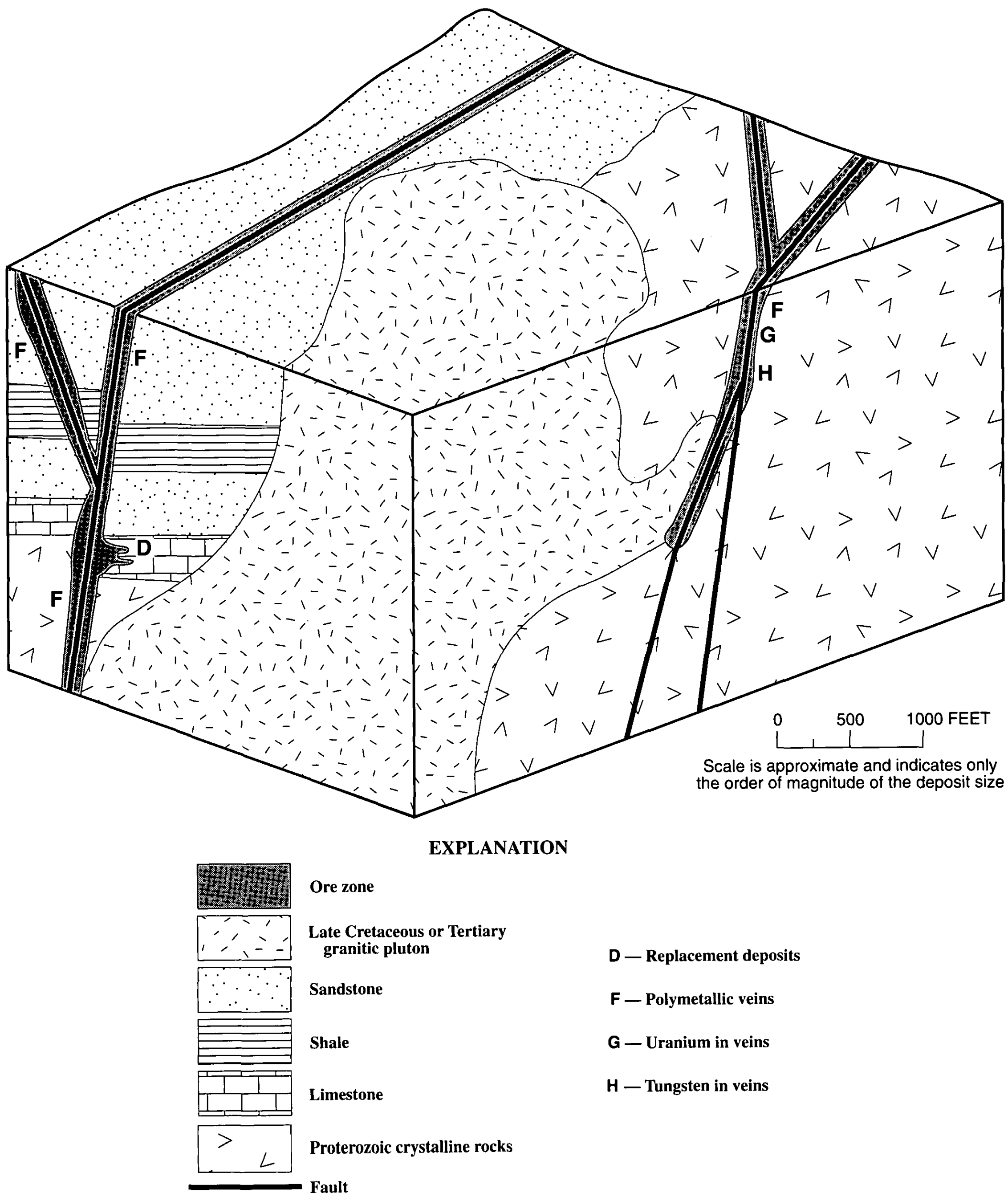


Figure 27. Schematic diagram of polymetallic vein (F), vein uranium (G), and vein tungsten (H) deposits.

River, Frisco, Montezuma, Tennessee Pass, Holy Cross City, and Aspen mining districts.

ASSESSMENT CRITERIA

1. Presence of base or precious metals.
2. Presence of high-angle faults, shear zones, fault intersections, or intrusive contacts.
3. Presence of plutonic or hypabyssal igneous bodies of Late Cretaceous or Tertiary age.

ASSESSMENT

Area F1.—Gold-bearing veins were mined at the Gray Eagle mine, north of New Castle, above East Elk Creek (Vanderwilt, 1937). Veins are in Proterozoic hornblende gneiss. This small area has a high resource potential for additional small deposits of metals in veins (pl. 1, fig 28) with certainty level D (table 2).

Area F2.—South of the Flat Tops Wilderness in the northern part of the Forest, small amounts of ore were

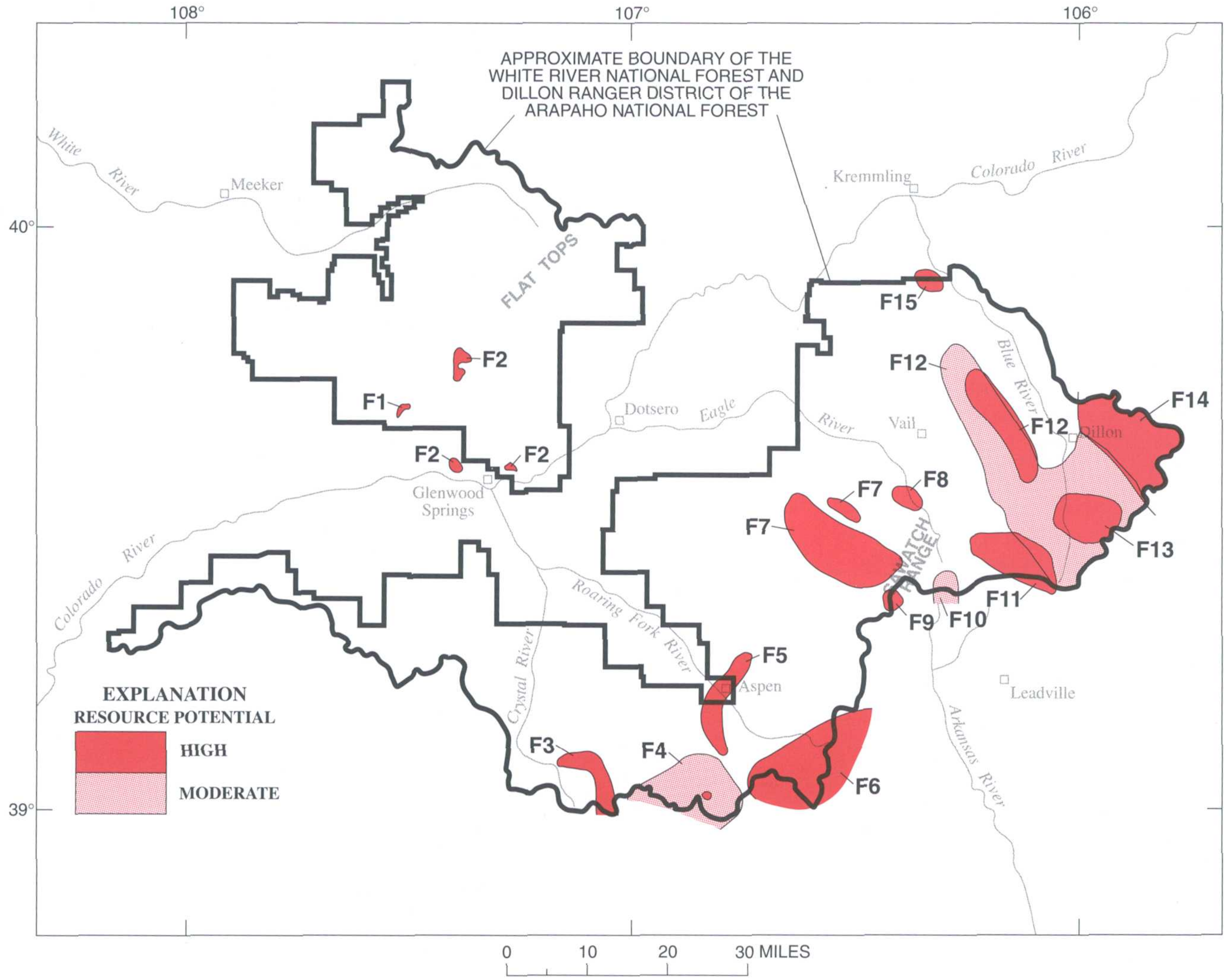


Figure 28. Mineral resource potential map for polymetallic vein deposits (F) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

produced from the Carbonate mining district (Brown, 1990). Gold and silver are present in fissure veins and stockworks in the Leadville Limestone and limestones in the Chaffee Group along the crest of the White River uplift. A minor amount of zinc ore was produced from the Defiance mine. Copper and lead minerals are also present. The southernmost of these areas, at the Windy Point mine, contained the largest lead-zinc deposit in the district (Brown, 1990). These three parcels have high resource potential for additional small deposits of metals in veins (pl. 1, fig. 28) with certainty level D (table 2).

Area F3.—A north-south-trending zone, which includes the Crystal River mining district, has a high resource potential for additional medium-sized deposits of metals in veins (pl. 1, fig. 28) with certainty level D (table 2). Lead, zinc, silver, copper, and minor amounts of gold have been mined in this area. Cambrian through Cretaceous sedimentary rocks and Precambrian gneiss underlying the area have been upwarped by intrusion of a Tertiary granite pluton to form the Treasure Mountain dome. Deposits are associated with northwest-trending faults and fissure veins that cut across the Treasure Mountain dome.

Area F4.—Sulfides occur in veins in the granodiorite of the White Rock pluton and in adjacent rocks. Deposits consist mostly of pyrite, quartz, and carbonate, but some veins contain sphalerite, argentiferous galena, malachite, azurite, and, rarely, gold (Bryant, 1979). Production from the veins has been small. The most well-known productive locality is at the Montezuma mine, just northeast of Castle Peak, where 6,700 short tons of ore were mined (Bryant, 1979). The area encompassing the White Rock pluton and adjacent country rocks is assigned a moderate resource potential for small deposits of metals in veins (pl. 1, fig. 28) with certainty level C (table 2). The area surrounding the Montezuma mine has a high potential for additional small deposits with certainty level D (pl. 1, fig. 28), due to the known production of metals.

Area F5.—An elongate zone that includes the Aspen and Lenado mining districts has a high resource potential for large deposits of metals in veins (pl. 1, fig. 28) with certainty level D (table 2). The zone is bounded by the Sawatch uplift on the east and the Castle Creek fault on the west. Faults controlled much of the ore deposition in the Aspen district (Bryant, 1979).

Area F6.—Area F6 includes the Independence and Lincoln Gulch mining districts. In the Independence mining district, gold and silver were produced from veins in Proterozoic crystalline rocks (Ludington and Ellis, 1981). The mines are on veins that are nearly parallel to, but outside of, the northern edge of the collapse structure of the Grizzly Peak caldera. In the Lincoln Gulch district, polymetallic veins are in ash-flow tuffs, breccias, and breccia pipes of the Grizzly Peak caldera itself. Favorable indications for resource potential in area F6 include the presence of faults, shear zones, and igneous contacts, anomalous concentrations of base and precious metals in rock and stream-sediment samples, mineralized and altered rock, and known mining activity. This area has high resource potential for medium-sized deposits of metals in veins (pl. 1, fig. 28) with certainty level D (table 2).

Area F7.—Two northwest-trending areas in the northern Sawatch Range have high mineral resource potential for small deposits of base and precious metals in veins (pl. 1, fig. 28) with certainty level D (table 2). These areas contain Laramide, and possibly younger, intrusive rocks; they have abundant fracture systems and veins containing base and precious metals. Lead, copper, zinc, tungsten, gold, silver, molybdenum, and arsenic are present in anomalous concentrations in stream-sediment samples (Wallace and others, 1989). The small northern zone encompasses the Discovery Tunnel, where mining has exploited base metals along several veins. The large southern zone includes several mining districts, and both base and precious metals are present.

Area F8.—Area F8 includes the Gilman mining district. Although the most productive of the deposits at Gilman are replacement deposits, base- and precious-metal veins are also present in the Sawatch Quartzite and underlying Proterozoic crystalline rocks (Lovering and others, 1978). Minor amounts of telluride ore are also in both of these units. The area encompassing the Gilman mining district has a high potential for medium-sized deposits of metals in veins (pl. 1, fig. 28) with certainty level D (table 2).

Area F9.—The area at the head of West Tennessee Creek, in the vicinity of the Homestake mine, has high potential for small deposits of metals in veins (pl. 1, fig. 28) with certainty level D (table 2). Veins have been exploited in the Homestake mine and other smaller mines in the vicinity. Stream-sediment samples contain anomalous concentrations of lead, zinc, copper, silver, and molybdenum (Wallace and others, 1989).

Area F10.—The area around Tennessee Pass has moderate resource potential for small deposits of base and precious metals in veins (pl. 1, fig. 28) with certainty level C (table 2). In this area, the dominant type of deposit is the replacement-type deposit in the Leadville Limestone. Minor amounts of metal-bearing veins are present in Proterozoic crystalline rocks and porphyries and in quartzites of the Sawatch Quartzite and Minturn Formation. The veins contain pyrite, quartz, and, locally, gold; only traces of base metals have been observed (Brown, 1990).

Area F11.—Area F11 includes the Kokomo-Tenmile and Upper Blue River mining districts. Veins are present and are of local economic interest, but replacement deposits are the major type of deposit in these two districts. Producing veins contain lead, silver, zinc, and gold and are found in the Maroon Formation, Laramide or younger intrusives, and Proterozoic metamorphic rocks (Bergendahl and Koschmann, 1971). This area has a high potential for small deposits of base and precious metals in veins (pl. 1, fig. 28) with certainty level D (table 2).

Area F12.—A large area on the eastern side of the Forest has high and moderate resource potential for medium-sized deposits of metals in veins. This area encompasses much of the Gore Range and the northern part of the Tenmile Range; it includes the North Rock Creek and Frisco mining districts. In the Gore Range, visible evidence of metals is sparse, but the stream-sediment samples contain anomalous concentrations of copper, lead, zinc, silver, gold, molybdenum, bismuth, arsenic, antimony, cadmium, mercury, and tin (Tweto and others, 1970). The Gore Range is underlain by Proterozoic crystalline rock, which is a favorable host rock for vein deposits. Favorable structures include major faults both parallel and crosscutting the range. High mineral resource potential for metals in veins (pl. 1, fig. 28) with certainty level D (table 2) is assigned to an area with known production, abundant vein occurrences, and persistent anomalous concentrations of base and precious metals in stream-sediment samples (pl. 1, fig. 28). Moderate resource potential (pl. 1, fig. 28) with certainty level C (table 2) is assigned to the remaining area. The area of moderate resource potential also includes land between areas of high potential in the Frisco, Montezuma, Upper Blue River, and Breckenridge mining districts, where there has been known production from veins.

Area F13.—An area encompassing much of the Breckenridge mining district has high resource potential for large deposits of base and precious metals in veins (pl. 1, fig. 28) with certainty level D (table 2). Vein-type deposits have been the most productive type of deposit in the district, and most of the production is from a small area that extends from Little Mountain to Mineral Hill. Metals occur along faults in Tertiary intrusives and the Dakota Sandstone, but some veins are also found in shale units. The major components of veins are copper, lead, zinc, gold, and silver (Lovering and Goddard, 1950).

Area F14.—In the Montezuma mining district, all of the ore produced was in veins containing gold, silver, copper, lead, zinc, arsenic, antimony, and bismuth (Lovering, 1935). Veins are present in the Tertiary Montezuma stock and the surrounding Proterozoic country rock, but the largest and most productive veins are in Proterozoic pegmatite and gneiss. Most of the veins are along the eastern side of the stock, in the Montezuma shear zone. This area has high mineral resource potential for medium-sized deposits of base and precious metals in veins (pl. 1, fig. 28) with certainty level D (table 2).

Area F15.—In the northeastern part of the Forest, metals in veins are present in sedimentary rocks surrounding the Tertiary plug at Green Mountain. Copper, lead, zinc, and silver were mined along the contact of the intrusive with the Dakota Sandstone, in a black shaley bed in the Dakota, and in a coarse breccia zone at the contact with the intrusive (McCulloch and Huleatt, 1946). This area has a high resource potential for small deposits of base and precious metals in veins (pl. 1, fig. 28) with certainty level D (table 2).

ECONOMIC SIGNIFICANCE

Polymetallic vein deposits commonly produce copper, lead, zinc, and precious metals. The U.S. has a net import reliance of 8 percent lead, 9 percent copper, and 61 percent zinc (U.S. Bureau of Mines, 1990). Porphyry copper mines elsewhere in the Southwest produce the major portion of this metal in the U.S., whereas the mid-continent 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, although the presence of silver and gold as byproducts would certainly enhance the possibility of development. Because veins in the Forest are likely to be small and potentially rich, production from them is likely to have only local economic impact.

VEIN URANIUM (G)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is uranium; trace amounts of gold, silver, antimony, lead, zinc, and molybdenum occur.

HOST ROCKS

Host rocks are Proterozoic granitic rock, gneiss, and pegmatite and the Dakota Sandstone.

STRUCTURAL CONTROL

Deposits are in or along fractures, particularly within faults of the Homestake shear zone.

AGE

Unknown, although probably Late Cretaceous to Tertiary.

DEPOSIT DESCRIPTION

These types of deposits occur in silicified and brecciated veins along fault zones (fig. 27). Minerals include varying amounts of autunite, torbernite, uraninite, uranophane, and quartz. Little is known about the genesis of these deposits in the Forest. Comparison with similar deposits in granitic and metamorphic rocks (Nash and others, 1981; Wallace and Karlson, 1985), however, suggests that they formed by leaching of uranium from Proterozoic basement rocks by meteoric waters. Regional heating and movement of the fluids along basement faults then lead to the formation of the uranium deposit. Igneous activity in the Laramide could have provided the necessary heat.

GEOCHEMICAL SIGNATURE

No elements were present in anomalous concentrations in stream-sediment samples from the drainages around Mt. Yeckel. A geochemical signature commonly associated with uranium in epithermal veins is uranium, mercury, arsenic, antimony, fluorine, molybdenum, and tungsten (Worl and others, 1989).

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.

KNOWN DEPOSITS

The only known occurrence of uranium-bearing veins in the Forest in Proterozoic rock is in the Frying Pan claim on Mt. Yeckel, in the western Sawatch Range. Very little is known of this deposit.

ASSESSMENT CRITERIA

1. Evidence of uranium minerals.
2. Presence of steeply dipping fractures, joints, or shear zones.
3. Presence of quartz veins or silicified faults.

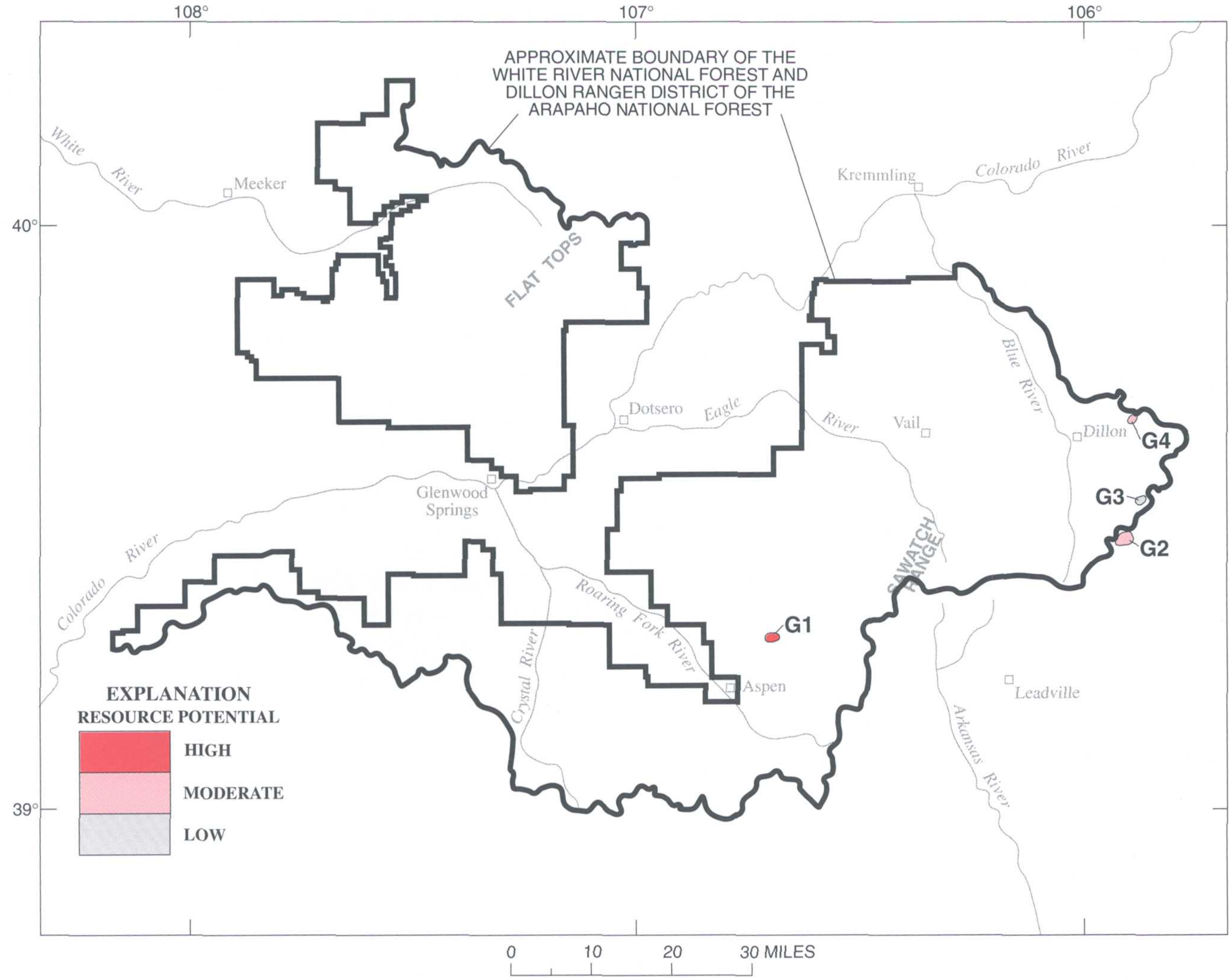


Figure 29. Mineral resource potential map for vein uranium deposits (G) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

ASSESSMENT

Area G1.—A small area around Mt. Yeckel has high resource potential for small deposits of uranium in veins (pl. 1, fig. 29) with certainty level C (table 2). Within this area, uranium minerals occur in a silicified breccia that cuts Proterozoic crystalline rocks. The vein was mined in the late 1950's and early 1960's.

Area G2.—On the southeastern Forest boundary, north of Boreas Peak, autunite is found in joints in the Dakota Sandstone and Proterozoic crystalline rock (Nelson-Moore and others, 1978). Several prospect pits and adits are in the general area. This area has a moderate resource potential for small uranium deposits in veins (pl. 1, fig. 29) with certainty level B (table 2).

Area G3.—Northwest of Whale Peak, in the eastern part of the Forest, a fissure vein in Proterozoic crystalline rock containing U_3O_8 (0.027 percent) has been noted (Nelson-Moore and others, 1978). This area has a low resource potential for small deposits of uranium in veins (pl. 1, fig. 29) with certainty level B (table 2).

Area G4.—A shear zone in Proterozoic crystalline rocks just south of Loveland Pass, contains high amounts of uranium and was assayed at 0.031 to 0.964 percent U_3O_8 (Nelson-Moore and others, 1978). This area has moderate resource potential for small deposits of vein uranium (pl. 1, fig. 29) with certainty level B (table 2).

ECONOMIC SIGNIFICANCE

The uranium industry in the U.S. is nearly inactive and may remain in this condition in the near future. Import and export figures are proprietary (U.S. Bureau of Mines, 1990). It would take a major increase in demand for uranium for small mines to become competitive.

VEIN TUNGSTEN (H)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is tungsten; gold, silver, and zinc are trace metals.

HOST ROCKS

Host rocks are Proterozoic migmatite, granulite, and banded gneiss.

STRUCTURAL CONTROL

Mineralized rock is in fault and shear zones that crosscut Proterozoic rock. In the Upper Blue River mining district, mineralized veins are in steeply dipping faults that strike N. 20° W. to N. 20° E. and show minor displacement. In the Frisco area, veins strike north and northwest.

AGE

The age of mineralization is unknown but is probably Tertiary.

DEPOSIT DESCRIPTION

Veins occur in faults and shear zones in Proterozoic crystalline rock (fig. 27). Veins contain quartz, pyrite, galena, sphalerite, and chalcopyrite with lesser amounts of molybdenite, huebernite (manganese-rich wolframite), bismuthinite, specular hematite, pyrrhotite, gold, and silver. Carbonate gangue is common. Veins are less than 1–5 ft wide and have short strike lengths, usually a few hundred ft maximum (Brown, 1990).

The most extensively mineralized area in the Upper Blue River district is in the vicinity of North Star Mountain, west of Hoosier Pass; gold and tungsten have been produced from this locale. In this area, polymetallic tungsten-bearing veins crosscut Proterozoic granitic rocks. Veins are oxidized and enriched in precious metals in the upper portion, usually the upper 200 ft or less. Zoning is evident: from magnetite and hematite closest to the vein, to silver and lead in the middle zone, to sulfides along the outer periphery (Brown, 1990).

GEOCHEMICAL SIGNATURE

Geochemical signatures include anomalous amounts of tungsten, gold, silver, zinc, copper, bismuth, and molybdenum in rock and stream-sediment samples.

GEOPHYSICAL SIGNATURE

Most veins are too small to be detected by regional gravity and magnetic surveys. Some intrusives and major structures do exhibit prominent anomalies and steep gradient zones in the magnetic- and gravity-anomaly data. Many areas of extensive veining and wallrock alteration are characterized by magnetic lows due to destruction of magnetite; however, delineating these lows requires very detailed geophysical surveys.

KNOWN DEPOSITS

Only the Upper Blue River district produced tungsten, although the primary product for the district was gold (Brown, 1990).

ASSESSMENT CRITERIA

1. Presence of regional faults, particularly those that strike N. 20° W. to N. 20° E.
2. Presence of quartz veins in Proterozoic rocks.
3. Presence of hydrothermal alteration; some minor argillic alteration.
4. Presence of huebnerite-bearing quartz veins.

ASSESSMENT

Area H1.—A small area near the town of Frisco has moderate resource potential for small deposits of tungsten in veins (pl. 1, fig. 30) with certainty level C (table 2). Many of the rock samples collected from this area contain anomalously high concentrations of tungsten (Brown, 1990) and anomalous amounts of gold; base-metal concentrations are low.

Area H2.—A part of the Upper Blue River mining district has moderate resource potential for small deposits of tungsten in veins (pl. 1, fig. 30) with certainty level C (table 2). Although gold was the primary commodity in the district, tungsten, silver, and base metals were also produced (Brown, 1990). Polymetallic veins contain huebnerite, a tungsten-bearing mineral.

ECONOMIC SIGNIFICANCE

Although the U.S. imports 73 percent of its tungsten (U.S. Bureau of Mines, 1990) and considers it a strategic and critical mineral, there is an overabundance of tungsten in the world. Large quantities of low-priced tungsten are available from China, South America, and Australia. Tungsten-quartz

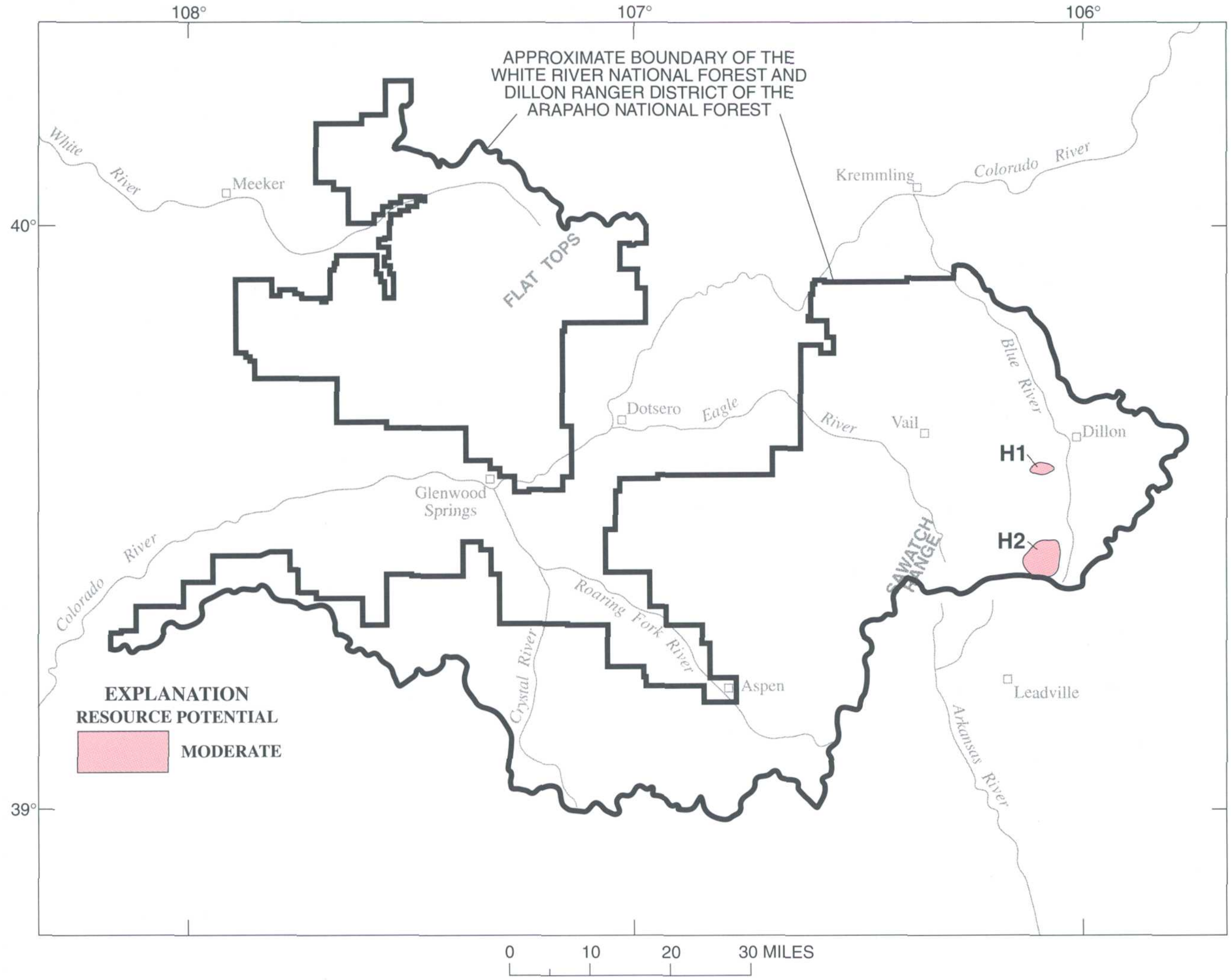


Figure 30. Mineral resource potential map for vein tungsten deposits (H) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

vein deposits in the Forest could be exploited by small mining operations at significantly higher cost.

SANDSTONE COPPER (I)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

Commodities are copper and uranium; byproducts are silver and vanadium.

HOST ROCKS

Host rocks include red-bed sequences containing green or gray shale, siltstone, sandstone, thinly laminated carbonate and evaporite beds, local channel conglomerate, and some thinly laminated silty dolomite. In the Forest, possible host rocks are the Chinle, Minturn, State Bridge, and Maroon Formations. Copper-silver minerals also occur in the Entrada and Dakota Sandstones at two different locales.

STRUCTURAL CONTROL

On a large scale, deposits are expected in interbedded, transgressive, marine shale and sandstone in places where these lithologies are associated with limestone and gypsum, especially in facies deposited in lagoonal basins. Ore occurs along oxidation-reduction boundaries, such as boundaries between carbonaceous material or algal mat and host rock. Fault-bounded intracratonic basins such as the central Colorado trough (Eagle Basin) is a favorable tectonic setting.

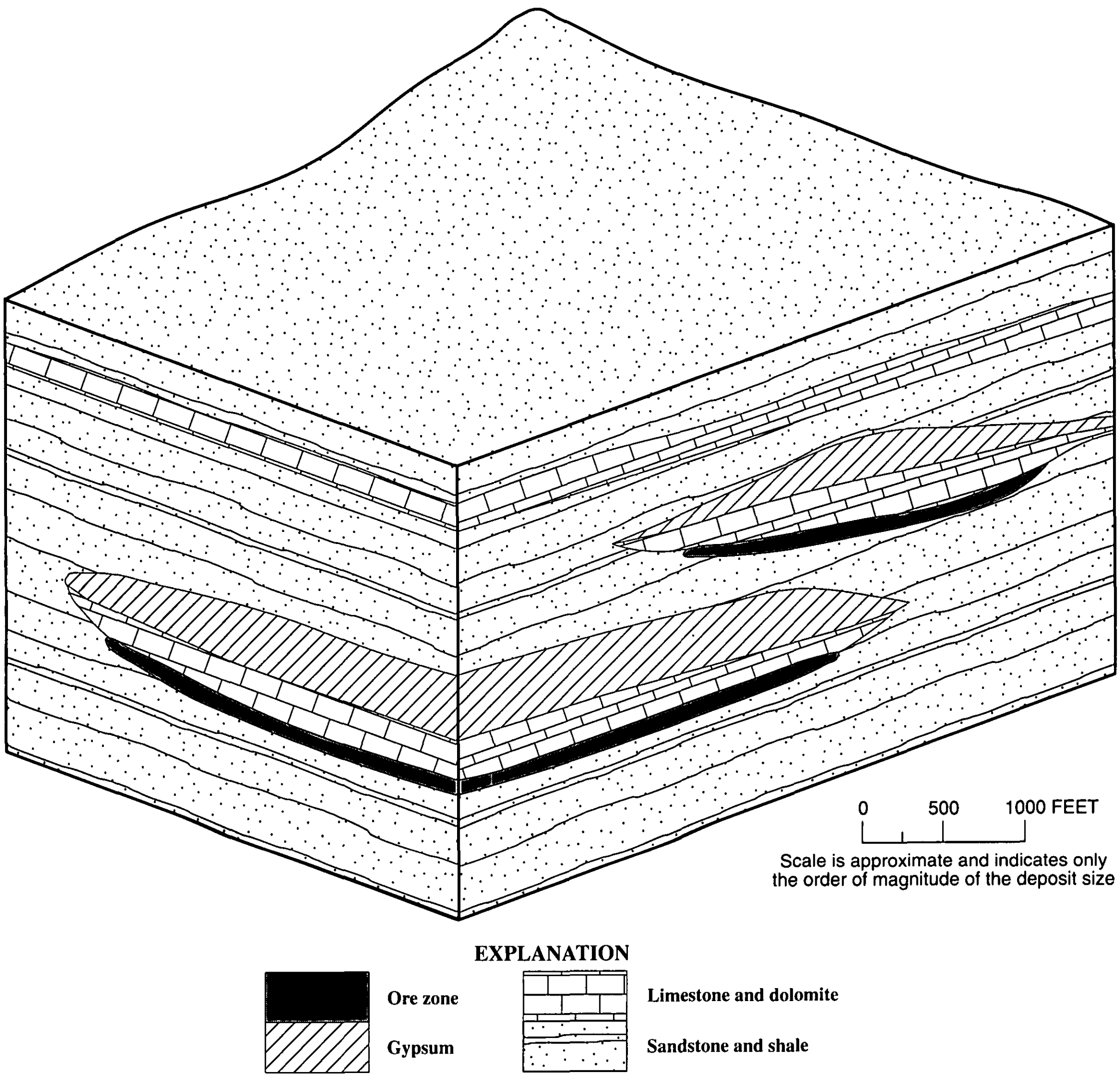


Figure 31. Schematic diagram of sandstone copper deposit (deposit type I).

AGE

The age of mineralization is generally Permian to Triassic but may be as young as Cretaceous.

DEPOSIT DESCRIPTION

Deposits consist of stratabound, disseminated, copper-sulfide minerals in or near organic-rich, chemically reduced sedimentary rocks (fig. 31). In areas of deposition, copper precipitated as sulfides from epigenetic cupriferous solutions in reducing environments. Ore occurs in low-pH environments and on boundaries between oxidized and reduced sedimentary rock. The copper minerals in these deposits are disseminated but are also present in stockwork and in breccia.

Sandstone-hosted copper deposits occur in tectonically active intracratonic settings, commonly in fault-bounded intracratonic basins. Most of these deposits formed early in the diagenetic history of their enclosing sedimentary rocks from brines derived from the sedimentary basin itself (Gustafson and Williams, 1981). In Colorado, the common environment of deposition for the host rock is a marine transgressive facies. Sandstone-hosted copper deposits are sometimes intermingled with sandstone uranium deposits.

Chalcocite, azurite, and malachite are the chief copper minerals; pyrite is common; and bornite and native silver are present locally. Lateral and vertical zonation typically follows this sequence: barren, chalcocite, bornite, chalcopyrite, and pyrite (Gustafson and Williams, 1981). Some deposits contain carrollite, cobalt-bearing pyrite, and germanium minerals. Alteration consists of a green, white, or gray color in red beds (reduced). Surface exposures may be completely leached.

GEOCHEMICAL SIGNATURE

Copper, silver, lead, and zinc are present in anomalous concentrations; the concentration of gold is low.

GEOPHYSICAL SIGNATURE

Some red-bed-sequence rocks display magnetic highs where iron is oxidized, such as at Red Table Mountain. Reduced iron sedimentary rocks would generate relative magnetic lows; however, interbedding between oxidized and reduced sedimentary rocks would be difficult to detect. Gravity gradients and deflections can identify faults that bound favorable sedimentary basins. Radiometric mapping can outline areas of associated uranium in the near-surface (less than 20 inches deep). A Th/U ratio greater than 4:1 implies uranium enrichment.

KNOWN DEPOSITS

There are no known deposits in the Forest. However, just outside of the Forest, in the Brush Creek mining district, copper-silver minerals that may have formed in this type of a deposit are in the Entrada Sandstone at Horse Mountain (Gableman, 1950). South of the Forest, in the Sangre de Cristo Range, occurrences of copper minerals, some containing small amounts of uranium, are abundant near the contact between the Minturn and Sangre de Cristo Formations (Taylor and others, 1984).

ASSESSMENT CRITERIA

1. Presence of marine transgressive and evaporite facies of the Minturn, Maroon, Chinle, or State Bridge Formations or the Entrada and Dakota Sandstones.
2. Presence of stratabound copper minerals.
3. Presence of carbonaceous materials or algal mats.
4. Anomalous copper or silver concentrations in stream-sediment samples.

ASSESSMENT

Area I1.—On Snowmass Creek, on the east side of Eagle Mountain, minor amounts of copper-silver ore were produced at the Snowmass Creek mine. The mine is in the lower part of the Dakota Sandstone, where sulfides replace plant fragments in a bed rich in plant debris. Metals occur at various places in the Dakota Sandstone for about 2 mi along the Snowmass Creek fault zone; however, high silver values are only present at the Snowmass Creek mine (Bryant, 1979). The Snowmass Creek fault had post-Dakota movement, which occurred during emplacement of a nearby pluton. As an alternate hypothesis, the deposits could be considered as low-temperature hydrothermal deposits related to the intrusion of the adjacent stock and its concomitant faulting. However, due to selective mineralization along a reduced horizon and the significant lack of other metals, the deposit is considered to be of the sandstone-copper-model type. The area along the fault in the Dakota Sandstone has a high resource potential for small deposits of copper in sandstone-copper deposits (pl. 1, fig. 32) with certainty level D (table 2).

Area I2.—A small area just outside the north-central part of the Forest has high resource potential for small copper deposits in sandstone (pl. 1, fig. 32) with certainty level C (table 2). In this area, copper-silver minerals occur in one favorable horizon just above the base of the Entrada Sandstone (Gabelman, 1950), near the Lady Bell fault. The ore minerals are malachite, azurite, argentite, cerargyrite, and native silver; minor amounts of vanadium and trace amounts of uranium are also present. Gabelman (1950), suggests that the sandstone was affected by hypogene solutions from the nearby Fulford stock, resulting in the deposition of copper-silver minerals. Until this deposit undergoes further study, however, it is classified in this report as sandstone-copper deposit rather than a hydrothermal one because of the mineral assemblage present.

ECONOMIC SIGNIFICANCE

Sandstone-hosted copper deposits have major economic importance in eastern Europe and central Africa. Large deposits of this type have not been found in Colorado, despite long-term prospecting in favorable environments. Currently, the U.S. uses 91 percent domestic copper (U.S. Bureau of Mines, 1990), which is produced primarily from large copper porphyry deposits (stockwork-copper deposit type). In the Forest, some copper was produced from the Dakota Sandstone at the Snowmass Creek mine, and only two small areas were identified as having potential for additional deposits. The economic impact of future discoveries is likely to be only local.

SANDSTONE URANIUM-VANADIUM (J)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

Commodities are uranium and vanadium; the byproduct is copper.

HOST ROCKS

Host rocks are feldspathic or tuffaceous sandstone deposited in a continental environment. In the Forest, the

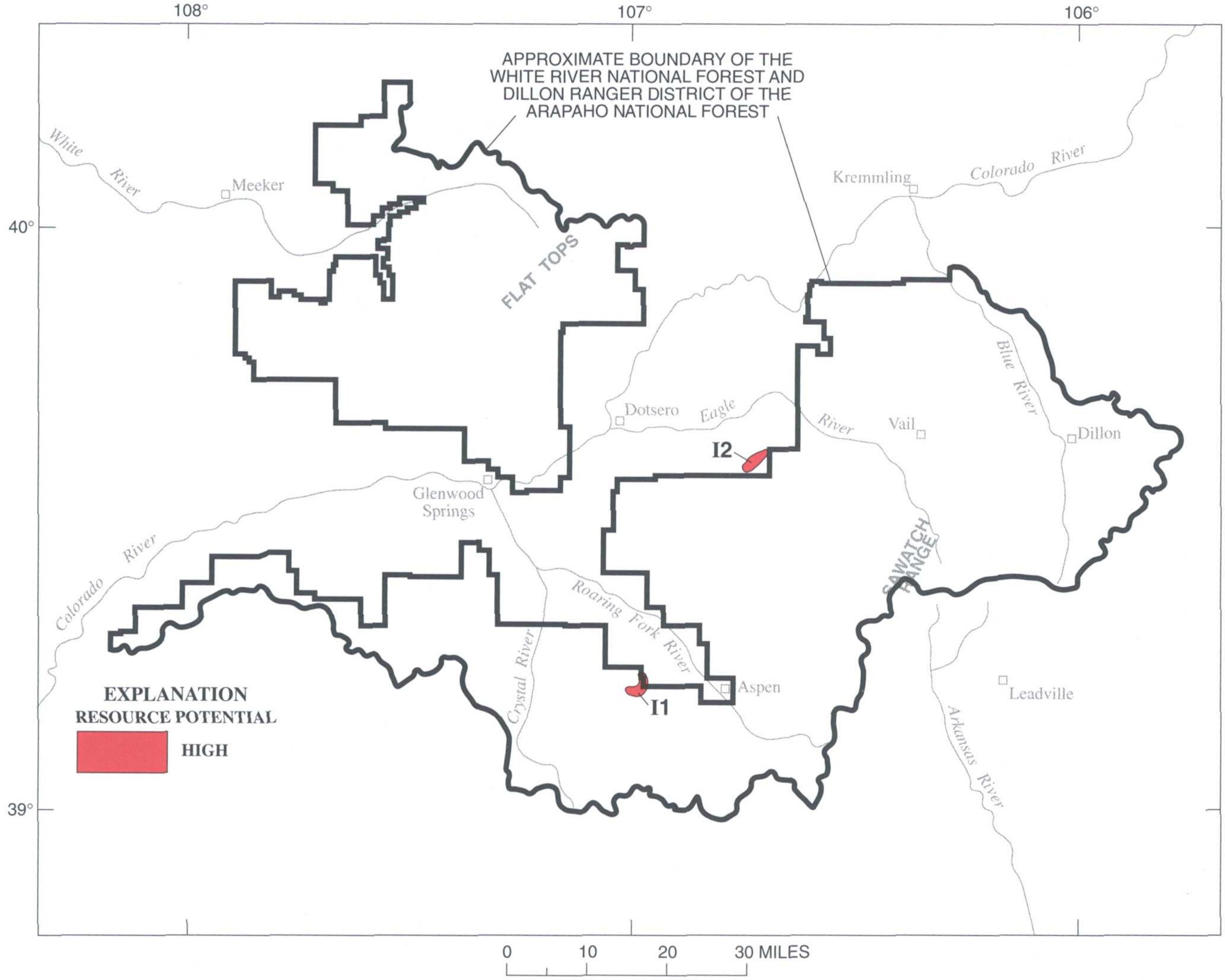


Figure 32. Mineral resource potential map for sandstone copper deposits (I) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

units that contain uranium ore include the Maroon Formation, the Salt Wash Member of the Morrison Formation, the Entrada, Glen Canyon, and Navajo Sandstones, and sandstones in the Chinle Formation. The Dakota Sandstone is also a possible host.

STRUCTURAL CONTROL

Structural control is variable. Of the two known uranium districts, the Rifle and the Uranium Peak district, only the latter shows any structural control. Uranium-vanadium deposits in the Rifle district are found around the nose of an anticline, near the northern end of the Grand Hogback. Although the Grand Hogback and several sets of faults are prominent in the Rifle district, they apparently do not control ore deposition.

AGE

Mesozoic.

DEPOSIT DESCRIPTION

Deposits form as microcrystalline uranium oxides and silicates and are deposited during diagenesis in locally reduced environments in fine- to medium-grained sandstone beds. Some uranium oxides 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 the uranium deposits.

Deposits usually occur as massive and tabular ore bodies that are nearly concordant with gross sedimentary structures of the host sandstone (fig. 33*A*). However, deposits may also form as "roll-front" bodies that are crescent shaped and discordant to bedding in cross section but are elongate and nearly concordant to bedding in plan view (fig. 33*B*). Tabular uranium occurs as lenses within reduced sandstone, and roll-front deposits occur at interfaces between oxidized and reduced ground.

Primary ore minerals are carnotite, tyuyamunite, roscoelite, montroseite, galena, chalcopyrite, pyrite, sphalerite, and marcasite. Oxidized portions of the deposits contain uranophane, autunite, azurite, and malachite. Ore minerals are deposited in locations where replacement of wood or other carbonaceous material has occurred. The carbonaceous material reduces the uranium and provides for the precipitation of the primary uranium minerals. Contemporaneous felsic volcanism or eroding felsic plutons are considered to have been the source of the uranium. In tabular ore, the source rocks for ore-related fluids are commonly in overlying or underlying mud-flat-facies sedimentary rocks.

GEOCHEMICAL SIGNATURE

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

GEOPHYSICAL SIGNATURE

No expression was recognized in regional aeromagnetic or gravity data. However, tabular ore bodies may have a low magnetic susceptibility. Anomalous radioactivity may be observed over areas with a high concentration of uranium.

KNOWN DEPOSITS

Known deposits are northeast of Rifle, in the Rifle district, and in the northwesternmost corner of the study area, in the Uranium Peak mining district.

ASSESSMENT CRITERIA

1. Presence of the Maroon Formation, the Salt Wash Member of the Morrison Formation, the Entrada, Glen Canyon, and Navajo Sandstones, sandstones in the Chinle Formation, or the Dakota Sandstone.
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 surface radioactivity would reveal shallow surficial deposits but would not be helpful in locating buried deposits.

ASSESSMENT

Area J1.—Two areas in the western part of the Forest have high resource potential for small sandstone uranium deposits (pl. 1, fig. 34) with certainty level D (table 2). These two areas include the Uranium Peak and Rifle mining districts, which have recorded uranium production. Host rocks are the Entrada and Navajo Sandstones and the Chinle and Morrison Formations (Nelson-Moore and others, 1978). A high resource potential is assigned because of the presence of favorable host rocks, anomalous concentrations of vanadium in stream-sediment samples (fig. 10), and the fact that the areas are known uranium and vanadium producers.

Area J2.—A broad northwest-trending belt of sedimentary rocks in the western part of the Forest has low resource potential for uranium in small deposits (pl. 1, fig. 34) with certainty level C (table 2). Favorable host rocks define the limits of the area of potential. Many of the stream-sediment samples within this area contain anomalous concentrations of vanadium (fig. 10). Although the same host rocks are present in the northern part of the Forest, none of the stream-sediment samples from that area contained anomalous amounts of vanadium. The rocks within this belt are also close to known uranium producers in the Rifle and Uranium Peak districts. For these reasons, the entire belt of rocks is assigned a low resource potential for uranium with certainty level C.

Area J3.—A small area near Red and White Mountain has high mineral resource potential for small sandstone uranium deposits (pl. 1, fig. 34) with certainty level D (table 2). At the western edge of the area of potential, a small amount of uranium and vanadium were produced from the Arrowhead mine. Uranium minerals were found in the Shinarump Member of the Chinle Formation. Uranium minerals were noted in the same unit at the eastern edge of the area of potential (Nelson-Moore and others, 1978).

Area J4.—A small area about 6 mi north of Vail Pass has high resource potential for small deposits of uranium in sandstone (pl. 1, fig. 34) with certainty level D (table 2). A small amount of uranium was mined from the Maroon Formation on the Dorado claims in the mid-1960's (Nelson-Moore and others, 1978).

ECONOMIC SIGNIFICANCE

Uranium deposits in sandstone have yielded most of the uranium produced in the U.S. and an additional large quantity of byproduct vanadium. Currently, the U.S. imports 35 percent more vanadium than it exports; the status of uranium is proprietary. Colorado has produced considerable quantities of uranium from the Uravan mineral belt, southwest of the Forest, but only a few areas in the Forest have produced small amounts of uranium. Exploration for these deposits awaits renewed interest in uranium.

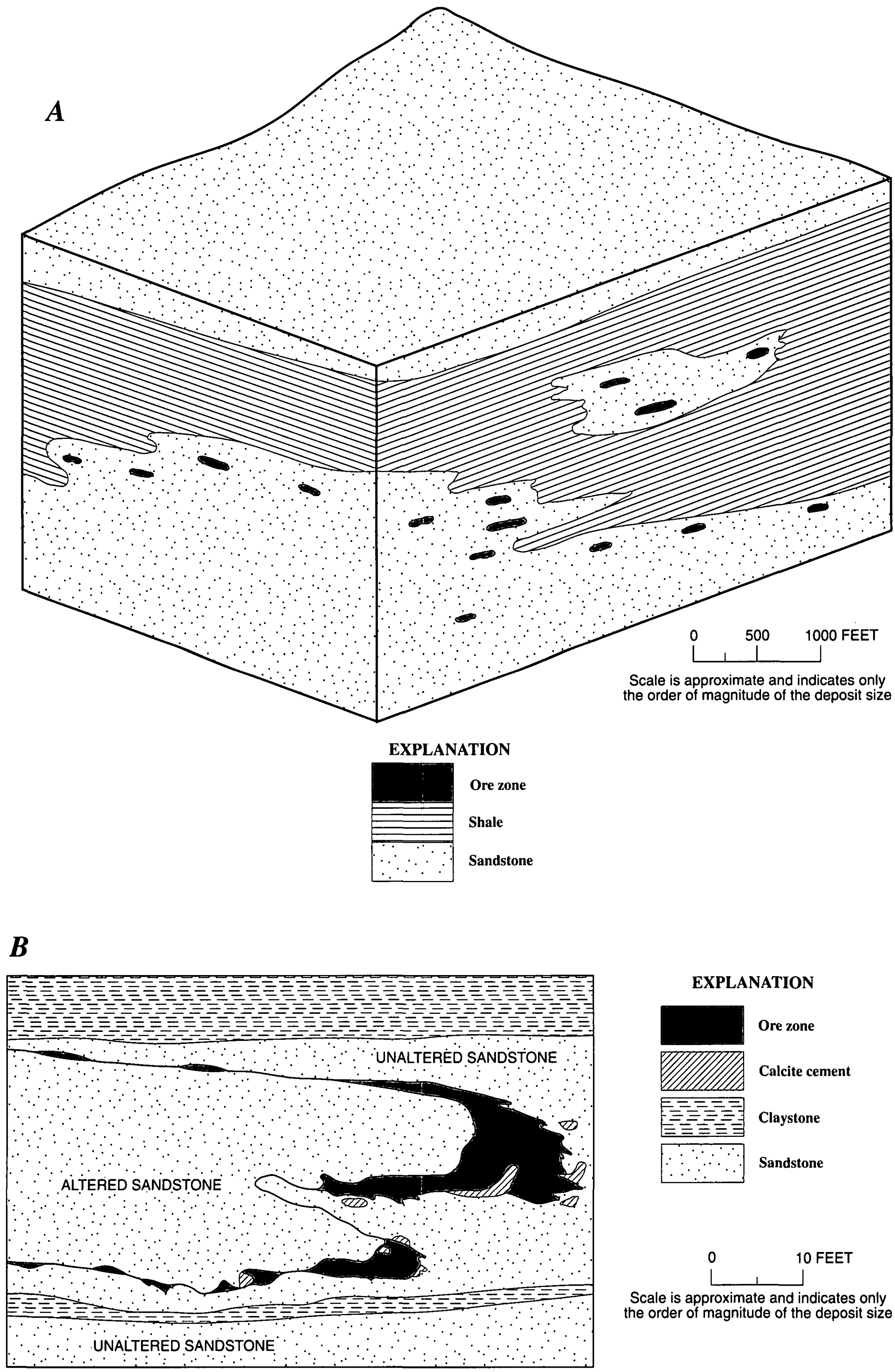


Figure 33. *A*, Schematic diagram of sandstone uranium-vanadium deposits, tabular type. *B*, Schematic diagram of sandstone uranium-vanadium deposits, roll-front type. Modified from Jensen and Bateman (1981).

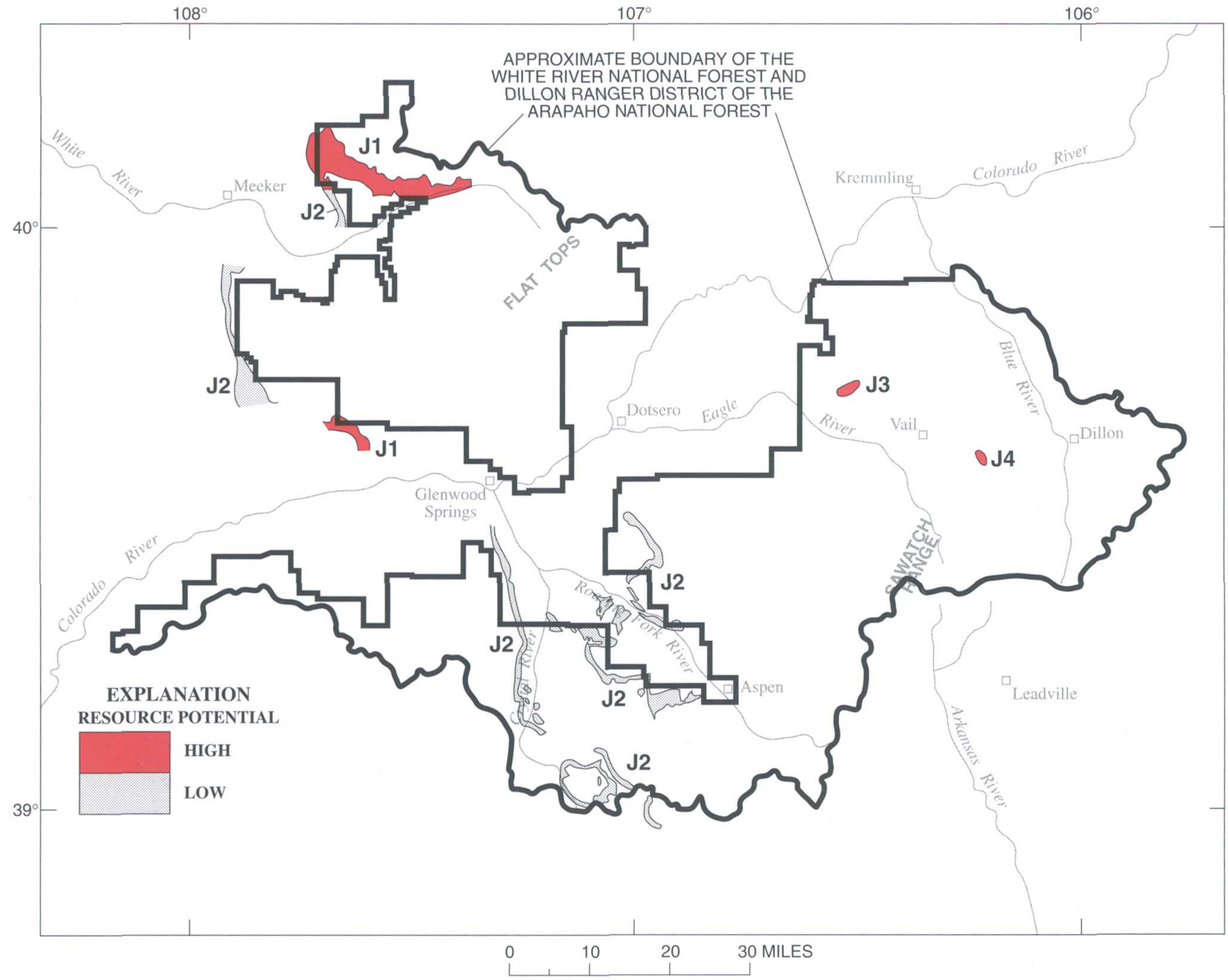


Figure 34. Mineral resource potential map for sandstone uranium-vanadium deposits (J) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

PLACER GOLD (K)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is gold; silver and bismuth are trace metals.

HOST ROCKS

Placer deposits formed in modern alluvium and in Pleistocene fluvial sediments that were deposited by streams that drained Tertiary erosion surfaces. Placer deposits are found near the bottom of gravels deposited by present-day streams, on terraces related to the present streams, in fluvial-glacial sediments, and in erosional debris on slopes.

STRUCTURAL AND LITHOLOGIC CONTROLS

Structure and lithology have little influence on the location of placer deposits. Deposits are usually downstream from known precious-metal lode deposits, and most can be related to veins in Proterozoic or Paleozoic rocks. Some placers may be derived, in part, from the reworking of paleoplacers. Flow patterns of the streams generally deposit the heaviest minerals on the inside of oxbows and in pools cut into the bedrock. As a result, the highest values of gold are on bedrock at the base of gravel deposits. The bedrock may provide natural traps, such as riffles (as when the stream cuts down through beds of shale) or fractures in the bedrock.

AGE

Most of the gold in the Forest came from Tertiary veins in Proterozoic and Paleozoic bedrock. This bedrock was eroded in Tertiary and Quaternary time. The most productive gravels were deposited in the Quaternary.

DEPOSIT DESCRIPTION

Placers are irregularly shaped accumulations of heavy minerals near the bottom of gravel deposits. The placers in

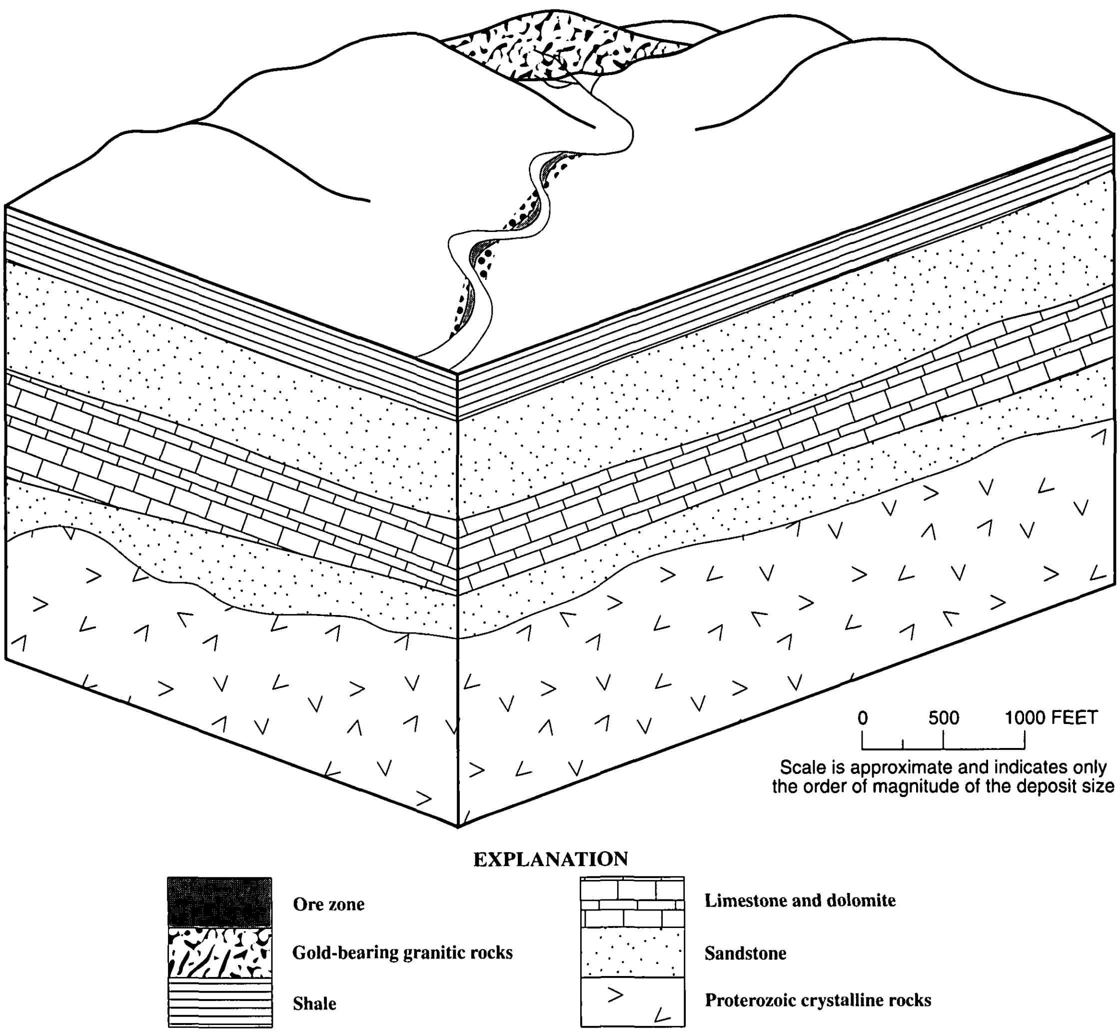


Figure 35. Schematic diagram of placer gold deposit (deposit type K).

the Forest are small and range in size from less than one acre to several hundred acres. The average grade of ore was approximately 0.01 ounces per cubic yard.

The Forest has two distinct types of placer deposits. The eluvial deposits, such as many of those near Breckenridge, formed on hillsides below outcropping gold-bearing veins in shale and porphyry. The coarse, wiry, and flaky gold moved down the slopes along with soil and angular rock material and accumulated as a concentrate near the valley bottoms. The maximum thickness of these gravels was about 25 ft in the gulch bottoms (Parker, 1961, 1974).

The second type of deposits, alluvial, are more common and more extensive. These formed in modern or paleo-streams with moderate gradient (fig. 35). Turbulent and irregular flow patterns separated light from heavy minerals. These placers vary in thickness from 50 to 90 ft and in width from 500 to 3,000 ft. Gold is concentrated in ribbons or streaks in individual channels that are normally 180 to 400 ft wide (Parker, 1961, 1974). Associated black sands contain magnetite, chromite, ilmenite, hematite, monazite, pyrite, zircon, garnet, and rutile.

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.

KNOWN DEPOSITS

Placer deposits have produced more gold than lode deposits in the Breckenridge mining district. Other placers are south of Breckenridge, near Hoosier Pass, and north of Breckenridge, in the vicinity of Dillon Lake, at the Soda Gulch and Buffalo placers. In the Tenmile Valley, there are small placers at McNulty Gulch and at the Follette placer, near Mayflower Gulch. There is a small deposit at Lake Creek, close to the town of Edwards. Reports of an old placer in Homestake Creek have not been verified (Parker, 1961, 1974).

ASSESSMENT CRITERIA

1. Presence of alluvial deposits downstream from known precious-metal deposits.
2. Presence of adequate amounts of alluvial gravel.
3. Anomalous concentrations of titanium, iron, or base and precious metals in panned-concentrate samples.

ASSESSMENT

Placer deposits in the Forest have been worked intermittently since the mid-1800's. These early operations were inefficient. Mined areas may still contain economic quantities of gold and silver.

Area K1.—A small area called the Continental placer, in West Maroon Creek, was mined for placer deposits (U.S. Geological Survey, 1990) and is assigned a moderate resource potential for additional, small, undiscovered placer gold deposits (pl. 1, fig. 36) with certainty level C (table 2). The source of the gold is unknown but could have been from disseminated sulfides in the metamorphosed Maroon Formation or from veins in the White Rock pluton.

Area K2.—A small area along the upper reaches of Roaring Fork River has low potential for small placer deposits (pl. 1, fig. 36) with certainty level C (table 2). This area is downstream from the Independence mining district, where precious metals were mined—the area is mentioned in MRDS (Mineral Resources Data System) (U.S. Geological Survey, 1990). Ample amounts of alluvial material are present in the drainage. Gold is present in minor quantities in panned-concentrate samples.

Area K3.—Moderate potential exists in a small area for small placers near the junction of Creamery Gulch and Lake Creek (pl. 1, fig. 36) with certainty level C (table 2). About 10,000 cubic yards of gravel have been mined near the mouth of East Lake Creek, but there are no records of the grade (Parker, 1974). The source may have been near the head of East Lake Creek, at the Ohio-Discovery vein.

Area K4.—Two drainages along the east side of the Sawatch Range have low potential for small placer gold deposits (pl. 1, fig. 36) with certainty level B (table 2): Cross Creek, on the north, and Homestake Creek, on the south. Although many of the major drainages in the Sawatch Range have sources of lode gold, Quaternary glacial activity removed most of the fluvial deposits. Both Cross Creek and Homestake Creek have minor alluvial deposits in their downstream reaches, and a source of lode gold is present in the headwaters of both drainages. Working of placer deposits in Homestake Creek was reported in 1880, but the existence of these deposits have not been confirmed (Parker, 1974). The entire valley has been strongly glaciated, and much of the alluvium has been removed from the valley. Area K4 has a low potential for placer gold deposits. Visible free gold was noted in panned concentrates in the upper reaches of Cross Creek (Wallace and others, 1989), but due to the minimal amount of fluvial material, the valley has a low resource potential for gold in placer deposits.

Area K5.—Two small areas, just south of Tennessee Pass, outside of the Forest boundary, have moderate potential for small placer gold deposits (pl. 1, fig. 36) with certainty level C (table 2). The larger placer deposits are in a small valley east of Tennessee Creek (the eastern K5 area), and smaller deposits have been worked in the gulches east of Buckeye Peak (the western K5 area). The principal sources of the gold were probably the deposits of the Jennie June group of claims (or similar ones nearby), but the presence of placer gold upstream from the Jennie June group also suggests that veins in the Minturn Formation and in porphyries supplied some of the gold (Tweto, 1956).

Area K6.—A moderate potential for placer gold deposits exists in McNulty Gulch and Follette Placer area in the Tenmile Valley (pl. 1, fig. 36) with certainty level C (table 2). The source of the gold in McNulty Gulch has not been determined; it is possible that the source has not been discovered. The source of gold in the Follette placer is probably the veins at the head of Mayflower Gulch. The rest of the area of former placers is covered by the tailings ponds from the Climax molybdenum deposit.

Area K7.—A large area of high resource potential for medium-sized deposits of placer gold and silver is in the drainage of the upper Blue River, downslope and downstream from known lode gold deposits (pl. 1, fig. 36) and has a certainty level D (table 2). Gold probably can be recovered by reworking old dredge tailings because former mining methods were inefficient.

Area K8.—There is moderate potential for small placer deposits in two small areas near Dillon Reservoir, west of Dillon, (pl. 1, fig. 36) with certainty level C (table 2). Of the small placers that were once worked in this area, only the Soda Gulch and Buffalo placers were not submerged by the reservoir. The placer workings are in glacial deposits from the Tenmile Creek drainage. The drift is characterized by rocks derived from the Kokomo-Climax area, and the gold likely came from the same source rather than the slopes of the Gore Range (Tweto, 1956). Deposits would probably be low grade and small.

ECONOMIC SIGNIFICANCE

Gold is a commodity that is in constant demand. Unlike lode-gold deposits, small placer deposits can be worked at a

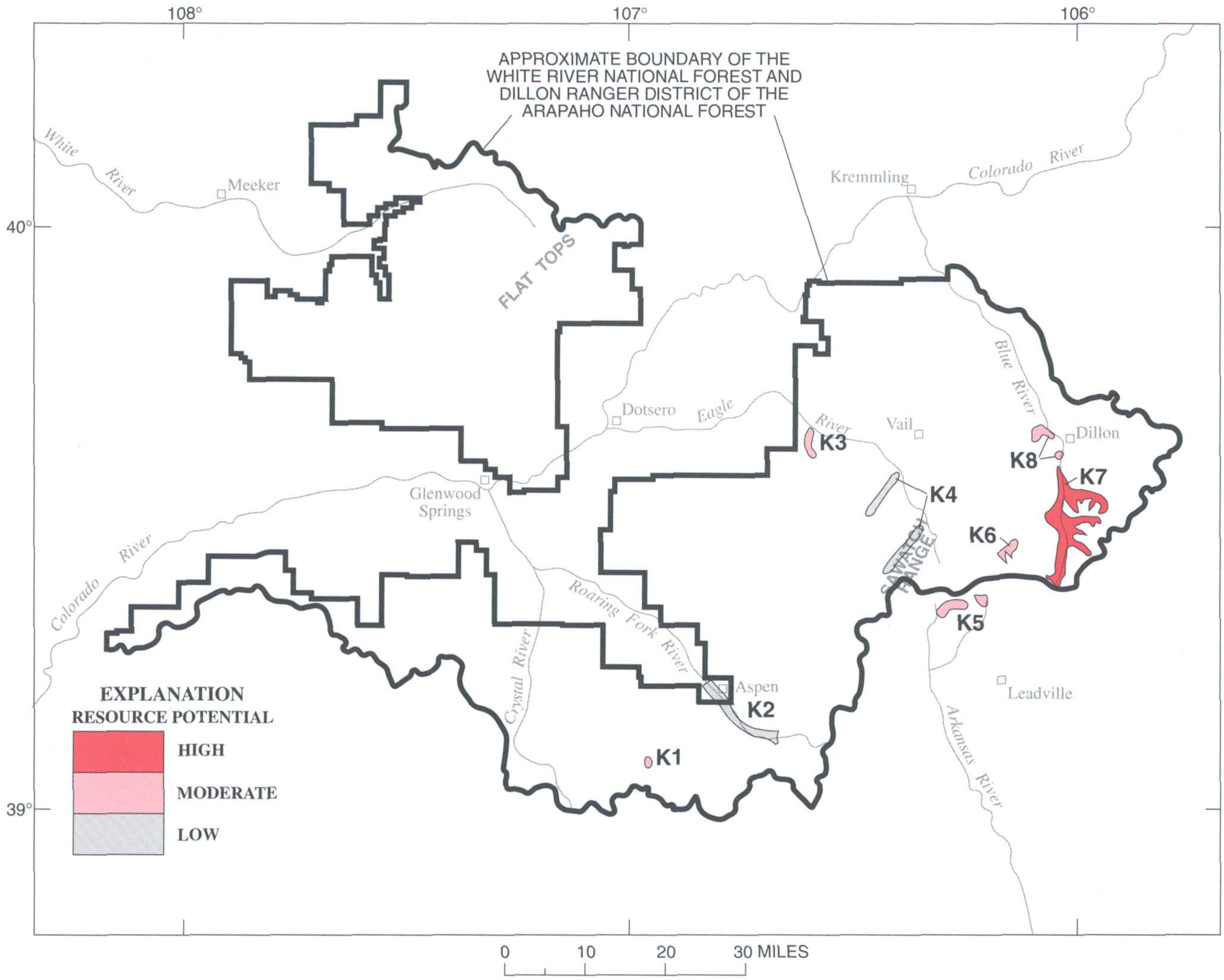


Figure 36. Mineral resource potential map for placer gold deposits (K) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

low cost, making them attractive to individuals or small operations. The major drawbacks to mining the placer deposits of Colorado are that they (1) tend to be small and low grade, (2) require large amounts of water, (3) are subject to stringent environmental regulations, and (4) may be in areas valued as prime real estate (Parker, 1961, 1974). Although most of the known deposits have already been exploited, there will always be interest in gold placers in the Forest.

STRATABOUND SULFIDES IN PROTEROZOIC ROCKS (L)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodities are copper, lead, zinc, gold, and silver.

HOST ROCKS

Proterozoic calc-silicate and hornblende gneiss, amphibolite, and alternating felsic gneiss units are host rocks for these deposits in the Forest.

STRUCTURAL CONTROL

No regional structural control is evident. Deposits occur as stratabound layers within gneiss; they tend to cluster and follow specific stratigraphic horizons.

AGE

The age of the deposits is Proterozoic: the same age as the enclosing rock.

DEPOSIT DESCRIPTION

No deposits are known in the Forest, but deposits occur in similar terranes in Colorado. The following discussion is from Sheridan and others (1990). Sphalerite, chalcopyrite, and galena are the principal ore minerals in these deposits; silver and gold may be present in significant amounts. 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 (fig. 37). The sulfide minerals are commonly medium grained, although fine- and coarse-grained varieties are also present. The sulfide ore minerals weather to produce oxide, carbonate, and sulfate minerals.

The stratabound deposits are generally considered to be metamorphosed volcanic-hosted sulfide deposits. In these deposits, the sulfide minerals were syngenetically deposited with felsic and mafic volcanic rocks in a submarine environment. Deposition of the metals probably was the result of exhalative discharge of hydrothermal fluids from vents in the sea floor. Later metamorphism converted the volcanic rocks to amphibolite, calc-silicate, and felsic gneisses.

GEOCHEMICAL SIGNATURE

Geochemical signatures include anomalous amounts of copper and lead in stream-sediment samples and anomalous amounts of copper, lead, and zinc in rock samples. Anomalous amounts of nickel may be associated with magnesium-rich rocks. In the Sawatch Range, stream-sediment samples from drainages containing deposits of this type yielded slightly anomalous amounts of silver, gold, copper, lead, zinc, and molybdenum (Wallace and others, 1989).

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 picked up by regional surveys.

KNOWN DEPOSITS

In the Forest, no such deposits have been mined. However, there are related occurrences of disseminated sulfides in Proterozoic gneisses in the eastern part of the Forest.

ASSESSMENT CRITERIA

1. Presence of Proterozoic gneiss, especially amphibolite and calc-silicate rocks.
2. Presence of base or precious metals.
3. Metals conformable with layers.

ASSESSMENT

Area L1.—Two small areas on the southern flank of the White River uplift contain exposures of amphibolite and hornblende gneiss in some of the deeper canyons. No geochemical data is available from these areas, and the rocks have not been studied in detail. The westernmost of these exposures, along East Elk Creek, hosts the Gray Eagle mine, a vein-type deposit (F) with gold and silver (U.S. Geological Survey, 1990). It is unknown whether any stratabound deposits are present. All of the exposures of amphibolite and hornblende gneiss in this general area have unknown potential for stratabound sulfide deposits (pl. 1, fig. 38) with certainty level A (table 2).

Area L2.—A small area along the west side of Lime Creek has low resource potential for small stratabound metal deposits (pl. 1, fig. 38) with certainty level C (table 2). Small, discontinuous zones with pyrite, magnetite, and minor chalcopyrite are associated with two small mafic bodies (Wallace and others, 1989). Stream-sediment samples from Lime Creek defined weak copper anomalies, although other veins, younger than Proterozoic in age, are exposed in the drainage. Rock samples from the sulfide zones contain slightly elevated concentrations of copper and detectable silver.

Area L3.—The area extending from Mormon Creek to west of Tennessee Pass has low potential for small stratabound metal deposits (pl. 1, fig. 38) with certainty level C (table 2). Calc-silicate gneiss, amphibolite, and felsic gneiss form an east-trending belt and contain pyrite and pyrrhotite in disseminations and conformable stringers (Wallace and others, 1989). Gahnite was identified northeast of Homestake Peak (Wallace and others, 1989). Stream-sediment and rock samples from this belt contain slightly anomalous concentrations of silver, gold, copper, molybdenum, lead, and zinc.

Area L4.—A small area just outside of the Forest, near Mt. Massive, has low potential for small deposits of stratabound metals (pl. 1, fig. 38) with certainty level C (table 2). Copper and zinc are present in anomalous concentrations at two sites in this area in a biotite and migmatite gneiss (Van Loenen, 1985; Van Loenen and others, 1989).

Area L5.—A north-south-trending belt of hornblende gneiss crops out along the upper reaches of the Eagle River, near Camp Hale. No geochemical data are available from this area, and the rocks have not been adequately studied. The area is therefore assigned unknown potential for small stratabound sulfide deposits (pl. 1, fig. 38) with certainty level A (table 2).

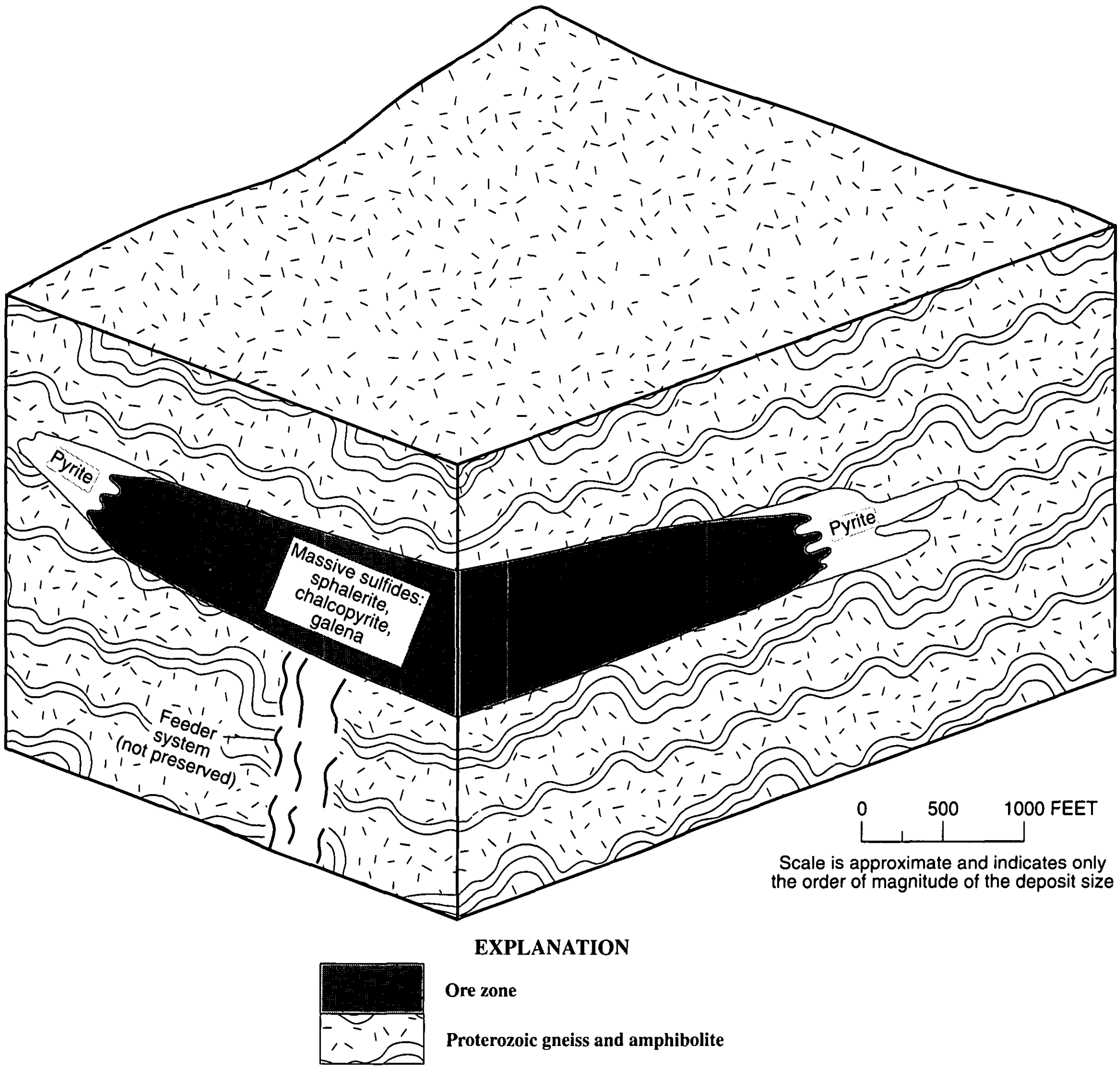


Figure 37. Schematic diagram of stratabound sulfide deposit in Proterozoic rock (deposit type L).

Area L6.—An area just east of Tenmile Peak contains outcrops of Proterozoic hornblende gneiss and amphibolite. Geochemical data are not available from this area, and the rocks have not been studied in detail. The area therefore has been assigned unknown potential for small stratabound sulfide deposits (pl. 1, fig. 38) with certainty level A (table 2).

ECONOMIC SIGNIFICANCE

The U.S. supplies 91 percent of its own copper and 92 percent of its own lead. Zinc is supplied primarily (61 percent) from large-tonnage foreign sources (U.S. Bureau of Mines, 1990). South of the Forest, the Sedalia mine near Salida produced copper and zinc for many years from a deposit of this type. Discovery of a deposit of this size in the Forest would have a significant impact on the local economy. The presence of significant amounts of silver would certainly enhance the possibility of development. Deposits of this type are not a major world supplier of metals.

HIGH-CALCIUM LIMESTONE (M)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is high-calcium limestone; dimension stone and gravel are byproducts.

HOST ROCKS

The Leadville Limestone is the host formation for these deposits in the Forest.

STRUCTURAL CONTROL

Deposits are not dependent upon structural controls, except as related to the uplift and (or) erosion that exposed the Leadville Limestone. The Leadville crops out mainly

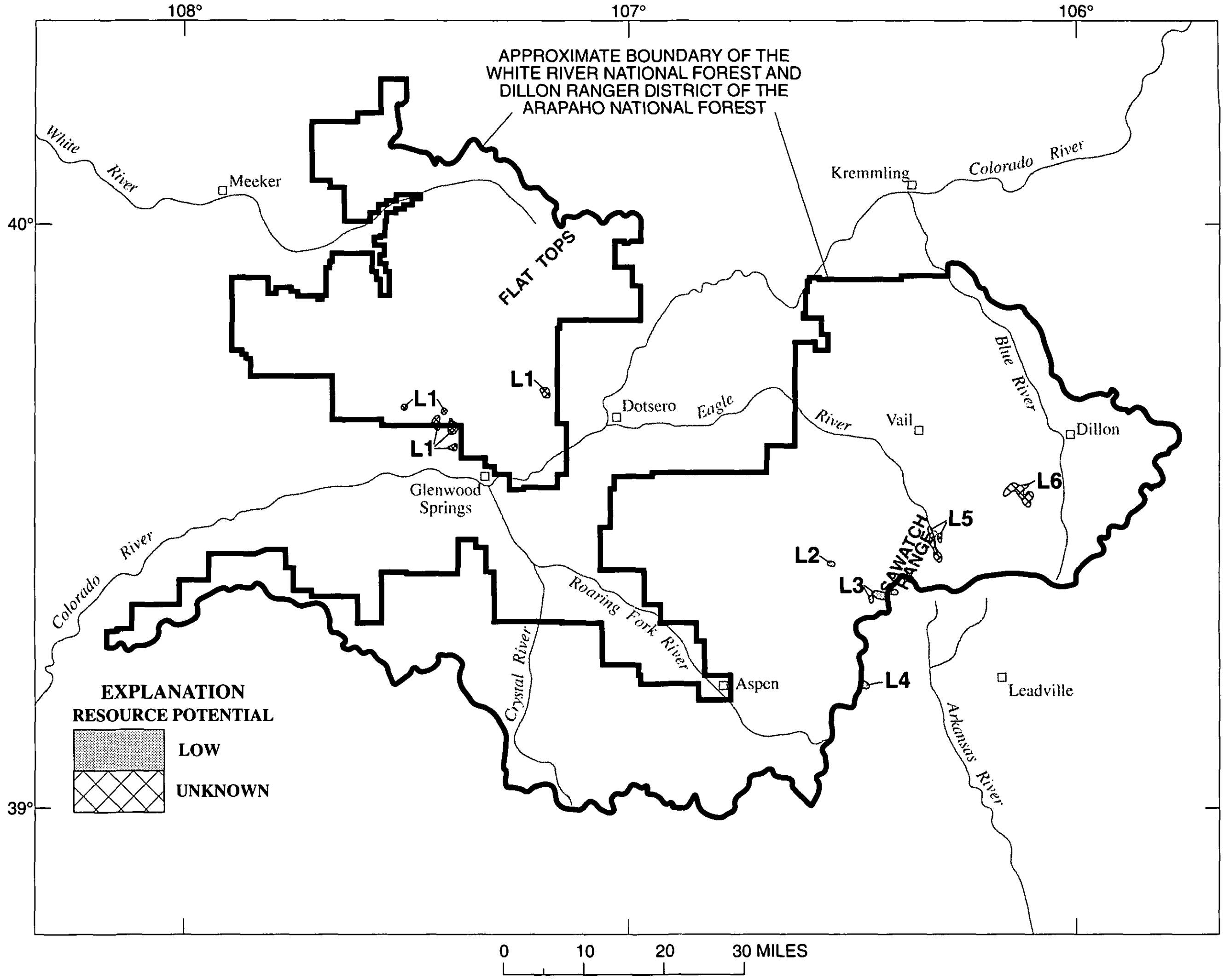


Figure 38. Mineral resource potential map for stratabound sulfides in Proterozoic rocks (L) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

along the flanks of the Sawatch anticline and on the southeast side of the Flat Tops.

AGE

The Leadville Limestone is Mississippian in age.

DEPOSIT DESCRIPTION

High-calcium deposits in the Leadville Limestone are found in calcium-rich zones in unaltered or unmineralized rock. A high-calcium layer near the top of the Leadville covered by a thin layer of reddish-brown shale was identified by drilling in an area southeast of the Flat Tops (Wark, 1980). Additional drilling would be required in order to determine the lateral continuity of the high-calcium layers.

GEOCHEMICAL SIGNATURE

The Leadville Limestone does not contain a suite of characteristic trace metals. The outcrop extent of the Leadville is well known and stream-sediment geochemical data are not needed to define the extent.

GEOPHYSICAL SIGNATURE

Seismic techniques would be of help in determining the extent, depth, or thickness of the Leadville Limestone.

KNOWN DEPOSITS

No deposits are known within the Forest. Areas of high-calcium limestone have been identified southeast of the Flat

Tops Wilderness, north of Willow Peak (Wark, 1980), and on the northwest side of the Sawatch Range (Lundby and Brown, 1987).

ASSESSMENT CRITERIA

1. Presence of unmineralized and unaltered outcrops of the Leadville Limestone.

ASSESSMENT

Area M1.—Outcrops of the Leadville Limestone along the southern margin of the White River uplift have a high resource potential for medium-sized deposits of high-calcium limestone (pl. 2, fig. 39) with certainty level C (table 2). Favorable factors include outcrops of the limestone, lack of significant metals, and proximity to known reserves of metallurgical limestone, just northwest of Dotsero along the Forest boundary (Wark, 1980).

Area M2.—A small area of Leadville Limestone, north of Willow Peak, has a high resource potential for medium-sized deposits of high-calcium limestone (pl. 2, fig. 39) with certainty level D (table 2). The area has been identified as a commercial source for limestone by core drilling that delineated a 100-ft-thick bed of high-calcium limestone near the top of the Leadville (Wark, 1980).

Area M3.—An area of Leadville Limestone, around Treasure Mountain in the southwestern part of the Forest, has moderate potential for medium-sized deposits of high-calcium limestone (pl. 2, fig. 39) with certainty level C (table 2). Although outcrops of the Leadville Limestone are present, the area is heavily mineralized. No data are available concerning the purity of the limestone in the area.

Area M4.—Outcrops of Leadville Limestone, on the southwest side of the Sawatch Range near Aspen, have a moderate resource potential for medium-sized high-calcium limestone deposits (pl. 2, fig. 39) with certainty level C (table 2). Favorable criteria include the presence of Leadville outcrops and proximity to other areas of favorable limestone. However, because of the intense mineralization in the Aspen area, it is likely that much of the limestone has been altered.

Area M5.—Outcrops of Leadville Limestone along the flanks of the Sawatch anticline have a high resource potential for medium-sized deposits of high-calcium limestone (pl. 2, fig. 39) with certainty level C (table 2). Beds of high-purity limestone were mined between Biglow and Thomasville, along the Fryingpan River within the Forest (Wallace and others, 1989). Unaltered and unmineralized outcrops of the Leadville are present within this area. Analyses of Leadville Limestone along the western and northwestern parts of the Sawatch Range indicate that the limestone contains more than 98 percent $CaCO_3$ (Lundby and Brown, 1987). However, due to mineralization in the vicinity of Gilman and southward, the Leadville there has a moderate potential for limestone resources (pl. 2, fig. 39) with certainty level C (table 2).

Area M6.—Small areas of outcrop of the Leadville Limestone in the Tenmile Range have a moderate resource potential for limestone (pl. 2, fig. 39) with certainty level B (table 2). Although outcrops of the Leadville are present in this area, no data are available concerning the purity of the rock. This area is heavily mineralized, and the limestone is probably altered.

ECONOMIC SIGNIFICANCE

The U.S. provides all of the lime that it needs. Large parts of the Leadville Limestone may be a high-calcium variety suitable for chemical and metallurgical uses. The Leadville Limestone has not been mined within the Forest, and deposits in the Leadville could be an excellent source of high-calcium limestone.

GYPSUM IN EVAPORITE DEPOSITS (N)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

Gypsum is the commodity.

HOST ROCKS

Deposits are in the Eagle Valley Evaporite.

STRUCTURAL CONTROL

The greatest thickness of gypsum is at the southeastern end of the Eagle Basin, in the vicinity of the town of Eagle, which is outside of the Forest.

AGE

The gypsum in the Eagle Valley Evaporite sequence is Pennsylvanian in age.

DEPOSIT DESCRIPTION

The Eagle Valley Evaporite contains variable amounts of gypsiferous mudstone and siltstone, calcareous sandstone,

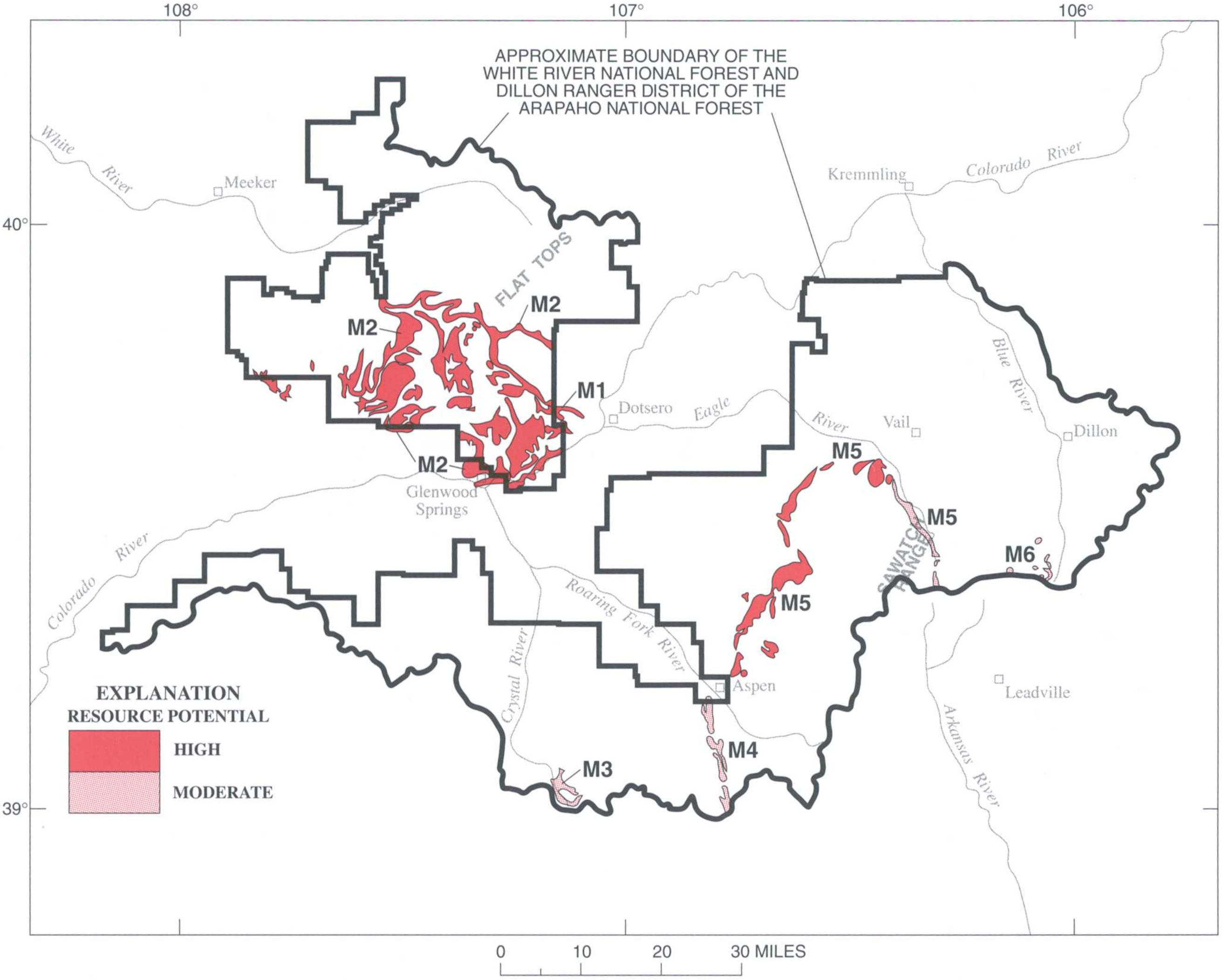


Figure 39. Mineral resource potential map for deposits of high-calcium limestone (M) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

gypsum, anhydrite, limestone, halite, and potash. The formation was deposited in the Eagle Basin (fig. 6) during Pennsylvanian time. The maximum thickness of the evaporite sequence occurs in the area near Eagle and Gypsum—a more rapidly subsiding portion of the basin (Mallory, 1971) (fig. 40). The Eagle Valley Evaporite exceeds 9,000 ft in thickness in this area. Along the margins of the main part of the Eagle Valley Evaporite, sections of the Pennsylvanian and Permian Maroon Formation locally contain isolated lenses of gypsum.

Since deposition, the Eagle Valley Evaporite has been subjected to the following: load metamorphism, Laramide orogenic movement, formation of diapiric anticlines, and local contortion due to flowage and hydration of anhydrite (Mallory, 1977). Load metamorphism and loss of water converted gypsum to anhydrite at depths of more than several hundred feet. The gypsum currently at the surface has been rehydrated from anhydrite.

GEOCHEMICAL SIGNATURE

The Eagle Valley Evaporite could be delineated by sulfur and sulfate content, but because the extent of the outcrop of the formation is well known, such work is not necessary.

GEOPHYSICAL SIGNATURE

Regional geophysical techniques would not be of help in determining the location of gypsum units within the Eagle Valley Evaporite.

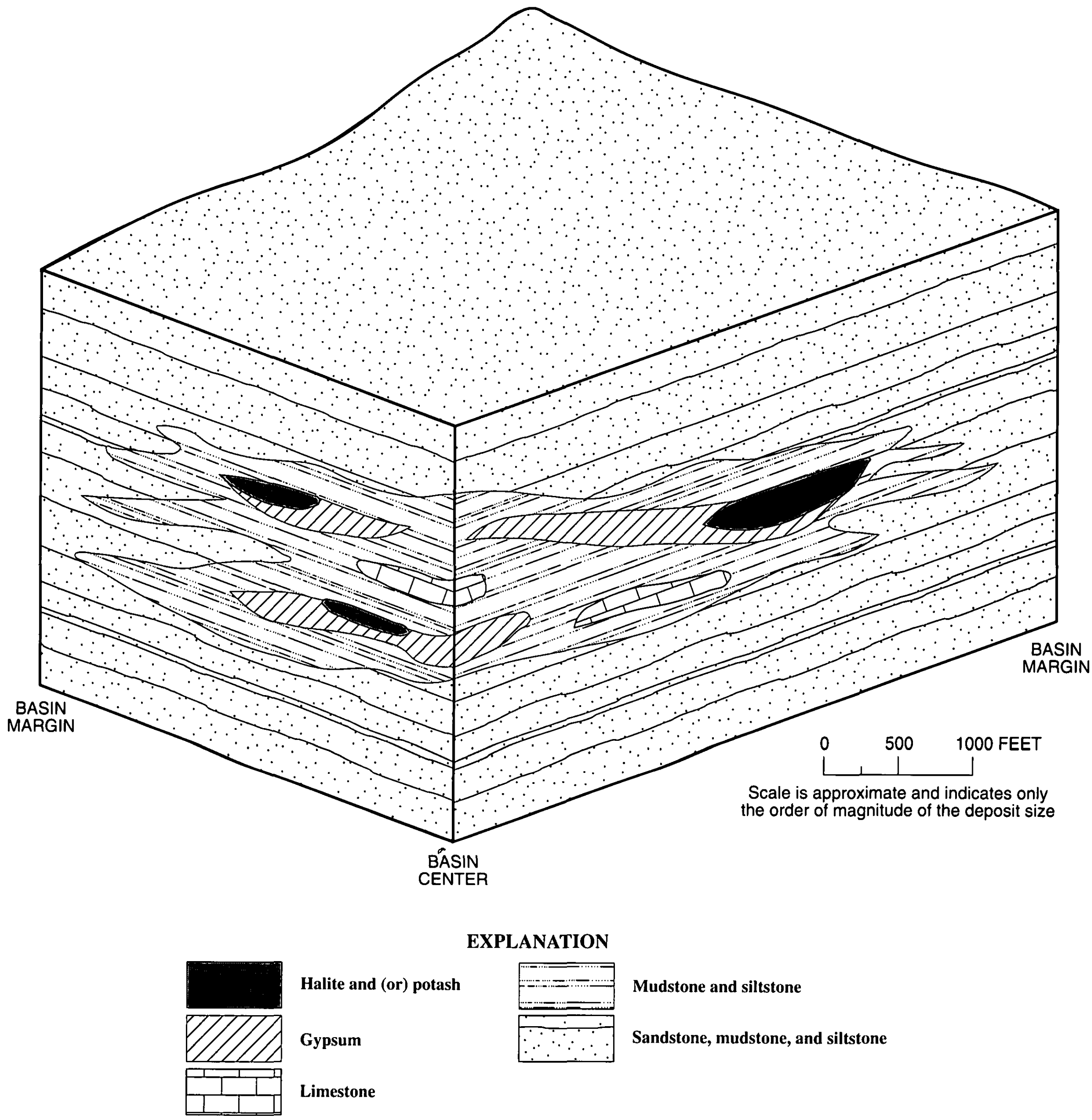


Figure 40. Schematic diagram of gypsum in an evaporite deposit (deposit type N).

KNOWN DEPOSITS

Gypsum was mined near the town Ruedi, on the Fryingpan River, from a 50-ft-thick bed between 1907 and 1911.

ASSESSMENT CRITERIA

1. Presence of thick sections of gypsum in the Eagle Valley Evaporite.
2. Minimal amounts of mud and clay in gypsum.

ASSESSMENT

Area N1.—Eagle Valley Evaporite outcrops across the Forest have a moderate resource potential for small deposits of gypsum (pl. 2, fig. 41) with certainty level B (table 2). Favorable criteria consist of the presence of gypsum.

Area N2.—Where mining has occurred near Ruedi, the Eagle Valley Evaporite has a high resource potential for additional small gypsum deposits (pl. 2, fig. 41) with certainty level D (table 2). The Eagle Valley Evaporite exceeds 2,000 ft in thickness in the Ruedi area.

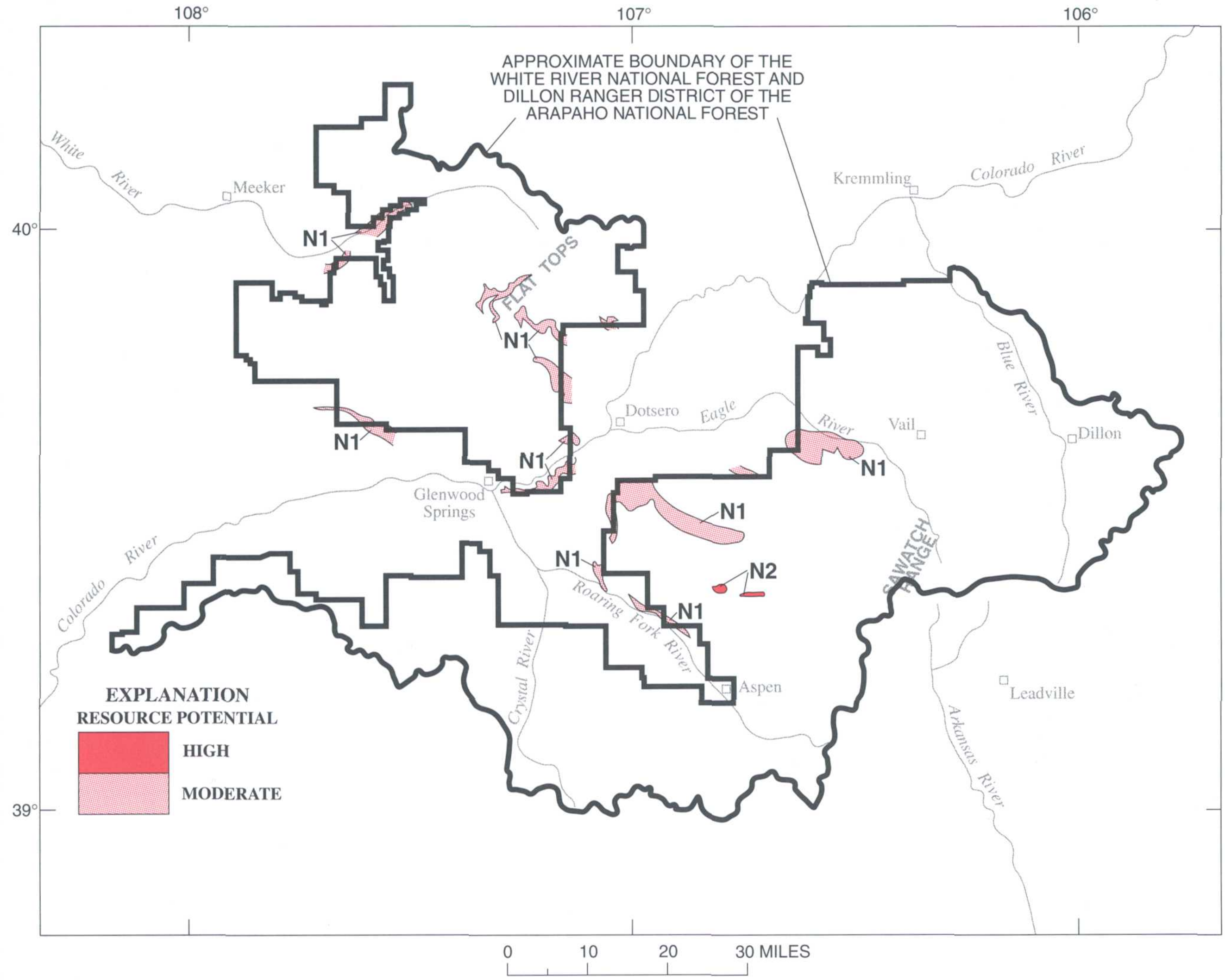


Figure 41. Mineral resource potential map for gypsum in evaporite deposits (N) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

ECONOMIC SIGNIFICANCE

The U.S. has a net important reliance of 37 percent on gypsum (U.S. Bureau of Mines, 1990). Deposits in the Forest are likely to be small and of local importance.

MINOR OCCURRENCES

PEGMATITE MINERALS

Pegmatite dikes are common in Proterozoic granitic rocks throughout the Forest. They are composed of feldspar, quartz, and mica, but could locally contain minerals of commercial importance, such as beryl, cassiterite, scheelite, spodumene, uranium minerals, and rare-earth minerals. Pegmatites elsewhere in the U.S. have been a commercial source for these minerals, but there is no recorded production in the Forest. Although pegmatites are relatively common in Forest, most are fairly simple and do not contain minable quantities of commercially important minerals.

HALITE AND POTASH

In the central part of the Forest, the Eagle Valley Evaporite contains halite and traces of potash, although only a small amount of these water-soluble minerals can be found (Mallory, 1971) (see fig. 40). North of the town of Gypsum, halite is present at a depth of 1,400 ft, and two 6- and 7-ft-thick beds containing potash were reported at depths of between 3,600 and 4,000 ft (Mallory, 1971). No commercial production from saline deposits has taken place within or adjacent to the Forest. Mallory (1971) notes that the questionable quality of the Eagle Valley salines places them in a less favorable position to be exploited than those from established sources outside of the Forest.

BOG IRON ORE

Bog iron ore occurs in slope wash and gravel near the head of Snake River, 2 to 3 mi south-southeast of Montezuma (Patton, 1909; Lovering, 1935). The deposit is composed of unconsolidated and waterlogged to well-consolidated, porous to clinky, high-grade limonite, goethite, and turgite (hydrous hematite) (U.S. Geological Survey, 1990). Pyrite-bearing slope wash derived from Proterozoic biotite gneiss is the source of the iron. Similar ore, from outside the Forest, south of Webster Pass, contains approximately 68 percent Fe_2O_3, 22 percent organic matter, 7 percent SiO_2, 2 percent P_2O_5, and 1 percent CaO and was used as a flux in nearby smelters in the 1870's (Lovering, 1935). No production has been recorded since that time.

COPPER-NICKEL DEPOSITS

In the area of the Flat Tops, in the northwestern part of the Forest, almost all of the stream-sediment samples from basins draining this area have anomalous concentrations of nickel (fig. 9). This is in contrast to other areas of basalt in the Forest, which did not have any anomalous concentrations of nickel in their drainage basins. The only possible known analog for these types of deposits are Noril'sk deposits, a rare deposit in the former USSR described by Page (1986) and Naldrett and others (1992). They were thought to form where picritic (iron-rich) magma has intruded through evaporites or pyritic shale and formed sills in flood basalts during active faulting. However, more recent work by Zientek and others (written commun., 1990) suggests that the Noril'sk deposits formed by a different mechanism. There is currently no model deposit that would conform to the features observed in the Flat Tops area. It is also possible that the basalts in the area of the Flat Tops are particularly rich in nickel and copper and are not mineralized.

MINERAL RESOURCES—LEASABLE COMMODITIES

Oil and gas, oil shale, potash, sodium, native asphalt, bitumen or bituminous rock, phosphate, and coal are leasable commodities or "leasing act minerals." They were excluded from the provisions of General Mining Law of 1872 by the Mineral Leasing Act of 1920, which set up regulations requiring prospect permits and leases to control the exploration, development, and production of these leasing act minerals. Geothermal energy was added to the list of leasable commodities by the Geothermal Steam Act of 1970.

COMMODITIES

Known occurrences of leasable commodities were studied by the U.S. Bureau of Mines and are described in Brown (1990). The potential for additional deposits of these minerals is assessed in this report. Coal and natural gas have been produced in the Forest, and geothermal resources have been identified. No potash, sodium, asphalt, or phosphate resources are known in the Forest or the adjacent lands.

PRODUCTION HISTORY

The occurrence of oil and gas in the vicinity of the Forest dates from 1902, when the DeBeque gas field was discovered about 5 mi west of the Forest. There was relatively low activity, however, until the late 1950's and early 1960's when the Pacific Northwest pipeline was installed. Development of fields has been relatively expensive in recent years due to high drilling and operating costs; development has been controlled mostly by natural gas prices and has been restricted to areas of easy access (Brown, 1990). Parts of four gas fields are within the Forest, all of them within the Piceance Basin (fig. 6), west of Glenwood Springs. These include the Divide Creek, Hells Gulch, Horsethief Creek, and Wolf Creek fields. The Divide Creek field is the only field currently producing in the Forest.

Coal resources are known in the southwestern part of the Forest, mostly in the Carbondale coal field. Production from the Carbondale field totals about 32 million short tons during the last 100 years (Brown, 1990). In recent years, difficult mining conditions have limited production in the Carbondale field to coking coal for metallurgical purposes (Collins, 1975). As of 1988, the Dutch Creek mine was the only operating mine in the field.

Oil shale occurs in the Green River Formation in areas adjacent to the Forest. None has been produced from the Forest, but there is a small area of moderate potential.

There is no Known Geothermal Resource Area designated in the Forest, but at least five groups of geothermal springs lie in or near the Forest. Hot springs are the principal surface expression of geothermal occurrences and have been the principal focus of geothermal investigations in Colorado. The most significant geothermal area near the Forest is a zone along either side of the Colorado River between Dotsero, on the east, and South Canyon, on the west (Pearl, 1980). This zone crosses the Forest in the Glenwood Canyon area and includes three of the five thermal-spring groups that are near, but not within, the Forest. Two undeveloped and isolated hot springs are south of the zone, within the boundaries of the Forest. Adjacent to the

Forest, Glenwood Hot Springs has been developed for recreational and therapeutic purposes.

MINERAL RESOURCE POTENTIAL—LEASABLE COMMODITIES

The White River National Forest and the Dillon Ranger District of the Arapaho National Forest were evaluated for undiscovered resources of leasable commodities of various deposit types. In this section, the characteristics of known deposits are briefly summarized for assessment purposes, and areas in the Forest are evaluated for resource potential according to the stated assessment criteria. Definitions of the levels of mineral resource potential are given in Appendix 2.

OIL AND GAS (O)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodities are oil and gas.

HOST ROCKS

Oil- and gas-producing stratigraphic units in and near the Forest include the following: Mesaverde Group (including, in descending order, the Rollins, Cozzette, and Corcoran Members of the Iles and Mount Garfield Formations), Mancos Shale, Wasatch Formation, Shinarump Member of the Chinle Formation, Niobrara Limestone, Dakota Sandstone, Weber and Minturn Formations, Ohio Creek Member of the Hunter Canyon Formation, Entrada Sandstone, and Sundance Formation (Colorado Oil and Gas Conservation Commission, 1982, 1988). Gas occurs predominantly in the Mesaverde Group (Dunn, 1974). In the Forest, production has been from the Mesaverde Group.

STRUCTURAL CONTROL

Accumulations occur in structural and stratigraphic traps. Structural traps include features such as anticlines and fractures, and stratigraphic traps include pinchouts, channel margins, and changes in porosity. The Divide Creek and Wolf Creek anticlines in the Forest have been particularly productive structures. Natural fractures serve as the primary conduits for fluid movement (Johnson, 1989).

AGE

In the vicinity of the Forest, ages of reservoir rocks range from Pennsylvanian and Permian to Paleocene and Eocene. Within the boundaries of the Forest, the age of the reservoir rocks is Cretaceous.

DEPOSIT DESCRIPTION

A large number of accumulations of gas are in the vicinity of the Forest, and three fields are within the boundaries of the Forest itself (fig. 42). These accumulations are all in the Mesaverde Group, specifically the Cozzette, Rollins, and Corcoran Members of the Iles and Mount Garfield Formations. South of the Colorado River, the Corcoran and Cozzette Members are the most productive members in the Mesaverde (Johnson, 1989); they represent marginal-marine and nonmarine depositional facies.

Gas accumulated in the Mesaverde Group as the result of a long and complex process; the discussion that follows is paraphrased from Johnson (1989). The Mesaverde was formed from sediments deposited in marine and coastal-plain environments. Intense regional diagenesis, in part due to long-term exposure to surface weathering prior to burial, resulted in an early loss of permeability in the rocks. This was followed by deep burial, which, in turn, generated thermal gas from coal in the Mesaverde and organic-rich beds in the underlying Mancos Shale.

A ring of Mesaverde outcrops adjacent to Laramide uplifts have stood high above the basin floor from Laramide time to the present day. These exposures served as entry points for fluid movement into the Mesaverde. A natural fracture system provided pathways for migration of the gases.

Although the Mesaverde can be productive both on and off structures, the majority of gas has been produced from two, large, closed structures that crosscut the Forest: the Divide Creek and Wolf Creek anticlines.

GEOCHEMICAL SIGNATURE

Geochemical prospecting is not generally used to detect the presence of oil and gas deposits. However, many oil fields are characterized by anomalous concentrations of base metals, primarily lead and zinc, sulfur, complex organic compounds, and gases such as methane and hydrogen sulfide. Stream-sediment and groundwater geochemical surveys are of little help in assessing the energy resource potential for oil and natural gas. Other techniques such as rare-gas detection, source-rock analysis, gas chromatography, and isotope analysis of brines in ground water and drill holes may be used as exploration tools.

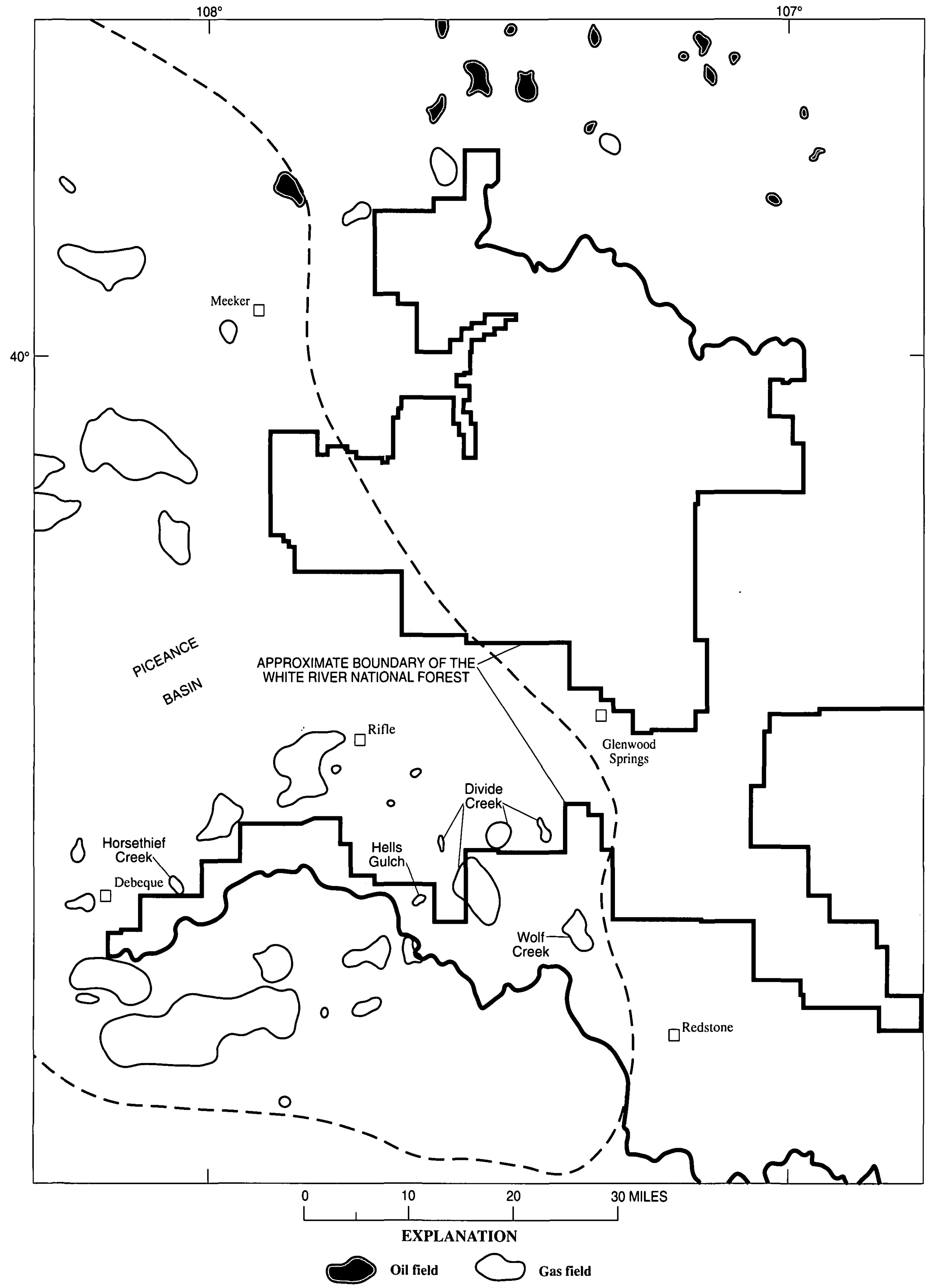


Figure 42. Map showing location of oil and gas fields in and adjacent to the western part of the White River National Forest, Colorado.

GEOPHYSICAL SIGNATURE

Most oil fields are discovered through a combination of knowledge of surface and subsurface geology and geophysical exploration techniques, primarily seismic refraction and reflection profiling. These techniques can be used to reconstruct the configuration of subsurface strata.

KNOWN DEPOSITS

Known oil fields in the Forest include Hells Gulch (abandoned), Wolf Creek (abandoned), and Divide Creek (currently operative) (fig. 42). Portions of four gas fields are within the Forest: Wolf Creek, Divide Creek, Horsethief Creek, and Hells Gulch; Divide Creek is the only field that is currently in production.

ASSESSMENT CRITERIA

1. Presence of favorable reservoir rocks in the subsurface. All sedimentary rocks Pennsylvanian and younger in age are favorable. The Cozzette and Corcoran Members of the Iles and Mount Garfield Formations of the Mesaverde Group are particularly favorable in this part of the Forest.
2. Presence of favorable hydrocarbon source rocks in the subsurface. Organic-rich strata of Mesozoic age are present.
3. Presence of stratigraphic or structural traps. The regional pinchout of the Weber Sandstone is a potential host and trap for oil.

ASSESSMENT

Area O1.—An area in the northernmost part of the Forest has high potential for medium to large accumulations of oil and gas (pl. 2, fig. 43) with certainty level D (table 2). Oil and gas fields are present in the general vicinity north of the Forest. Although no fields are within the Forest, favorable strata are present.

Area O2.—An area in the southwesternmost part of the Forest has high potential for medium to large accumulations of oil and gas (mostly gas) (pl. 2, fig. 43) with certainty level D (table 2). Fourteen natural gas fields are present in this general vicinity (fig. 43). Of these, four gas fields are actually in the Forest, but only one of them is currently in production. Favorable reservoir and host rocks are present in the Forest, and significant structural traps trend across the Forest in this vicinity.

ECONOMIC SIGNIFICANCE

Oil and gas are two of the main energy sources for the United States. Extensive reserves of oil and gas are known elsewhere in the Uinta, Sand Wash, and Piceance Basins in northwestern Colorado and eastern Utah. Although very little oil or natural gas is currently produced from the Forest and its adjacent lands, exploration for these accumulations is unlikely to diminish in the near future.

COAL (P)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is coal.

HOST ROCKS

Deposits are restricted to the Bowie Shale and Paonia Shale Members of the Williams Fork Formation, which is part of the Mesaverde Group; most of the coal occurs in the Bowie Shale Member.

STRUCTURAL CONTROL

The coal beds are not structurally controlled. However, coal deposits are exposed along the Grand Hogback monocline (fig. 6 and pl. 2), a prominent structural feature at the eastern margin of the Piceance Basin. Along the monocline, the Mesaverde dips 10°–50° W. for several miles before it flattens out and is buried under a thick sequence of younger sedimentary rocks. The only exceptions to the deep burial or absence of Mesaverde Group rocks away from the Grand Hogback occur (1), about 10–12 mi west of the monocline, in the Divide Peak area, where uplift and erosion associated with the Divide Creek anticline have exposed the Mesaverde Group, and (2), in the extreme northern tip of the Forest, east of Meeker, where small areas are underlain by the Williams Fork Formation (pl. 2).

A number of folds and faults are superimposed on the Grand Hogback, especially in the southern part of the Forest. The most notable structure is the Coal Basin anticline, west of Redstone (pl. 2). The northwest-plunging anticline interrupts the westward regional dip of the Grand Hogback. Erosion breached the anticline and outlined a broad valley surrounded by outward-dipping, exposed, coal-bearing strata. The Coal Basin area is on the flanks of the anticline; the basin area is the source for most of the coal production in the Forest.

AGE

All coal deposits are in the Upper Cretaceous Mesaverde Group.

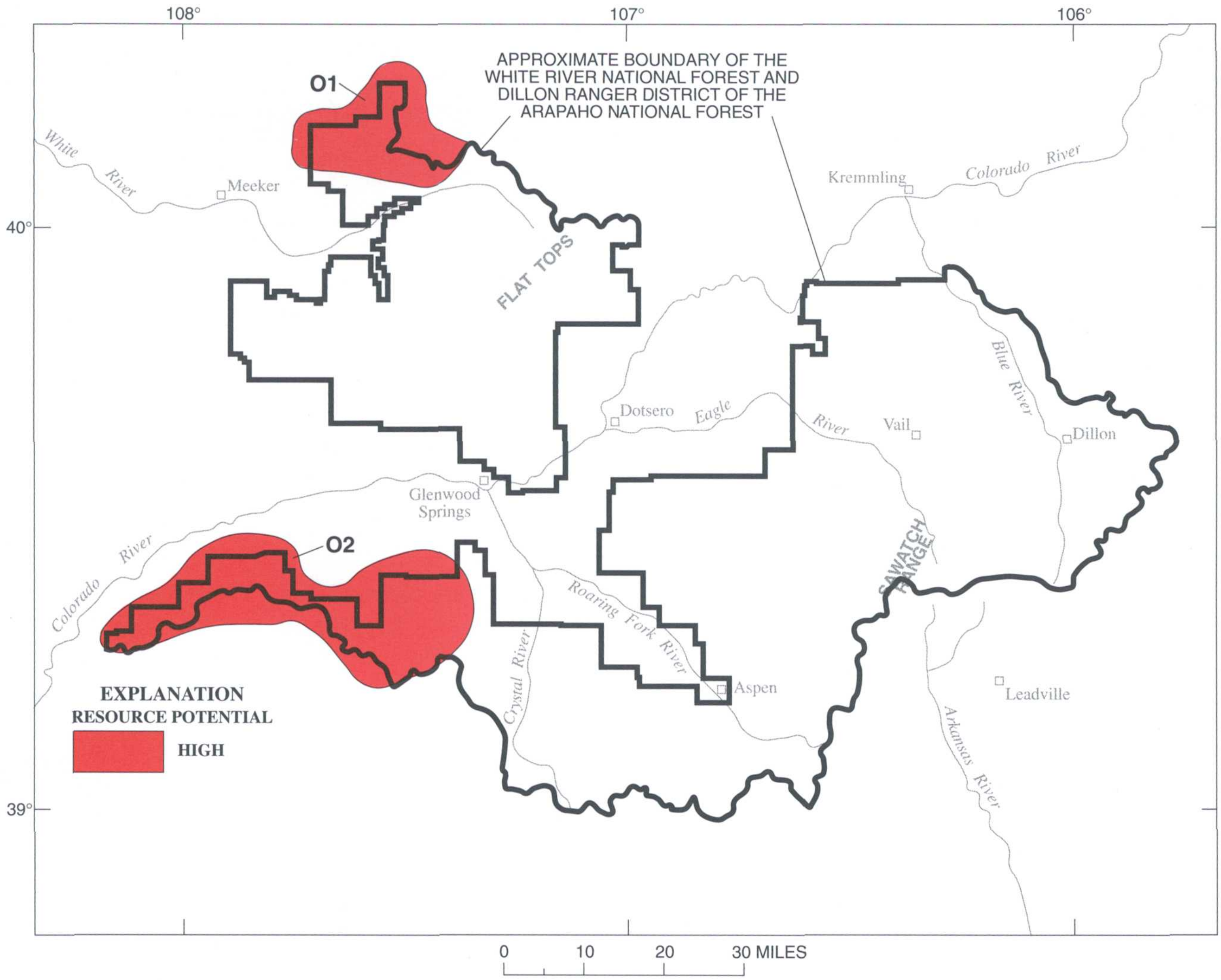


Figure 43. Mineral resource potential map for oil and gas (O) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

DEPOSIT DESCRIPTION

The Mesaverde Group was formed from sediments deposited in a Cretaceous deltaic system and consists of interbedded marine, delta-front, brackish, and freshwater shale, sandstone, siltstone, mudstone, and coal. The coal deposits formed from the decomposition and alteration of woody organic remains. As indicated by low sulfur content, the coals are presumably of freshwater origin (Collins, 1975).

The coal-bearing units in the Mesaverde Group are the Bowie and Paonia Shale Members of the Williams Fork Formation; most of the minable coal occurs in the Bowie Shale Member. The Williams Fork Formation contains at least 10 coal seams that individually exceed 42 inches in thickness (Averitt, 1966). The Carbondale coal field largely coincides with the outcrop of the Mesaverde Group along the Grand Hogback from Newcastle and, from there, south to near Marble (pl. 2).

Coal quality varies according to bed and from one area to another. About 93 percent of the coal in the Carbondale field is bituminous, and 7 percent is anthracite (Hornbaker and others, 1976). North of Thompson Creek (pl. 2), the coal is mostly high volatile A and B bituminous coal, and rank changes are gradual and regular. Many exposures of coal in this area have been burned to clinker. Most of the coal in the Carbondale field has been produced from deposits with less than 1,000 ft of overburden.

GEOCHEMICAL SIGNATURE

Coal deposits are seldom detected by regional geochemical techniques. However, some coal does contain anomalous concentrations of heavy metals, particularly uranium, selenium, molybdenum, gold, zinc, and sulfur. Conventional stream-sediment or groundwater geochemical surveys are of little help in assessing the mineral potential of coal deposits.

GEOPHYSICAL SIGNATURE

The most useful geophysical technique is drilling. Borehole signatures are helpful in accurately defining areas underlain by coal.

KNOWN DEPOSITS

Coal has been mined from the Carbondale coal field in Pitkin, Gunnison, and Garfield Counties, in the southwestern part of the Forest.

ASSESSMENT CRITERIA

1. Presence of the Bowie or Paonia Shale Members of the Williams Fork Formation of the Mesaverde Group.
2. Presence of the Grand Hogback or anticlinal structures.
3. Overburden of not more than 3,000 ft.

ASSESSMENT

Area P1.—A small area in the northernmost part of the Forest, at Wilson Mesa east of Meeker, has moderate energy resource potential for coal (pl. 2, fig. 44) with certainty level C (table 2). Within this area, a small outcrop of the Mesaverde Group is exposed due to folding by an anticline.

Area P2.—In the southwestern part of the Forest, rocks of the Mesaverde Group are exposed along the Divide Creek anticline. This area of outcrop is assigned a moderate resource potential for coal (pl. 2, fig. 44) with certainty level C (table 2), due to favorable host rock, favorable structure, and proximity to an area with known coal resources. Although coal underlies most of the western part of the Forest, most of it is buried too deeply to be considered a resource (Kent and Arndt, 1980).

Area P3.—An area in the southwestern part of the Forest has high potential for coal resources (pl. 2, fig. 44) with certainty level D (table 2). The area of potential includes the Carbondale coal field, where outcrops of the Mesaverde Group have been tilted by the Grand Hogback or folded by the Coal Basin anticline. At least 15 coal mines are in this area (Brown, 1990).

Area P4.—The Mesaverde Group is exposed along the Grand Hogback in the southwestern part of the Forest. No coal mines are in this area. The area of outcrop has a moderate resource potential for coal (pl. 2, fig. 44) with certainty level B (table 2), due to favorable host rock and proximity to known coal resources.

ECONOMIC SIGNIFICANCE

Coal is one of the major energy sources in the United States, but only a minor amount is mined from the Forest. Extensive reserves of coal are known elsewhere in the Uinta Basin, in northwestern Colorado and eastern Utah. These areas constitute one of the largest coal-producing regions in the western U.S. and will produce much more coal than the Forest. As of 1988, the Dutch Creek mine, in the Carbondale coal field, was the only operating mine in the Forest (Brown, 1990).

All coal production from the Carbondale field in the Forest has been from underground mines. Several complicating factors exist that make it necessary to use specialized mining methods, and as a result, mining is relatively expensive (Brown, 1990). The rugged topography also limits transport of the coal to markets. Most of the coal produced from the Carbondale field has been coking coal for metallurgical applications.

COALBED METHANE (Q)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is methane.

HOST ROCKS

Coalbed methane is restricted to coal in the Bowie Shale and Paonia Shale Members of the Williams Fork Formation, which is part of the Mesaverde Group; most of the coal occurs in the Bowie Shale Member.

STRUCTURAL CONTROL

Stratigraphic traps are very important and include deltaic lenses, channel and bar sandstones, permeability pinch outs, and asphalt seals.

AGE

All coal deposits are in the Upper Cretaceous Mesaverde Group.

DEPOSIT DESCRIPTION

The Mesaverde Group was formed from sediments deposited in a Cretaceous deltaic system and consists of

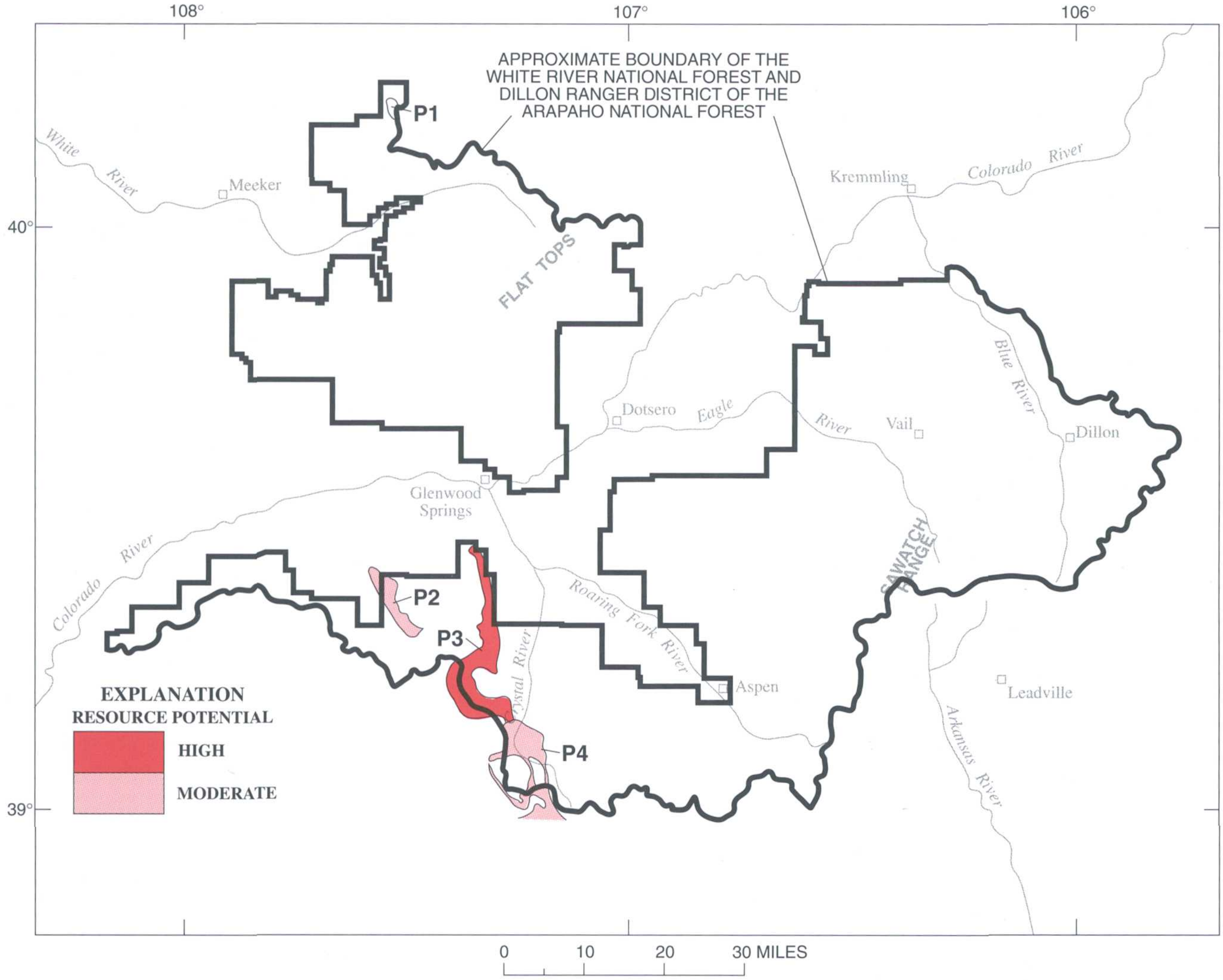


Figure 44. Mineral resource potential map for coal (P) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

interbedded marine, delta-front, brackish, and freshwater shale, sandstone, siltstone, mudstone, and coal. Coal deposits formed from the decomposition and alteration of woody organic remains.

The coal-bearing units in the Mesaverde Group are the Bowie and Paonia Shale Members of the Williams Fork Formation; most of the minable coal occurs in the Bowie Shale Member. The Carbondale coal field largely coincides with the outcrop of the Mesaverde Group along the Grand Hogback, from Newcastle south to near Marble (pl. 2). Mean vitrinite-reflectance and total-organic-carbon studies by Nuccio and Schenck (1986) also support the Mesaverde Group as an excellent source rock for gas.

Coalbed methane is formed at low temperatures (< 75°C) by biogenic processes and, at higher temperatures, by thermal breakdown of the coal. The methane is found in coals either adsorbed on the coal surfaces, as free gas in fractures and large pores, or dissolved in the ground water in coal beds (Rightmire, 1984). The amount of gas stored in the coals is influenced by depth of burial and its related pressure, rank of coal, and the time-maturity relationship. The Carbondale coal field has long been known for having high-methane coals.

GEOCHEMICAL SIGNATURE

Coalbed methane deposits are not detected by regional geochemical techniques.

GEOPHYSICAL SIGNATURE

Geophysical techniques are of little help in exploration for coalbed methane.

KNOWN DEPOSITS

Coal has been mined from the Carbondale coal field in Pitkin, Gunnison, and Garfield Counties, in the southwestern part of the Forest. Although coalbed methane has not been produced from the Carbondale field, much of the field has been monitored for emissions. The field is known for numerous safety and regulatory problems, and many miners have been killed from explosions or gas fires (Choate and others, 1984).

ASSESSMENT CRITERIA

1. Presence of the Bowie or Paonia Shale Members of the Williams Fork Formation of the Mesaverde Group.
2. Presence of methane.

ASSESSMENT

Area Q1.—A small area in the northernmost part of the Forest, at Wilson Mesa east of Meeker, has moderate energy resource potential for coalbed methane (pl. 2, fig. 45) with certainty level C (table 2). Although the Mesaverde Group is exposed in this area, the coals are not known for having high gas content.

Area Q2.—In the southwestern part of the Forest, rocks of the Mesaverde Group are exposed along the Divide Creek anticline. This area of outcrop is assigned a moderate resource potential for coalbed methane (pl. 2, fig. 45) with certainty level C (table 2). A moderate potential is assigned due to favorable host rock, favorable structure, and proximity to an area with known coalbed methane resources. Oryx Energy reported that ten new wells were drilled for methane in the Divide Creek field (Gas Research Institute, 1990).

Area Q3.—An area in the southwestern part of the Forest has high potential for coalbed methane resources (pl. 2, fig. 45) with certainty level D (table 2). The area of potential includes the Carbondale coal field, which is known for its high-methane coals. The weighted average gas content for some of the coals in Coal Basin has been determined to be 569 cubic feet per short ton (Choate and others, 1984). The vitrinite-reflectance and total-organic-carbon study by Nuccio and Schenk (1986) of rocks from this area indicates that the Mesaverde is an excellent source rock for gas.

Area Q4.—The Mesaverde Group is exposed along the Grand Hogback in the southwestern part of the Forest. The area of outcrop has a moderate resource potential for coalbed methane (pl. 2, fig. 45) with certainty level B (table 2), due to favorable host rock and proximity to known resources of coalbed methane.

ECONOMIC SIGNIFICANCE

The presence of methane in coal beds has been recognized for hundreds of years as a hazard to coal mining, but only recently has its potential as an energy resource begun to be recognized. Coalbed methane can be a useful energy source for the United States, but only a minor amount could be recovered from the Forest. Extensive reserves of coalbed methane are known elsewhere in the Uinta and Piceance Basins, in northwestern Colorado and eastern Utah. All coal production in the Forest has been from the Carbondale field and has been from underground mines. Several complicating factors exist that make it necessary to use specialized mining methods, and as a result, mining is relatively expensive (Brown, 1990).

OIL SHALE (R)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is oil shale.

HOST ROCK

Accumulations of oil shale occur in the Green River Formation. The most oil-rich layers are near the top of the formation, in the Parachute Creek Member. The Mahogany zone is the richest and most widespread of the oil-bearing units within the Parachute Creek Member.

STRUCTURAL CONTROL

Oil shale is not structurally controlled, but it is restricted to favorable lithologic layers.

AGE

Accumulations occur in the Eocene Green River Formation.

DEPOSIT DESCRIPTION

The Green River Formation is composed of a sequence of predominately lacustrine rocks, with interfingering fluvial rocks. The formation covers an area of about 16,400 square miles and is from 1,500 to 2,000 ft thick (Jaffe, 1962). In the area of the Forest, the formation was deposited during Eocene time in a large lake called Lake Uinta (Newman, 1980).

Blue-green algae in the surface waters of the lake settled to the bottom and decomposed to form the kerogen in oil shale within the Parachute Creek Member. Conditions remained relatively constant for long periods of time, resulting in the deposition of 2,000 ft of oil shale. When a gradual regression took place, the lake developed a thermal and chemical stratification—this produced reducing and high-pH conditions in its deeper waters, and the lake became

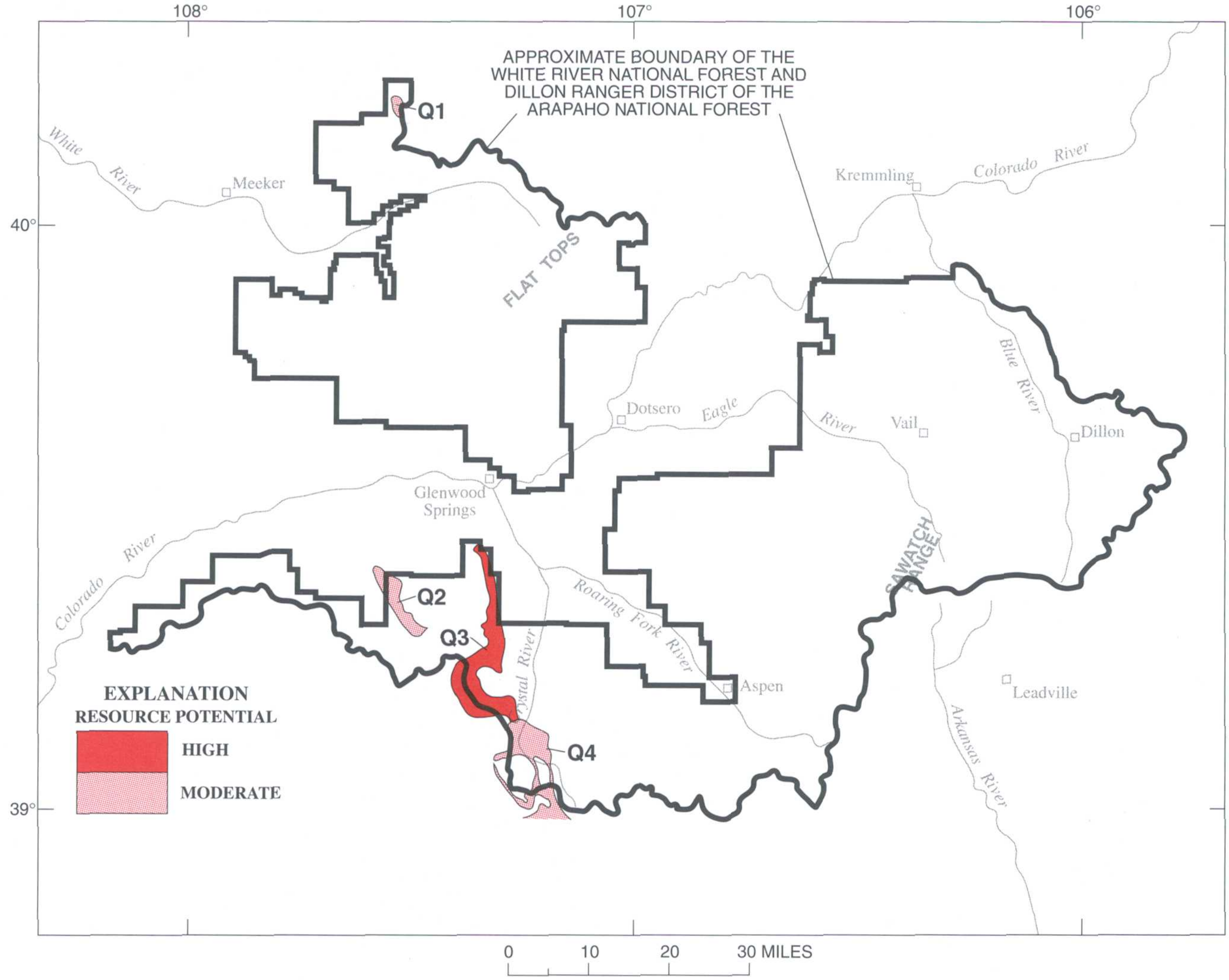


Figure 45. Mineral resource potential map for coalbed methane (Q) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

enriched in sodium carbonate (Newman, 1980). This lead to the deposition of sodium salts such as trona and nahcolite.

GEOCHEMICAL SIGNATURE

Oil-shale deposits are seldom detected by standard geochemical techniques. Conventional stream-sediment or groundwater geochemical surveys are not very useful in assessing the mineral potential of oil-shale deposits.

GEOPHYSICAL SIGNATURE

Drilling studies are the most useful geophysical techniques and are necessary to accurately define any favorable areas. Seismic data could help determine the depth to favorable units and any subsurface structures once a specific unit is targeted.

KNOWN DEPOSITS

No oil-shale deposits are known in the Forest.

ASSESSMENT CRITERIA

1. Presence of the Green River Formation, especially the Parachute Creek member.
2. Presence of oil-shale beds at least 10 ft thick.
3. Presence of at least 25 gallons of oil per ton in oil shale.

ASSESSMENT

Area R1.—An area in the southwestern part of the Forest is underlain by the Green River Formation and is rated as having moderate energy resource potential for oil shale (pl.

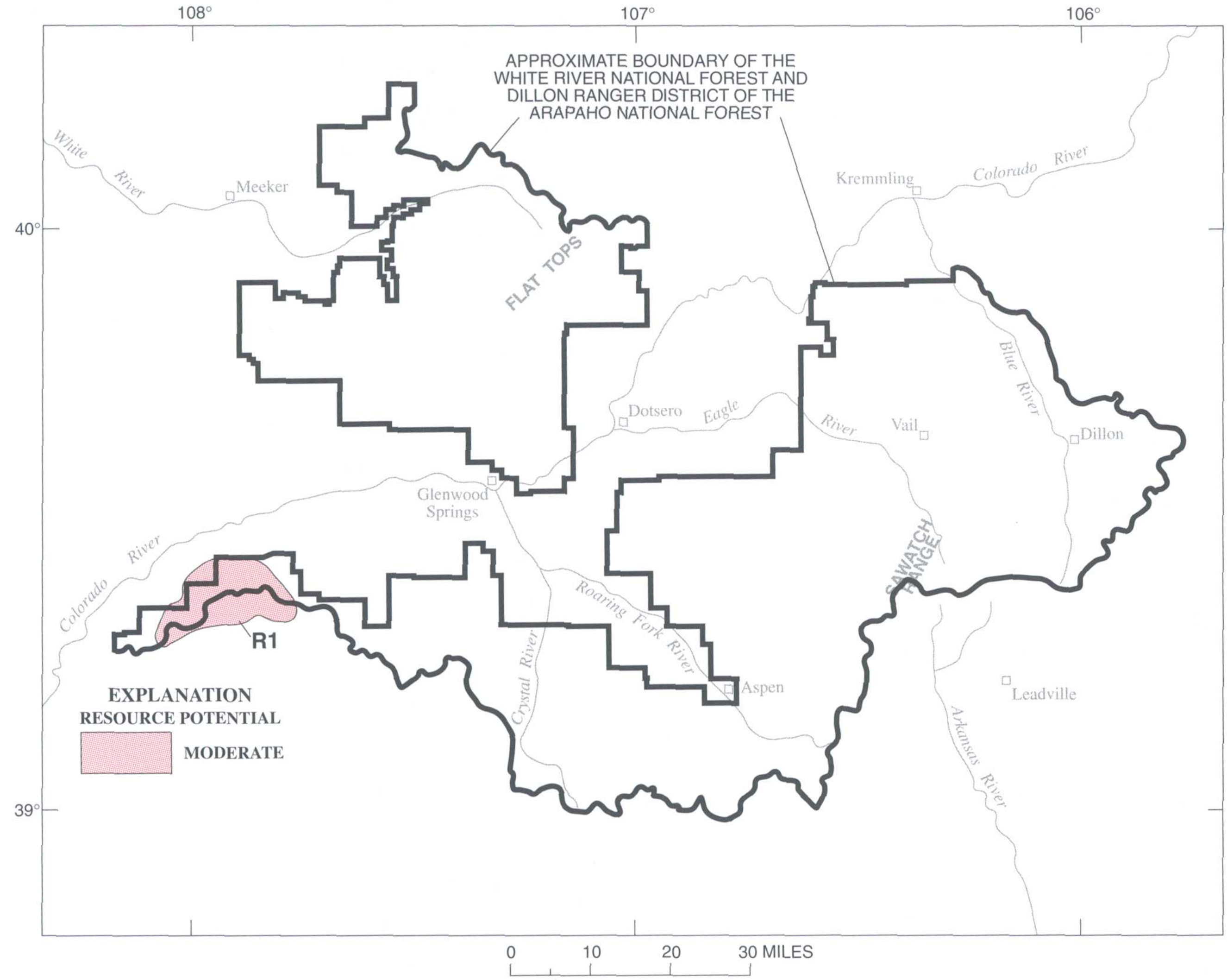


Figure 46. Mineral resource potential map for oil shale (R) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

2, fig. 46) with certainty level C (table 2). The easternmost part of area R1 is rated as having less than 25 gallons of oil per ton in oil shale (U.S. Geological Survey and Colorado Geological Survey, 1977). Keighin (1975) places area R1 outside of the boundary that marks the limit of the rich oil-shale zone that is northwest of the Forest.

ECONOMIC SIGNIFICANCE

Deposits of oil shale occur in many countries of the world. Several areas of extensive oil-shale deposits are present in the U.S., but the most extensive deposits are in the Green River Formation in Colorado, Utah, and Wyoming. The deposit in Colorado may be one of the largest known oil-shale deposits in the world with respect to the amount of reserves (Jaffe, 1962). Although the amount of oil potentially available in oil shale is enormous, no viable commercial operations have yet been established in the U.S. Required capital costs, damage to the environment, problems with water supply, and instability of the world petroleum market are all factors that inhibit commercial development (Cameron, 1986). The amount of oil shale in the Forest is small compared to deposits located in the Piceance Basin to the northwest.

GEOTHERMAL ENERGY (S)

COMMODITIES, BYPRODUCTS, AND TRACE METALS

The commodity is hot water.

HOST ROCKS

In the Forest, hot springs are found in rocks ranging from Mississippian to Cretaceous in age. These include the

Leadville Limestone (Mississippian), Maroon Formation (Pennsylvanian and Permian), and the Dakota Sandstone (Cretaceous). However, the presence of hot springs is dependent on both structure and the presence of hydrothermal systems, not host rock.

STRUCTURAL CONTROL

Discharge areas are located along faults.

AGE

Holocene. Hot springs are heated by currently active hydrothermal systems.

DEPOSIT DESCRIPTION

Thermal springs are most common in areas of high regional geothermal gradients or in the vicinity of young volcanics and intrusions. Three areas of geothermal resources are in and near the western part of the Forest: an area along the Colorado River and small areas at Penny and Conundrum Hot Springs. The springs along the Colorado River are all near young basalt flows. Penny and Conundrum Hot Springs are adjacent to Tertiary intrusions. Flows range from small trickles to large-volume flows, and water temperatures at the surface range from 32°C to 50°C (table 7).

GEOCHEMICAL SIGNATURE

Thermal springs vary in chemical composition, depending on the rocks they interact with as they rise to the surface. Thermal water at Dotsero has high dissolved sodium, chlorine, calcium, and magnesium, suggesting that the ascending water may have encountered evaporite deposits at depth. The geochemistry of the thermal water may not be significantly different, however, from that from springs and wells at lower temperatures.

GEOPHYSICAL SIGNATURE

Geophysical techniques are of little help in exploration for, or the assessment of, hot springs or geothermal resources. Geophysical techniques can, however, locate areas of igneous activity that provide the source of heat for the thermal waters.

KNOWN DEPOSITS

Three groups of thermal springs are along the Colorado River, adjacent to the Forest: Dotsero, Glenwood, and South Canyon Hot Springs. Two isolated hot springs to the south, Penny and Conundrum Hot Springs, are within the boundaries of the Forest. All of the springs are undeveloped except for Glenwood Hot Springs, which has been developed into a resort and spa for recreational and therapeutic uses.

Table 7. Flow rates and temperatures of hot springs in and near the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

[Gpm, gallons per minute; --, no data; temp., temperature in °C]

Location	Flow rate (gpm)	Surface temp.	Subsurface temp.
Colorado River:			
Dotsero	--	32	32
South Canyon	14–25	48	100
Glenwood Springs	2,700	49	75
Penny Hot Springs	22	50	60
Conundrum Hot Springs	60	35	40–50

ASSESSMENT CRITERIA

1. Presence of springs with elevated temperatures.
2. Proximity to areas of relatively young volcanic or intrusive rocks.
3. Presence of regional faults.

ASSESSMENT

Area S1.—An area along the Colorado River, between Dotsero and South Canyon, has high energy resource potential for geothermal energy for recreational and therapeutic uses (pl. 2, fig. 47) with certainty level D (table 2). The surface water temperature of the springs is too low for generating steam.

Area S2.—A small area, at Penny Hot Springs, has high energy resource potential for geothermal energy for recreational and therapeutic uses (pl. 2, fig. 47) with certainty level D (table 2). The surface water temperature of the spring is too low for generating steam.

Area S3.—A small area, at Conundrum Hot Springs, has high energy resource potential for geothermal energy for recreational and therapeutic uses (pl. 2, fig. 47) with certainty level D (table 2). The surface water temperature of the spring is too low for generating steam.

ECONOMIC SIGNIFICANCE

Glenwood Hot Springs has been used for many years for both recreational and therapeutic purposes. The temperatures of the thermal springs in the area are too low for power generation. However, the springs can provide recreation and health benefits for the foreseeable future.

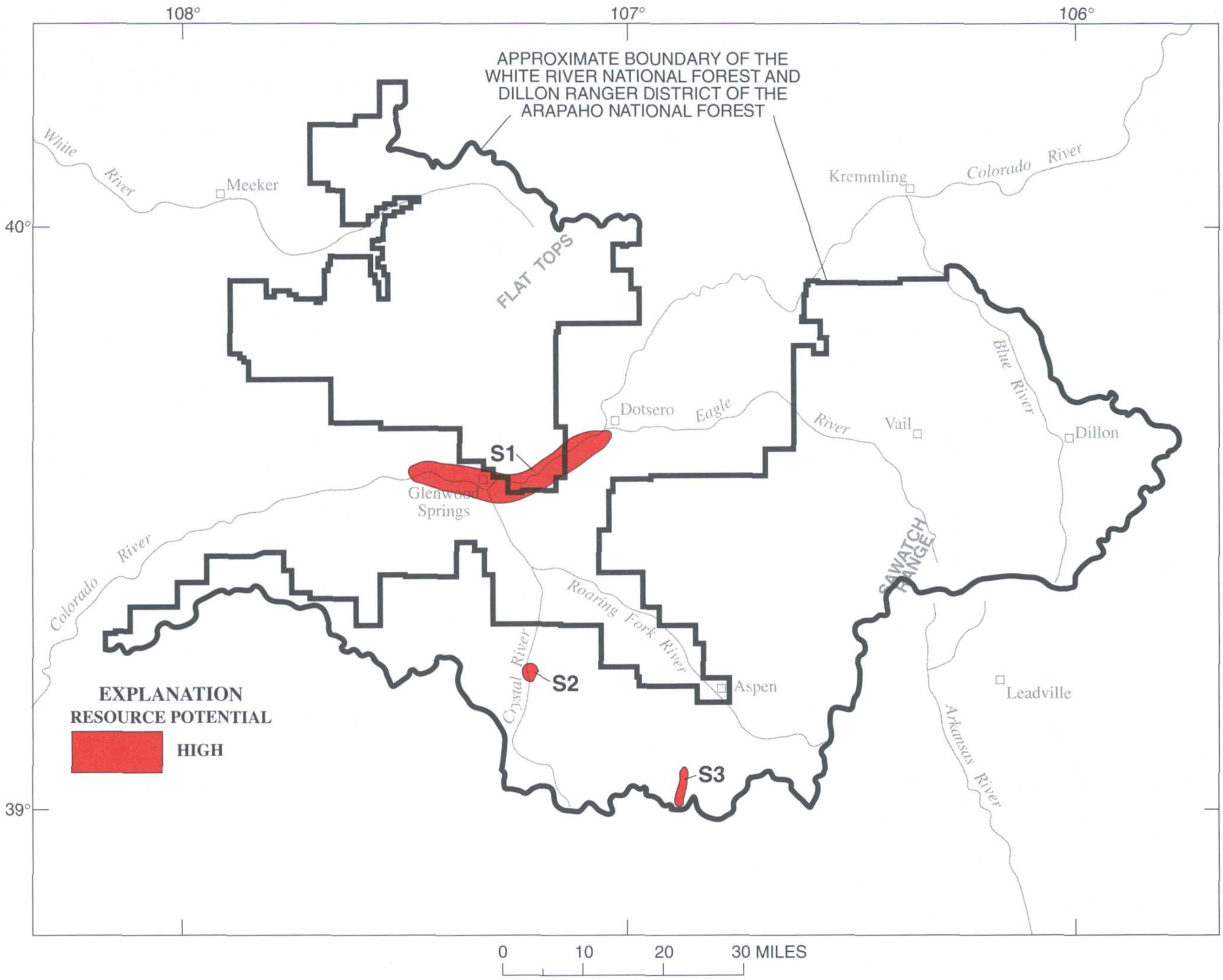


Figure 47. Mineral resource potential map for geothermal energy (S) in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Areas of potential are described in the text and listed in table 2.

MINERAL RESOURCES—SALABLE COMMODITIES

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

The General Mining Law of 1872 declared "* * *all valuable mineral deposits in lands belonging to the United States* * *to be free and open to exploration and purchase." The law authorized placer and lode mining claims to be located on lands containing valuable minerals; this Act still forms the bulk of present-day mining law. In 1892, lands valuable for building stone came under the purview of the mining law. The Federal Mineral Materials Act of 1947 permitted the Secretary of the Interior to sell sand, stone, gravel, and common clay through a contract of sale. The Multiple Surfaces Use Act of 1955 removed petrified wood, common varieties of sand and gravel, stone, pumice, volcanic cinders (including scoria), and some clay from the category of locatable commodities and placed them under the Minerals Material Act as salable commodities. Several exceptions to the salable category are: block pumice, perlite, and some forms of dimension stone such as travertine, high-quality marble, and micaceous metaquartzite—these remain locatable commodities. Particular minerals must be reviewed on a case-by-case basis in light of past legal decisions to determine whether they are salable. For a mineral such as dimension stone to be classified as locatable, it must exhibit a unique property that will give the material a distinct and special value in the market place. Salable commodities generally have a low unit value (value per ton), and their exploitation is dependent on easy access to transportation; they are generally used near the production site.

Numerous deposits of sand and gravel are located within major drainages in the Forest, and the deposits are being exploited for concrete and structural aggregate materials, road fill, mortar, and other uses. Quarries are in use around the Forest as needed; some are dormant at this time. An inventory of nonmetallic mining and processing operations (Schwochow, 1981) noted 53 sites for rock, sand and gravel, rubble, and borrow material on Forest land. Local needs are usually short term. Fluvial deposits satisfy most needs, except for special aggregate demands that can be met by several different material types, including limestone, sandstone, basalt, and granite. End uses may include aggregate, road material, and cement manufacture.

Dimension-stone sources in the Forest include marble and moss rock that are used mainly for exterior and interior decorative work; both of these are classified as salable commodities. Both white and black marble (Kness, 1984; Bryant, 1979) are found in the southwestern part of the Forest. Two sites have been quarried in the past; the Yule Marble quarry reopened in 1990 and is producing white marble (Aspen Times, 1990). The marble from the Yule quarry has been used for several monuments in the Washington, D.C. area and for 59 other buildings in the U.S. Production of black marble has been limited. Decorative rock, such as moss rock, can be found on the flanks of Red Table Mountain, Porphyry Mountain, and Burnt Mountain (pl. 1).

Crushed aggregates, usable for roadway materials and general construction, are derived from limestone, basalt, sandstone, and granite quarries (Tweto and others, 1978). Rock quarries are scattered around the Forest where topography does not inhibit excavation. Sites for limestone include the Flat Tops and an area surrounding the anticlinal core of the Sawatch Range. Sandstone sites are located west of the Flat Tops Wilderness, northeast of Spring Park Reservoir, and east of Hardscrabble Mountain (pl. 1). Sites for basalt are located on Basalt Mountain and in the Flat Tops. Granite is found along the Crystal River and within the Maroon Bells–Snowmass Wilderness.

Lightweight aggregates include volcanic ash, pumice, and scoria (Tweto and others, 1978). Production and use of the aggregates is limited. End uses include roofing and decorative stone, lightweight structural concrete, and gas-barbecue briquettes. The only other salable mineral commodity is clay. Clay resources are located in the Dakota Sandstone, south of Dillon Reservoir.

MINERAL RESOURCE POTENTIAL—SALABLE COMMODITIES

The evaluation of resource potential for sand and gravel, dimension stone, crushed aggregates, and lightweight aggregates follows. Income from these commodities will vary according to site accessibility, unit value, and cost of production. Environmental factors limiting development, such as ground disturbance due to bulk mining, have not been considered in this assessment of resource potential. The 1:250,000 scale of this assessment is not appropriate to limit the definition and exact location of areas of potential.

SAND AND GRAVEL

Sufficient sand and gravel resources are present to meet most needs, including Forest road construction. The major drainages (including the Eagle, Fryingpan, Roaring Fork, Crystal, White, and Blue Rivers, and their tributaries) provide source materials (fig. 48). Most sedimentary bedrock formations (Maroon Formation, Minturn Formation, Belden Formation, and Eagle Valley Evaporite) contain too much clay and gypsum to be commercially usable. Limited amounts of sand and gravel can be found in unconsolidated Pleistocene glacial deposits at higher elevations.

DIMENSION STONE

There are several source areas for dimension stone within the Forest. Both white and black marble are present in the southwestern part of the Forest, south of the towns of Marble and Aspen, respectively. The white marble is part of the Leadville Limestone and is located on the west flank of Treasure Mountain, about 2 mi southeast of Marble, in the Yule Creek valley (pl. 1). The marble cliff is about 4,000 ft in length and as much as 239 ft thick, but only 100-150 ft of its thickness is of commercial quality. Other sources are present that are either not decoratively pleasing, in poor quarrying locations, or too thin for commercial development. The source of the black marble is the Belden Formation, on the east side of the headwaters of Conundrum Creek, about 6 mi south of Aspen. The marble may be as much as 100 ft thick and over 300 ft in length. Reserves of both the white and black marble may be found at depth. Jet-black marble has also been found at the base of Mt. Sopris, near Marble (Pay Dirt, Sept. 1992, p. 21B). The appearance and aesthetic qualities of the marble must be appropriate to its intended use; its physical characteristics (including strength, weathering characteristics, ease of quarrying, and absence of cracks) must also suit its intended use.

Moss rock can be picked up from loose material on the flanks of Red Table Mountain, Porphyry Mountain, and Burnt Mountain. A medium- to coarse-grained red sandstone, medium-gray, fine-grained limestone, and a pinkish, equigranular granite, all covered by lichens, are appealing. Resources are abundant.

CRUSHED AGGREGATE

Crushed aggregate sources in granite, basalt, and limestone are scattered around the Forest (fig. 48). The sources of granite are mainly sills, dikes, small stocks, or irregular

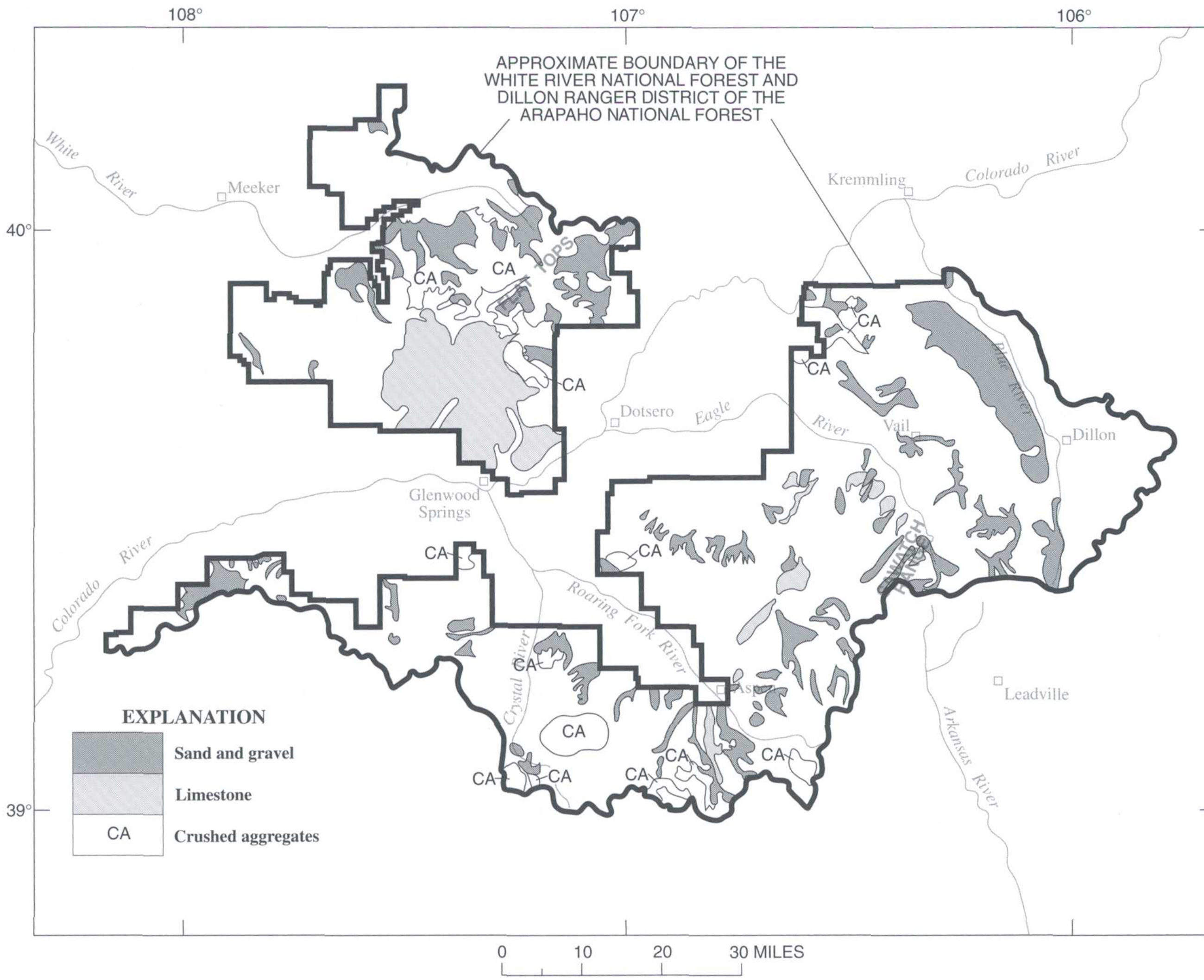


Figure 48. Map showing location of salable commodities in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

bodies of middle Tertiary granodiorite to quartz monzonite; some Late Cretaceous granitic rocks are also included. Sources of basalt occur mainly in the Flat Tops as lava-flow layers of dense, black, alkali basalt that vary in thickness. Scattered basalt dikes and plugs are also sources of crushed aggregate. The primary common limestone source is the Leadville Limestone. This formation crops out around the core of the north-trending Sawatch Range and across the Flat Tops Plateau. All of these units have been exploited to some degree for crushed rock, but an in-depth assessment will require mapping at a larger scale.

LIGHTWEIGHT AGGREGATE

Lightweight aggregate resources (including volcanic ash, scoria, and pumice) are distributed throughout the Forest in limited amounts and contain variable amounts of impurities. These rocks are generally found near the vent source. Small outcrops of volcanic ash and scoria are found in the alluvium and glacial deposits in the valley along the Blue River. Limited quantities of pumice occur north of the Flat Tops. A minor amount of exploitation of the pumice has occurred. Additional mapping at a larger scale is needed for assessment.

CLAY

Clay resources are limited to the Cretaceous Dakota Sandstone. The Dakota crops out along the western edge of the Grand Hogback and southwest of the Roaring Fork River, from Basalt to Aspen (pl. 1). Clays were sampled from seams that ranged from 4 to 15 ft in width (Van Sant, 1959) and are not of refractory-brick quality.

ASSESSMENT OF METAL ENDOWMENT USING GRADE-TONNAGE MODELS

INTRODUCTION

At the request of the U.S. Forest Service, the U.S. Geological Survey is providing subjective probabilistic estimates for the existence and number of undiscovered deposits within the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado. Assessment was possible, given current available information, for four deposit types: stockwork molybdenum, polymetallic vein, polymetallic replacement, and placer gold deposits. Several deposit types are known to occur, or have the potential for occurrence, within the Forest—these could not be evaluated because critical data needed for the estimation process are currently not available. The results of the assessment are provided for use by the U.S. Forest Service in land-use planning and minerals-potential supply analysis in anticipation of any conceivable development of mineral deposits that might be discovered in the Forest.

ASSESSMENT METHOD

The first step in the assessment was to compile geological, geochemical, geophysical, and mineral resource data for the Forest and to use the data to identify attributes that are characteristic of deposit types that occur or could occur within the Forest. The second step was to use those attributes to delineate areas or tracts favorable for the occurrence of those deposit types within the Forest; these areas are described earlier in this report. The third step was to make subjective estimates regarding the number of undiscovered deposits that might occur in the Forest.

A fixed but unknown number of deposits actually occur within the Forest, and it is difficult, if not nearly impossible, to correctly estimate this number. This estimation process is necessarily subjective and is based upon consideration of the geologic, geochemical, and geophysical data and the distribution of terranes favorable for deposits. In cases where information is sparse, the confidence level regarding the number of deposits is much less than in cases where more information is available. Presenting the estimates of the number of deposits in a probabilistic framework acknowledges these conditions. Thus, the number of undiscovered deposits is estimated at the 90th, 50th, and 10th percentile probability levels.

The estimate of the number of deposits at the 90 percent confidence level is the least speculative of the three levels and is closely related to the number of known deposits of that type in the Forest (Singer and Ovenshine, 1979). The degree to which the "known" deposits in an area have been explored is directly related to the uncertainty of the estimates. The estimate of the number of deposits at the 50 percent confidence level can be based on a number of concepts that are more speculative. For example, the estimate can depend on the extent of mineral exploration, the proportion of tracts that have unconsolidated surficial deposits, or the proportion of tracts that may have appropriate geologic conditions at depth. The estimate of the number of deposits at the 10 percent level is the most speculative of the three; its absolute upper limit would theoretically be the number of deposits that could physically occur in the Forest. This estimate is based on attributes such as the number of related deposits in the area, geochemical anomalies, or zones of alteration that compare favorably with alteration patterns in the deposit model. Half of the estimated number of deposits at each confidence level is expected to be larger than the median tonnage for the specific grade-tonnage model (Cox and Singer, 1986).

Although undiscovered deposits are more likely to occur, by definition, in areas of high potential, they can occur in any region having appropriate geologic attributes. Undiscovered resources that are extensions of historical mining areas (for example tailings from gold placers) were not considered to be undiscovered deposits and were not included in the estimates.

After the assessment team estimated the number of undiscovered deposits in the Forest, the data were entered into the MARK3 computer program (Drew and others, 1986; Root and Scott, 1988; Root and others, 1992), which contains the data from the grade and tonnage-frequency distributions in Cox and Singer (1986). MARK3 combines information from the grade and tonnage models with the estimations of the numbers of undiscovered deposits and selects in a random manner (Monte Carlo simulation) various metal tonnages, or endowments, that would likely occur together in the undiscovered deposits. Undiscovered grade and tonnage data are obtained using curves produced from data from discovered deposits having similar attributes. Grade and tonnage distributions for each deposit type are assumed by the MARK3 program to be representative of all deposits with similar geologic, geophysical, and geochemical characteristics.

The MARK3 program allows for dependency of grade and tonnage variables by treating them as individually normal or jointly bivariate normal (Root and Scott, 1988). These variables are usually independent and not normal, but they are made dependent for MARK3 in order to estimate undiscovered grades and tonnages. In other words, independent data, by its very nature, cannot be used to predict grade and tonnages. The grade and tonnage data are, therefore, 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 of the product of grade and tonnage values is then set equal to the mean of the metal content. This method then brings the two variables, grade and tonnage, into what is mathematically called a cumulative distribution function that is jointly bivariate (see Drew and others, 1986; Root and Scott, 1988; and Root and others, 1992).

Four deposit types within the Forest have sufficient data to effectively compare them with models in Cox and Singer (1986) and to quantitatively assess undiscovered metallic resources. These include the following: stockwork molybdenum, polymetallic vein, polymetallic replacement, and placer gold deposits (table 8). The remaining deposit types in the Forest lack pertinent data for quantitative assessment.

RESULTS

Results for the four deposit types are presented in table 8 at the 90th, 50th, and 10th percentile confidence levels. The sorted simulation runs from the MARK3 computer program are included in Appendix 4.

STOCKWORK MOLYBDENUM DEPOSITS

The assessment team estimated a 90 percent chance of no undiscovered deposits of this type, a 50 percent chance of one undiscovered deposit, and a 10 percent chance of one undiscovered deposit in the Forest. Using these values and the grade-tonnage data from the stockwork molybdenum model (Cox and Singer, 1986, model 16; Luddington, 1986), the MARK3 program produced a mean of 430,000 undiscovered tonnes of molybdenum in the Forest and a mean of 220 million undiscovered tonnes of mineralized rock (table 8). These values are slightly above the median tonnage for the distribution of Cox and Singer (1986) for deposits worldwide.

The Climax molybdenum mine is within a few miles of the southeastern border of the Forest and, as of 1976, had supplied at least half the world's molybdenum for 50 years (Govett and Govett, 1976). Areas within and around the Forest with characteristics similar to those at the Climax mine have been thoroughly explored by industry. However, it is quite possible that there could be deposits that are not exposed at the surface. Currently, the identified resources of molybdenum are about 6 million tonnes in the U.S. and a total of 13 million tonnes in the world (U.S. Bureau of Mines, 1990).

POLYMETALLIC VEIN DEPOSITS

The assessment team estimated a 90 percent chance of at least one undiscovered deposit of this type, a 50 percent chance of three undiscovered deposits, and a 10 percent chance of five undiscovered deposits in the Forest. Using these values and grade-tonnage data from the polymetallic vein model (Cox and Singer, 1986, model 22c; Cox, 1986), the MARK3 program estimated an average of 20,000 tonnes of lead, 14,000 tonnes zinc, 330 tonnes copper, 8 million troy ounces of silver and 23,000 troy ounces of gold in the Forest (table 8). A mean value of 280,000 tonnes of total mineralized rock may be present. These values are among the highest indicated on the distribution curve of Cox and Singer (1986) for deposits worldwide.

Several factors may affect the values estimated by MARK3 for this model. Zinc grades from past production figures are probably underestimated because zinc interfered with the smelting process and was avoided in mining and (or) penalized at the smelter. The grade and tonnage models used were only for base-metal polymetallic veins because data for precious metal veins were inadequate. Nearly 60 percent of the data for the tonnage-grade curves were from a mining district in Canada, and this bias may affect the model in ways that are not currently identifiable. Cox and Singer (1986, model 22c) also classify as one deposit mines or workings within 0.6 mi of one another that have a minimum of 100 tonnes of ore.

Production of base and precious metals from some of the mining districts in and adjacent to the Forest is important to the local economy, but Colorado is not a leading producer of any of these commodities. Currently, identified resources of lead, zinc, and copper are at least 22, 50, and 90 million tonnes, respectively, in the U.S. and a total of 1.5, 1.9, and 2.5 billion tonnes in the world (U.S. Bureau of Mines, 1990). World resources of silver and gold are 2.3 and 2.4 billion troy ounces, respectively, with total U.S. resources at 13 billion troy ounces for silver and 300 million troy ounces for gold (U.S. Bureau of Mines, 1990).

POLYMETALLIC REPLACEMENT DEPOSITS

The assessment team estimated a 90 percent chance of no undiscovered deposits of this type, a 50 percent chance of one undiscovered deposit, and a 10 percent chance of one undiscovered deposit in the Forest. Using these values and grade-tonnage data from the polymetallic replacement deposit model (Cox and Singer, 1986, model 19a; Morris, 1986; and Mosier and others, 1986), the MARK3 program estimated an average of 220,000 tonnes of lead, 250,000 tonnes of zinc, 9,800 tonnes of copper, 26 million troy ounces of silver, and 100,000 troy ounces of gold for the Forest (table 8). The mean amount of mineralized rock is 4 million tonnes. These values are among the lowest values for the distribution as presented by Cox and Singer (1986) for deposits worldwide. Lead, zinc, and copper replacement deposits occur in the Aspen, Gilman, Leadville, and Kokomo-Tenmile mining districts.

Several factors may effect the MARK3 estimations for this model. The grade and tonnage curves included vein deposits transitional to replacement deposits. Only districts with combined production and reserves of at least 100,000

Table 8. Quantitative estimates of undiscovered resources of stockwork molybdenum, polymetallic vein, polymetallic replacement, and placer gold deposits in the White River National Forest and Dillon Ranger District of the Arapaho National Forest, Colorado.

[Values, except number of deposits, in metric tonnes unless indicated as troy ounces (oz). Percentages in column headings refer to confidence levels for estimates of undiscovered deposits occurring in the Forest]

Metal	90%	50%	10%	Mean
		Stockwork molybdenum		
Mo	0	230,000	1,200,000	430,000
Total mineralized rock	0	130,000,000	620,000,000	220,000,000
Number of deposits	0	1	1	
		Polymetallic veins		
Pb	57	4,600	55,000	20,400
Zn	0	1,300	39,000	14,000
Cu	0	53	370	330
Ag	16,400 oz	1,029,000 oz	14,468,000 oz	8,037,500 oz
Au	0	612 oz	41,800 oz	22,800 oz
Total mineralized rock	350	56,000	840,000	280,000
Number of deposits	0	3	5	
		Polymetallic replacement		
Pb	0	29,000	510,000	220,000
Zn	0	14,000	620,000	250,000
Cu	0	0	21,000	9,800
Ag	0	1,896,900 oz	67,515,400 oz	26,041,500 oz
Au	0	0	147,900 oz	99,600 oz
Total mineralized rock	0	6,200,000	12,000,000	4,100,000
Number of deposits	0	1	1	
		Placer gold		
Au	180 oz	3,100 oz	23,000 oz	7,000 oz
Total mineralized rock	1,500	130,000	1,000,000	330,000
Number of deposits	0	1	2	

tonnes were used in constructing the grade and tonnage curves. Tonnages for many districts, particularly in the U.S., are biased because only production data were available. Zinc grades from past production figures are also probably underestimated because of early difficulties in processing zinc oxides.

Currently, identified resources of lead, zinc, and copper are least 22, 50, and 90 million tonnes, respectively, in the United States and a total of 1.4, 1.8, and 2.3 billion tonnes in the world (U.S. Bureau of Mines, 1990). World resources of silver and gold are 2.3 and 2.4 billion troy ounces, with total U.S. resources for the two metals at 13 billion and 300 million troy ounces respectively (U.S. Bureau of Mines, 1990).

PLACER GOLD DEPOSITS

The assessment team estimated a 90 percent chance of no undiscovered deposits in the Forest, a 50 percent chance of one undiscovered deposit, and a 10 percent chance of two placer gold deposits that are yet to be discovered in the Forest. Using these values and a modified grade-tonnage curve from the placer gold deposit model (Cox and Singer, 1986, model 39a; Yeend, 1986), the MARK3 program yielded a mean of 7,000 troy ounces of gold in the Forest and mean of 330,000 tonnes of mineralized rock (table 8). The modified grade-tonnage curve differed from the one presented in Cox and Singer (1986) in that it did not include very large placers (tens of millions of tons); the modified curve was deemed more appropriate for describing placers worked by small-volume mining (J. Bliss and G. Orris, written commun., 1992) such as those within the Forest. Two other factors might additionally influence the values estimated by MARK3 for this model: Some grades and tonnages in the modified grade-tonnage curve are only estimated due to a limited production record; also, Cox and Singer (1986, model 19a) use the term deposit to include mines or workings within 1 mi of one another.

The mean values of placer gold for the Forest are below the median tonnage for deposits worldwide (Cox and Singer, 1986). Currently, identified resources of gold are 300 million troy ounces in the United States and a total of about 2.4 billion troy ounces in the world (U.S. Bureau of Mines, 1990).

Some of the old placers in the Breckenridge area are now being reclaimed to improve the appearance of stream drainages around the resort town.

RECOMMENDATIONS FOR FUTURE STUDIES OF MINERAL RESOURCE POTENTIAL

The White River National Forest and Dillon Ranger District of the Arapaho National Forest host a wide variety of mineral resources that have been extensively mined and prospected. Most of the mineral deposit types have been studied in detail; others have been examined in a reconnaissance manner. However, many of the geologic terranes in the Forest have not yet been mapped or sampled in sufficient detail to adequately assess the mineral resource potential. Wallace and others (1988) discussed some of the recommendations for future studies in their report on the Leadville 1°×2° quadrangle.

Massive sulfide deposits in Proterozoic volcanic sequences are important metal resources in North America and in Colorado. Deposits have not been recognized in the Forest, although Proterozoic metavolcanic rocks have been mapped. In order to better assess the potential for these deposits, known metavolcanic rocks in the Forest should be physically described and chemically characterized, and any associated sulfide deposits should be examined. Determinations of the physical and chemical properties of the rocks would assist interpretation of geophysical data. Tracts of metamorphic rocks should be examined to identify metavolcanic rocks and any associated sulfides. Only by identifying and characterizing the metavolcanic rocks and known massive sulfide occurrences can the potential for unexplored areas be determined.

A large area of the Flat Tops, in the northwestern part of the Forest, has anomalous concentrations of copper and nickel in many of the stream-sediment samples from drainages in the area. No known analog exists for a copper-nickel deposit in the geologic environment of the Flat Tops. In order to properly evaluate the resource potential of this area, the petrology and geochemistry of the basalts should be characterized, and the possible origins of a deposit should be investigated.

Sandstone-hosted copper, silver, uranium, and vanadium deposits have been identified in the Forest, but the vast expanse of clastic sedimentary rocks allows for a variety of other "sandstone-hosted" deposit types. The formations and facies that host the known deposits need to be studied, and this information should be interpreted using the results of modern sedimentological studies of the units. This would permit specific areas and facies to be selected for field and geochemical study—these ares would then be evaluated using models derived from known deposits.

Veins containing tungsten and uranium have been found in the Forest, but little is understood regarding their genesis. Detailed field and geochemical studies are necessary to understand their origin and geologic environment so that predictions can be made concerning other areas where similar veins may be present.

The Mississippian Leadville Limestone and other middle Paleozoic carbonate units are the major host rocks for the rich replacement ore bodies at Gilman, Aspen, and Leadville. Mineralization in large part occurred in the Oligocene, but evidence suggests that some mineralization occurred as a result of Mississippian cave-filling mineralization ("Sherman-type" deposits). The Leadville Limestone is dolomitized in mineralized areas, most of which are in the southeastern part of the Forest, and karst-related cave systems and collapse breccias are common in many of the exposures in the Forest. In order to better evaluate the resource potential for Sherman-type Pb-Zn-Ag deposits in carbonate rocks outside of known mineralized areas, particularly in and around the White River Plateau, the distribution and age of solution breccias must be established. In addition, the relations between mineralization and dolomitization, igneous activity, and cave formation should be evaluated as critical criteria for assessment. With these data, tracts outside of known mineralized areas can be more adequately assessed for resource potential.

Placer deposits derived from source rocks from Proterozoic to Tertiary in age occur in the Forest. Consideration should be given to the resource potential of fossil placers as well as those in modern fluvial systems. If geochronologic study of vein and exhalative deposits indicates pre-Tertiary sources of gold, then pre-Tertiary fluvial sedimentary rocks should be evaluated for placer gold deposits.

Laramide uplift and plutonism drastically influenced mineralization in the Forest, particularly in the eastern parts. In order to adequately address the mineral resources in the Forest, Laramide contributions to structural development and mineral deposits should be further evaluated. Mapping in and around the major uplifts should constrain the timing of uplift, measure the amount of uplift, and identify structures that were integral to the uplift. In addition, the role of Laramide intrusives in the structural and geochemical development of the region must be addressed during mapping studies.

In order for most of the above recommendations to be carried out, additional geologic mapping of Forest and adjacent lands is necessary. Much of the Forest has been mapped at 1:24,000 scale, whereas geologic maps of other parts of the Forest are still only available at a geologic-reconnaissance scale of 1:250,000. Some of the known mineralized and altered areas need to be mapped in much greater detail. The processes of mineral exploration and resource assessment are not static. As new concepts are formulated and new deposit types are recognized, various geologic terranes may be reexamined several times. Detailed geologic maps are critical for evaluating mineral resource potential.

Stream-sediment and groundwater geochemical data of a reconnaissance nature are available for the Forest and adjacent lands from NURE surveys, but localities sampled by those studies are too widely spaced to be useful in resource assessment for metals in most areas. Even in areas where geochemical coverage is adequate, data from different surveys cannot be easily integrated because of differences in sample media and analytical techniques. Some of the land in the Forest should be resampled to generate a consistent data set. These areas are outlined by Wallace and others (1988). Data from previous studies need to be augmented by additional samples and analyses for elements such as gold, silver, mercury, uranium, vanadium, and other elements that are directly related to mineral deposits in the area. Rock samples, stream-sediment samples, and panned-concentrate fractions of stream sediments should be collected and samples analyzed for a basic suite of at least 30 elements.

Geochemical sampling in the Forest should focus on areas of the Forest within the Colorado Mineral Belt. Areas within the boundaries of previously sampled Wilderness and Wilderness Study Areas may be largely excluded because data are available. Areas outside the boundaries of the Colorado Mineral Belt should selectively be sampled; they may contain exposures of favorable host rocks but lack geochemical data.

An area in the vicinity of the Fulford stock, between the Proterozoic rocks of the northern Sawatch Range and the Eagle River, should be sampled in detail. Metals have been found in some of the sedimentary rocks adjacent to the stock, but the extent of the metals is unknown. The large area of the White River Plateau that is north and northwest of Glenwood Springs should also be sampled in detail. In this area, there are extensive exposures of mid-Paleozoic carbonate rocks that locally host small lead and zinc deposits. Basalts in the western part of the Flat Tops area also contain a high concentration of nickel in stream-sediment samples and should be sampled to determine the origin of the nickel. In the northwestern part of the Forest, the entire drainage basin of Rifle Creek should be sampled in detail. The basin contains important vanadium deposits on the north side of the Grand Hogback, in Jurassic sedimentary rocks, and a commercial lead and zinc mine is in Mississippian Leadville Limestone, a few miles farther north. South of the White River Plateau, the upper drainage basin of West Divide Creek should also be sampled. In this area, Upper Cretaceous and lower Tertiary sedimentary rocks and a small Tertiary pluton are exposed; scattered anomalies in stream-sediment samples for silver, lead, and bismuth have been reported.

Previous aeromagnetic surveys detected only about five percent of the potential magnetic sources in the Forest, due largely to the methods used and the level of technology available at the time that the surveys were flown. A state-of-the-art aeromagnetic survey is recommended for the Forest, with flight lines spaced 0.5 mi apart and draped 1,000 ft above terrain (76 percent coverage of surface sources). Such a survey could be used to detect magnetic units at all scales throughout the Forest, to help construct a depth-to-magnetic-basement map, to model tectonic and structural geometries, and to search for slightly magnetic horizons within sedimentary piles. Such a survey would give good regional information, but it stops short of the level of detail needed for prospecting (i.e., 1/8-mile spacing at 300 ft draped).

More than two-thirds of the existing gravity stations are in the eastern one-third of the Forest, and large tracts in the remainder of the Forest have no gravity data. Obtaining data from more gravity stations in the western two-thirds of the Forest is recommended. These data would help to identify buried felsic plutons, and they would provide details on the shape of known intrusive bodies. Data collection should focus on specific districts and geologic terranes in concert with geologic and geochemical studies.

REFERENCES CITED

Anderson, J.L., and Thomas, W.M., 1985, Proterozoic anorogenic two-mica granites: Silver Plume and St.Vrain batholiths of Colorado: Geology, v. 13, p. 177–180.

Aspen Times, September 13, 1990, Living the past: Historic quarry comes back to life, p. 13a.

Averitt, Paul, 1966, Coking-coal deposits of the Western United States: U.S. Geological Survey Bulletin 1222–G, 48 p.

Baskin, G.D., 1987, Mineral resources of the Collegiate Peaks Wilderness, Chaffee, Gunnison, Lake, and Pitkin Counties, Colorado: U.S. Bureau of Mines Open-File Report MLA 45–87, 100 p.

Beaty, D.W., Saunders, D.M., Landis, G.P., Naeser, C.W., and Tschauder, R.J., 1985, Two episodes of sulfide deposition in paleo-caves in the Leadville Dolomite at Red Cliff, Colorado, *in* 1985 SEPM Midyear Meeting Field Guides: Society of Economic Paleontologists and Mineralogists, p. 6–127–6-136

Beaty, D.W., Landis, G.P., and Thompson, T.B., 1990, Carbonate-hosted sulfide deposits of the central Colorado Mineral Belt: Introduction, general discussion, and summary, *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. 1–18.

Behre, C.H., Jr., 1953, Geology and ore deposits of the west slope of the Mosquito Range, Colorado: U.S. Geological Survey Professional Paper 235, 176 p.

Behrendt, J.E., and Bajwa, L.Y., 1974, Bouguer gravity map of Colorado: U.S. Geological Survey Geophysical Investigations Map GP–895, scale 1:500,000.

Bergendahl, M.H., and Koschmann, A.H., 1971, Ore deposits of the Kokomo-Tenmile district, Colorado: U.S. Geological Survey Professional Paper 652, 53 p.

Blakely, R.J., and Simpson, R.W., 1986, Approximating edges of source bodies from magnetic or gravity anomalies: Geophysics, v. 51, p. 1494–1498.

Boardman, S.J., and Condie, K.C., 1986, Early Proterozoic bimodal volcanic rocks in central Colorado, U.S.A., part II: Geochemistry, petrogenesis, and tectonic setting: Precambrian Research, v. 34, p. 37–68.

Bolivar, S.L., Hill, D.E., Bunker, M.E., Cheadle III, J., Minor, M.M., Sandoval, W., Talcott, C.L., Trujillo, L., and Waterbury, G.R., 1979, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Craig NTMS quadrangle, Colorado, including concentrations of forty-three additional elements: U.S. Department of Energy Open-File Report GJBX-76(79), 238 p., 5 plates.

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

Brown, S.D., 1990, Mineral appraisal of the White River National Forest, Colorado: U.S. Bureau of Mines Open-File Report MLA 9-90, 378 p.

Broxton, D.E., Morris, W.A., Bolivar, S.L., Apel, C.T., Gallimore, D.L., George, W.E., Hensley, W.K., McInteer, C., Minor, M.M., and Zelezny, W.F., 1979, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Montrose NTMS Quadrangle, Colorado, including concentrations of forty-three additional elements: U.S. Department of Energy Open-File Report GJBX-125(79), 255 p., 5 plates.

Bryant, Bruce, 1969, Geologic map of the Maroon Bells quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-788, scale 1:24,000.

Bryant, Bruce, 1979, Geology of the Aspen 15-minute quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geological Survey Professional Paper 1073, 146 p.

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

Cameron, E.N., 1986, At the crossroads, the mineral problems of the United States: New York, John Wiley & Sons, Inc., 320 p.

Campbell, D.L., 1981, Aeromagnetic and complete Bouguer gravity anomaly maps of the Hunter-Fryingpan Wilderness area, Pitkin County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1236-C, scale 1:50,000.

———1985, Gravity and aeromagnetic maps of the Maroon Bells-Snowmass Wilderness and additions, Pitkin and Gunnison Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1647-B, scale 1:100,000.

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.

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.

———1966, Geophysical investigations over Precambrian rocks, northwestern Uncompahgre Plateau, Utah and Colorado: American Association of Petroleum Geologists Bulletin, v. 50, p. 1423-1443.

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

Cashion, W.B., compiler, 1973, Geologic and structure map of the Grand Junction quadrangle, Colorado, and Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-736, scale 1:250,000.

Choate, R., Jurich, D., and Saulnier, G.J., Jr., 1984, Geologic overview, coal deposits, and potential for methane recovery from coalbeds, Piceance Basin—Colorado, *in* Rightmire, C.T., Eddy, G.E., and Kirr, J.N., eds., Coalbed Methane Resources of the U.S.: American Association of Petroleum Geologists, Studies in Geology Series No. 17, p. 223-251.

Cocker, M.D., and Pride, D.E., 1 988, Geology and mineral-chemical zoning in the Wire Patch intrusive complex, Breckenridge mining district, Colorado, *in* Kisvarsanyi, Geza and Grant, S.K., North American Conference on Tectonic Control of Ore Deposits and the Vertical and Horizonal Extent of Ore Systems: University of Missouri—Rolla Proceedings volume, p. 142-159.

Collins, B.A., 1975, Geology of the coal deposits of the Carbondale, Grand Hogback, and southern Danforth Hills coal fields, southeastern Piceance Basin, Colorado: Golden, Colorado School of Mines Ph.D. dissertation T-1688, 218 p.

Colorado Oil and Gas Conservation Commission, 1982, Oil and gas statistics—1981: Colorado Department of Natural Resources, 241 p.

———1988, Oil and gas statistics—1987: Colorado Department of Natural Resources, no pagination.

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

Cox, D.P., 1986, Descriptive model of polymetallic veins, *in* Cox D.P., and Singer D.A., eds., Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, p. 125-129.

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

Cruson, M.G., 1973, Geology and ore deposits of the Grizzly Peak cauldron complex, Sawatch Range, Colorado: Golden, Colorado School of Mines, unpub. Ph.D. dissertation, 181 p.

DeWitt, Ed, Redden, J.A., Wilson, A.B., and Buscher, David, 1986, Mineral resource potential and geology of the Black Hills National Forest, South Dakota and Wyoming, *with a section on* Salable commodities, by J.S. Dersch: U.S. Geological Survey Bulletin 1580, 135 p.

De Voto, R.H., 1983, Central Colorado karst-controlled lead-zinc-silver deposits (Leadville, Gilman, Aspen, and others), a Late Paleozoic Mississippi-Valley-type district, *in* The Genesis of Rocky Mountain Ore Deposits: Changes with Time and Tectonics, Proceedings of the Denver Region Exploration Geologists Society, p. 51-70.

Drew, L.J., Bliss, J.D., Bowen, R.W., Bridges N.J., Cox, D.P., De Young, J.C. Jr., Houghton, J.C., Ludington, Steve, Menzie, W.D., Page, N.J., Root, D.H., 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.

Dunn, H.L., 1974, Geology of Petroleum in the Piceance Creek Basin, Northwestern Colorado, *in* Energy Resources of the Piceance Creek Basin, Colorado: Rocky Mountain Association of Geologists 25th field conference Guidebook, p. 217-223.

Epis, R.C., and Chapin, C.E., 1975, Geomorphic and tectonic implications of the post-Laramide, late Eocene erosion surface in the southern Rocky Mountains: Geological Society of America Memoir 144, p. 45-74.

Freeman, V.L., 1971, Stratigraphy of the State Bridge Formation in the Woody Creek quadrangle, Pitkin and Eagle Counties, Colorado: U.S. Geological Survey Bulletin 1324-F, 17 p.

Freeman, V.L., Campbell, D.L., King, H.D., Weisner, R.C., and Bieniewski, C.L., 1985, Mineral resource potential of the Maroon Bells-Snowmass Wilderness and additions, Gunnison and Pitkin Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1647-A, scale 1:100,000.

Fridrich, C.J., and Mahood, G.A., 1984, Reverse zoning in the resurgent intrusions of the Grizzly Peak cauldron, Sawatch Range, Colorado: Geological Society of America Bulletin, v. 95, p. 779-787.

Gabelman, J.W., 1950, Geology and ore deposits of the Fulford mining district, Eagle County, Colorado: Golden, Colorado School of Mines, unpub. Ph.D. dissertation, 189 p.

Gas Research Institute, 1990, Quarterly review of methane from coal seams technology, v. 7, no. 3, 49 p.

Geodata, International, 1981, Aerial radiometric and magnetic survey, Grand Junction, Colorado, Utah: U.S. Department of Energy Report GJBX-112(81), scale 1:250,000.

Geometrics, 1979, Aerial gamma ray and magnetic survey, Uncompahgre uplift project, Leadville quadrangle, Colorado, final report v. 2: U.S. Department of Energy Report GJBX-95(79), scale 1:250,000.

Godson, R.H., Plesha, J.L., Sneddon, R.A., and Krizman, R.W., 1985, Aeromagnetic map of Mt. Massive and vicinity, Colorado: U.S. Geological Survey Open-File Report 85-735, scale 1:100,000.

Godson, R.H., and Webring, M.W., 1982, CONTOUR—A modification of G.I. Evendon's general purpose contouring program: U.S. Geological Survey Open-File Report 82-797, 73 p.

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.

Govett, G.J.S., and Govett, M.H., eds., 1976, World Mineral Supplies—Assessment and perspective: Elsevier Publishing Company, 472 p.

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.

Gries, Robbie, 1983, North-south compression of Rocky Mountain foreland structures, *in* Lowell, J.D., and Gries, Robbie, eds., Rocky Mountain Foreland Basins and Uplifts: Denver, Colorado, Rocky Mountain Association of Geologists, p. 9-32.

Grout, M.A., Abrams, G.A., Tang, R.L., Hainsworth, T.S., and Verbeek, E.R., in press, Late Laramide thrust-related and evaporite-domed anticlines in the southern Piceance Basin, northeastern Colorado Plateau: American Association of Petroleum Geologists Bulletin.

Gustafson, L.B., and Williams, Neil, 1981, Sediment-hosted stratiform deposits of copper, lead, and zinc, *in* Skinner, B.J., ed., Economic Geology 75th Anniversary Volume: El Paso, Texas, Economic Geology Publishing Company, p. 139-178.

Hannah, J.L., 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, p. 347-358.

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

Hornbaker, A.L., Holt, R.D., and Murray, D.K., 1976, 1975 summary of coal resources in Colorado: Colorado Geological Survey Special Publication 9, 17 p.

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.

Jaffe, F.C., 1962, Geology and mineralogy of the oil shales of the Green River Formation, Colorado, Utah, Wyoming: Colorado School of Mines Mineral Industries Bulletin, v. 5, no. 3, 15 p.

Jensen, M.L, and Bateman, A.M, 1981, Economic Mineral Deposits, 3rd ed.: New York, John Wiley and Sons, 593 p.

Johansing, R.J., and Thompson, T.B., 1990, Geology and origin of Sherman-type deposits, 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. 367-394.

Johnson, R.C., 1989, Geologic history and hydrocarbon potential of Late-Cretaceous-age, low permeability reservoirs, Piceance Basin, Western Colorado: U.S. Geological Survey Bulletin 1787, 51 p.

Keighin, C.W., 1975, Resource appraisal of oil shale in the Green River Formation, Piceance Creek Basin, Colorado: Colorado School of Mines Quarterly, 8th Oil Shale Symposium, v. 70, no. 3, p. 57-68.

Kent, B.H., and Arndt, H.H., 1980, Geology of the Carbondale coal mining area, Garfield and Pitkin Counties, Colorado, as related to subsurface hydraulic mining potential: U.S. Geological Survey Open-File Report 80-709, 99 p.

Kluth, C.F., and Coney, P.J., 1981, Plate tectonics of the ancestral Rocky Mountains: Geology, v. 9, p. 10-15.

Kness, R.F., 1984, Mineral investigations of the Raggeds Wilderness Area, Gunnison County, Colorado: U.S. Bureau of Mines Open-File Report MLA 80-507, 86 p.

Koschmann, A.H., and Wells, F.G., 1946, Preliminary report on the Kokomo mining district, Colorado: Colorado Scientific Society Proceedings, v. 15, no. 2, p. 51-112.

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 Report GJBX-153(79), scale 1:250,000.

Langeheim, R.L., Jr., 1952, Pennsylvanian and Permian stratigraphy in Crested Butte quadrangle, Gunnison County, Colorado: American Association of Petroleum Geologists Bulletin, v. 36, no. 4, p. 543-574.

Langfeldt, S.L., Youngquist, C.A., D'Andrea, Jr., R.F., Zinkl, R.J., Shettel, Jr., D.L., Broxton, D.E., Hansel, J.N., McInteer, C., and Minor, M.M., 1981, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Grand Junction NTMS quadrangle, Colorado/Utah: U.S. Department of Energy Open-File Report GJBX-264(81), 142 p., 7 plates.

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.

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

Lovering, T.S., and Goddard, E.N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geological Survey Professional Paper 223, 319 p.

Lovering, T.S., Tweto, Ogden, and Lovering, T.G., 1978, Ore deposits of the Gilman district, Eagle County, Colorado: U.S. Geological Survey Professional Paper 1017, 90 p.

Ludington, S.D., 1986, Descriptive model of Climax Mo deposits, *in* Cox D.P., and Singer D.A., eds., Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, p. 73-75.

Ludington, Steve, and Ellis, C.E., 1981, Mineral resource potential of the Hunter-Fryingpan Wilderness Area and the Porphyry Mountain Wilderness Study Area, Pitkin County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1236-D, scale 1:50,000.

Lundby, William, and Brown, S.D., 1987, Mineral resources of the Holy Cross Wilderness, Eagle, Lake, and Pitkin Counties, Colorado: U.S. Bureau of Mines Open-File Report 3-87, 162 p.

Mallory, W.W., 1971, The Eagle Valley Evaporite, northwest Colorado—A regional synthesis: U.S. Geological Survey Bulletin 1311-E, 37 p.

Mallory, W.W., 1977, Regional aspects of the Eagle Valley Evaporite, *in* Veal, H.K., ed., Exploration Frontiers of the Central and Southern Rockies: Rocky Mountain Association of Geologists, 1977 symposium, p. 191-196.

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.

McCulloch, R.B., and Huleatt, W.P., 1946, Exploration of the Big Four zinc-silver mine, Summit County, Colorado: U.S. Bureau of Mines Report of Investigations 3884, 7 p.

Miller, W.R., and Ficklin, W.H., 1976, Molybdenum mineralization in the White River National Forest, Colorado: U.S. Geological Survey Open-File Report 76-711, 29 p.

Morris, H.T., 1986, Descriptive model of polymetallic replacement deposits, *in* Cox, D.P and Singer, D.A., eds., Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, p. 99-100.

Mosier, D.L., Morris, H.T., and Singer, D.A., 1986, Grade and tonnage model of polymetallic replacement deposits, *in* Cox, D.P. and Singer, D.A., eds., Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, p. 101-104.

Moss, C.K., and Abrams, G.A., 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.

Mutschler, F.E., 1970, Geologic map of the Snowmass Mountain quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-853, scale 1:24,000.

Mutschler, F.E., 1976, Crystallization of a soda granite, Treasure Mountain dome, Colorado, and the genesis of stockwork molybdenite deposits, *in* Woodward, L.E., and Northrop, S.A., eds., Tectonics and Mineral

Resources of Southwestern North America: New Mexico Geological Society Special Publication no. 6, p. 199–205.

Mutschler, F.E., Larson, E.E., and Bruce, R.M., 1987, Laramide and younger magmatism in Colorado—New petrologic and tectonic variations on old themes, *in* Drexler, J.W., and Larson, E.E., eds., Cenozoic Volcanism in the Southern Rocky Mountains Revisited: A Tribute to Rudy C. Epis—Part 1: Colorado School of Mines Quarterly, v. 82, no. 4, p. 1–47.

Mutschler, F.E., Ernst, D.R., Gaskill, D.L., and Billings, Patty, 1981, Igneous rocks of the Elk Mountains and vicinity, Colorado—Chemistry and related ore deposits, *in* Epis, R.C., and Callender, J.F., eds., Western Slope, Colorado: New Mexico Geological Society Guidebook, 32nd Field Conference, p. 317–324.

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 Abstracts with Programs, v. 5, no. 6, p. 498.

Naldrett, A.J., Lightfoot, P.C., Fedorenko, V., Doherty, W., and Gorbachev, N.S., 1992, Geology and geochemistry of intrusions and flood basalts of the Noril'sk region, USSR, with implications for the origin of Ni-Cu ores: Economic Geology, v. 87, no. 4, p. 975–1004.

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.

Nelson-Moore, J.L., Collins, D.B., and Hornbaker, A.L., 1978, Radioactive mineral occurrences of Colorado and bibliography: Colorado Geological Survey Bulletin 40, 1054 p.

Neuerburg, G.J., 1971, Maps showing distribution of selected accessory minerals in the Montezuma stock, Summit County, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I–608, scale 1:31,680 and 1:48,000.

Neuerburg, G.J., Botinelly Theodore, and Watterson, J.R., 1974, Molybdenite in the Montezuma district of central Colorado: U.S. Geological Survey Circular 704, 21 p.

Newman, K.R., 1980, Geology of oil shale in Piceance Creek Basin, Colorado, *in* Kent, H.C., ed., Colorado Geology: Rocky Mountain Association of Geologists, 1980 Symposium, p. 199–203.

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., and Johnson, K.S., eds., New Interpretations of Northwest Colorado Geology: Denver, Rocky Mountain Association of Geologists, 1986 Symposium, Denver, Colo., p. 259–264.

Obradovich, J.P., Mutschler, F.E., and Bryant, Bruce, 1969, Potassium-argon ages bearing on the igneous and tectonic history of the Elk Mountains and vicinity: A preliminary report: Geological Society of America Bulletin, v. 80, p. 1749–1756.

Page, N.J., 1986, Descriptive model of Noril'sk Cu-Ni-PGE, *in* Cox, D.P., and Singer, D.A., eds., Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, p. 17.

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

Parker, B.H., Jr., 1974, Gold placers in Colorado: Colorado School of Mines Quarterly, v. 69, nos. 3 and 4, p. 1-268 and p. 1-224.

Patton, H.B., 1909, The Montezuma mining district of Summit County, Colorado: Colorado Geological Survey First Report, 1908, p. 105–144.

Pay Dirt, September 1992, p. 21B.

Pearl, R.H., 1980, Geothermal resources of Colorado: Colorado Geological Survey Map Series 14, scale 1:500,000.

Pillmore, K.A., and Leanderson, P.J., 1983, Geology and mineralization of the Paradise stock, Gunnison County, Colorado [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 276.

Planner, H.N., Apel, C.T., Fuka, M.A., George, W.E., Hansel, J.M., Hensley, W.K., and Pirtle, J., 1981, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Leadville NTMS quadrangle, Colorado, including concentrations of forty-two additional elements: U.S. Department of Energy Open-File Report GJBX-13(81), 185 p., 1 plate.

Rightmire, C.T., 1984, Coalbed methane resource, *in* Rightmire, C.T., Eddy, G.E., and Kirr, J.N., eds., Coalbed Methane Resources of the U.S.: American Association of Petroleum Geologists, Studies in Geology, Series 17, p. 1–13.

Romberger, S.B., 1980, Metallic mineral resources of Colorado, *in* Kent, H.C., and Porter, K.W., Colorado Geology: Rocky Mountain Association of Geologists, 1980 Symposium, p. 225–236.

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.

Schwochow, S.D., 1981, Inventory of nonmetallic mining and processing operations in Colorado: Colorado Geological Survey Map Series 17, scale 1:250,000, 39 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., Hasler, J.W., and Earhart, R.L., 1990, Geologic map of stratabound exhalative and related occurrences in Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1971, scale 1:1,000,000.

Shettel, Jr., D.L., Langfeldt, S.L., Youngquist, C.A., D'Andrea, Jr., R.F., Zinkl, R.J., Bolivar, S.L., Garcia, S.R., George, W.E., and Hanks, D., 1981, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Denver NTMS quadrangle, Colorado: U.S. Department of Energy Open-File Report GJBX–263(81), 153 p., 17 plates.

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

Soulliere, S.J., Arnold, M.A., Hassemer, J.R., Martin, R.A., Kluender, S.E., and Zelten, J.E., 1986, Mineral resources of the Bull Gulch Wilderness Study Area, Eagle County, Colorado: U.S. Geological Survey Bulletin 1717–C, 12 p.

Soulliere, S.J., Arnold, M.A., Kluender, S.E., and Zelten, J.E., 1985a, Mineral resources of the Eagle Mountain Wilderness Study Area, Pitkin County, Colorado: U.S. Geological Survey Bulletin 1717–B, 9 p.

Soulliere, S.J., Arnold, M.A., Kluender, S.E., 1985b, Mineral resources of the Hack Lake Wilderness Study Area, Garfield County, Colorado: U.S. Geological Survey Bulletin 1717–A, 5 p.

Stein, H.J., 1985, A lead, strontium, and sulfur isotope study of Laramide-Tertiary intrusions and mineralization in the Colorado Mineral Belt with emphasis on Climax-type porphyry molybdenum systems plus a summary of other newly acquired isotopic and rare earth element data: Chapel Hill, University of North Carolina, Ph.D.dissertation, 500 p.

Streckeisen, A.L., chairman, and others, 1973, Plutonic rocks—classification and nomenclature recommended by the IUGS subcommission of the systematics of igneous rocks: Geotimes, v. 18, no. 10, p. 26–30.

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 1638, 42 p.

Theobald, P.K., Bielski, A.M., Eppinger, R.G., Moss, C.K., Kreidler, T.J., and Barton, H.N., 1983, 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 1:24,000.

Tschauder, R.J., and Landis, G.P., 1985, Late Paleozoic karst development and mineralization in central Colorado, *in* De Voto, R.H., ed., Sedimentology, Dolomitization, Karstification, and Mineralization of the Leadville Limestone (Mississippian), Central Colorado: Society for

Economic Paleontologists and Mineralogists, Guidebook no. 6, p. 79–91.

Tschauder, R.J., Landis, G.P., and Noyes, R.R., 1990, Paleozoic karst caves and mineralization in central Colorado: I. Geologic framework, mineralogy, and cave morphology, *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 no. 7, p. 308–338.

Tweto, Ogden, 1956, Geology of the Tennessee Pass Area, Eagle and Lake Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Field Studies Map MF–34, scale 1:14,400.

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

———1977, Tectonic history of west-central Colorado, *in* Veal, H.K., ed., Exploration Frontiers of the Central and Southern Rockies: Denver, Rocky Mountain Association of Geologists, Denver, p. 11–22.

———1980, Tectonic history of Colorado, *in* Kent, H.C., and Porter, K.W., eds., Colorado Geology: Denver, Rocky Mountain Association of Geologists, p. 5–9.

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 Lovering, T.A., 1977, Geology of the Minturn 15-minute quadrangle, Eagle and Summit Counties, Colorado: United States Geological Survey Professional Paper 956, 96 p.

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

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, 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 Map I–999, scale 1:250,000.

Tweto, Ogden, Steven, T.A., Hail, W.J., Jr., and Moench, R.H., 1976, Preliminary geologic map of the Montrose 1°×2° quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–761, scale 1:250,000.

U.S. Bureau of Mines, 1990, Mineral Commodity Summaries, 199 p.

———1992, Mineral Commodity Summaries, 204 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 Arkansas Valley and vicinity, Colorado: U.S. Geological Survey Open-File Report 78–112, scale 1:125,000.

———1979a, Aeromagnetic map of the Hunter-Fryingpan Wilderness Area, Colorado: U.S. Geological Survey Open-File Report 79–1226, scale 1:62,500.

———1979b, Aeromagnetic map of the Maroon Bells area, Colorado: U.S. Geological Survey Open-File Report 79–1449, scale 1:62,500.

———1982, Aeromagnetic map of the Buffalo Peaks area, Colorado: U.S. Geological Survey Open-File Report 82–978, scale 1:62,500.

———1990, Mineral Resources Data System [MRDS, formerly Computer Resources Information Bank, CRIB: active computer file; data available from U.S. Geological Survey, Branch of Resource Analysis, Building 25, Denver Federal Center, Denver, Colo. 80225].

U.S. Geological Survey and Colorado Geological Survey, 1977, Energy resources map of Colorado: U.S. Geological Survey Miscellaneous Investigations Map I–1039, scale 1:500,000.

Van Loenen, R.E., 1985, Geologic map of the Mount Massive Wilderness, Lake County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–1792–A, scale 1:50,000.

Van Loenen, R.E., Lee, G.K., Campbell, D.L., and Thompson, J.R., 1989, Mineral resource appraisal of the Mount Massive Wilderness, Lake County, Colorado: U.S. Geological Survey Bulletin 1636, 18 p.

Van Sant, J.N., 1959, Refractory-clay deposits of Colorado: U.S. Bureau of Mines Report of Investigations 5553, p. 120–135.

Vanderwilt, J.W., 1937, Geology and mineral deposits of the Snowmass Mountain area, Gunnison County, Colorado: U.S. Geological Survey Bulletin 884, 184 p.

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 No. 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.

Wallace, A.R., and Naeser, C.W., 1986, Laramide uplift of the northern Sawatch Range, Colorado [abs.]: Geological Society of America Abstracts with Programs, v. 18, p. 420.

Wallace, A.R., Lee, G.K., Campbell, D.L., Lundby, William, and Brown, S.D., 1989, Mineral resources of the Holy Cross Wilderness Area, Eagle, Pitkin, and Lake Counties, Colorado: U.S. Geological Survey Bulletin 1879, 22 p.

Wallace, Alan, Ludington, Steve, Lovering, T.G., Campbell, D.L., Case, J.E., Grauch, V.J.S., and Knepper, Dan, 1988, A mineral pre-assessment of the Leadville 1°×2° quadrangle, Colorado: U.S. Geological Survey Open-File Report 88–074, 57 p.

Wark, J.A., 1980, Development of a metallurgical limestone deposit, *in* Schwochow, S.D., ed., Proceedings of the Fifteenth Forum on Geology of Industrial Minerals: Colorado Geological Survey Resource Series 8, p. 53–62.

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

Weisner, R.C., and Bieniewski, C.L., 1984, Mineral investigation of the Maroon Bells–Snowmass Wilderness and three adjacent Wilderness Study Areas, Gunnison and Pitkin Counties, Colorado: U.S. Bureau of Mines Open-File Report MLA 23–84, 159 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.

Worl, R.G., Wilson, A.B., Smith, C.L., and Kleinkopf, M.D., 1989, Mineral resource potential and geology of the Challis National Forest, Idaho, *with a section on* Salable minerals, by R.C. Sykes: U.S. Geological Survey Bulletin 1873, 101 p.

Yeend, W.E., 1986 Descriptive 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.

APPENDIXES 1–4

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.

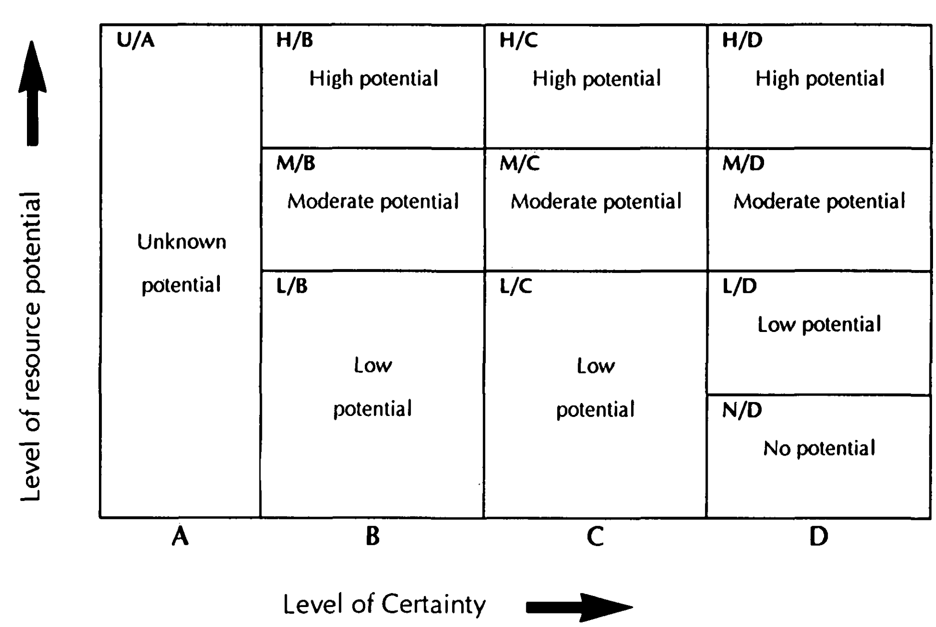
Abstracted with minor modifications from:

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, south-central Colorado, *with a section on* Salable minerals, by J.S. Dersch: U.S. Geological Survey Bulletin 1638, p. 40–42.

Levels of Certainty



APPENDIX 3. SIZE CLASSIFICATION OF DEPOSITS

Various sizes of deposits are discussed throughout the text of this report, and the table below lists the size classification used for various deposits (small, medium, large) for locatable commodities (A–N). The work by Cox and Singer (1986) contains graphs for most of the model types that show the proportion of deposits versus tonnage. The upper size limit for small deposits was taken from the 90th percentile, and the upper limit for medium deposits was taken from the 50th percentile. The 50th percentile was used in order to moderate the range in medium-size deposits. Some of these numbers were slightly modified to fit the range of known deposits in the Forest. Values for vein uranium, sandstone uranium-vanadium, stratabound massive sulfides, gypsum, and limestone are not included in Cox and Singer (1986) and were taken from Worl and others (1989) and DeWitt and others (1986).

[<, less than; >, greater than]

Type of deposit	Size of deposit (short tons)		
	Small	Medium	Large
A. Stockwork Mo	<50,000,000	50,000,000–220,000,000	>220,000,000
B. Stockwork Cu-Mo	<20,000,000	20,000,000–90,000,000	>90,000,000
C. Skarn	<35,000	35,000–600,000	>600,000
D. Polymetallic replacement	<250,000	250,000–2,000,000	>2,000,000
E. Sherman Pb-Zn-Ag	<2,400,000	2,400,000–40,000,000	>40,000,000
F. Polymetallic veins	<10,000	10,000–200,000	>200,000
G. Vein U	<5,000	5,000–100,000	>100,000
H. Vein W	<50,000	50,000–600,000	>600,000
I. Sandstone Cu	<1,500,000	1,500,000–25,000,000	>25,000,000
J. Sandstone U-V	<10,000	10,000–50,000	>50,000
K. Placer Au	<22,000	22,000–1,100,000	>1,100,000
L. Stratabound metals	<550,000	550,000–5,500,000	>5,000,000
M. Limestone	<100,000	100,000–10,000,000	>1,0000,000
N. Gypsum	<100,000	100,000–1,000,000	>1,000,000

APPENDIX 4. SORTED SIMULATION RESULTS FROM THE MARK3 COMPUTER PROGRAM

The following data are results from the MARK3 computer program, which uses the Monte Carlo method to simulate discoveries of 4,999 hypothetical "deposits" by random selection from a chosen model's grade and tonnage curves (curves are shown in Cox and Singer, 1986). The selected "deposits" have grades and total tonnes associated with them. The two factors are thus used to estimate tonnes of the metallic elements in the deposits. The 4,999 "deposits" are ranked according to size from smallest to largest, and the mean number of deposits and mean tonnages are calculated from that total. Once the "deposits" are ranked, the 1st deposit, 500th deposit, 1,000th deposit, etc., are printed in tables (included in this appendix). The deposit ranked 500th represents the 10th percentile (500/4,999) for speculative tonnes; the 2,500th "deposit" represents the 50th percentile for speculative tonnes; and the 4,500th "deposit" represents the 90th percentile for speculative tonnes.

The tables of frequency distributions below show the weighting of the number of "deposits" chosen for the 90th, 50th, and 10th percentile estimates. The numbers are produced by an estimate of numbers of undiscovered deposits at those confidence intervals.

Stockwork Molybdenum Deposits

[N, number of deposits; FREQ(N), number of random picks from the grade/tonnage curve for that percentile; PROB(N), conditional probability for the number of deposits; mean, mean tonnage. The total number of deposits selected always totals 4,999]

Percentile	Number of deposits
90th	0
50th	1
10th	1

N=0 FREQ(N)=1,478 PROB(N)=0.3
N=1 FREQ(N)=3,521 PROB(N)=0.7
Mean number of deposits=0.7

Rank	Mo (tonnes)	Total mineralized rock (tonnes)
1	0	0
500	0	0
1,000	0	0
1,500	16,000	10,000,000
2,000	100,000	57,000,000
2,500	230,000	130,000,000
3,000	360,000	200,000,000
3,500	530,000	270,000,000
4,000	770,000	430,000,000
4,500	1,200,000	620,000,000
4,999	4,400,000	1,100,000,000
Mean	430,000	220,000,000

Placer Gold Deposits

[N, number of deposits; FREQ(N), number of random picks from the grade/tonnage curve for that percentile; PROB(N), conditional probability for the number of deposits; mean, mean tonnage. The total number of deposits selected always totals 4,999]

Percentile	Number of deposits
90th	0
50th	1
10th	2

N=0 FREQ(N)=1,490 PROB(N)=0.3
N=1 FREQ(N)=2,016 PROB(N)=0.4
N=2 FREQ(N)=1,493 PROB(N)=0.3
Mean number of deposits=1.0

Rank	Au (troy oz)	Total mineralized rock (tonnes)
1	0	0
500	180	1,500
1,000	640	7,800
1,500	1,200	34,000
2,000	2,100	79,000
2,500	3,100	130,000
3,000	45,000	200,000
3,500	64,000	320,000
4,000	96,000	540,000
4,500	180,000	1,000,000
4,999	230,000	3,300,000
Mean	7,000	330,000

Polymetallic Vein Deposits

[N, number of deposits; FREQ(N), number of random picks from the grade/tonnage curve for that percentile; PROB(N), conditional probability for the number of deposits. The total number of deposits selected always totals 4,999]

Percentile	Number of deposits
90th	1
50th	3
10th	5

N=0	FREQ(N)=327	PROB(N)=0.06
N=1	FREQ(N)=650	PROB(N)=0.13
N=2	FREQ(N)=994	PROB(N)=0.20
N=3	FREQ(N)=1,063	PROB(N)=0.20
N=4	FREQ(N)=950	PROB(N)=0.20
N=5	FREQ(N)=1,015	PROB(N)=0.20

Mean number of deposits=2.9

Rank	Copper (tonnes)	Gold* (tonnes)	Zinc (tonnes)	Silver* (tonnes)	Lead (tonnes)	Total mineralized rock (tonnes)
1	0	0	0	0	0	0
500	0	0	0	0	0	0
1,000	0	0	0	0	0	0
1,500	0	0	0	0	0	0
2,000	0	0	2,900	0	12000	22,0000
2,500	0	0	14,000	59	29,000	6,200,000
3,000	360	0.11	45,000	130	58,000	1,200,000
3,500	1,500	0.49	110,000	260	110,000	2,400,000
4,000	56,000	1.4	240,000	660	220,000	4,500,000
4,500	21,000	4.6	620,000	2,100	510,000	12,000,000
4,999	1,400,000	770	10,000,000	55,000	11,000,000	66,000,000
Mean	9,800	3.1	250,000	810	220,000	4,100,000

* To convert to troy ounces, multiply values by 32,150.

Polymetallic Replacement Deposits

[N, number of deposits; FREQ(N), number of random picks from the grade/tonnage curve for that percentile; PROB(N), conditional probability for the number of deposits. The total number of deposits selected always totals 4,999]

Percentile	Number of deposits
90th	0
50th	1
10th	1

N=0 FREQ(N)=1,542 PROB(N)=0.30
N=1 FREQ(N)=3,457 PROB(N)=0.70
Mean number of deposits=0.7

Rank	Copper (tonnes)	Gold* (tonnes)	Zinc (tonnes)	Silver* (tonnes)	Lead (tonnes)	Total mineralized rock (tonnes)
1	0	0	0	0	0	0
500	0	0	0	0	0	0
1,000	0	0	0	0	0	0
1,500	0	0	0	0	0	0
2,000	0	0	2,900	0	12000	22,0000
2,500	0	0	14,000	59	29,000	6,200,000
3,000	360	0.11	45,000	130	58,000	1,200,000
3,500	1,500	0.49	110,000	260	110,000	2,400,000
4,000	56,000	1.4	240,000	660	220,000	4,500,000
4,500	21,000	4.6	620,000	2,100	510,000	12,000,000
4,999	1,400,000	770	10,000,000	55,000	11,000,000	66,000,000
Mean	9,800	3.1	250,000	810	220,000	4,100,000

* To convert to troy ounces, multiply values by 32,150.

Published in the Central Region, Denver, Colorado
Manuscript approved for publication May 12, 1992
Edited by Richard W. Scott, Jr.
Graphics by Bill Stephens, Branch of Central Mineral Resources
Type composed by Shelly A. Fields