An Assessment of the Mineral Resource Potential of the San Isabel National Forest, South–Central Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 1638

An Assessment of the Mineral Resource Potential of the San Isabel National Forest, South–Central Colorado

By Richard B. Taylor, Rebecca J. Stoneman, and
Sherman P. Marsh
U.S. Geological Survey

With a section on SALABLE MINERALS

By John S. Dersch
U.S. Forest Service

U.S. GEOLOGICAL SURVEY BULLETIN 1638

DEPARTMENT OF THE INTERIOR
WILLIAM P. CLARK, Secretary

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

UNITED STATES GOVERNMENT PRINTING OFFICE: 1984

For sale by the Superintendent of Documents
U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

PLATES

FIGURES

TABLES

An Assessment of the Mineral Resource Potential of the San Isabel National Forest, South-Central Colorado

By Richard B. Taylor, Rebecca J. Stoneman, *and* Sherman P. Marsh
U.S. Geological Survey
with a section on Salable minerals
By John S. Dersch, U.S. Forest Service

SUMMARY

This assessment of the mineral resource potential of the San Isabel National Forest, Colo., was made to assist the U.S. Forest Service in fulfilling requirements of Title 36, Chapter 2, Part 219.22, Code of Federal Regulations, and to supply resource information and interpretations so that the mineral resources of this forest can be considered with other resources in land use planning. Geologic, geochemical, and geophysical data were compiled at 1:250,000 scale, and all available published information on mineral deposits and occurrences was used in assessing the mineral resource potential of the forest, as of June 1984.

The mineral resource potential of some of the wilderness study areas in the forest has already been evaluated by the U.S. Geological Survey and the U.S. Bureau of Mines; published studies cover the Sangre de Cristo, Greenhorn, Spanish Peaks, and Buffalo Peaks Wilderness Study Areas.

The Colorado mineral belt, a concentration of mineral deposits and related intrusive igneous rocks, extends southward across the northern part of the forest. Mining and exploration are active. The famous Climax mine, a leading producer of molybdenum, is in the northern end of the forest; other mines produce silver, gold, lead, zinc, and copper. Limestone, gypsum, sand and gravel, and other nonmetallic commodities are also being mined. Active exploration programs by industry are seeking new deposits of base and precious metals, uranium, geothermal energy, and nonmetallic commodities. The San Isabel National Forest is endowed with a wealth of mineral resources, and mining has played a central role in the history of this area. Future economically important mineral production seems assured.

Character and Geologic Setting

The San Isabel National Forest contains 1,940 sq mi in the southern Rocky Mountains and includes parts of the Sawatch and Sangre de Cristo Ranges, the Wet Mountains, and the Spanish Peaks. It extends 160 mi south-southeast from north of Leadville to south of the Spanish Peaks. The rugged and mountainous terrain ranges in altitude from 14,433 ft at the top of Mt. Elbert, Colorado's highest mountain, to about 6,200 ft south of Canon City.

The rocks in the forest range in age from nearly 2 billion-year-old Precambrian gneisses to alluvial gravels still being deposited. The geologic record begins with Precambrian sedimentary and volcanic rocks deposited about 1,800 million years ago. These rocks were metamorphosed and intruded by large masses of granitic rocks about 1,700 million years ago and were again intruded by granitic rocks about 1,400 million years ago. No record remains of the succeeding 900 million years. In the lower Paleozoic, 525 to 320 million years ago, a sequence of laterally persistent limestone and sandstone beds was deposited in relatively shallow water in a stable marine environment. About 320 million years ago, active mountain building across the area formed the Ancestral Rockies, a series of block-faulted mountains and deep basins. Rocks deposited in these basins are made up of fine- to coarse-grained sediments which laterally vary greatly in composition, depending upon their position in the basins. A period of erosion created a surface of relatively gentle relief upon which sands and shales were deposited in early and middle Mesozoic time. The ocean transgressed the region in Cretaceous time and covered the area of the forest from about 100 million years ago until about 75 million years ago. Active mountain building, starting about 72 million years ago (the Laramide orogeny), raised the area above the sea and created mountains and deep bordering structural basins in South Park and in the Raton area. Igneous activity, both volcanic and intrusive, accompanied this period of mountain building. By about 40 million years ago, erosion had formed a broad surface of low relief across much of the area. Middle Tertiary volcanic eruptions formed many scattered clusters of volcanoes, and tuffs from calderas spread widely across the surface. Much of the area of the forest was covered by volcanic rocks of one sort or another. Block faulting related to a continental-scale structure, the Rio Grande rift, broke the area in later Tertiary time, down faulting the upper Arkansas Valley and the San Luis Valley and raising the Sawatch, Mosquito, and Sangre de Cristo Ranges, and the Wet Mountains. This period of faulting started about 25 million years ago and continues at the present. Glaciers shaped the mountains, starting about 1.5 million years ago; remnants of glaciers and rock glaciers (rock fragments cemented by ice that move like glaciers) are still active.

Mineral Resources

Mineral production began in the San Isabel National Forest about 1859, when placer gold was discovered in drainages tributary to the upper Arkansas River. The California and Iowa Gulch placers near Leadville brought gold seekers whose prospecting activities soon spread to nearby bedrock areas, and by the late 1800's most of the large mineralized districts had been found. The silver-bearing lead-zinc districts, such as Leadville and Monarch, became the principal producers after 1877 when smelters for lead carbonate ores were built. Although the Leadville district, Colorado's first true bonanza mining camp, dominated early mining history, the sustained yield of molybdenum from the Climax mine, in nearly continuous production since 1924, has been the most important economically in recent years. For nearly thirty years it produced the bulk of the world's molybdenum, and despite new finds elsewhere, it remains a major source.

Resource Potential—Locatable and Leasable Minerals

The assessment of mineral resource potential in this report is summarized in table 1, which lists the principal

Table 1. Summary of areas of high and moderate mineral resource potential

Commodity	Area of resource potential (square miles)		Deposit type[1]
	High	Moderate	
Metals (Ag,Au,Cu, Mo,Pb,U,Zn)------	252	383	1,3,4,5,6,7,8,10
Thorium------------	42	-	2
Uranium------------	22	1	9
Feldspar and pegmatite minerals--	26	10	11,12
Fluorspar----------	2	-	13
Limestone----------	34	3	14
Gypsum-------------	35	-	15
Geothermal energy--	8	-	16
Coal---------------	30	-	17

[1]Numbers are keyed to list that follows immediately.

locatable and leasable commodities, gives the total area having high resource potential or moderate resource potential for each commodity, and indicates the kind of deposit expected. Figure 1 shows areas of high and moderate mineral resource potential for locatable minerals; figure 2 shows areas of high and moderate resource potential for leasable minerals.

Principal Types of Deposits

1. Precambrian, volcanic-related, stratabound deposits; deposited on a sea floor about 1,800 million years ago; principally contain copper and zinc or tungsten and copper. The principal areas of resource potential make up an east-west belt 10 mi wide crossing the Arkansas Valley in the vicinity of Salida.

2. Cambrian vein deposits; related to igneous intrusions emplaced about 515 million years ago; principally valuable for thorium, but also contain minor amounts of rare-earth elements. Fringes of a large mineralized area that has high resource potential—the Wet Mountains thorium district—extend into the western part of the Wet Mountains portion of the forest.

3. Sediment-hosted stratabound and fissure-filling deposits; formed in "red bed" sandstone and mudstone; deposited about 300 million years ago while the Ancestral Rockies were forming; principally contain copper and uranium. The main area of high resource potential extends northward from Salida within the eastern part of the forest.

4. Skarn deposits; formed at the contacts between intrusive igneous rocks and reactive host rocks; contain iron, copper, and other metals. The main area of high resource potential is northeast of Salida where a large mass of intrusive igneous rock of Cretaceous age cuts Paleozoic sedimentary rocks.

5. Porphyry-type stockwork deposits; formed in the upper parts of granitic masses of moderate size; contain molybdenum, copper, and other commodities (tungsten, rare-earth elements, topaz, fluorite) in lesser amounts. The major areas of high potential are in the northwestern part of the forest in the Sawatch Range.

6. Disseminated and stockwork deposits; formed in structurally favorable parts of large plutons; contain molybdenum and copper and other commodities. The major areas of high potential are in the northwestern part of the forest in the Sawatch Range.

7. Replacement deposits in Paleozoic rocks; formed by hydrothermal solutions reacting with limestone and dolomite; contain silver, gold, and base metals. The principal areas of high resource potential include the margins of the Leadville mining district in the Mosquito Range and rocks near Monarch Pass in the Sawatch Range west of Salida.

8. Vein deposits; formed in fissures and fractures in siliceous host rocks; contain gold, silver, and base metals, with minor amounts of uranium. The principal areas of high resource potential are associated with granitic rocks intruded 75 to 25 million years ago in the northern part of the forest.

9. Sandstone-hosted deposits; formed in sandstone and other sedimentary rocks from percolating solutions; principally valuable for uranium and vanadium, but may also contain small amounts of metals such as silver and selenium. The principal favorable areas follow paleovalleys crossing the forest east of the Arkansas Valley between Buena Vista and Salida; another is located on the southwestern slope of the Wet Mountains.

10. Placer deposits; deposited by streams that traversed gold-bearing bedrock areas; principally valuable for gold. The principal areas of past production are in the northern part of the forest in reaches of the streams between the steep mountain fronts and the flood plains flanking the Arkansas River.

11. Pegmatite deposits; feldspar and rare minerals such as beryl crystallized within Precambrian pegmatites; these minerals formed from small masses of volatile-rich magma that crystallized slowly, which allowed individual crystals to reach large size. The principal pegmatite area in the forest is east of Buena Vista.

12. Pegmatite deposits; rare minerals such as beryl (aquamarine) and phenakite formed in pegmatite in large Tertiary igneous masses. The area of high resource potential is in the Sawatch Range, northwest of Salida, on the western side of Mount Antero.

13. Fluorspar formed in veins and mineralized fractures; associated with relatively young hot spring systems fed by deeply circulating ground water. Parts of the Poncha Springs fluorspar district extend into the forest south of Salida.

14. Limestone and dolomite; pure beds of calcite or dolomite make up parts of the Paleozoic sedimentary section. The principal areas of high resource potential for these commodities are in the southern Sawatch Range west of Salida, where mining is currently active (1984), and in a belt through the northern part of the Sangre de Cristo Range and extending northward across the Arkansas River.

15. Gypsum; beds of gypsum make up parts of the Paleozoic sedimentary section. The principal area of high resource potential extends northward from Salida in the eastern part of the forest.

16. Geothermal energy; manifested by natural hot waters and steam. The principal areas of high resource potential extend along the west margin of the upper Arkansas Valley near Buena Vista.

17. Coal deposits; formed from sedimentary accumulations of organic materials. In the forest, coal re-

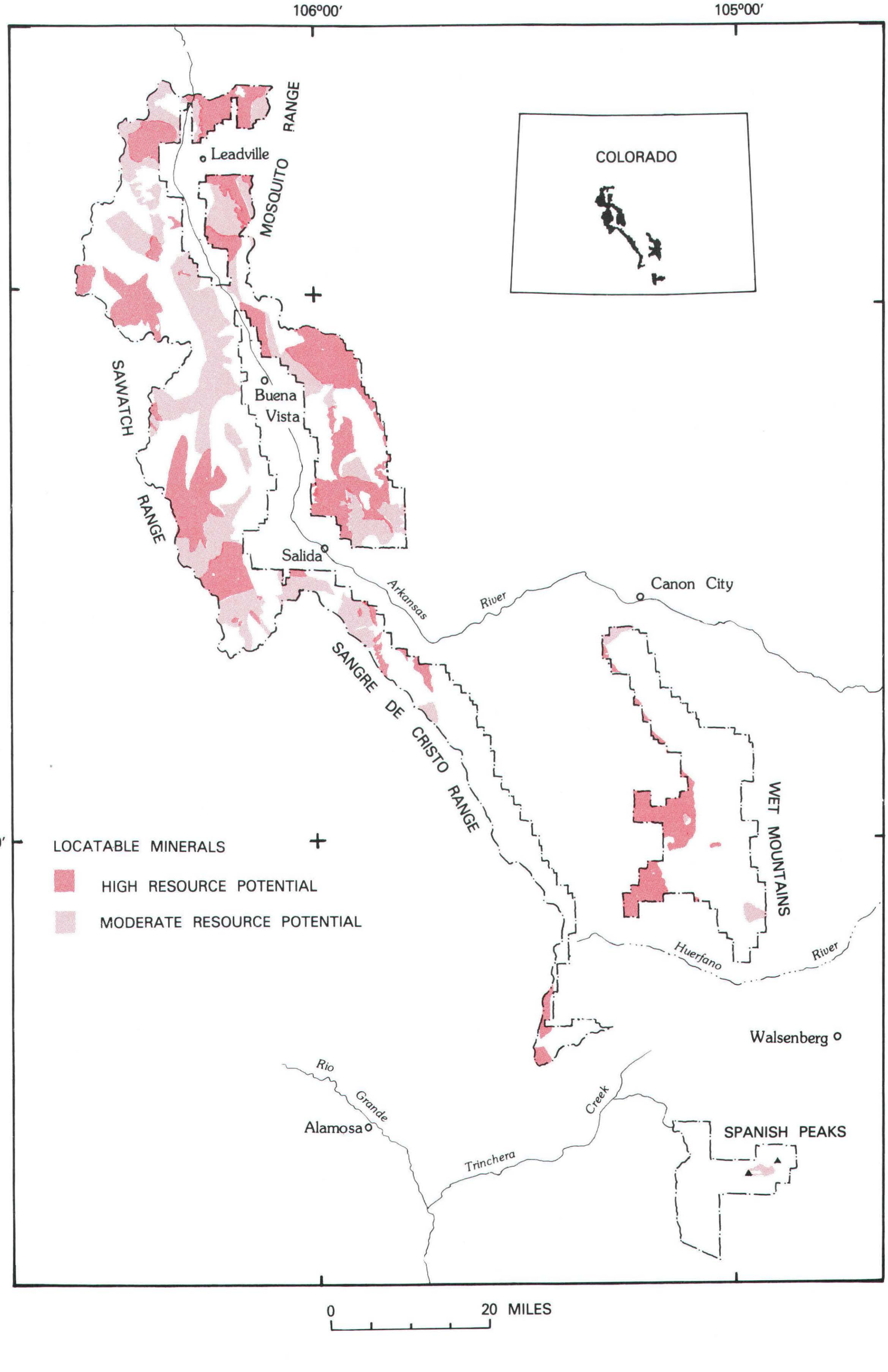


Figure 1. Map showing resource potential for locatable minerals, San Isabel National Forest, Colo.

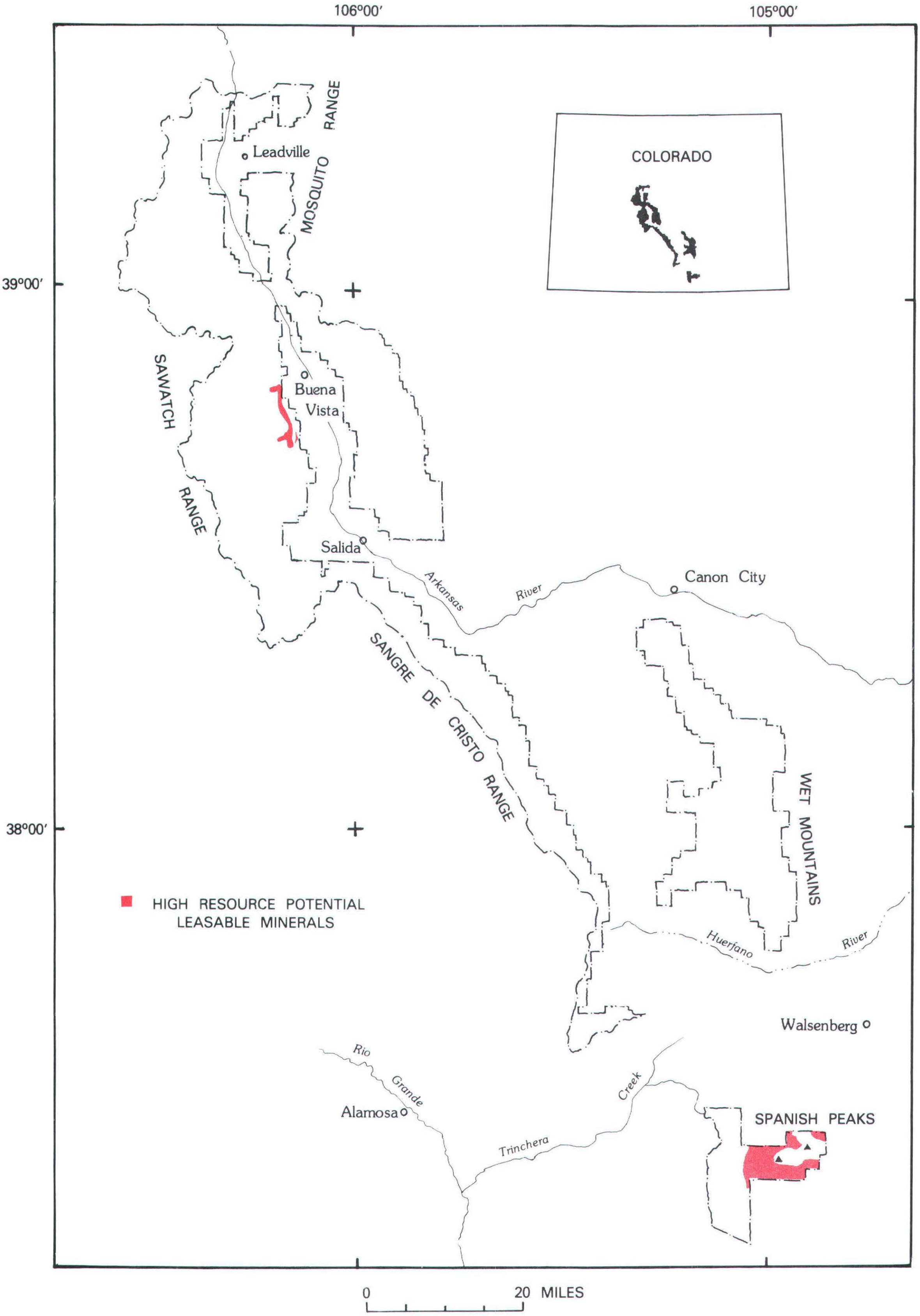


Figure 2. Map showing resource potential for leasable minerals, San Isabel National Forest, Colo.

sources are restricted to parts of the Cretaceous sequence near the Spanish Peaks.

Resource Potential—Salable Minerals

Sand and gravel adequate for construction needs are available in almost all parts of the forest. Areas of high potential for sand and gravel shown on figure 3 are only the Pleistocene and Holocene glacial and alluvial deposits that could be shown at 1:250,000 scale (pl. 1). Local needs can also be met from deposits of these materials too small to be shown here, both from alluvial deposits and from bedrock units such as limestone, which can supply special aggregates as needed.

Deposits of clay suitable for refractory brick are limited within the forest to the eastern edge of the Wet Mountains; much larger deposits are found in adjacent areas outside the forest.

Suggestions for Further Work

The long history of mining in the San Isabel National Forest has focused geologic attention on this area since its bonanza days late in the 19th century. Certain information is yet needed for resource assessment. Detailed geologic mapping of the gneissic rocks and of parts of the Sawatch Range is required to better understand the resource potential of the Precambrian rocks and of the hydrothermal systems inside and outside the major Cretaceous and Tertiary intrusive igneous rock masses. These studies should be augmented with geochemical surveys that would supply analytical data on rocks and on the heavy (panned-concentrate) fractions of stream-sediment samples. The available information on stream-sediment chemistry should be supplemented with reliable analyses for elements such as gold, silver, zinc, mercury, arsenic, and molybdenum. Additional geophysical surveys are needed; detailed aeromagnetic maps would assist in outlining buried plutons and large hydrothermally altered areas. A detailed radiometric study (potassium, uranium, and thorium) of the Sawatch Range would especially assist evaluation of the potential for concealed stockwork deposits of copper and molybdenum suggested as likely in this report.

INTRODUCTION

This report and accompanying maps present an assessment of the mineral resource potential of the San Isabel National Forest, Colo., based on information available as of June 1984. This forest contains 1,940 sq mi (1,241,450 acres) of rugged, mountainous terrain bounded by the Continental Divide on the west and stretching south-southeast a distance of 160 mi from north of the famous mining districts of Climax and Leadville to south of the Spanish Peaks (fig. 4). This assessment was undertaken to assist the U.S. Forest Service in fulfilling the requirements of the Code of Federal Regulations (36 CFR 219.22) to supply information and interpretations needed so that the mineral resources of this area can be considered along with other kinds of resources in land use planning. This assessment of the mineral resource potential of the San Isabel National Forest is a pilot study, one undertaken to establish feasibility and methodology for future studies of other forests.

The first step in analyzing the mineral resource potential (definitions of terms used are provided in Appendix 1) was compilation of a geologic map (pl. 1) at a scale of 1:250,000, using the best available geologic mapping at any scale. Magnetic and gravity data from several geophysical surveys were assembled and brought to this same map scale, but lack of time precluded merging and recontouring the data. Geochemical data from studies ranging in scale of reporting from 1:50,000 to 1:250,000 were also brought together for analysis at 1:250,000 scale but were not assembled into a coherent data set. The different sampling plans, sample media, and analytical procedures used in the several geochemical surveys preclude integration of these data. The most valuable geochemical data available were the analyses of stream-sediment and panned-concentrate samples from studies of the Spanish Peaks, Greenhorn, Buffalo Peaks, and Sangre de Cristo Wilderness Study Areas obtained through the U.S. Geological Survey (USGS) and unpublished USGS data from the Pueblo 1°×2° topographic quadrangle. The only geochemical data covering the entire area of the forest came from the U.S. Department of Energy NURE (National Uranium Resource Evaluation) studies of the Montrose, Leadville, Pueblo, and Trinidad 1°×2° topographic quadrangles (see Appendix 2). Information on mines, prospects, and resources from the USGS Mineral Resource Data System and from the U.S. Bureau of Mines MILS system was examined and assembled. Mine and prospect locations from 1:24,000-scale topographic maps were plotted at 1:250,000 scale. Using information on known deposits in and near the area and published descriptions of deposit types, we analyzed the assembled data according to standard procedures (Shawe, 1981).

This study relies primarily on information from published literature and from reports "in press" at the time of preparation. Personal experience gained by the authors during prior field work in the area helped greatly in interpreting the assembled data. In addition, many other geologists with the USGS were consulted, and their help is gratefully acknowledged. Lacking the opportunity for new field studies, we did not fill gaps in knowledge nor did we reconcile discrepancies between geologic,

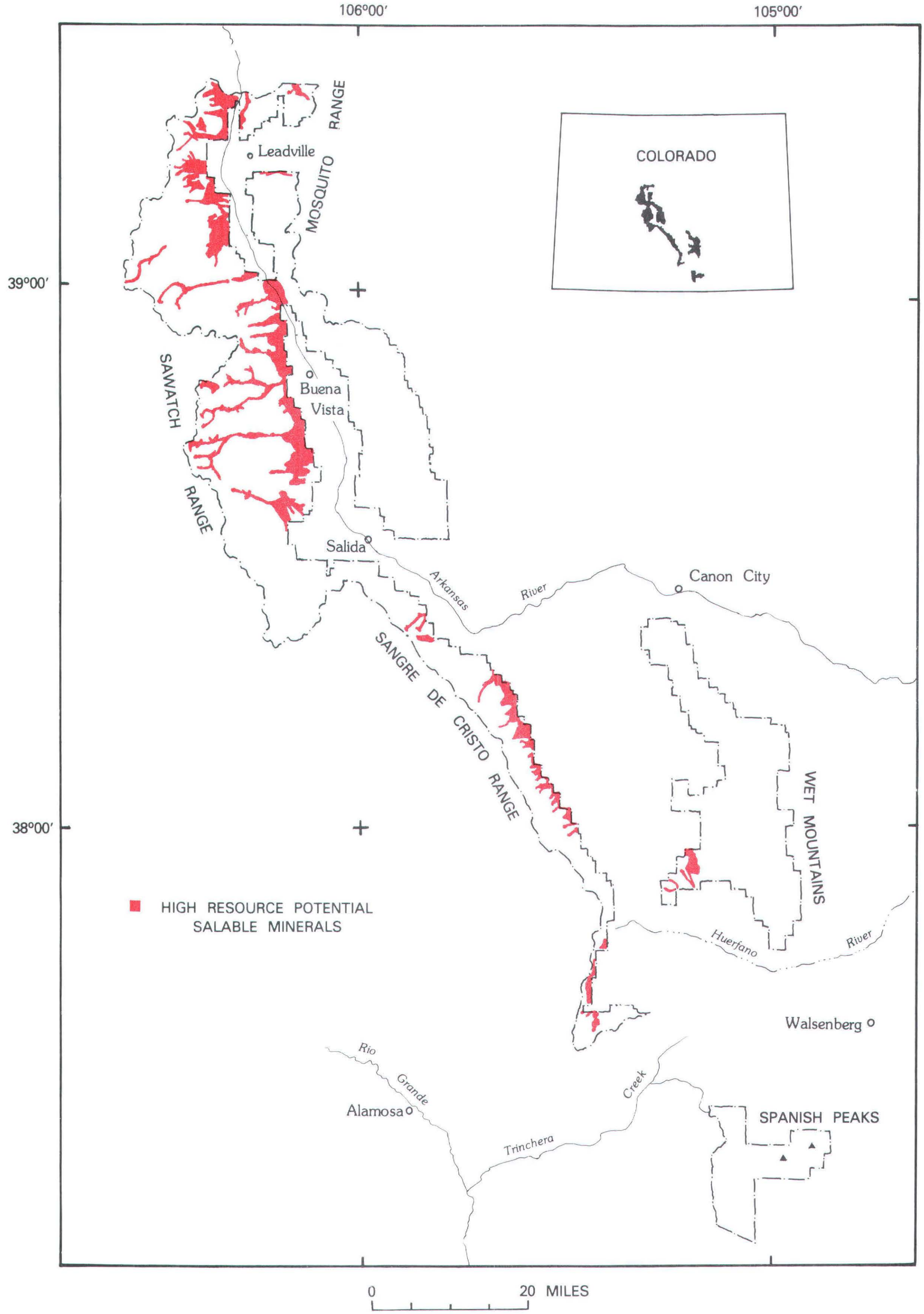


Figure 3. Map showing resource potential for salable minerals, San Isabel National Forest, Colo.

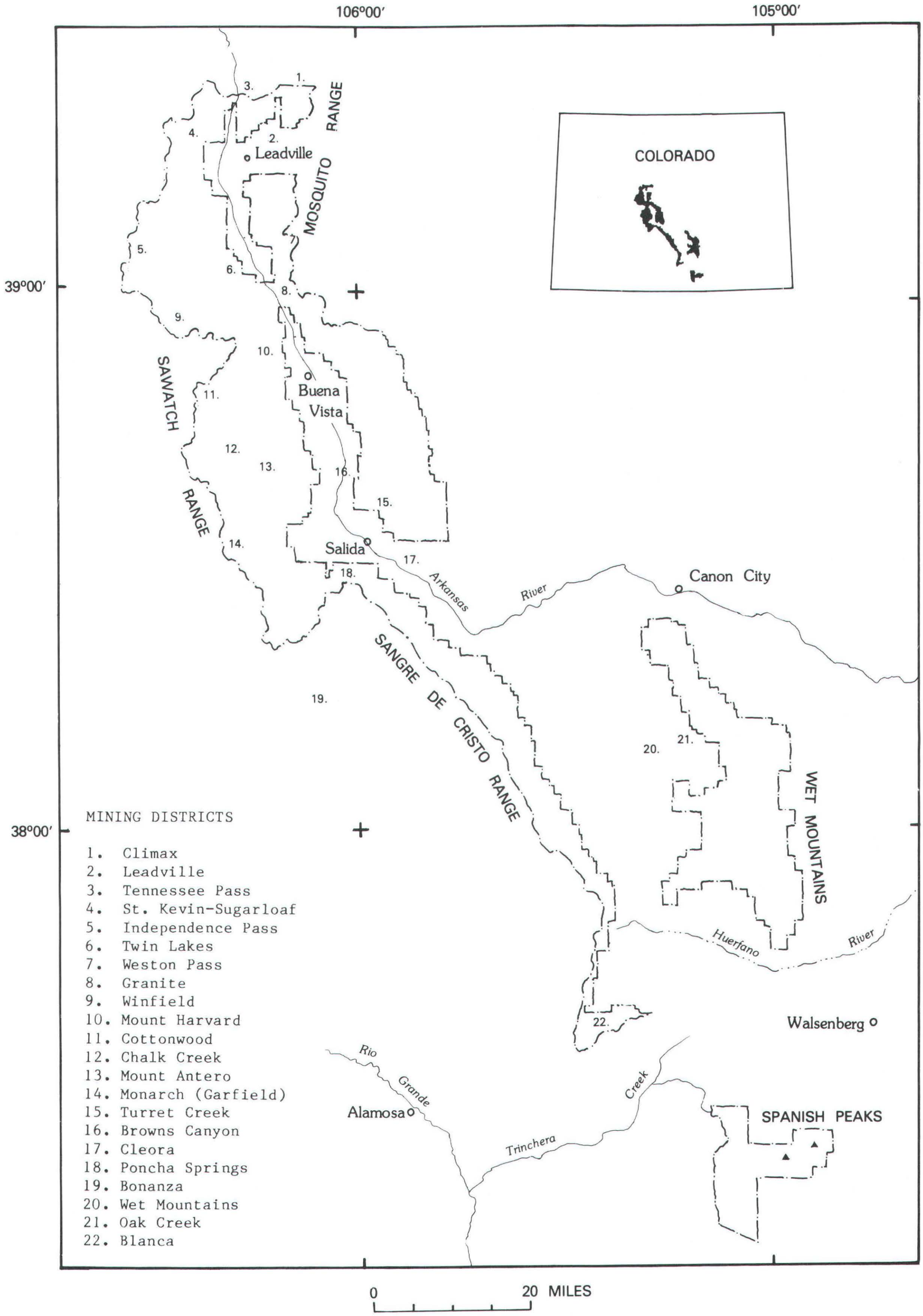


Figure 4. Index map showing location of the San Isabel National Forest and principal mining districts in, or extending into, the forest.

geochemical, and geophysical surveys of different parts of the area. 1:500,000-scale geologic, aeromagnetic, and gravity maps of Colorado provided a synoptic framework within which more detailed studies of small areas were interpreted.

Although this report is drawn chiefly from previously published information, specific references have been kept to a minimum to avoid excessive interference with the continuity of the text. Where possible, general references (such as volumes of collected papers) are cited, rather than each of the many contained titles. The reference list is divided into three sections—geology and mineral resources, geochemistry, and geophysics—to make evident the nature of published reports from the separate disciplines. Recommendations for further studies indicate data needed for more adequate assessment of parts of the forest.

GEOLOGY

The San Isabel National Forest (referred to as "the forest" in this report) includes the eastern Sawatch Range, parts of the Mosquito Range, the Sangre de Cristo Range, the southern Wet Mountains, and the Spanish Peaks, all elements of the southern Rocky Mountains. It surrounds the upper Arkansas Valley. The forest is characterized by rugged mountains rising above glaciated valleys and by altitudes ranging from 14,433 ft at the top of Mt. Elbert, Colorado's highest mountain, to 6,200 ft at the foot of the Wet Mountains south of Canon City. The rocks range from gneiss nearly 2 billion years old to alluvial gravel still being deposited by modern streams. The mountains have been shaped by fluvial and glacial processes, and much of the physiography resulted from tectonism during the past 25 million years. Fault scarps cutting Quaternary and Holocene deposits show that parts of this area are still tectonically active.

Geologic Framework

The oldest rocks in the San Isabel National Forest were formed by volcanic activity and sedimentation in Early Proterozoic time, about 1,800 million years ago. These rocks were intensely deformed and regionally metamorphosed, intruded by plutonic rocks about 1,700 million years ago, and again intruded by plutonic rocks about 1,400 million years ago. The Paleozoic sedimentary rocks of Cambrian through Mississippian age were deposited in a marine, stable-shelf environment; sedimentation was interrupted episodically by epeirogeny and erosion. Block faulting in Pennsylvanian time formed major uplifts, known as the Ancestral Rockies, separated by basins forming parts of the central Colorado trough, which received marine and continental clastic sediments. The Ancestral Rockies were reduced to a low plain by middle Mesozoic time, and the area of the forest was covered by sediments. A major seaway covered the area in Cretaceous time, and thick sections of marine shale were deposited. Late in the Cretaceous during the final regression of the seas from this area, the Laramide orogeny began. This orogenic period lasted into the Eocene and created mountain uplifts bordered by structural and topographic basins. The principal uplifts formed near the sites of the modern Sawatch, Mosquito, and Sangre de Cristo Ranges, and the Wet Mountains; major downwarps formed the South Park and Raton basins. Igneous activity accompanying the tectonism formed numerous small, hypabyssal masses in the Leadville area, a batholith southeast of Twin Lakes Reservoir, and a stock that has laccolithic margins northeast of Salida. By the end of the Eocene, a large part of the area was eroded to a surface of gentle relief, but mountain masses rose from this surface in the northern part of the forest. A period of volcanism began in Oligocene time and lasted into the Miocene. Great ashflow eruptions came from calderas in the Sawatch Range, including the Grizzly Peak and Mount Princeton calderas, and spread blankets of tuff eastward across the forest. Concurrently, active volcanoes and volcano clusters formed across the area. Block faulting began in the Miocene and has continued into Holocene time, breaking the continuity of the Eocene erosion surface and shaping modern topographic features. The upper Arkansas Valley segment of the Rio Grande Rift system formed at this time. The mountains were sculpted by glaciers and by high-gradient streams, and alluvial materials were deposited in nearby valleys to create the present landscape of the forest.

The structural grain of the area was established in Precambrian time; the faulting that formed the Ancestral Rockies, the Laramide uplifts, and the existing (Neogene) mountains follow in large part the fault and shear systems first active in the Precambrian.

Precambrian Rocks and Structures

The Precambrian rocks of the San Isabel National Forest include the Early Proterozoic gneiss complex—rocks metamorphosed from a pre-1,700 m.y. assemblage of sedimentary, volcanic, and intrusive igneous rocks—and granitic rocks of the Routt and Berthoud Plutonic Suites. The Routt Plutonic Suite includes 1,650–1,730 m.y. old igneous rocks such as the Boulder Creek Granodiorite, and the Berthoud Plutonic Suite includes 1,350–1,400 m.y. old igneous rocks such as the Silver Plume and San Isabel Granites. Descriptions of some of these rocks and isotopic dates for some are given by Peterman and others (1968) and Tweto (1977).

Early Proterozoic Gneiss Complex

The Early Proterozoic gneiss complex consists principally of gneiss formed by high-grade regional metamorphism of interbedded shale, impure sandstone, basaltic to rhyolitic volcanic rocks, and intrusive masses related to the volcanic rocks. The complex consists of various kinds of gneiss, in the main biotite-quartz-plagioclase gneiss, biotite-hornblende-plagioclase gneiss, amphibolite, and biotite-quartz-plagioclase-microcline gneiss, but also includes minor quantities of calc-silicate gneiss, impure marble, and quartzite. Locally the rocks contain garnet, pyroxene, cordierite, pyrite, or other metamorphic minerals in minor amounts. All of the rocks belong to the amphibolite facies of regional metamorphism, and in much of the area they contain sillimanite and (or) other minerals indicative of the highest metamorphic grade in this facies. In much of the forest the rocks were highly deformed, folded, and contorted during regional metamorphism. In the northern Sangre de Cristo Range and the southern Sawatch Range, the rocks have a slightly lower metamorphic grade and their degree of deformation is much less; primary structures preserved in these gneiss units indicate sedimentary and volcanic protoliths.

Routt Plutonic Suite

The plutonic rocks of the Routt Plutonic Suite range in composition from gabbro to granite, but most are calc-alkaline granodiorite and quartz monzonite. These rocks were emplaced late in the principal period of regional metamorphism, during the last period of regional-scale folding that accompanied this metamorphism. The rocks are generally foliated, and some are greatly deformed. The small masses and parts of the contact zones of the large plutons conform to the structure of the enclosing gneiss. The outer parts of the large plutons are commonly more deformed than the inner, and some foliate structures differ from primary igneous flow features, indicating a post-emplacement origin for much of the foliation.

Berthoud Plutonic Suite

The rocks of the Berthoud Plutonic Suite are predominantly quartz monzonite and granite. The rocks were emplaced after the main period of regional metamorphism and folding, although locally emplacement was accompanied by plastic folding of the gneissic rocks and by cataclasis. The most abundant rock type is peraluminous two-mica quartz monzonite or granite of moderate grain size, resembling the Silver Plume Granite of the central Front Range. This rock has little foliate structure except for primary flow structures recognizable by parallel orientation of tabular feldspar (both microcline and plagioclase) crystals. A second major rock type constitutes the San Isabel pluton in the southern Wet Mountains. This pluton is composed of several intrusive phases ranging from coarse-grained quartz monzonite to fine-grained rocks having aplitic textures. The rocks are little foliated and are massive in appearance, except at the eastern border of the pluton where they contain abundant inclusions of well-foliated gneisses of varying composition.

Precambrian Structure

The layered rocks of the Early Proterozoic gneiss complex were probably folded and faulted to some extent before metamorphism, but these early structural events have been obscured by the deformation accompanying regional metamorphism. The gneisses were intensely folded in many areas, and isoclinally in some, during this period of metamorphism and plastic folding. In the southern part of the area, north-northwest-trending faulting began late in this period, but before emplacement of the younger plutons of the Routt Plutonic Suite. Northeast-trending cataclastic shear zones in the northern part of the forest west of Leadville formed while plutons of the Berthoud Plutonic Suite were being emplaced. Other major fault systems formed later in the Precambrian. Some of these are north-northwest-trending zones of major strike-slip displacement. The faults and shear zones that formed in the Precambrian have reactivated many times since then and have localized many younger tectonic features.

Paleozoic Rocks and Structures

Sedimentary rocks ranging in age from Late Cambrian through Mississippian were deposited in a stable environment on a surface of low relief cut in Precambrian rocks. Deposition of marine clastic and carbonate rocks was interrupted by episodic emergence as reflected by unconformities and local channels. The principal Paleozoic sedimentary rock units in the forest are, from oldest to youngest, the Upper Cambrian Sawatch Sandstone and Peerless Formation (dolomitic sandstone and shale); the Ordovician Manitou Limestone (or Dolomite), Harding Sandstone, and Fremont Limestone; the Devonian Parting Formation (sandstone, limestone, and shale) and Devonian and Mississippian(?) Dyer Dolomite and Gilman Sandstone; and the Mississippian Leadville Limestone.

Sedimentary rocks of Pennsylvanian age were deposited during active block faulting, which formed the deep basins and high intervening ranges of the Ancestral Rocky Mountains. Structural relief may have been as much as 10,000 ft. The sedimentary rocks deposited in this environment are characterized by rapid lateral and vertical changes in lithology and variations in thickness. The principal Pennsylvanian units of the forest are, from oldest to youngest, the Belden Formation (dark-gray marine shale and interbedded mudstone and arkosic sandstone), the Minturn Formation (gray marine sandstone, shale, conglomerate, and evaporite beds in a sub-basin southwest of South Park), and the lower part of the Sangre de Cristo Formation (red and green sandstone, shale, and conglomerate).

Sedimentary rocks of Permian age in the forest were deposited in parts of fault-block basins of Pennsylvanian ancestry. The Permian part of the Sangre de Cristo Formation—and particularly the uppermost part, the Crestone Conglomerate Member (Munger, 1965)—contains boulder conglomerate and sandstone of alluvial and debris-flow origin in an area of great topographic relief.

Mesozoic Rocks and Structures

The Jurassic is principally represented in the forest by the Morrison Formation, composed of alternating, variegated mudstone and sandstone deposited in fluviatile and flood-plain environments across a surface of generally gentle relief, with local mountains standing above it. The lengthy period of erosion between the end of Permian deposition in this area and the beginning of Jurassic deposition was a time of tectonic quiescence.

The Cretaceous rocks of the forest record the transgression and regression of the sea. The Purgatoire Formation and Dakota Sandstone, at the base of the Cretaceous section, were deposited in fluviatile, deltaic, and coastal-plain environments; succeeding marine deposition is represented by the Graneros Shale, the Greenhorn Limestone, the Carlile Shale, the Niobrara Formation (calcareous shale and limestone of the Colorado Group), and the Pierre Shale. The succeeding Trinidad Sandstone is a delta-front deposit. The final regression of the sea from the area took place in the Late Cretaceous when the Vermejo Formation (sandstone, shale, and coal beds) was deposited on a delta plain marginal to the sea. The overlying Cretaceous and Paleocene Raton Formation (conglomerate, sandstone, shale, and coal beds) is regarded as a swamp and flood-plain deposit. The Trinidad, Vermejo, and Raton Formations are found near the Spanish Peaks and were deposited in a structural sag named the Raton Basin. The Laramide orogeny began during this Cretaceous marine regression and continued into the Eocene.

Igneous activity began early in the Laramide orogeny, about 72 million years ago, in the Late Cretaceous, and continued until about 50 million years ago, in Eocene time. It was concentrated in a northeast-trending belt that extends across Colorado from the State's southwest corner to the mountain front near Boulder. Laramide igneous rocks are abundant in the northern part of the forest near Leadville; they also make up the Whitehorn stock (71 m.y.), northeast of Salida, and the Twin Lakes batholith, southeast of Independence Pass. The early Laramide igneous rocks are only a little older than nearby marine Cretaceous rocks. Some of these Laramide intrusions fed volcanoes that provided volcanic detritus to the coeval sedimentary rocks deposited in nearby basins.

The broad anticline encompassing the modern Sawatch and Mosquito Ranges formed a little more than 70 m.y. ago, and there was probably a similar, if smaller, anticlinal uplift along the Wet Mountains, continuing south of the modern mountain block along the Greenhorn anticline. Another regional Laramide structural element forms a northwest-trending belt of thrust faults stretching from the Sangre de Cristo Range, just west of the Spanish Peaks, northward through the forest to the central Sawatch Range, near Tincup Pass. Geologists mapping this area have not traced these faults in detail, nor have they worked out the relationships between the thrusts and younger high-angle faults.

Tertiary Rocks and Structures

In the vicinity of the Spanish Peaks, fluvial sediments comprising lower Tertiary rock units were shed from highlands to the west and north and were deposited in the northern part of the Raton Basin. These units include the Paleocene Poison Canyon Formation (conglomerate, sandstone, and shale; to the south includes beds of Cretaceous age) and the Eocene Huerfano, Cuchara, and Farisita Formations. The Huerfano, Cuchara, and Farisita are partial lateral equivalents that are characterized by differences related to provenance of the sediments. They do not appear to be successive elements of a Tertiary basin fill. The Huerfano largely came from a western source, with a large contribution from Pennsylvanian-Permian clastic rocks. The Farisita reflects its eastern source in the Precambrian rocks of the Wet Mountains. The Cuchara seems to be made up of interlayered and intertonguing sediments from both eastern and western sources.

In the remainder of the forest, the earliest Tertiary sedimentary rocks are the channel-fill deposits of the Echo Park Alluvium of late Eocene age. By this time, erosion under conditions of tectonic stability had cut a broad piedmont plain, called the late Eocene surface. Alluvial materials were deposited along broad shallow channels cut into this surface that transgressed a great variety of older rocks. This surface was surmounted by mountains in the Sawatch Range and northern Mosquito Range.

Most of the forest was covered by the middle Tertiary volcanic field that developed after the end of the Laramide orogeny. Igneous activity started in latest Eocene time (about 40 m.y. ago) and persisted into early Miocene time (until about 20 m.y. ago). Volcanic rocks covered the late Eocene erosion surface. Important features in the forest include the eastern edge of the Grizzly Peak caldera, the volcanic-plutonic complex marked by the Mount Princeton batholith, the northern part of the Bonanza volcanic center, stocks in the Sangre de Cristo Range south of Hayden Pass and in the Wet Mountains east of Deer Peak, and the intrusive masses and swarms of dikes of the Spanish Peaks. Outflow from the igneous centers covered much of the area. An early major ash flow, the Wall Mountain Tuff (35–36 m.y. age), spread across the late Eocene surface from a source in the southern Sawatch Range eastward beyond the limits of the modern Front Range. Other volcanic and clastic rock units accumulated in Oligocene basins and paleochannels; the thickest unit in the forest is the Oligocene Antero Formation, consisting of fluvial and lake beds largely made up of andesitic and rhyolitic volcanic ash.

The middle Tertiary intrusive rocks in the Sawatch Range represent plutonic parts of a major volcanic system. The Mount Princeton batholith, north of Monarch Pass, is an almost circular mass about 14 mi in diameter that occupies the only possible position for the major caldera that must have been the source for the Wall Mountain Tuff and other major ash-flow sheets to the east.

Extensional tectonism, beginning about 27 m.y. ago, disrupted the Oligocene volcanic field by block faulting; the major trough caused by this tectonism is the Rio Grande rift (or depression), which includes the upper Arkansas Valley between Salida and Leadville, and the structurally continuous San Luis Valley to the south. Other basins formed at this time are the Wet Mountain Valley and Huerfano Park. Uplifts include the Sawatch Range, the Mosquito Range, and the Sangre de Cristo Range. Rifting was accompanied by basaltic volcanism, perhaps represented in the forest by flows north of Cameron Mountain. Pulses of tectonic activity took place in the late Oligocene and in the latest Miocene or early Pliocene; active tectonism still persists.

The block fault basins that formed in Miocene time received sediments from the adjoining highlands. Lower Miocene through Pliocene alluvial-fan deposits, stream and lake deposits, and volcanic ash form valley fills that may be as much as 4,000 ft thick in the deep parts of the basins, as near Salida. Thinner deposits covered channelled intermontane surfaces. Several names have been applied to these deposits: in the mountains north of the Arkansas River they have been called the Wagontongue Formation; in the upper Arkansas Valley, the Dry Union Formation; and in the Wet Mountain Valley, the Santa Fe Formation.

Quaternary Rocks and Structures

Pleistocene and Holocene alpine glacial till, glaciofluvial sand and gravel, and alluvial deposits record the glaciation that affected considerable areas of the forest. The central parts of the high ranges were extensively glaciated, and ice flowed down major valleys in the Sangre de Cristo, Mosquito, and Sawatch Ranges.

Pediment surfaces of several ages in the upper Arkansas Valley, Wet Mountain Valley, and Huerfano Park record stages in the lowering of the erosional base level during Pleistocene and Holocene time. Surficial processes are still forming unconsolidated deposits, including rock glaciers, landslides, and alluvium and colluvium.

Periodic minor earthquakes and fault scarps in glacial moraines, alluvial fans, and pediment gravels indicate that faults are still active in this area.

MINERAL RESOURCES—LOCATABLE MINERALS

Locatable minerals include all minerals subject to exploration, development, and production under the Federal General Mining Law of 1872. Most metals and industrial minerals are included in this group and are considered in this section.

Mining and Exploration History

Prospecting began in Colorado on the eastern slope of the Rocky Mountains in 1858, and activity spread westward across the state in the following year. Placer mining began along the Arkansas River in 1859, but the focus of activity shifted to the California Gulch placers (pl. 1) near Leadville, in the northern part of the San Isabel National Forest, in either 1859 or 1860. The placers of California and Iowa Gulches were active until 1886. Gold lodes were found in 1868 in the Leadville district. Major interest shifted from gold to silver with the construction of the first smelter in 1877. The silver came from silver-bearing lead carbonate ore bodies formed by supergene oxidation of primary-sulfide replacement masses. Zinc became the principal commodity mined after 1903 when large, mixed-sulfide (sphalerite, galena, and pyrite) replacement ore bodies were developed. Most of the mines at Leadville closed by 1957, although a few are still actively producing silver, zinc, and other metals.

The Chalk Creek district was discovered in the late 1860's, and subsequently has yielded more than 220,000 oz of gold, in addition to large amounts of silver, lead, and zinc, and some copper. The district's biggest producer, the Mary Murphy mine, was in nearly continuous operation from 1870 to 1925 and has been operated episodically since then. The gold came from pyritic quartz veins that were worked through a vertical range of about 2,200 ft.

The Monarch District was discovered in 1878 and exploited rich oxidized ores from 1883 to 1893 when the price of silver dropped and the district was almost abandoned. The district has been intermittently active during times of high metal prices since then. The chief production from the district has been silver, lead, and zinc, and some copper and byproduct gold. The ore deposits are replacements of Paleozoic carbonate rocks and veins in Paleozoic clastic sedimentary rocks and Precambrian crystalline rocks.

The Independence Pass district was discovered in 1879 and was active principally before 1900. Gold-bearing quartz veins cut Precambrian rocks and Tertiary intrusive rocks. Few production records exist.

Iron deposits in the Turret Creek District were mined in the latter part of the 19th century and yielded about 250,000 tons of magnetite ore. Mining ceased in 1899 because grades of ore dropped from 60 to 43 percent iron, and the content of sulfur and other impurities became too high in the deep ores.

The San Isabel National Forest includes the giant Climax molybdenum deposit; production started in 1917. The mine was shut down from 1919 until 1924, started bulk mining in the mid-1930's, and has been in almost continuous production since that time. Until 1955, Climax was the only porphyry molybdenum deposit known. For many years it provided more than 80 percent of the world's molybdenum production.

The area west of Ilse and north and east of Westcliffe includes the Wet Mountains thorium district, one of the two most important known concentrations of thorium veins in the United States. A small part of this mineralized area is within the San Isabel National Forest. The thorium deposits were found in the 1950's during a period of intensive prospecting for uranium. The area has been extensively explored, but mine workings and drill data extend to depths of only about 400 ft. Barite has been mined in small quantities from some of the thorium veins near Ilse.

Metals

Precambrian stratabound metallic-sulfide deposits were formed about 1,800 million years ago when the gneiss protolith was deposited and were metamorphosed along with the protolith during Precambrian regional metamorphism. Two types of deposits have been recognized: the first includes massive and disseminated sulfides, chiefly of zinc and copper, but also containing silver, gold, and lead, and the second contains disseminated copper in sulfides and tungsten in the mineral scheelite. An example of the first is the Sedalia mine, about 4 mi north of Salida, and of the second, the Cleora area, 3 mi southeast of Salida.

The Wet Mountains thorium district is partly in the forest. Thorium occurs in veins related to Cambrian alkalic intrusions, including the McClure Mountain and Gem Park Complexes and the igneous complex of Democrat Creek, all of which crop out between the Wet Mountains and the Sangre de Cristo Range. Possible byproducts include rare-earth elements and niobium. Minor quantities of lead, barite, uranium, and beryllium are present in some of the veins.

Metallic deposits in Pennsylvanian-Permian clastic sedimentary rocks in the Mosquito and Sangre de Cristo Ranges include syngenetic, sediment-hosted copper, silver, and uranium occurrences and fracture fillings containing the same metals.

Ore deposits formed in igneous-hydrothermal systems related to Cretaceous and Tertiary igneous rocks can be grouped into five main categories for assessment purposes:

(1) Porphyry-type deposits are located in or near apices of stocks and are hosted by the intrusive rock and adjacent country rock. The chief commodity is molybdenum; copper and precious metals are possible coproducts; and tin, rare-earth elements, uranium and thorium, tungsten, topaz, and tantalum are possible byproducts. The major known deposit in the forest is developed by the Climax molybdenum mine; several other porphyry deposits have been explored by drilling but are not currently being mined.

(2) Stockwork and disseminated deposits of molybdenum, copper, and other metals are situated in the upper parts of certain major plutons, but they lack the geometry and wall-rock relationships typical of the porphyry-type deposits. The chief known concentrations are molybdenum in the Winfield area and copper, molybdenum, and other metals in the Mount Princeton area.

(3) Skarn deposits are chiefly controlled by contacts between intrusive rocks and favorable country rocks, such as limestone and dolomite. The commodities to be expected depend upon the compositions of the intrusive rock and the host rock: iron and base metals are expected near granodiorite and mafic intrusions; tungsten, copper, and precious metals are more likely to occur near quartz monzonite and granitic intrusions. Iron skarns (magnetite) have been exploited in the Turret district; small amounts of molybdenum and copper have been reported in skarns around the Mount Princeton batholith. Base- and precious-metal sulfide-replacement deposits occur in marble in the Monarch mining district. The sulfide minerals are associated with magnetite, diopside, and andradite, which formed by contact metamorphism of carbonate strata adjacent to the Mount Princeton pluton. It is not clear from published descriptions whether the ore deposits were metamorphosed or whether they were formed after metamorphism. For assessment purposes, these deposits are included with the replacement deposits in Paleozoic rocks.

(4) Replacement deposits are found in the lower Paleozoic rocks in the Leadville and Monarch mining districts and include crosscutting veins and stratabound lenticular mantos. Commodities include silver, lead, and zinc, and lesser gold, copper, manganese, and other metals.

(5) Veins follow fractures in silicic volcanic and intrusive rocks of Cretaceous and Tertiary ages and in Precambrian gneiss and intrusive rocks. The principal ore was deposited in open fracture systems above or adjacent to plutons. The plutons provided heat (and at least some metals) to hydrothermal convection cells set up in adjacent rocks. The principal commodities are gold and silver; copper, lead, and zinc are coproducts or byproducts. Examples include the Chalk Creek district (gold veins in Tertiary intrusions), Granite district (gold veins in Precambrian intrusions), and the Marshall Pass district just outside the forest (uranium in veins cutting Precambrian gneisses and forming replacement deposits in the Paleozoic sedimentary rocks). In most districts known for replacement deposits in limestone and dolomite, veins are present in the crystalline rocks beneath the mantos and, in part, mark the feeder systems that supplied hydrothermal solutions to the carbonate rocks.

Uranium has been prospected for since the 1950's; the search has concentrated on sandstone deposits and on veins that were mined for base and precious metals in the late 1800's and early 1900's. Uranium deposits in sandstone were discovered in the 1950's in the Tallahassee Creek district. Exploration in the 1960's concentrated on paleovalleys south and east of the Mosquito Range (and found major extensions of the Tallahassee Creek district) and on the Antero Formation and the underlying rocks in the Antero Basin to the east. Other exploration concentrated on the Farisita Conglomerate in the northern part of Huerfano Park. A few tons of ore was shipped from this area, but no large mines were developed.

Mining started in the forest as early as 1859 exploiting gold placer deposits, and areas remain that are favorable for the occurrence of placer gold resources. Drainages tributary to the Arkansas River have had the greatest production and still seem to have the highest resource potential. Small placers have yielded gold in the vicinity of the Spanish Peaks.

Industrial Minerals

Fracture-controlled fluorspar deposits in and near the San Isabel National Forest include the Poncha Springs fluorspar district and the Browns Canyon district near Salida. These deposits are related to Miocene or younger hydrothermal systems that followed faults related to the Rio Grande rift system; they were deposited in a very shallow, possibly hot spring, environment.

Feldspar and other commodities have been produced from the Turret Creek, Mount Antero, and Trout Creek pegmatite areas. The principal commodities include: feldspar, mica, beryl, and columbite-tantalite in the Turret Creek area; feldspar and rare-earth minerals from the Trout Creek area; and beryl, phenakite, fluorite, and smoky quartz (gems and mineral specimens) from Mount Antero. The pegmatites of the Turret Creek and Trout Creek areas are Precambrian in age and are related to granodiorite of the Routt Plutonic Suite (1,700 m.y.). The pegmatite bodies of the Mount Antero area are related to the mid-Tertiary Mount Antero stock, a late intrusion within the Mount Princeton batholith. Beryl in quartz veins and disseminated in granite and greisen accompanies the Mount Antero pegmatites.

Gypsum is currently being produced from the Pennsylvanian Minturn Formation a few miles east of the forest boundary, near Hayden Pass. Evaporite facies rocks containing gypsum in the Belden and Minturn Formations extend north from Hayden Pass into South Park, a distance of about 16 mi.

Limestone and dolomite of metallurgical grade and limestone of chemical grade used for sugar refining have been quarried from beds near the base of the Leadville Limestone near Wellsville and at Monarch Pass. High-purity dolomite has been mined near Canon City from the Fremont Dolomite. These formations crop out in many places in the forest.

RESOURCE POTENTIAL—LOCATABLE MINERALS

Evaluation of the San Isabel National Forest for locatable minerals was done for 15 deposit types (pl. 2). In this section, the characteristics of known deposits are briefly summarized for assessment purposes, and areas in the forest are evaluated according to the stated assessment criteria. Definitions of terminology used, specifically the meaning of the several levels of resource potential, are in Appendix 1.

Precambrian Stratabound Deposits—Copper-Zinc and Tungsten-Copper

Commodities

Copper, zinc, tungsten; coproduct or byproduct tungsten, lead, silver, and possibly gold.

Host Rocks

Deposits are in Precambrian metasedimentary and metavolcanic gneiss of the Early Proterozoic gneiss complex (map units Xhg, Xgn, and Xfh, pl. 1). The most favorable rocks in these units are those that have alternating feldspathic and calcium-magnesium-rich layers. Some deposits, particularly tungsten-copper varieties, are contained in calc-silicate and hornblende gneiss, in rocks containing abundant hornblende, pyroxene, garnet, epidote, and calcic plagioclase.

Structural Control

No regional structural control on the distribution of deposits and occurrences is evident. Deposits are stratabound layers within the gneiss complex; they tend to cluster spatially and follow specific stratigraphic horizons.

Age

Precambrian; metals are believed to have been deposited concurrently with the sedimentary and volcaniclastic rocks that were the protolith of the gneiss. Lead isotope studies on galena suggest ages similar to those of the enclosing gneiss, between 1,700 and 1,800 m.y.

Deposit Description

Deposits range from small pods, irregular masses, and lenses a few feet in size to lenticular masses some tens of feet thick and as much as several thousand feet across (fig. 5). Shapes are complex and are modified by folding. Deposits range from a few hundred pounds to several million tons. Ore minerals are dominantly sphalerite, chalcopyrite, galena, gahnite or zincian spinel, scheelite and (or) powellite, and molybdenite. Gangue minerals include amphibole, pyroxene, garnet, pyrite and (or) pyrrhotite, biotite, plagioclase, quartz, and others.

Geochemical Signature

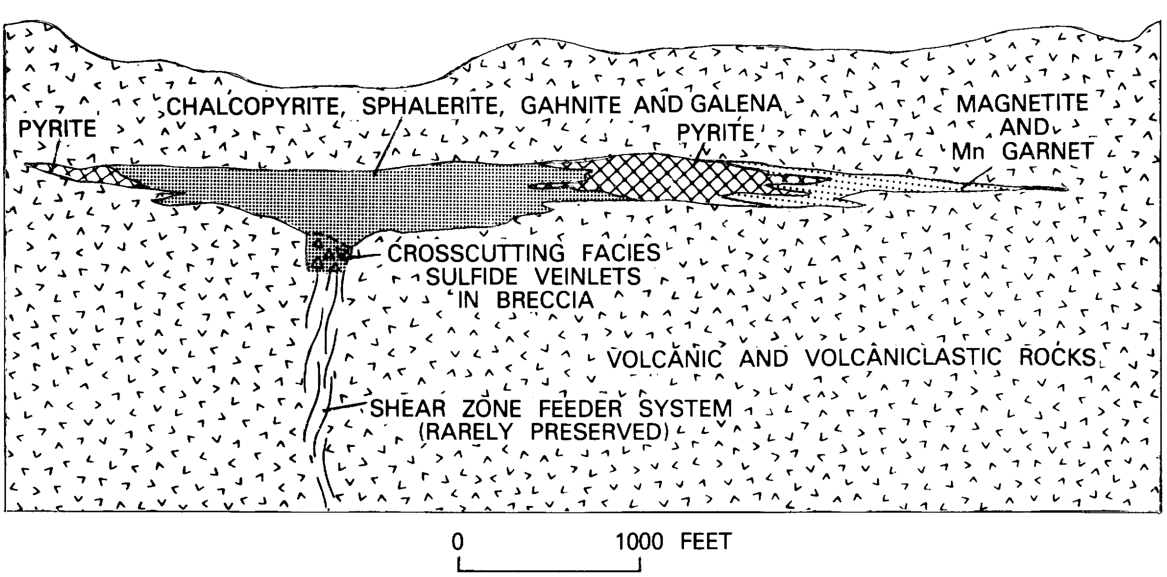
Stream-sediment samples (NURE) from some areas of known occurrences are anomalous in copper, lead, tungsten, and tin relative to areas lacking occurrences. The favorable gneiss bodies are associated with high concentrations of chromium, nickel, and cobalt, which seem due to the composition of mafic rock layers rather than to the deposits. Where analytical data from panned concentrates are available, tungsten concentrations greater than 100 ppm are characteristic. Tungsten is associated with both the zinc-copper and tungsten-copper deposit types and seems to be a geochemical guide to favorable areas.

Geophysical Signature

No evidence of terrane favorability could be discovered in regional aeromagnetic or gravity data.

Assessment Criteria

1. Presence of Precambrian gneiss, especially alternating felsic and mafic layers, and presence of calc-silicate layers; detailed mapping not available for most of forest.
2. Anomalous copper and lead in stream-sediment samples, tungsten about 100 ppm in panned concentrates;



Scale indicates order of magnitude

Figure 5. Idealized section of Precambrian stratabound sulfide deposit.

no panned-concentrate data available for most of forest; chromium, nickel, and cobalt concentrations above 50th percentile in NURE data.

3. Presence of known occurrences; the tendency for clustering of deposits and occurrences is well established.

Assessment

Major parts of the Early Proterozoic gneiss sequence have a lithology favorable for stratabound sulfide occurrences. Areas that have favorable stratigraphy and known occurrences are given high resource potential. The principal area encompasses a belt of gneiss extending westward from the Turret district towards the Gunnison area (towards the Gunnison gold belt). The large area of gneiss north of this belt has a favorable stratigraphy but contains few known occurrences; it is assigned moderate resource potential. The gneiss units at the north end of the Sangre de Cristo Range have favorable lithology, and geochemical anomalies were found, but no occurrences have been identified; this area is assigned a moderate resource potential. Gneiss units near Blanca Peak and west of the Spanish Peaks do not have favorable lithologies, and no stratabound sulfide occurrences have been found; the area is assigned low resource potential. An area of gneiss at the southern end of the Wet Mountains has favorable lithology, and anomalous amounts of tungsten were identified in the Greenhorn Wilderness Study Area assessment; this area is assigned moderate resource potential. The area of gneiss with verified occurrences west of Lake Isabel is assigned high resource potential. An area south of Deer Peak is assigned moderate resource potential on the basis of favorable lithology, geochemical anomalies probably, but not unequivocally, related to stratabound sulfides, and reported, but not verified, occurrences.

Economic Significance

Stratabound sulfide deposits may be large and high in grade; the closest large mine exploiting this type of deposit is the Pecos mine, in the mountains east of Santa Fe, N. Mex., a major producer of zinc, lead, copper, gold, and silver. The largest known deposit of this type in Colorado is at the Sedalia mine, about 4 mi north of Salida. This mine produced about 90,000 tons of ore (chiefly copper and zinc sulfates) from an oxidized zone formed by weathering from primary-sulfide minerals. The stratabound sulfide deposit type is economically important, and the belt of rocks in the forest assigned high resource potential has been the subject of intense recent prospecting and exploration. Although tungsten has been sought in stratabound deposits, the overall low grade and widely scattered concentrations discourage prospecting, even though small amounts of scheelite have been produced during times of high tungsten prices.

Thorium Vein Deposits

Commodities

Thorium; byproduct rare-earth elements, niobium; minor byproduct barite, lead, uranium, beryllium.

Host Rocks

Veins are found in Precambrian rocks of all types; most veins are in Precambrian gneiss. Brick-red to dark-gray syenite and mafic alkaline dikes accompany the vein zones.

Structural Control

Veins are concentrated in zones near faults, and most trend northwest to north-northwest. The veins and vein zones tend to cut the foliation of the host gneiss at a high angle.

Age

The veins are regarded as Cambrian in age, as they are clearly associated with alkaline mafic-syenite intrusions that have been dated at about 515 m.y. in age.

Deposit Description

The fracture zones containing thorium veins are persistent linear features as much as 8 mi long (fig. 6). The thorium veins may be as wide as 3 ft but are highly variable in width and in extent along fracture zones. The vein mineralogy is complex: most of the thorium is contained in thorite; quartz, carbonate minerals, and barite are commonly present; and galena, chlorite, xenotime, brockite, sphalerite, rutile, and many other minerals have been identified. Surface traces of the veins are marked by radioactive limonitic "rusty" zones. Veins change little with depth to the limits of present exploration, about 400 ft.

Geochemical Signature

No evidence of terrane favorability could be ascertained from the NURE stream-sediment geochemical data. The thorium analyses of stream sediments show high concentrations associated with igneous rock terranes; the highest concentrations are in units of the Berthoud Plutonic Suite rather than in either the Wet Mountains

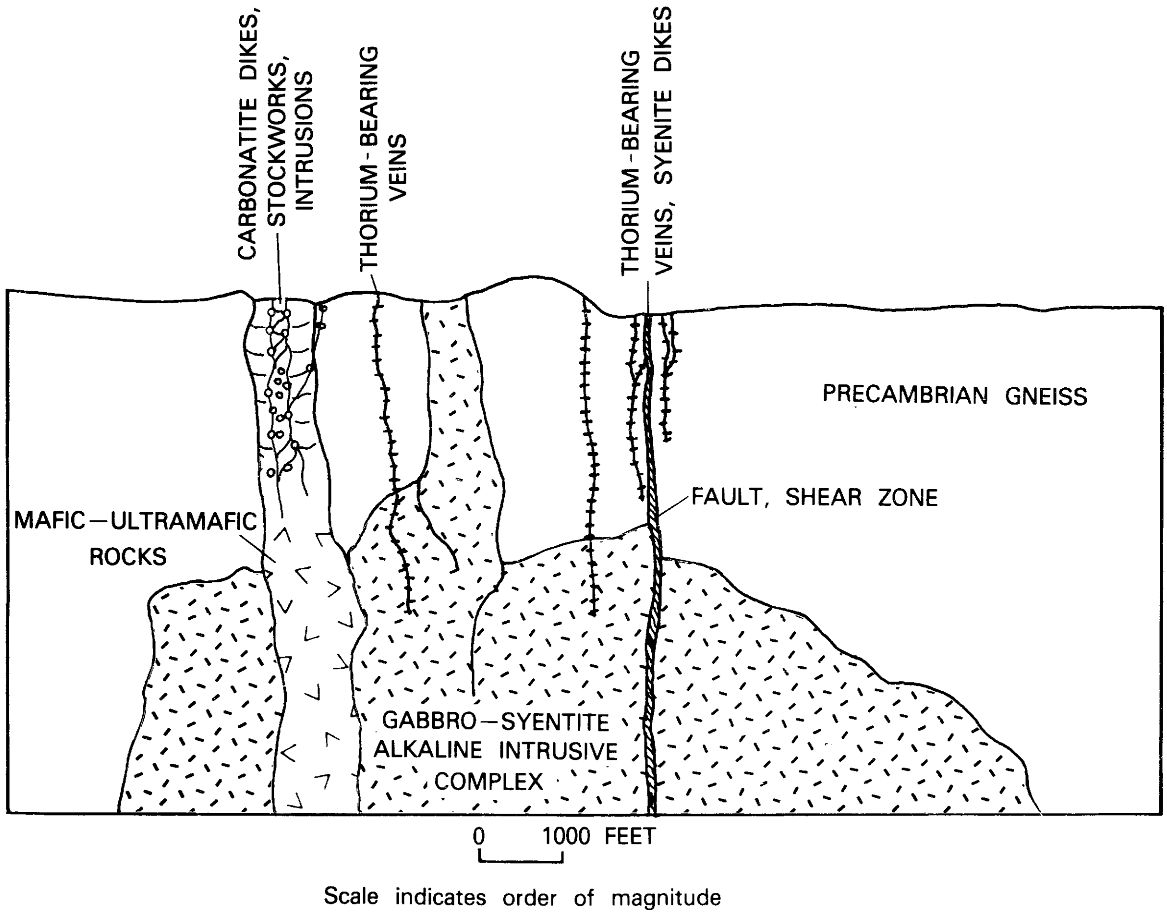


Figure 6. Idealized section of Cambrian gabbro-syenite alkaline intrusive complex showing location of niobium-bearing carbonatite and thorium-bearing vein deposits.

thorium district or in the Powderhorn thorium district (50 mi west of the forest).

Geophysical Signature

No evidence of terrane favorability could be ascertained from regional geophysical data.

Assessment Criteria

1. Presence of thorium deposits or occurrences.
2. Presence of radioactive vein zones and (or) the brick-red syenite dikes commonly associated with the vein zones.

Assessment

On the basis of the occurrence of the brick-red syenite dikes and radioactive vein occurrences, parts of the forest are assigned moderate thorium resource potential. Data are inadequate; these parts of the forest are at the periphery of the district, where veins are widely spaced and mineralization is apt to have been less intense than in the central parts of the district. Exploration and prospecting have not developed information on the vertical extent of the veins, even in the principal parts of the district.

Economic Significance

At the present time the demand for thorium is small in relation to the available supply, which now comes from monazite, a byproduct of titanium and tin mining. If, at some future time, thorium should be used in nuclear reactors (thorium breeder reactors), the enlarged demand for thorium would make veins of the type found in the Wet Mountains district interesting exploration targets.

Sediment-Hosted Syngenetic Deposits—Copper and Uranium

Commodities

Copper, uranium; byproduct silver, vanadium.

Host Rocks

Deposits are expected in Pennsylvanian and Permian clastic rocks, chiefly Minturn Formation (part of map unit IPmb, pl. 1) and Sangre de Cristo Formation (map unit PIPs).

Stratigraphic Control

Deposits are expected in transgressive marine shale, interbedded with sandstone, limestone, and gypsum, especially in facies deposited in lagoonal basins. Mineralization is localized by oxidation-reduction boundaries and is especially influenced by carbonaceous material in lenses or beds.

Structural Control

The favored tectonic setting is in fault-bounded intracratonic basins such as the central Colorado trough, a major feature of the Ancestral Rockies.

Deposit Description

Deposits are of two types: stratiform and fracture fillings (fig. 7). In the Sangre de Cristo Range, stratiform occurrences are lenses less than 3 ft thick that extend as much as 100 ft along strike; fracture fillings along faults and shear zones are as much as several feet wide and several hundreds of feet long. The mineralized rock is discontinuous and variable in grade. The copper is chiefly in chalcocite, azurite, and malachite; the uranium is in yellow secondary minerals or in unidentified form in black, organic-rich sediments.

Age

The stratiform deposits are Pennsylvanian and Permian; the fracture fillings are probably Laramide (Late Cretaceous through Eocene) and are believed formed by remobilization of metals from the stratiform deposits during and after the Laramide thrusting and folding of the Sangre de Cristo Range.

Geochemical Signature

The areas assigned moderate potential for copper based on assessment criteria below show copper concentrations above the 50th percentile in NURE surveys of stream sediments, whereas areas of the same rocks to the south generally have copper determinations below the 50th percentile. No other elements seemed to correlate well with the geologic data.

Geophysical Signature

No expression was recognized in regional aeromagnetic or gravity data.

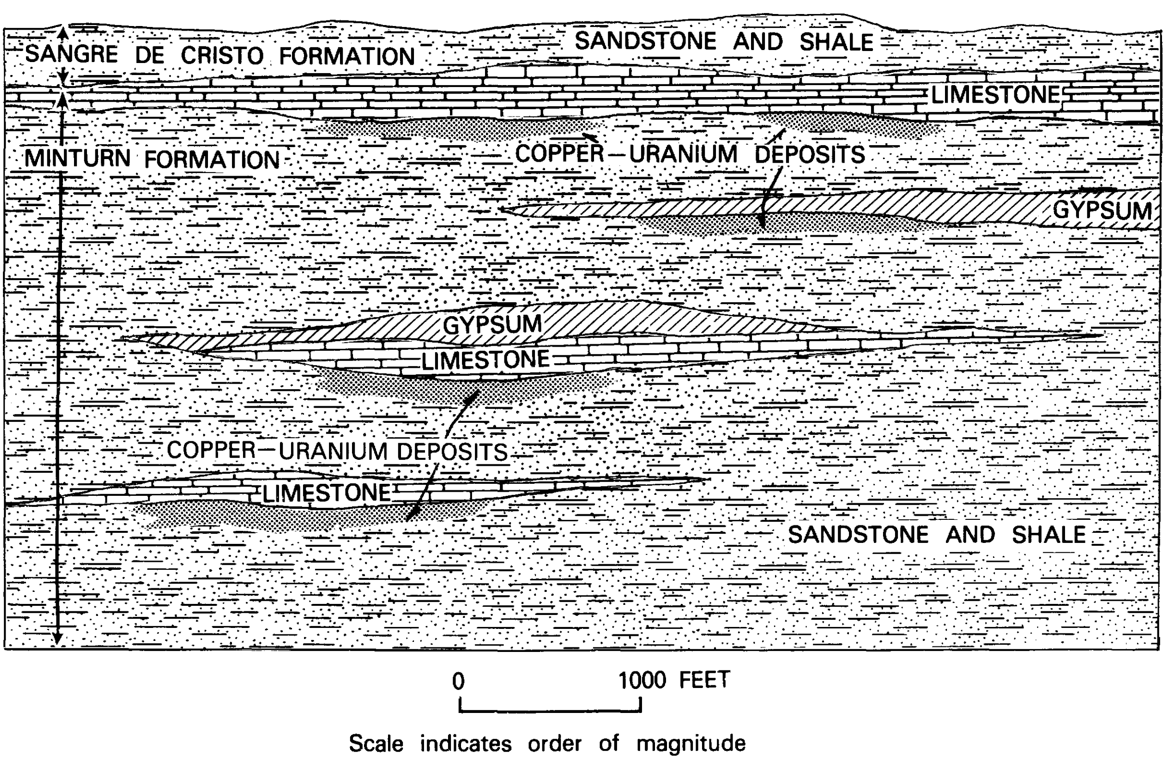


Figure 7. Idealized section showing locations of syngenetic sediment-hosted deposits.

Assessment Criteria

1. Presence of marine transgressive and evaporite facies rocks of the Minturn and Sangre de Cristo Formations, either at the surface or in the subsurface.

2. Presence of occurrences of copper or uranium minerals in these rocks, either stratabound or redistributed into fractures.

3. Copper concentrations in stream sediments above the 50th percentile in most stream-sediment samples of the NURE surveys.

Assessment

Occurrences of copper minerals, some also containing small amounts of uranium, are abundant in the stratigraphic section near the contact between the Minturn and Sangre de Cristo Formations in the Sangre de Cristo Range. These occurrences are small and of irregular, but generally low, grade. The sedimentary environment of these occurrences is not favorable for resource accumulation. A more favorable group of rocks is found at the north end of the Sangre de Cristo Range and extending northward into South Park. This area is assigned moderate resource potential for metals in stratabound deposits. The area underlain by Minturn Formation near Leadville lacks the sedimentary facies favorable for resource occurrence. The area of moderate resource potential for this kind of deposit is coextensive with the area of high resource potential for gypsum (see Gypsum deposits in Phanerozoic rocks).

Economic Significance

Sediment-hosted copper deposits, some also containing uranium, silver, and other metals, have major economic importance in eastern Europe and Africa. The Pennsylvanian-Permian rocks of Colorado are in many ways like those containing the large deposits of eastern Europe; the deposits formed in lagoonal environments and are associated with sand, shale, and evaporite. Large deposits have not been found in Colorado, despite long-term prospecting of a broadly favorable environment containing many occurrences of copper and other metals. Worldwide, the deposit type is significant, and a reasonable possibility for resources in rocks of the forest must be assumed until physical exploration provides adequate data for more specific appraisal.

Skarn deposits—Iron, copper, and other metals

Commodities

Iron; coproduct or byproduct copper, gold, tungsten.

Host Rocks

Paleozoic carbonate rocks are especially favorable, but skarn (contact metasomatic) deposits are possible near the margins of plutons in almost any country rock of composition differing chemically from the intrusive rock. Plutons of granitic to granodioritic composition are favorable.

Structural Control

Deposits are near the contacts of plutons with favorable host rocks. Bed-by-bed differences in alteration, recrystallization, and replacement are noted within deposits.

Age

Late Cretaceous and Tertiary; the host rocks may be of any preintrusive age. No skarn deposits have been recognized at the margins of Precambrian plutons within the forest.

Deposit Description

Iron deposits at the Calumet mine are tabular, as much as 55 ft thick and 550 ft wide, and persist 2,000 ft down the dip of the beds (fig. 8). Iron concentrations continue even farther down the dip of the beds, but mining stopped where the sulfide component increased beyond tolerable limits for iron ore. The host rock is Leadville Limestone, selectively mineralized, silicated, and recrystallized depending on the composition of the beds. Ores are made up of magnetite, hematite, and silicate minerals. Small amounts of sulfides, including pyrite and chalcopyrite, are locally present, and trace amounts of copper, lead, gold, silver, vanadium, manganese, and uranium have been reported.

Geochemical Signature

Some evidence of skarn mineralization was found in NURE stream-sediment geochemical data. Tungsten concentrations above the 95th percentile were found in the central Leadville district (outside the forest) and near the intrusive contact between the Paleozoic section and the Mount Princeton batholith; these values are interpreted as related to contact metasomatism. No evidence of the skarns of the Turret district could be seen in the NURE geochemical data.

Geophysical Signature

Magnetite-rich zones crossed by flight lines show clearly on regional aeromagnetic maps, generally as zones of strong magnetic gradient. Contact zones between plutons and country rock may or may not show on either

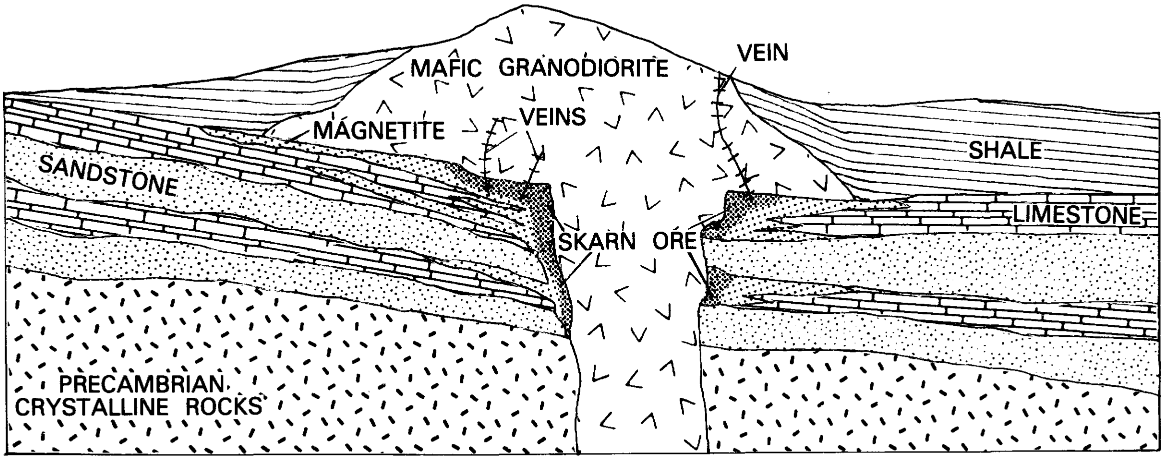


Figure 8. Idealized section showing location of skarn deposits

aeromagnetic or on gravity maps, depending on the contrast in magnetic susceptibility between intrusive phases and host rocks.

Assessment Criteria

1. Presence of contact zones between sedimentary rocks and intrusive igneous rocks around granodioritic plutons large enough to have contact-metamorphic aureoles, especially contact zones between plutons and Paleozoic carbonate rocks.
2. Presence of skarn minerals, particularly magnetite and various sulfide species, in outcrop or subsurface.
3. Aeromagnetic anomalies indicating presence of plutons, position of contacts, and presence of zones rich in magnetite.

Assessment

Aeromagnetic anomalies indicate that rock enriched in magnetite extends from the skarn mined in the Turret district towards feeders of the laccolithic Whitehorn stock. A favorable contact zone between granodiorite (Cretaceous Whitehorn Granodiorite) and carbonate (Mississippian Leadville Limestone) is predicted beneath the laccolithic shelf of igneous rock. The increasing sulfide content reported in the lower parts of the magnetite orebodies suggests resource possibilities for copper and other metals in the skarn. A high resource potential is assigned to this area of steep magnetic gradient.

Aeromagnetic anomalies around Rito Alto stock (Sangre de Cristo Range) show the magnetic dipole expected over a steep-sided granodiorite stock; skarn deposits, if present at the contact between the stock and the lower Paleozoic carbonate, would be deeply buried. A low resource potential is assigned to this area for this type of deposit, on the basis of available geophysical data.

Economic Significance

Skarn deposits constitute an important resource type; copper, molybdenum, tungsten, and iron are the principal commodities of interest in the forest. Significant masses of mineralized rock may be expected at considerable depth and can only be explored by drilling. Mining operations would be largely underground.

Porphyry Stockwork Deposits—Molybdenum and Copper

Commodities

Molybdenum and (or) copper; byproduct tin, tungsten, rare-earth elements (monazite), niobium, topaz, thorium, uranium, pyrite (from Climax-type molybdenum deposit); gold, silver (from copper porphyry).

Host Rocks

Quartz monzonite or granite stocks host most deposits; almost any type of rocks adjacent to or overlying the intrusive mass may also be mineralized.

Structural Control

The position of stocks hosting the deposits is generally structurally controlled; many are located on or near faults of regional extent. Patterns of intrusion-related faults may indicate the location of intrusive centers (radial and (or) ring structures); these faults may localize dike swarms (radial dikes, inward-dipping cone sheets). Ore deposits are localized by zones of hydrofracturing in upper parts of composite stock systems. The stock geometry favorable for ore is one in which restricted volumes of rock are mineralized by a hydrothermal system derived from a much larger volume of rock supplying metals. Favorable systems have multiple stages of intrusion and mineralization.

Age

Late Cretaceous, Tertiary (Oligocene, Miocene); mineralization is associated with late-stage magmatic and hydrothermal activity.

Deposit Description

Orebodies consist of stockworks of quartz veinlets containing molybdenite and (or) chalcopyrite, pyrite, and other sulfide minerals in felsic porphyry and in adjacent and overlying country rocks (fig. 9). The ore minerals occur in the veinlets (90 percent of the molybdenum) and are also disseminated in the rock between the veinlets (10 percent of the molybdenum). The forest contains the Climax deposit, the type example of a molybdenum stockwork porphyry deposit. This deposit initially contained a half billion tons of molybdenum ore. Quartz-molybdenite veinlets are dispersed through a fractured mass of Precambrian granitic rocks, schist and gneiss, and granitic porphyry intrusive rock overlying a granitic stock. Metal grades in deposits of this type range from about 0.1 to more than 1 percent. Deposits are some thousands of feet across and several hundred to a few thousand feet thick. Zoned assemblages of alteration minerals have been recognized; potassium feldspar and quartz-sericite-pyrite are located in and near the mineralized rocks, and argillic and propylitic alteration minerals toward the periphery of the altered system.

Geochemical Signature

NURE geochemical data reflect veins and mineralized rock peripheral to the core intrusions rather than the postulated stockwork deposits, except where such deposits are exposed. In the NURE geochemical data, the mineralized porphyry system including the exposed Climax deposit is marked only by a single stream-sediment sample having high copper content.

Geophysical Signature

Stocks hosting porphyry-type deposits may show as aeromagnetic anomalies on regional aeromagnetic surveys

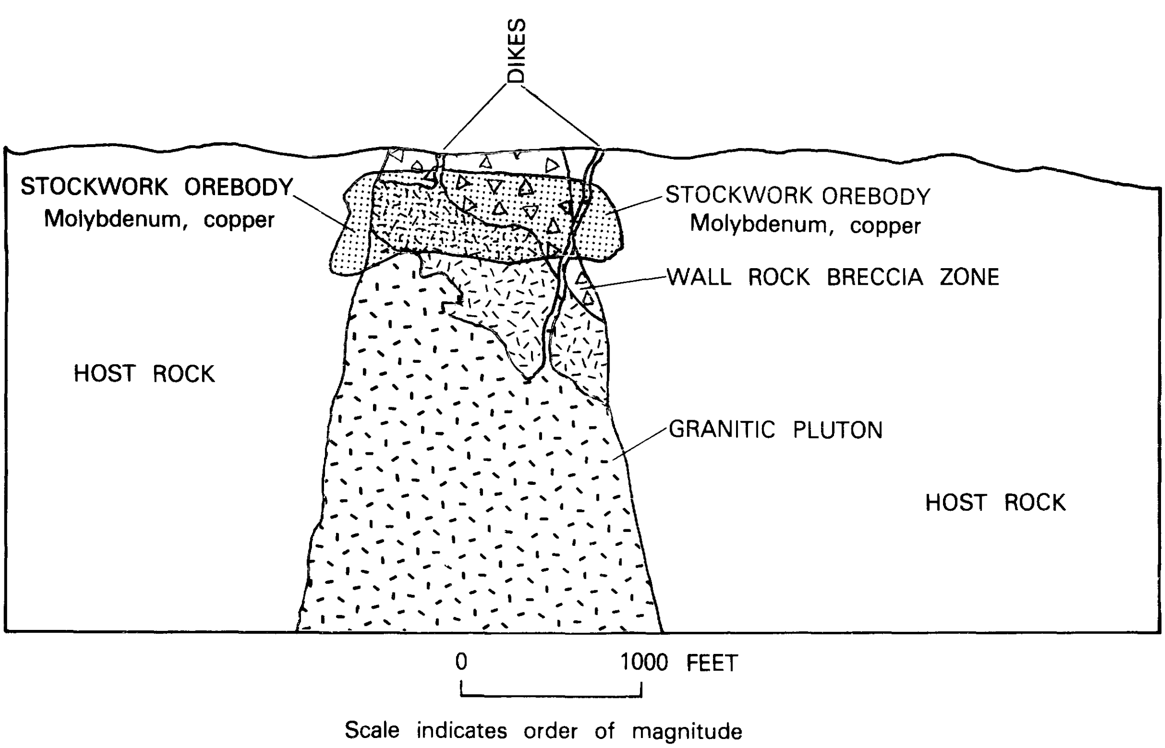


Figure 9. Idealized section of porphyry stockwork deposit.

if the magnetic contrast between the stock and the country rocks is great enough.

Assessment Criteria

1. Presence of granitic stock, either observed or inferred from (a) fracture and dike patterns, (b) aeromagnetic anomalies, (c) zoned assemblages of alteration minerals, or (d) geochemical anomalies.
2. Multistage igneous activity.
3. Stock composed of granite to quartz monzonite (if buried, inferred from chemistry of related dikes).
4. Past hydrothermal activity (alteration minerals in zonal patterns, veins, silicified rock).

Assessment

The distribution of fractures and of signs of hydrothermal activity (veins, alteration minerals) indicate stocks at depth at several locations. Near Turquoise Lake, radial and concentric patterns of faults and dikes and presence of alteration minerals (including turquoise) indicating past activity of hydrothermal solutions are the basis for assigning a high resource potential to a sizable area. Although no stock crops out, drilling by industry has located at least one possible porphyry-type mass.

The intrusion at Chalk Mountain occupies a favorable structural position, and although it is not a probable host, the possibility of stocks below this hypabyssal mass or in its vicinity has led to assignment of unknown potential for porphyry deposits in this area. No subsurface data are available that would assist determination of the position or nature of a possible hidden stock in this area.

A small area on the west side of Mount Antero, in and adjacent to the Oligocene Mount Antero Granite pluton, meets criteria for high resource potential for a molybdenum stockwork porphyry deposit. Veins and dikes together with the presence of beryl and rocks with high molybdenum content indicate the possibility of a concealed, strongly mineralized rock mass. A part of this area has been drilled, but the results are not available.

Economic Significance

Porphyry stockwork deposits may be very large and can be mined by underground bulk-mining methods, such as block caving, that are economically feasible at the present time. Deposits of this type have been the target of exploration by industry and will be sought and mined when the economic climate creates a need for molybdenum and copper. Mining and milling operations must be of large size to process the high volumes of low-grade ores. Operations are likely to be of long duration.

Disseminated and Stockwork Deposits in Plutonic Rocks—Molybdenum and Copper

Commodities

Molybdenum, copper; byproduct gold, silver, other metals.

Host Rocks

Parts of composite granitic plutons of large (batholithic) dimensions.

Structural Control

Mineralization and any resulting resources are controlled by internal structures in apical parts of large intrusive bodies. These internal structures may be related in part to regional structure (transecting faults) or may be controlled entirely by multistage intrusions in a single major pluton.

Age

Late Cretaceous, Tertiary (Oligocene, Miocene); mineralization is associated with late-stage magmatic and hydrothermal activity.

Deposit Description

Veins, veinlet stockworks, disseminated sulfides, and pegmatitic zones containing sulfide minerals may be distributed through large volumes of igneous rock (fig. 10).

Geochemical Signature

No signature directly representing this kind of deposit could be ascertained from available NURE geochemical data. The stream-sediment analyses for copper from both the Winfield and Chalk Creek areas were above the 50th percentile; these high concentrations are interpreted as largely representing veins, at least for the Chalk Creek area.

Geophysical Signature

The location of granitic plutons is reflected in both gravity and magnetic data, but no geophysical signature is recognized as diagnostic of mineral deposits. Detailed aeromagnetic or gravity surveys may show anomalies due to destruction of magnetite or replacement of denser minerals by less dense ones related to mineralization, but such surveys are not available in critical areas of the forest.

Assessment Criteria

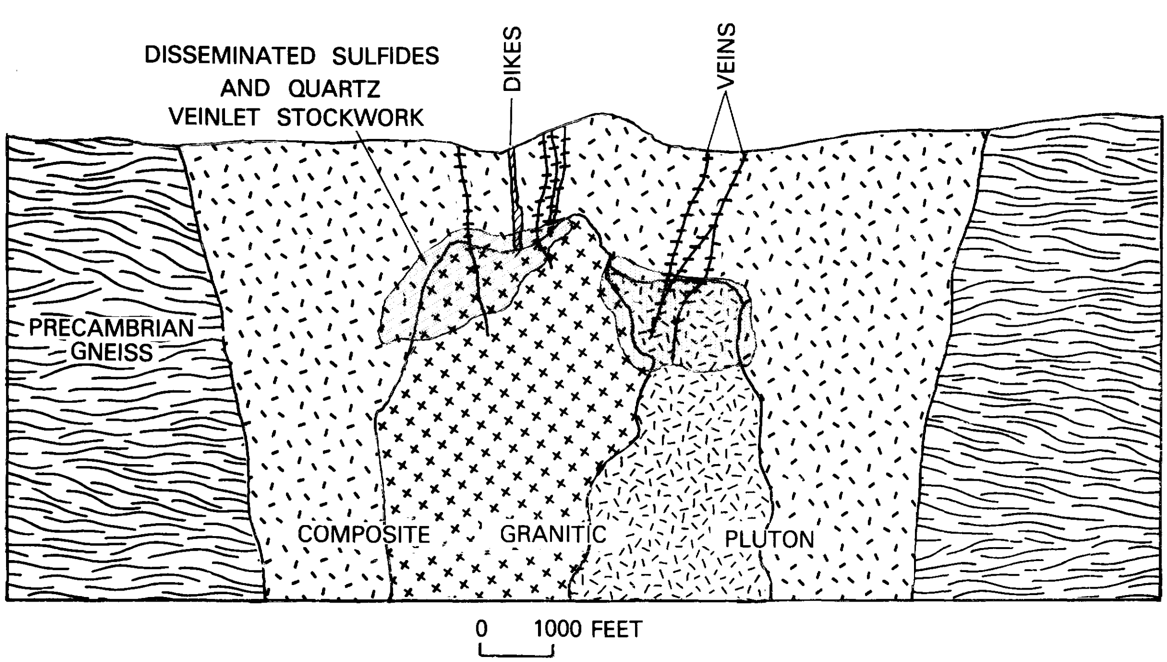
1. Presence of granitic mass of large proportions, either cropping out or predicted in the subsurface from geologic evidence.
2. Indications of multistage igneous activity.
3. Favorable igneous chemistry, granite to quartz monzonite.
4. Indications of hydrothermal activity such as extensive alteration zones, veins, and geochemical anomalies (copper).
5. Presence of quartz-sulfide veinlets in stockworks.

Assessment

Two zones have been identified that meet the five assessment criteria: (1) a zone crossing the Mount Princeton batholith, and (2) the southern part of the Twin Lakes batholith.

The Mount Princeton batholith is a nearly circular, steep-sided pluton interpreted to be the source of ashflows found east of the forest, and thus to be the roots of a major caldera. Two curving mineralized fracture zones cross the batholith: the western and stronger zone is marked by the highly mineralized (gold) vein system that includes the Mary Murphy mine, by widespread pyritic rocks, and by a dike of Mount Aetna Quartz Monzonite Porphyry; the eastern zone is marked by areas of mineralized and altered rock that include the Stanley mine (Dings and Robinson, 1957). Indications of dilation, including major porphyry dikes injected into tensional fractures and abundant fracture-filling quartz veins, suggest that a hidden late pluton follows a north-northeast zone transecting the cauldron. The abundance of gold veins indicates that a major hydrothermal cell was generated within the rocks of the Mount Princeton batholith in this area and extended out along fractures away from the batholith. Possible concealed disseminated and stockwork deposits are suggested for apical parts of the postulated concealed pluton; a high resource potential is assigned to the area encompassing the southern part of this pluton. A moderate resource potential is assigned to the northern part of this zone, where indications of the activity of hydrothermal systems are weaker and less continuous.

The southern part of the Twin Lakes batholith is characterized by zones of disseminated ore minerals and by veins, both containing molybdenite, as well as by veins containing base and precious metals. This area is assigned



Scale indicates order of magnitude

Figure 10. Idealized section of disseminated and stockwork deposits in Tertiary and Cretaceous plutonic rocks.

high potential for molybdenum resources and probable byproduct copper. Exploration has failed to identify ore bodies, but has verified that mineralization has taken place over a large area.

Economic Significance

Like the porphyry stockwork deposits described previously, the stockwork and disseminated deposits of this ore type may be large in volume but low in grade.

Replacement Deposits in Paleozoic Rocks—Silver, Gold, and Base Metals

Commodities

Silver, lead, zinc; coproduct or byproduct gold, copper; minor products, manganese, uranium.

Host Rocks

Paleozoic rocks, principally limestone and dolomite (map unit M€r, pl. 1). Certain dolomite beds in the Leadville Limestone are especially favorable, but all carbonate beds and even some noncarbonate clastic units may contain replacement ores in intensely mineralized areas.

Structural Control

Replacement bodies in the Leadville district are generally in dolomite beds interleaved with sheets of intrusive rock. The largest bodies are in carbonate rocks, either beneath porphyry sills or beneath shale of the Belden Formation. Structural preparation of the ground by faulting seems required, and proximity to Late Cretaceous or Tertiary igneous masses is favorable, if not required. Veins fill fractures in Paleozoic beds and may extend into crystalline rocks beneath the sedimentary rocks. Many of the veins occupy fractures that fed hydrothermal fluids to the ore system.

Age

Late Cretaceous and Tertiary, probably Cretaceous through early Miocene.

Deposit Description

Deposits range from small pods and veins to mixed-sulfide replacement bodies several thousands of feet long, several hundreds of feet wide, and many tens of feet thick. The shapes are irregular, structurally controlled, and modified by supergene processes (fig. 11). Most of the ore bodies at Leadville consisted principally of pyrite, sphalerite, and galena. They contained a few ounces of silver per ton (in argentiferous galena, argentite, tetrahedrite, and chalcopyrite) and a few hundredths of an ounce of gold per ton (native gold, also in chalcopyrite). Much of the ore at Leadville and some in other districts was oxidized; the sulfide minerals were destroyed and replaced by oxides and carbonates, and, in the main, the grade of the ore increased during this process. Veins may extend into crystalline rocks beneath the replacement ores.

Geochemical Signature

NURE stream-sediment samples from areas of known mineral deposits of this type are high in lead (above 50th percentile, some samples above the 95th percentile) and generally above the 50th percentile in copper content.

Geophysical Signature

In some places regional aeromagnetic and gravity data can be used to detect the major faults that controlled or influenced mineralization and assist in locating possible buried plutons that supplied heat, solutions, and metals to hydrothermal systems. No direct evidence of mineralized rock can be found in this kind of geophysical data.

Assessment Criteria

1. Presence of lower or middle Paleozoic carbonate rocks at the surface, or presence in the subsurface inferred from geologic data.
2. Presence of mines and (or) occurrences of base-metal sulfides in veins or disseminated in Paleozoic carbonate rocks.
3. Presence of Cretaceous and (or) Tertiary plutons, dikes, sills.
4. Most NURE stream-sediment samples contain lead and copper concentrations above the 50th percentile.

Assessment

Assessment criteria are satisfied for areas underlain by lower Paleozoic rocks in the northeastern part of the forest surrounding the Leadville district, extending from its northern boundary to Weston Pass; this area is assigned high resource potential. The favorable carbonate rocks are deeply buried in a part of this area. Over much of the area, mineralization was intense, if not active everywhere. Difficulties in prospecting and mining caused by glacial cover and by sheets of intrusive rock have resulted in some areas being left almost unexplored.

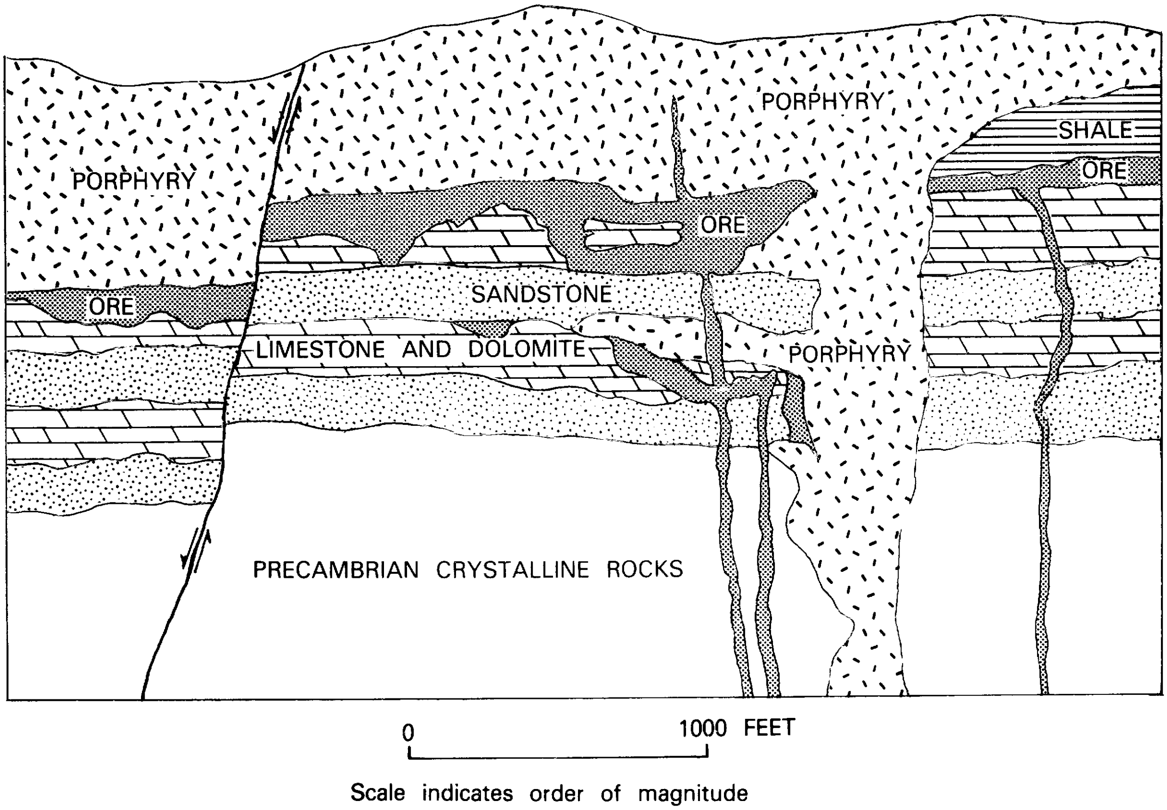


Figure 11. Idealized section of replacement deposits in Paleozoic rocks.

The lower Paleozoic rocks south of Buffalo Peaks show few signs that mineralization took place, so we assigned the area low resource potential for replacement deposits.

Areas underlain by lower Paleozoic rocks north and south of the Mount Princeton batholith are extensively mineralized and are assigned high resource potential for replacement deposits. Mineralization was produced by extensive mid-Tertiary hydrothermal systems related to the cooling Mount Princeton batholith in the southern Sawatch Range.

The lower Paleozoic rocks of the northern Sangre de Cristo Range are assigned low mineral resource potential for replacement deposits. Some evidence of mineralization is evident locally, as at prospects near the Bushnell Lakes and at Galena Peak, but these occurrences are too scattered and too small to indicate the likelihood of resources. Several Tertiary dikes and plutons are known, but lower Paleozoic rocks are not exposed near the plutons. Lower Paleozoic carbonate beds may exist several thousand feet below the surface adjacent to the Rito Alto stock and to the stock just south of Hayden Pass, but these environments cannot be evaluated from existing data.

Economic Significance

Replacement deposits in the Paleozoic limestones, both the primary sulfide ores and the secondary deposits formed by oxidation, constitute an important deposit type within the forest. Deposits may be large and high grade and may contain significant quantities of precious metals. Despite extensive past mining, undiscovered resources probably still exist within the previously worked areas in deeper, less accessible parts of the Paleozoic section. Epithermal feeder veins may exist beneath the replacement deposits, and these have been tested in only a few mines. Future exploration would largely be conducted by drilling.

Epithermal Vein Deposits—Gold, Silver, Base Metals, and Uranium

Commodities

Gold, silver, base metals, uranium (fluorite is assessed separately).

Host Rocks

Almost all kinds of hard, brittle, and readily fractured rocks.

Structural Control

Strong structural controls are evident in areas where veins follow faults and fracture systems of regional extent. Fracture systems that were open during hydrothermal activity are the most favorable. Igneous intrusions supplied the heat that drove mineralizing convection cells containing fluids largely made up of meteoric water. The metals partly were derived from the igneous intrusions and partly were leached from country rocks by the circulating waters and were deposited as veins along fracture systems.

Age

The veins are Late Cretaceous and Tertiary in age, and they were formed by hydrothermal systems set up by silicic plutons of Laramide and younger age.

Deposit Description

The geometry of the veins and the vein systems is controlled by the distribution and size of fractures and is modified by movements along the fractures taking place during and after vein filling. Cavity filling and replacement of the country rock are both important in forming ore deposits, but to varying degrees in different vein systems. Veins are normally flanked by zones of altered rock, and in some places enough ore minerals occur in the altered rock that it can be mined. Veins may extend several thousand feet along their strike; they may be as much as a few tens of feet wide. Within a vein, the ore generally varies in tenor and pinches and swells both laterally and vertically. A vertical range for ore of several hundred to a few thousand feet has been observed; structures are much more continuous than ore.

Geochemical Signature

NURE stream-sediment samples in some areas that are known to have veins are high in copper and lead (most stream-sediment samples above 50th percentile, many above 95th percentile), but samples from other areas lack one or both of these elements. Areas of quartz-pyrite-gold veins are not distinguishable from barren areas using the limited element suite available in these data. These geochemical data serve to help confirm areas of resource potential, but cannot be used independently in assessment.

Geophysical Signature

Many areas of extensive veins and rock alteration are characterized by magnetic lows due to destruction of magnetite, but these lows are difficult to interpret and are best seen on survey data more detailed than those available for the forest.

Assessment Criteria

1. Presence of veins, prospects, or mines on vein systems.
2. Faulted and fractured rock.
3. Presence of altered areas as indicated by geochemical anomalies, primarily copper and lead concentrations above the 50th percentile (NURE stream-sediment data), in areas of silicic igneous rocks.

Assessment

The northern part of the forest has major vein systems containing base and precious metals. The principal centers for these systems are the Leadville mining district, the igneous intrusions near the Turquoise Lakes, the volcanic center near Independence Pass, the Twin Lakes pluton near Winfield, and the Mount Princeton batholith. Major vein zones follow the north- to north-northwest-trending fault zones along the margins of the upper Arkansas Valley. Lesser vein systems in the Sawatch Range extend into the forest from the Bonanza volcanic center, in the Sangre de Cristo Range, surround the stock at Cottonwood Peak, and follow faults near Blanca Peak. Scattered veins occur in the zone of contact metamorphism around the intrusion at West Spanish Peak.

The assignment of moderate resource potential to the area around the Rito Alto stock (Cottonwood Peak in the Sangre de Cristo Range) follows the evaluation of Johnson and others (1984). Although the area has been prospected since the turn of the century, no significant deposits have been found. Molybdenite-quartz veins occur in the granodiorite of the stock in one place, and a quartz-beryl veinlet and fragments of mica greisen were found near the top of Cottonwood Peak, yet signs of pervasive alteration are lacking, and the stock seems to have been eroded below the depth of likely porphyry stockwork mineral deposits. A vein model is invoked here as indicating possible resources, but with little certainty that the geology fits the model.

As detailed data on many of the vein systems are lacking, and the available NURE geochemical data are inadequate for evaluation of resource potential, much of this assessment is subjective judgment based on the distribution of mines and prospects and published descriptions of parts of the mineralized ground. The existence of large-scale vein systems is well documented, but much better geologic data are needed to support a reliable resource assessment.

Economic Significance

Epithermal veins have been a major source of base and precious metals, and additional resources probably still exist in untested parts of the vein systems.

Uranium Deposits in Sandstone

Commodities

Uranium; byproduct vanadium.

Host Rocks

Clastic sedimentary rocks deposited in a continental environment; these include the Antero Formation, the Farisita Conglomerate, and parts of tuffaceous units (map unit Ta, and parts of Th and Taf, pl. 1).

Age

The host rocks in the forest are Tertiary, Paleocene to Oligocene; the age of the mineralization is uncertain.

Deposit Description

Sandstone-type deposits are stratabound and peneconcordant; the mineralization may be tabular and nearly concordant with gross sedimentary structures of the host sandstone, or it may form "roll front" bodies that are crescent shaped and discordant to bedding in cross section but elongate and nearly concordant to bedding in plan. Ore minerals in reduced (dark-colored) rocks include pitchblende and coffinite accompanied by pyrite and other sulfides. Ore minerals in oxidized rocks include carnotite, autunite, and other species (yellow ores). Deposition of uranium is localized by carbonaceous matter, sulfides, and other reductants. The host rocks are medium- to coarse-grained sedimentary rocks; many are feldspathic or tuffaceous and contain mudstone layers. Mineralized rock forms masses as much as several tens of feet thick and tens to hundreds of feet long and wide. The U_3O_8 concentration in the average ore mined ranges from about 0.15 to 0.30 percent; ore bodies range in size from a few tons to more than 10 million tons.

Assessment criteria

1. Presence of continental clastic rocks, including sandstone and conglomerate, either at the surface or in the subsurface, as projected from geologic information.
2. Presence of uranium sources, including Precambrian granitic rocks and (or) tuffaceous sediments.
3. Presence of carbonaceous beds or other reductants to cause deposition of uranium.
4. Presence of uranium occurrences, either within the forest or in the same units in adjoining areas.

Assessment

Three areas are assigned moderate potential for sandstone-type uranium resources. Clastic, generally tuffaceous rocks deposited in an Eocene paleovalley at Trout Creek Pass and in the paleovalley crossing the Whitehorn stock east of the Turret district meet assessment criteria (Dickinson and Hills, 1982). The volume of the sediments in these two paleovalleys is small. A small area in the forest east of these paleovalleys is underlain by Antero Formation and lies at the fringe of the Antero basin. This area meets assessment criteria and is assigned moderate potential for uranium resources, although it lacks a large volume of host rock within the forest. Considerable drilling was done for uranium in the late 1970's east of the forest, but the results of the drilling have not been published.

Occurrences of uranium minerals have been noted in the Farisita Conglomerate northwest of Gardner, some in and some outside the forest. Both oxidized (yellow secondary minerals, including autunite) and unoxidized (pitchblende) minerals have been reported. The host beds are carbonaceous shale and sandstone. A few tons of ore have been produced, and extensive drilling has been conducted. High resource potential has been assigned to the area underlain by the Farisita Conglomerate in view of the known deposits and the considerable volume of untested sedimentary rock.

Economic Significance

Uranium deposits in sandstone have yielded most of the uranium produced in the United States and an additional large quantity of byproduct vanadium. The major Tallahassee Creek district belongs to this deposit type and is hosted by rocks similar to those in the paleovalleys listed above and by formations that may underlie the Antero Formation. Exploration for deposits of this type awaits renewed interest in uranium.

Placer Deposits—Gold

Commodity

Gold; byproduct silver.

Host Rocks

Alluvial deposits (parts of map units Qa, Ts, pl. 1).

Age

Tertiary and Quaternary.

Lithologic Control

The distribution of placer ground is determined by ancient and modern drainage patterns. The general depositional elements are stream and river channel deposits, alluvial-fan deposits, and basin deposits. Processes bearing on the distribution of placer gold include chemical and mechanical weathering of primary gold-bearing deposits, movement of detritus, concentration of heavy particles in selected parts of the alluvial debris, and deposition in pay streaks, particularly near the bottoms of stream channels.

Deposit Description

Placer gold is recovered from alluvial gravels derived from primary lodes. Favorable alluvial systems have gold sources upstream from fluvial deposits. No direct correlation can be postulated between the size of an existing lode system and the size of the placer deposits in the alluvial system below it. Most placer deposits were formed in streams of moderate gradient, where turbulent and irregular flow patterns effectively separate heavy from light components. Although the gravels are essentially continuous deposits, gold concentrations constitute only small parts of the gravel deposits. Alluvial fans and basin sediments also contain gold, but generally winnowing has not produced placer gold concentrations. The gold particles in most placer deposits contain 10–25 percent silver, and this silver is a byproduct of the placer mining.

Geochemical Signature

Regional geochemical surveys furnish no direct evidence of favorability.

Geophysical Signature

Regional surveys furnish no useful information.

Assessment Criteria

1. Presence of old placer "diggings."
2. Presence of alluvial deposits downstream from areas of known gold-bearing deposits.

Assessment

Favorable placer ground has been exploited downstream from large mineralized systems in the forest since the mid-1800's (Parker, 1974). Most of this ground lies along tributaries to the Arkansas River. Some of the important areas include the California, Iowa, and Colorado Gulches near Leadville, and Willow and Cache Creeks near the Twin Lakes Reservoir. Alluvial deposits in these immediate areas are assigned a high resource potential.

The potential for stream placer resources in terrain such as the San Isabel National Forest cannot be well assessed or shown at a 1:250,000 scale. The small size of the placers precludes showing their distribution, and the geologic map necessarily emphasizes bedrock at the expense of showing small areas of alluvial units.

Numerous, perhaps all, other streams in the area have been prospected for placer gold. Gold-seekers have examined alluvial deposits for more than 100 years, and it seems unlikely that near-surface gravels are untested or can be expected to have extensive gold deposits. Certain alluvial gravels lack evidence of past successful exploitation, yet major gold lode deposits are upstream in the drainage basin supplying the alluvial material. In particular, Chalk Creek and its tributaries drain the important gold-producing area containing the Mary Murphy mine, yet they are not listed as producers in the most complete tabulation available (Parker, 1974). Available data are not adequate for us to evaluate alluvial deposits in the forest for placer gold resources.

Parts of the Miocene basin-fill sediments in the Arkansas Valley contain alluvial-fan deposits that derived part of their material from eroded mineralized systems. Information necessary for assessment of these concealed beds is lacking. These areas are assigned an unknown potential for placer gold resources and are mentioned here to call attention to the possibility of such occurrence.

Placer mining on a small scale has been conducted in streams radiating from the small mineralized areas at the Spanish Peaks. Alluvial deposits are not shown on the geologic map (pl. 1) in this area because of their small size.

Economic Significance

Placer deposits attracted small mining operations in the early days of mining in Colorado because they were easily discovered and could be mined without expensive equipment. As high-grade, near-surface ground was worked out, costs rose and are especially high now when possibly severe environmental impacts must be mitigated. The future of placer operations in the forest is questionable, principally because of the cost of environmental constraints.

Precambrian Pegmatites—Feldspar and Pegmatite Minerals

Commodities

Feldspar, beryl, mica; byproduct columbite-tantalite, rare-earth minerals, lithium minerals.

Host Rocks

Precambrian pegmatites containing concentrations of valuable minerals intrude rocks of the Routt Plutonic Suite and adjacent gneiss.

Structural Control

Pegmatite bodies that have economic potential are characterized by considerable size and strong compositional zoning and are concentrated near the margins of plutons of the Routt Suite, especially in cupolas; not all the marginal zones are favorable.

Deposit Description

Pegmatite bodies that have been opened by prospects or mines are generally tens of feet thick and have a strike length of several hundred to several thousand feet. Most are tabular in general shape but are irregular or branching in detail; most dip steeply and are zoned internally (fig. 12). The zoning is complex in detail (Hanley and others, 1950); most have a biotite-rich wall zone next to the rock they intrude, an intermediate zone of feldspar and quartz, and a core rich in quartz. The valuable minerals, including beryl, lithia mica, and rare-earth minerals, are usually concentrated in zones within the pegmatite that tend to parallel the margins of the pegmatite because the mass cooled and crystallized gradually from the outside in.

Geochemical Signature

Stream-sediment samples from areas intruded by many pegmatite bodies have anomalous concentrations of tin and, in some, tungsten. Available NURE geochemical data, however, do not distinguish between pegmatite areas and some "tin" granite plutons, and so should be used to help confirm areas of pegmatite concentration rather than to define them.

Geophysical Signature

Some of the marginal zones of Routt Suite plutons show clearly on aeromagnetic maps. The pegmatite bodies themselves are too small to be distinguished on regional geophysical maps.

Assessment Criteria

1. Location near margins of Routt Suite plutons.
2. Presence of pegmatite, prospects and mines in pegmatite, occurrences of beryl or lithium minerals.
3. Tin concentrations greater than the 95th percentile in NURE stream-sediment data.

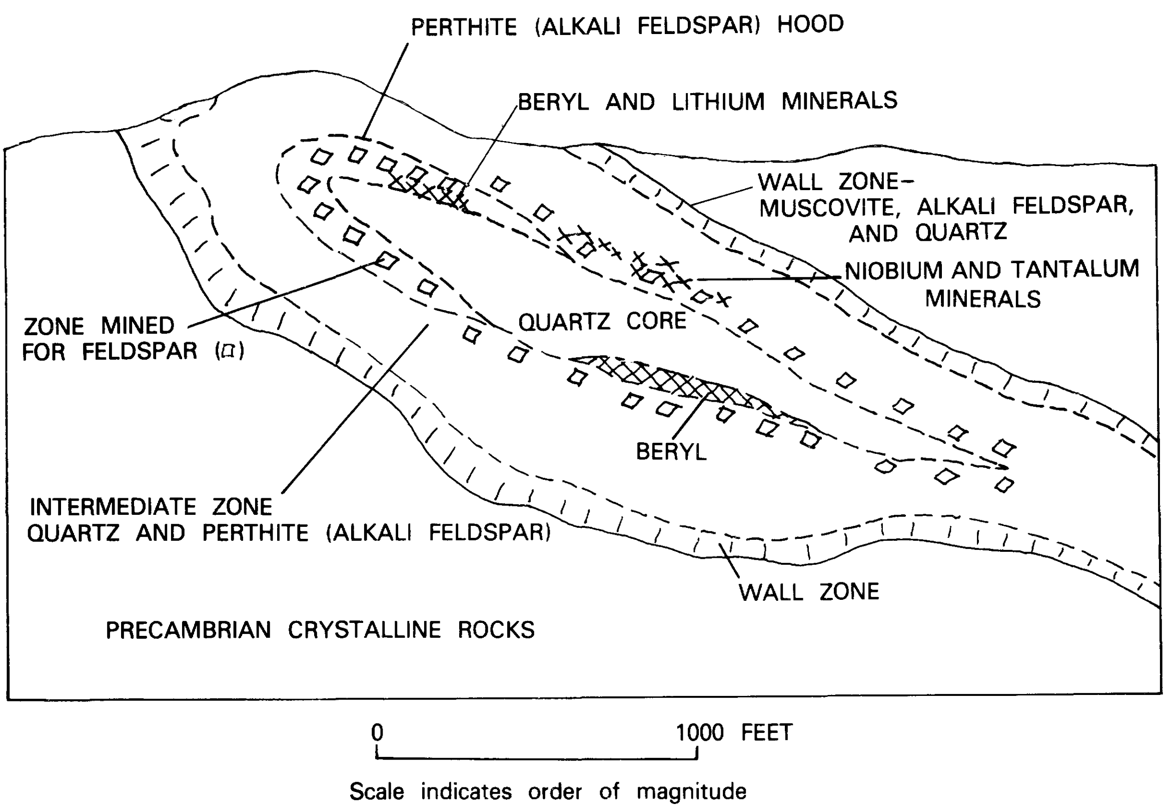


Figure 12. Idealized section of zoned granitic pegmatite representative of type associated with margins of plutons of the Routt Plutonic Suite.

Assessment

The Turret and Trout Creek Pass areas, which are known to have pegmatite bodies, are assigned high resource potential. Near Turret, rocks of the Trout Creek batholith intrude gneissic rocks. The reason that pegmatite bodies are clustered near Trout Creek Pass is not evident from available geologic maps. A contact between two plutons within the Trout Creek batholith is a possible explanation.

Economic Significance

The future of pegmatite mining operations in the forest depends largely on demand for feldspar, chiefly by the ceramic industry. Although lithium, beryllium, niobium, tantalum, rare-earth elements, and mica have been the focus of much past mining, nonpegmatite deposits have become the major sources for most of these commodities. Pegmatite remains the major source for alkali feldspar, and some of the rare elements listed above (used in the space and defense industries) might be recovered as byproducts of feldspar mining.

Tertiary Pegmatites—Pegmatite Minerals

Commodities

Aquamarine (beryl), phenakite, bertrandite, topaz (gems and mineral specimens), molybdenum.

Host Rocks

Pegmatite minerals occur in pegmatite veins and greisen in the Mount Antero Granite (mapped with the Mount Princeton pluton, map unit Tmi, pl.1).

Lithologic Control

Beryllium minerals are contained in the Mount Antero Granite—a pluton within the composite Mount Princeton batholith—in miarolitic cavities in the granite, in quartz-sulfide veins cutting the granite, and in pegmatite bodies. Molybdenite is a component of the greisen assemblage, and in places it is sufficiently abundant to warrant exploration. During World War I, the California mine produced small quantities of molybdenum from a quartz-molybdenite-beryl vein.

Deposit Description

Details of the pegmatite, vein, and miarolitic occurrences are described by Dings and Robinson (1957) and are not repeated here. In general, the pegmatites are small and are associated with greisen zones and with beryl in quartz veins.

Assessment

The outcrop area of the Mount Antero Granite pluton is assigned high resource potential for specimen and gem beryl and phenakite. Minor beryl has been found near the summit of Cottonwood Peak in late-stage granitic intrusions and small bodies of greisen in the Rito Alto stock; these bodies are too small to be shown on plate 2 in this report.

Economic Evaluation

The specimens and gems in the Tertiary pegmatite of the Mount Antero area will continue to attract the interest of collectors and possibly will be the focus of small mining operations in the future. The molybdenum once mined from veins in this area is of little future interest because large porphyry stockwork deposits have supplanted veins as the primary source of this metal.

Veins and Fissure Fillings Containing Fluorspar

Commodity

Fluorspar (fluorite).

Host Rocks

The known deposits are in Precambrian crystalline rocks, but almost any fractured rock can serve as a host.

Structural Control

Deposits are localized along geologically young faults and breccia zones.

Age

Miocene to Holocene(?).

Deposit Description

Veins mined for fluorspar in the Poncha Springs district were as much as 45 ft thick and extended 2,600 ft along strike. Fluorspar has been mined through a vertical range of more than 1,000 ft. Fluorite in these deposits is generally fine grained and constitutes 20–75 percent of the veins. Other minerals found with fluorite are chalcedony (rather than coarsely crystalline quartz), locally abundant calcite and clay, and generally sparse pyrite, barite, and manganese oxides. The Browns Canyon deposits are just outside the forest boundaries, but they resemble those of the Poncha Springs district.

Geochemical Signature

No signature is distinguishable in NURE data.

Geophysical Signature

Some major faults near fluorite deposits show on regional aeromagnetic surveys; the deposits themselves have no expression in regional geophysical data.

Assessment Criteria

1. Presence of known fluorite mines, prospects.
2. Fluorite found with chalcedony, low-temperature-alteration mineral assemblages.

Resource Assessment

The Poncha Springs fluorspar district and nearby zones of fractured rock are assigned high mineral resource potential for fluorspar. The Poncha Springs district still has resource potential for fluorspar, primarily in deep unexplored parts of the vein system, and perhaps also in lateral extensions concealed beneath basin-fill deposits. No other areas in the forest meet criteria for the model used for fluorspar assessment. Fractured rocks near faults related to the Rio Grande rift system may be favorable in some places where they are concealed beneath Quaternary deposits, but no evidence exists to identify such new areas.

Economic Significance

The Poncha Springs district presently is inactive; about 85 percent of United States needs for fluorspar are met from foreign sources. Further development would require a major change in demand for fluorspar.

Limestone and Dolomite in Phanerozoic Rocks

Commodities

High-purity limestone, magnesian limestone, and dolomite.

Host Rocks

Paleozoic carbonate rocks.

Age

Ordovician and Mississippian.

Lithologic Control

Beds of high-purity limestone and dolomite are found in the Leadville Limestone and Fremont Dolomite (parts of map unit MꞒr, pl. 1). Details of the depositional controls of pure carbonate beds within these formations are not available.

Deposit Description

The thickness of beds of high-purity carbonate rocks varies from place to place. Near Monarch Pass, a bed almost 100 ft thick of high-calcium limestone near the base of the Leadville Limestone has been mined since 1930. Near Wellsville, the Leadville contains several beds of high-calcium limestone, and one bed is about 20–25 ft thick. Near Canon City, high-purity dolomite is mined from the Fremont Dolomite through a continuous stratigraphic interval of about 130 ft.

Assessment Criteria

1. Presence of lower Paleozoic strata, Fremont and Leadville Formations at the surface.
2. Presence of quarries.
3. No evidence of mineralized or altered rock (both indicate possible problems meeting purity requirements).

Assessment

Areas of outcrop of map unit MꞒr (pl. 1) including the Fremont and Leadville Formations have been assigned high resource potential for limestone and dolomite, where this unit is remote from hydrothermal mineral deposits.

Economic Significance

Limestone is currently being mined; mining is likely to continue for the foreseeable future. The low unit value of limestone and dolomite favors development of areas close to ready transportation facilities. Requirements for high-purity limestones are approximately the same for metallurgical and chemical uses as for the sugar beet industry and other agricultural uses. In general, the rock needs to contain 95 percent or more $CaCO_3$, 2 percent or less $MgCO_3$, and 3 percent or less insoluble materials. Dolomitic limestone that has $MgCO_3$ content from 20 to 40 percent can be used in the manufacture of lime and in scrubbers for coal-fired power plants. High-purity dolomite has been mined for use in steel plants.

Gypsum Deposits in Phanerozoic Rocks

Commodity

Gypsum.

Host Rocks

Minturn and Belden Formations (map unit IPmb, pl.1).

Age

Pennsylvanian.

Lithologic Control

Gypsum beds are contained in evaporite facies rocks in the Minturn and Belden Formations. Rocks of this facies crop out in an area from South Park to Wellsville and possibly extend south from Wellsville into a poorly exposed and structurally complex part of the Sangre de Cristo Range.

Deposit Description

Multiple beds of gypsum are interbedded with shale (fig. 13). The gypsum beds are lenticular, and in folded areas they are thickened locally by plastic flow. At the north end of the forest, beds as much as 50 ft thick are known; near Wellsville, five beds are present, some of which are as much as 15 ft thick.

Assessment Criteria

1. Presence of evaporite facies rocks of the Minturn or Belden Formations at the surface, or presence in subsurface inferred from geologic data.
2. Presence of gypsum beds.

Assessment

The Minturn and Belden Formations between South Park and Wellsville include evaporite facies rocks containing gypsum beds, and this area is assigned high resource potential for gypsum. The evaporite facies rocks may extend south of the known area of distribution into the northern part of the Sangre de Cristo Range; this possible extension is assigned moderate resource potential because it is in a facies transition zone where lenticular gypsum beds give way to clastic (shale) beds to the south. Gypsum beds, if they extend into this area, are probably highly folded, judging from the complex regional structure.

Economic Significance

Gypsum deposits are currently being mined, and this mining probably will continue for the foreseeable future. When the deposits being mined are exhausted, new deposits will probably be sought in the areas assigned high potential where gypsum is known to exist and where established transportation routes are close.

Minor Commodities

A number of mineral deposit types in the forest rate attention, yet are not of sufficient economic significance

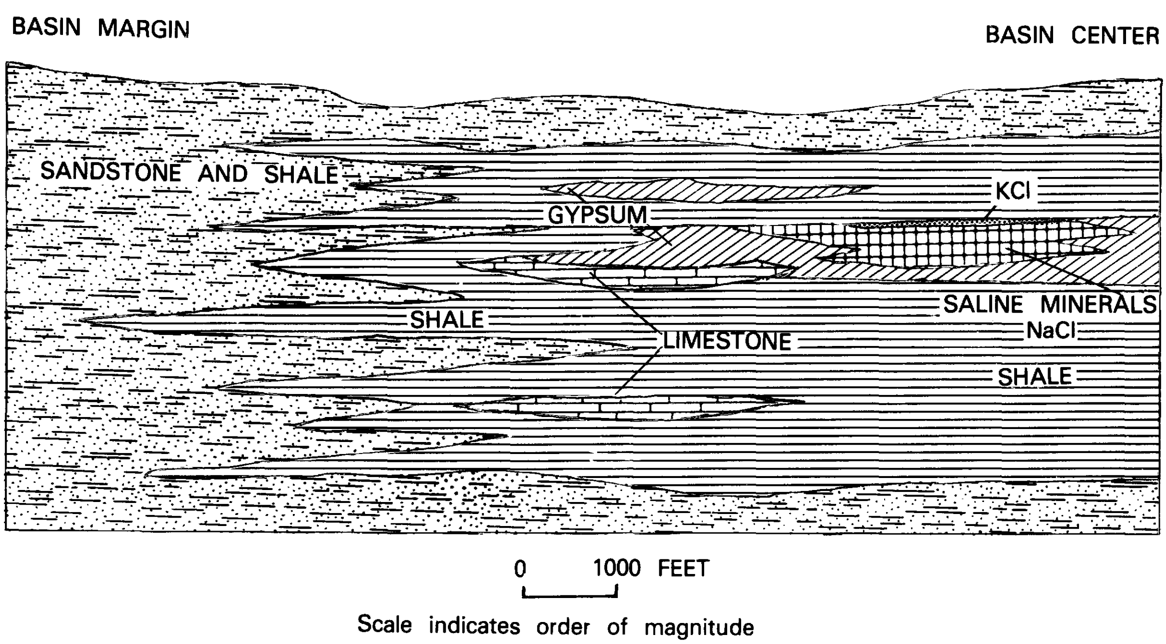


Figure 13. Idealized section showing relationships between clastic and chemically precipitated sedimentary rocks.

to be assessed in the same way as the major types previously discussed. They are briefly described below.

Graphite

A deposit of graphite was mined in 1909 about 2 mi northeast of Turret where several beds of former carbonaceous shale, now containing graphite, were found in metamorphosed Paleozoic rocks adjacent to the Cretaceous Whitehorn stock. The principal bed is 3–4 ft thick and extends a mile along strike. Less than half of this bed contained enough graphite to be considered ore; the graphite ore that was produced contained 75–90 percent carbon (Bastin, 1911, 1914). The relatively low grade of most of this graphite-bearing rock has discouraged further exploration, and the area around Turret is assigned low resource potential for graphite.

Aluminosilicate Minerals

Andalusite and sillimanite have been found in aluminous Precambrian metasedimentary gneiss. Fibrous sillimanite is an important component of many high-grade gneiss bodies but has not been reported in sufficiently pure concentrations to constitute a resource within the forest. Dumortierite and corundum have been reported to be in a pegmatite vein along Grape Creek (Finlay, 1907), which probably is in the forest. Although these minerals have considerable value when sufficiently pure, the reported deposits in the forest probably have specimen value only.

Topaz has been produced from the Climax ore body as a minor byproduct of molybdenum mining; it has largely been used for sand casting, although it can be used in ceramics if fluorine is removed by preheating. Although topaz might be recovered from other porphyry mining operations, it is not sufficiently abundant or valuable to be the primary product.

Manganese

Fissure fillings containing manganese oxides (wad, pyrolusite, and psilomelane) in Paleozoic limestone at several localities from Wellsville to the Turret district were worked during the period 1916–1920. The oxide minerals are believed to have formed by decomposition of manganoan siderite. The few car loads of ore mined contained about 40 percent manganese. Estimated reserves are only about 2,000 tons.

Manganese ore in oxidized parts of lead-silver deposits in the Leadville district was mined between 1891 and 1925. The district yielded about 810,000 tons of generally low grade ore (Emmons and others, 1927), and the district was reported to contain about 2 million tons of inferred reserves (unoxidized manganoan siderite, 10–15 percent manganese, 20 percent iron) according to Hedges (1940).

The low-grade manganese deposits of the forest may contain small quantities of rock that can be sources of manganese under emergency conditions, but they should not be considered resources at this time.

Tin

Small amounts of tin (cassiterite) have been produced as a byproduct of molybdenum mining from the Climax ore body. Cassiterite may be found in some of the other porphyry deposits in the forest, but probably in such small quantities that it does not constitute a resource independent of other commodities.

Small masses of high-silica, "tin" rhyolite east of Nathrop (Nathrop Volcanics, map unit Tbr, pl. 1) resemble parts of the rhyolite dome fields of New Mexico (Black Range) that have produced small quantities of cassiterite. Most of the cassiterite of the Black Range is believed to have been deposited along with silica and iron oxide minerals from a vapor phase during cooling of rhyolite domes. Although cassiterite has not been reported from the Nathrop area, it may be present in amounts insufficient to constitute a tin resource.

Turquoise

Workings about 7 mi northwest of Leadville have yielded gem turquoise since the days of the prehistoric Indians. Turquoise in veins and nodules in altered granite formed as an alteration mineral within a hyrothermal cell generated by concealed igneous rocks of the Turquoise Lake center. Turquoise has been noted at two mines in this area and may occur at others. Assessment of the resource potential of the area for turquoise is not appropriate to the scale of this study.

Uranium

Uranium occurrences in the Harding Sandstone (Ordovician) have been classified as nonchannel-controlled peneconcordant deposits having characteristics of syngenetic phosphorites (Dickinson and Hills, 1982). Uranium has been produced from the Harding at the Beginner's Luck claim (11.8 kg U_3O_8 produced), on Wild Cherry Creek 15 mi southeast of Villa Grove, and from the Marshall Pass district; both areas are close to, but outside, the San Isabel National Forest. The mineralized zone in the Harding in the Marshall Pass district is 3–6 ft thick, and the U_3O_8 concentration in the zone ranges from 100 to 300 ppm, values which qualify the ground as "favorable" according to NURE criteria. Within the forest, grades and thicknesses seem to be too low to qualify the Harding as a uranium resource as defined in the present study (see Appendix 1).

A small quantity of uranium "ore" (510 tons, 0.13 percent U_3O_8, 0.009 percent V_2O_5) was produced from the Stumbling Stud mine at Badito Cone (south end of the Wet Mountains). The uranium minerals there are in veinlets and are disseminated in a Tertiary (Miocene?) alkalic intrusion (map unit Tmi, pl. 1) and in the Dakota, Purgatoire, and Morrison Formations (map units Kd, Jm, pl. 1). The chief uranium mineral, perhaps coffinite, is accompanied by fluorite and a zirconium-bearing mineral; no uranium was recovered from the "ore" because of metallurgical problems (Toth and others, 1983). Low resource potential is assigned to the area because of the limited size and low grade of the deposit.

Vermiculite

Vermiculite has been reported from the area north of Salida (Eckel, 1961) as occurring in "veins," but it seems rather to have formed by the weathering of biotite mica in inclusions of mafic gneiss in granodiorite. The resource potential of this area for vermiculite is regarded as low.

MINERAL RESOURCES—LEASABLE MINERALS

The Mineral Leasing Act of 1920 excepted oil and gas, oil shale, potash, sodium, native asphalt, bitumen or bituminous rock, phosphate, and coal from the provisions of the General Mining Law of 1872 and set up laws to control the right to explore for, develop, and produce specific minerals through a system of prospecting permits and leases. These commodities are sometimes referred to as leasing act minerals but are called leasable minerals in this report. The Geothermal Steam Act of 1970 adds geothermal energy to the list of leasable minerals.

No records of production exist for oil, gas, oil shale, potash, sodium, asphalt, bituminous rock, and phosphate in the forest.

Margins of the forest fringing the upper Arkansas Valley border known areas of hot springs; on the west side of the valley, these include the Chalk Creek (Mount Princeton Hot Springs) and Cottonwood Creek areas; on the east side, the Buena Vista and Browns Canyon areas; and on the south, the Poncha Pass area. Only the Chalk Creek and Cottonwood Creek areas extend into the forest.

Formations known to have produced coal crop out in the vicinity of the Spanish Peaks and underlie a part of the forest. The Spanish Peaks lie astride the boundary between the Trinidad and Walsenberg coal fields, an arbitrary division of a single coal basin drawn along the Huerfano-Las Animas county line.

No other leasable minerals have been found within the forest. Although gypsum-bearing evaporite facies rocks are present in the Pennsylvanian-Permian section, no deposits formed from hypersaline brines that might contain sodium and potassium resources are known on forest lands.

RESOURCE POTENTIAL—LEASABLE MINERALS

This evaluation of the mineral resource potential of the San Isabel National Forest for leasable minerals recognizes a high potential for geothermal energy and coal. Definitions of terminology used, specifically the several levels of resource potential, are provided in Appendix 1.

The San Isabel National Forest is assigned a low potential for oil and gas resources. The only areas in the forest underlain by thick sections of sedimentary rocks are in the central Sangre de Cristo Range and the Spanish Peaks. These areas have been assigned low resource potential in previous evaluations (Miller, 1983). The four critical requirements for hydrocarbon accumulation—(1) reservoir (porous) rocks, (2) hydrocarbon (organic-rich) source beds, (3) impermeable seal to prevent loss of hydrocarbons, and (4) favorable thermal history—are not met by any areas in the forest. Assessment of the oil and gas potential of the forest in the southern part of the Sangre de Cristo Range is difficult because of structural complexities. Favorable source and host rocks for oil and gas occur in Huerfano Park to the east of the forest but are not exposed in the forest. Because a zone of thrust faults extends through the forest and into Huerfano Park, we must consider the possibility that favorable strata (source and reservoir rocks) are present beneath the thrusts. A detailed analysis of the structure of this area requires subsurface and seismic-section data not presently available. If favorable rocks such as Cretaceous sandstone and shale extend under the forest beneath the thrusts, the area underlain by them is small and details of its subsurface structure are unknown. On the basis of available information, the likelihood of the occurrence of oil or gas resources is judged low.

Geothermal Resources

Commodity

Geothermal energy (steam, hot water).

Host Rocks

Fractured and (or) permeable rocks of any formation.

Age

Holocene; geothermal resources are likely in areas of high modern heat flow resulting either from high regional geothermal gradients or from proximity to young intrusions or magma bodies.

Description

Hot springs and thermal wells associated with intense zeolitic alteration characterize the Mount Princeton geothermal area. The thermal system is active at present, and temperatures of 38.5–85°C have been recorded. The water pH is nearly neutral to slightly basic (7.6–9.6). The composition of the water varies from sodium sulfate-sodium bicarbonate types to sodium bicarbonate types. On the basis of water geochemistry, subsurface temperatures are estimated to be 125°C.

Thermal springs are also present at Browns Canyon, Poncha Pass, and in areas in the San Luis Valley, south of the San Isabel National Forest. The Browns Canyon and Poncha Springs thermal springs are near fluorspar deposits that may have formed during earlier stages of hot spring activity. The thermal water is regarded as meteoric water circulated to great depths along faults and fractures related to the Rio Grande rift system, where it is heated by contact with hot rocks and returned to the surface. The high heat flow of this area, two or three times normal geothermal gradient, facilitates heating of the water.

Assessment Criteria

1. Presence of hot springs or thermal wells.
2. Presence of hydrothermal alteration minerals, such as sulfates, zeolites, clays, and fluorine minerals.
3. Proximity to fractured zones, especially to faults of the Rio Grande rift system.
4. Proximity to areas of Holocene volcanism or igneous intrusion.

Assessment

Areas that have hot springs and altered rock are clearly adjacent to Miocene and younger faults of the Rio Grande rift system and possibly areas where northerly trending faults are intersected at high angles by cross faults. Exploration for geothermal resources has been concentrated near hot springs. Geothermal resources are also likely along other parts of the Neogene fault system of the upper Arkansas Valley, but data sufficient to indicate the level of resource favorability are lacking for many areas. A high potential is assigned areas surounding known geothermal features, and a low potential is assigned areas of most Neogene fault and fracture systems where there is no indication of a modern hot water system.

An area of unknown potential for geothermal resources is shown (pl. 2) in the upper Arkansas Valley where Tertiary and Quaternary cover masks the nature of systems circulating deep ground water.

Economic Significance

Geothermal energy is eagerly sought because it is regarded as environmentally clean (despite problems of exploiting highly saline waters), and the cost of generating facilities is relatively modest if steam is present. The areas in the forest that have high potential for geothermal resources have been tested by limited drilling, and hot water, not steam, has been found. These areas will continue to be of interest, and as technology evolves they may well be exploited in the future.

Coal Deposits in Phanerozoic Rocks

Commodity

Coal, chiefly bituminous; anthracite may be present locally near intrusive rocks that cut the coal-bearing horizons.

Host Rocks

Vermejo and Raton Formations (map unit TKr, pl. 1).

Age

Late Cretaceous and Paleocene.

Deposit Description

The Vermejo and Raton Formations yield high-volatile bituminous coal, generally of coking quality. Both formations contain multiple and lenticular coal beds, generally less than 10 ft thick. Almost all mining has been from the Vermejo Formation because its coal beds are generally thicker and higher in quality than those in the Raton. Coal beds in the vicinity of the intrusive rocks have been upgraded, and in some places even coked, by heat from dikes, sills, and other intrusions.

Assessment Criteria

1. Presence of Vermejo and (or) Raton Formations at the surface or in the subsurface, as inferred from geologic data.
2. Evaluation of the effects of nearby igneous intrusive rocks that cut these formations.

Assessment

The Vermejo and Raton Formations underlie the eastern part of the forest in the vicinity of the Spanish Peaks. The rocks dip steeply eastward from the outcrop area and probably lie at depths greater than 3,000 ft in the eastern part of the forest. The heat from the intrusions of East and West Spanish Peaks and from the radial dike swarm centered on the western intrusive has undoubtedly baked, upgraded, and possibly coked parts of the coal beds. The area underlain by the Vermejo and Raton Formations is assigned a high resource potential for coal.

Economic Significance

The depth of the coal, its probable variability in quality due to thermal effects caused by the Tertiary igneous activity, and the lenticular nature of the coal beds in these formations will make exploration and mining (by conventional underground techniques) costly and difficult. The possibility for anthracite near the contacts with the plutons may be the principal focus of interest in the forest.

MINERAL RESOURCES—SALABLE MINERALS By John S. Dersch, U.S. Forest Service

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

Sand and gravel deposits are abundant in all parts of the forest and are exploited for road fill, aggregate for concrete, macadam, mortar, and other purposes. Certain quarries are used regularly; eight sites are currently active (1984). An upper Pleistocene glacial deposit of fairly well sorted granitic materials about 2.5 mi southwest of Tennessee Pass has been the source of sand and gravel for an active operation since 1946. Schwochow (1981) recorded 40 sites for rock, sand, sand and gravel, rubble, and borrow materials on forest lands. Many other places are mined as local needs for road fill and construction create a short-term demand. The principal production is from fluvial deposits, but special needs for aggregate, such as for crushed limestone, are met by quarrying bedrock.

Dimension stone has been quarried from the Whitehorn stock (Turret mining district). Granodiorite from this mass has a distinctive appearance, and the stone has been used locally. Marble for local use has been quarried near Turret and from the Monarch district.

Pumice and perlite deposits have been prospected on the north flank of Ruby Mountain, near Nathrop, but have had no significant production.

Although specimens of petrified wood can be found in the Antero Formation and in some Quaternary gravel, it has not been found anywhere in the forest in the quantity and quality required to constitute a resource.

Clay suitable for refractory bricks has been mined from the Dry Creek Canyon Member of the Dakota Sandstone and from the Purgatoire Formation where these units crop out along the eastern edge of the Wet Mountains near Beulah and Rye. Within the forest, the known clay beds are not of adequate quality and must be mixed with higher grade clays to make a satisfactory raw material for refractory brick. Mineral industry activity, therefore, has been limited to prospecting.

RESOURCE POTENTIAL—SALABLE MINERALS

The mineral resource potential for sand and gravel, pumicite and scoria, and bulk clays is evaluated here. Income from the sale of these mineral commodities will vary according to accessibility, unit value and cost, and amount produced. Environmental factors, such as ground disturbance due to bulk mining, have not been considered in this assessment.

Sand and Gravel

Sand and gravel for road construction are available in the forest in quantities adequate for most needs. Almost all the bedrock units disaggregate on weathering to form alluvial deposits suitable for construction. Only the Pennsylvanian-Permian sedimentary units (PIPs, IPmb, PIPf, pl. 1), the Cretaceous shale (Ks), and parts of the Miocene basin-fill deposits (Ts) contain too much clay to serve as good sources. Limestone and dolomite for concrete aggregate can be obtained by crushing the Paleozoic rocks (M€r). The glacial and fluvial units (Qa) are most commonly exploited. The distribution of these units is shown on plate 1.

The distribution of alluvial units cannot be shown well at 1:250,000 scale; therefore, the geologic map cannot be used to inventory all sources of materials. For land management purposes, however, this assessment indicates that local sources of sand and gravel can be found in almost all parts of the forest and that materials are available to meet special needs. The map showing the distribution of salable minerals (fig. 3) in the Summary section of this report, shows the general distribution of the Quaternary alluvium (map unit Qa, pl. 1) because it is the most likely unit to provide sand and gravel.

Dimension Stone

Sources of dimension stone, including igneous rocks and marble, are found in many places in the forest. Each must be evaluated as resources according to the proposed use (and value) of the material. The appearance and aesthetic qualities must be appropriate to the use, as must be the physical characteristics, including strength, weathering characteristics, ease of quarrying, and freedom from cracks. Detailed assessments of each rock type cannot be made using maps at 1:250,000 scale.

Pumice and Perlite

Volcanic rocks containing pumice, perlite, scoria, and other sources of lightweight aggregate are present only in small amounts in the forest. Rocks near Nathrop do contain pumice and perlite, but quantities are small and the deposits have not been exploited. Details of the distribution of these kinds of materials in other volcanic areas within the forest are not available: these include parts of volcanic fields near Bonanza and Independence Pass. The forest is appraised as having low resource potential for these kinds of materials on the basis of present knowledge of the volcanic sections.

Clay

Sources of clay suitable for refractory brick making are limited to outcrops of Dakota and Purgatoire Formations on the eastern edge of the Wet Mountains. Known clay beds are too low in quality to have been of interest for mining so far. The detail of information developed by this study is not adequate to be used to determine quality or quantity of this possible clay resource. The outcrops of formations containing clay are very restricted in size in the forest, especially as compared with the large areas of Dakota and Purgatoire outcrop just outside forest boundaries. The larger outcrops of these units would probably be exploited before the smaller ones inside the forest are developed. Needs for clay for brick making will determine if and when the deposits in the forest are mined.

RECOMMENDATIONS FOR FUTURE STUDIES OF MINERAL RESOURCE POTENTIAL

The rich mineral resource endowment of parts of the San Isabel National Forest has prompted close study of the geology and mineral deposits. The study of the Leadville mining district and its ores by Emmons and others (1927) is a geologic classic, even though it was published long after the bonanza days of the district were over. Parts of the forest, however, have not yet been studied in sufficient detail to assess their mineral resource potential adequately.

Most of the detailed geologic studies in the forest predate understanding of the Precambrian stratabound deposits, thus much additional detailed geologic study is needed of the Precambrian gneiss. The large area of gneiss (map unit Xfh, pl. 1) in the vicinity of Monarch Pass needs especially detailed geologic and geochemical study. Mapping at 1:24,000 scale is required to understand the genesis of the gneiss and determine the geologic environments in which the gneiss protolith formed. Faults having large displacement exist in the area, and other unmapped faults probably are present. The fracture and fault systems must be established if the ore systems of all ages are to be understood. In particular, the major structural blocks of Precambrian gneiss must be delineated as a first step in geologic evaluation of the area.

The major hydrothermal systems associated with the internal parts of the Mount Princeton batholith have been crudely delineated (pl. 2) as areas of high resource potential, but the internal structure of the batholith and its relation to the geometry of hydrothermal systems are not well known. Detailed (unpublished) mapping of the southern part of the batholith indicates the presence of many separate intrusions, but comparable studies have not been attempted in other parts of the batholith. A detailed (draped) radiometric survey to delineate the uranium, thorium, and potassium distribution in the Chalk Creek district, and perhaps for the entire Mount Princeton batholith would be especially desirable to delineate areas where latent potassium metasomatism might disclose concealed plutons and attendant hydrothermal systems containing copper and molybdenum resources. Field studies of rock alteration patterns and detailed geochemical surveys would assist in evaluating the likelihood of concealed porphyry systems.

The quality of the 1:250,000-scale geologic mapping covering the San Isabel National Forest varies. The maps of the Leadville and Pueblo 1°×2° topographic quadrangles meet all standards for general purpose geologic mapping. The map of the Montrose 1°×2° topographic quadrangle was more quickly done and needs additional detail in the southern Sawatch Range. The Trinidad 1°×2° topographic quadrangle needs restudy because Precambrian rocks were not classified according to modern standards on the published map and the level of geologic detail shown is inadequate. Fortunately for this evaluation, recent studies of the Sangre de Cristo and Spanish Peaks Wilderness Study Areas fill in much needed detail, but the Precambrian gneiss of the Spanish Peaks area and the Greenhorn area require modern geologic mapping to support adequate resource assessment.

No adequate geochemical data exist for the parts of the forest in the Leadville, Montrose, and Trinidad $1^\circ \times 2^\circ$ topographic quadrangles. The analyses obtained from the NURE surveys are not adequate for assessment, and data on gold, silver, molybdenum, zinc, and arsenic are needed to evaluate possible mineralized systems related to the silicic plutons. The NURE data should be augmented with analyses of panned-concentrate samples and rock samples to evaluate the nature of the hydrothermal systems.

The entire forest should be surveyed by modern aeromagnetic methods (flight-line spacing about one-half mile). Excellent aeromagnetic surveys are available for parts of the forest, but not for the western part, where this assessment has indicated areas of high mineral resource potential. Evidence for concealed plutons might be obtained, and areas of hydrothermally altered rocks might be expressed as magnetic lows due to destruction of magnetite.

Many areas covered by Quaternary and Tertiary valley-fill deposits are shown as having unknown resource potential for metals and for geothermal energy. Detailed geophysical studies, and possibly physical exploration, would be required to assess these areas.

For certain kinds of deposits, such as placer gold and construction materials, detailed, site-specific studies would be required to evaluate the resource potential. Maps at 1:250,000 scale are too general to be used to determine the potential for many commodities that are in small deposits not related to major geologic systems.

Studies are now being conducted in the Sawatch Range to determine the mineral resource potential of the Holy Cross, Mt. Massive, and Collegiate Peaks Wilderness areas. The results of these surveys should be incorporated into the planning process for the San Isabel National Forest.

SELECTED REFERENCES

Geology and Mineral Resources

Adams, J. W., Arengi, J. T., and Parrish, I. S., 1980, Uranium- and thorium-bearing pegmatites of the United States: U.S. Department of Energy Open-File Report GJBX–166(80), 127 p.

Armbrustmacher, T. J., 1976, Thorium deposits in the Wet Mountains area, Fremont and Custer Counties, Colorado: U.S. Geological Survey Open-File Report 78–177, 18 p.

Bastin, E. S., 1911, Graphite: U.S. Geological Survey mineral resources of the United States, 1909, pt. 2, p. 819–820.

———1914, Graphite: U.S. Geological Survey mineral resources of the United States, 1913, pt. 2, p. 197–198.

Boyer, R. E., 1962, Petrology and structure of the southern Wet Mountains, Colorado: Geological Society of America Bulletin, v. 73, p. 1047–1070.

Brobst, D. A., and Pratt, W. P., 1973, eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, 722 p.

Budding, K. E., and Kluender, S. E., 1983, Mineral resource potential map of the Spanish Peaks Wilderness Study Area, Huerfano and Las Animas Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–1542–C, scale 1:50,000.

Budding, K. E., and Lawrence, V. A., 1983, Reconnaissance geologic map of the Spanish Peaks Wilderness Study Area, Huerfano and Las Animas Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–1542–A, scale 1:50,000.

Case, J. E., 1967, Geophysical ore guides along the Colorado mineral belt: U.S. Geological Survey Open-File Report 67–39, 21 p.

Collins, D. B., Graham, D. C., and Hornbaker, A. L., 1980, Leadville quadrangle, Colorado (National Uranium Resource Evaluation): U.S. Department of Energy, PGJ–027(80).

Curtis, B. F., ed., 1975, Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, 279 p.

Del Rio, S. M., ed., 1960, Mineral resources of Colorado, first sequel: Denver, Colorado Mineral Resources Board, 764 p.

Dickinson, K. A., and Hills, F. A., 1982, Pueblo quadrangle, Colorado (National Uranium Resource Evaluation): U.S. Department of Energy, PGJ/F–075(82), 109 p.

Dings, M. G., and Robinson, C. S., 1957, Geology and ore deposits of the Garfield quadrangle, Colorado: U.S. Geological Survey Professional Paper 289, 110 p.

Eckel, E. B., 1961, Minerals of Colorado; a 100–year record: U.S. Geological Survey Bulletin 1114, 399 p.

Emmons, S. F., Irving, J. D., and Loughlin, G. F., 1927, Geology and ore deposits of the Leadville mining district, Colorado: U.S. Geological Survey Professional Paper 148, 368 p.

Epis, R. C., and Weimer, R. J., eds., 1976, Studies in Colorado field geology: Professional Contributions of Colorado School of Mines, no. 8, 552 p.

Erickson, R. L., ed., 1982, Characteristics of mineral deposit occurrences: U.S. Geological Survey Open-File Report 82–795, 248 p.

Finlay, G. I., 1907, On an occurrence of corundum and dumortierite in pegmatite in Colorado (near Canon City): Journal of Geology, v. 15, p. 479–484.

Goodknight, C. S., and Ludlam, J. R., 1981, Montrose Quadrangle, Colorado (National Uranium Resource Evaluation): U.S. Department of Energy, GJQ–010(81).

Guyton, J. S., Hutton, J. R., and Sokolsky, G. E., 1960, Geology of the Devils Hole Area, Custer and Huerfano Counties, Colorado: Ann Arbor, University of Michigan M.S. thesis, 81 p.

Hanley, J. B., Heinrich, E. W., and Page, L. R., 1950, Pegmatite investigations in Colorado, Wyoming, and Utah 1942–1944: U.S. Geological Survey Professional Paper 227, 125 p.

Hedges, J. H., 1940, Mineral industries survey of the United States; Colorado, Lake County: U.S. Bureau of Mines Information Circular 7125, 23 p.

Hedlund, D. C., Nowlan, G. A., and Woods, R. H., 1983, Mineral resource potential of the Buffalo Peaks Wilderness Study Area, Pike and San Isabel National Forests, Lake, Park, and Chaffee Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–1628–A, scale 1:50,000.

Johnson, B. R., Lindsey, D. A., Bruce, R. M., and Soulliere, S. J., in press, Reconnaissance geologic map of the Sangre de Cristo Wilderness Study Area, south-central Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–1635–B, scale 1:62,500.

Johnson, B. R., Lindsey, D. A., Ellis, C. E., Hannigan, B. J., and Thompson, J. R., 1984, Mineral resource potential of the Sangre de Cristo Wilderness Study Area, south-central Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–1635–A, scale 1:62,500.

Johnson, R. B., 1969, Geologic map of the Trinidad quadrangle, south central Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–558, scale 1:250,000.

Johnson, V. C., McCarn, D. W., Kocis, D. E., Walker, B. W., and Reinhart, W. R., 1980, Trinidad Quadrangle, Colorado (National Uranium Resource Evaluation): U.S. Department of Energy, PGJ–031(81).

Jones, E. L., Jr., 1920, Some deposits of manganese ore in Colorado: U.S. Geological Survey Bulletin 715–D, 72 p.

Kent, H. C., and Porter, K. W., eds., 1980, Colorado geology: Denver, Colo., Rocky Mountain Association of Geologists, 258 p.

Koschman, A. H., and Bergendahl, M. H., 1968, Principal gold-producing districts of the United States: U.S. Geological Survey Professional Paper 610, 283 p.

Landis, E. R., 1959, Coal resources of Colorado: U.S. Geological Survey Bulletin 1072–C, 232 p.

Miller, B. M., ed., 1983, Petroleum potential of wilderness lands in the western United States: U.S. Geological Survey Circular 902–A–P.

Munger, R. D., 1965, Structural geology of the Spread Eagle Peak area, Sangre de Cristo Mountains, Colorado: Mountain Geologist, v. 2, no. 1, p. 3–21.

Nelson-Moore, J. L., Collins, D. B., and Hornbaker, A. L., 1978, Radioactive mineral occurrences of Colorado: Colorado Geological Survey Bulletin 40, 1054 p.

Parker, B. H., Jr., 1974, Gold placers of Colorado: Colorado School of Mines Quarterly, v. 69, no. 3, 268 p., and no 4, 224 p.

Peterman, Z. E., Hedge, C. E., and Braddock, W. A., 1968, Age of Precambrian events in the northeastern Front Range, Colorado: Journal of Geophysical Research, v. 73, p. 2277–2296.

Schwochow, S. D., 1981, Inventory of nonmetallic mining and processing operations in Colorado: Colorado Geological Survey Map Series 17, 39 p.

Scott, G. R., and Taylor, R. B., 1975, Post-Paleocene Tertiary rocks and Quaternary volcanic ash of the Wet Mountain Valley, Colorado: U.S. Geological Survey Professional Paper 868, 15 p.

Scott, G. R., Taylor, R. B., Epis, I. C., and Wobus, R. A., 1978, Geologic map of the Pueblo 1°×2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1022, scale 1:250,000.

Sharp, W. N., 1976, Geologic map and details of the beryllium and molybdenum occurrences, Mount Antero, Chaffee County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–810, scale 1:24,000.

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.

Skinner, B. J., ed., 1981, Seventy-fifth anniversary volume, 1905–1980: Economic Geology Publishing Co., 964 p.

Staatz, M. H., Armbrustmacher, T. J., Olson, J. C., Brownfield, I. K., Brock, M. R., Lemons, J. F., Jr., Coppa, L. V., and Clingan, B. V., 1979, Principal thorium resources in the United States: U.S. Geological Survey Circular 805, 42 p.

Toth, M. I., Birch, D. R., and Baskin, G. D., 1983, Mineral resource potential of the Greenhorn Mountain Wilderness Study Area, Huerfano and Pueblo Counties, Colorado: U.S. Geological Survey Open-File Report 83–467, 9 p.

Tweto, Ogden, 1977, Nomenclature of Precambrian rocks in Colorado: U.S. Geological Survey Bulletin 1422–D, 22 p.

———in press, Rock units of the Precambrian basement in Colorado: U.S. Geological Survey Professional Paper 1321–A.

Tweto, Ogden, Moench, R. H., and Reed, J. C., Jr., 1978, Geologic map of the Leadville 1°×2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–999, scale 1:250,000.

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, 1975, Mineral facts and problems: U.S. Bureau of Mines Bulletin 667, 1259 p.

U.S. Bureau of Mines and U.S. Geological Survey, 1980, Principles of a resource/reserve classification for minerals: U.S. Geological Survey Circular 831, 5 p.

U.S. Geological Survey, 1964, Mineral and water resources of Colorado: Washington, D.C., U.S. Government Printing Office, 302 p.

Geochemistry

Bolivar, S. L., Balog, S. H., Campbell, Katherine, Weaver, T. A., and Wecksung, G. W., 1981, Multisource data set

integration and characterization of uranium mineralization for the Montrose quadrangle, Colorado: Los Alamos Scientific Laboratory Informal Report LA-8807-MS, 172 p.
Budding, K. E., and Lawrence, V. A., 1983, Geochemical map of the Spanish Peaks Wilderness Study Area, Huerfano and Las Animas Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-1542-B, scale 1:50,000.
Shannon, S. S., Jr., 1978a, Uranium hydrogeochemical and stream sediment reconnaissance of the Pueblo NTMS Quadrangle, Colorado: Los Alamos Scientific Laboratory Informal Report LA-7341-MS, 77 p.
———1978b, Uranium hydrogeochemical and stream sediment reconnaissance of the Pueblo NTMS Quadrangle, Colorado, including concentrations of forty-three additional elements: Los Alamos Scientific Laboratory Informal Report LA-7341-MS, supplement, 141 p.
U.S. Department of Energy, 1984, Geochemical analyses of stream-sediment samples from the Leadville 1°×2° quadrangle, Colorado: U.S. Department of Energy Open-File Report GJBX 1381. [Data available on magnetic tape from Bendix Field Engineering Corp., P.O. Box 1569, Grand Junction, Colorado 89501.]
———1984, Geochemical analyses of stream-sediment samples from the Montrose 1°×2° quadrangle, Colorado: U.S. Department of Energy Open-File Report GJBX 12579 and GJBX 10581. [Data available on magnetic tape from Bendix Field Engineering Corp., P.O. Box 1569, Grand Junction, Colorado 89501.]
———1984, Geochemical analyses of stream-sediment samples from the Pueblo 1°×2° quadrangle, Colorado: U.S. Department of Energy Open-File Report GJBX 1479 and GJBX 4279. [Data available on magnetic tape from Bendix Field Engineering Corp., P.O. Box 1569, Grand Junction, Colorado 89501.]
———1984, Geochemical analyses of stream-sediment samples from the Trinidad 1°×2° quadrangle, Colorado: U.S. Department of Energy Open-File Report GJBX 13978 and GJBX 13880. [Data available on magnetic tape from Bendix Field Engineering Corp., P.O. Box 1569, Grand Junction, Colorado 89501.]

Geophysics

Behrendt, J. C., and Bajwa, L. Y., 1974, Bouguer gravity map of Colorado: U.S. Geological Survey Geophysical Investigations Map GP-895, scale 1:500,000.
Boler, F. M., Klein, D. K., and Kleinkopf, M. D., 1982, Bouguer gravity map of the Pueblo 1°×2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1419-A, scale 1:250,000.
Case, J. E., 1967, Geophysical ore guides along the Colorado mineral belt: U.S. Geological Survey Open-File Report 67-39, 21 p.
Cordell, Lindrith, Keller, G. R., and Hildenbrand, T. G., 1982, Bouguer gravity map of the Rio Grande Rift, Colorado, New Mexico, and Texas: U.S. Geological Survey Geophysical Investigations Map GP-949, scale 1:1,000,000.
Kleinkopf, M. D., Peterson, D. L., and Johnson, R. B., 1970, Reconnaissance geophysical studies in the Trinidad quadrangle, south-central Colorado: U.S. Geological Survey Professional Paper 700-B, p. 78-85.
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.
U.S. Geological Survey, 1970, Aeromagnetic map of the Cripple Creek-Saguache area, south-central Colorado: U.S. Geological Survey Open-File Report 70-336, scale 1:62,500.
———1978, Aeromagnetic map of the Arkansas Valley and vicinity, Colorado: U.S. Geological Survey Open-File Report 78-112, scale 1:125,000.
———1979a, Aeromagnetic map of the Hunter Frying Pan area, Colorado: U.S. Geological Survey Open-File Report 79-1226, scale 1:62,500.
———1979b, Aeromagnetic map of the Pueblo area, Colorado: U.S. Geological Survey Open-File Report 79-1368, scale 1:62,500.
———1979c, Aeromagnetic map of the Westcliffe-Royal Gorge area, Custer and Fremont Counties, Colorado: U.S. Geological Survey Geophysical Investigations Map GP-929, scale 1:62,500.
———1982, Aeromagnetic map of the Buffalo Peaks area, Colorado: U.S. Geological Survey Open-File Report 82-978, scale 1:50,000.
———1983, Aeromagnetic map of the Sangre de Cristo Mountains, Colorado: U.S. Geological Survey Open-File Report 83-60, scale 1:62,500.
Zietz, Isidore, and Kirby, J. R., Jr., 1972, Aeromagnetic map of Colorado: U.S. Geological Survey Geophysical Investigations Map GP-836, scale 1:500,000.

APPENDIX 1. Definition of levels of mineral resource potential and certainty of assessment

Mineral resource potential is defined as the likelihood of the presence of mineral resources in a defined area; it is not a measure of the amount of resources or their profitability.

Mineral resources are concentrations of naturally occurring solid, liquid, or gaseous materials in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Low mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment where the existence of resources is unlikely. This level of potential embraces areas of dispersed mineralized rock as well as areas having few or no indications of mineralization. Assignment of low potential requires specific positive knowledge; it is not to be used as a catchall for areas where adequate data are lacking.

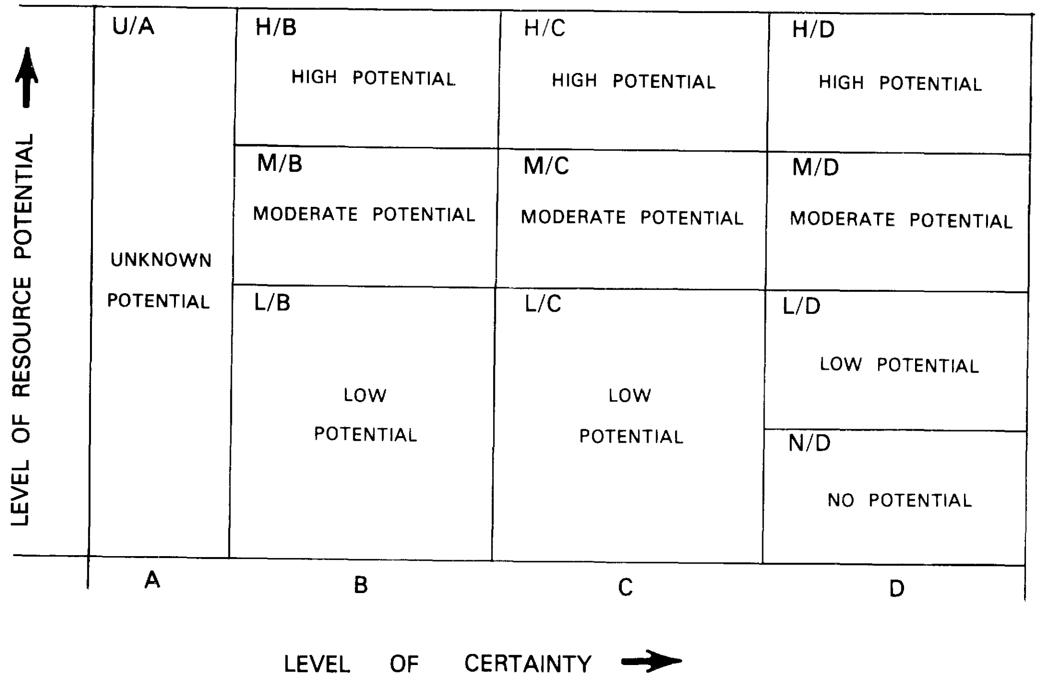


Figure 14. Major elements of mineral resource potential/certainty classification.

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 chance for resource accumulation, and where an application of genetic and (or) occurrence models indicates favorable ground.

High mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resources, where interpretations of data indicate a high likelihood for resource accumulation, where data support occurrence and (or) genetic models indicating presence of resources, and where evidence indicates that mineral concentration has taken place. Assignment of high resource potential requires positive knowledge that resource-forming processes have been active in at least part of the area; it does not require that occurrences or deposits be identified.

Unknown mineral resource potential is assigned to areas where the level of knowledge is so inadequate that classification of the area as high, moderate, or low would be misleading. The phrase "no mineral resource potential" applies only to a specific resource type in a well-defined area. This phrase should not be used if there is the slightest possibility of resource occurrence; it is not appropriate as the summary rating for any area.

Expressions of the certainty of the mineral resource assessment incorporate a consideration of (1) the adequacy of the geologic, geochemical, geophysical, and resource data base available at the time of the assessment, (2) the adequacy of the occurrence or genetic model used as the basis for a specific evaluation, and (3) an evaluation of the likelihood that the expected mineral endowment of the area is, or could be, economically extractable.

Levels of certainty of assessments are denoted by letters, A–D (fig. 14).

A. The available data are not adequate to determine the level of mineral resource potential. Level A is used with an assignment of unknown mineral resource potential.

B. The available data are adequate to suggest the geologic environment and the level of mineral resource potential, but either evidence is insufficient to establish precisely the likelihood of resource occurrence, or occurrence and (or) genetic models are not known well enough for predictive resource assessment.

C. The available data give a good indication of the geologic environment and the level of mineral resource potential, but additional evidence is needed to establish precisely the likelihood of resource occurrence, the activity of resource-forming processes, or available occurrence and (or) genetic models are minimal for predictive applications.

D. The available data clearly define the geologic environment and the level of mineral resource potential, and indicate the activity of resource-forming processes. Key evidence to interpret the presence or absence of specified types of resources is available, and occurrence and (or) genetic models are adequate for predictive resource assessment.

APPENDIX 2. Geochemical data

Analyses of stream-sediment samples (−100 mesh fraction) made during the NURE (National Uranium Resource Evaluation) program formed the only geochemical data base available for the entire San Isabel National Forest. Experience using NURE geochemical data suggests that analytical problems must be anticipated for samples where high amounts of zirconium, rare-earth elements, and other interfering elements may be present. Analytical interferences greatly influence true detection limits for many elements as well as the accuracy and precision of determinations. Evaluation of these data indicate that only a small part of the NURE stream-sediment geochemical data should be used. Maps showing these data were plotted at 1:250,000 scale, with the analyses grouped according to percentile values. For elements with sufficient unqualified data and analytically significant range, plots were made that separated data at the 50th and at the 95th percentile points. For the other elements, plots separated data at the 95th percentile only. As NURE samples were collected and analyzed on a quadrangle-by-quadrangle basis (1°×2° topographic quadrangles) and analytical procedures were not always the same, no attempt was made here to combine the results of the four separate quadrangles that cover the forest. Each quadrangle was plotted separately, the data inside the forest limits used for interpretation, and the data outside the forest used to assist in determining the geochemical signatures for major rock units and for the different deposit types. The table below gives the percentile break points (in parts per million for all elements, except for uranium, which is given in parts per billion) used in the map plots for this study. The geochemical signatures presented in the geologic models constructed for this study are based on the limited NURE data set.

Most of these geochemical data, like all data gained by analysis of the fine (−100 mesh) fraction of stream sediments, reflect the major rock types in an area better than its mineral deposits. They have been useful in sorting out the geochemical terranes of the forest and provide evidence useful in substantiating resource assessments for some of the resource types of the forest.

In addition to the geochemical data listed here, this assessment of mineral resource potential incorporates the geochemical data used in the assessments of the Sangre de Cristo, Greenhorn, Buffalo Peaks, and Spanish Peaks Wilderness Study Areas. These surveys included data from stream sediment (−80 mesh samples) and from panned concentrates (nonmagnetic, heavy-mineral fraction), and analytical techniques included semiquantitative spectrographic and atomic absorption techniques. The geochemical signatures listed for the ore models in this text do not incorporate these data, as they are not available for most of the forest.

Quadrangle---	Leadville		Montrose		Pueblo		Trinidad	
Percentile break point--	50	95	50	95	50	95	50	95
Co	8.5	19	9.9	20	10.5	20.5	11	22
Cu	29	55	28	80	25	51	25	44
Cr	54	135	36	95	40	95	42	80
Fe	25,700	59,000	27,500	70,000	23,000	55,000	30,000	70,000
Mn	425	1,155	850	1,760	600	1,600	550	1,080
Ni	16	37	---	31	15.5	37	20	29
Pb	8	60	17	130	16	43	9.5	19.5
Sn	---	10	---	10	---	10	---	10
Th	12	60	11	45	13	55	10	15.5
U (ppb)	5.2	18	4.5	30	4.7	15	3.7	7.8
W	---	15	---	21	---	17	---	16.1

U.S. GOVERNMENT PRINTING OFFICE: 1984 O-421-614