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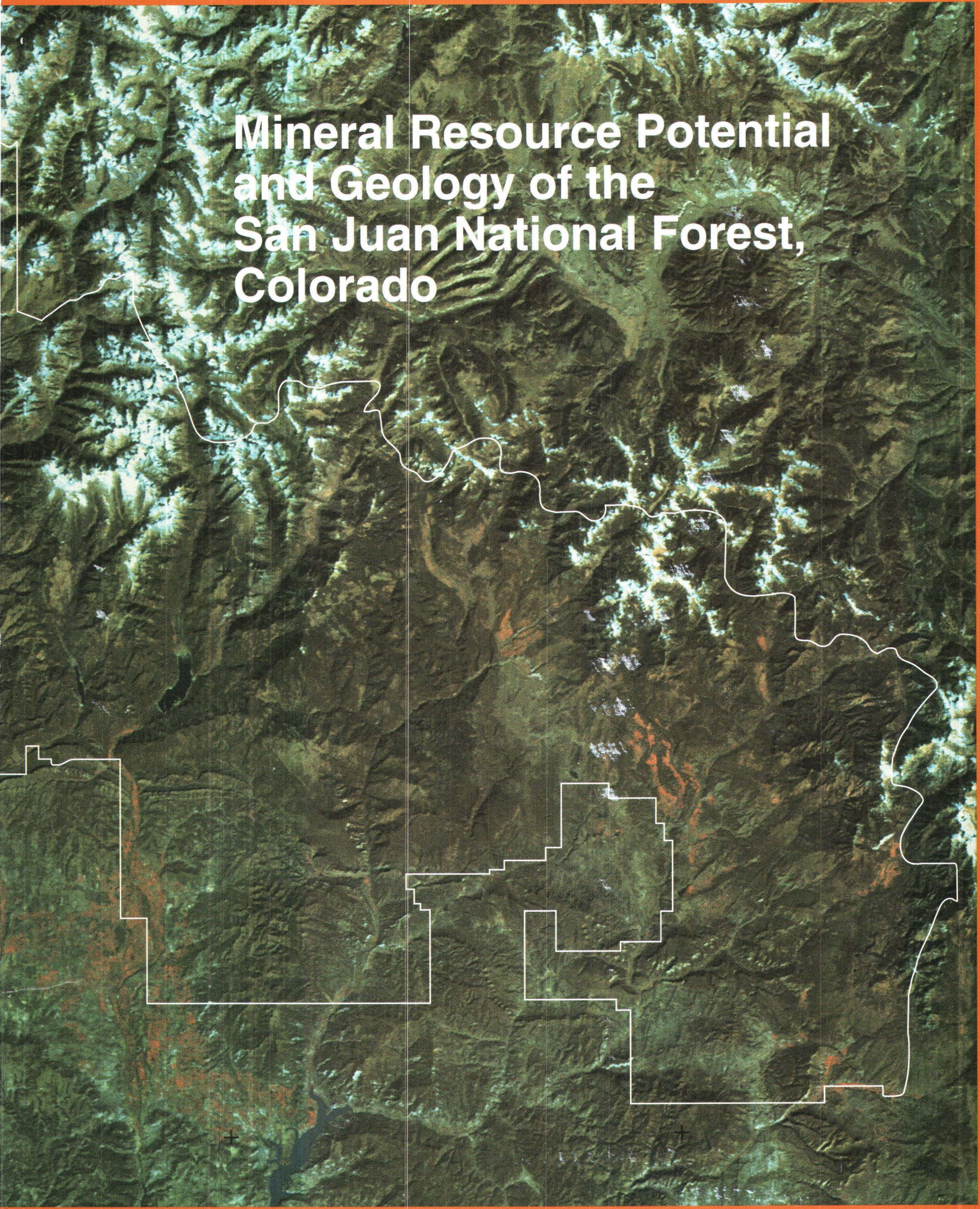
Mineral Resource Potential and Geology of the San Juan National Forest, Colorado



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Cover. Color infrared Landsat multispectral scanner image of the San Juan National Forest and vicinity in early October. Red and brown shades represent vegetation; green represents areas of rock and soil containing iron oxides; blue represents rock and soil with little or no iron-oxide content; and white represents snow. Satellite image taken from an altitude of 705 km. Approximate boundary of the San Juan National Forest is shown by white line.

Mineral Resource Potential and Geology of the San Juan National Forest, Colorado

Edited by Richard E. Van Loenen *and* Anthony B. Gibbons
U.S. Geological Survey

With a section on Salable Minerals

By Andrew G. Raby *and* John S. Dersch
U.S. Forest Service

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SUMMARY

USGS BULLETIN 2127:

MINERAL RESOURCE POTENTIAL AND GEOLOGY OF THE SAN JUAN NATIONAL FOREST

- The San Juan National Forest ("the Forest") contains many famous mining districts, such as those at Rico and La Plata, but there is no significant mining being done within the Forest today.
- Fourteen types of locatable mineral deposits were assessed, and, of those, five were assessed quantitatively.
- The five, quantitatively assessed, undiscovered locatable mineral deposits could possibly contain as much as 136,500 metric tons of copper, 17 metric tons of gold, 223,000 metric tons of zinc, 1,425 metric tons of silver, 184,000 metric tons of lead, and 33,900 metric tons of molybdenum. The probability that these amounts exist is 10 percent or less.
- Estimates were made of the amount of leasable commodities, including conventional oil and gas, gas in tight (impermeable) sandstone reservoirs, coal, and coal-bed gas that could be present in the Forest.
- Sixteen million barrels of oil and 26 billion cubic feet of gas or more may be present in conventional reservoirs.
- Recoverable gas in tight gas reservoirs may total as much as 18 billion cubic feet.
- Six billion short tons of bituminous coal may be present.
- Coal beds may contain 1 1/2 trillion cubic feet of gas.
- Considering the vast size of the Forest, the estimated amounts of leasable commodities are relatively small.
- Most leasable minerals are concentrated in a small southern area of the Forest that overlaps the energy-rich San Juan Basin.
- It is not implied that any commodities, leasable or locatable, could be extracted for a profit, even if they were discovered.
- Salable minerals, such as sand, gravel, and building stone, are abundant within the Forest.
- Favorable areas that may contain mineral resources are shown on figures and plates of this report.
- Seventeen scientists within the U.S. Geological Survey and the U.S. Forest Service contributed to this assessment.

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MINERAL RESOURCE POTENTIAL AND GEOLOGY OF THE SAN JUAN NATIONAL FOREST, COLORADO

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SUMMARY

This summary is presented in a nontechnical format for the aid of land-use planners and other nonscientific personnel.

The assessment of the mineral resource potential of San Juan National Forest, Colorado (referred to as "the Forest" in this report) (fig. 1), was made to assist the U.S. Forest Service in fulfilling the requirements of the Code of Federal Regulations (Title 36, Chapter 2, part 219.22). This section of the Code requires the Forest Service to develop information and interpretations needed to assure that the mineral resources of areas under its administration can be considered along with other kinds of resources in land-use planning.

This report addresses the potential for undiscovered mineral and energy resources in the Forest. A geologic map of the Forest was compiled at 1:250,000 scale, and field studies were conducted to collect rock and stream-sediment samples and geophysical data—mining districts were also visited. All available information, as of January 1, 1993, both published and unpublished, concerning mineral deposits and energy sources in the Forest was used in establishing mineral resource potential. The resources assessed in this study are (1) locatable resources, mainly metals, (2) leasable resources (energy resources), which include oil, gas, coal, and geothermal resources, and (3) salable minerals, such as sand and gravel and building stone. Quantitative estimates of the number and size of some undiscovered mineral deposits were established, and estimates of the amounts of oil, gas, and coal and coal-bed gas that could be present in the Forest are given.

Mineral resources in about 20 percent of the San Juan National Forest were assessed previously under the Wilderness Program by the U.S. Bureau of Mines (USBM) and the U.S. Geological Survey (USGS). Wilderness Areas within or partly within the Forest are the Weminuche, Lizard Head, West Needles, South San Juan, and Piedra areas.

Prospecting and mining have been carried on in San Juan National Forest for more than 120 years. Major deposits of gold, silver, lead, copper, zinc, uranium, and vanadium were mined, and mining activities played a major role in the settlement and development of the region. Oil and gas contribute little to the Forest's mineral endowment, but coal has played a vital role in the past, and recently discovered coal-bed gases are being evaluated as a possible source of energy. Salable minerals, such as sand, gravel, and building stone, are abundant in the Forest.

Environmental restraints imposed under the Wilderness Act, 1964, greatly restrict mineral extraction on Wilderness lands in the Forest. In other parts of the Forest, small underground mining operations are likely to continue. Large open pits with heap leaching of low-grade ores may not be compatible with the pristine and harsh environment found in many parts of the Forest.

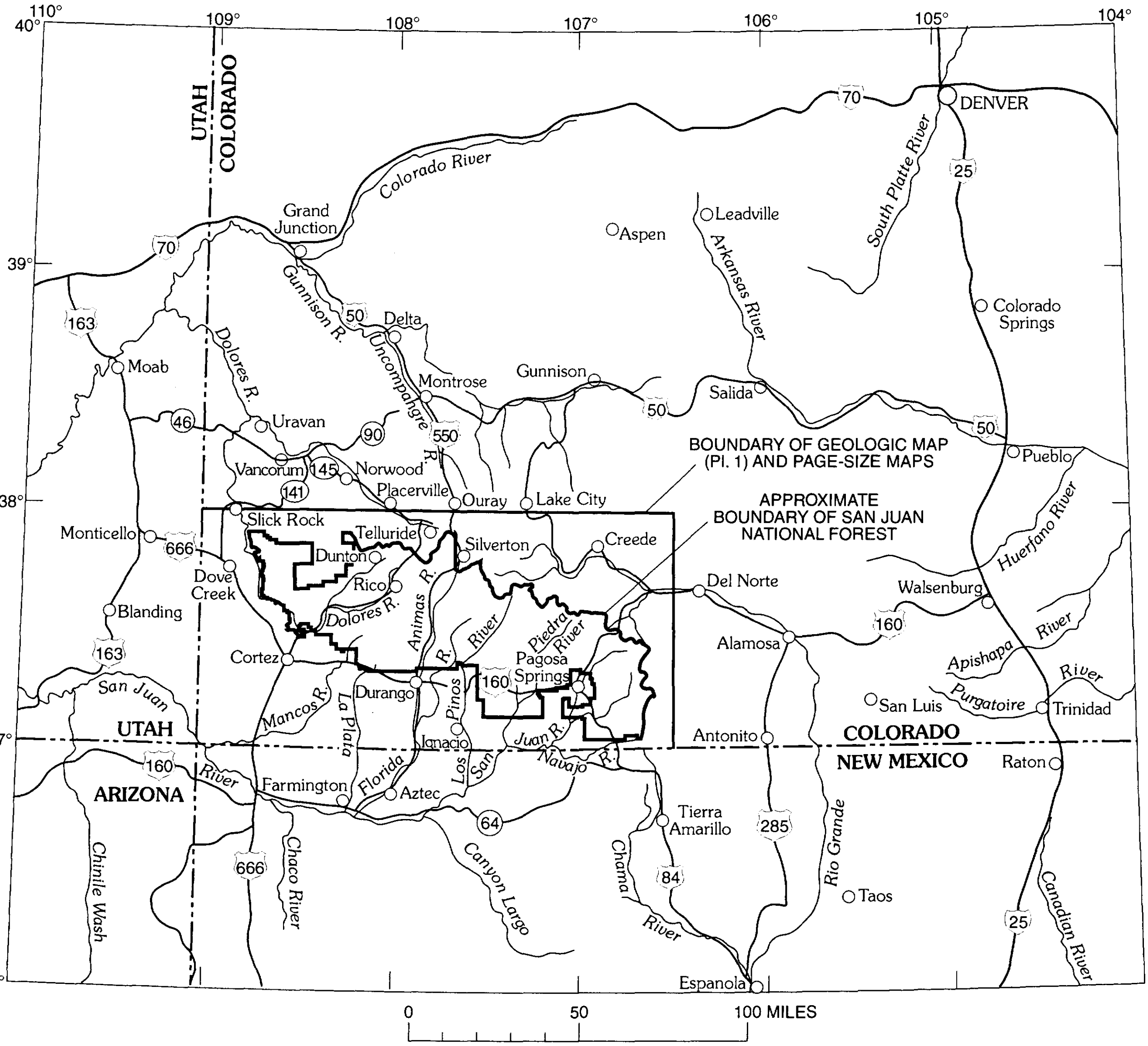


Figure 1. Location map showing regional setting of the San Juan National Forest and vicinity.

CHARACTER AND GEOLOGIC SETTING

The San Juan National Forest includes about 2.1 million acres of chiefly mountainous terrain that stretches for nearly 120 mi east to west and 45 mi north to south. It lies southwest of the Continental Divide, and all drainage from the Forest is into tributaries to the Colorado River. The Forest rises from about 6,000-ft elevation in the canyonlands along its south and west sides to the spectacular mountainous terrain, where the elevation of many peaks is more than 13,000 ft. Mountains and ranges of the region include the Needle, San Miguel, La Plata, and San Juan, although the entire region is often referred to simply as the San Juan Mountains.

The rocks exposed in the San Juan National Forest represent an assemblage of sedimentary, plutonic, and volcanic rocks that accumulated over a time span of nearly 1.8 billion years. The oldest rocks (Proterozoic crystalline rocks) (see geologic time chart in Appendix II) are exposed in the Needle Mountains in the central region of the Forest. These ancient rocks are flanked on the north and east by young Tertiary volcanics and on the south and west by Paleozoic and younger sedimentary rocks that were laid down in ancient depositional sites called the Paradox and San Juan Basins. Major rivers and streams, assisted by intense glacial erosion, have cut deep canyons throughout much of the Forest, producing the landscape seen today.

The geologic framework of San Juan National Forest area results from a long and complex history of faulting and uplift, basin development, sedimentation, plutonism, and volcanism. As recorded in the rocks of San Juan National Forest, the sequence is as follows: (1) deposition of sedimentary rocks that were later metamorphosed and still later were invaded by a succession of plutonic intrusive bodies from 1.7 to about 1.4 billion years ago (1.7–1.4 Ga), (2) a gap in the rock record for next 900 million years due to erosion or nondeposition, (3) alternation of deposition of clastic and carbonate rocks with minor local uplift and erosion between about 550 to 320 million years ago (550–320 Ma), (4) the first cycle of uplift of the Uncompahgre–San Luis highlands, an element of the ancestral Rocky Mountains, beginning about 320 Ma, (5) profound erosion of the uplift and deposition of "redbeds" and other continental clastic sediments from 365 to about 140 Ma, (6) deposition of sediment in and adjacent to the great Cretaceous seas that covered the region intermittently from 140 to about 70 Ma, (7) renewed uplift resulting from compressional forces during the Laramide orogeny along trends similar to those of the ancestral Rocky Mountains accompanied by intrusion of ore-related plutons about 70 to 65 Ma, (8) massive volcanism beginning about 40 Ma and continuing to about 20 Ma, followed by, or accompanied by, ore-related igneous intrusions, and (9) a final pulse of ore-related igneous intrusive activity during the period from 10 to 5 Ma, followed by fluvial and glacial processes that formed the present-day landscape.

With respect to the development of mineral resources in the Forest, the most important of the above events are those numbered 3, 4, 6, 7, 8, and 9. Event 3 included development of the carbonate rock terrane, destined to become the exclusive host to certain kinds of metallic mineral deposits. Event 4, initial rise of the Uncompahgre uplift, brought about erosion of the carbonate rock terrane from the eastern and northeastern parts of the Forest. The present-day consequence is that deposit types that require a carbonate host can be expected only in the central and western areas of the Forest.

Event 6, deposition of clastic sediments in and, more importantly for mineral wealth, adjacent to the Cretaceous sea resulted in development of thick coals. These coals are valuable in themselves and form the basis of today's resources of coal-bed gas (commonly called "coal-bed methane," after its principal constituent).

Events 7, 8, and 9 are stages in a long period of tectonic and magmatic activity extending from the Late Cretaceous (about 70 Ma) essentially to the present. This was the principal period of introduction of metals into the San Juan Mountains area. The colorful mining history of the San Juans is almost entirely the story of the extraction of these metals.

Event 5, although significant with respect to mineral resources in the San Juan National Forest, is less important than the events discussed above. Deposits of uranium and vanadium, some within the Forest but most outside of the Forest to the northwest, formed as part of the sedimentary history of the continental clastic rocks that were deposited during the late Paleozoic–early Mesozoic span of this event (about 290 to 140 Ma).

MINERAL AND ENERGY RESOURCES

Prospecting and mining in the San Juan Mountains go back more than 120 years. The first discovery of gold in this region was just north of the Forest near Silverton in 1848. In the 1860's, signs of gold and silver were found near the future sites of Durango, Silverton, and Rico. Mining of placer gold began near Summitville and Silverton in 1870, and along the La Plata River in 1873. However, it was not until a treaty was made with the Utes in 1874 that the region was opened to prospecting and settlement. Lode deposits of silver and gold were soon discovered, and most of the richest deposits of the region were mined during the period 1875–1900. Within the Forest, early-exploited deposits include those of Rico, La Plata, the Needle Mountains, and those near Silverton.

Depletion of near-surface ores amenable to the crude milling procedures of the time, and the collapse of silver prices in 1893, caused most of the early mines to close in the mid-1890's. Metal production peaked between 1900 and 1910, and, after World War II, new technologies for exploration, mining, and milling caused renewed activity in the major mine-mill complexes in and near the San Juan National Forest. Uranium and vanadium were mined at Graysill in the 1950's. Mining and exploration activity declined rapidly in the 1980's, and, by 1992, no major mines were operating in the Forest.

Energy resources of the Forest include coal, which was mined on a small scale for more than a century. No coal mines are active today, but coal-bed gas is currently being developed from coal beds in the southern area of the Forest that lies within the San Juan Basin. Relatively little exploratory drilling for conventional sources of oil and gas has been done within the Forest, and none of this has been productive. Widely separated areas of the Forest contain one or more hot or warm natural springs or artesian wells; none of them have been used as sources of geothermal energy.

Construction materials are abundant across the Forest. They include locally important commodities such as sand and gravel and building stone (dimension stone).

RESOURCE POTENTIAL

The mineral resources represent three categories: locatable, leasable, and salable. Areas judged as favorable for the occurrence of these resources are shown on figures 2 through 4. Areas shown as favorable for specific types of resources are estimated using criteria specific to the resource types as well as geologic, geochemical, geophysical, and mineral-occurrence and production information of a more general kind. Favorable areas are the most likely areas of the Forest to contain undiscovered deposits because they generally have similar attributes to those areas hosting deposits elsewhere in the Forest or in other parts of the United States. However, rating an area as favorable does not guarantee that deposits are present; it merely indicates that they are likely to be present based on analogy with other similar areas.

LOCATABLE RESOURCES

Locatable minerals, as defined by the General Mining Law of 1872, include most metals that occur in lode or placer deposits. The locatable mineral deposits in the Forest (see fig. 2) are classified according to the type of geologic terrane to which they are most closely related. These terranes, in declining order of importance of their related deposits, are (I) intrusive, (II) volcanic, (III) clastic, and (IV) surficial (table 1). Each terrane may contain a number of different deposit types.

The locatable mineral resource potential of the San Juan National Forest is based primarily on its geologic setting and on our interpretations of the likelihood that favorable rocks are present. These interpretations consider results of previous studies on the geology and mineral deposits in the Forest, mining history and production, geochemistry and geophysics, and data from mineral files. The available information was utilized according to procedures outlined by Shawe (1981) and Taylor and Steven (1983). Known ore deposits and mineral occurrences in and near the Forest were assigned to various descriptive ore-deposit models, and these same attributes, as defined by the models, were used to define favorable areas within permissive terranes in the Forest. The use of the term "favorable" is defined in the Locatable Mineral Resources section of this report. Deposit types were assigned letters (A, B, C, and so forth), and these letter designations are used throughout the text, on figures, and on plates. Areas that are favorable for specific types of locatable deposits are shown on plate 2 and summarized on figures 2 and 35 through 51. Table 1 lists the important types of locatable mineral deposits that are present or may be present in the Forest, and table 2 shows quantitative estimates for metals that may be contained in five of these deposit types.

QUANTITATIVE ASSESSMENT OF LOCATABLE RESOURCES

Quantitative estimates of the number of undiscovered deposits are calculated using established methods (Menzie and Singer, 1990) for deposit types that fit existing descriptive and grade and tonnage models (Cox and Singer, 1986). Deposit types that presently have only unsuitable grade and tonnage models, or for which such models do not yet exist, are presented in such a way that quantitative methods can be applied when suitable grade and tonnage models become available. Characteristics and relative metal potential of unusual or unconventional mineral deposits for which data are clearly inadequate to prepare deposit or grade and tonnage models are summarized more briefly. The methodology of the quantitative assessment of locatable minerals in the Forest is given in Appendix I.

Estimates of undiscovered resources were made for five types of deposits (table 2) according to procedures outlined in Appendix I. Data are inadequate to estimate resources for other types of deposits in San Juan National Forest at this time.

LEASABLE RESOURCES (ENERGY RESOURCES)

Leasable commodities are those that may be extracted on the basis of a lease agreement with the U.S. Forest Service. Besides coal and geothermal sources, leasable commodities include oil and gas from both conventional and unconventional sources. Conventional sources are from reservoirs that have natural porosities and permeabilities that allow oil and gas to migrate freely to the well bore. Unconventional sources are from reservoirs that require some sort of stimulation, such as fracturing or dewatering, before production can begin. These sources include gas from coal beds and tight gas sands. Qualified wells producing from unconventional sources receive tax incentives. Most of the leasable commodities are concentrated in a small southern area of the Forest that overlaps the energy-rich San Juan Basin.

Estimates of undiscovered oil and gas resources in the Forest were derived from the 1989 National Assessment of Undiscovered Oil and Gas Resources (U.S. Geological Survey and Minerals Management Service, 1989), which used a methodology based on analysis of petroleum exploration plays. A play is a set of oil or gas accumulations that are geologically, geographically, and temporally related and that exist by virtue of identical or similar geological conditions. The oil or gas accumulations may be real or hypothetical, and discovered or undiscovered. Such geological characteristics as reservoir lithology, timing and migration, trapping mechanisms, and source rock are taken into consideration in the definition and evaluation of each play.

Favorable areas for oil and gas resources from conventional reservoirs within the San Juan National Forest are concentrated in the southeastern and northwestern ends of the Forest (fig. 3, areas O, P, Q, R). The southeastern area is part of or immediately adjacent to the San Juan Basin and the San Juan sag (see fig. 65), whereas all parts of the northwestern area are either within or adjacent to the Paradox Basin. A most likely subjective estimate of the total amount of conventional oil and gas in the Forest is 16 million barrels of oil and 26 billion cubic feet of gas.

Favorable areas for gas from tight gas sands, an unconventional source, is within the northeast part of the San Juan

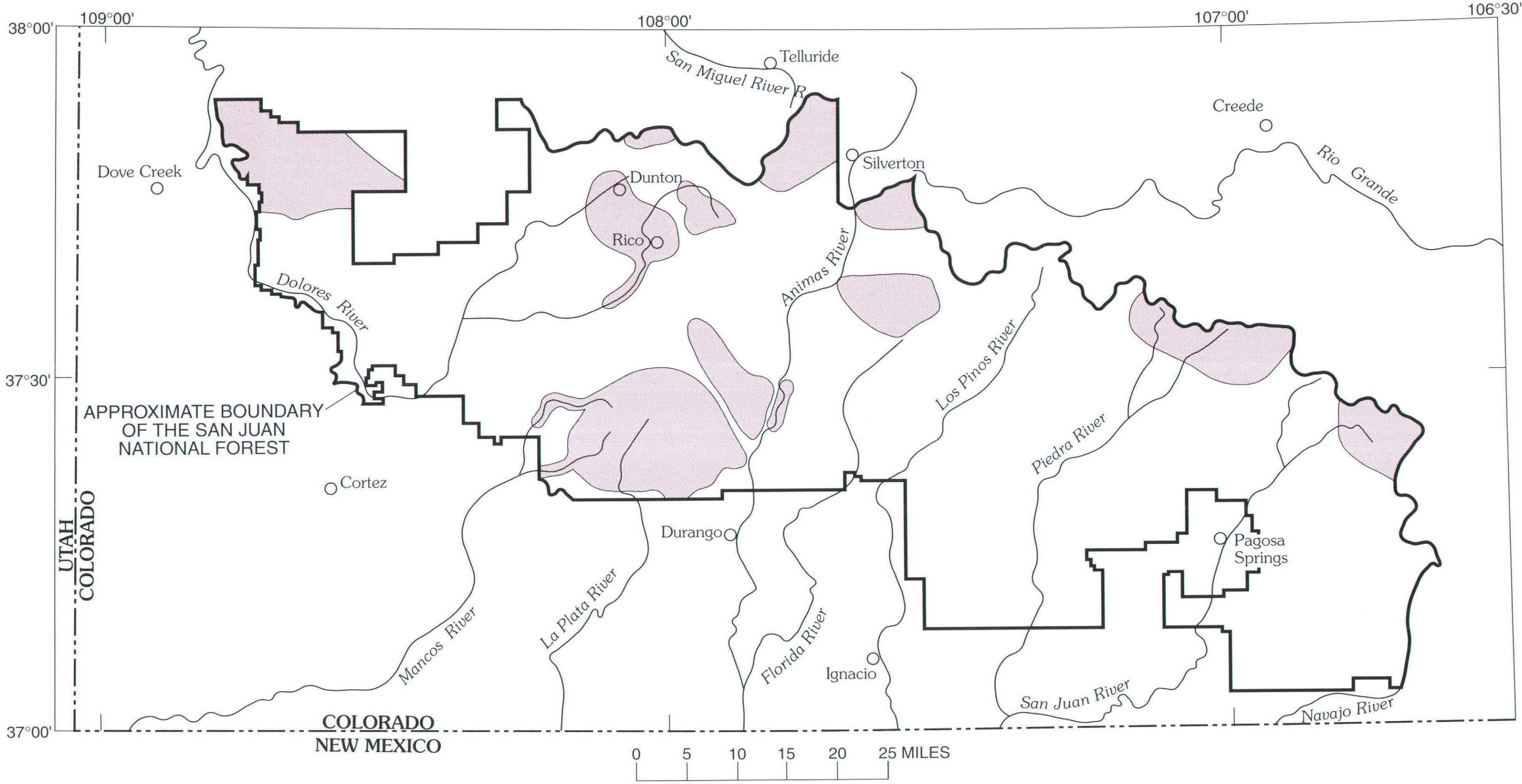


Figure 2. Map showing areas favorable for locatable mineral resources in the San Juan National Forest

Table 1. Types of locatable mineral deposits assessed in the San Juan National Forest.

	I. Deposits Genetically Related to Rocks of the Cretaceous-Tertiary Intrusive Terrane
Aa.	Stockwork molybdenum; deposits are found in or closely associated with small high-silica porphyry intrusive complexes that have multiple intrusive stages. Deposits may also contain tin, tungsten, and bismuth. Favorable areas of the Forest are at Rico, an area west of Silverton, Chicago Basin, and Crater Lake (fig. 35).
Ab.	Polymetallic veins, skarns, and replacement deposits adjacent to molybdenum-mineralized porphyry stocks; gold, silver, lead, zinc, and copper-bearing veins in Proterozoic rock around the Chicago Basin stock (fig. 36).
B.	Porphyry copper-molybdenum deposits; magmatic-hydrothermal mineralization in quartz stockwork veinlets and disseminated in potassic-altered porphyritic stock and adjacent wall rocks. Deposits may also contain Ag and Au. Areas of the Forest considered to be favorable are an area west of Silverton, Rico, the Allard stock in the La Plata district, and Crater Lake (fig. 38).
C.	Polymetallic replacement and skarn deposits; hydrothermal deposits of Ag, Pb, Zn, and Cu sulfide minerals in massive lenses, pipe-shaped bodies, and associated veins in limestone, dolostone, or other soluble strata that are replaced by ore. Favorable areas are southwest of Silverton, the Dunton-Rico area, and the La Plata Mountain region (fig. 40).
D.	Au-Ag-Te veins; hydrothermal deposits associated with alkalic intrusive rocks. Deposits also contain Cu, Pb, and Zn. The large area in the La Plata Mountains is favorable for additional deposits of this type (fig. 42).
E.	Vein uranium related to 1.4-billion- and 10-million-year-old granites intruding Middle and (or) Early Proterozoic rocks; vein deposits with the older granites serving as both the source of uranium and host to vein deposits. Veins also contain Au and Ag. Area favorable for this type of deposit is in the Needle Mountains (fig. 42).
	II. Deposits Related to Rocks of the Tertiary Volcanic Terrane
F.	Epithermal vein deposits hosted by Proterozoic rock (fig. 42). Includes the following three deposit types.
F1.	Epithermal Au-Ag-Te vein deposits; vein deposits formed from hydrothermal solutions probably related to nearby Tertiary age igneous intrusive activity. Deposits also contain lead and zinc. Favorable area is within and near the Beartown mining district.
F2.	Polymetallic epithermal veins; hydrothermal vein deposits related to nearby Tertiary age igneous intrusive activity. Deposits also contain Au, Ag, base metals, and U. The area of Whitehead Gulch-Deer Park east to Beartown and south to Elk Park is favorable for this type deposit.
F3.	Epithermal uranium vein deposits; hydrothermal deposit in fractures in Uncompahgre quartzite and slates. Area around the Centennial mine near Elk Park is favorable.
G.	Creede epithermal veins in Tertiary volcanic terrane. Favorable areas are west of Silverton, Crater Creek/Quartz Creek, Mt. Wilson, and Piedra Peak (fig. 44).
H.	Epithermal quartz-alunite gold deposits in Tertiary volcanic terrane; associated with acid-sulfate alteration. Deposits also contain silver. Favorable areas are Crater Creek/Quartz Creek, Calico Peak, and Piedra Peak (fig. 46).
	III. Deposits Genetically Related to Rocks of the Paleozoic-Tertiary Clastic Terrane
I.	Sandstone uranium; stratiform deposits of Salt Wash and related types are found in sandstones in the lower (pre-Cretaceous) part of the clastic terrane. Favorable areas are in the extreme northwest corner and in the central part, north of Durango (fig. 48).
J.	Sandstone vanadium-uranium; stratiform deposits of Placerville type are found in the upper part of the Entrada Sandstone of Middle Jurassic age. Favorable areas are at Graysill, northeast of Rico, and the in the southern part of the La Plata Mountains (fig. 50).
	IV. Deposits Related to the Quaternary Surficial Terrane
K.	Gold placers; concentrations of gold in alluvial gravel deposits downstream from lode deposits. Areas favorable are gravel deposits along the Dolores, Mancos, La Plata, and Animas Rivers (fig. 51).

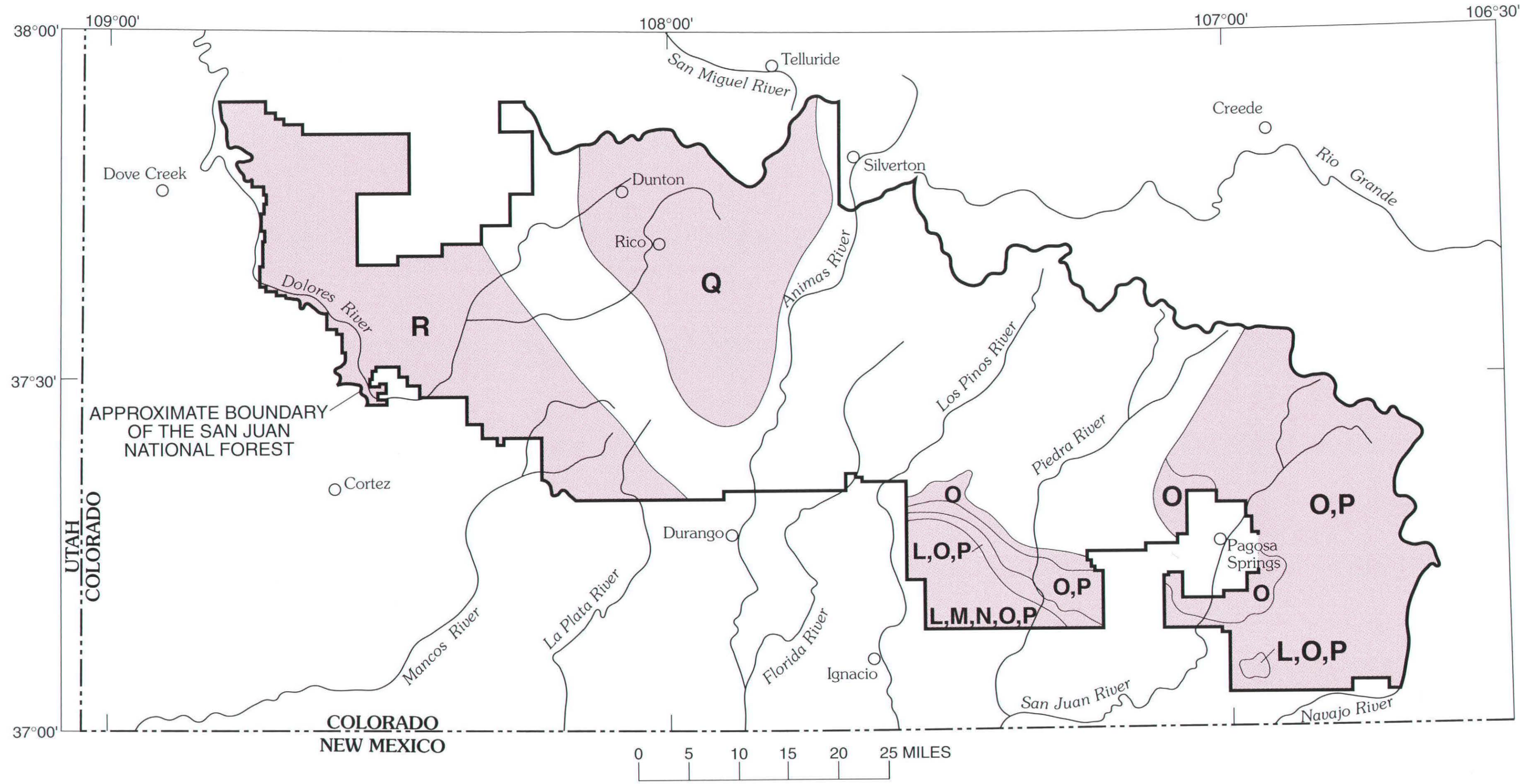
Basin in the south-central part of the Forest (fig. 3, area N). A most likely estimate for the amount of tight gas in the Forest is 18 billion cubic feet.

The coal resource potential in and near San Juan National Forest was rated as low, moderate to high, and high (fig. 59), but only one favorable area is shown on figure 3: area L. This area corresponds to the area having high potential for coal. Several levels of resource potential, rather than a single level of favorability, such as was used for locatable minerals, could be assigned for coal because of the large

Table 2. Quantitative estimates of undiscovered resources of five types of locatable mineral deposits in the San Juan National Forest.
[Values, except number of deposits, in metric tons. Percentages in column headings refer to confidence levels for estimates of undiscovered deposits occurring in the Forest]

	Present at probability of					Mean
	90%	50%	10%	5%	1%	value
Stockwork molybdenum						
Deposit type Aa (this report); model 16 (Cox and Singer, 1986)						
Number of deposits	0	0	0	0	1	0.0562
Metal amounts:						
Mo	0	0	0	0	1,100,000	31,000
Total mineralized rock	0	0	0	0	720,000,000	18,000,000
Probability that number of deposits = 0 is 0.97						
Porphyry copper-molybdenum						
Deposit type B (this report); model 17 (Cox and Singer, 1986)						
Number of deposits	0	0	0	0	1	0.0304
Metal amounts:						
Cu	0	0	0	0	1,700,000	120,000
Au	0	0	0	0	14	0.9
Ag	0	0	0	0	150	16
Mo	0	0	0	0	22,000	2,900
Total mineralized rock	0	0	0	0	380,000,000	16,000,000
Probability that number of deposits = 0 is 0.97						
Polymetallic replacement and skarns						
Deposit type C (this report); model 19a (Cox and Singer, 1986)						
Number of deposits	0	0	1	2	4	0.4485
Metal amounts:						
Cu	0	0	8,900	28,000	140,000	6,600
Au	0	0	1.89	7.2	47	2.1
Zn	0	0	360,000	930,000	3,000,000	160,000
Ag	0	0	950	3,000	11,000	560
Pb	0	0	310,000	820,000	2,800,000	150,000
Total mineralized rock	0	0	7,100,000	18,000,000	51,000,000	2,900,000
Probability that number of deposits = 0 is 0.70						
Creede epithermal veins						
Deposit type G (this report); model 25b (Cox and Singer, 1986)						
Number of deposits	0	0	1	2	2	0.3801
Metal amounts:						
Cu	0	0	7,200	21,000	89,000	4,100
Au	0	0	9.73	28	140	7.3
Zn	0	0	96,000	320,000	1,300,000	63,000
Ag	0	0	760	2,300	17,000	810
Pb	0	0	84,000	190,000	620,000	34,000
Total mineralized rock	0	0	6,400,000	14,000,000	91,000,000	3,000,000
Probability that number of deposits = 0 is 0.70						
Epithermal quartz-alunite gold veins						
Deposit type H (this report); model 25e (Cox and Singer, 1986)						
Number of deposits	0	0	0	2	3	0.1816
Metal amounts:						
Cu	0	0	0	1,500	170,000	5,800
Au	0	0	0	41	180	6.7
Ag	0	0	0	140	1,100	40
Total mineralized rock	0	0	0	6,000,000	20,000,000	840,000
Probability that number of deposits = 0 is 0.91						

amount and high quality of data available. Much of the coal data, such as bed thickness, rank of coal, and depth of overburden, were obtained from recent drilling programs that explored for coal-bed gas. These new data, added to the results of previous coal evaluations, allowed an estimate of original, measured, indicated, inferred, and hypothetical coal resources. The resources are listed by township and range in tables 4 and 5, shown later in this report. As much as 6 billion



EXPLANATION

- **L** Coal
- **M** Coal-bed gas
- **N** Tight gas sands
- **O** Oil and gas in Dakota Play
- **P** Oil and gas in Fractured Mancos Shale Play
- **Q** Oil and gas in Silverton Delta Play
- **R** Oil and gas in Carbonate Buildup Play

Figure 3. Map showing areas favorable for leasable minerals (energy resources) in the San Juan National Forest.

short tons of bituminous coal in the Fruitland Formation (Upper Cretaceous) may be present in the southeastern part of the San Juan National Forest.

The south-central part of the San Juan National Forest, in the northern part of the San Juan Basin, is considered to have significant potential for coal-bed gas resources in the Upper Cretaceous Fruitland Formation (fig. 3, area M). Estimates of in-place gas resources in Fruitland coal beds in the San Juan Basin have been made using information on thickness, areal extent, density, rank, and gas content of coal beds. For Fruitland coal beds occurring within the Forest at depths greater than 500 ft, in-place resources of coal-bed gas are estimated to be in the range from 1 to 3.5 trillion cubic feet, with a most likely estimate of about 1.5 trillion cubic feet. These figures do not represent the amount of gas that can actually be developed because that amount is strongly affected by (1) present-day depth of burial of coal beds, (2) ease of dewatering of the coal, and (3) local topography.

The potential for significant development of hydrothermal resources in the San Juan National Forest is slight. Most of the thermal springs yield only moderately hot water in relatively small quantities and are remote from potential markets, such as large towns.

SALABLE MINERALS

Salable mineral materials, obtainable by purchase from the U.S. Forest Service, are sufficiently abundant across the Forest to meet current Forest Service demands as well as private needs in developing areas. Salable minerals addressed specifically in this report are sand and gravel and building stone (dimension stone). Figure 4 shows areas within the Forest that are favorable for containing these salable minerals.

Sand and gravel are abundant in alluvial and glacial-drift deposits along most major drainages in the San Juan National Forest, including the Dolores, Mancos, La Plata, Animas, Florida, Los Pinos, Piedra, and San Juan Rivers. Sand and gravel are used mainly for road construction and road-surface maintenance. The supply is adequate for anticipated needs.

Sources of building stone, of both sedimentary and igneous origins, occur throughout the Forest. Demand for building stone is growing in developing areas such as Aspen, Telluride, and Durango. This material is primarily valued for its appearance, including weathered color and texture, any encrusting lichens and moss, and the shape and size of individual blocks. Most building stone is found in weathered outcrops and talus heaps of the Cretaceous Dakota Sandstone and Mesaverde Formation and of other sandstone layers in Jurassic and Cretaceous strata. Some building stone is collected from weathered igneous rock deposited in rock glaciers and talus slopes at higher elevations. Such deposits are common in many localities, including Groundhog Mountain, the La Plata Mountains, Graysill Mountain, Jackson Mountain, and the canyons and drainages of the southeastern San Juan Mountains.

INTRODUCTION

This report and the accompanying maps and figures constitute an assessment of the mineral resource potential of the San Juan National Forest, Colorado. The resources assessed in this study are defined as (1) locatable resources, mainly metals, (2) leasable resources (energy resources), which include oil, gas, coal, and geothermal energy, and (3) salable minerals, such as sand and gravel and dimension stone. The assessment is based on information available as of January 1993.

The San Juan National Forest contains about 3,280 mi^2 (2,100,000 acres) of mostly mountainous terrain located in nine counties in southwestern Colorado. It is bounded by the Continental Divide to the northeast and stretches for nearly 120 mi from near Wolf Creek Pass on the east side to within about 13 mi of the Utah-Colorado border on the west (fig. 5).

The information provided in this report is to assist the U.S. Forest Service (USFS) in fulfilling the requirements of the Code of Federal Regulations (36 CFR 219.22). This section of the Code requires the Forest Service to supply information and interpretations needed to assure that the mineral resources of areas under its administration can be considered along with other kinds of resources in land-use planning. The U.S Bureau of Mines (Neubert and others, 1992) studied known resources, including identified resources, and delineated areas of development potential in established mining districts of the San Juan National Forest; however, this study addresses the potential for undiscovered mineral and energy resources in the Forest. This report relies, to a large extent, on information compiled from published literature, which includes many studies of the geology and ore deposits in the Forest. Information from published sources is integrated with our interpretations of geophysical and geochemical data, information gained from field studies conducted for this report, and unpublished data from private oil and gas and mining companies concerning the assessment of energy and mineral resources.

A geologic map forms the fundamental basis for assessing mineral resources; therefore, the first step in this assessment was to prepare such a map (plate 1) of the Forest and surrounding area at a scale of 1:250,000. The map is a slightly modified enlargement of a part of the State geologic map of Colorado (Tweto, 1979, scale 1:500,000). Gregory N. Green and Edward J. LaRock (USGS) prepared the map from a digital database of the geologic map of Colorado (Green, 1992) by extracting that part of the State geologic map that contains the Forest. Delineation of some of the

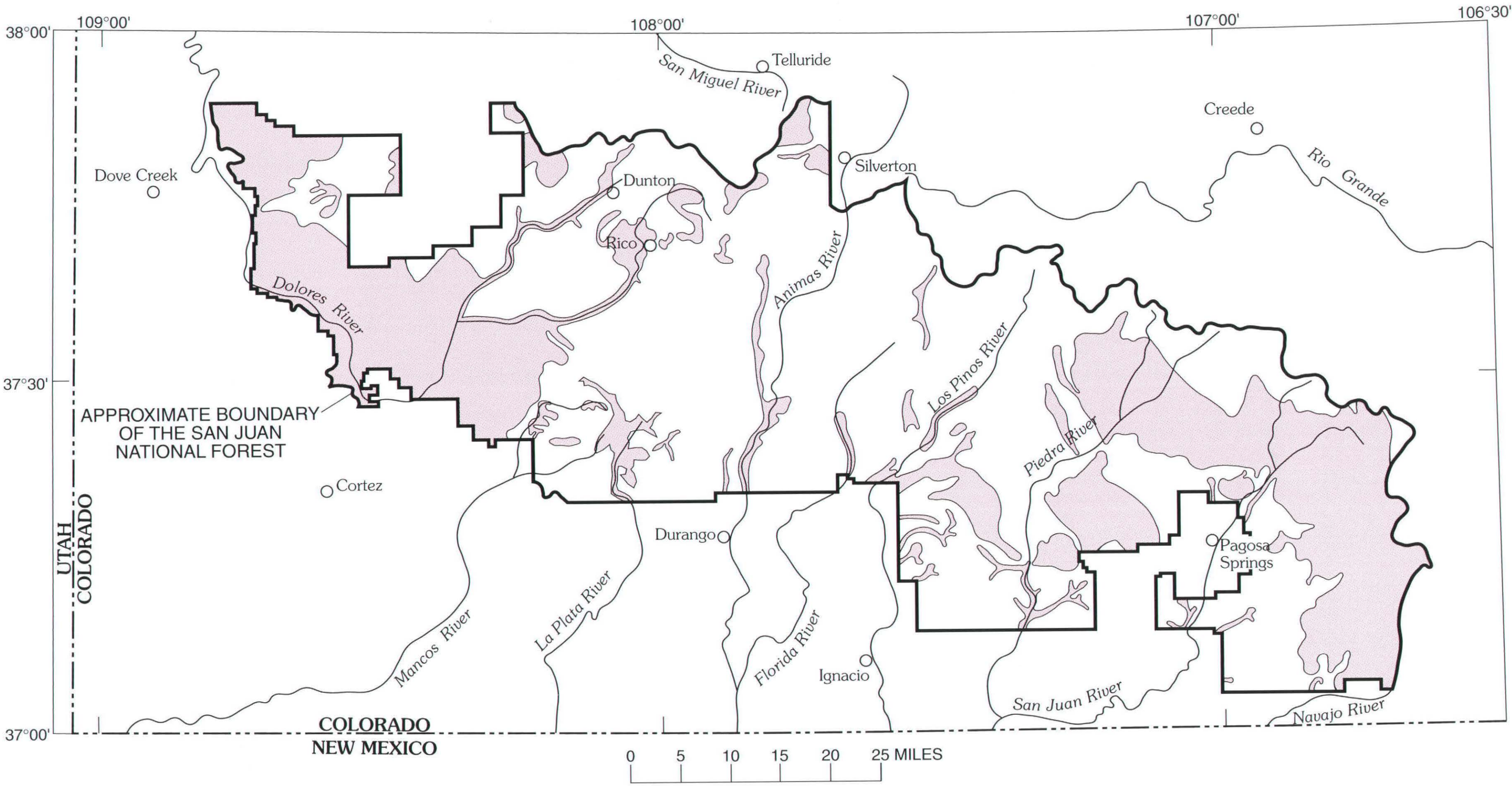


Figure 4. Map showing areas favorable for salable commodities (sand and gravel, and dimension stone) in the San Juan National Forest.

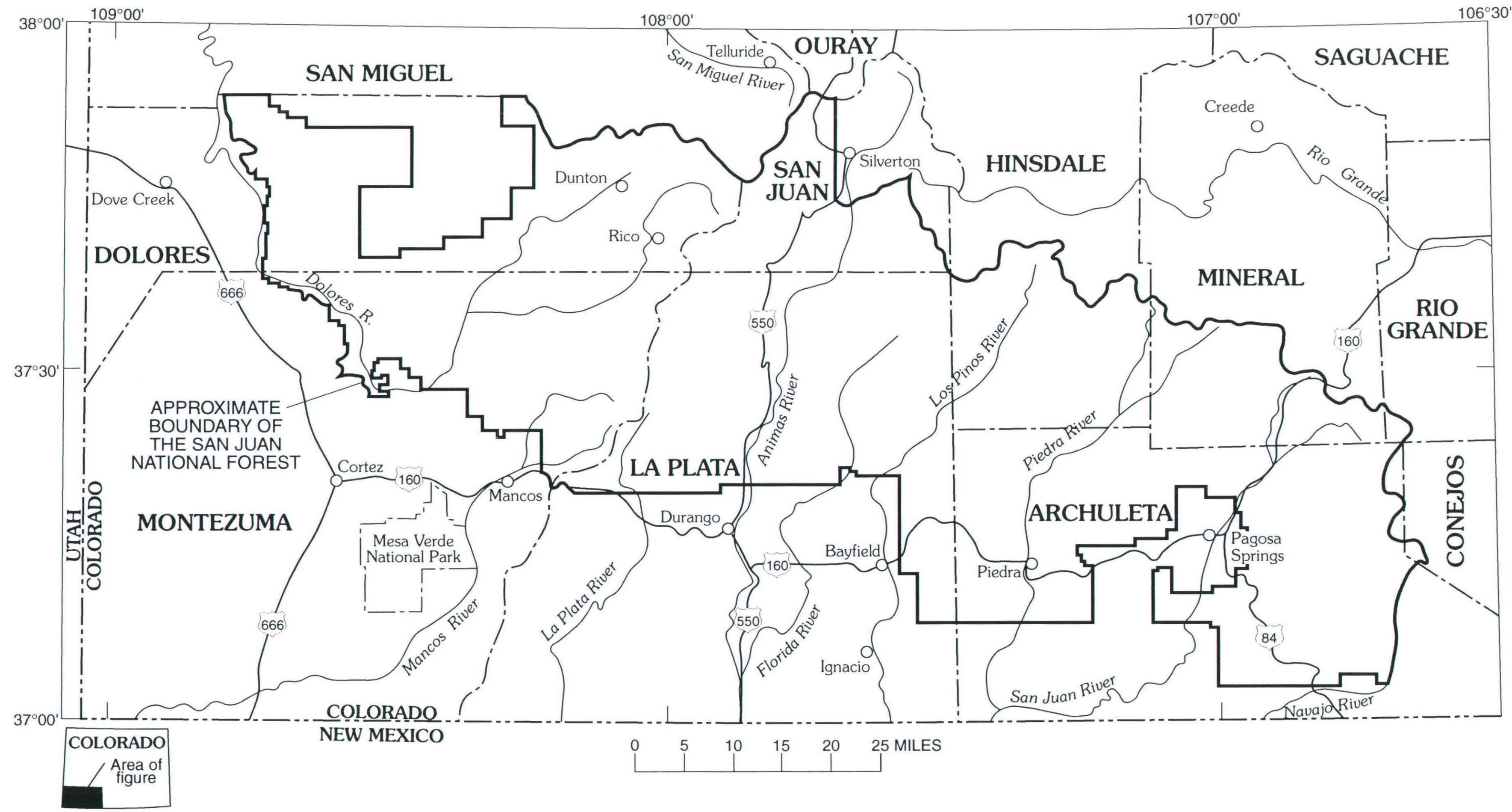


Figure 5. Map of San Juan National Forest and vicinity showing county boundaries.

Proterozoic rock units follows the geologic map of Durango quadrangle (Steven and others, 1974, scale 1:250,000) in order to show more detail. Other Proterozoic map units were changed to incorporate nomenclature changes of Tweto (1987). Numerous geologic maps were utilized by Tweto in compiling the Forest portion of the State map; however, most of the geology is taken from the Cortez (Haynes and others, 1972) and Durango (Steven and others, 1974) 1°×2° geologic quadrangles (scale 1:250,000). For more detail in a specific area, readers are referred to references given on the State geologic map or to geologic quadrangle maps.

Geophysical data used in the locatable mineral resource assessment of the Forest include regional aeromagnetic and gravity data. Aeromagnetic data from eight separate surveys were processed and merged into one composite data set for interpretation. These surveys were completed during the past several years in support of tasks that included preparation of Indian land and Wilderness mineral assessments. A gravity anomaly map was prepared using existing data supplemented by new data obtained for this study. Gamma-ray radioactivity maps were prepared and interpretations made using data from the National Uranium Resource Evaluation (NURE) Program, and Landsat (satellite) images were used for identification of linear features and areas of alteration.

Geochemical data for the locatable mineral resource assessment were compiled from sources that include NURE data and USGS studies of areas proposed for Wilderness status. This database was augmented by collecting and analyzing samples from specific areas of the Forest. The sampling focused on those areas of the Forest that reportedly contained anomalous amounts of elements commonly associated with mineralization but not known to contain any mineralized rock.

The mineral resources of nearly 20 percent of the Forest (about 375,000 acres) were evaluated in the late 1960's, 1970's, and 1980's by the USGS and the U.S. Bureau of Mines under the Wilderness Program (fig. 6). The Wilderness Areas and the principal references to the studies are: Weminuche (Steven and others, 1969), Lizard Head (Bromfield and Williams, 1972), West Needles (Van Loenen and Scott, 1985), South San Juan (U.S. Geological Survey and U.S. Bureau of Mines, 1985), and the Piedra (Bush and others, 1983). The mineral resource potential of the Wilderness Areas, as established at the time of the studies, are generally accepted in this report. New data available since these evaluations were made have, however, allowed a reassessment of the mineral resources in some parts of Wilderness lands.

Information on mines and prospects in San Juan National Forest comes from many sources. The USBM recently completed a comprehensive study of most known mines and prospects in the Forest (Neubert and others, 1992). The USGS Mineral Resource Data System (MRDS) (U.S. Geological Survey, 1986) contains nearly 2,000 entries for sites within the Forest, although most are sand and gravel deposits, and these mineral data along with other published information were used to characterize or define various deposit types. Private companies shared important unpublished information concerning metallic mineral exploration drilling projects for several localities within the Forest.

Leasable minerals in San Juan National Forest include conventional and unconventional oil and gas as well as coal and coal-bed gas. Areas of the Forest considered favorable for the different categories of leasable resources are shown on figure 3.

Estimates of undiscovered oil and gas resources in the Forest are derived from the 1989 National Assessment of Undiscovered Oil and Gas Resources (U.S. Geological Survey and Minerals Management Service, 1989), hereinafter called "the 1989 National Assessment." This assessment used a methodology based on analysis of petroleum exploration plays. A play is a set of oil or gas accumulations that are geologically, geographically, and temporally related and that exist by virtue of identical or similar geological conditions. The oil or gas accumulations may be real or hypothetical, and discovered or undiscovered. Reservoir lithology, timing and migration, trapping mechanisms, and source rock are taken into consideration in the definition and evaluation of each play.

The oil and gas plays used in the San Juan National Forest assessment were those used for the area in Powers (1993) and Peterson (1989). There has been relatively little exploratory drilling within the Forest and little testing of most of the plays in its immediate vicinity. Thus, much of the assessment of oil and gas resources in the Forest is based either on projections from adjacent areas or on analogy to similar settings elsewhere. For the San Juan National Forest assessment, individual play evaluations have been combined subjectively into a single oil and gas resource number for each of two regions, a southeastern region and a northwestern region, which abut along the line of the Animas River.

Tight gas reservoirs are present in a small area of the Forest that overlaps the San Juan Basin (fig. 62). A brief analysis of the character of these tight gas reservoirs and their resource potential in the Forest was made by reviewing well logs, stratigraphy and structures, and production history of gas wells in this area and elsewhere in the Forest.

The coal geology of the Forest is summarized from previous studies, and new resource calculations for both coal and coal-bed gas were made using data obtained from recent coal-bed gas exploration.

The potential for salable minerals in the Forest was established by identifying terranes that have known resources and reserves of certain commodities and delineating similar terranes that may contain these commodities in other parts of the Forest. The areas that have potential for salable minerals are shown on plate 4. These interpretations draw heavily on site-specific data given in the industrial minerals section of the USBM report (Neubert and others, 1992).

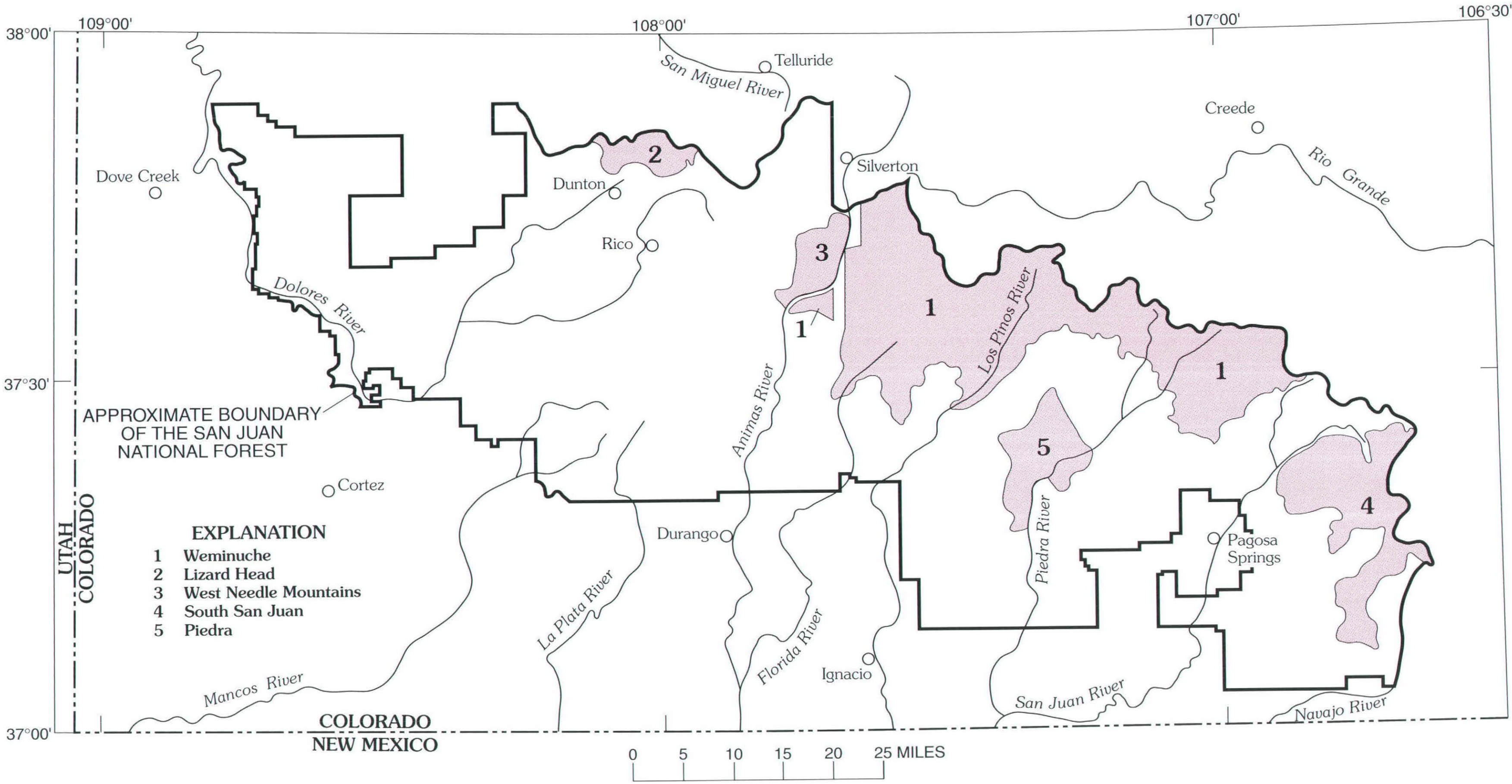


Figure 6. Map showing Wilderness Areas in the San Juan National Forest.

Some members of the project made brief visits in the Forest to examine mineral deposits and their geologic settings and to collect samples and geophysical data during the summers of 1991 and 1992. Nonproject geologists with the USGS, USBM, USFS, other government agencies, and private mining companies were consulted during the course of this evaluation, and their advice is gratefully acknowledged.

GEOLOGY

The San Juan National Forest is in the Southern Rocky Mountain and the Colorado Plateau physiographic provinces. The northeastern part of the Forest is in the Southern Rocky Mountain province and includes most of the San Juan Mountains. The western and southern parts of the Forest are in the canyonlands and plateaus of the Paradox and San Juan Basins of the Colorado Plateau province (fig. 7). Geologically, the Forest comprises an uplifted core of Proterozoic rocks, exposed near the center of the Forest, that is flanked on the north and east by Tertiary volcanics of the San Juan volcanic field and on the south and west by Paleozoic and younger sedimentary rocks of the Paradox and San Juan Basins. The rocks exposed in the Forest represent a suite of sedimentary, plutonic, and volcanic rocks that accumulated over a time span of nearly 1.8 billion years. The topography of the Forest ranges from about 6,000-ft elevation in the canyonlands along its south and west sides to the spectacular terrain of the San Juan Mountains, where many peaks are more than 14,000-ft elevation. Streams, rivers, and glaciers have cut deep canyons that drain the Forest into the San Juan and Dolores Rivers, which are tributaries of the Colorado River. Late Cretaceous and early Tertiary tectonism, mid-Tertiary volcanism, and glacial and fluvial processes are mainly responsible for the physiography seen in the Forest today.

GEOLOGIC FRAMEWORK

The geologic framework of the San Juan National Forest is a result of a long and complex tectonic history of faulting and uplift. This history began during the Proterozoic Eon when continental-scale tectonism affected a large part of what is now the Western United States. Two linear tectonic zones (lineaments) intersect in this area of southwest Colorado and southeast Utah (fig. 8). The northwesterly trending zone is part of the Wichita lineament (Baars, 1976), whereas the northeasterly trending zone is part of the Colorado lineament (Warner, 1978). Faults along the Colorado lineament are thought to have influenced the location of the much younger Colorado Mineral Belt (Tweto and Sims, 1960) (fig. 8). All tectonic events that affect the geology of the Forest closely follow patterns that were first established in Proterozoic time.

The Uncompahgre and San Luis uplifts are structural elements along the northwest-trending Wichita lineament (fig. 8). Throughout geologic time, these uplifts and related faults have played a major role in controlling the distribution and, in many cases, the supply of sediments to the Forest region. Since Proterozoic time, the northwesterly trending uplifts have undergone at least two cycles of uplift and erosion. The first cycle began in late Paleozoic and ended in early Mesozoic time when the ancestral Rocky Mountains formed; the more recent cycle ended near the close of Cretaceous time as part of the Laramide orogeny.

The San Luis uplift lies southwest of and parallel to the much more extensive Uncompahgre uplift. The two uplifts have similar histories of movement. The San Luis uplift extends from near Rico, southeast through the San Juan Mountains, and into north-central New Mexico (see fig. 7). The Grenadier highlands (represented by the present-day Needle Mountains of the Forest) are a part of the San Luis uplift. These highlands remained a topographic high throughout most of Paleozoic time and are made up of crystalline rocks of Early and Middle Proterozoic age, which are the oldest rocks in the Forest. These crystalline rocks originated from sediments, igneous intrusives, and volcanic material that began to accumulate more than 1.7 b.y. ago. They consist of at least two sequences of highly deformed metamorphic rocks that were intruded by a succession of plutonic bodies between about 1.7 and 1.4 Ga (Barker, 1969b). All of the crystalline rocks were deeply eroded by the beginning of the Paleozoic Era.

The regional depositional history of the Paleozoic Era began in Late Cambrian time when sandstones, derived in part from the old Grenadier (San Luis) highlands in the northeastern part the Forest and from other highlands southwest of the Forest, were deposited unconformably over the Proterozoic basement. The Cambrian sandstones largely escaped erosion and are preserved as the Ignacio Quartzite (Upper Cambrian). A long interval of tectonic stability ended the early Paleozoic. Ordovician and Silurian rocks are entirely absent from this region of the Forest.

Deposition resumed in Late Devonian time as seas, advancing from the west, covered all the Forest area (Elbert Formation) except the San Luis highlands. Later, in Devonian and Mississippian time, the site of the San Luis highlands, along with the rest of the Forest, was covered by carbonate sedimentary rocks (Upper Devonian Ouray Limestone and Lower Mississippian Leadville Limestone) deposited from shallow marine seas. The Uncompahgre–San Luis highlands were beginning to emerge by this time, and they mark the easternmost advance of the Late Mississippian sea. By Middle Pennsylvanian time, the Uncompahgre–San Luis highland was a prominent range of the ancestral Rocky Mountains. To the west of the rising mountain range and expressing the same tectonism, deep subsidence produced the Paradox Basin. Great thicknesses of shales and evaporite beds filled this basin, which overlaps the western part of the

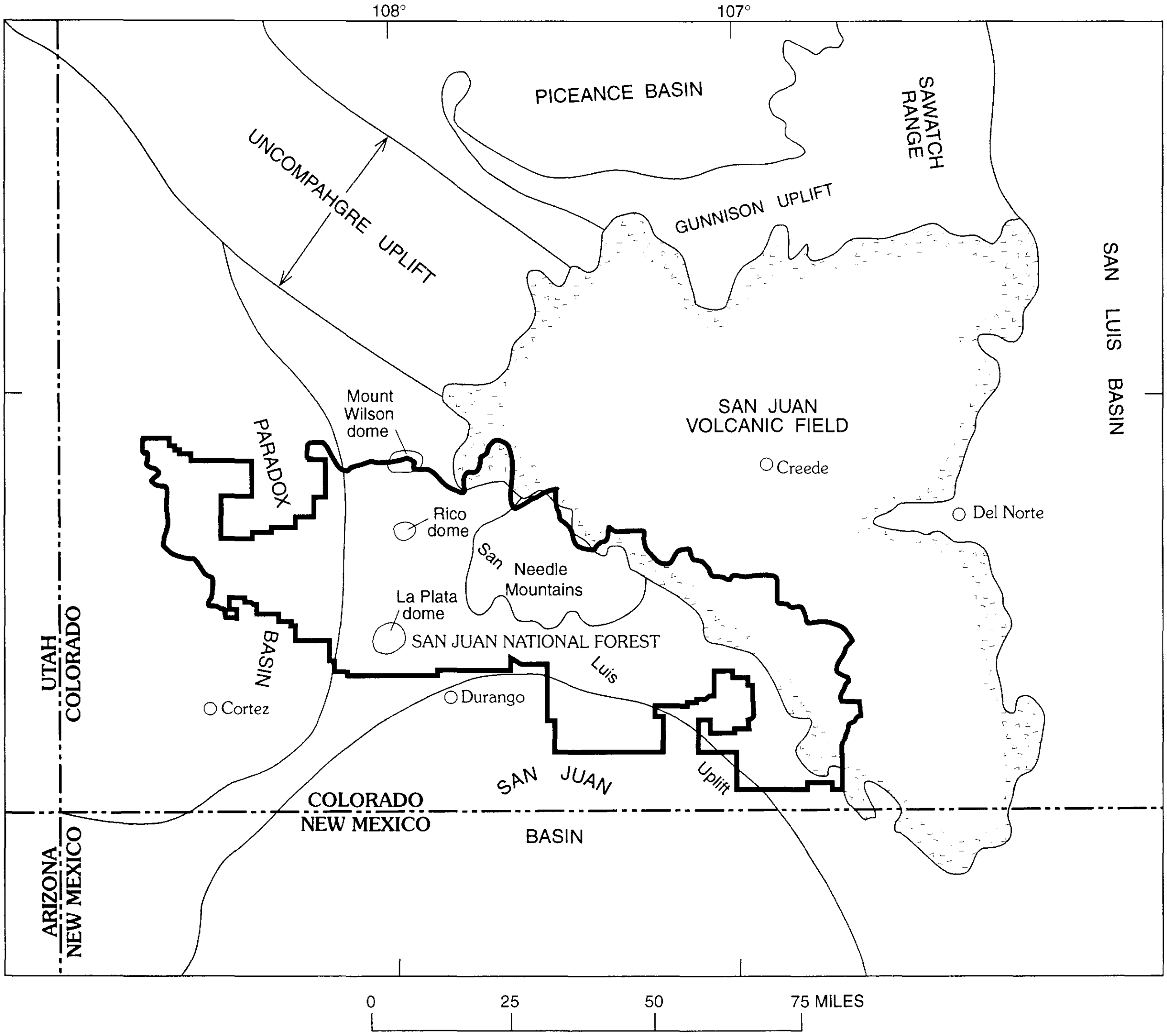


Figure 7. Map of southwest Colorado showing the San Juan National Forest, major structural elements, and the San Juan volcanic field.

Forest (fig. 7). The evaporite beds pinch out along the eastern edge of the Paradox Basin, but thick deposits of coeval carbonates, shales, and sandstones continue eastward across the Forest and wedge out against the Uncompahgre–San Luis highlands. At the end of the Paleozoic Era, the Uncompahgre–San Luis highlands were rapidly being eroded, shedding an apron of arkosic material southwestward and depositing them in coastal lowlands. These deposits are present today as redbed fanglomerates of the Permian Cutler Formation, which underlies the central and southwestern parts of the Forest area. Sedimentation ceased by the end of Early Permian time, and the region became part of a continental landmass.

The Mesozoic record begins in Late Triassic time, when nonmarine redbeds of the Dolores Formation, similar to those of the earlier Cutler Formation, were deposited across most of the region. Subsequent erosion removed most pre-Jurassic rocks from the highlands and exposed Proterozoic basement rocks. During Jurassic time, the San Juan Basin to the south was subsiding, and nonmarine sediments (Middle Jurassic Wanakah Formation and Entrada Sandstone, and Upper Jurassic Morrison Formation) were accumulating over almost the entire region. Nonmarine sedimentation was succeeded by both marine and nonmarine sedimentation during the Cretaceous when this region was covered intermittently by an epeirogenic sea, part of the Cretaceous seaway. Intertidal sandstones (Lower Cretaceous Burro Canyon Formation and Upper Cretaceous Dakota Sandstone) were covered with great volumes of marine shales (Upper Cretaceous Mancos and Lewis Shales). Nonmarine lagoonal sediment (including the thick coal beds of the Upper Cretaceous Fruitland Formation) were deposited shoreward of the seaway as the strandline moved back and forth across the region.

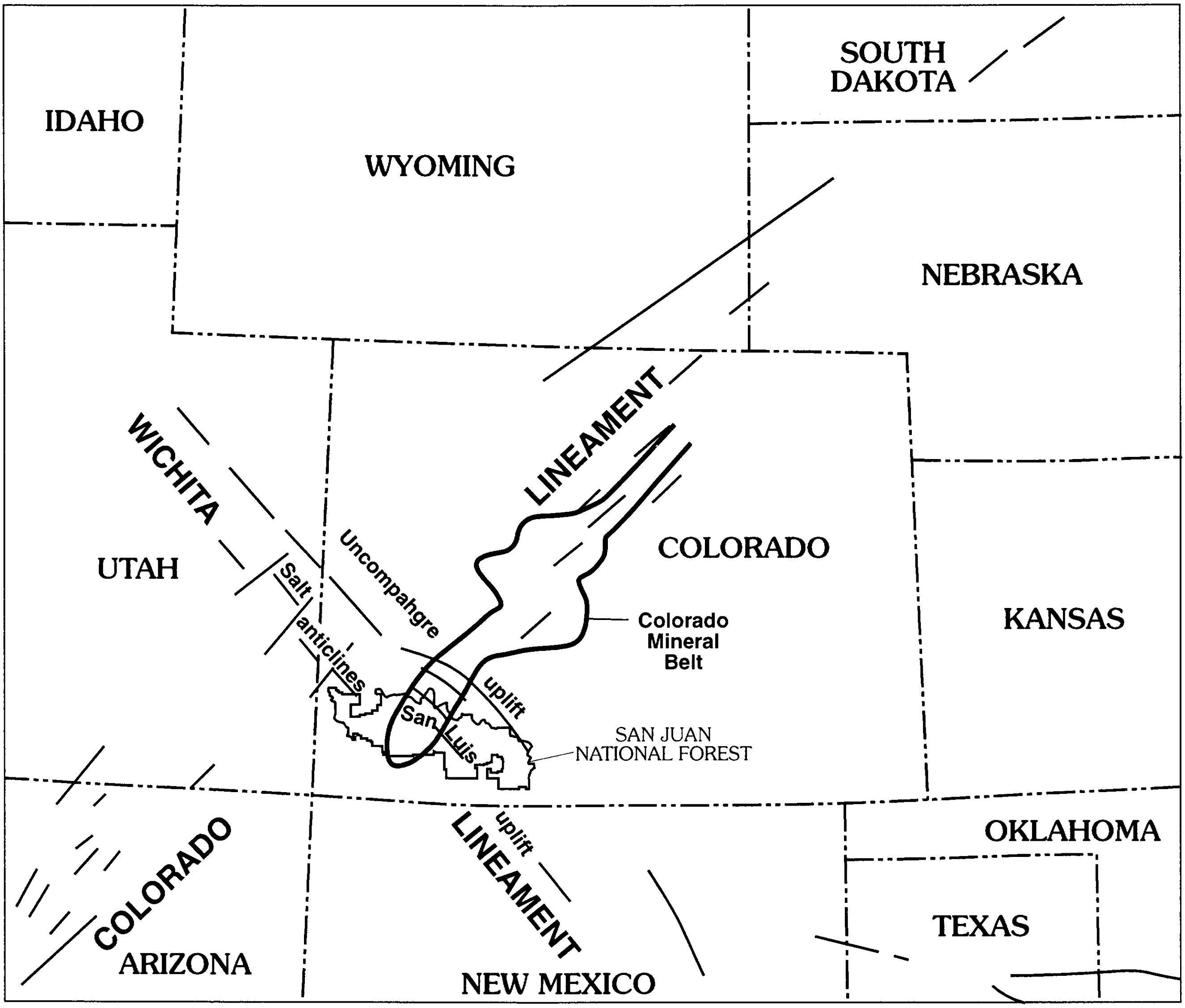


Figure 8. Map showing trends of two major lineaments that intersect in the region of the San Juan National Forest, major uplifts, and the Colorado Mineral Belt. Map modified from Stevenson and Baars (1986).

In the area of the San Juan National Forest, deposition of sediment from the Cretaceous sea ended about 70 Ma with the onset of the Laramide orogeny, a 35-m.y. period of tectonic activity. The Cretaceous sea retreated to the northeast for the last time as renewed upwarping, caused by the orogeny, began along the Uncompahgre–San Luis uplift. Subsequent erosion removed all the sedimentary rock cover from the Needle Mountains and the area to the north, reexposing Proterozoic rocks. Across the Forest, to the east and southeast of the Needle Mountains, only the upper parts of the thick rock cover were removed, leaving all rock units from Middle Jurassic Entrada Sandstone to a position within the Upper Cretaceous Lewis Shale to be covered later with younger volcanic material (Steven and others, 1969). The identity of rocks beneath the volcanic cover is important in assessing energy resources.

Uplift and faulting during the Laramide orogeny were accompanied by igneous intrusive activity and related mineralization. The first volcanoes probably appeared in the San Juan volcanic field (fig. 7) at this time. This is indicated by presence of abundant volcanic debris in the Animas Formation of Late Cretaceous and Tertiary age, even though no evidence of Laramide-age volcanic sites survives in the Forest area. Emplacement of intrusive stocks and laccoliths caused structural doming of the thick sedimentary rock section in several areas of the Forest. Deep erosion of domes at La Plata, Rico, and Mt. Wilson (fig. 7) exposes intrusive and sedimentary rocks that are richly mineralized. Periods of quiescence, erosion, and basin filling followed the Laramide orogeny.

The dominance of igneous intrusion in the San Juan Mountains was replaced by a dominance of volcanism, which prevailed for the next 25 million years. During this time, great thicknesses of volcanic material accumulated in the San Juan volcanic field (fig. 7), which once covered a much larger part of the San Juan National Forest than it does today. Lavas and pyroclastic materials were extruded from many centers, now marked by calderas that are scattered throughout the volcanic field. Although sites of formerly active centers lie outside the Forest, those close by, such as the Platoro and South River calderas to the east and the Silverton caldera to the north, supplied material that covered large areas of the northeastern and eastern parts of the Forest (fig. 14). Intermittent intrusive activity and related mineralization within and near the calderas accompanied the extrusive activity. A final pulse of intrusive activity occurred in the Forest, less than 10 m.y. ago, when small stocks, accompanied by base- and precious-metal mineralization, were emplaced at Rico (fig. 15) and Chicago Basin.

Today's Forest landscape is largely the result of sculpturing by fluvial processes. Glacial processes have contributed to erosion of the hard and resistant rocks that make up the mountain ranges. The northeastern edge of the Forest, along the Continental Divide, is capped by relatively hard volcanic rocks that form the high plateau of the San Juan Mountains. The western edge of the volcanic pile is deeply dissected and forms cliffs with vertical faces as much as several thousand feet high. From the base of the cliffs, the softer underlying sedimentary rock section dips gently, with only local interruptions due to folding and faulting, southwestward across the Forest.

MINERAL AND ENERGY RESOURCES

The mineral and energy resources of the San Juan National Forest formed from many different processes throughout geologic history. Beginning in the Middle Proterozoic, granitic plutons were emplaced that were enriched in metals; in addition to forming deposits in the plutons themselves, circulating hydrothermal systems, fueled by much younger intrusives, transported metals to adjacent country rock. Later, during Paleozoic time, few metals were introduced, but great thicknesses of carbonate strata were deposited. Later, during the Cretaceous, some of the carbonate minerals reacted with fluids from igneous intrusive activity and were replaced by metallic ore minerals. Moveover, the permeability of these carbonate beds was to make them suitable as reservoir rocks for subsequently generated oil and gas.

During Mesozoic time, mostly clastic sediments were deposited. Metallic ore deposits formed in some of the clastic formations, and, in others, organic material accumulated to form thick coal beds that later generated coal-bed gas. Some sediments deposited during the late Mesozoic are highly productive reservoir beds for oil and gas; others are thought to be petroleum source rocks.

The first of three important metallogenic episodes to affect the area of the Forest began with emplacement of metal-bearing Laramide intrusives. During this episode, nearly the entire stratigraphic section, where exposed to intrusive activity, was a potential host for veins or replacement deposits of metals. A second major metallogenic episode, related to igneous activity in and near the San Juan volcanic field, occurred during mid- to late-Tertiary time. Mineralization took place mainly in structures related to large calderas but came from magmatic systems generally younger than and, perhaps, unrelated to major volcanism and caldera-forming events. All of the important mid- to late-Tertiary deposits are outside the Forest, but some of the more extensive hydrothermal systems followed fractures into the Forest, where they affected all types of rock. The third and final mineralizing event took place less than 10 m.y. ago when small plutons were emplaced that supplied metals and heat to hydrothermal systems. Mineralization occurred in the plutons themselves, as replacements in plutonic host rocks, or in country rock, in fractures that were either preexisting or newly formed by emplacement of plutons. Geothermal activity in some parts of the Forest may be related to this period of igneous intrusion.

Gold-bearing gravels are present along some of the major streams below mining districts. Erosion by streams and glaciers of lode gold deposits, formed during earlier mineralizing events, supplied the gold to these placers.

GEOLOGIC TERRANES

As defined here, a terrane is simply a rock unit or group of related rock units and (or) the area or areas in which they occur. The classification of rocks, based primarily on age, that is employed in the preceding section and on the geologic map (plate 1) plays an essential role in defining the geologic framework of the San Juan National Forest area. However, it is not the most useful basis for a consideration of the mineral resource potential of the Forest. This purpose is better served by a classification based primarily on rock types and only secondarily on age. The units of such a classification will have, either as "ore-bringers" or as host rocks or both, very different potentials for the development of different kinds of mineral deposits. These rock-type based units will be called "terranes" in this report. Time spans of terranes may overlap the formal geologic eras or periods and may also overlap one another (fig. 9).

The six terranes distinguished in the San Juan National Forest are, in chronological order of development:

- Proterozoic crystalline rock terrane (includes both igneous and metamorphic crystalline rocks)
- Paleozoic carbonate terrane

Conventional geologic time-rock unit	Terrane
Quaternary Rocks	Surficial (K)
Tertiary Rocks	Volcanic (F, G, H) / Intrusive (A, B, C, D, E)
Mesozoic Rocks	Clastic (J, I)
Paleozoic Rocks	Carbonate
Proterozoic Rocks	Crystalline

Figure 9. Relation of major conventional time-rock (time-stratigraphic) units to geologic terranes based on rock type, San Juan National Forest. Letters indicate deposit types (see table 1) genetically associated with terrane in which they appear.

- Paleozoic-Tertiary clastic terrane
- Cretaceous-Tertiary intrusive terrane
- Tertiary volcanic terrane
- Quaternary surficial terrane.

Characteristics of each terrane and its relationship to locatable mineral deposits are discussed in the following section. Deposit types associated with the terranes are shown on figure 9 (see also table 1). Maps are provided that show the locations of all terranes (figs. 10–14), except for the surficial terrane. Mineral deposits in the Forest are classified in four of the six terranes listed above: (I) deposits genetically related to rocks of the Cretaceous-Tertiary intrusive terrane, (II) deposits related to rocks of the Tertiary volcanic terrane, (III) deposits genetically related to rocks of the Paleozoic-Tertiary clastic terrane, and (IV) deposits related to the Quaternary surficial terrane. Deposits in the Proterozoic crystalline rock terrane and in the Paleozoic carbonate terrane are genetically related to the Cretaceous-Tertiary intrusive terrane and are described under category I.

PROTEROZOIC CRYSTALLINE ROCK TERRANE

The crystalline rock terrane includes metamorphic rocks and igneous rocks exposed over about 425 mi^2 of the north-central part of the Forest and locally at Rico and along the Piedra River (fig. 10). These rocks formed 1.8–1.4 b.y. ago and are exposed today as a result of deep erosion. Similar crystalline rocks underlie the rest of the Forest, except where they are displaced locally by plutons, but are concealed by a thick cover of Phanerozoic sedimentary and volcanic rocks. Proterozoic crystalline rock forms the core of the scenic and rugged Needle Mountains.

The crystalline rocks are relatively unimportant in terms of ore deposits compared to the much younger intrusive rocks in the Forest. They do, however, contain fracture systems that provide sites for mineralization that originated from younger magmatic and hydrothermal events and may have provided some metals to ore deposits in much younger rock. Parts of the terrane have been explored for fossil placer uranium and gold and for sources of iron.

The crystalline rocks resulted from two separate cycles of sedimentation, volcanism, and plutonism over a 400-m.y. period. As recorded in the Needle Mountains, the stages of the first cycle were (1) volcanism and accompanying sedimentation that resulted in thick sequences of interlayered rocks, (2) a tectonic episode that included intense folding and amphibolite-grade metamorphism of the layered sequences producing the Early Proterozoic Irving Formation and Twilight Gneiss, (3) intrusion of the Early Proterozoic Bakers Bridge and Tenmile Granites into the Irving Formation and Twilight Gneiss, and (4) a major hiatus in deposition accompanied by uplift and profound erosion (Barker, 1969b). The second cycle consisted of (1) deposition of the Early and Middle Proterozoic Vallecito Conglomerate and Uncompahgre Formation, (2) easterly trending isoclinal folding and metamorphism, (3) Middle Proterozoic intrusion of the large Eolus Granite batholith, the Trimble Granite, and other small plutons, and (4) deep erosion of the Proterozoic terrane prior to deposition of Cambrian and younger sediments (Barker, 1969b).

METAMORPHIC ROCK

The Irving Formation (Xi, plate 1) and the Twilight Gneiss (Xtw) are the oldest rocks in the Forest (more than 1,750 Ma) and are included in the Early Proterozoic layered gneiss complex of Tweto (1987). Both rock units are predominantly metavolcanic with large components of sedimentary material.

The Irving Formation consists of amphibolites, mica schist, metagraywacke, meta-andesite, greenstones, metasiltstone, quartzite, conglomerate, and banded iron-formation (Barker, 1969a, p. 5). As part of the Weminuche Wilderness (fig. 6) evaluation by Steven and others (1969), the banded iron-formation was studied as a potential resource of iron. The iron-formation crops out in the Forest about 8 mi northeast of Vallecito Reservoir (plate 1). It is a laminated magnetite-quartz rock in widely separated beds 4 inches to 50 ft thick. The iron content, which averages somewhat less than 15 percent, is considered far too low to be of economic value, given the relatively small deposit size.

The Twilight Gneiss is leucocratic, quartzo-feldspathic, biotitic, amphibolitic, and quartzitic (Van Loenen and Scott, 1985). The felsic and mafic components, both strongly foliated, have an interlayered and often interfingering relationship. The Twilight Gneiss, which forms the rugged peaks in the West Needle Mountains, hosts veins containing

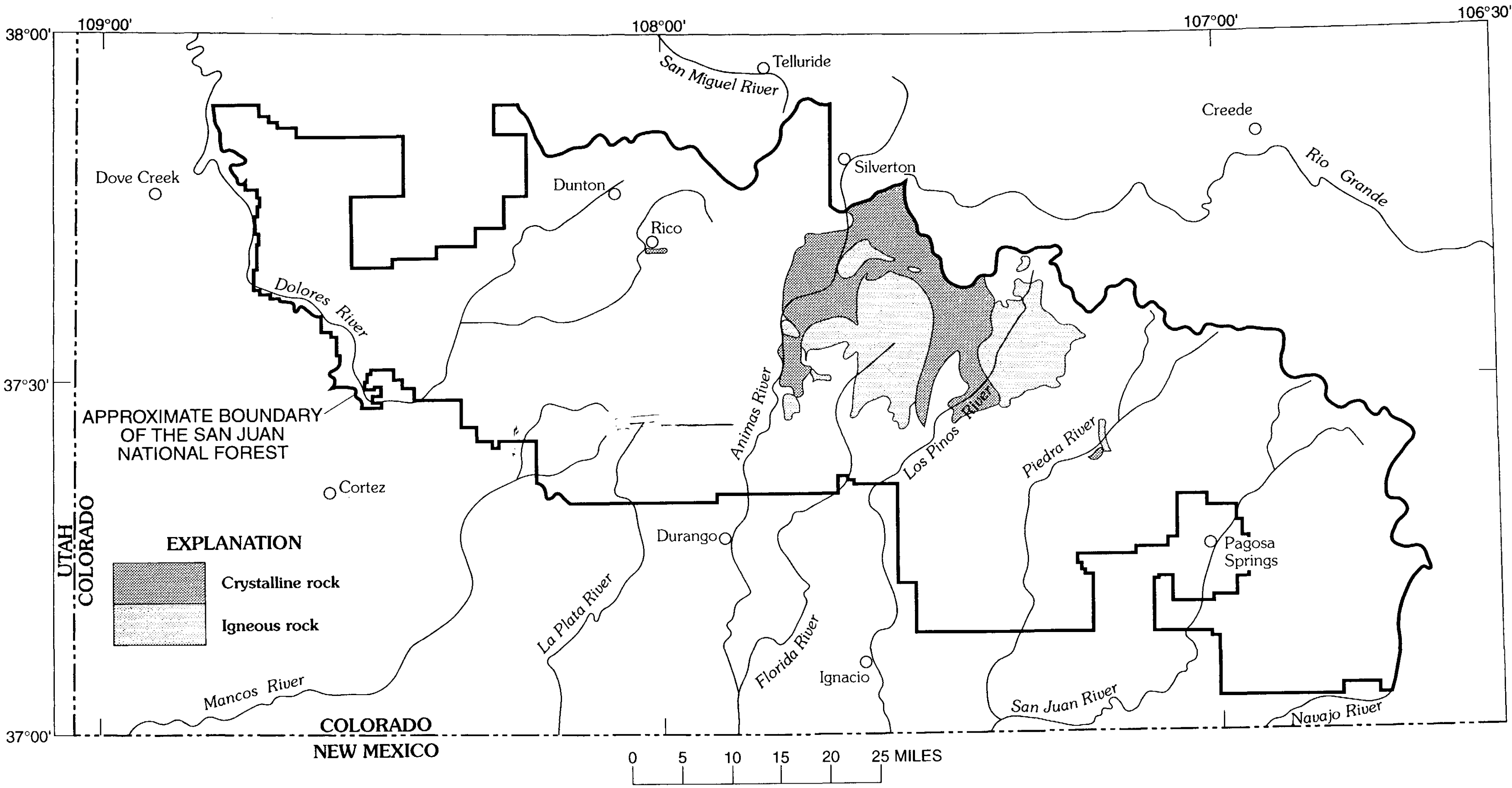


Figure 10. Map showing location of Proterozoic crystalline and igneous rock terrane exposed in the San Juan National Forest.

base and precious metals in the Needle Mountains mining district.

Following tight folding, invasions by intrusives, and metamorphism of the first generation of sedimentary deposits, the second cycle of sedimentation began with accumulation of the parent materials of the Vallecito Conglomerate (YXv) and Uncompahgre Formation (YXu). These rock units occupy an arcuate segment of the Forest beginning just north of Vallecito Reservoir and continuing northwest to near Engineer Mountain (plate 1). The Vallecito is probably a lateral facies of the Uncompahgre, with the Vallecito occupying a generally lower position (Tweto, 1987).

The Vallecito Conglomerate is a quartzose conglomerate that contains clasts of quartzite, quartz, chert, red and black jasper, banded iron-formation, and minor quantities of other rock types. It is at least 2,400 ft thick and may be as much as 5,000 ft thick (Barker, 1969b, p. A1).

The Uncompahgre Formation is a thick sequence (more than 8,000 ft) of intercalated quartzite, slates, and conglomerate. Maroon to white, fine- to medium-grained quartzites are predominant. Intercalated black, green, and maroon slates, in units as much as several hundred feet thick, constitute 25 percent of the formation. The basal conglomerate is characterized by 1- to 5-inch rounded clasts of white quartz, biotite gneiss, and banded ironstone—lithologies that are common in the underlying Irving Formation. Rocks of the Uncompahgre Formation were isoclinally folded along easterly to southeasterly trends. Tight folding caused the quartzite to fracture locally, creating the conditions necessary for mineralization such as that observed in the Elk Park district (fig. 20). The spectacular scenery of the Grenadier Range, which makes up the northern end of the Needle Mountains (plate 1), is due to erosional remnants of the steeply dipping beds of hard quartzite of the Uncompahgre Formation.

Some conglomerates of Proterozoic age, deposited under special conditions, are host to important fossil placer gold and uranium deposits. Both the Vallecito Conglomerate and the basal conglomerate of the Uncompahgre Formation were studied extensively by Burns and others (1980) for their uranium potential and by Barker (1969a) for their gold potential. Neither of the conglomerates was considered favorable for fossil-placer uranium deposits because they lack several characteristics required by ore deposits of this type. The most important requirement is that the host conglomerates be older than 2,200 Ma. This is thought to be the time when free oxygen, which tends to decompose uranium minerals exposed to surface conditions, was first introduced into the Earth's atmosphere. The conglomerate of the Uncompahgre Formation is less than 1,700 Ma, and the Vallecito Conglomerate is probably coeval. These conglomerates do not contain pyrite (iron sulfide, FeS_2) but do contain iron oxide minerals, which suggests that the conglomerates were deposited under oxidizing conditions (Burns and others, 1980; Theis and others, 1981). Thus, conditions were not appropriate for the formation of uranium placer deposits.

Little, if any, gold is present in the conglomerates. Barker (1969a) concluded that the paucity of gold in the Vallecito and Uncompahgre conglomerates resulted from a paucity of gold in their source rocks. The conglomerates were derived from a gold-poor terrane of quartzite, jasper, biotite gneiss, and iron-formation (probably the Irving Formation).

INTRUSIVE ROCK

The oldest intrusive igneous rocks are the Bakers Bridge and Tenmile Granites. These granites, which are included in the Early Proterozoic Routt Plutonic Suite (Tweto, 1987), are both about 1,700 Ma, and they intrude older layered rock (Twilight Gneiss and Irving Formation) (plate 1). Dating of these granites, neither of which is known to contain ore deposits, establishes the minimum age of the layered rocks. The Bakers Bridge Granite crops out near Rockwood, about 14 mi north of Durango. It is a small stock of pale-red, coarse-grained, homogeneous granite that locally contains amphibolite inclusions. It is characterized by large microcline perthite phenocrysts. The Tenmile Granite is a small stock bisected by the Animas River about 8 mi south of Silverton. This granite is mainly pink to light gray, medium to coarse grained, sometimes displays foliation, and contains amphibolite inclusions.

The final episode of Proterozoic igneous activity took place about 1,400 Ma with the emplacement of the Eolus Granite, Trimble Granite, Electra Lake Gabbro, and the melasyenite of Ute Creek. These rocks belong to the Middle Proterozoic Berthoud Plutonic Suite (Tweto, 1987). The Eolus and Trimble Granites locally contain ore deposits.

The Eolus Granite (Ye) crops out in two separate bodies, one near the center of the Needle Mountains and the other about 10 mi to the east. It consists mainly of pink to brick-red biotite-hornblende quartz monzonite and biotite quartz monzonite. Large microcline phenocrysts (0.5–1.5 inch long) are characteristic of the Eolus. The Needle Mountains mining district is centered over the western body of Eolus Granite.

The Trimble Granite (Ytr) was intruded into the western body of Eolus Granite. It is mainly a pale-red, porphyritic, fine- to medium-grained biotite granite and is distinguished from its host Eolus Granite by its finer grain size. The contacts are generally sharp, and many apophyses of Trimble extend into the Eolus. Its similar composition and intrusive position within the Eolus suggest a genetic relationship. Studies by Collier (1985) suggest that the Trimble is a late-stage differentiate of its parent Eolus Granite. This late-stage granite is enriched in uranium, which forms ore deposits in places where the granite is broken by faults and fractures. These are vein uranium deposits (table 1, deposit type E).

PALEOZOIC CARBONATE TERRANE

The carbonate terrane (fig. 11) in the San Juan National Forest contains several thousand feet of limestone and dolostone. Upon contact with mineralizing solutions, carbonate minerals are commonly replaced by ore minerals (table 1, deposit type C). Polymetallic replacement and skarn deposits have been mined in carbonate rock at Rico and in the La Plata mining district.

As used in this report, the carbonate terrane includes all of the strata deposited from Cambrian through Middle Pennsylvanian time because most of these strata are carbonate rocks, although clastic rocks are also present. The carbonate terrane is considered permissive terrane for locatable mineral deposits not only in areas where it is exposed at the surface but also in areas where it comes within 3,000 ft of the surface. The permissive areal extent of the carbonate terrane, surface and subsurface, is shown on figure 11.

The carbonate terrane is exposed in an arcuate pattern on the flanks of and in small outliers on the uplifted Proterozoic basement rocks in the central region of the Forest. Farther west, these rocks are exposed in the cores of the Rico and La Plata domes (fig. 7). In the subsurface, this terrane extends westward past the line defining its permissive extent in figure 11 and beyond the boundary of the map. Its eastern limit is where it pinches out owing to nondeposition or erosion over the Uncompahgre–San Luis uplift. This pinchout occurs to the west of the area now covered by volcanic rocks, except in the north-central part of the Forest west of Silverton, where carbonate terrane underlies the volcanics.

Sediments of the carbonate terrane were deposited in two very distinct environments. From Cambrian through Mississippian time, deposition was in an environment of regional stability. During Pennsylvanian time, however, deposition of carbonates took place in a setting provided by the more localized pattern of uplift and basining that marked the latter part of the Paleozoic.

Cambrian, Devonian, and Mississippian marine carbonate and clastic rocks were deposited intermittently from shallow seas in a major geosyncline along the western edge of a craton. Rock units of this group are the Upper Cambrian Ignacio Quartzite, Upper Devonian Elbert and Ouray Formations, and the Lower Mississippian Leadville Limestone. These formations are meagerly exposed in a few small outcrops in and around the Proterozoic rock of the Needle Mountains. They are absent in the southeastern part of the Forest and are deeply buried beneath the western part. The formations are not differentiated on plate 1 but are combined alternatively in either map unit MD€ (Mississippian, Devonian, and Cambrian) or unit MD (Mississippian and Devonian).

The oldest carbonate rocks of the carbonate terrane are intertidal dolostones in the upper part of the Elbert Formation. They overlie older clastic rocks of the terrane, represented by the lower part of the Elbert and by the Ignacio Quartzite. Known mineralization in the Elbert Formation is limited to an occurrence of uranium in an area north of Durango. The Elbert Formation is overlain by the Upper Devonian Ouray Limestone, which grades upward into the Lower Mississippian Leadville Limestone. The Leadville represents a deeper marine environment than the Ouray.

In the Rico mining district, where they were metamorphosed by a monzonite intrusive body of Late Cretaceous–early Tertiary age, the Ouray and Leadville Limestones are host to contact-metamorphic deposits (skarns) (table 1, deposit type C) (McKnight, 1974). The skarns contain base metals with by-product silver and gold. Although found at shallow depths at Rico, the Ouray and Leadville are deeply buried (to more than 3,000 ft) in the La Plata mining district, as well as in much of the rest of the Forest. Along the west side of the West Needle Mountains, these formations, in common with Proterozoic rocks of the area, are hosts to small quartz-fissure veins that contain traces of gold and silver (Scott, 1983).

An erosional episode followed Leadville deposition, producing a karst surface now buried in shale and regolith of the Middle and Lower Pennsylvanian Molas Formation. Following Molas deposition, the uppermost part of the carbonate terrane was laid down in basins that formed adjacent to the developing Uncompahgre–San Luis uplifts. Thick deposits of carbonates, evaporites, and clastic sediments of the Upper and Middle Pennsylvanian Hermosa Group accumulated in the Forest area during later Pennsylvanian time.

In the central part of the Forest where it is widely exposed, the Hermosa Group is as much as 2,500 ft thick and consists mainly of marine limestones, sandstones, and shales. These deposits were laid down in three parts, beginning with sandstones and shales and thin limestone beds deposited in a shallow-water marine-transgressive environment. These earliest sediments were followed by massive limestones and interbedded black shales deposited in a deeper marine environment. Hermosa deposition ended with sandstone, shale, conglomerate, and thin limestone deposited in a near-shore regressive-marine environment. In the Paradox Basin to the west, where the Hermosa Group is entirely in the subsurface, the medial limestone unit of the outcropping formation is represented by evaporites.

Rocks of the Hermosa Group are host to the principal ore deposits of the Rico district. These are massive sulfide replacement deposits (table 1, deposit type C) in limestones of the middle part of the formation and related vein deposits in sandstones of the upper part. The deposits contain base-metal ores with by-product silver and gold (McKnight, 1974). Other deposits, very small as compared to those at Rico, occur in the Hermosa limestones in the Cave Basin district northeast of Durango.

Only the upper 500 ft of the Hermosa is exposed in the La Plata district (Eckel, 1949). The limestone beds that host ore at Rico are probably present at depth in the La Plata

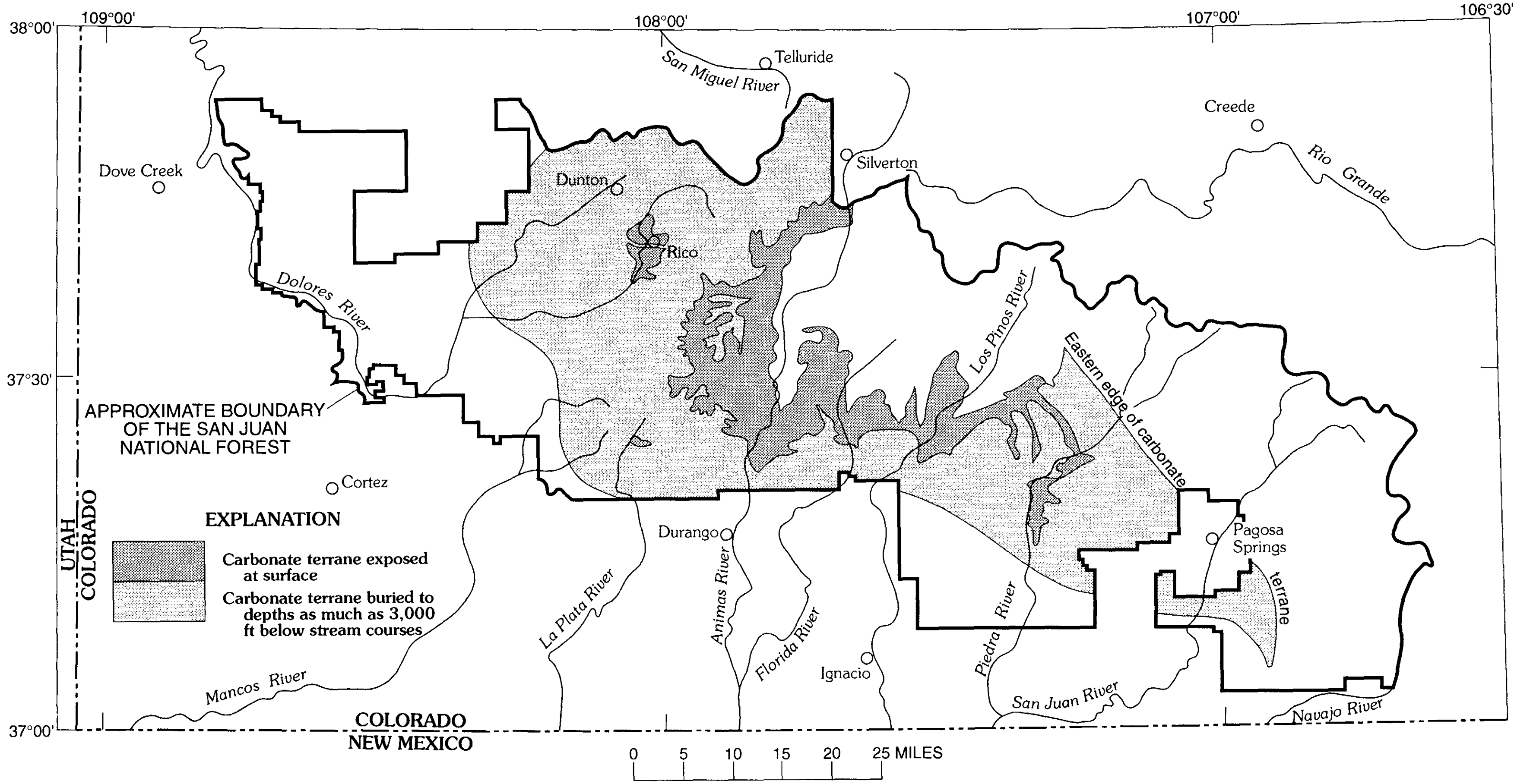


Figure 11. Map showing location of Paleozoic carbonate terrane in the San Juan National Forest.

district but have not been explored. Where they are cut by Late Cretaceous–early Tertiary intrusive bodies, these beds are potential hosts for ore deposits.

The Hermosa Group along the east flank of the Paradox Basin, but mostly below the terrane shown on figure 11, may contain reservoirs for oil and gas in the Silverton Delta Play and Carbonate Buildup Play, discussed later under energy resources.

Stratigraphically separated from the carbonate terrane by nearly 3,000 ft of clastic strata, mostly representing Lower Permian Cutler Formation and Upper Triassic Dolores Formation redbeds, is the Middle Jurassic Pony Express Limestone Member of the Wanakah Formation. This limestone, only 0–25 ft thick and mapped with the clastic terrane (fig. 12), is nonetheless an important host rock for replacement deposits in the La Plata mining district. It is absent from the Rico district.

PALEOZOIC-TERTIARY CLASTIC TERRANE

The clastic rock terrane in the San Juan National Forest (fig. 12) includes a thick sequence of sedimentary rocks deposited during the later part of the Paleozoic and during the Mesozoic and Cenozoic Eras. Some of the younger formations, notably the Upper Cretaceous Dakota Sandstone (Kd, Kdb) and Mancos Shale (Km, Kmj), form a gently dipping surface over large expanses of the Forest, whereas older clastic rocks are exposed mainly in canyon walls.

The clastic rock terrane (fig. 12) is a wedge of continental and marine strata that thickens to the west and south from the Uncompahgre–San Luis uplifts into the Paradox and San Juan Basins. The oldest exposed rocks of the sequence crop out around the central Needle Mountains uplift, with progressively younger rocks exposed to the west, south, and east. Clastic rocks are exposed on the surface of nearly two-thirds of the Forest. Exposures are absent only over the uplifted areas in the central part, where they have been removed by erosion, and in the eastern part, where the clastic rocks are covered by volcanic rock.

Rocks of the clastic terrane locally host vein and replacement deposits (table 1, deposit types C, D), but these are essentially results of igneous intrusive activity and are described in the section on the Cretaceous-Tertiary intrusive terrane. Other kinds of mineral deposits have a genetic relationship to the clastic terrane. Such include sandstone-hosted uranium-vanadium and copper deposited during diagenesis of the sedimentary rock. Permissive rocks for sandstone-hosted deposits make up only a small fraction of the very thick clastic rock terrane. A much larger part of this terrane is of major importance for energy resources. The Cretaceous units contain thick coal beds as well as other rock layers that are possible sources of, or both conventional and unconventional reservoirs for, oil and gas. These resources are discussed in later under energy resources.

Sandstone-hosted uranium ore deposits (table 1, deposit types I, J) and minor occurrences are present in and near the Forest in several formations of the clastic terrane. At least 20 of the formations that occur in the Forest are known to host occurrences or ore deposits of uranium and vanadium in the Southwestern United States (Neubert and others, 1992). Uranium-vanadium and copper deposits that have been mined in the Forest occur in the Lower Permian and Middle and Upper Pennsylvanian Rico Formation (PIPrh), the Upper Triassic Dolores Formation (TRd, TRPdc), and the Middle Jurassic Entrada Sandstone (Jmse, Jmjwe). Uranium and vanadium deposits in the Forest are small compared to the large deposits found in the Upper Triassic Chinle Formation (Dolores equivalent) and in the Upper Jurassic Morrison Formation (Jm, Jmjw, Jmse, Jmjwe) northwest of the Forest in the Slick Rock district (fig. 16). Sandstone-hosted ore deposits are dependent on favorable lithologies, such as medium-grained sandstone enclosed in shales, permeable and gently dipping beds, and the presence of a reducing agent such as organic material.

The Lower Permian and Upper and Middle Pennsylvanian Rico Formation, a mixed unit, is included in the lowermost part of the clastic rock terrane mainly because it contains sandstone uranium deposits. Lithologically, the Rico is transitional between the carbonate and clastic terranes and contains limestones as well as both marine and continental clastic rocks. It is included in the carbonate terrane on the map figures and plates in this report because it is combined with the much thicker Hermosa Group as a single map unit (PIPrh) of dominantly carbonate lithology.

Uranium occurs associated with fossil plant fragments in fluvial sandstones of the Rico Formation at Tripp Gulch (Neubert and others, 1992, p. 235). A few hundred tons[1] of rock containing 0.25 percent U_3O_8 were identified at Tripp Gulch, one of only two areas in the Forest that have been mined for uranium, but only a few pounds were produced (Theis and others, 1981). Most of the Rico sandstones are unfavorable for uranium deposits because they are thin and laterally discontinuous and contain only sparse amounts of organic debris (Theis and others, 1981).

Rocks overlying the Rico Formation, and shown on figure 12 as the lowermost part of the clastic terrane, are the picturesque "redbeds" of the Lower Permian Cutler Formation (Pc, TRPdc) and the Upper Triassic Dolores Formation (TRd, TRPdc). These formations have a combined thickness of nearly 3,000 ft and crop out extensively in the central part of the Forest (plate 1). Within the Forest, both units are oxidized, as indicated by their red color, and oxidation is generally not conducive to sandstone uranium deposits. Beyond

[1]The term "ton," as used in this report, refers to metric ton unless specified otherwise.

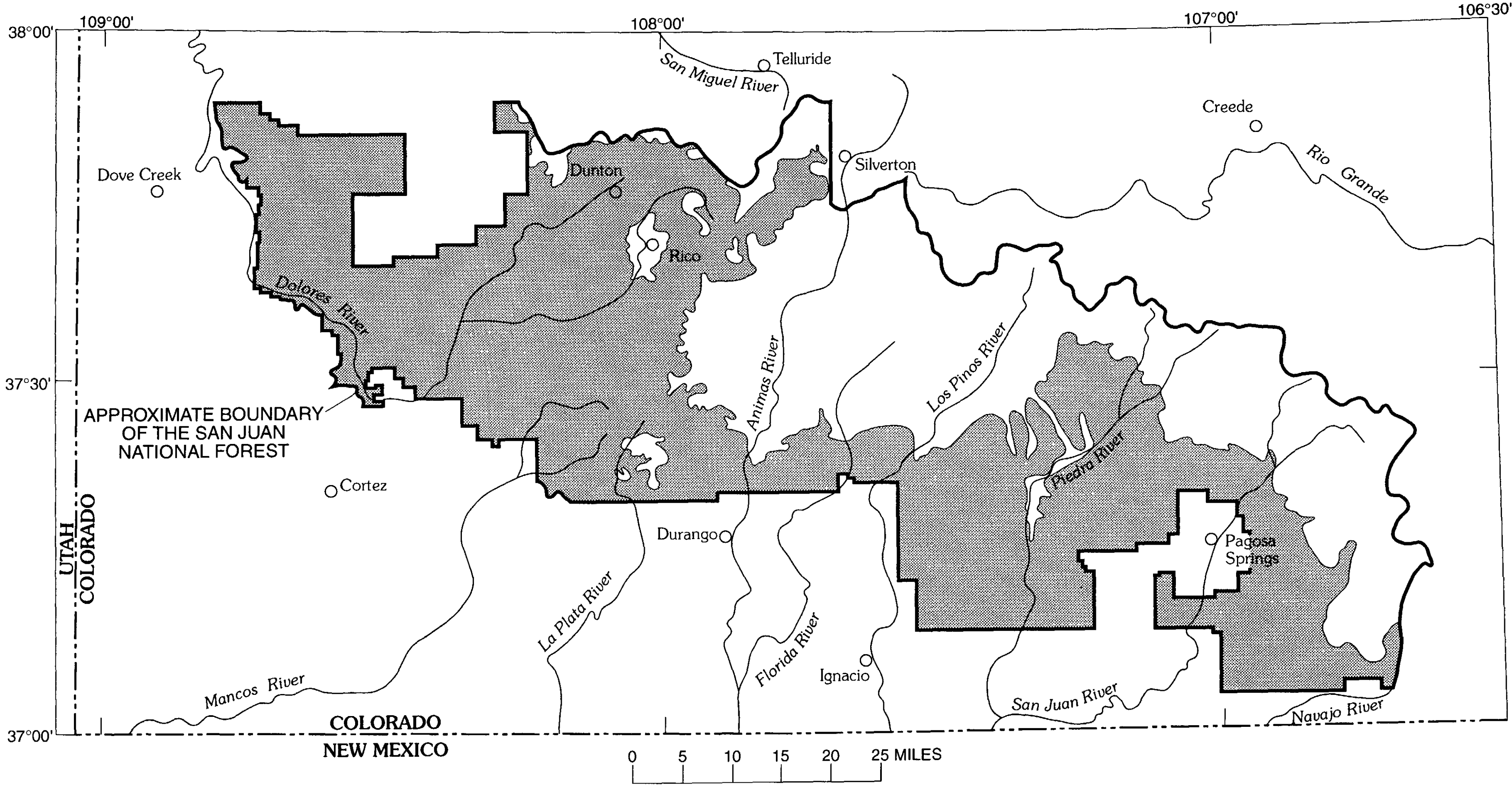


Figure 12. Map showing location of Paleozoic-Tertiary clastic terrane in the San Juan National Forest.

the northwestern edge of the Forest, where it was deposited in a relatively anoxic environment, the Cutler is favorable for uranium, as is the Chinle Formation (T̄Rkc, JT̄Rgc), a largely unoxidized stratigraphic equivalent of the Dolores Formation (Neubert and others, 1992, p. 220).

Along Bear Creek, an east tributary of the Dolores River heading in the La Plata Mountains (plate 1), the Dolores Formation contains small deposits of copper that may be of sedimentary origin. Fossil plant remains that served as reductants were replaced by copper sulfides in sandstones. All of the deposits occur adjacent to an igneous dike, however, making a purely sedimentary origin uncertain. This is the only such site known in the Forest.

The Middle Jurassic Entrada Sandstone (Jmse, Jmjwe), which overlies the Dolores Formation, is the only rock unit in the Forest known to contain significant amounts of sandstone uranium and vanadium (table 1, deposit type J). The Entrada was deposited in an eolian and coastal dune environment. It consists of clean, permeable, medium-grained sands and generally lacks clays and obvious reductants, such as organic material, that could serve to stabilize uranium minerals. At Graysill, east of Rico, sandstones in the upper part of the Entrada, just below its contact with the overlying Wanakah Formation, were mined for vanadium and uranium (see discussion under Graysill district).

The Middle Jurassic Wanakah Formation (Jmjw, Jmjwe), composed mostly of eolian and interdunal sandstone and limestones, is not known to host uranium deposits. However, the Pony Express Limestone Member of the Wanakah is a host for precious- and base-metal replacement deposits in the La Plata mining district.

The Morrison Formation (Jm, Jmjw, Jmse, Jmjwe) overlies the Wanakah Formation and crops out in the central part of the Forest and just beyond its western boundary along tributaries to the Dolores River. The Morrison is as much as 800 ft thick and consists of sandstone with interbedded clays and mudstones of the Salt Wash Member overlain by mostly varicolored claystone and sandstone of the Brushy Basin Member. The fluvial and lacustrine sandstones of the Salt Wash Member were deposited under sedimentary conditions that locally were favorable to formation of world-class uranium ore bodies (table 1, deposit type I), such as those in the Slick Rock mining district northwest of the Forest (fig. 16). Outcrops of the Morrison were extensively prospected in the Forest during the "uranium boom" of the 1950's, but little was found, and no mining took place. Away from outcrops, the Morrison is deeply buried beneath younger clastic rocks.

The uppermost units of the clastic terrane, including several thousand feet of Upper Cretaceous marine and nonmarine sandstones and shales and Cenozoic sedimentary rocks as well, are not known to contain sandstone uranium or other metallic mineral deposits formed by sedimentary or diagenetic processes. They do contain important energy resources, including coal, coal-bed gas, and conventional oil and gas, as well as accumulations of carbon dioxide.

CRETACEOUS-TERTIARY INTRUSIVE TERRANE

Several episodes of intrusive activity during Late Cretaceous and Tertiary time are recorded by igneous rocks of the San Juan National Forest. These intrusive bodies initiated the ore-forming processes and attendant mineralization in nearly all of the important mining districts in the Forest. The intrusives are either host to mineralization themselves and (or) are accompanied by ore occurrences in the invaded rocks nearby. Deposit types genetically related to rocks of the intrusive terrane include stockwork Mo (deposit type A), porphyry Cu (deposit type B), polymetallic replacement and skarns (deposit type C), Au-Ag-Te veins (deposit type D), and vein uranium (deposit type E) (table 1).

As used in this report, the intrusive terrane (fig. 13) includes only rocks intruded during three time periods, (1) Late Cretaceous–early Tertiary time (TKi), (2) middle Tertiary, from 40 to 20 m.y. ago (Tmi), and (3) late Tertiary, less than 20 m.y. ago (Tui) (plate 1). However, there is considerable overlap of the time boundaries by the associated mineralization, especially during middle to late Tertiary time (Lipman and others, 1976).

LATE CRETACEOUS AND EARLY TERTIARY INTRUSIVE TERRANE

This terrane is composed of igneous rocks emplaced during the Laramide orogeny (see TKi on plate 1), a period of domal uplift accompanied by erosion, folding, faulting, and igneous activity that lasted from 70 Ma (near the end of Cretaceous time) to about 60 Ma (near the middle of the Paleocene). Ore deposits genetically related to the intrusives are found in Paleozoic and Mesozoic sedimentary and Proterozoic metamorphic host rocks and include the most intensely mineralized rock in the Forest. Remnants of two deeply eroded centers of this terrane are at Rico and La Plata. Another intrusive center at Ouray, 10 mi north of the Forest, is of similar age and mineralization to those at Rico and La Plata but not so deeply eroded. The three centers are aligned along a north-northeast-trending fold structure caused by Laramide deformation that may have influenced the location of the intrusive bodies (Tweto, 1968, p. 570). The alignment and location of these intrusives define the southernmost extent of the Laramide-age Colorado Mineral Belt.

The Cretaceous-Tertiary intrusive terrane results from multiple stages of igneous activity. The early stage was a nonmineralizing mountain-building event caused by the emplacement of laccoliths and sills in upper Paleozoic and Mesozoic sedimentary rock. Later stages of igneous activity included the intrusion of stocks and the development of mineralizing systems.

During the first stage of igneous activity, domal uplifts developed as a result of the emplacement of thick concordant

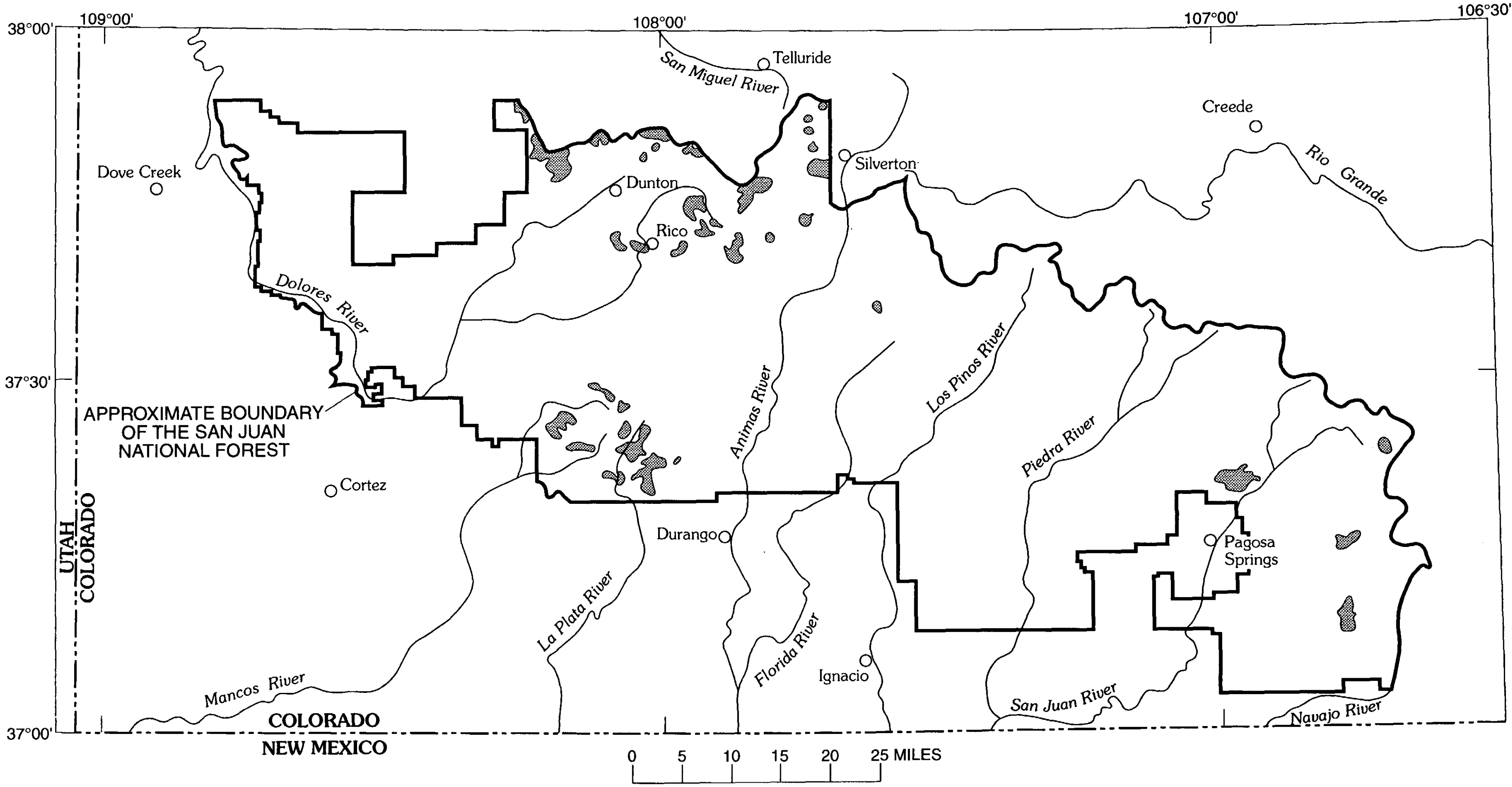


Figure 13. Map showing location of the Cretaceous-Tertiary intrusive terrane in the San Juan National Forest.

bodies of igneous rock as laccoliths. Sedimentary rocks in the La Plata Mountains were domed up as much as 6,000 ft, and rocks at Rico were domed as much as 4,000 ft. Deep erosion has since exposed a thickness of sedimentary rock equal to or exceeding the amount of structural uplift.

The early concordant bodies are mainly porphyritic, with compositions ranging from diorite to syenite, whereas the later intrusive rocks consist of generally discordant bodies of nonporphyritic rocks that are largely alkalic in composition. Mineralization of the Cretaceous-Tertiary intrusive terrane in the La Plata and Rico districts is discussed later in under mining districts and mineral resources.

MIDDLE TERTIARY INTRUSIVE TERRANE

The second stage of igneous intrusive activity took place between late Eocene and early Miocene time at about 40–20 Ma (see unit Tmi on plate 1). These intrusives are mainly quartz-bearing porphyritic rock of intermediate to felsic composition. They are exposed within and adjacent to the volcanic terrane along the northeastern and northern part of the Forest. Mountains in the western part of the San Miguel Range are made up of intrusive rock of this age. These magmas were emplaced as small composite stocks, laccoliths, dikes, and sills into hosts ranging from Upper Cretaceous sedimentary rock to mid-Tertiary volcanics. Some mineralization in the Forest is thought to be associated with stocks intruded during this time period into fractures around the margin of the Silverton caldera (Lipman and others, 1976), with stocks in structures that may be related to the Platoro caldera along the eastern part of the Forest near the Summitville mining district (Brock and Gaskill, 1985, p. 30), and with the intrusive complex at Mt. Wilson that lies on the western fringe of the Telluride-Silverton region (Bromfield and Williams, 1972). Many bodies of intrusive rock (Tmi) shown on plate 1 are small laccoliths, sills, and dikes emplaced in Upper Cretaceous sedimentary rock without any accompanying mineralization.

LATE TERTIARY INTRUSIVE TERRANE

Two igneous bodies about 10 Ma may represent the latest stage of intrusive activity in the Forest. These are the Chicago Basin stock and a laccolithic body about 5 mi east of Rico (plate 1). The Chicago Basin stock is a multiphase intrusive complex centered in the Needle Mountains mining district. Schmitt and Raymond (1977) reported ages of 10 Ma and 9 Ma for different phases of the stock. It has close genetic ties to mineralization in the district, having supplied both metals and heat to convection systems in surrounding rocks (Collier, 1985; Schmitt and Raymond, 1977).

No known mineralization is associated with the laccolith east of Rico. Mineralization of similar age has been found nearby, however. Recent exploration beneath the Rico mining district has identified mineralization that is thought to be related to an intrusive event that occurred about 5 Ma (Cameron and others, 1986), possibly the final stage of intrusive activity in the Forest.

TERTIARY VOLCANIC TERRANE

The volcanic terrane, in the northeastern part of the Forest along the Continental Divide (fig. 14), includes only a small part of the San Juan volcanic field (see fig. 7). Ore deposits are considered to belong to the volcanic rock terrane when they have no readily identifiable intrusive source, even though the deposits are probably genetically related to an intrusive event. The volcanic terrane is of major importance to some ore deposit types because it contains the fracture systems that localize many deposits. Igneous intrusions, hydrothermal alteration, and mineralization are concentrated within ring fracture zones and through-going faults and fractures related to caldera formation. Metals were probably supplied to deposits dominantly from sources at depth rather than from the volcanic rocks. The most likely sources of ore metals are late-stage Tertiary intrusives and (or) underlying Proterozoic basement rock and other country rock from which metals were leached by circulating hydrothermal fluids.

Volcanic rocks near the Forest, at Silverton, Creede, and Summitville, host some of the most intensely mineralized rock in the southern Rocky Mountains. Of particular interest in this Forest study are volcanic rocks adjacent to the mining districts at Silverton and Summitville. Several known extrusive centers are scattered throughout the San Juan volcanic field, but all are outside the Forest except for the southwestern edge of the Silverton caldera (fig. 14). The South River caldera structure, at the eastern edge of the Forest (Lipman and Sawyer, 1988), is apparently unmineralized. Ore deposits in the volcanic terrane are Creede-type epithermal veins (deposit type G) and epithermal quartz-alunite gold deposits (deposit type H), and epithermal vein deposits related to volcanic terrane but hosted by Proterozoic rocks (deposit type F) (table 1).

Two episodes of volcanic activity affected the Forest area during Late Cretaceous–early Tertiary (Laramide) regional uplift. The intrusive centers of this age at Rico and La Plata probably had extrusive components, later removed by erosion. Evidence of these volcanics is seen only as volcanogenic sediment in the Telluride Conglomerate and Blanco Basin Formation of early Eocene age (Te). The mid-Tertiary episode of voluminous volcanism followed the deposition of these sediments (Steven and others, 1969).

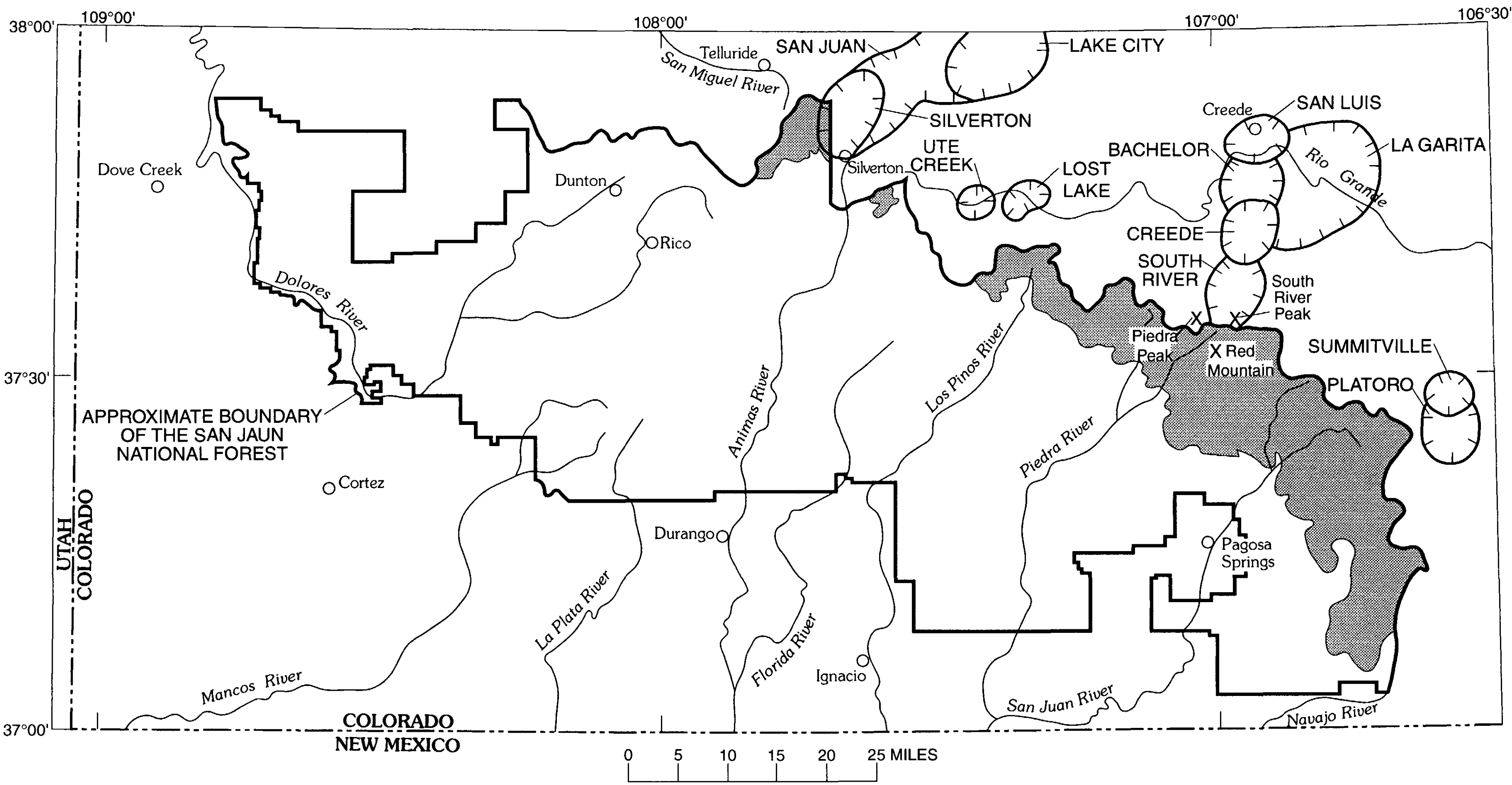


Figure 14. Map showing Tertiary volcanic terrane in the San Juan National Forest and adjacent major calderas (hachured pattern) to the northeast.

The mid-Tertiary and younger volcanic rocks comprise an interfingering mixture of lava and pyroclastics erupted from many different centers that underwent periods of doming and collapse as calderas evolved. The rocks of the San Juan volcanic field were derived essentially from three stages of activity: (1) eruption of intermediate-composition lavas and breccias, (2) deposition of ash-flow tuff, and (3) eruption of basalts and rhyolites.

In the first stage of activity, lavas and breccias were erupted from 35–30 Ma (Steven and others, 1974). These rocks make up about two-thirds of the volume of material in the San Juan volcanic field. They consist largely of andesite and rhyodacite deposited on an irregular surface ranging in age from Proterozoic to Tertiary. They are exposed extensively in the southeastern parts of the Forest (shown on plate 1 as Tpl). From 30 to about 26 Ma, the major volcanic activity consisted of emplacement of ash-flow tuffs (Taf on plate 1). Recurrent explosive eruptions of ash and related flows during this period led to the collapse of many calderas in the San Juan volcanic field. Lavas and ash-flow tuffs filled the collapsed calderas. Concurrently, granitic intrusions invaded the margins of the calderas and may have triggered resurgent doming within the calderas (Lipman and others, 1976). Beginning about 25 Ma and continuing to 5 Ma, the volcanic activity in the San Juan volcanic field consisted of volumetrically meager but widespread flows of basalt and rhyolite erupted from local centers.

Ring fractures and other subsidence faults that developed in response to the collapse of calderas and resurgent doming provided the channels for later intrusive igneous rock and circulating hydrothermal systems in the volcanic rock terrane. Lipman and others (1976) have shown that mineralization and major alteration occurred intermittently from about 30 to 10 m.y. ago. Lipman and others (1976) further add that "most of the richest ores in the Silverton area were deposited 5 to 10 m.y. after caldera collapse, during an extended period when minor quartz porphyry intrusions were emplaced sporadically along caldera-related structures." Ores in the Creede mining district (25 Ma), hosted by the Bachelor caldera, formed about 1 m.y. after the youngest volcanism related to caldera collapse (about 26 Ma) (Bethke and others, 1976). Ores at Summitville probably formed less than half a million years after the intrusion (27 Ma) of the host quartz latite porphyry at South Mountain (fig. 23) and prior to the eruption of rhyolite that overlies the quartz latite south of the district (at 20.2 Ma). Placing the Summitville mineralization within this interval is a date of 22.5 Ma obtained on hydrothermal alunite (Mehnert and others, 1973).

QUATERNARY SURFICIAL TERRANE

Surficial deposits are widespread across the Forest, although they are shown only sparingly as a geologic map unit on plate 1. Virtually every stream course in the Forest contains at least a small amount of alluvial fill, but deposits are difficult to show on a map of this scale, and no figure was constructed to show this terrane. Locatable mineral resources in this terrane are placer gold deposits in gravels (table 1, deposit type K) found downstream from some of the important mining districts. Known placer deposits in the Forest include those of the Dolores, Mancos, and Animas Rivers. Gravels of the surficial terrane consist of Pleistocene-age glacial deposits and Holocene (modern) stream-laid alluvium.

LOCATABLE MINERAL RESOURCES

By Richard E. Van Loenen, J. Thomas Nash, Nora K. Foley, *and* Anthony B. Gibbons

EXPLORATION AND MINING HISTORY

Prospecting and mining have been active in the San Juan Mountains for more than 120 years. In the 18th century, Spanish explorers visited the La Plata Mountains and reported silver mines in operation (Eckel, 1949). In 1848, a member of the Fremont exploration party discovered gold near the future site of Lake City. Prospectors entered the area in the 1860's, found encouraging signs of gold and silver near the future sites of Durango, Silverton, and Rico, but were driven away by Indians. In spite of hostility, mining of placer gold commenced near Summitville and Silverton in 1870 and along the La Plata River in 1873. A treaty with the Ute Indians in 1874 officially opened the region to prospecting and settlement. Lode deposits of silver and gold were soon discovered, and most of the richest deposits of the region were mined from 1875 to 1900. Depletion of near-surface ores amenable to the crude milling procedures of the time, and the collapse of silver prices in 1893, caused most of the mines to close in the mid-90's. New technologies for exploration, mining, and milling allowed renewed activity in the 20th century, and the trend changed to consolidation of production from many small mines to a few major mine-mill complexes in and near the San Juan National Forest. Mining and exploration activity declined rapidly because of low metal prices, high cost of production, and environmental restraints in the 1980's, and, in 1992, no major mines were operating in the Forest.

The first discovery of placer gold in the San Juan Mountains was made in 1870 in the Summitville district. Lode deposits of gold were located in the district the following year. News of this discovery created a rush to the San Juan Mountains that resulted in the discovery of most of the currently known mining districts in the region. In the period 1873–87, more than $2 million of ore was produced at Summitville, chiefly gold (Steven and Ratté, 1960). All dollar values given in this section of the report are for metals at the time of production. As with most mining camps, Summitville went through a series of active and idle periods. Production was about $7,430,000 through 1949, 95 percent from gold (257,000 oz). From 1986 through 1991, an open-pit mine and heap-leach operation produced approximately 300,000 oz Au from zones left by earlier underground mining (Gray and Coolbaugh, in press). Exploratory drilling, 2,000 ft below the open pit, encountered an intrusion with characteristics of a porphyry copper deposit, but apparently the depth and copper grades were unfavorable for further exploration or mining.

Just a few miles west of the Summitville district, within the Forest, prospectors located claims as early as 1882 and established mines at several localities in the Crater Creek (Elwood) district, but there has been no production of significance (Lindquist, 1985). Three claims in the district were patented; dump size indicates that underground workings are small and there is no record of production (Neubert and others, 1992, p. 213). Exploration after 1975 was directed at potential bulk-minable Cu, Mo, or Au deposits associated with a concealed intrusion that created substantial alteration at the surface (Brock and others, 1985).

The Rico district was prospected intermittently for 10 years following the first claim in 1869 (McKnight, 1974), but activity increased sharply in 1879 with the discovery of rich lodes containing oxidized silver deposits that were easily mined and milled. The peak of silver production, more than 2,677,000 oz (McKnight, 1974), came in 1893, and by 1900 nearly all of the rich, oxidized deposits of silver were exhausted. In the 1920's, mining at Rico was revived when metallurgical advances in the flotation process permitted effective separation and concentration of base-metal sulfide minerals. For the first time, zinc in the district could be produced profitably, whereas in the past, zinc drew a penalty at the smelter. The most recent mining at Rico, 1955–64, was for pyrite used to produce sulfuric acid for uranium mills of the Colorado Plateau. Total production for the period 1879–1968 was $47,940,501; of this, the values were approximately 36 percent Zn, 32 percent Pb, 24 percent Ag, 4 percent Cu, and 4 percent Au (lode Au) (McKnight, 1974). Exploration in 1978–82 outlined a molybdenum deposit 3,000–4,000 ft below underground workings in the district and as much as 6,000 ft below the surface.

Early prospectors found placer gold deposits near the mouth of La Plata Canyon in 1873, and they soon found lode deposits in the La Plata Mountains. Ore mineralogy was more diverse in this district than in most of the region and included relatively rare silver-gold-telluride minerals that caused problems in the early mills. Most years, more silver than gold was produced, but the total dollar value of the gold was about twice that of silver. Many of the lode deposits contain substantial amounts of copper, lead, and zinc, but their cumulative value has been much lower than that of the precious metals. Of interest more scientific than economic, platinum and palladium were found in an unusual copper deposit at Copper Hill; drilling and geologic studies by the USGS and USBM during World War II indicated that the deposits were locally rich in Cu-Pt-Pd but too small in size to be economically important (Eckel, 1949, p. 63). Production through 1937 was $5,741,711 (Eckel, 1949), 76 percent from gold and 22 percent from silver. There has been production in the past 20 years, and, at present, it is from small, high-grade silver-gold-telluride veins such as the Bessie G, but the value is not known to us. Exploration in the 1970's–1980's focused on the known but unmeasured disseminated copper deposit around the Allard mine (fig. 22) and on gold targets.

Mining has been important in the Eureka, Red Mountain, Sneffels, Telluride, and Ophir (Iron Springs) districts since the 1870's. These districts surround and include the narrow northern finger of the Forest that extends to Red Mountain Pass (on the San Juan County line). Production of gold, silver, and base metals from these districts exceeds several hundred million dollars (Burbank and Luedke, 1968). Several of the large mines in the Red Mountain district have workings that are astride the Forest boundaries. The large Idarado and Camp Bird mines were closed in the mid-1980's, and the Sunnyside mine was closed in 1991. These mines are outside the Forest. Exploration activity in the Red Mountain district in the past 30 years has been directed at deposit types that have not been mined there in the past: porphyry copper, stockwork molybdenum, base metals in skarn, and bulk-minable gold. Targets ranged from the surface at Red Mountain No. 3 to several thousand feet deep.

The Mt. Wilson and Trout Lake mining districts have been prospected since the 1870's, and several small but rich deposits were mined (Bromfield and Williams, 1972). The Silver Pick mine in the Mt. Wilson district produced about $700,000 in gold, mostly before 1900, and the San Bernardo mine in the Trout Lake district produced about $900,000 in silver, lead, gold, and copper, mostly between 1910 and 1966. A disseminated, porphyry copper deposit was identified in the Mt. Wilson district and explored in the 1960's (Bromfield and Williams, 1972).

The Needle Mountains and Beartown mining districts had substantial production from lode deposits prior to 1900. High-grade gold-telluride deposits yielded about $200,000 in the Beartown district, and silver-gold-base-metal veins of unknown value were mined in the Needle Mountains (Steven and others, 1969). In the 1950's–1970's, uranium veins were explored in the Needle Mountains at Elk Park and Florida Mountain; a small amount of uranium was produced at Elk Park, and the veins at Florida Mountain were extensively drilled. A stockwork molybdenum deposit in a highly altered intrusion at Chicago Basin was drilled by several companies during the 1960's–1970's.

West of the San Juan National Forest, in the Slick Rock district, uranium deposits in sandstone were prospected and mined in the 1940's and 1950's. Some exploration and drilling for uranium were conducted within the Forest on the edge of the district with no significant discoveries. Vanadium deposits in sandstone were mined in the Graysill district east of Rico during the 1950's. As of 1978, historic production for the Graysill district was about 770 tons of V_2O_5 and 25 tons of U_3O_8 (Campbell and others, 1982).

Evidence of prospecting is visible throughout the San Juan National Forest as prospect pits and small mines that tested surface indications. Some of the better known areas of prospecting and small-scale mining, not previously mentioned, include the Cave Basin area (copper-lead-silver-gold), Trout Creek area (native sulfur deposits outside the Forest), and Piedra Peak area (large area of iron-rich alteration partly outside the Forest) (Steven and others, 1969).

Exploration and mining in the San Juan National Forest has been cyclical for more than 120 years, buffeted by factors ranging from problems with Indians to mine-safety inspections, penalties for zinc to incentives for uranium, lack of transportation to crowding by recreational tourists. Currently (1993), the mining infrastructure for exploration, mining, and milling is at the lowest level in more than a century. Yet, proven ore reserves remain in idle mines, and exploration targets abound. Geologic evidence, described in following pages, suggests the presence of additional resources of the type traditionally mined in the region, as well as several types of new deposits. The future of exploration and mining in the Forest will be influenced more by economic and social issues than by geology.

MINING DISTRICTS

Mining districts in and near the Forest are characterized by specific types of ore deposits. Attributes of these deposits are considered in assessing other terranes for similar but undiscovered deposits. The following contains a summary of production from different types of deposits, a discussion on the origin of metals, and maps showing locations and geology of selected districts. (The boundaries of the mining districts are poorly defined; therefore they are shown only as numbers on figure 15.) For more information on production, refer to a report by the U.S. Bureau of Mines (Neubert and others, 1992, 311 p.) that gives production figures for many individual mines within mining districts.

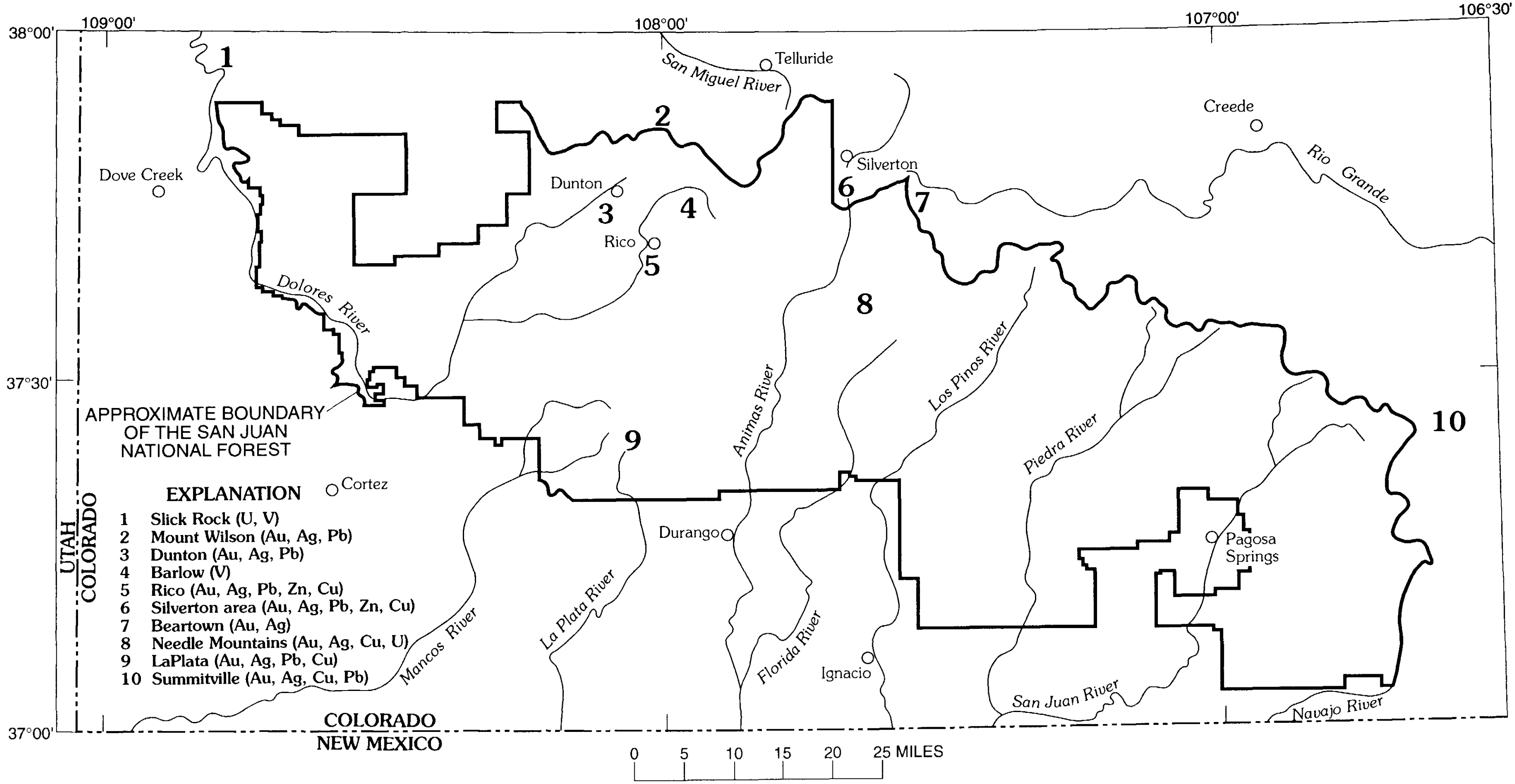


Figure 15. Map showing major mining districts and their locatable resources in and adjacent to the San Juan National Forest.

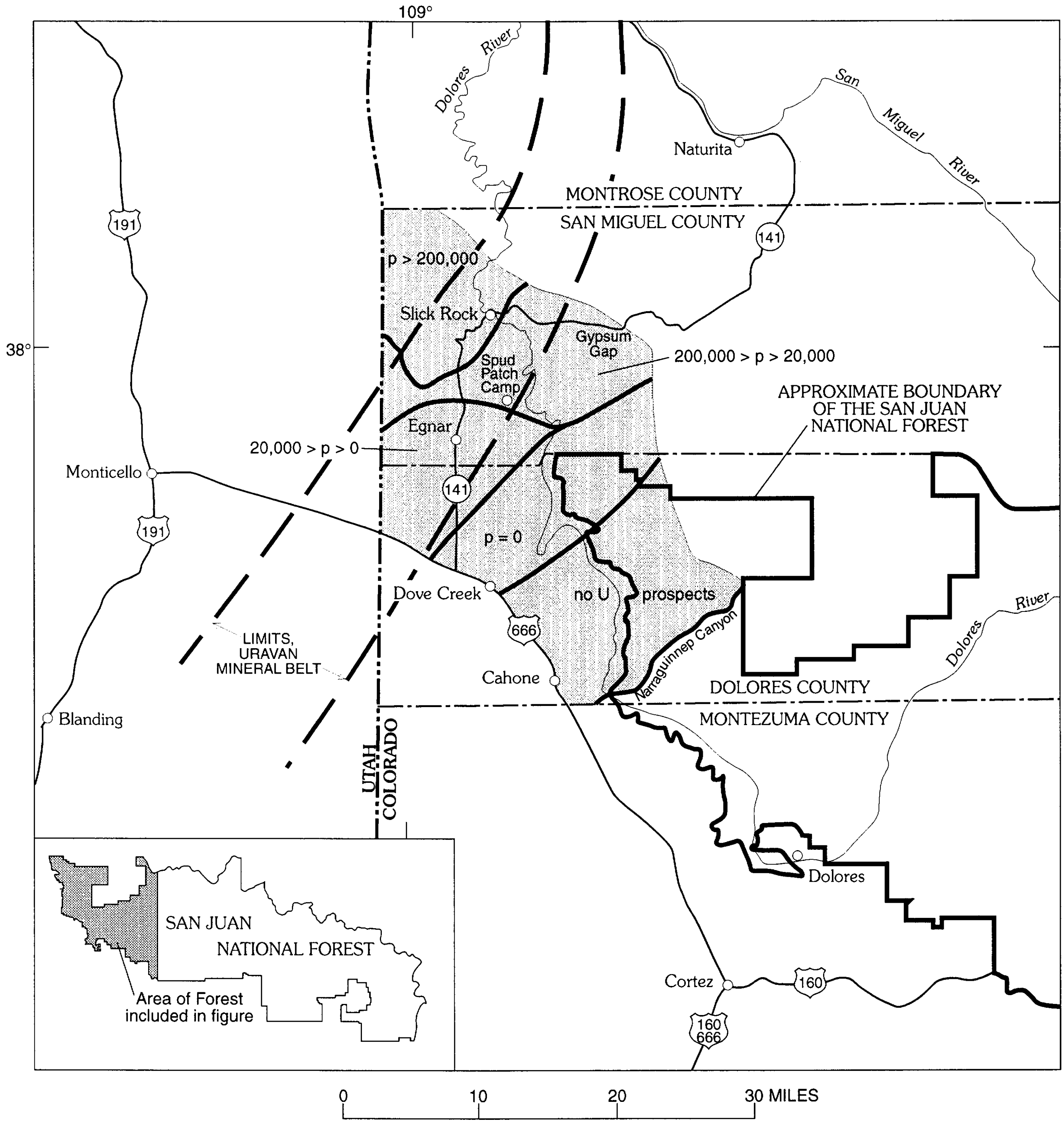


Figure 16. Map showing Slick Rock uranium district, Colorado. Subdivisions of district (patterned) have maximum deposit size indicated in terms of pounds of U_3O_8 produced (p). Production data from Williams (1964) and Haynes and others (1972). Limits of Uravan mineral belt from Fischer and Hilpert (1952) and Butler and Fischer (1978).

SLICK ROCK DISTRICT

The Slick Rock mining district, known for its world-class uranium deposits, includes the northwesternmost part of the Forest (fig. 16). The district is in the Uravan mineral belt, and its southeastern limit is just west of the Forest (fig. 16). It comprises an upland of relatively low relief except near the Dolores River, which flows in a deep canyon.

Mining of the uraniferous ores has continued intermittently since about 1900. During some years, vanadium or radium, rather than uranium, has been the commodity sought. Most of the approximately 2,100,000 tons of ore produced to date has been mined since 1949 for its uranium content. Average ore grade has been about 0.22 percent U_3O_8 and 1.7 percent V_2O_5. Previous studies of the district, or of parts of it, have been numerous and include those by Shawe and others (1959), Butler and Fischer (1978), and Campbell and others (1982).

The geologic structure of the district is that of a regional homocline in sedimentary strata that dips 2°–3° westward. In the eastern part of the district, the homocline is interrupted by mainly northwest-trending, commonly faulted folds of the salt anticline belt of the Paradox Basin (figs. 7, 8). The sedimentary rocks belong to the Paleozoic-Tertiary clastic terrane (described previously) and range from the Lower Permian Cutler Formation to the Upper Cretaceous Mancos Shale.

Uranium-vanadium ore of the Slick Rock mining district occurs in peneconcordant deposits in fluviatile sandstone (deposit type I) typified by those of the Salt Wash Member of the Upper Jurassic Morrison Formation. Although roll-type, bedding-transgressive deposits are present, most of the Morrison deposits in the district are very nearly concordant with bedding (Shawe and others, 1959). Principal uranium ore minerals are uraninite and coffinite in unoxidized ore and carnotite and tyuyamunite where ore has been oxidized near the surface.

The part of the Slick Rock mining district in the Forest is favorable for undiscovered uranium deposits because it is underlain by rock formations that have been productive in nearby areas to the west and north. However, figure 16 indicates that this part of district has had no uranium production and that most of it lacks uranium prospects. The Salt Wash Member of the Upper Jurassic Morrison Formation is buried under as much as 700 ft of overlying strata in the corner of the Forest lying nearest the productive part of the Slick Rock district (fig. 16). Still more deeply buried are the Lower Permian Cutler Formation and the Moss Back Member of the Upper Triassic Chinle (Dolores equivalent) Formation, both of which could be uranium-bearing in the same area (Campbell and others, 1982; Shawe, 1969).

MT. WILSON DISTRICT

The Mt. Wilson district is centered along the Forest boundary about 15 mi north of Rico (fig. 15). The district includes numerous mines and prospects; however, most of the production (95 percent) came from just one mine, the Silver Pick, which lies outside the Forest just west of Wilson Peak. The total value of ore from the district is about $858,000, which included 32,000 oz of gold, 95,000 oz of silver, and only a very minor (less than $1,000) amount of copper and lead. Several mines were established in Navajo Basin, which is in the Forest in the southern part of the district, but little, if any, ore was produced.

The salient geologic feature in the Mt. Wilson district is the Tertiary-age Wilson Peak stock. The stock is composite, consisting of granogabbro, followed by granodiorite and porphyritic quartz monzonite, which contains disseminated copper mineralization (Bromfield and Williams, 1972). West-trending fissure veins that cut the stock and adjacent sedimentary rocks localized mineralization.

Some exploration activity, as recent as 1969, has taken place (Bromfield and Williams, 1972), but the district is now a part of the Lizard Head Wilderness, formerly known as the Wilson Mountains Primitive Area.

DUNTON DISTRICT (LONE CONE)

The Dunton mining district is along the West Dolores River about 6 mi northwest of Rico (fig. 17). Significant amounts of silver and gold were taken from this district, chiefly from the Emma, Emma Cross-Cut, and Smuggler mines. Although records of production for the district are poor, it is thought that at least $600,000 in silver and gold and some lead and copper were mined from 1896 to 1950 (Bromfield and Williams, 1972). Some exploration and development were done in the Dunton district by mining companies in the 1970's and 1980's. The Emma mine was purchased by a Canadian company in 1970 that did extensive restoration work over a period of about 10 years; gold and silver resources were identified, but only a small amount of ore was actually shipped (Neubert, 1992, p. 9). In 1988, a drilling program failed to extend the area of known mineralization at the Emma mine (Neubert and others, 1992, p. 9).

Mineralization in the Dunton district is in fault-controlled veins in the Lower Permian Cutler and the Upper Triassic Dolores Formations. The district is broken by a system of north-northwest-trending faults that form a graben to the northeast of Dunton (fig. 17). The faulting probably formed concurrent with the doming at Rico. Doming at Rico was caused by the emplacement of igneous stocks during Tertiary time (Bush and Bromfield, 1966). The Emma and Emma Cross-Cut mines exploited veins along the Emma fault, whereas the Smuggler mine is along the Almont fault; both faults are southwest of the graben (fig. 17). The primary ore minerals are argentite, pyrargyrite, proustite, chalcopyrite, galena, and sphalerite.

GRAYSILL DISTRICT

The Graysill mining district is within the Forest a few miles northeast of Rico on the east side of the Dolores River

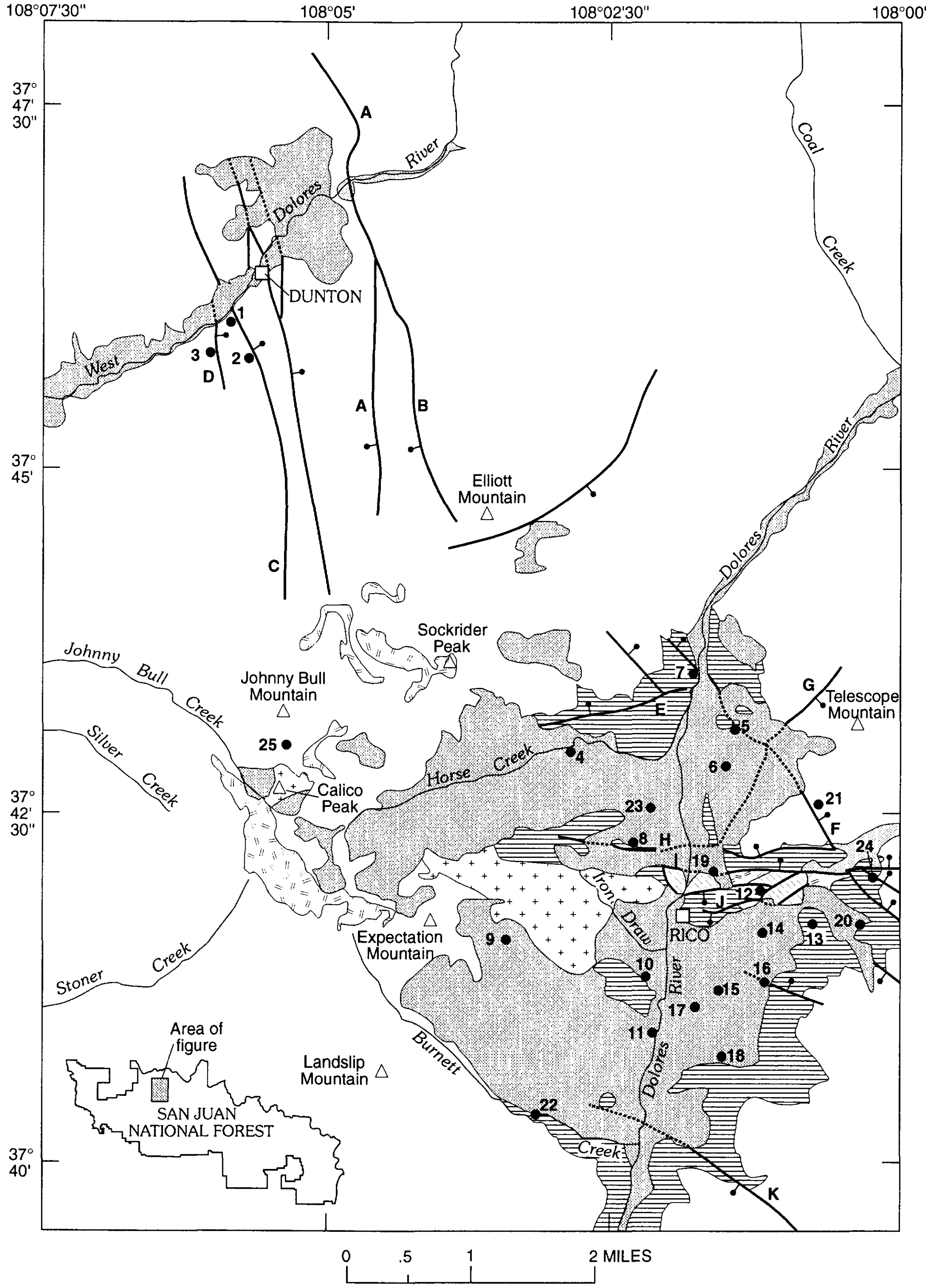
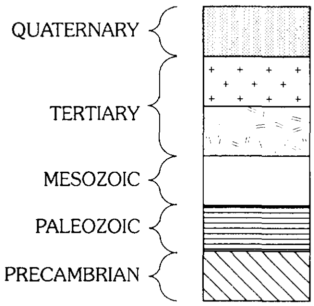


Figure 17 (above and facing page). Map showing principal mines and generalized geology of the Rico and Dunton mining districts, San Juan National Forest. After Bush and Bromfield (1966) and Pratt and others (1969). Numbers indicate localities mentioned in the text.

(fig. 18) (see also Neubert and others, 1992, p. 225). It is partly in the drainage of the Dolores River and partly in that of Hermosa Creek. The topography is steep and, in part, alpine.

The Graysill district produced vanadium and uranium for about 20 years after World War II. Approximately 32,000 tons of ore was mined at an average grade of about 2.41 percent V_2O_5 and 0.08 percent U_3O_8. Nearly all of this total came from the Graysill mine itself (fig. 18). About 200 tons of ore was mined at the Barlow Creek mines, about 3 mi northwest of Graysill mine (Nelson-Moore and others, 1978). No production is known from the Spanish King

EXPLANATION



Surficial deposits

Stock of igneous rock

Sill of igneous rock

Rocks of clastic terrane

Rocks of carbonate terrane

Crystalline rock

G ······· **Fault**—Dotted where concealed. Bar and ball on downthrown side. Keyed by letter to list below

A Dunton	**E** Sandstone Mtn.	**I** Last Chance
B Papoose	**F** Blackhawk	**J** Smelter
C Emma	**G** Princeton	**K** Spruce Gulch
D Almont	**H** Nellis Bly	

●3 **Mine or prospect. Keyed by number to list below**

1 Emma mine	**14** Revenue mine
2 Emma Cross-Cut	**15** Enterprise mine
3 Smuggler mine	**16** Laura mine
4 Puzzle mine	**17** Lexington mine
5 Logan mine	**18** Silver Glance mine
6 Mountain Spring mine	**19** Nora mine
7 ABC mine	**20** Sunflower mine
8 Aztec mine	**21** Worlds Fair prospect
9 Expectation mine	**22** Blue Bell mine
10 Jones mine	**23** Sambo mine
11 Silver Swan mine	**24** Silver Creek molybdenum deposit (Cameron and others, 1986)
12 Larsen tunnel	
13 Union Carbonate mine	**25** Johnny Bull mine

mine, approximately 2.5 mi southwest of Graysill mine (fig. 18).

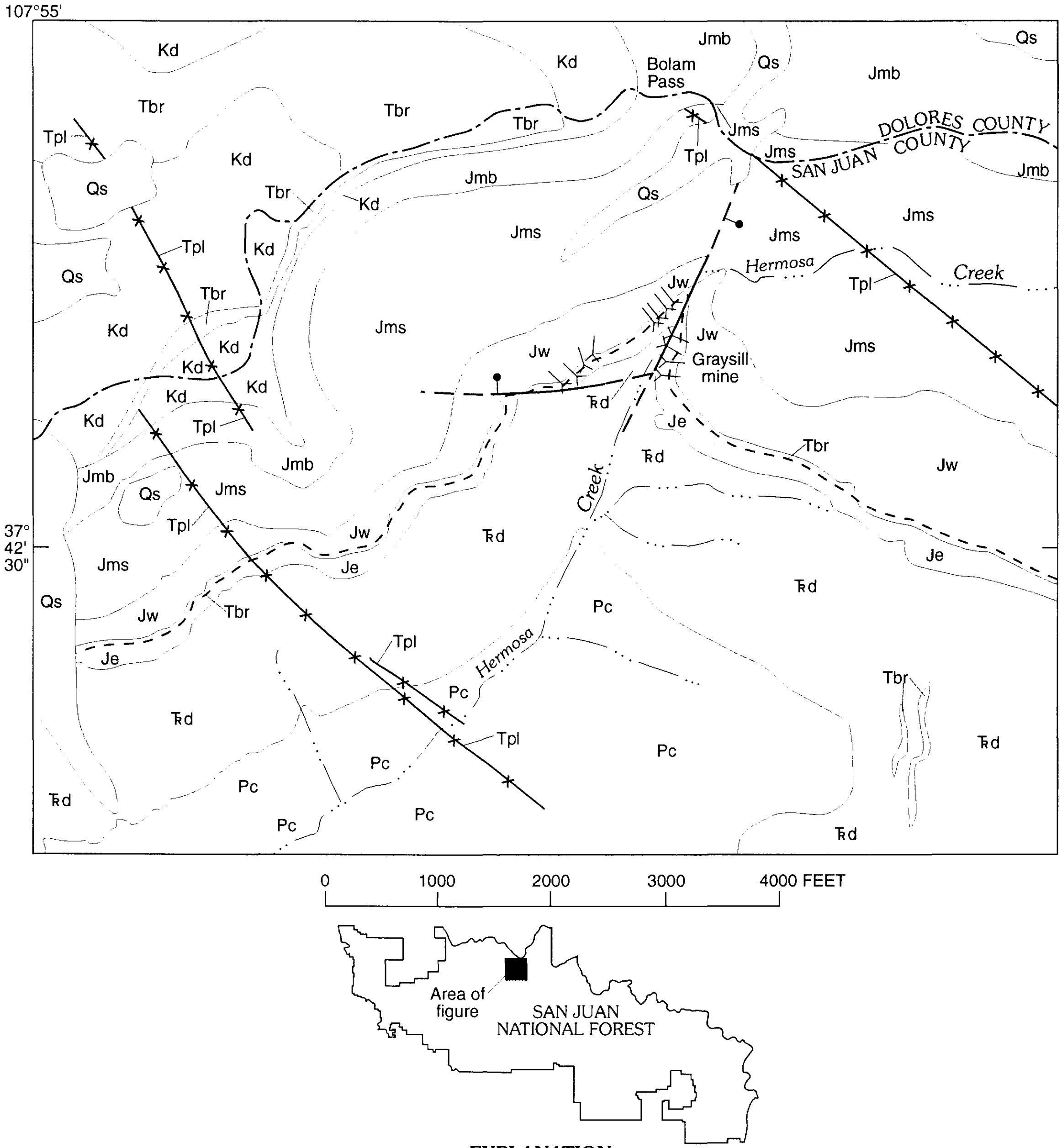
The geologic structure of the district is that of a sedimentary homocline dipping steeply northwest off the Needle Mountains. However, the structure is modified by faulting and by concordant and discordant intrusions of igneous rock. Sill intrusions are physically associated with the ore at both the Graysill (fig. 18) and Barlow Creek mines.

All deposits of the district are of the Placerville roscoelite vanadium-uranium type (table 1, deposit type J). Roscoelite is a vanadium-bearing mineral of the mica group. The ore zone is in sandstone near the top of the Middle Jurassic Entrada Sandstone underlying the basal Pony Express Limestone Member of the Wanakah Formation, also Middle Jurassic. This limestone is about 20–25 ft thick at the Graysill mine.

The Graysill district is favorable for undiscovered roscoelite deposits of uranium and vanadium. About 100,000 tons of unmined ore was estimated to be present on the Graysill property (Morehouse and Pursely, 1952). Inasmuch as known production for the entire district is less than half of that figure, substantial tonnages remain in the ground if the estimate was accurate.

RICO DISTRICT

Ores rich in silver, lead, and zinc, with modest gold and copper, have been mined from deposits in the Rico mining district (fig. 17) from Mesozoic sedimentary strata since 1879 (McKnight, 1974). A structural dome exposes a thick section (about 6,000 ft) of Pennsylvanian and Permian redbed sandstones and shales on the flanks of a monzonite stock. Mine workings and drill holes encountered Upper Devonian Ouray Limestone and Lower Mississippian Leadville Limestone with a combined thickness of about 160 ft. Early mining exploited oxidized silver-rich blanket deposits (localities 14–18, fig. 17) that were near the surface; these ores were amenable to the crude milling methods of the era, and they were largely exhausted by 1900. In the 20th century, mining focused on base-metal sulfide ores that permeate limestone beds adjacent to major faults (localities 5–13, 19–21, fig. 17). These polymetallic replacement-type ores (table 1, deposit type C), discussed further under mineral resources, were processed by new flotation methods to concentrate lead, zinc, and copper-sulfide minerals with by-product silver and gold. Similar massive pyrite bodies



EXPLANATION

Qs	**Surficial deposits (Holocene and Pleistocene)**	Je	**Entrada Sandstone (Middle Jurassic)**
Tpl	**Pyroxene lamprophyre (Pliocene or Miocene)**	Ꞧ	**Dolores Formation (Upper Triassic)**
Tbr	**Biotite rhyodacite (Miocene)**—Forms sill shown as mine	Pc	**Cutler Formation (Lower Permian)**
Kd	**Dakota Sandstone (Upper Cretaceous)**		**Contact**
Jmb	**Brushy Basin Member, Morrison Formation (Upper Jurassic)**		**Fault**—Dashed where inferred. Bar and ball on downthrown side
Jms	**Salt Wash Sandstone Member, Morrison Formation (Upper Jurassic)**		**Adit**
Jw	**Wanakah Formation (Middle Jurassic)**—Includes basal Pony Express Limestone Member, about 20 ft thick at Graysill mine		

Figure 18. Geologic map of the Graysill mine area in the Graysill vanadium-uranium mining district, San Juan National Forest. Map shows local relations of ore zone, marked by mine workings (adits), to Entrada Sandstone host rock and rhyodacite sill of map unit Tbr. After Pratt (1976) and Martin (1992).

were mined from 1955 to 1964 to make sulfuric acid used in uranium mills.

Total production from the district has been about 14,500,000 oz silver, 83,000 oz gold, 84,000 tons lead, 83,000 tons zinc, and 5,300 tons copper. Production was valued at about $48 million, of which about 36 percent came from zinc, 31 percent from lead, and 24 percent from silver. Production from individual mines is given in Neubert and others (1992, p. 29–50).

Exploration in the past three decades has focused on intersections of faults with deeper limestone beds and on porphyry-type targets below and west of the historic mining area. No significant polymetallic replacement deposits have been located in the deep limestones, despite similarities to other districts in the Western United States (McKnight, 1974). Altered igneous rocks west of Rico near Calico Peak (fig. 17) have attracted exploration interest for copper and molybdenum. A bold drilling program by the Anaconda Company, based on district zoning, discovered the Silver Creek molybdenum deposit (table 1, deposit type B) (location 24, fig. 17) in 1981. This deposit resembles the Climax mine, Colorado, but the high-grade molybdenum zones are more than 3,900 ft deep (Cameron and others, 1986).

SILVERTON AREA

In the 1870's, important mining camps were established in the Eureka, Red Mountain, Sneffels, Telluride, and Ophir districts that surround and include parts of the narrow northern finger of the Forest, an area that extends north to Red Mountain Pass on the San Juan County line and the Animas district, which includes a small eastern part of the narrow northern finger and the area of Whitehead Peak extending north to Silverton (fig. 19). These districts are within and peripheral to the Silverton caldera complex. In excess of 40 million tons of gold, silver, and base-metal ore having a value in excess of several hundred million dollars (Burbank and Luedke, 1968, table 2; Mosier and others, 1986) has been produced. The reader is also referred to Neubert and others (1992, p. 150–207). Two of the districts in the Silverton area that are closest to the Forest (Red Mountain and Animas) are discussed below.

Red Mountain district.—This district is about 8 mi north of Silverton (fig. 19); it is described by Burbank and Luedke (1969), Elevatorski (1982), and Hutchinson (1988). Ore was first discovered in the district in 1881. Cumulative gold production has been estimated at 1.6 million oz (Burbank and Luedke, 1969), mainly from breccia pipes, chimneys, and vein-type deposits within the margin of the ring faults on the northwest flank of the Silverton caldera. In many of the mines, gold is associated with copper in chimney deposits near volcanic pipes filled with breccia, quartz latite, porphyry, and rhyolite. Dominant ore minerals were pyrite, enargite, chalcopyrite, tennantite, chalcocite, covellite, stromeyerite, bornite, tetrahedrite, galena, and sphalerite. Several large mines in the Red Mountain district have workings that straddle the Forest boundary. The Idarado and Camp Bird mines (fig. 19) were open until the mid-1980's, and the Sunnyside mine (fig. 19) was open until 1991. Exploration activity in the Red Mountain district in the past 30 years has been directed primarily at deeper deposits, types that have not been mined there in the past: porphyry copper, stockwork molybdenum, skarn-related base metals, and bulk-minable gold. Exploration targets ranged from the stock exposed at the surface at Red Mountain No. 3, to porphyry and skarn deposits several thousand feet deep. Results of biotite chemistry suggest to T. Gilzean and G. Brimhall (written commun., 1987) that the root system at Red Mountain is more akin to a porphyry copper system than a molybdenum one. K-Ar age dates suggest that two distinct thermal events, one at 23 Ma and another at 11 Ma, may have affected the Red Mountain district (Lipman and others, 1976). Other areas of the narrow northern finger of the San Juan National Forest that also may have porphyry-style mineralization include the Sultan Mountain stock (Moly Mountain) (fig. 19, location 10), Anvil Mountain (location 1), and Horseshoe Bend (Chattanooga) (location 5). Moly Mountain, a porphyritic monzonite intrusion (25.1 Ma) that crops out along the northern side of the Sultan Mountain monzonite stock (25.9 Ma), has quartz plus molybdenite veinlets in mixed sericite to argillically altered rocks and Pb-Zn-pyrite mineralization peripheral to the stock (Ringrose and others, 1986).

Animas (or South Silverton) district.—The Animas mining district is in the northern part of San Juan County; it is described by Elevatorski (1982) and Varnes (1963). The main mining area extends from the town of Silverton east and southeast for about 5 mi. Areas included within the bounds of the district are the Arrastra Basin No. 2, Silver Lake No. 9, Cunningham Creek No. 4, and the Maggie Creek No. 7 mining areas (fig. 19). The first reported occurrence of gold in this district was in the 1870's when placer gold was discovered near Arrastra Gulch. Lode gold was first reported soon after on the Little Giant claims on the north side of the gulch. Cumulative production of gold (including placer) is reported as 850,000 oz (Mosier and others, 1986), mostly as a by-product of base-metal mining. The mineralized region is generally north of the subsided block of the south rim of the Silverton caldera. Ore deposits are vein types filling fissures radial to or concentric with the caldera rim (table 1, deposit type G). The ores are localized in fractures and shear zones of andesitic and rhyodacite flows, breccias, and tuffs of the Tertiary (Oligocene) Silverton Volcanics. Historically, ore grades averaged about 0.1 oz gold, 2.9 oz silver, 2 percent lead, 0.3 percent zinc, and 0.45 percent copper.

As much as half of the production of the district (about 425,000 oz gold) came from the Shenandoah-Dives group (Mosier and others, 1986), including the North Star (King

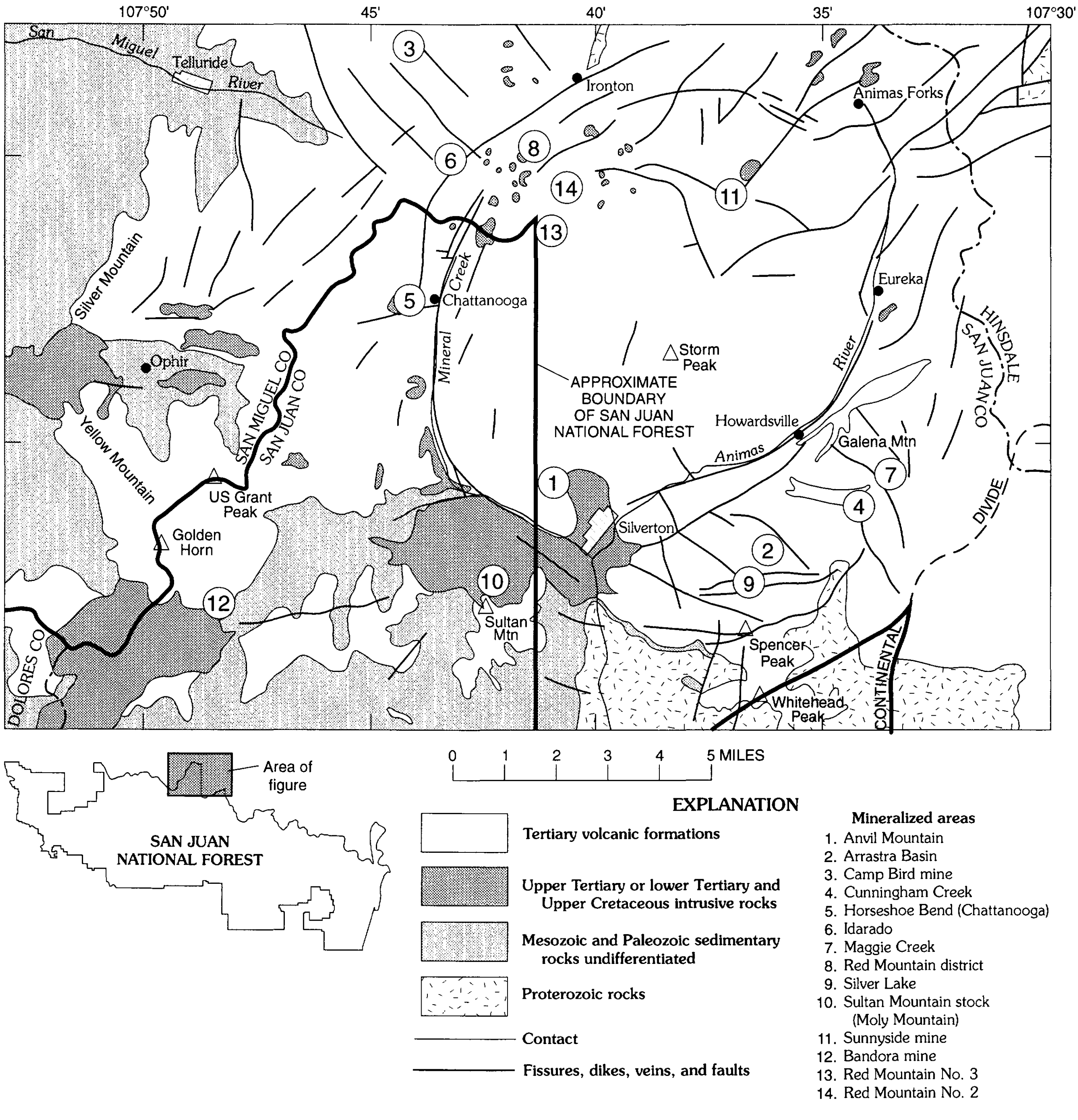


Figure 19. Map showing generalized geology and location of some principal mines in the Silverton region in and near the San Juan National Forest.

Solomon), Dives, Shenandoah No. 3, and Mayflower mines in the Arrastra Basin mineralized area (fig. 19, location 2). A number of the veins are adjacent to andesitic dikes. The base-metal ores contain argentiferous galena, argentiferous gray native copper, galena, chalcopyrite, pyrite, sphalerite, and a little native gold in a gangue of quartz and calcite. More than 100,000 oz of gold (Mosier and others, 1986) were recovered from the Silver Lake, New York, Titusville (Letter G), Royal, and Stelzner mines, which all border Silver Lake (fig. 19, location 9). Au-Ag-Pb-Cu-Zn were recovered from veins 2–5 ft wide. At the Iowa and Royal Tiger mines, also near Silver Lake, high values of gold (as much as 0.5 oz Au per ton) (Mosier and others, 1986) also accompanied the high-grade silver-lead ores.

In recent years, gold and base metals have been recovered from mines along Cunningham Creek, about 2 mi southeast of Howardsville (fig. 19, location 4). These include The Pride of the West, the Osceoloa-Pride, and Emma mines. The most recently active mines include the Osceoloa-Pride, Emma, Ezra-R, and Valley Forge.

BEARTOWN DISTRICT (BEAR CREEK) AND NEARBY WHITEHEAD GULCH AND ELK PARK MINERALIZED AREAS

The Beartown mining district is along the Forest boundary about 12 mi southeast of Silverton (fig. 20). This district, which covers about 2 mi^2 of the northern part of the Needle Mountains, is known for its small but rich gold-silver-telluride veins (table 1, deposit type F1). Less than a half million dollars worth of gold and silver and a very minor amount of copper and lead were mined, most prior to 1900. Some activity was noted in the district as recently as 1961 (Steven and others, 1969). Five major mines exploited gold-bearing quartz veins that fill fractures in Precambrian quartzite and slates of the Uncompahgre Formation and gneisses of the Irving Formation. Folds and foliation in the Precambrian rock trend east-west, whereas the fractures, some of which host Au-Ag-Te veins, trend north-south. The Precambrian host rocks are overlain to the north by Tertiary volcanics. The origin of the metals is not clearly known; however, hydrothermal alteration in the overlying volcanics suggests a Tertiary age for fracturing and mineralization (Steven and others, 1969). Gold- and silver-tellurides and tetrahedrite are the dominant ore minerals, and they occur in small high-grade pockets along barren quartz veins. Alteration of the Precambrian host rock adjacent to veins is minor or absent. Limonite staining of the quartz veins is common. Gangue minerals include barite, calcite, and clays; fluorite is absent.

The area shown on figure 20, known as the Beartown district, contains several mines, but most are outside the Forest. The district has potential for other small deposits of gold-silver tellurides, but the fissures are too small to contain large bodies of ore. Bedrock is well exposed in the district and in the surrounding areas, which makes it unlikely that the conspicuous rusty quartz veins that often contain ore could remain undiscovered. A geochemical survey of the area by Steven and others (1969) found little evidence for mineral potential outside the Beartown district.

A mineralized area occurs in Whitehead Gulch, about 10 mi northwest of the Beartown district and 6 mi south of Silverton (fig. 20). It is about 2 mi south of the southern extent of the highly mineralized area related to the Silverton caldera. The Whitehead Gulch area contains numerous quartz-pyrite veins that occupy northerly trending fractures in the Early Proterozoic Irving Formation (Steven and others, 1969; Korzeb and Scott, 1985). These fractures do not extend into the overlying volcanics but were probably reactivated locally during the Tertiary volcanic activity and related mineralization (Steven and others, 1969).

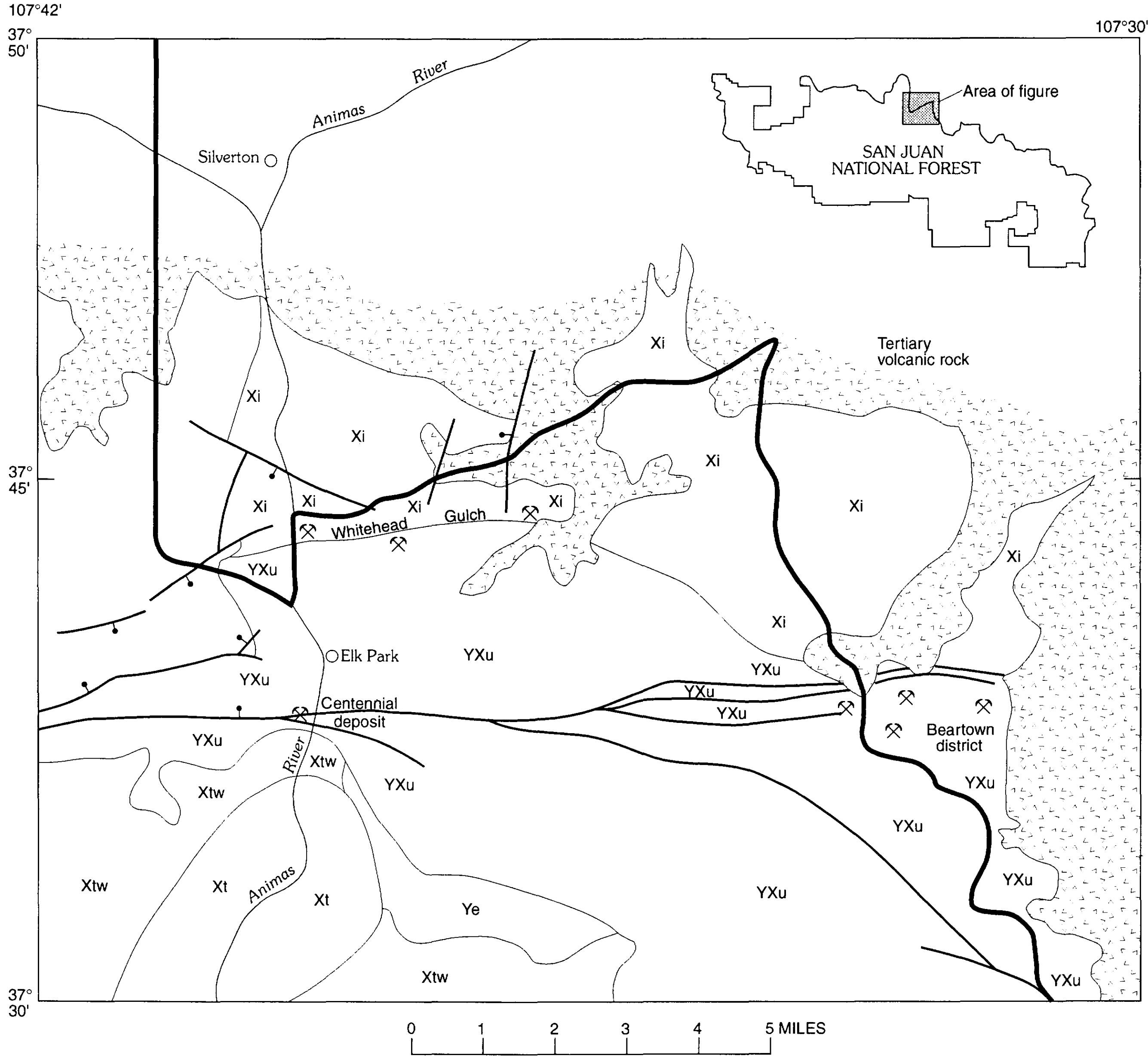
The veins in the area are small, less than a few hundred feet in length, and most contain galena and sphalerite. Korzeb and Scott (1985) reported detectable amounts of silver and gold in samples from the area, but no resources were identified. The area contains several patented claims. Underground workings and surface pits explored several veins, but actual production of ore was probably minimal.

This zone, peripheral to the rich ores at Silverton, is favorable for small epithermal veins (table 1, deposit type F2) containing base and precious metals.

Another mineralized area is about 5 mi south of Whitehead Gulch on the west bank of the Animas River, 10 mi south of Silverton (fig. 20). In 1956, uranium was discovered there in what is called the Centennial deposit, about 1 mi south of Elk Park (fig. 20). Sporadic production from this deposit has amounted to about 300 tons of ore that averaged approximately 0.2 percent U_3O_8 (Scott, 1983). An extensive drilling program during 1980 and 1981 by Exxon Minerals Company resulted in the delineation of a large mineralized body. The known surface extent of this deposit is at least twice the size of the surface expression of the 40-million-pound Schwartzwalder uranium mine in Clear Creek, just west of Denver (Bailey, 1982). The uranium is in fissure veins that occupy fractures in the quartzites and slates of the Uncompahgre Formation (table 1, deposit type F3). The rocks are intensely folded and fractured along east-west trends. Major structures extend for nearly 10 mi to the east in the quartzite to the vicinity of Beartown mining district and to the west for several miles (fig. 20), but there is no evidence of mineralization along them. Base and precious metals are present in some veins in the Centennial deposit (veins that are low in uranium) but in concentrations too low to recover. Rocks of the Uncompahgre Formation are in very rugged, mountainous terrain that would make exploration and development of a mine difficult. Furthermore, except for a small area at Elk Park, the Uncompahgre Formation is within the boundaries of the West Needle Mountain and the Weminuche Wildernesses (see fig. 6), which are closed to mining.

NEEDLE MOUNTAINS DISTRICT

The Needle Mountains district is centered around Vallecito Basin about 30 mi northeast of Durango and 15 mi south of Silverton (fig. 21). The district covers about 12 mi^2, most of which lies above 12,000 ft in a very rugged part of the Weminuche Wilderness. Patented mining claims are present within the wilderness. Mining and exploration in the Needle Mountains district has been relatively unproductive from the time of its discovery through the 1970's, when larger companies explored the region using new technologies along with deep core drilling. Mining activity began in 1881, continued sporadically until 1917, and resumed in 1934 when the price of gold increased. Although records are poor, Steven and others (1969, p. F83) estimated the total value of metals from 1881 to about 1935 at $12,500, most of



EXPLANATION

Ye	Eolus Granite (Middle Proterozoic)
YXu	Uncompahgre Formation (Middle and Early Proterozoic)
Xt	Tenmile Granite (Early Proterozoic)
Xi	Irving Formation (Early Proterozoic)
Xtw	Twilight Gneiss (Early Proterozoic)
	Fault
	Mine

Figure 20. Map showing locations of Beartown mining district and Whitehead Gulch and Elk Park mineralized areas.

which was from silver and possibly some from gold. Although mining of base and precious metals has long since ceased, there was renewed interest in the district, beginning in early 1960's, by large companies exploring for other types of deposits. AMAX drilled several holes in 1960, and in 1976 through 1978, to test a molybdenum target in Chicago Basin near the center of the district. Due to the low grade of ore, AMAX withdrew its claim to the area. Uranium was discovered in the district in 1974 by Public Service Company of Oklahoma (PSO) using airborne radiometric surveys. In the hope of establishing their nuclear fuel reserves, PSO began an intense drilling program in 1976 that continued through

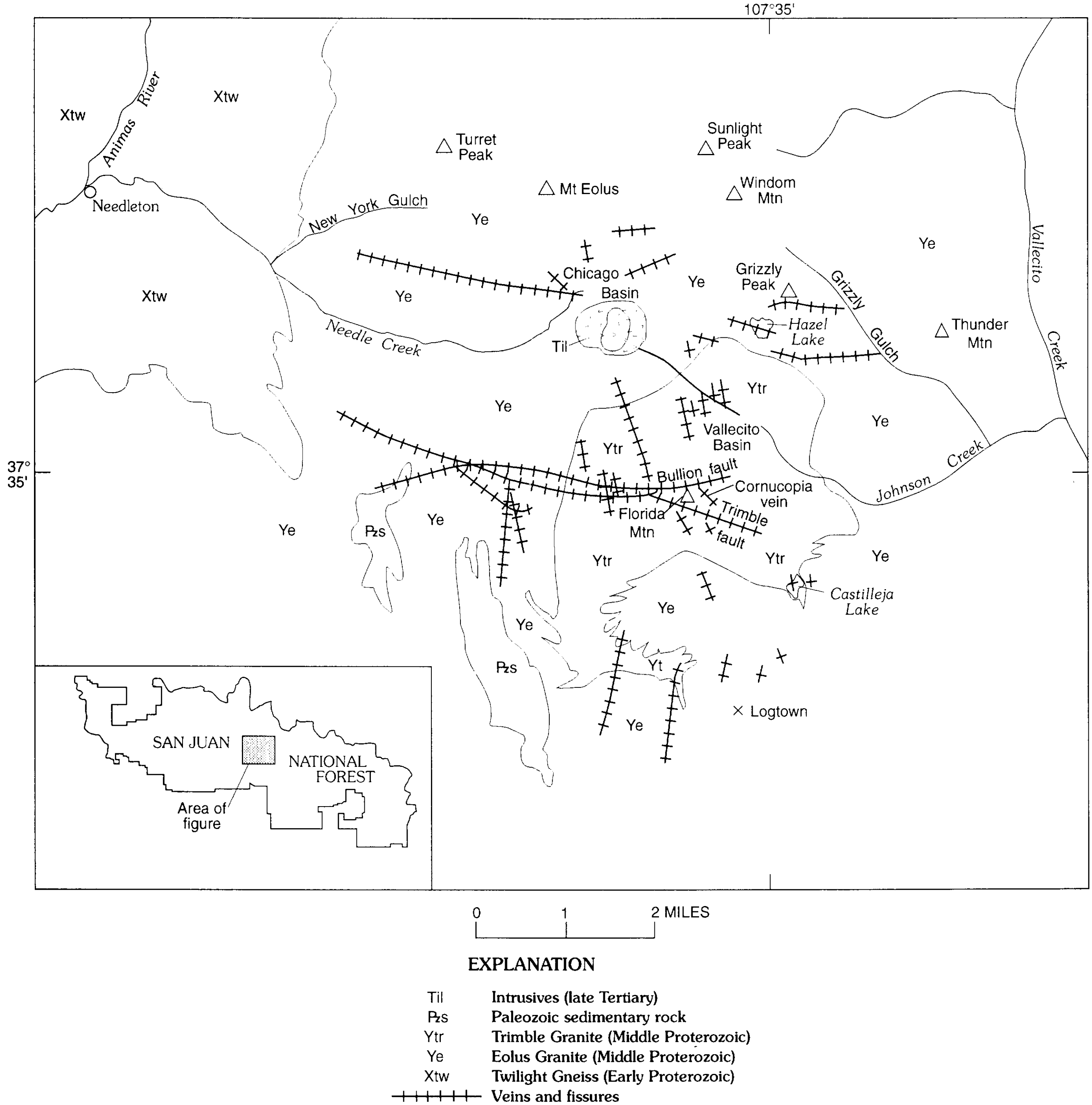


Figure 21. Map showing Needle Mountains mining district. From Steven and others (1969) and Schmidt and Raymond (1977).

1978. Although uranium reserves were found, PSO withdrew from the district because of low demand for uranium and an unclear nuclear policy from the U.S. Department of Energy (Collier, 1985). Currently, there is little, if any, activity in the district.

Mineralization in the Needle Mountains mining district consists of polymetallic veins (table 1, deposit type Ab), stockwork molybdenum (deposit type Aa), and intragranitic vein uranium (deposit type E). These deposits resulted from two separate multiphase intrusive events that began in the Middle Proterozoic (1,400 Ma) with the intrusion of the Eolus and Trimble Granites and resumed in the Miocene (10 Ma) with the intrusion of the Chicago Basin stock.

At least three intrusive phases of the older rock, as identified by Collier (1985), are present: (1) the main body of the Eolus, (2) a comagmatic and more primitive phase of the Trimble Granite mapped also as Eolus Granite, and (3) the final phase the Trimble Granite, which contains anomalous amounts of uranium (15 ppm). The Trimble Granite was enriched in uranium minerals, such as uraninite, during periods of rock melting and differentiation (Collier, 1985). These uranium minerals were later destroyed by hydrothermal systems during the Miocene event that liberated uranium from the Trimble Granite for concentration in the vein systems. Accessory minerals, such as allanite and zircon, host the uranium in the earlier phases of Eolus Granite, so this uranium is not available for concentration in vein deposits. Allanite and zircon resist weathering and do not give up their uranium content. They do, however, contribute to the high concentrations of uranium found in stream sediments in the region.

During Miocene time (about 10 Ma), the Chicago Basin stock was emplaced. Geochemical evidence indicates that the exposed part of the stock in Chicago Basin is part of a larger body that may extend beneath Vallecito Basin to the southeast (Schmitt and Raymond, 1977; Collier, 1985). The stock is a composite hypabyssal body of granite and rhyolite porphyries. Exploration drilling identified more than five intrusive phases, some of which contain small amounts of molybdenum.

Although these intrusions at Chicago Basin supplied molybdenum and base and precious metals, they probably did not supply uranium to the nearby Florida Mountain area (fig. 21). They did, however, establish the convective circulation system by which uranium was leached from the Precambrian granite country rocks in the nearby Florida Mountain area, and they also helped open preexisting fractures during intrusion (Collier, 1985). As a result of the exploration and drilling program by PSO, substantial resources of uranium occur in this area. As summarized by Collier (1985), "The Florida Mountain block alone appears to contain a potential of at least 3,000 tons of U_3O_8, and has the potential for considerably more. Including speculative reserve estimates for Grizzly Gulch and Thunder Mountain, as well as additional uranium which might be discovered by more drilling or during mining, the Florida Mountain area and its immediate surroundings may contain as much as 10,000 tons of U_3O_8."

Metalliferous veins are widely scattered throughout the mining district (fig. 21). They are altered fissure zones with disseminated pyrite and quartz veins with or without sulfide and minor gangue minerals (Steven and others, 1969). Most of the early production came from oxidized ores mined near the surface that were rich in silver and gold.

The fractures that control mineralization in the district are of two distinctive types: (1) a set of radial fractures extending outward from Chicago Basin intrusive center, which were caused by emplacement of the stock, and (2) fractures that follow regional joint trends in the Precambrian granites and gneiss, some of which were probably reactivated during the intrusive event.

LA PLATA DISTRICT (MAY DAY, ORO FINO)

The La Plata mining district is centered about 15 mi northwest of Durango (fig. 22). Mines in this famous district are scattered over some 60 mi^2 of the rugged La Plata Mountains. All known mines and prospects were evaluated by Neubert and others (1992, p. 64–147), but only a brief summary is given here. Early-day production records are poor, but rough estimates indicate that well over 200,000 oz of gold, 2,000,000 oz of silver, and several hundred thousand pounds of copper and lead have been recovered since 1873 (Eckel, 1949). At today's prices, the total production from the district would amount to about $90 million dollars (Neubert and others, 1992). Most of this production was after 1900, and mining and exploration in the district have continued intermittently to the present. From 1980 to the present, there have been several drilling projects in various parts of the district, some caved adits have been reopened and ore has been recovered from at least three semi-active mines, some of the old mine dumps have been processed, and two placers have been worked seasonally (Neubert and others, 1992).

The geology of the La Plata mining district was studied by Eckel (1949), who mapped the district and described the ore deposits in a very comprehensive work that is the basis for almost all subsequent studies carried out in the mining district. Davis and Streufert (1990, p. 55) present results of studies on the origin of metals in some of the deposits.

The geologic setting of the La Plata Mountains is a structural dome caused by intrusion of Late Cretaceous and earliest Tertiary (75–65 Ma, Cunningham and others, 1977) laccoliths, sills, dikes, and stocks into mainly clastic Paleozoic and Mesozoic sedimentary rocks. The sedimentary rocks have been uplifted nearly 6,000 ft over an area about 15 mi in diameter. Mineralization is scattered throughout the core and flanks of the dome.

Two stages of igneous rock are present at La Plata. The first, which was largely responsible for the doming, were porphyritic rocks of diorite and monzonite composition emplaced as sills and laccoliths and unrelated to mineralization. The second stage was the intrusion of generally nonporphyritic rock of alkalic composition. These rocks of syenite, monzonite, and diorite were emplaced as five stocks (fig. 22) that cut both the early intrusives and sedimentary rocks. Heat generated by this second stage of igneous activity caused a metamorphic aureole in the sedimentary rock throughout the core of the La Plata Mountains. Silicification and bleaching of the country rock were pervasive. This late stage of igneous activity probably supplied the metals and heat to the circulating hydrothermal system in the mining district (Eckel, 1949).

Several normal faults, which radiate from the center of the dome and others concentric to it, formed as a response to the early dome-forming intrusions (Eckel, 1949). Some of these structures were reopened, and new faults formed during the second stage of intrusion. Ore

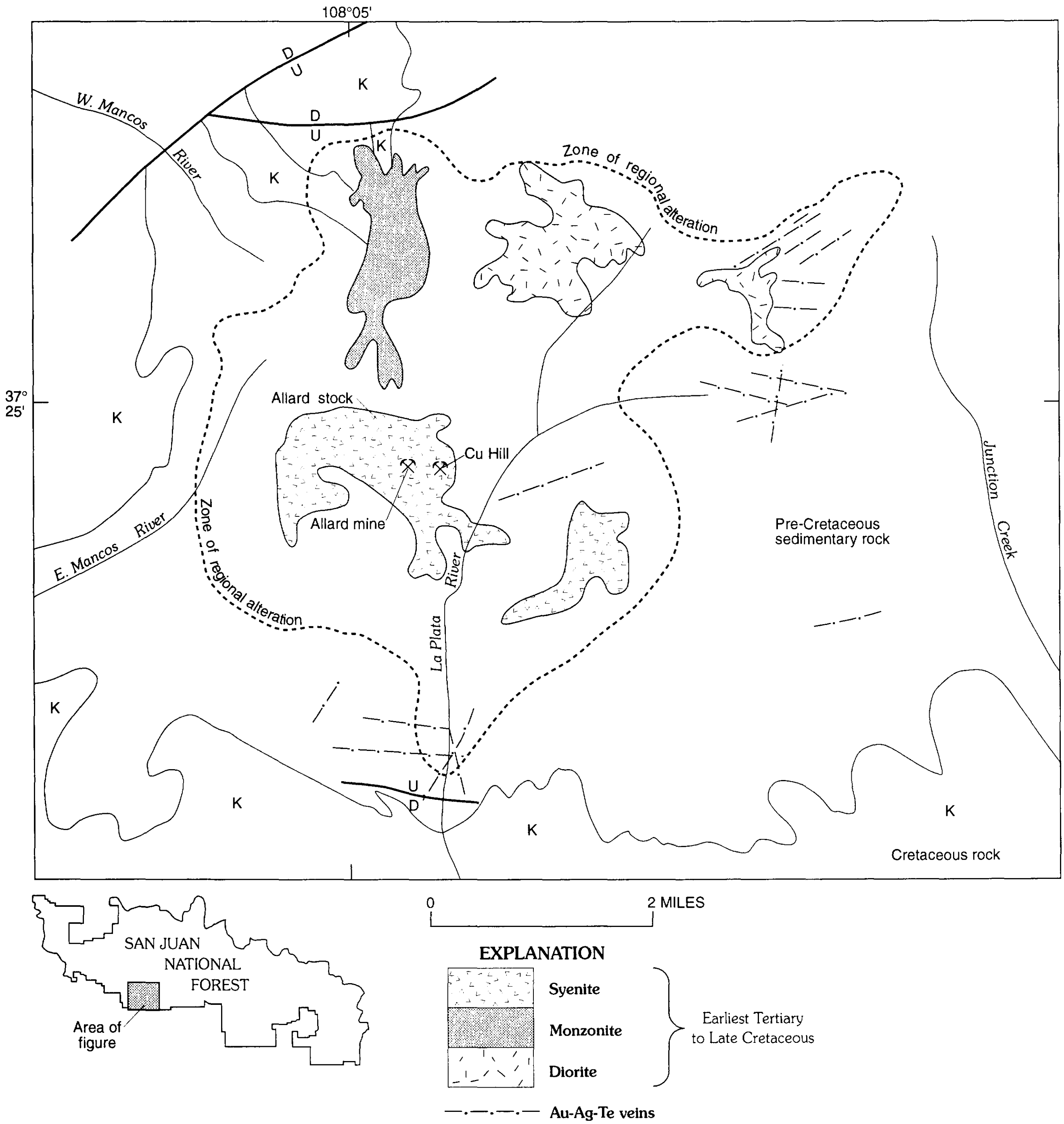


Figure 22. Map of La Plata mining district showing igneous stocks related to mineralization. Modified from Saunders and May (1986).

deposits were localized along these newly opened faults (Eckel, 1949).

Several types of ore deposits are known in the La Plata mining district; however, it is best known for its rich vein and replacement deposits of gold and silver-bearing telluride ore (table 1, deposit type D). These ores account for more than 95 percent of the total production in the La Plata district.

SUMMITVILLE AREA

The small, but rich Summitville mining district is remote from other productive mining districts in the San Juan Mountains (figs. 15, 23). The first comprehensive study of the geology of the Summitville district was by Steven and Ratté (1960). The Summitville deposits occur

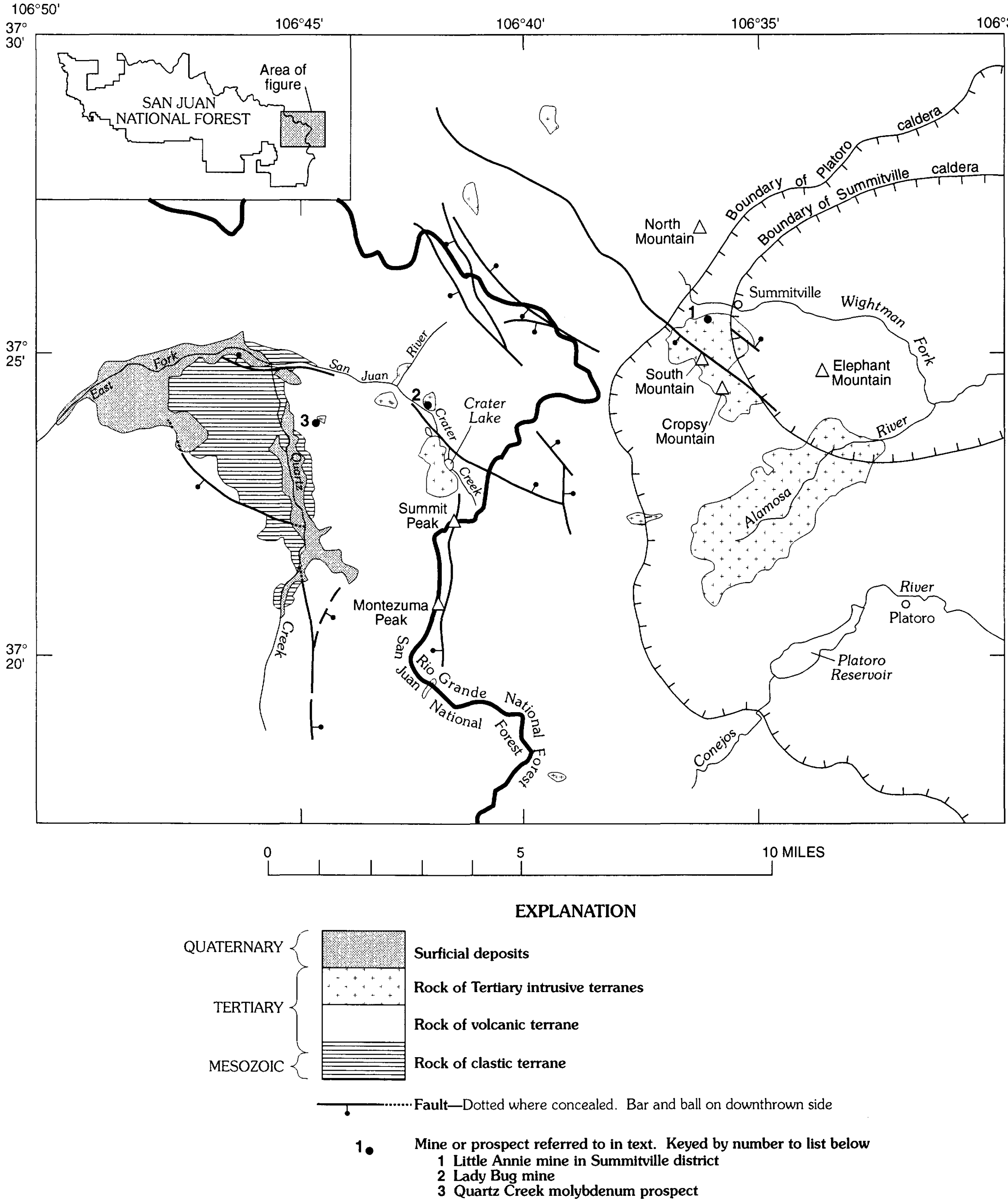


Figure 23. Map showing generalized geology of Summitville district and related mineralized areas in the San Juan National Forest. Geology from Brock and Gaskill (1985), Lipman (1974), and Steven and Ratté (1960).

just outside of the eastern boundary of the Forest, on the western margin of the Platoro-Summitville caldera complex within the South Mountain quartz latite, a hypabyssal stock. The deposit is a classic example of epithermal quartz-alunite gold mineralization associated with acid-sulfate alteration (table 1, deposit type H). Intense acid-leaching along fractures in the quartz latite has produced up to 230-ft-thick irregular pipes and lenticular pods of vuggy silica that are developed vertically for more than 1,000 ft. The vuggy silica hosts native gold with accompanying covellite, chalcopyrite, enargite, luzonite, and minor kaolinite gangue. Gold was initially discovered in 1870 in Wightmans Fork Creek. Subsequent discoveries led to the opening of the Little Annie mine (fig. 23) and other lodes and the erection of stamp mills by 1875 (Henderson, 1926). Deposits were worked intermittently until 1942 and produced about 260,000 oz of gold from underground workings. During the late 1960's and early 1970's, attempts were made to mine copper from underground workings in the district, but they were unsuccessful. The deposit was reopened in 1986 and mined by open-pit methods until 1992; during this period, nearly 300,000 oz of gold were produced by Gallactic Resources, a Canadian company. The Summitville district has produced more than 1.6 million tons of ore. The chief values are from gold, with lesser values from silver, copper, and lead.

Adjacent to Summitville, the Crater Lake–Quartz Creek district abuts the San Juan National Forest boundary (fig. 23). The district contains large areas of altered and iron-stained rock centered in the Crater Creek drainage that have been explored for base and precious metals periodically since 1882 (Brock and Gaskill, 1985). Smaller altered zones and veins surround the larger area, and hydrothermally altered rock extends eastward from Crater Creek toward Summitville. Four lines of evidence suggest a buried mineralized stock beneath the Crater Creek altered area (Brock and others, 1985): (1) presence of several small mineralized plutons within the area of alteration, (2) prevalent fractures throughout the area, (3) zonal alteration patterns, and (4) coincident gravity and aeromagnetic anomalies. Sulfide minerals disseminated in the altered rock include pyrite (up to a few percent), calcite, quartz, and trace pyrrhotite, chalcopyrite, and molybdenite. Only a couple dozen veins more than 1 ft thick have been found both within and beyond the Crater Creek area. Most surface exposures contain only quartz plus pyrite, but some also contain calcite. Galena, sphalerite, and chalcopyrite are visible in only a few of the veins and fracture zones. At the Lady Bug mine (location 2, fig. 23), a few hundred meters of mine workings follow a system of narrow veins containing sphalerite, galena, and chalcopyrite in a gangue of quartz, calcite, and pyrite. Brock and Gaskill (1985) proposed that the altered and mineralized rock and the results of geophysical studies suggest the existence of a buried mineralized stock having a geologic setting typical of most porphyry-type copper deposits. However, recent drilling by Noranda indicates only a small, relatively unmineralized, monzonitic intrusion (about 40 ft thick) at depth at Crater Creek (Neubert and others, 1992, p. 216).

At Quartz Creek, approximately 3 mi west of Crater Creek, an andesite porphyry with iron oxides and gold is exposed at the surface (Brock and Gaskill, 1985; Brock and others, 1985). This area was drilled as a Climax-type molybdenum prospect (R. McKusker, oral commun., 1992), but the results were not impressive. No quartz veining occurs at the surface, although there is an oxidized stockwork. Clots of molybdenite, stockwork chalcopyrite, and low-grade gold were found.

GEOPHYSICAL STUDIES

By Anne E. McCafferty, James A. Pitkin, *and* Cathy M. Ager

AEROMAGNETIC AND GRAVITY ANOMALY STUDIES

CHARACTER OF DATA

Aeromagnetic and gravity anomaly data are available for the Forest area (McCafferty, in press) and were interpreted for this study. The aeromagnetic and gravity anomaly maps provide information regarding the distribution and configuration of crystalline basement rocks, structural and lithologic provinces, zones of crustal weakness, and the distribution of intrusive igneous rocks and sedimentary basins. The sources of major magnetic and gravity anomalies within and surrounding the Forest area are discussed, and models for a specific aeromagnetic anomaly are presented in this section.

Aeromagnetic anomaly maps show changes in the Earth's magnetic field that correspond to variations in the amounts of magnetic minerals in rocks, chiefly the mineral magnetite. In general, sedimentary rocks are weakly magnetic. Therefore, the magnetic anomaly maps reveal lithologic and structural changes related to the magnetic rock properties of volcanic and crystalline rocks that are likely to contain enough magnetic minerals to produce anomalies. Aeromagnetic anomaly maps are particularly useful in identifying the presence of buried geologic features, such as intrusive bodies, which often have strong magnetization relative to the surrounding rock. Figure 24 is an aeromagnetic map of the Forest area and represents the compilation of data from eight separate surveys flown over the course of 2 decades with different flight specifications (McCafferty, in press). The surveys have been analytically processed and merged into one composite data set represented at a datum of 1,000 ft above topography to facilitate interpretation of anomalies in a consistent fashion.

Gravity anomalies result from lateral variations in rock densities and are useful in extending geologic mapping into areas covered by surficial deposits and in determining the subsurface position and attitude of geologic contacts that coincide with density boundaries. Figure 25 is an isostatic gravity anomaly map of the Forest area (McCafferty, in press) that enhances gravity anomalies associated with shallow crustal sources. The reconnaissance nature of the gravity station spacing prohibits any detailed interpretations of the structural and lithologic complexities within the Forest. However, the gravity anomaly map is useful in distinguishing large geologic units that have strong density contrasts.

DISCUSSION

The magnetic anomaly map for the central part of the San Juan Mountains is dominated by the effects of the ash-flow tuff units of the San Juan volcanic field in the form of hundreds of short-wavelength, high-amplitude anomaly highs and lows caused by normal and reversely magnetized volcanic units. The cluttered character of the anomaly field tends to mask any geophysical signature of underlying rock units or subsurface structure. Some of the calderas of the San Juans, most of which lie outside the Forest (fig. 14), have distinct magnetic signatures. The prominent 15- to 25-km-wide circular magnetic anomaly highs over the Creede and La Garita calderas (fig. 14; fig. 24, CC, LC) delineate the intracaldera ash-flow tuffs and structural margins (Williams and Abrams, 1987). A magnetic anomaly low occurs over the Silverton caldera (fig. 24, SC) and is flanked on the south by a linear anomaly high coinciding with the intrusive rocks of the Sultan Mountain stock (fig. 24, SS). The prominent low within the caldera may represent an area that has undergone hydrothermal alteration.

The western extension of the San Juan Mountains into the Colorado Plateau encompasses a group of middle Tertiary stocks and laccoliths. Major magnetic anomaly highs coincide with the Dolores Peak stock (DS), the Mt. Wilson stock (MS), Ophir stock (OS), the Grizzly Peak stock (GS), and the Sultan Mountain stock (SS, fig. 24). The anomalies are caused by a combination of (1) the strong magnetization contrast between the nonmagnetic pre-intrusive sedimentary rock and the intermediate to mafic igneous rocks of the stocks, and (2) the relatively great depth to which the stocks extend (Popenoe, 1972). Another predominant aeromagnetic high coincides with an exposure of the Middle Proterozoic Electra Lake Gabbro (fig. 24, EG) in the West Needle

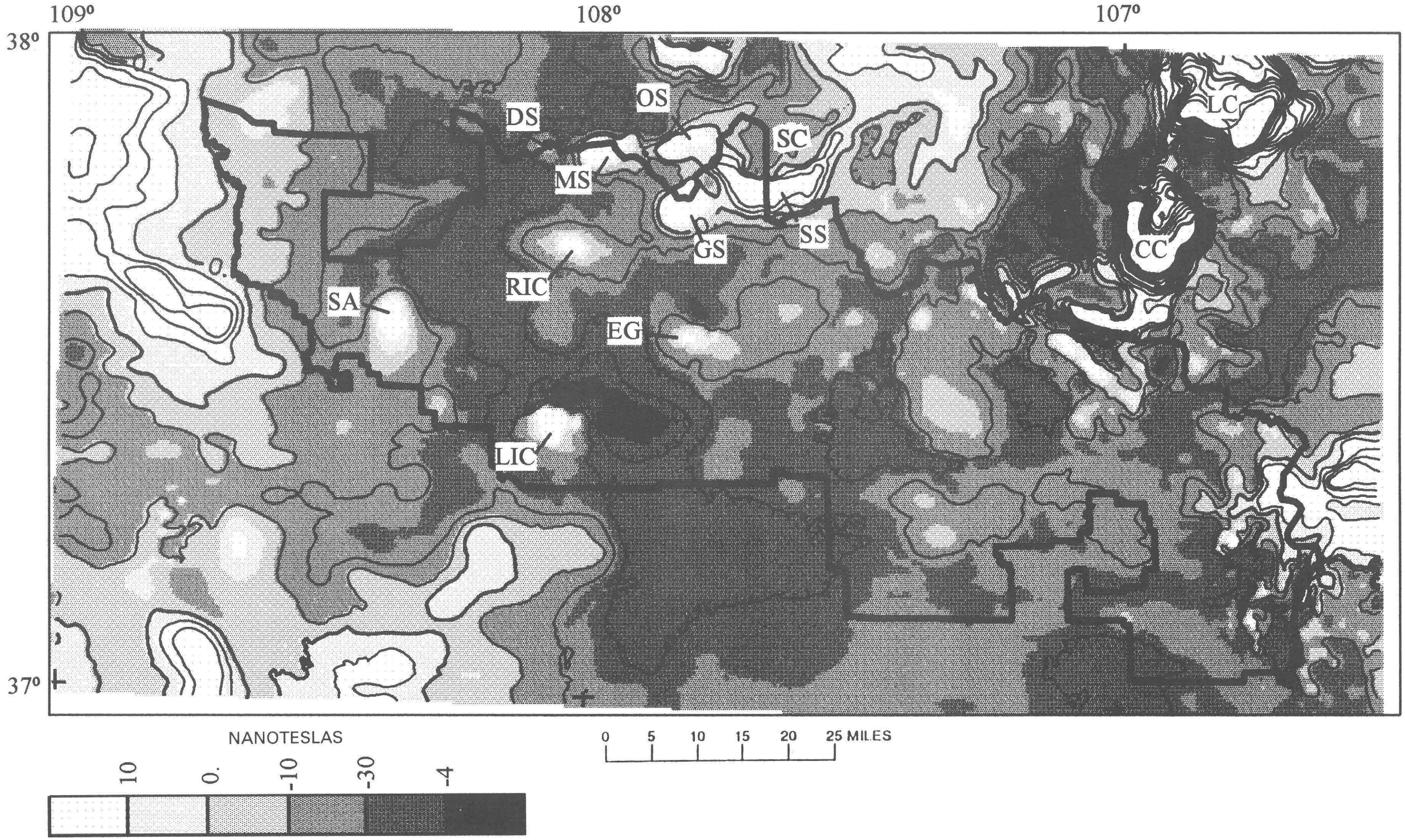


Figure 24. Aeromagnetic anomaly map of the San Juan National Forest (McCafferty, in press). Data from eight separate surveys have been merged and presented at a constant datum of 1,000 ft above topography. Contour interval is 100 nanoteslas for black contours. Hachures show areas of magnetic anomaly lows. Forest boundary is shown as heavy black line. Selected features discussed in text include: CC, Creede caldera; LC, La Garita caldera; SC, Silverton caldera; RIC, Rico igneous center; LIC, La Plata igneous center; SA, Stoner anomaly; EG, Electra Lake Gabbro; DS, Dolores Peak stock; OS, Ophir stock; GS, Grizzly Peak stock; SS, Sultan Mountain stock; MS, Mount Wilson stock.

Mountains. The magnetic anomaly is much larger than the outcrop, suggesting a greater subsurface extension of gabbro.

The northeast part of the gravity anomaly map (fig. 25) is dominated by a regional gravity low that has been interpreted to delineate the presence of a large, concealed batholith genetically related to the caldera complexes (Plouff and Pakiser, 1972). The regional gravity low extends across and includes the 25- by 45-km complex of Precambrian rocks in the Needle Mountains. Plouff and Pakiser (1972) interpret the extension of the gravity low to represent more of the batholith underlying a thin plate of Precambrian rock.

Individual calderas and most of the intrusive stocks in the western part of the San Juan Mountains do not appear as distinct anomalies because there is not enough of a density contrast between the igneous units and the underlying batholith to cause an anomaly. The Electra Lake Gabbro is the only igneous body in the western part of the San Juan Mountains that is associated with any significant gravity anomaly high. The San Juan Basin (fig. 7) coincides with a large, long-wavelength gravity anomaly low corresponding to the thick sedimentary section within the basin. The magnetic anomaly low also indicates the thick sequence of nonmagnetic sedimentary rock and the great depth to basement.

The interpretation of individual magnetic anomalies becomes significantly less difficult west of the San Juan Mountains. The map is no longer dominated and complicated by the short-wavelength effects of the tuffs of the San Juan volcanic field but, for the most part, is influenced by the presence of exposed and buried stocks or upwarps of the Precambrian surface. Of particular interest are the prominent magnetic anomaly highs that cover the Rico and La Plata igneous centers (RIC, LIC on fig. 24). The centers are dissected domes of multiple sills and laccoliths of diorite to syenite composition that have intruded Paleozoic and Mesozoic rocks. The anomaly highs are the result of the magnetization contrast between nonmagnetic sedimentary rock and magnetic igneous rocks of intermediate composition. The anomaly highs over both centers crudely follow the mapped geology but appear more uniform than the dispersion of outcrops would suggest. This results partly from the insufficient number of magnetic observations over these areas. The character of the anomalies could be the result of the wide flight-line spacing, which would tend to smooth out and combine the effects of several separate sources into one large anomaly. (Both areas are covered by surveys flown with flight lines collected along an east-west direction every 1 mi.) Alternatively, the anomalies could represent a deeply buried, composite stock that is the source of the various igneous units mapped at the surface.

To the west of the Rico and La Plata igneous centers, and directly west of the town of Stoner, is a prominent high-amplitude aeromagnetic high (fig. 26), herein referred to as the "Stoner anomaly." The anomaly is well defined by approximately 12 east-west-trending flight lines that cross the area. No surface rock unit could account for the anomaly; nonmagnetic Upper Cretaceous Dakota Sandstone blankets the area. The similar geophysical expression to the anomalies at the Rico and La Plata igneous centers prompted a closer examination of the Stoner anomaly.

An initial model was developed to test whether the Stoner anomaly could be caused by the same type of rocks exposed at the La Plata and Rico igneous centers by assuming a susceptibility consistent with the exposed units. A flight line was extracted from the original data and modeled (shown as A-A′ on fig. 26) using a 2.5-dimensional modeling program (Webring, 1985). The following parameters were assumed: induced magnetization, a susceptibility of 0.003, and a depth beneath the topographic surface of 2.6 km. The susceptibility of 0.003 is the average value given for a syenite (Telford and others, 1978) and was chosen because syenite is the principal lithology of the Allard stock in the La Plata igneous center. The depth to the source was constrained by drill-hole data (S. Condon, written commun., 1992). A drill hole is located directly on the peak of the Stoner anomaly (fig. 27) and was undoubtedly drilled to determine the source of the high. However, the drill log indicates that no igneous rock or any other rock type likely to be the source of the anomaly was encountered throughout the depth of the hole (8,297 ft). Therefore, the source of the anomaly must be deeper than 8,297 ft. The Precambrian basement is shown in figure 27 for reference and is estimated to be gently westward dipping from 1,500 ft below sea level on the west to 3,048 ft above sea level to the east in the area of profile A-A′ (W.C. Butler, written commun., 1993).

The result of the initial model (not shown), using the syenite susceptibility, yielded a poor fit to the observed anomaly. The amplitude of the model anomaly was far below that of the observed anomaly, indicating a larger susceptibility was required to fit the anomaly.

Two alternate models were calculated to yield better fits to the observed anomaly and are shown in figure 27. Both models require that the source be eastward dipping. Model A places the source within the sedimentary section above the basement and does a marginally better job of fitting the observed anomaly in comparison with model B (fig. 27). Model B places the source within the Precambrian basement.

Drill-hole data, for the area within four townships that cover the Stoner anomaly, are plotted on figure 26 (S. Condon, written commun., 1993). All holes bottomed within the sedimentary section and ranged in depths from 4,461 ft to 9,000 ft. Three drill holes show log records that noted the presence of igneous sills (d1, d2, and d3, fig. 26); only the log for hole d1 notes where the sill was encountered. The sill was within a salt unit of the Paradox Formation (Middle Pennsylvanian) at a depth of 6,497 ft. Holes d2 and d3

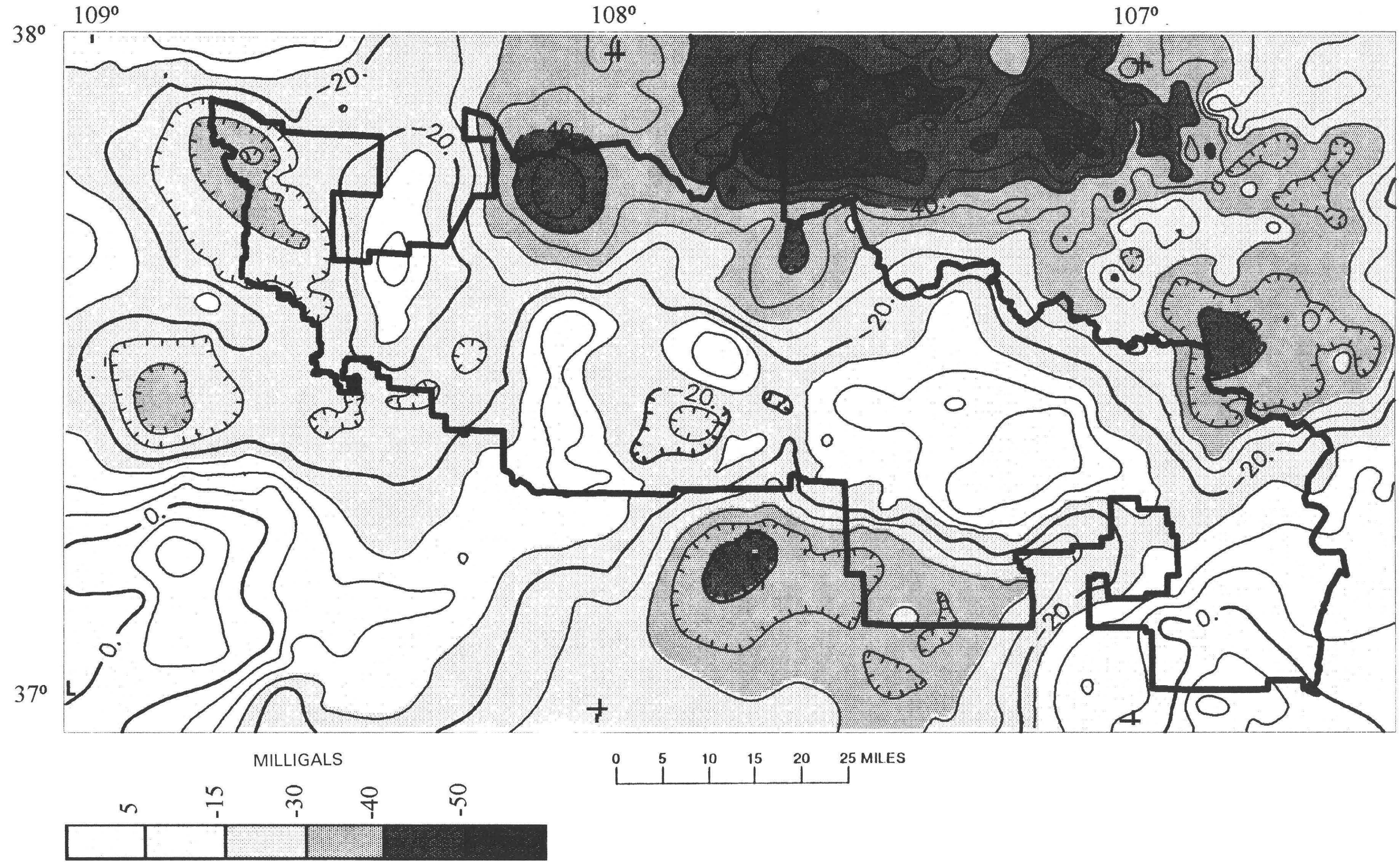


Figure 25. Isostatic gravity anomaly map of the San Juan National Forest (McCafferty, in press). Contour interval is 5 mGal. Hachures show areas of gravity anomaly lows. Forest boundary is shown as heavy black line.

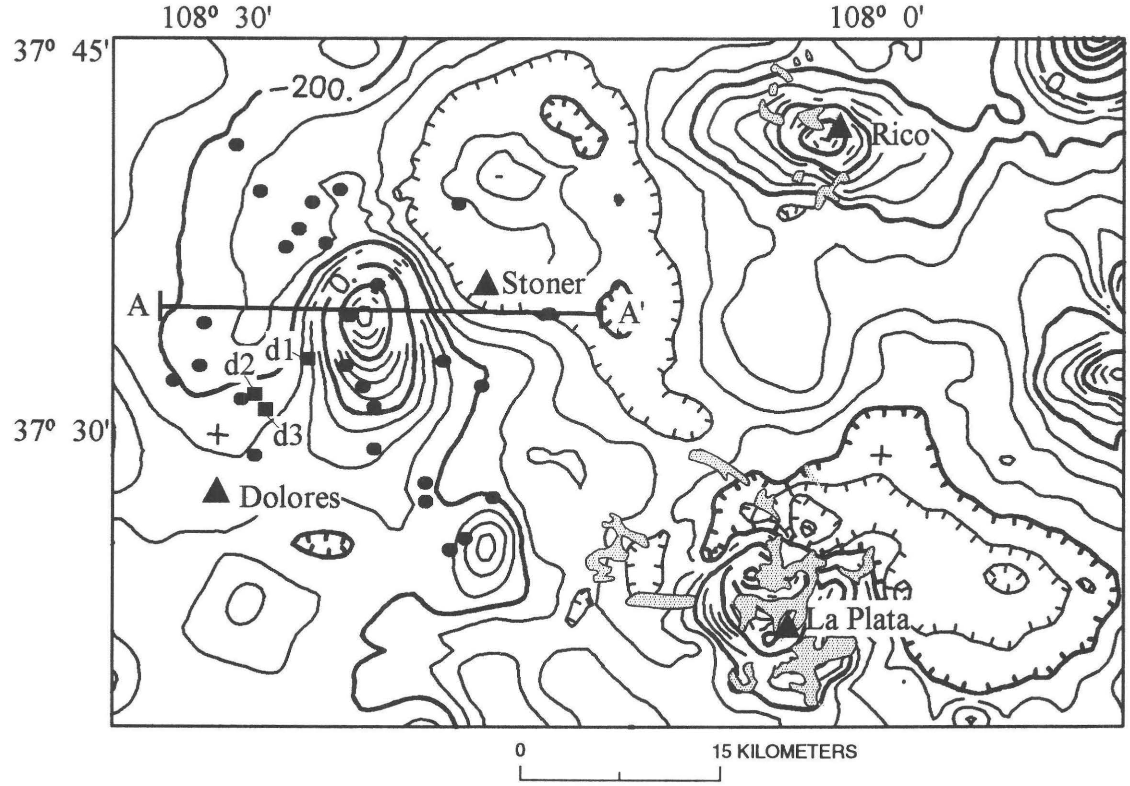


Figure 26. Aeromagnetic anomaly map of a part of the San Juan National Forest. Contour interval is 50 nanoteslas. Hachures show areas of magnetic lows. Triangles indicate towns. Circles and squares show drill hole locations in the vicinity of magnetic model profile A-A′. Drill holes labeled d1, d2, and d3 indicate holes that encountered igneous sills. Rocks associated with the La Plata and Rico igneous centers are shown in gray pattern.

bottomed in Lower Mississippian Leadville Limestone, but the logs do not record where the sill was encountered in the sedimentary section.

The conclusions to the modeling process are that the source of the Stoner anomaly (1) is substantially more mafic than the rocks associated with the exposed parts of the La Plata and Rico igneous centers, (2) is eastward dipping, (3) is located either in the basement not far from the sedimentary-basement interface or located above the basement within the pre-Pennsylvanian sedimentary section, and (4) is post-Pennsylvanian, based on drill data.

GAMMA-RAY RADIOACTIVITY

Aerial gamma-ray spectrometer data from the NURE program were used to prepare potassium (K), uranium (U), and thorium (Th) aeroradioactivity contour maps of the Forest. Details of data acquisition and map preparation and a set of the maps at 1:250,000 scale are published separately (Pitkin, in press). Color and black-and-white aeroradioactivity contour maps at 1:250,000 scale were used in the mineral-resource-appraisal process described in this report.

Aeroradioactivity is the measurement of terrestrial radioactivity with instruments operated in low-flying aircraft. The radioactivity measured is from the near-surface (as deep as 50 cm) distribution of the natural radioelements K, U, and Th. NURE aerial systems were quantitatively calibrated at sites of known radioelement concentrations, permitting quantitative reporting of survey data in percent for K and ppm for U and Th (assuming equilibrium in the respective decay series). The near-surface distribution of K, U, and Th reflects mostly bedrock lithology and modifications due to weathering, erosion, transportation, ground-water movement, and hydrothermal alteration. Common rock types (felsic igneous rocks, arkosic sandstones, and shales) are generally more radioactive (contain more radioactive minerals) than mafic igneous rocks, clean sandstones, and limestones.

Figures 28, 29, and 30 are, respectively, K, U, and Th aeroradioactivity gray-scale contour maps of the Forest. The maps include place names to facilitate the discussion. The aeroradioactivity maps show that the Forest, in general, is characterized by low to moderate radioelement concentrations, especially west of about longitude 107°15′ W. Exceptions to this generalization include areas of higher radioactivity in the approximate central part of the Forest, adjacent to and west of Silverton and southwest, south, and southeast of that city, northwest of Durango, and at the northwestern tip of the Forest, in the Disappointment Creek area.

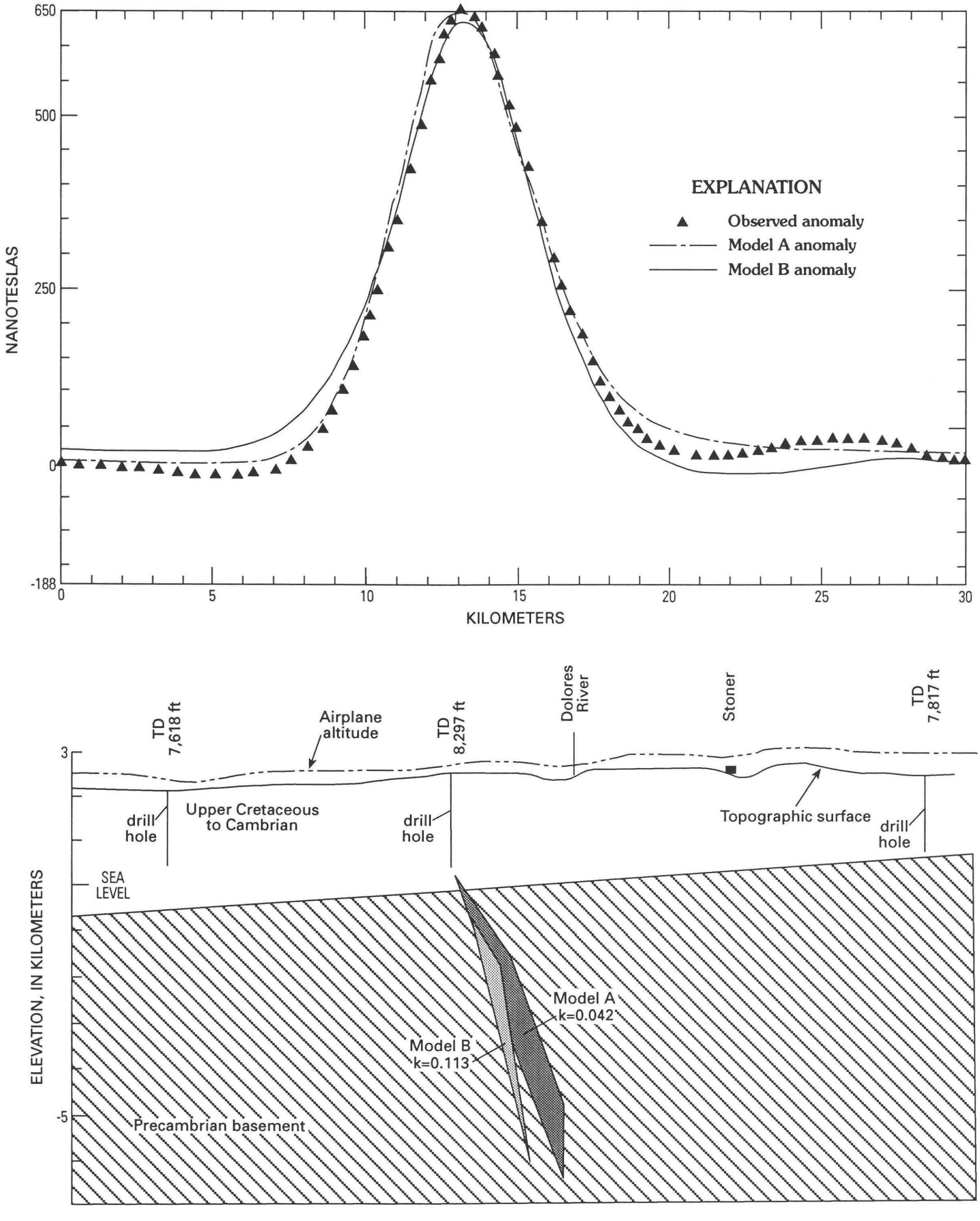


Figure 27. Two possible magnetic models of buried bodies for the Stoner anomaly. Location of profile A-A′ is shown on figure 26. Susceptibilities are in cgs units (dimensionless). Drill holes along profile A-A′ are labeled and total depth (TD) is given in feet for each. Model A places the source for the Stoner anomaly within the sedimentary section. Model B places source within the Precambrian basement, close to the sedimentary-basement interface.

That part of the Forest west of longitude 107°15′ W. has relative concentrations that range from 0.6 to 1.2 percent K, from 1.0 to 2.6 ppm U, and from 5 to 9 ppm Th; bedrock is mostly Paleozoic and Mesozoic sedimentary rocks with relatively lesser quantities of radioactive minerals. The areas in the central part of the Forest that have higher concentrations of K, U, and Th have bedrock sources of Tertiary felsic igneous rocks for the features adjacent to Silverton and west and southwest of that city. South and southeast of Silverton, rock sources are

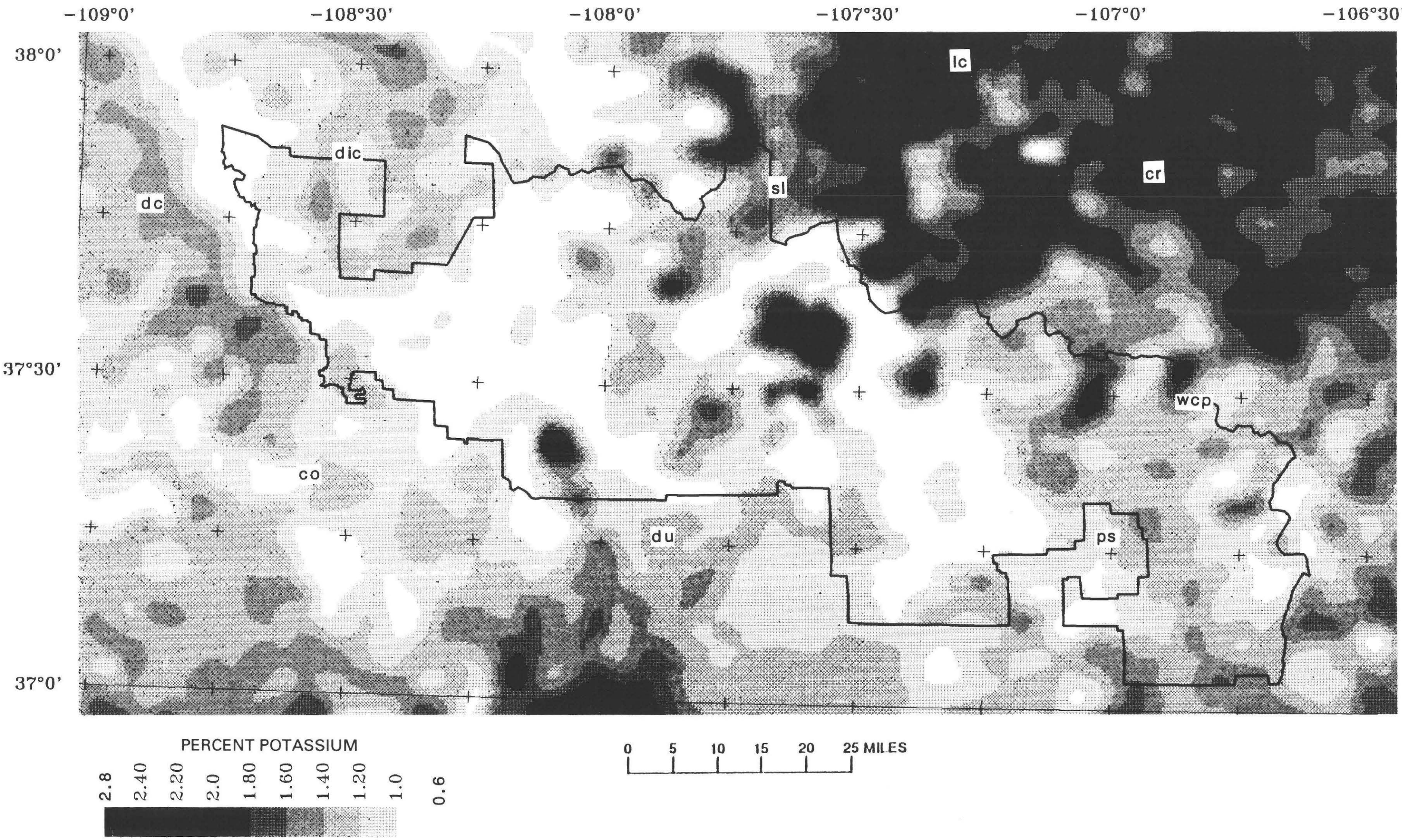


Figure 28. Potassium aeroradioactivity gray-scale contour map of the San Juan National Forest. Contour interval 0.2 percent K. Geographic locations: co, Cortez; cr, Creede; dc, Dove Creek; dic, Disappointment Creek; du, Durango; ps, Pagosa Springs; lc, Lake City; sl, Silverton; wcp, Wolf Creek Pass. Solid line indicates approximate boundary of the San Juan National Forest.

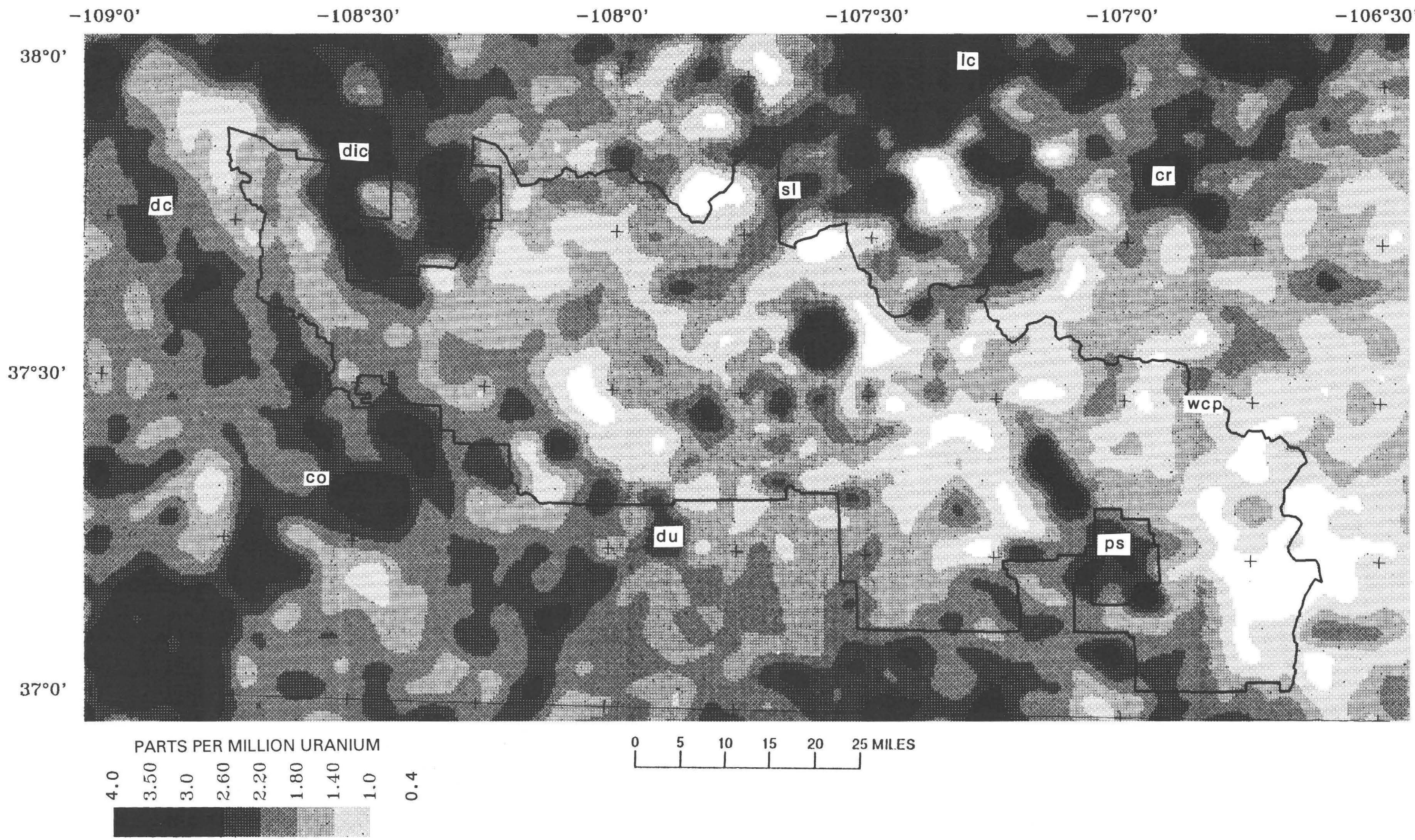


Figure 29. Uranium aeroradioactivity gray-scale contour map of the San Juan National Forest. Contour interval 0.4 and 0.5 ppm U. Abbreviations are same as those on figure 28. Solid line indicates approximate boundary of the San Juan National Forest.

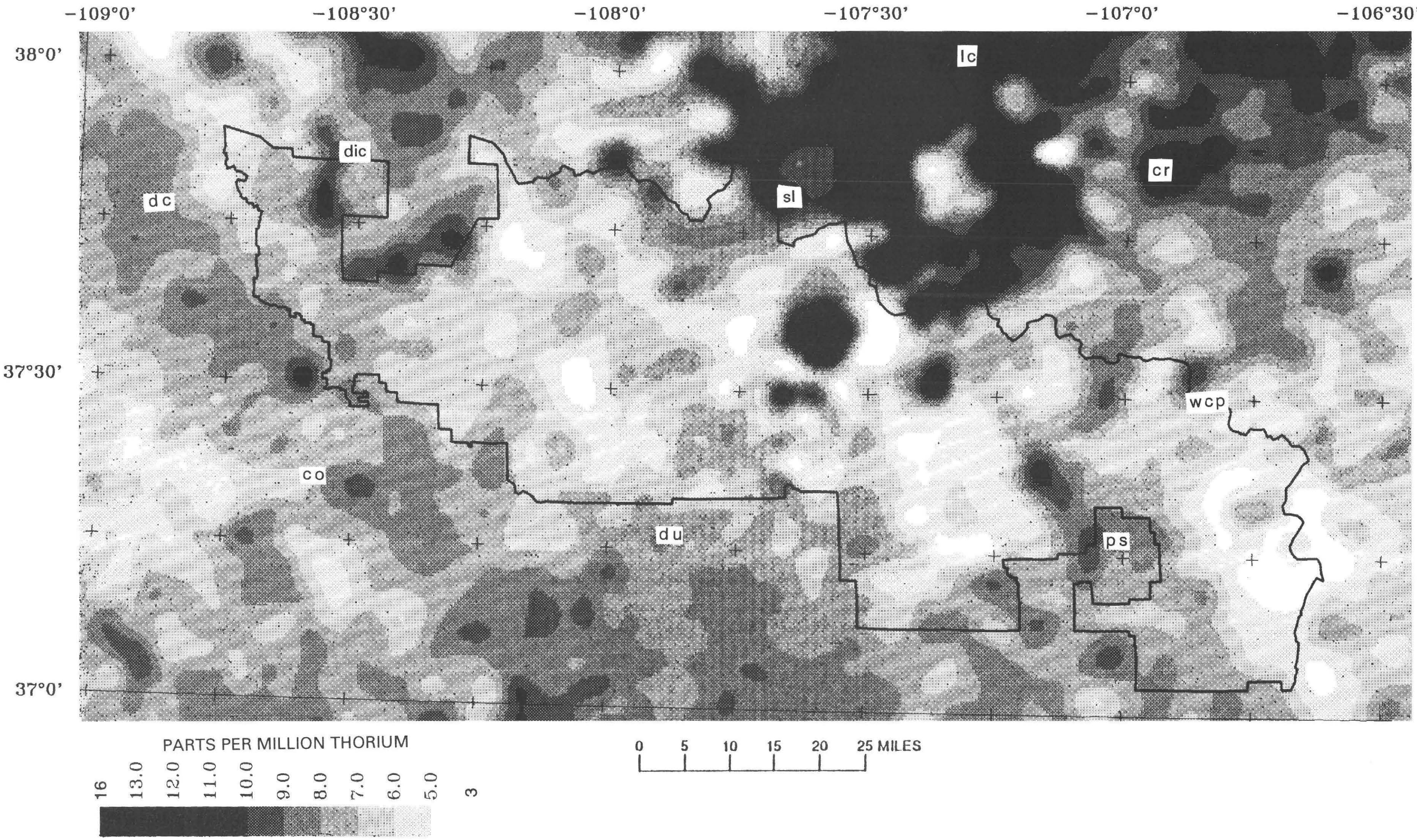


Figure 30. Thorium aeroradioactivity gray-scale contour map of the San Juan National Forest. Contour interval 1 ppm Th. Abbreviations are same as those on figure 28. Solid line indicates approximate boundary of the San Juan National Forest.

Precambrian felsic igneous and metamorphic rocks, one radioactive source being uraniferous veins in granite in the Needle Mountains. Radioelement concentrations vary for the more radioactive rocks in the central part of the Forest, ranging from 1.8 to 2.8 percent K, from 2.2 to 4.0 ppm U, and from 10 to 16 ppm Th. In the Needle Mountains, the area of higher K has a greater areal extent, especially to the northwest, than the areas of higher U and Th. Northwest of Durango, the syenitic Allard stock of Laramide age in the La Plata district displays its alkaline nature with a prominent K high (2.4 to 2.8 percent) and accompanying relatively undistinguished U (2.6 to 3.0 ppm) and Th (8 to 9 ppm). The Disappointment Creek feature relates Upper Cretaceous Mancos Shale and radioactive heavy minerals and (or) uraniferous shale as sources for distinct patterns of U (2.2 to 3.5 ppm), Th (8 to 11 ppm), and K (1.2 to 1.8 percent). The Mancos Shale is also the source of moderate U features (2.2 to 3.0 ppm) northwest and southeast of the Allard stock.

Ratioing of the radioelement data (not shown in this report) can highlight nuances in distributions not apparent in contour maps. Examples include in the vicinity of Silverton, where Tertiary igneous rocks have relatively greater U comparative to K or Th, and in the vicinity of Rico southwest of Silverton where Tertiary intrusive rocks have relatively greater Th compared to U or K. West of Silverton, along the Forest boundary at about longitude 108° W., the quartz monzonite at Mt. Wilson has relative highs of all three radioelements. Southeast of Silverton, Precambrian rocks have relatively greater Th, compared to K or U. The Mancos Shale variably has U greater than K or Th, and Th greater than K or U, possibly indicating differing radioactive heavy-mineral (monazite, zircon) concentrations and, locally, coincident highs of all three radioelements.

In the eastern part of the Forest, east of about longitude 107°15′ W., moderate K concentrations (1.0 to 1.6 percent) and low to moderate U (0.4 to 1.8 ppm) and Th (3 to 9 ppm) reflect the presence of mostly calc-alkaline Tertiary igneous rocks. The east side of the Forest, south and southeast of Wolf Creek Pass, has notably low radioelement concentrations (0.6 to 1.2 percent K, 0.4 to 1.4 ppm U, 3 to 6 ppm Th). Tertiary igneous rocks of more felsic composition do occur in the area, as evidenced by several areas of slightly higher concentrations. More felsic, more radioactive rocks also occur along the Forest boundary from Wolf Creek Pass west-northwest toward Silverton, as evidenced by occurrences of moderate to high radioelement concentrations along that boundary. Northwest of Pagosa Springs, distinct U (2.2 to 3.5 ppm) and less distinct Th (9 to 11 ppm) anomalies reflect the presence of the Lewis Shale of Late Cretaceous age.

REMOTE SENSING

Satellite images are used in mineral exploration to detect surface alteration associated with ore deposits and to map regional and local fracture systems that may control concentrations of ore deposits. Images of the Forest and surrounding area were analyzed for the presence of limonite (iron oxide associated with altered rock) and for linear features that may include fracture systems.

METHODS

Landsat multispectral scanner (MSS) digital image data were digitally processed for photogeologic interpretation of linear features and for limonite mapping in the San Juan National Forest. Higher peaks in the San Juan Mountains are snow covered in these October 1975 and 1976 images. In-house USGS REMAPP (remote sensing array processing procedures) software was used for digital image processing (Sawatzky, 1985).

LIMONITE MAP

A ratio of MSS bands 4 and 5 detects the presence in rocks of intense Fe^{3+} absorption caused by ferric-oxide and hydrous ferric-oxide minerals, collectively known as limonite. MSS data lack the spectral information to allow either separation of hydrothermally altered limonitic rocks from limonitic-weathering unaltered rocks, or identification of nonlimonitic hydrothermally altered rocks. In addition, vegetation cover and high topographic relief can interfere with the computerized limonite-mapping processes. Therefore, field studies generally are required to confirm that a particular area determined using the MSS 4/5 ratio is indeed hydrothermally altered (W.J. Ehmann and L.C. Rowan, written commun., 1987).

A limonite map was prepared from a ratio of MSS bands 4 and 5 in an attempt to identify any unknown areas of limonite that could be related to mineralized rock. Because the high peaks were covered by snow and many of the slopes and lower elevations were covered by dense vegetation, only scattered areas of limonite were mapped, primarily on and near some of the known "red" mountains of the Forest.

LINEAR FEATURES MAP

Linear features were mapped from black-and-white positive transparencies of Landsat MSS bands 5 and 6. The relative number of linear features mapped can indicate both the tendency of an area to be fractured and the orientations of the stress and fracture patterns. A map of linear-feature concentration patterns shows areas with high numbers of linear features and, thus, areas more likely to have greater fracturing (fig. 31).

Some of the most prominent concentrations of linear features occur in the following areas (letters are keyed to those shown on fig. 31):

A. Northwest corner of the Forest: These features along the Dolores River are spatially related to the distribution of the Dakota Sandstone located near the crest of the Dolores anticline (Haynes and others, 1972).

B. North of the town of Dolores: This group of northeast-trending features parallels House Creek (Haynes and others, 1972) and partially coincides with the area of the Stoner magnetic anomaly discussed previously.

C. Mesa Verde area: Features here are probably associated with fracture-controlled (joint) drainages that extend through the Upper Cretaceous Cliff House Sandstone down into the Menefee Formation and the Point Lookout Sandstone (plate 1) on the mesa itself and along the Mancos River.

D. Hogback monocline and vicinity: The features along the Hogback monocline are associated with the exposed Upper Cretaceous sandstone. Other linear features in the area of the monocline include those along the Animas River and its tributaries and those at the eastern edge of the monocline associated with a swarm of north- and northeast-trending dikes extending from the San Juan Basin northward into the volcanic field of the San Juan Mountains. South of the monocline, the features not associated with the Animas River drainage to the west or the dike swarm to the east occur primarily in Eocene sediments derived from erosion of the Laramide San Juan uplift to the north. Aside from the cluster of features southeast of the town of Ignacio, none of the feature concentrations south of the monocline is clearly associated with known structures (Knepper, 1982).

E. Needle and West Needle Mountains: This is a minor cluster of features in the Early Proterozoic Irving Formation and Middle Proterozoic Eolus Granite (metavolcanic and metasedimentary rocks, plate 1).

F. Silverton and Lake City calderas: Both calderas are partially included in a broad, poorly defined cluster of features that extends southeastward to cover northeast-trending canyons cut in volcanic rock.

G. La Garita caldera: There is a small concentration of features inside the caldera.

H. Along the Dolores River northeast of Dolores: These features make up a broad, poorly defined cluster along the river as it cuts into the Dolores (Upper Triassic) and Cutler (Lower Permian) Formations (plate 1) and along a few scattered north-trending faults.

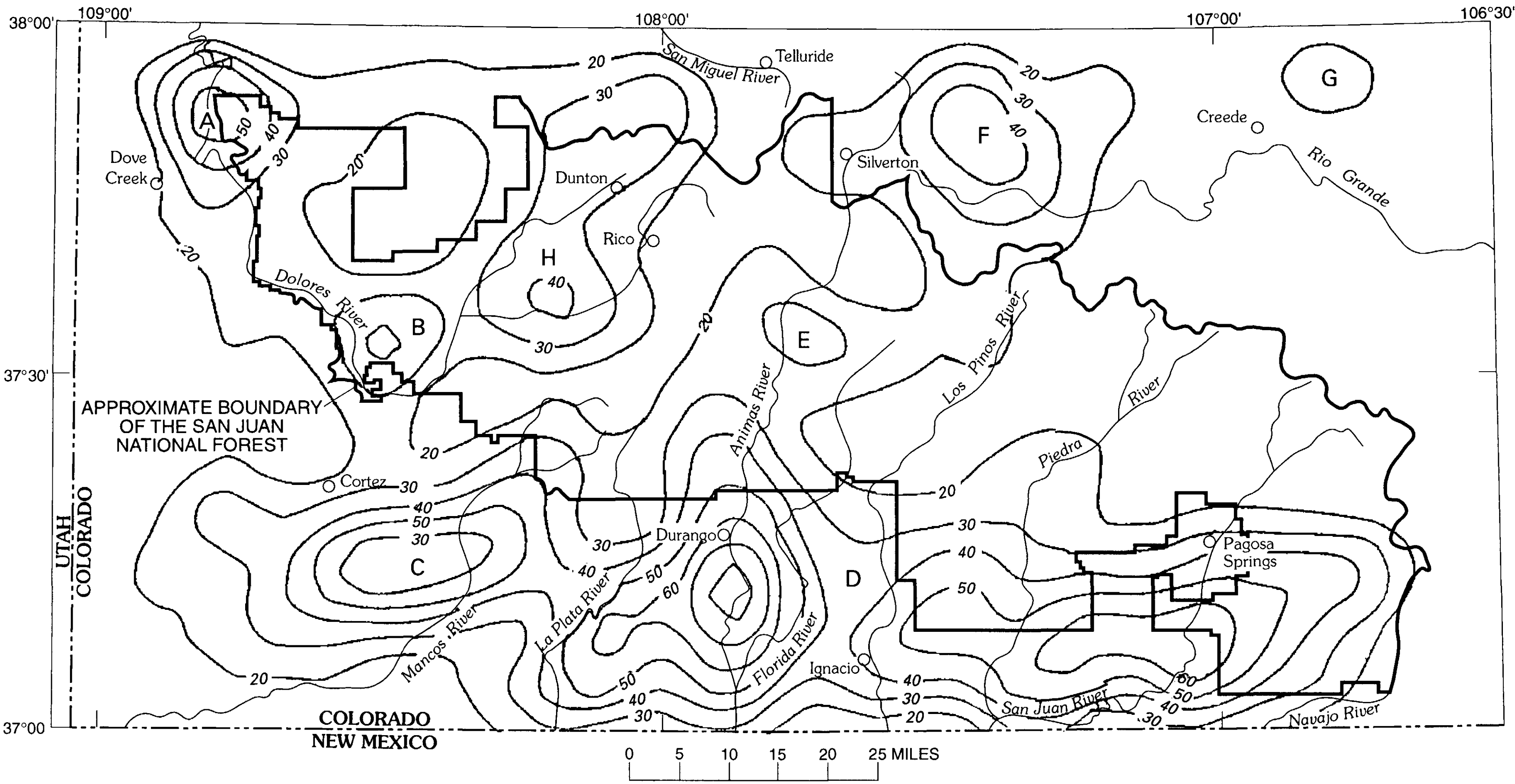


Figure 31. Linear-feature concentration patterns in and near the San Juan National Forest. Letters are keyed to discussion in text.

GEOCHEMISTRY

By H.N. Barton

Geochemical surveys of the Forest and adjacent areas, conducted by Government agencies for mineral resource assessments, have been utilized in this project. Three studies provide useful geochemical information: (1) National Uranium Resource Evaluation (NURE) studies conducted by the Department of Energy (DOE), (2) U.S. Geological Survey (USGS) Wilderness studies, and (3) USGS geochemical studies of specific areas of the San Juan National Forest.

GEOCHEMISTRY DATABASE

Sampling in the NURE program provides good, uniform coverage of the Forest and generally appropriate geochemical analyses for most elements of interest to this assessment; molybdenum was not determined in these analyses. Results of the NURE program for stream sediments, reported for the Cortez and Durango 1°×2° quadrangles (Warren, 1979; Shannon, 1980), were utilized but simplified to include only the results for 1,728 sites within or a few miles beyond the Forest. The NURE sample sites are shown on figure 32. This data set included information on 43 elements, many of which were not pertinent to this study. Results from previous USGS Wilderness studies of five areas within the Forest (fig. 6) were also examined; interpretations of these results were published between 1969 and 1985. Finally, new sampling and analysis were undertaken in 1991–92 (Barton and others, 1992) to fill gaps in existing surveys and to check previously reported anomalies and areas of interest in this assessment. Analytical methods, described elsewhere, differ in these studies, but all are considered reliable for the relatively higher concentrations that define anomalies used to interpret areas of mineral potential. The chief limitations of the geochemical database are the small number of molybdenum and gold analyses; to compensate for these shortcomings, we utilized information for generally associated elements, such as copper and silver.

GEOCHEMICAL ANOMALIES

High geochemical values of interest in this study are termed anomalous. The range of anomalous values can be determined by a statistical method, such as the upper 10th percentile, or by comparison to a standard value, such as world crustal abundance (Rose and others, 1979); for emphasis, a value can be termed "highly anomalous," if the concentration is very high, or "weakly anomalous," if the concentration is only slightly unusual. In this report we will mention anomalies only for a limited number of elements known to occur in the ore deposits of the region (gold, silver, antimony, arsenic, bismuth, copper, molybdenum, lead, tungsten, zinc, and uranium), although other elements were considered in the study.

Mining districts, previously described and located on figure 15, generally are evident in the geochemical surveys. The Needle Mountains district produces anomalous values of antimony, bismuth, copper, gold, lead, silver, tungsten, uranium, and zinc in stream-sediment samples. The Beartown district, also in the Needle Mountains, yields stream sediments anomalous in antimony, bismuth, copper, gold, lead, silver, tungsten, uranium, and zinc. The Silverton area is anomalous in antimony, copper, gold, lead, silver, tungsten, and zinc and is weakly anomalous in bismuth. The Mt. Wilson district produces sediments that are anomalous in copper, lead, molybdenum, and zinc. The Dunton district is reflected in two sample sites that are anomalous in gold, silver, antimony, copper, lead, and zinc. The Rico district produces sediments that are anomalous in antimony, copper, lead, silver, tungsten, and zinc. The La Plata district produces anomalies in copper and gold. The Crater Lake–Quartz Creek district produces weak anomalies in lead, zinc, and gold in the NURE data, but stronger anomalies in copper, lead, molybdenum, silver, and zinc were found by the USGS (Brock and Lindquist, 1977). The Summitville district, east of the Forest, produces stream sediments that are anomalous in antimony, copper, gold, lead, tungsten, and zinc.

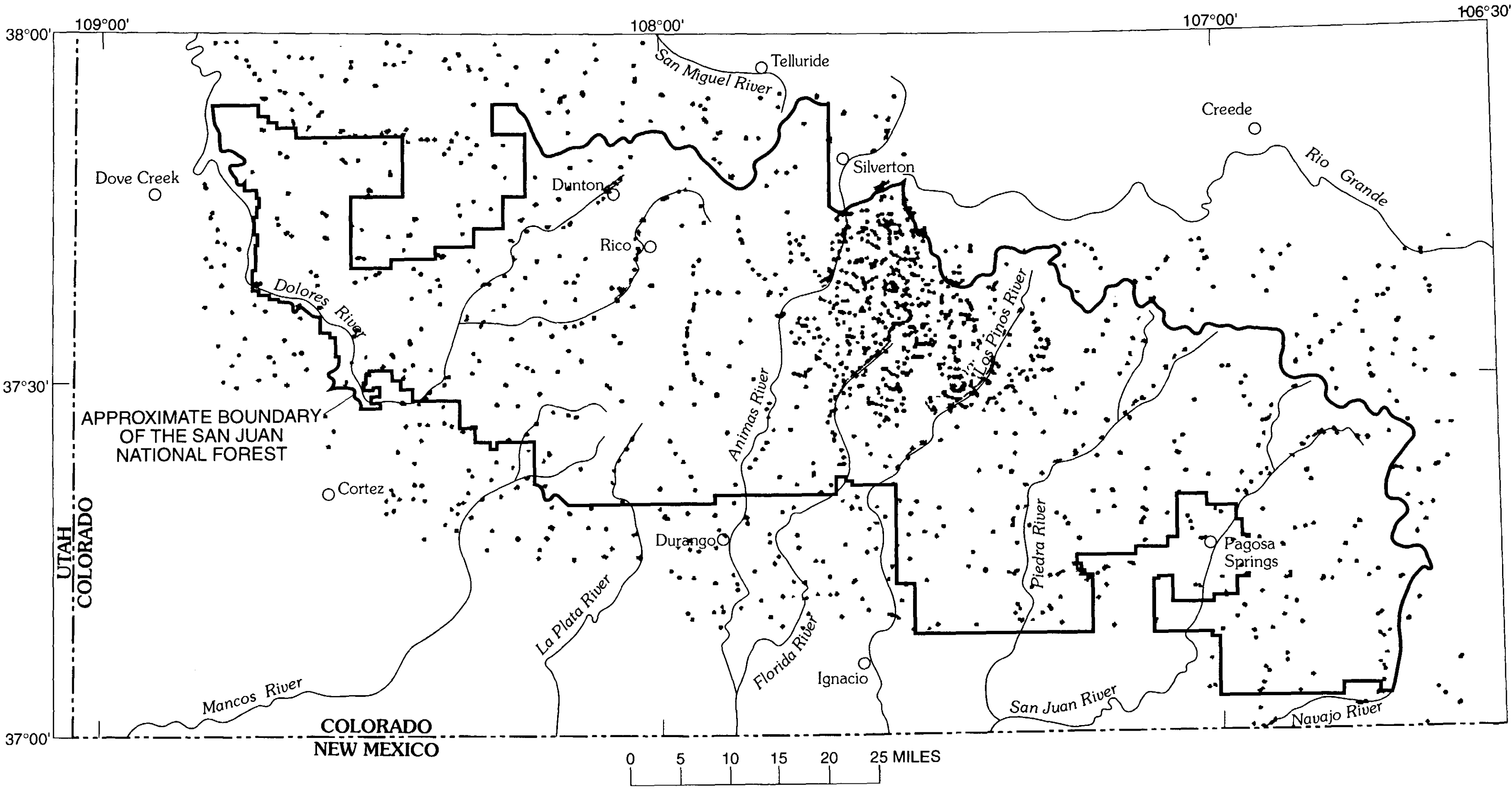


Figure 32. Map showing NURE stream-sediment sample localities, San Juan National Forest and vicinity.

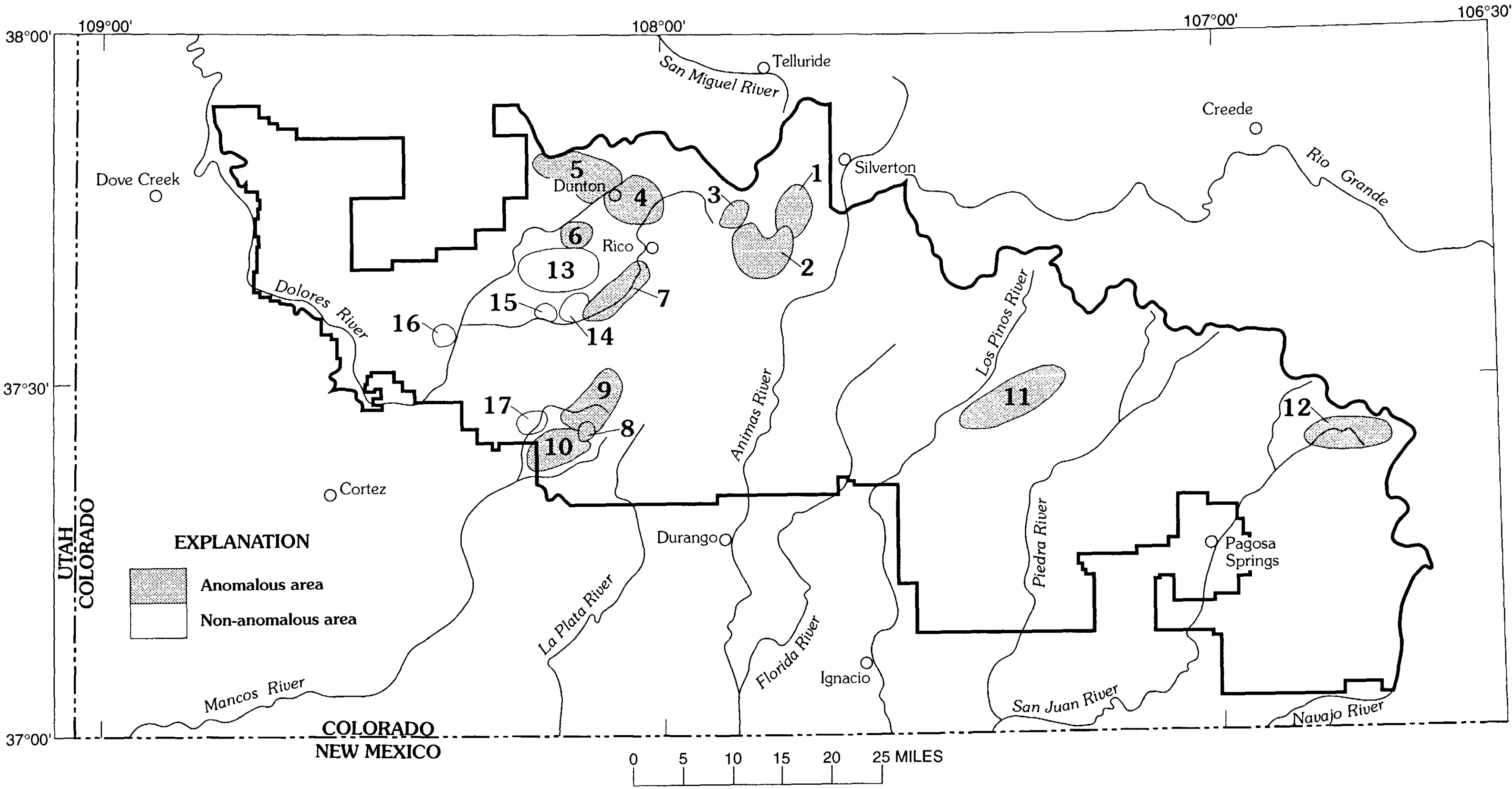


Figure 33. Map showing areas studied in USGS geochemical survey in the San Juan National Forest. Numbers key areas to discussion in text.

New geochemical surveys (Barton and others, 1992) confirmed and extended many of the anomalies described above. The locations of anomalous areas are shown on figure 33. Area 1 is anomalous in arsenic, antimony, gold, lead, and silver, and weakly anomalous in copper. Area 2 is anomalous in uranium and weakly anomalous in copper and lead. Area 3 is anomalous in arsenic, lead, molybdenum, silver, and zinc and weakly so in copper. Area 4 is anomalous in arsenic, lead, and zinc and weakly anomalous in antimony, copper, molybdenum, and silver. Area 5 is anomalous in antimony, lead, molybdenum, silver, and zinc and weakly anomalous in copper and uranium. Area 6 is anomalous in copper and silver and weakly anomalous in arsenic, lead, and zinc. Area 8 is anomalous in antimony, arsenic, copper, molybdenum, and zinc. Area 9 is anomalous in antimony, copper, molybdenum, and silver and weakly anomalous in arsenic, gold, lead, and zinc. Area 10 is anomalous in copper, molybdenum, and silver and weakly so in antimony, gold, lead, and zinc. Area 11 is anomalous in arsenic, gold, lead, and zinc and weakly anomalous in copper and molybdenum. Area 12 is anomalous in zinc and weakly anomalous in copper and molybdenum.

The USGS studies in 1991–92 also tested but failed to confirm anomalies in the NURE surveys at areas 13–17, figure 33. The lower values in the USGS survey are consistent with the paucity of prospects in these areas.

GEOCHEMICAL SIGNATURES

Multielement anomalies associated with ore deposits are more reliable for resource assessment than single-element anomalies. Geochemical signatures characteristic of the various deposit types in the Forest were determined by sampling mines and prospects, by inspecting geochemical results obtained by the U.S. Bureau of Mines for mine samples (Neubert and others, 1992), and from published studies of similar mines outside of the Forest. The geochemical signatures, described in the section, Mineral Resource Potential—Locatable Minerals, were used to interpret the geochemical database for areas favorable for certain kinds of ore deposits.

MINERAL RESOURCE POTENTIAL—LOCATABLE MINERALS

By Nora K. Foley, Richard E. Van Loenen, J. Thomas Nash, *and* Anthony B. Gibbons

ASSESSMENT OF ORE DEPOSITS

A quantitative assessment is based on the concept of a mineral deposit model, which is defined as the essential attributes of a particular group or class of mineral deposits, and a grade and tonnage model, which compares the grade or tonnage of a deposit to the cumulative proportion of deposits of a given type (Cox and Singer, 1986). The classic definition of a mineral deposit model is based on a collection of geophysical, geochemical, and geologic characteristics and is scale invariant (i.e., there is no distinction made between an occurrence and a mined ore deposit). For example, mineralized rock that fits the descriptive model of a Cu-Mo porphyry is a Cu-Mo porphyry whether the volume of mineralized rock fits in a hand sample or is the size of a world-class mine. In contrast, grade and tonnage models are constructed using mined deposits and lowest cutoff grades, and these vary based on economic factors, mining conditions (actual cutoff grades may be unknown, mining widths are not reported, exceedingly small deposits may be excluded), and geostatistical differences (whether deposits in a cluster are counted as individuals, resulting in many small entries, or as a single deposit, resulting in one large entry in a grade and tonnage model) (Cox and Singer, 1986).

When grade and tonnage models are used to estimate a number of undiscovered deposits, certain assumptions must be met (Cox and Singer, 1986). (1) All undiscovered deposits estimated must fall within the size range used in constructing the model, and whole, rather than portions of, undiscovered deposits are counted (e.g., if the model is constructed using districts, then estimates are given in number of undiscovered districts). (2) The unit size of deposit used to construct the grade and tonnage model must be known and the undiscovered deposits counted accordingly (e.g., as districts, individual deposits, all metals within a certain volume of rock, etc.). (3) In order for the estimated number of deposits to be consistent with a grade and tonnage model, approximately half the deposits estimated should have greater than the model's median tonnage or grade. The deposit size range, unit size, target areas, and median tonnage and grade values for grade and tonnage models considered in this study are taken from Cox and Singer (1986) and Bliss (1992). Some of the general descriptions and the criteria for assessing locatable mineral deposits outlined below are taken from Cox and Singer (1986).

Favorable areas for deposits are shown on plate 2, although references to the plate are not given in the following discussion.

DEPOSITS GENETICALLY RELATED TO ROCKS OF THE CRETACEOUS-TERTIARY INTRUSIVE TERRAIN

DEPOSIT TYPE Aa: STOCKWORK MOLYBDENUM DEPOSITS

In the Forest, mineralization related to stockwork molybdenum deposits occurs as: (Aa) stockwork of quartz and molybdenite associated with fluorite in granite porphyry, and (Ab) polymetallic veins, skarns, and replacement deposits adjacent to molybdenum-mineralized porphyry stock. Mineralization included in category Aa is covered by the descriptive and grade and tonnage model for Climax molybdenum deposits (no. 16 of Cox and Singer, 1986). However, this model does not include mineralization in adjacent country rocks, so these are described separately under deposit type Ab.

DESCRIPTION

Economic deposits of stockwork molybdenum are large tonnage and are bulk-mined by large open-pit or underground operations. The deposits are in or closely associated with small (<1 km^2) high-silica porphyry intrusive complexes that have multiple intrusive stages (fig. 34). Ore minerals typically occupy thin, closely spaced quartz stockwork veins but also can be in large veins or disseminated within altered rock.

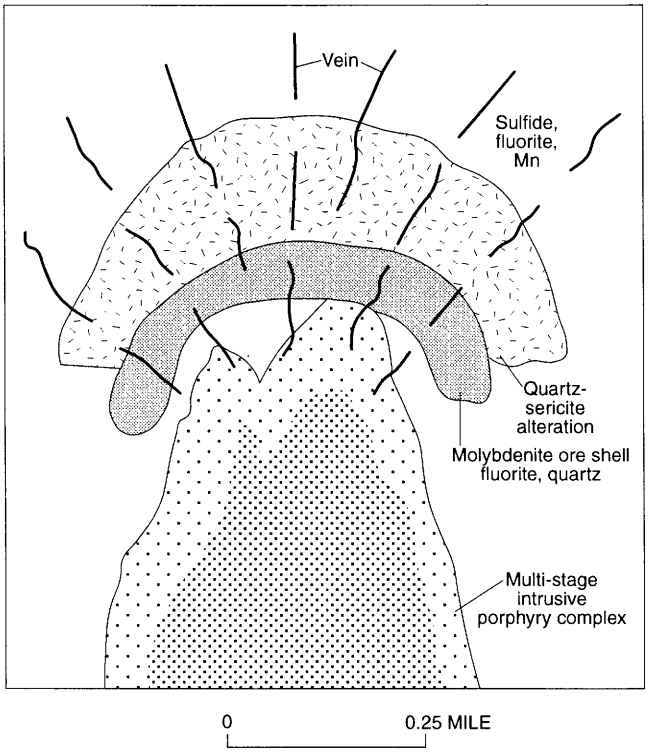


Figure 34. Schematic diagram of stockwork molybdenum deposit (deposit type Aa).

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include molybdenum and tungsten. The unique mill at Climax, Colo., had special facilities that recovered by-product minerals containing niobium, tin, tungsten, and rare earth elements.

HOST ROCKS

Host rocks are single or multi-stage porphyritic intrusions. Shallow level of emplacement creates abundant fractures and breccia structures that are filled by quartz and sulfide minerals. Very rich in F (from fluorite) and abundant quartz in veinlets and segregations.

ORE CONTROLS

Intrusions are commonly located along major high-angle faults and are located within cratons. Strong Precambrian gneisses or impermeable shales act as caprocks to confine magmatic-hydrothermal systems at Climax and Crested Butte, Colo.

AGE

In Colorado, ages range from mid to late Tertiary.

ORE GUIDES

Ore guides include intense quartz and potassic alteration and abundant fluorite; outer zones consist of argillic alteration. Argentiferous base-metal deposits may be peripheral to ore.

Geochemical signature.—Anomalous Mo, Sn, W, F, Bi, Rb, Pb, Zn, or U is in altered rocks and stream sediments; Cu is low in Climax-type deposits but is high in other varieties of molybdenite deposits.

Geophysical signature.—The geophysical signature is inconsistent. Some deposits are on the flanks of positive magnetic anomalies, suggesting larger plutons at depth. Magnetite in associated skarns can create local magnetic anomalies. Stock may be indicated by presence of gravity low. High radioelement content of pluton may be evident in aeroradiometric survey.

ASSESSMENT CRITERIA

1. Limiting criteria for descriptive model 16 (Cox and Singer, 1986) include: (a) situated in province rich in the element and having known deposits of this type, (b) presence of felsic hypabyssal plutons; siliceous and multi-stage intrusions are especially favorable, (c) presence of broad potassic-argillic alteration zones; weathering of pyrite may create broad zones of red iron-oxide minerals, (d) anomalous Mo, Sn, W, F, Bi, Rb, Pb, Zn, or U in rock or stream-sediment samples, (e) anomalous U in aeroradiometric survey.
2. Limiting criteria for grade and tonnage model 16 (Cox and Singer, 1986) include: (a) only whole districts were considered, (b) skarn deposits in adjacent country rock are not included in estimates (see deposit type Ab), (c) median tonnage = 200 million tons; median Mo grade = 0.19 percent Mo.

DISCUSSION

No deposits have been mined for molybdenum in the Forest, but several molybdenum prospects are known. World-class molybdenum deposits occur 30–60 mi to the east, northeast, and southeast at Climax and Crested Butte, Colo., and Questa, N. Mex.

Exploration for molybdenum was very active in the 1960's and 1970's, resulting in several discoveries in Tertiary intrusive complexes. Three targets west of Silverton (Anvil Mountain, Sultan Mountain stock (Moly Mountain), and Horseshoe Bend (Chattanooga); Aa1, Aa2, Aa3, fig. 35; see also fig. 19) were studied in detail (T. Glizean, student, and G. Brimhall, University of California, Berkeley, written commun., 1987), and several holes were drilled into each, disclosing felsic intrusions and alteration generally similar to that at Climax. Molybdenite-bearing veinlets were found, but grades at all three areas were subeconomic in these initial drill holes. The volcanic complex and alteration at Red Mountain No. 2 (see fig. 19) is similar to that at Climax but appears to be evidence for a buried porphyry copper deposit, considered later.

A small quartz porphyry stock at Quartz Creek (Crater Lake and Quartz Creek district; Aa4, fig. 35; see also fig. 23) is altered to quartz-pyrite at the surface, and a few drill holes about 1,000 ft deep encountered intense silicification and molybdenite veins at depth. The upper quartz-sericite-pyrite alteration zone contains anomalous amounts of gold and may be a porphyry gold prospect (Rytuba and Cox, 1991).

An intensely altered intrusive complex in the Needle Mountains mining district at Chicago Basin (Aa5, fig. 35; see also fig. 21) was investigated by Schmitt and Raymond (1977) and by several mining companies, and five drill holes (totaling 17,060 ft) were drilled. Five intrusive phases, a large breccia pipe, and two zones of molybdenum mineralization were found, a small one near the surface and a larger one >3,000 ft deep. The deep Mo target had many alteration and geochemical features of Climax type, but grades were consistently less than 0.1 percent MoS_2. A final report summarizing results from the 1975–79 investigations (Climax Molybdenum Co., unpub. report, 1979) concluded:

> The complex and repeated intrusive activity at Chicago Basin produced two distinct hydrothermal systems, both of which generated 100 to 200 million tons of 0.0X percent MoS_2. Though the intrusions were of sufficient size, neither * * * porphyry evolved a hydrothermal system that was strong enough to produce an economic deposit of molybdenite.

Difficult access and Wilderness land status were cited as nongeologic reasons for their decision to drop this prospect. We consider this deposit to be sufficiently tested to show that it does not meet the minimum grade standards for the Climax-type model. To the east of Chicago Basin, in the Vallecito Basin area (fig. 21), a "star-shaped pattern of Mo-bearing veins" and other features indicative of a possible buried stock at depth (T. Steven, oral commun., 1992) suggest a possible undiscovered Mo-porphyry deposit. Classic Mo-porphyry deposits generally do not have Mo signatures in adjacent country rocks; this may indicate that Mo was not deposited early in the intrusive history and argues against development of a large tonnage of ore. The deposit may not fit the existing model. The area has not been drilled to any appreciable depth.

Similar exploration beneath the Rico mining district (Aa6, fig. 35; see also fig. 17) by the Anaconda Co. in 1978–83 discovered a molybdenite deposit containing approximately 44 million tons of rock with an average grade of 0.31 percent Mo, plus indicated resources of more than 150 million tons (Cameron and others, 1986). The depth of greater than 3,900 ft makes this deposit uneconomic at 1992 prices for Mo. The deposit is geochemically similar to Climax but occurs in Proterozoic crystalline rock above a postulated 5-Ma intrusion. We consider this to be a discovered resource and will not consider it further. Altered intrusive rocks west of Rico, in the Horse Creek and Calico Peak area, considered to be prospective for molybdenite, will be considered later as targets for porphyry copper deposits.

ECONOMIC SIGNIFICANCE

Intensive exploration for molybdenum in the 1970's led to the discovery of many new deposits and prospects in the Western United States. Changes in milling technology in the past decade have increased recovery of molybdenum as a by-product from world porphyry copper deposits; in 1985, this amounted to 45 percent of world production of Mo. Depending upon price and demand scenarios, known reserves of molybdenum should be adequate for about 40 to 65 years (U.S. Bureau of Mines, 1987).

Decreased consumption has caused an excess of supply at this time (1992); many mines and drilled prospects are on standby status. Geologic and mining conditions in the Forest appear to be less favorable for molybdenum than in many other districts in the Western United States.

ASSESSMENT

The areas favorable (Aa1–Aa6) for model 16 (Cox and Singer, 1986) Climax-type molybdenum deposits are shown in table 2 by the mean number of deposits, the mean tonnage of Mo, and the total tonnage estimated using a computer program called MARK3. The program calculated a combined deposit tonnage of 18 million tons of rock containing a mean tonnage of 31,000 tons of (elemental) Mo metal that remains within the quantifiable areas (fig. 35) of the intrusive and volcanic rock tracts.

DEPOSIT TYPE Ab: POLYMETALLIC VEINS, SKARNS, AND REPLACEMENTS ADJACENT TO MOLYBDENUM-MINERALIZED PORPHYRY STOCKS

DESCRIPTION

Sphalerite, galena, chalcopyrite, tetrahedrite, and other sulfides, with gold and silver are deposited in veins in a gangue of quartz, pyrite, rhodochrosite, and fluorite. Veins occupy newly formed or reactivated old fractures caused by

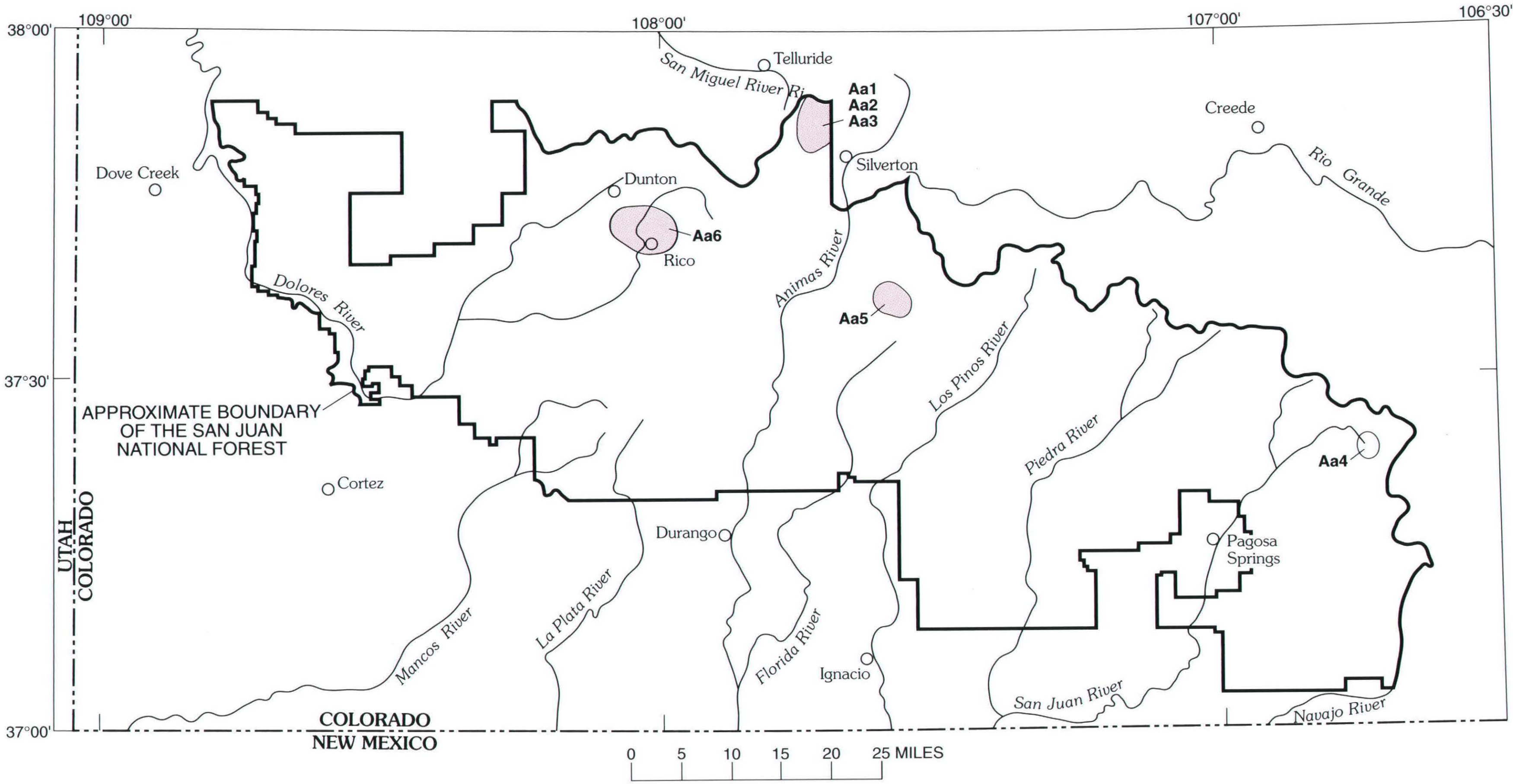


Figure 35. Map showing areas favorable for stockwork molybdenum deposits (deposit type Aa) in the San Juan National Forest.

the emplacement of the Chicago Basin stock. The stock may also be the source of the metals (fig. 34). The deposits are in Proterozoic rock in the Needle Mountains district, and they are spatially related to the vein uranium deposits (type E) that are present (Collier, 1985).

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include silver, gold, zinc, lead, and copper.

HOST ROCKS

Veins are hosted in fractures in Proterozoic metamorphic and igneous rocks.

ORE CONTROLS

Veins are deposited within through-going fractures in the country rock that follow regional joint trends, fractures that radiate from the stock, and those that are concentrated around it. Most are steeply dipping or vertical, and they tend to pinch and swell.

AGE

The age of these deposits is late Tertiary (about 10 Ma).

ORE GUIDES

Supergene enrichment, in upper parts of veins where exposed to oxidizing conditions, provide some of the richest ores. Argillic alteration is common, and veins have silicified central cores formed of late-stage quartz.

Geochemical signature.—The geochemical signature consits of anomalous Ag, As, Au, Ba, Bi, Cd, Mn, Sb, Sn, and W in addition to abundant Cu, Pb, Zn, and F in restricted areas.

Geophysical signature.—Veins are probably not detectable, but related stocks may be within a gravity low.

ASSESSMENT CRITERIA

Criteria used to identify deposit type Ab include the presence of: (a) terrane situated in metallogenic province known to contain this type of deposit, (b) a felsic hypabyssal pluton, (c) altered and fractured rock, (d) anomalous concentrations of base and precious metals.

DISCUSSION

Polymetallic veins are widely scattered throughout the Needle Mountains mining district (fig. 21), and many have been explored or mined since the late 1800's. There are no identified resources in veins of this type in the district (Neubert and others, 1992). Most of the early production came from oxidized ores near the surface that were enriched in silver and gold. Based on the presence of metal-bearing veins, the Chicago Basin stock, large areas of fractured rock, and major fault zones, the area shown on figure 36 is favorable for undiscovered polymetallic veins of this type. This area includes Proterozoic-age Eolus and Trimble Granites and the Twilight Gneiss. There is a concentration of veins in Vallecito Basin in addition to those veins around the Chicago Basin stock. A postulated intrusive body or an extension of the Chicago Basin stock beneath Vallecito Basin (see discussion above for deposit type Aa) would seemingly increase the likelihood for metal-rich veins in that area (Schmitt and Raymond, 1977; Steven and others, 1969; Collier, 1985). Molybdenum, which may have been supplied from an intrusive body below Vallecito Basin, is pervasive on fractured rock at the surface. Other metals could also have been supplied to the surface from an intrusive and therefore increased the favorability for polymetallic veins in the Vallecito Basin area. The extent of young intrusive rock beneath the favorable area is not clearly known; however, the dispersion of mineralization far from the exposed stock suggests that an intrusive system in the subsurface may be extensive.

ECONOMIC SIGNIFICANCE

Any discoveries of polymetallic vein deposits undoubtedly will result from further exploration and development of the known uranium deposits in the central part of the district (see discussion for deposit type E, vein uranium). The rugged terrain and Wilderness status of this tract preclude any near-future exploration and development.

ASSESSMENT

No descriptive or grade and tonnage model is available to quantitatively evaluate this deposit type. The area shown on figure 36 is favorable for undiscovered polymetallic veins of this type.

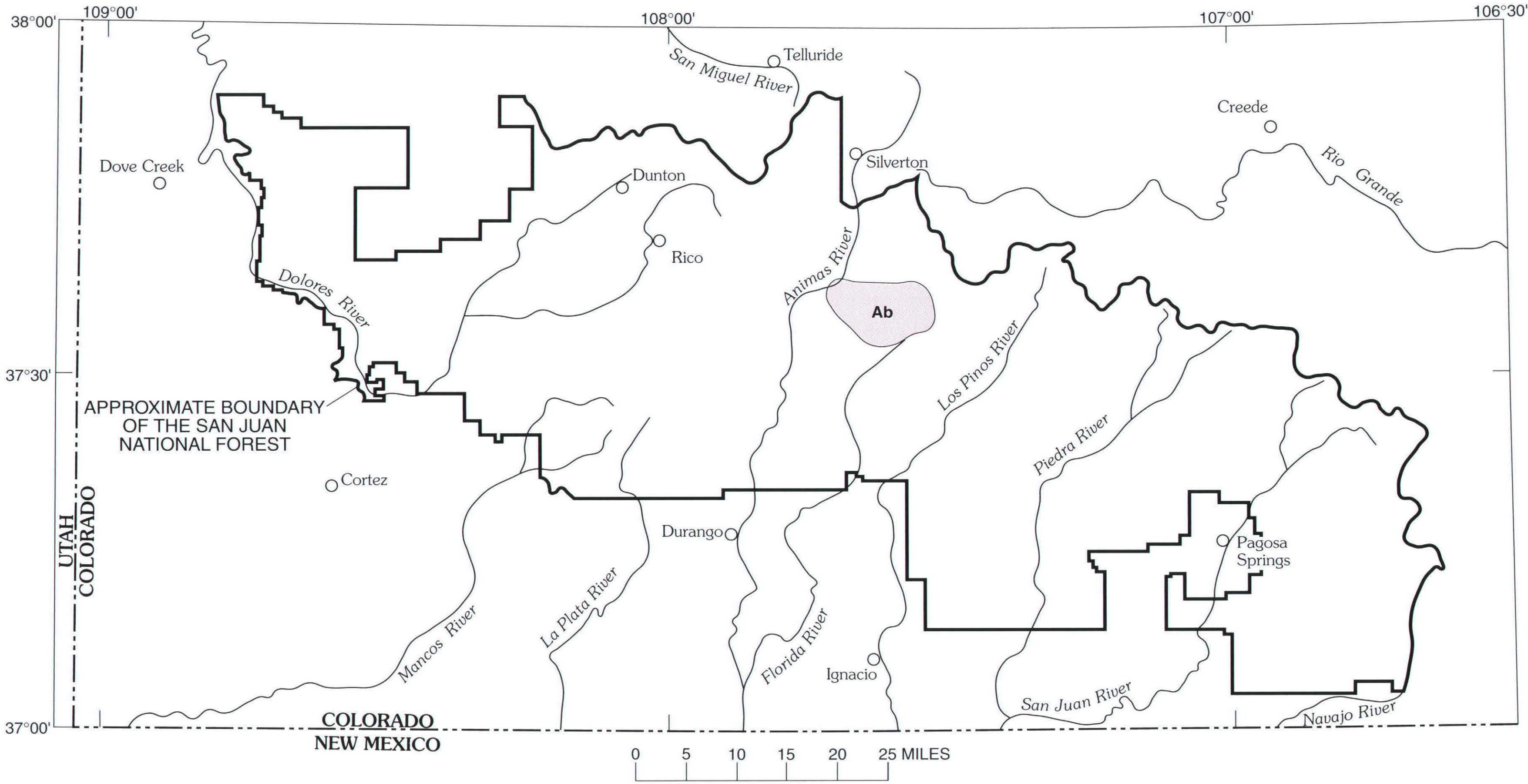


Figure 36. Map showing area favorable for polymetallic veins, skarns, and replacement deposits adjacent to Mo-mineralized porphyry stock (deposit type Ab) in the San Juan National Forest.

DEPOSIT TYPE B: PORPHYRY COPPER-MOLYBDENUM DEPOSITS

DESCRIPTION

Deposits are large (several square miles on the surface), generally bulk-minable deposits of chalcopyrite, pyrite, molybdenite, and other sulfide minerals in quartz stockwork veinlets and disseminated in potassic-altered porphyritic stock (fig. 37). Sulfide deposits may continue into adjacent metamorphosed wallrocks where they have the character of skarn deposits. Primary deposits are magmatic-hydrothermal but can be substantially modified and upgraded by supergene processes.

COMMODITIES AND BY-PRODUCTS

Commodoties and by-products include copper, molybdenum, silver, gold, and many trace constituents in sulfide concentrates.

HOST ROCKS

Host rocks are intermediate- to felsic-composition intrusive rocks with porphyritic texture. Ore-associated intrusions are generally small stocks less than 3 mi wide, but in places larger, deeper, equigranular plutons create ore. Classic deposits are associated with porphyritic stocks having coarse phenocrysts set in a microgranular matrix. Calcareous sedimentary rocks are generally most favorable for skarn-like extensions of ore. Dikes and breccia are common. Intense alteration zones are several miles wide.

AGE

These deposits may be any age, but they are mostly Mesozoic-Cenozoic in the Western United States.

ORE CONTROLS

Stocks tend to form in major fault zones of island-arc volcanic chains. Stocks are emplaced at shallow level, are highly fractured and brecciated, as are enclosing wallrocks. Peripheral faults host base-metal veins.

ORE GUIDES

The alteration systems are large and intense and are very colorful when weathered. The central core has added K-feldspar and sericite, which grades outward into sericitic and argillic types; all zones are rich in pyrite. Upper, shallow parts can have primary oxidation (alunite, anhydrite). Base-metal vein and skarn deposits, large or small, tend to form on flanks of stock.

Geochemical signature.—The geochemical signature includes Cu, Mo, Ag, Au, Pb, Zn, Fe, and K in rocks and stream-sediment samples and altered rocks rich in K, Rb, and Sr.

Geophysical signature.—The geophysical signature is inconsistent. Some deposits have a positive magnetic anomaly from magnetite in metamorphic wallrocks, but most have a low magnetic signature from sulfidation of rock-forming minerals.

ASSESSMENT CRITERIA

1. Criteria used to identify deposits that fit model 17 (Cox and Singer, 1986) (deposit type B) include presence of: (a) a metallogenic province noted for the contained metals and known economic deposits, (b) intermediate- to felsic-composition stocks and dikes having porphyritic texture (must be within Cretaceous-Tertiary igneous terrane as defined in this study (fig. 13)), (c) highly fractured or brecciated rocks with quartz and sulfide minerals in fractures, (d) wide spread potassic-argillic alteration with abundant pyrite (or colorful iron-oxide minerals in weathering zone), (e) anomalous Cu, Mo, Ag, Pb, Zn, Bi, W in stream-sediment samples; presence of these elements and K, Rb, or Sr in altered rock samples, (f) polymetallic vein, replacement, or skarn deposits peripheral to stock.
2. Limiting criteria for grade and tonnage model 17 (Cox and Singer, 1986) include: (a) Only whole districts were considered, (b) model is to be used in situations where it is not possible to use gold-rich or molybde num-rich models, (c) skarn deposits in adjacent country rock are included in estimates, (d) median tonnage = 140 million tons; median Cu grade = 0.54 percent Cu.

DISCUSSION

No copper has been produced from porphyry copper deposits in the Forest or other parts of Colorado, but several subeconomic prospects have been located in the State. One

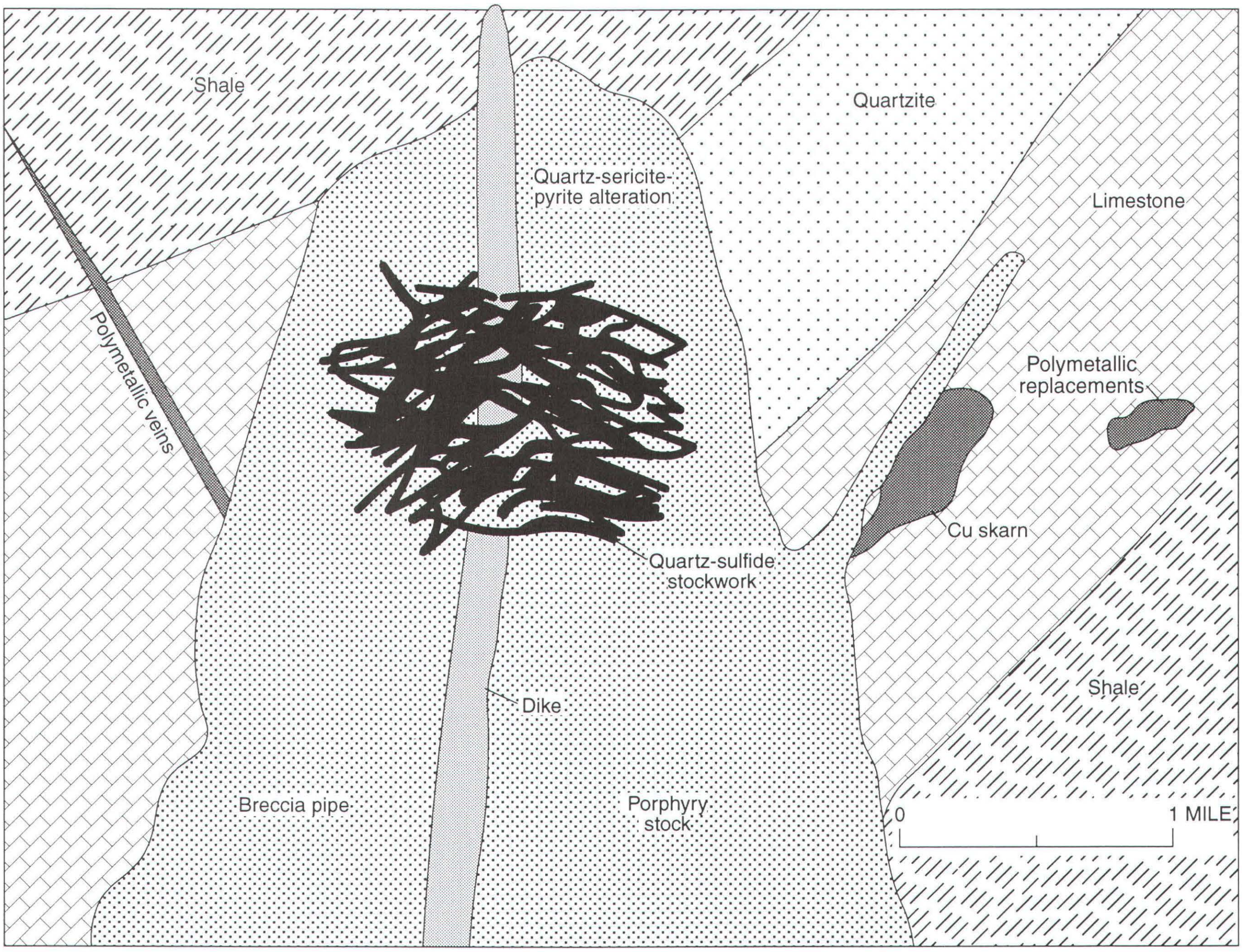


Figure 37. Schematic diagram of porphyry copper-molybdenum deposit (deposit type B).

of the first to be recognized was the vein and disseminated chalcopyrite in the Allard stock, La Plata district (B1, fig. 38, see also fig. 22; Eckel, 1949; Werle and others, 1984). The potassic-altered syenitic stock and copper minerals are well exposed, and, when weathered, they create a large area of brightly colored rocks and iron-oxide-coated stream gravels (a natural analog to acid mine drainage). The area was explored by the USGS and USBM during World War II, chiefly for associated Pt-Pd (Eckel, 1949), and drilled repeatedly by industry during the last 25 years. Assays of drill core typically are in the range of 0.3 to 0.5 percent Cu, less than 1 ppm Au, and less than 20 ppb (parts per billion) Pt and Pd across intervals of 500–1,000 ft (Neubert and others, 1992). The USBM calculated an "open-pittable inferred resource of 200 million tons grading 0.4 percent Cu, 60 ppb Au, 7 ppm Ag, and 5 ppb platinum group metals" (Neubert and others, 1992, p. 146). These results are consistent for the worldwide trend of alkalic porphyry systems to have more gold than those in the Southwest. Alkalic porphyry systems also tend to be smaller in size and lower in grade. There is sufficient drilling of the Allard stock to place that copper deposit in the measured category.

A quartz monzonite phase of the Wilson Peak stock contains a large zone of disseminated and vein-filling chalcopyrite (B2, fig. 38). The stock and copper deposit have many of the features of classic porphyry copper deposits but lack well-developed phyllic alteration and molybdenum; associated veins are rich in gold rather than base metals. From available information (excellent outcrops but no drilling), this prospect does not fit the grade and tonnage model of worldwide Cu porphyry deposits or a North American subset; the exposed deposit may be the deep part of an eroded porphyry system.

Several "red mountains" in the Forest comprise altered rocks above possible porphyry systems, several thousand feet below the surface. Bright-red to yellow iron-oxide minerals develop by weathering of disseminated pyrite emplaced as a halo above a deeper hydrothermal system. Depth to a possible ore deposit is difficult to estimate from geology and geochemistry and generally is

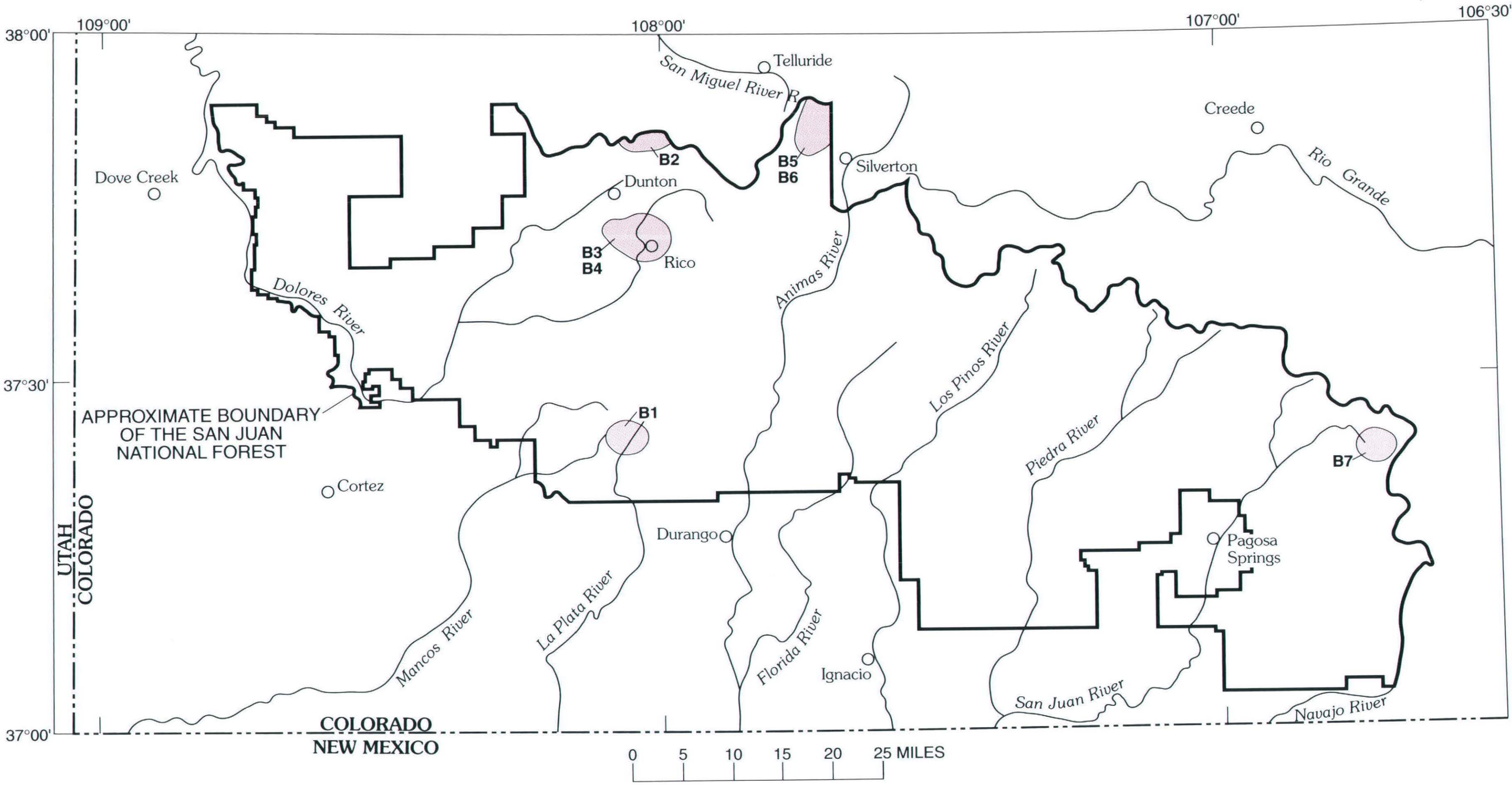


Figure 38. Map showing areas favorable for porphyry copper-molybdenum deposits (deposit type B) in the San Juan National Forest.

based on analogies to known deposits elsewhere. Calico Peak, west of Rico (B3, fig. 38; see also fig. 17), is a quartz porphyry stock intensely altered to alunite-silica-pyrite, similar to the subvolcanic complex at Summitville. Veins rich in gold and enargite were mined at the Johnny Bull (no. 25 on fig. 17) and other mines on the north margin of the stock (Ransome, 1901); these enargite-bearing veins are similar to those adjacent to one variety of porphyry copper deposit in El Salvador, Chile (Gustavson and Hunt, 1975). The stock at Calico Peak has a very interesting alteration system that could have associated copper or other kinds of deposits; however, we lack sufficient information to discuss it beyond the conceptual stage (see further discussion below).

East of Calico Peak, in the Horse Creek area (B4, fig. 38, and fig. 17), small areas of altered latite porphyry stock are exposed among large blocks of landslide material (Pratt and others, 1969). Small mines and prospects, not famous in comparison to the Rico mining area, are actually quite numerous considering the complications caused by landslides. The prospects contain a geochemical suite that includes Cu-Mo-Bi, and some dumps contain calc-silicate skarn assemblages with base-metal sulfide minerals. These geochemical features are suggestive of a deep base-metal target. This possible porphyry system could be related to either Miocene(?) plutonism or the young (5 Ma) geothermal event that affected a large area around Rico (Cunningham and others, 1977).

Large areas of red alteration near Red Mountain Pass, and especially on Red Mountain No. 3 (B5, fig. 38, and fig. 19), have been the subject of much exploration and speculation for the past 25 years. Most geologists agree that the exposed red rocks are high-level sericite-pyrite alteration and that any porphyry system must be at considerable depth. Breccia pipes containing rich base and precious metals occurring in mines in the area of Red Mountain Pass could have been explosive, high-level parts of a deeper system. This large system lies astride the Forest boundary, and the possible mineral deposit and potential mine infrastructure could well be in the San Juan National Forest.

Anvil Mountain, a red mountain northwest of Silverton (B6, fig. 38, and fig. 19), has been rumored to be prospective for copper; however, exposed intrusive rocks, their alteration style, and results from drilling are consistent with a Climax-type molybdenum system rather than a porphyry copper system (T. Casadevall, oral commun., 1992).

The Crater Creek area (B7, fig. 38, and fig. 23) may contain a buried porphyry copper system (Brock and Gaskill, 1985). Evidence includes zoned alteration patterns, abundant fractures, presence of small altered stocks, and coincident gravity and magnetic anomalies. A 1,000-ft drill hole near the Lady Bug mine (no. 2, fig. 23) encountered hundreds of feet of intense alunite alteration (similar to that at Summitville); Pb, Mo, and Mn increase down the hole, whereas Cu decreases and F is consistently high (Neubert and others, 1992, p. 216). None of these features is definitive, but the general situation may be similar to deeper parts of the Summitville district, only 5 mi to the east. An intrusion, with intense phyllic alteration and abundant pyrite, was encountered more than 2,500 ft below the gold mine at Summitville (Enders and Coolbaugh, 1987), but it does not show at the surface. Copper grades are not given, but the rock types and alteration assemblage indicate a "porphyry copper-type environment."

ECONOMIC SIGNIFICANCE

In the past decade, world copper production has been dominated by large bulk-minable porphyry deposits or others having substantial co-products such as Co or Ag; in 1985, 60 percent of the world's copper came from open-pit mines (U.S. Bureau of Mines, 1987). In 1985, reserves in countries with free-market economies amounted to about 349 million tons copper, chiefly in porphyry-type deposits—depending upon price and consumption scenarios, this is approximately a 60- to 80-year supply. More than 40 percent of this reserve is in explored or idle, nonproducing mines. The United States, with about 16 percent of free-market reserves, is second only to Chile.

The available information for possible deposits in the Forest, chiefly from outcrops and limited drilling, suggests that the stocks lack some the key petrologic features and alteration and fracture intensity known at mined deposits elsewhere. The possible deposits in the Forest do not appear to meet or exceed the geologic and engineering attributes of idle or drilled-out porphyry copper deposits in the Western United States.

ASSESSMENT

The areas favorable for model 17 (Cox and Singer, 1986) porphyry Cu districts are shown in table 2 by the mean number of deposits, the mean tonnages of each metal, and the total tonnages estimated using MARK3. The program scalculated that a mean value of 16 million tons of mineralized rock of this deposit type remain in the Forest—this includes mean tonnages of 120,000 tons of Cu, 0.9 tons of Au, 16 tons of Ag, and 2,900 tons of Mo.

DEPOSIT TYPE C: POLYMETALLIC REPLACEMENT AND SKARN DEPOSITS

DESCRIPTION

Hydrothermal deposits consist of Ag, Pb, Zn, and Cu sulfide minerals in bedded deposits (mantos), pipe-shaped bodies, and associated veins in limestone, dolostone, or other soluble strata that are replaced by ore and alteration minerals. Skarn deposits form by processes similar to those in replacement deposits but at higher temperature. Igneous intrusions generally are known to occur within about 0.5 mi. Vein or pipe structures serve as feeders and also may contain ore (fig. 39). At district scale, deposits tend to show mineralogical and compositional zonation from central Cu-Au (± Bi), to Pb-Ag, and outer Zn-Mn, and tend to grade into skarn-type deposits closer to source plutons. Examples include the Tintic and Park City districts, Utah; Rico district and Idarado mine, Colorado.

COMMODITIES

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

HOST ROCKS

Host rocks are limestone, dolostone, evaporite (gypsum), and interbedded shale and sandstone or quartzite; skarns most commonly occur in calcareous, contact-metamorphosed rocks. Ore-associated dikes and stocks tend to have porphyritic texture and felsic to intermediate composition.

ORE CONTROLS

Host strata are generally folded and faulted along former geosynclines. High- and low-angle (bedding plane) faults may be important controls. Zones of secondary porosity or breccia produced by hydrothermal leaching may be favored by high-grade ores. The structurally lowest carbonate strata tend to be favored for ore formation by ascending fluids.

AGE

Host rocks are commonly Paleozoic but can be any age; ore-associated intrusions are commonly Tertiary.

ORE GUIDES

Ore guides include silicification or dolomitization of limestone, with widespread pyrite or barite. Outer zones display jasperoid and manganese oxides along faults. Productive igneous rocks are argillized or chloritized. Vein deposits in nonreactive volcanic or sedimentary rocks can grade into replacement-type deposits in underlying carbonate strata. Skarns are characterized by calc-silicate minerals, such as garnet and diopside.

Geochemical signature.—Anomalous Cu, Pb, Zn, W, Ag, Au, Bi, Sb, Mn, Ba, Fe, or Mg is present in altered rock and stream-sediment samples.

Geophysical signature.—A geophysical signature is probably not evident in regional-scale surveys. Skarn deposits may contain magnetite and produce a positive magnetic anomaly. Ground electromagnetic surveys are useful but generally not available for regional assessments.

ASSESSMENT CRITERIA

1. Criteria used to identify polymetallic replacement deposits model 19a (Cox and Singer, 1986) (deposit type C) include presence of: (a) a province noted for base metals and having known base-metal ore deposits, (b) carbonate strata or evaporites; must be in carbonate terrane (fig. 11) as defined in this report, (c) vein-type polymetallic base-metal deposits (deposit type Ab), (d) porphyritic dikes and stocks, known or suspected porphyry deposits (types Aa, B), (e) jasperoid or calc-silicate alteration of carbonate rocks or argillic-propylitic alteration of igneous rocks; development of Mn-oxide minerals or barite along veins, (f) anomalous Cu, Pb, Zn, W, Ag, Au, As, Sb, Bi, Ba, Mn, Fe, or Mg in altered rocks or stream-sediment samples.
2. Limiting criteria for grade and tonnage model 19a (Cox and Singer, 1986) include: (a) only districts with combined production and reserves of greater than 100,000 tons were used, (b) median deposit size: tonnage = 1.8 million tons, grades = 5.2 percent Pb, 3.9 percent Zn, (c) model 19c is based on resources for a district, not an individual deposit; thus, the discussion below is directed chiefly at possibilities for an undiscovered cluster of deposits in an area of roughly 5 mi^2, similar in size to the Rico mining district.

DISCUSSION

Near-surface parts of the Forest having favorable host rocks are presumed to have been thoroughly prospected because prospectors understood this deposit type very well from experience at mining camps such as Rico and Leadville (~120 mi northeast of the Forest, fig. 1). Undiscovered deposits are likely, however, in areas of poor exposure, cover by alluvium or landslides (as at Rico), or at depths of several hundred feet. Very little

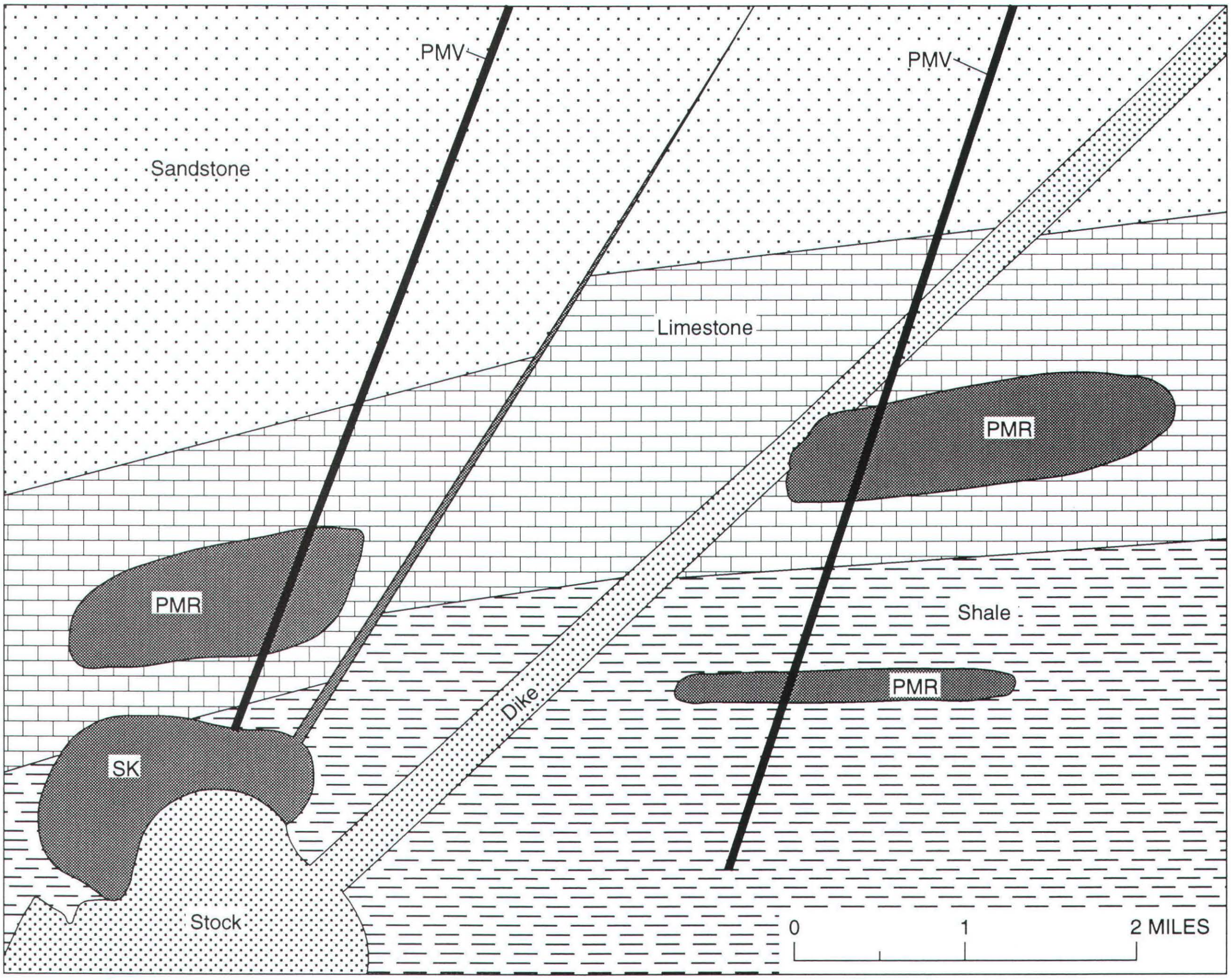


Figure 39. Schematic diagram of polymetallic replacement and skarn deposits in Paleozoic carbonate terrane (deposit type C). PMV, polymetallic vein; PMR, polymetallic replacement; SK, skarn.

exploration drilling for these deposits has been done outside of established mines.

The northern part of the Forest, west of Silverton (C1, fig. 40), contains intrusive rocks and carbonate rocks and Telluride Conglomerate (lower Eocene) that are known to be favorable host rocks at Rico and in the Idarado mine (no. 6 on fig. 19). Promising targets include calcareous strata (such as Lower Mississippian Leadville Limestone and Upper and Middle Pennsylvanian Hermosa Group) below known vein deposits (as in the Idarado mine) and especially in the vicinity of Tertiary stocks emplaced along the ring fracture zone of the Silverton caldera—these strata are about 3,000–4,000 ft below the elevation of Red Mountain Pass. Epithermal base-metal vein deposits near the surface in Tertiary volcanic rocks are an indication that base-metal-rich fluids passed through the favorable host rocks as they moved upward along structures. Deep drilling from within the Idarado mine (Mayor and Fisher, 1993) tested about 3,000 ft of Paleozoic strata and uppermost Proterozoic rocks, intersecting Pb-Zn-Cu mineralized calc-silicate skarn in calcareous rocks. The holes did not encounter the Tertiary intrusion that produced the high-temperature alteration and mineralization. Skarn-type deposits were mined at the Bandara mine and are exposed adjacent to the Sultan Mountain stock in Copper Creek (C1, fig. 40, and fig. 19). These same carbonate host rocks continue southwest toward Rico. A large area between Silverton and Rico, underlain by carbonate terrane and intrusive rocks, could contain polymetallic deposits similar to those in the Rico or La Plata districts. However, there is little positive evidence in the way of alteration or vein deposits at the surface.

Carbonate terrain surrounding Rico (C2, fig. 40) could possibly host replacement or skarn deposits, but they would be more than 3,000 ft below the surface. Vein deposits at Dunton (C3, fig. 40) and vein deposits marginal to the Rico district could indicate polymetallic deposits in deeper carbonate strata. Potential host rocks in the Mt. Wilson district would be more than a mile deep and are not evaluated.

Polymetallic replacement deposits have been suspected below the La Plata district (C4, fig. 40; Eckel, 1949), but only a few holes have been drilled to explore the likely intersections of mineralized structures with the Hermosa Group (the most favorable ore host at Rico) or deeper limestones. Similar deep targets exist in Paleozoic limestones below productive strata at Rico. A strong argument for these undiscovered deposits is the rule of thumb in other districts in the Rocky Mountains (i.e., East Tintic) that the best ore occurs in the lowest carbonate formations (Shepard and others, 1966). This is consistent with the concept that rising hydrothermal fluids form ore in the first carbonate formation encountered.

ECONOMIC SIGNIFICANCE

These deposits tend to be relatively small but rich. They generally have higher combined metal grades than other deposit types, and, if substantial amounts of gold or silver are present, they can be very valuable in a small volume. The bed-selective character of the ores generally requires small-scale underground mining, which in recent years has not been able to compete with bulk mining methods. A mill is required for making sulfide concentrates; in the past, small mines could use a mill at a large mine (such as at Silverton) to avoid the capital expenses and permitting required for a new one. Although these deposits are rich targets and historically have been suited for small-scale mining, engineering and investment aspects appear to be less favorable than for other deposit types.

The Cave Basin mineral area is listed by Davis and Streufert (1990) as containing Au-Ag-telluride vein deposits with unknown host rocks. Neubert and others (1992) list it as having low potential for "replacement/vein" deposits of Ag, Cu, Pb, and Zn. Steven and others (1969, p. F113) describe it as a replacement-type deposit in lower Paleozoic sandy limestone that produced Cu, Pb, Ag, and trace of Au.

There is no evidence in the literature or MRDS for economically significant W in skarn deposits of the Forest. Bismuth is remarkably high at Rico and also at the Idarado mine, where it was identified by USGS geochemists—this led to higher smelter payments and greater profits to the mine owners.

ASSESSMENT

The total values for model 19a (Cox and Singer, 1986) polymetallic replacement deposits are shown in table 2 by the mean number of deposits, the mean tonnages of each metal, and the total tonnages estimated using MARK3. The program calculated that a mean value of 2.9 million tons of mineralized rock of this deposit type remain in the Forest—this includes mean tonnages of 6,600 tons of Cu, 2.1 tons of Au, 160,000 tons of Zn, 560 tons of Ag, and 150,000 tons of Pb.

DEPOSIT TYPE D: Au-Ag-Te REPLACEMENT VEINS AND SKARNS

DESCRIPTION

This deposit type consists of gold, silver, telluride minerals, and fluorite in quartz veins and breccia bodies associated with hypabyssal or extrusive alkalic rocks. The deposits also contain Cu, Pb, and Zn. Veins that tend to be irregular and discontinuous occupy open space within fractures, fissures, and breccia zones in the igneous rock and its host. Telluride minerals containing Au and Ag formed late in the paragenetic sequence of a mineralizing system. Deposits tend to be small and "pockety" with extreme ranges in grade. Replacement deposits may form where veins intersect a favorable limestone host (fig. 41). Pyrite and other sulfides are generally sparse in rich deposits. Alkali feldspars, carbonate and sulfate minerals, roscoelite (vanadium-bearing mica) and fluorite are common gangue minerals. Related intrusive rock ranges from syenite to diorite with porphyritic to nonporphyritic textures. Examples included in descriptive and grade and tonnage model 22b (Cox and Singer, 1986) are: La Plata, Gold Hill, and Cripple Creek, Colorado; Zortman-Landusky, Montana; Kirkland Lake, Ontario, Canada (J.D. Bliss, written commun., 1991).

COMMODITIES AND BY-PRODUCTS

Commodoties and by-products include gold, silver, copper, lead, and zinc.

HOST ROCKS

Host rocks are syenite, monzonite, or diorite; or shoshonites. Host rocks may also include any rock susceptible to fracturing adjacent to intrusive complex.

ORE CONTROLS

Fracturing of country rock results, at least in part, from the emplacement of intrusive bodies. Contact metamorphic aureoles associated with intrusive rocks further enhances the ability to fracture the country rock. Subsidence structures

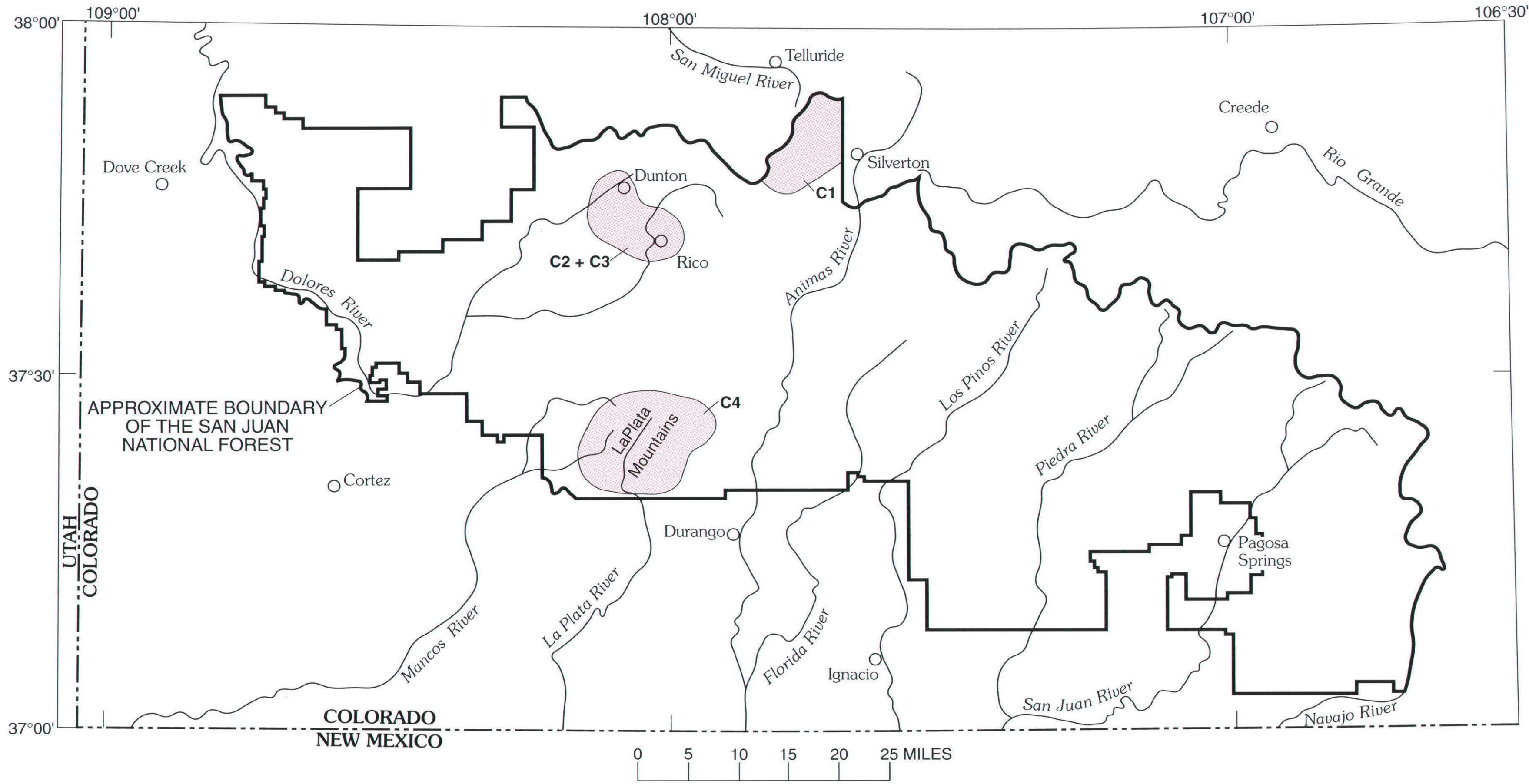


Figure 40. Map showing areas favorable for polymetallic replacement and skarn deposits (deposit type C) in the San Juan National Forest.

and volcanic breccias are important ore controls in extrusive terranes.

AGE

Mineralization is mainly Cretaceous and Tertiary but could be of any age. Country rocks may be any age.

ORE GUIDES

Ore deposits are surrounded by a thin envelope of altered wallrock. Intense silicification within the vein grades out into a thin argillic zone and into an intense zone of propylitic alteration.

Geochemical signature.—The geochemical signature consits of Au, Ag, Te, Cu, Pb, Zn, Sb, Hg, F, Ba, and possible platinum-group elements (PGE).

Geophysical signature.—On a regional scale, magnetic lows may develop over large areas of rock alteration associated with veins, but detailed ground surveys are required to identify individual veins.

ASSESSMENT CRITERIA

1. Criteria for Au-Ag-Te veins, based on descriptive model 22b (Cox and Singer, 1986), include the presence of: (a) terrane situated in metallogenic province known to contain this type of gold deposit, (b) hypabyssal igneous rock of alkaline composition, (c) faulted and fractured rock, (d) altered rock and stream sediments containing anomalous amounts of Au, Ag, Te, Cu, Pb, Zn, Sb, Hg, F, Ba.
2. Limiting criteria for grade and tonnage model 22b (Cox and Singer, 1986) include: (a) Localities included in model 22b are of a district scale. Mining properties with a spacing of 1 mi or less are treated as parts of the same district. With respect to La Plata, the PGE mineralization of Allard stock (fig. 22) was included as part of the entire district for statistical exercises; however, the authors note that many studies suggest that it may represent a separate mineralizing event (J.D. Bliss, written commun., 1991). (b) Preliminary regional target areas for model 22b are: 27 to 2,300 hectares, with a median value of 250 hectares; median tonnage = 2 million tons, median grade = 6.6 g/ton Au (Bliss and others, 1992).

DISCUSSION

Gold-silver-telluride veins of this type have been mined in the Forest from one principal area, the La Plata district northwest of Durango. Based on the presence of many significant deposits, this district is favorable for additional ore lenses of Au-Ag-Te veins and related replacement deposits. The principal vein deposits in the La Plata district (fig. 22) are localized in three areas (south, northeast, and northwest around the central core of the deeply eroded dome), although veins are found in virtually all igneous and sedimentary country rocks in the district. The most important hosts to veins are the Cutler, Entrada, and Wanakah (Pony Express Member) Formations, and the Junction Creek Sandstone and diorite-monzonite porphyry.

Veins occur as far as 8 mi east of the center of the district following west-northwest-trending fractures that probably intercept the core of the La Plata district. Thus, the area favorable for additional Au-Ag-Te veins includes both the La Plata district and numerous favorable fractures in the surrounding area (fig. 42). Although untested, the underlying Hermosa Group would seemingly be favorable for polymetallic replacement deposits (see deposit type C, above). Limestone beds in the Hermosa Group are the principal host for mineralization at Rico, and these beds are present 1,000–2,000 ft below the La Plata district. The Hermosa Group is more than 2,000 ft thick, with limestones interbedded in its lower two-thirds (Eckel, 1949).

ECONOMIC SIGNIFICANCE

Compared to the past, most gold-bearing veins mined individually and underground are considered economically unimportant. Today, gold can be mined from large, open-pit, low-grade, disseminated deposits. Low-grade Au deposits were first identified in the early 1960's as a potential source of gold, and, by the mid-1980's, many such deposits were being mined. The small tonnages of ore taken mainly from underground workings on veins in the Forest cannot compete with the large open-pit operations. Small-scale underground operations will probably continue to exploit extensions of veins and perhaps new discoveries will be made, but it is unlikely they would support a large profitable operation with on-site milling capabilities. There are no milling services presently available in the region. Large open-pit mines in the environmentally sensitive and rough mountainous terrains at La Plata seem unlikely. Fine mineral specimens, which normally command a far superior price than smelted gold, are known from the La Plata district. Specimen-quality Au-Ag-Te minerals were encountered

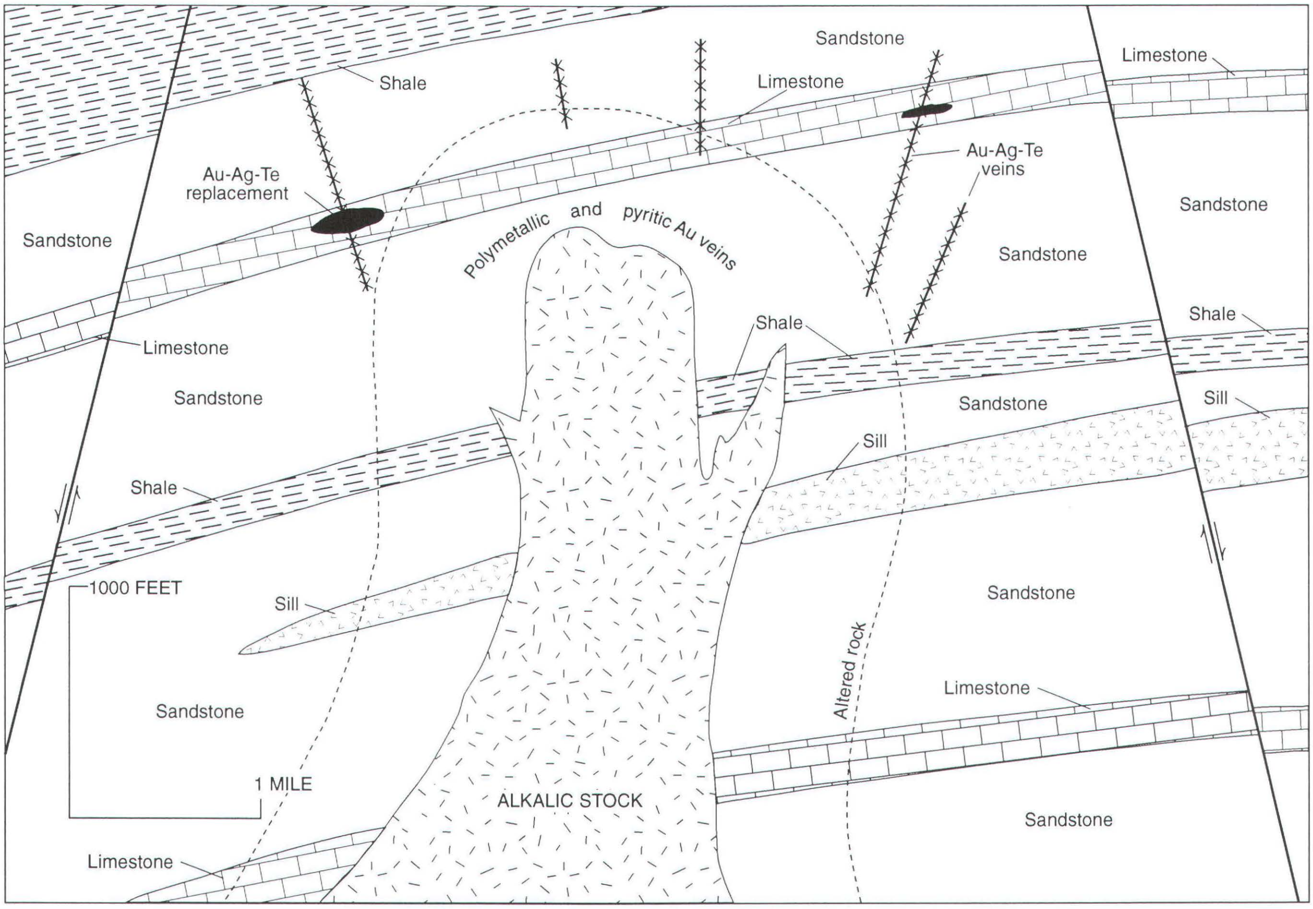


Figure 41. Schematic diagram of Au-Ag-Te replacement veins and skarns (deposit type D) in the La Plata district.

recently in the Bessie G mine (Neubert and others, 1992, p. 209).

ASSESSMENT

No additional target areas for entire districts of deposit type D, model 22b (Cox and Singer, 1986)—the size and extent and grades of the La Plata district—can be delineated within the Forest today, based on the unique geologic setting and existing geologic data. Areas within and adjacent to the established boundaries of the La Plata district have some potential for additional smaller ore lenses and veins of this type.

Within the La Plata district, the syenite of Allard stock (fig. 22) may be considered separately as an alkalic-syenitic porphyry Au-Cu deposit when appropriate descriptive and grade and tonnage models are available (M. Zientek, written commun., 1992). The area is well prospected and was drilled during World War II and in the 1970's. Chalcopyrite (averaging approximately 5 percent Cu) is pervasive in the syenite, which also contains K, Th, V, a few ppb PGE, and fluorine (F. Murchen, USBM, written commun., 1992).

DEPOSIT TYPE E: VEIN URANIUM RELATED TO 1.4-Ga AND 10-Ma GRANITES INTRUDING PROTEROZOIC ROCKS

DESCRIPTION

This deposit type consists of small uranium deposits in veins and fractures in granitic rock. Uranium is derived from the more felsic parts of multistage intrusive rock (the Trimble Granite). Hydrothermal alteration concentrated uranium along fractures in the highly differentiated granite, which has exceptionally high uranium content (15 ppm). Hypabyssal intrusive activity (Chicago Basin stock at less than 10 Ma) supplied heat for hydrothermal systems and structurally prepared the older granitic host for the convection system that leached uranium from granite and deposited it in veins (Collier, 1985).

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include uranium, gold, and silver.

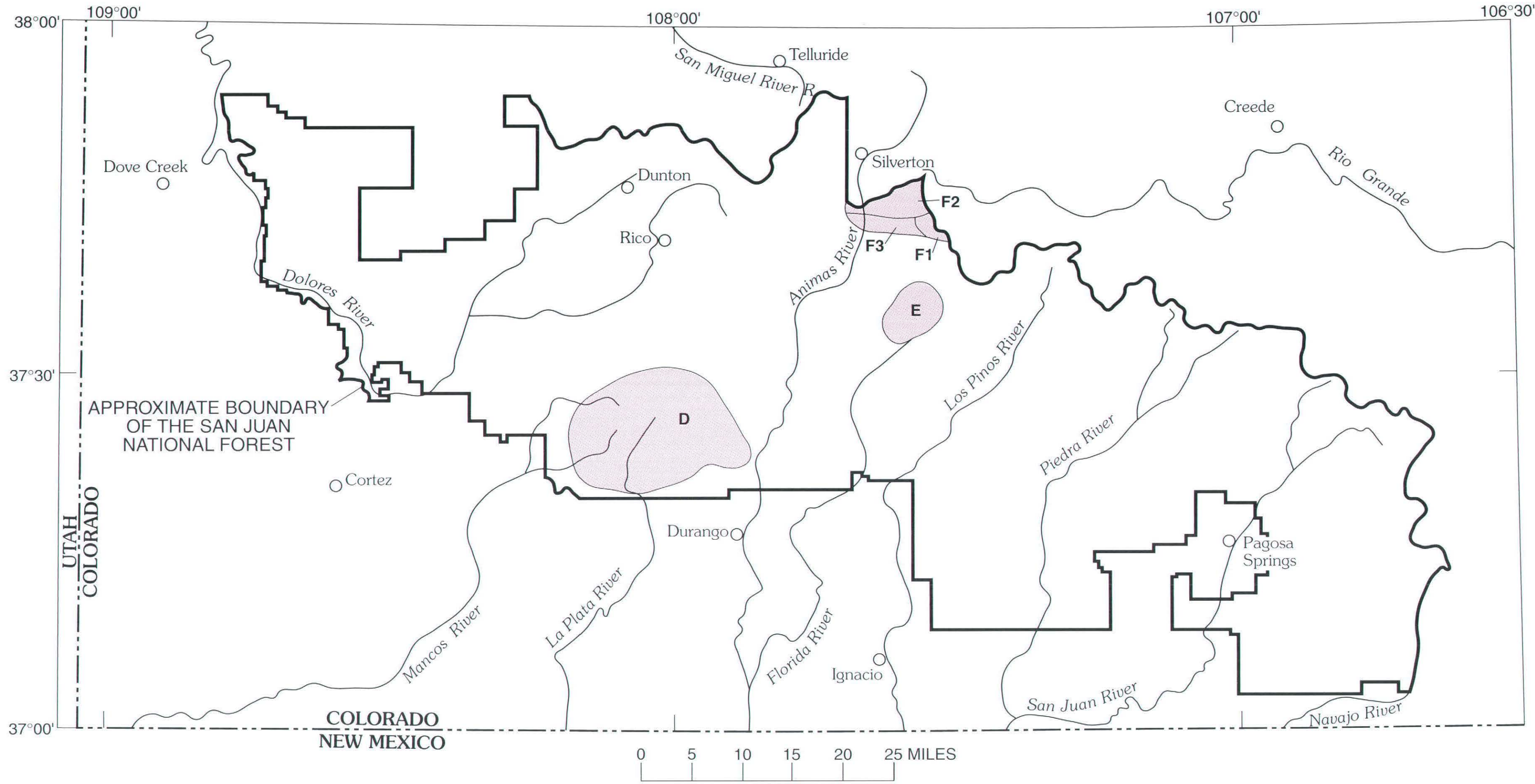


Figure 42. Map showing areas favorable for deposit types D, E, and F in the San Juan National Forest. D, Au-Ag-Te replacement veins and skarns in La Plata district; E, vein uranium related to 1.4-Ga and 10-Ma granites in the Needle Mountains district; F, volcanic-related epithermal vein deposits hosted by Proterozoic rock; F1, epithermal Au-Ag-Te deposits in Beartown district; F2, polymetallic epithermal veins in Whitehead Gulch area; F3, epithermal uranium vein deposits in Elk Park area.

HOST ROCKS

Biotitic granite is both the source of uranium and host to the vein deposits.

ORE CONTROLS

Fault zones with extensive brecciation of granitic host rock provide sites for mineral deposits. Structures probably originated in Precambrian time but were rejuvenated during Laramide time and again during a late Tertiary intrusive event (Steven and others, 1969).

AGE

Age of uranium mineralization is less than 10 Ma, and host rock is Precambrian (approximately 1.4 Ga; Tweto, 1987) Trimble and Eolus Granites.

ORE GUIDES

Fractured and brecciated granite is characterized by argillic alteration that grades into propylitic and chloritic alteration. The veins contain a central core of resistant silicified rock containing pyrite, termed breccia reefs, that stand above the altered vein material.

Geochemical signature.—The geochemical signature includes F, Ba, Th, and U in rocks and stream sediments and radioactivity in unaltered granites.

Geophysical signature.—Gravity and aeromagnetics may identify granite bodies but probably not fault zones. Airborne gamma-ray spectrometer surveys may indicate anomalous surface radioactivity (Theis and others, 1981).

ASSESSMENT CRITERIA

Limiting criteria for uranium veins includes presence of: (a) granitic body that is anomalous in uranium, (b) highly fractured and brecciated granitic rock, (c) breccia reefs, (d) altered rock along zones of fracturing, and (e) uranium minerals, fluorite and barite.

DISCUSSION

Intragranite deposits of uranium occur in the Florida Mountain area (fig. 21) of the Needle Mountains. Public Service Company of Oklahoma did extensive drilling to evaluate the uranium potential of several major structures in this area. The Bullion and Trimble faults and the Cornucopia vein (fig. 21) were primary targets for drilling. Collectively, these veins comprise a medium-sized deposit estimated to contain between 3,000 and 10,000 tons of U_3O_8 (Collier, 1985). No production has taken place. Collier (1985) gives evidence that the main body of Trimble Granite is the most promising of the granites to host vein uranium. Uranium occurs as much as 2 mi away on Thunder Mountain in pods of Trimble Granite within the Eolus Granite (fig. 21). Also see the discussion of Needle Mountains mining district.

ECONOMIC SIGNIFICANCE

Due to the very low demand for uranium, vein-type deposits are of little economic importance. Although these deposits might contain high-grade ore, they are low tonnage and cannot compete with the very large sandstone-hosted uranium deposits (deposit type I). All of the favorable granite terrane is in very rugged, mountainous terrain in the Weminuche Wilderness, which is closed to mining at the present time.

ASSESSMENT

No appropriate descriptive and grade and tonnage models are available for this deposit at this time. The mode and occurrence of the deposit type are relatively rare in the United States (Collier, 1985, p. 2). The Trimble Granite and adjacent areas a few miles into the Eolus Granite are considered favorable (E, fig. 42) in addition to the known deposits.

DEPOSITS RELATED TO ROCKS OF THE VOLCANIC TERRANE

DEPOSIT TYPE F: VOLCANIC-RELATED EPITHERMAL VEIN DEPOSITS HOSTED BY PROTEROZOIC ROCKS

DEPOSIT TYPE F1: EPITHERMAL Au-Ag-Te VEIN DEPOSITS HOSTED BY PROTEROZOIC ROCK

Au-Ag-Te deposits are one of the three distinct types of volcanic-related epithermal vein deposits that are hosted by Proterozoic metasedimentary rocks and gneisses within the Forest (fig. 42). The other two, to be discussed separately, are F2 (polymetallic vein deposits) and F3 (uranium vein deposits).

DESCRIPTION

This deposit type consists of epithermal Au-Ag-Te-bearing quartz veins occupying open space within fractures, fissures, and breccia zones in Proterozoic metamorphic rocks. They may be deposited distal to their source due, in part, to transport of metal-bearing fluids away from the source in through-going fractures.

COMMODITIES AND BY-PRODUCTS

Commodoties and by-products include gold, silver, copper, lead, and zinc.

HOST ROCKS

Within the Forest, Proterozoic quartzite, slate, and gneiss or any rock susceptible to fracturing may be host. Host-rock composition and lithology does not appear to influence mineralization.

ORE CONTROLS

Ore deposition is controlled by fracturing of country rock. Subsidence structures and volcanic breccias are important ore controls in extrusive terranes.

AGE

Known mineralization is Tertiary but could be of any age. Host rocks can be any age.

ORE GUIDES

Ore guides include presence of limonite-stained veins and gangue minerals including barite, calcite, and clay minerals and an absence of fluorite.

Geochemical signature.—The geochemical signature includes Au, Ag, Te, Cu, Pb, Zn, Sb, Hg, and Ba.

Geophysical signature.—On a regional scale, magnetic lows may develop over large areas of rock alteration associated with veins, but detailed ground surveys are required to identify individual veins.

ASSESSMENT CRITERIA

Criteria used to identify terrane favorable for epithermal Au-Ag-Te vein deposits include: (a) terrain situated in metallogenic province known to contain this type of vein, (b) faulted and fractured Proterozoic rock adjacent to hydrothermally altered volcanic sequence, (c) slightly altered rock and stream sediments containing anomalous amounts of Au, Ag, Te, Cu, Pb, Zn, Sb, Hg, and Ba.

DISCUSSION

Au-Ag-Te veins of this type have been mined near the Forest in the Beartown mining district (fig. 20), southeast of Silverton. The Beartown district is mostly outside the Forest; however, several veins are within the boundary (see fig. 20). Unlike the veins in the La Plata district, the veins in the Beartown district are hosted by Proterozoic metasediments, and no known intrusive bodies are exposed. The veins are hosted in north-trending fractures within the district, and little evidence was found in the Proterozoic terrane to extend the area of favorability (F1, fig. 42) into the Forest much beyond the Beartown district.

ECONOMIC SIGNIFICANCE

Most gold-bearing veins mined individually and underground are considered economically unimportant today, as compared to the past. The small tonnages of ore, mainly taken from underground workings on veins, cannot compete with large open-pit operations. Small-scale underground operations will probably continue to exploit extensions of veins, and perhaps new discoveries will be made, but it is unlikely they would support a large profitable operation with on-site milling capabilities. There are no milling services presently available in the region. Large open-pit mines in the environmentally sensitive and rugged mountainous terrains at Beartown seem unlikely. Mineral specimens, which normally command a far higher price than smelted gold, are known from the Beartown mining district.

ASSESSMENT

The Beartown mining district (fig. 20 and F1 on fig. 42) is favorable for additional small veins in the vicinity of known deposits. The fissures are too small to contain any large bodies of ore. Bedrock is well exposed in the district, making it unlikely that the conspicuous rusty quartz veins would remain undiscovered.

DEPOSIT TYPE F2: POLYMETALLIC EPITHERMAL VEINS HOSTED BY PROTEROZOIC ROCK

DESCRIPTION

This deposit type consists of a hydrothermal deposit formed at shallow depths (generally less than a few thousand feet) at relatively low temperatures in open fractures in Proterozoic rocks. Veins are usually steeply dipping and can range in size from tiny fissures to several feet in width.

Although a fracture may continue for great distances, vein fillings along strike of the fracture are much less continuous. Grade is quite variable, and veins tend to pinch and swell in the fractures. Metals are derived, in part, from an igneous system that also supplied the heat to drive the hydrothermal system. Metals are also leached from host rocks and deposited in veins by circulating meteoric waters.

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include gold, silver, base metals, and uranium.

HOST ROCKS

Host rocks are Proterozoic metamorphic rocks or any hard and brittle rock that fractures easily.

ORE CONTROLS

Rock failure resulting from the emplacement of plutons and orogeny control the fractures that link circulating hydrothermal systems.

AGE

This deposit type is Late Cretaceous and Tertiary in age.

ORE GUIDES

Ore guides include varying degrees of wallrock alteration adjacent to veins. Altered rock may also contain metals.

Geochemical signature.—Cu, Pb, and Zn in stream sediments might suggest the presence of vein deposits, but other evidence is necessary to establish mineral potential for an area.

Geophysical signature.—Detailed magnetic surveys might indicate lows over areas of intense alteration caused by mineralization along fractures.

ASSESSMENT CRITERIA

Criteria used to identify deposit type F2 include the presence of: (a) terrane situated in metallogenic province known to contain this type of vein deposit, (b) fractured and faulted rock, (c) altered rock, (d) Proterozoic rock.

DISCUSSION

Whitehead Gulch (fig. 20) is along the highly mineralized area (F2, fig. 42) bordering the southern part of the Silverton caldera (fig. 14). Veins follow northeast- and north-trending fractures and shear zones in Proterozoic rock (primarily the Irving Formation). Some alteration is found in the overlying volcanics, but the fractures are confined to Proterozoic rock and do not extend into overlying volcanics. Old fractures, adjacent to the Silverton caldera, were locally reactivated during Tertiary volcanic activity and related mineralization (Steven and others, 1969). Galena and sphalerite are present, and some silver has been reported (Steven and others, 1969). Large deposits are unlikely as veins are small and the fracture pattern is erratic in the Whitehead Gulch (fig. 20) area.

ASSESSMENT

All of the Irving Formation and the adjoining part of the Uncompahgre Formation are permissive for veins of this type in the Whitehead Gulch area. The area is considered favorable for small polymetallic epithermal veins and deposits (F2 on fig. 42).

DEPOSIT TYPE F3: EPITHERMAL URANIUM VEIN DEPOSITS HOSTED BY PROTEROZOIC ROCK

DESCRIPTION

This deposit type consists of structurally controlled uranium-bearing veins in quartzite. Pitchblende is the primary uranium mineral. The Centennial uranium deposit at Elk Park (fig. 20) is a small deposit of this type that has had minor production.

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include uranium, copper, cobalt, lead, molybdenum, nickel, silver, and zinc.

HOST ROCKS

The Uncompahgre Formation (quartzite) is a favorable host because of its brittle nature and relative ease of fracturing.

ORE CONTROLS

Deposit formed in fractures that developed as a result of tight isoclinal folds in quartzite. Deposit is between two major faults that trend east-west through the area (fig. 20).

AGE

This deposit type formed by Late Cretaceous(?) mineralization in Proterozoic host rocks.

ORE GUIDES

Very little wallrock alteration is associated with veins. Quartzite is primarily fresh with little chlorite alteration; no hematite is present.

Geochemical signature.—The geochemical signature includes U, Ag, Co in stream sediment below the mine. Mineralized rock contains U, Cu, Mo, Sb, As, W, Co, Ag, Au, and Be. Fresh quartzite is very low in metals.

Geophysical signature.—The geophysical signature is characterized by anomalous radioactivity due to uranium.

ASSESSMENT CRITERIA

Criteria used to identify deposit type F3 include the presence of: (a) Uncompahgre quartzite, (b) tight folds and fractures in quartzite, (c) anomalous radioactivity and uranium mineralization.

DISCUSSION

The Centennial deposit at Elk Park (fig. 20) has had a small amount of uranium production. Exploration in late 1970's and early 1980's by Exxon (Scott, 1983) has identified the limits of this deposit by drilling. Although suitable structures are present in the formation, other uranium occurrences are unknown in the Uncompahgre Formation. Major structures extend both east and west from Elk Park in the Uncompahgre quartzite, but there is no evidence of mineralization to the west and none known in the quartzite along these same structures for nearly 10 mi to the east.

The source of the uranium is unknown. Uranium is ubiquitous in the slates of the Uncompahgre Formation and, as Collier (1985) has demonstrated, in the Trimble Granite, which is about 15 mi to the south of Elk Park. Nearly 100 stream sediment samples taken from drainages that cut through large sections of the Uncompahgre are generally low in metals (Steven and others, 1969). Zinc was anomalous in some, but it probably came from the slates.

ECONOMIC SIGNIFICANCE

Due to the very low demand for uranium, vein-type deposits similar to the one at Elk Park are probably of little commercial interest. Although these deposits might contain high-grade ore, it would be of such low tonnage it could not compete with the very large sandstone-hosted uranium deposits. All of the Uncompahgre Formation is in very rugged, mountainous terrain, which would make exploration and development of a mine difficult. Furthermore, except for a small area at Elk Park, the Uncompahgre quartzite is within the boundaries of the West Needle Mountain and Weminuche Wilderness Areas, which are closed to mining at the present time.

ASSESSMENT

The Uncompahgre quartzite, where broken by east-west-trending faults east of the known Centennial uranium deposit (fig. 20), is considered favorable for similar uranium deposits. Faults that localized the deposit continue easterly for nearly 10 mi to the vicinity of Beartown (fig. 20). The likelihood that deposits similar to the Centennial are present is not high because of a lack of any surface indications of mineralization across the favorable area (F3, fig. 42).

DEPOSIT TYPE G: CREEDE -TYPE EPITHERMAL VEINS IN TERTIARY VOLCANIC TERRANE

DESCRIPTION

This deposit type consists of galena, sphalerite, chalcopyrite, sulfosalts, ± tellurides, ± gold in a gangue of quartz and carbonate contained in veins that fill structures hosted by felsic to intermediate volcanics (fig. 43*B*). Older miogeosynclinal evaporites or rocks with trapped seawater are associated with these deposits.

A classic example of this type of deposit, the Creede mining district, which is within the central San Juan volcanic field northeast of the Forest (fig. 7), was used to construct the descriptive model of Creede epithermal veins—model 25b (Cox and Singer, 1986). Other deposits of this type in Colorado, used to construct the grade and tonnage model, include the Bonanza, Animas, Eureka, Ophir, Sneffels, Red Mountain, and Telluride districts (all but Bonanza are within a few tens of miles of the northern boundary of the Forest) in the San Juan volcanic field. The Animas and Red Mountain districts are partly within the Forest.

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include silver, gold, zinc, lead, and copper.

HOST ROCKS

Rocks that host the veins are andesite, dacite, quartz latite, rhyodacite, rhyolite, and associated sedimentary rocks. Mineralization may be related to calc-alkaline or bimodal volcanism.

ORE CONTROLS

Ore controls include through-going fracture systems, major normal faults, fractures related to doming, ring fracture zones, and joints associated with calderas. Other controls include underlying or nearby older continental-shelf rocks with evaporitic basins, or island arcs that are rapidly uplifted.

AGE

Deposits of this type are mainly Tertiary (most are 29 to 4 Ma).

ORE GUIDES

There may be little near-surface expression of ore. Where fissures and faults extend to the surface, alteration guides along structures are (from surface to depth): quartz ± kaolinite + montmorillonite ± zeolites ± barite ± calcite; quartz + illite; quartz + adularia ± illite; quartz + chlorite. Country rock may be bleached, forming goethite, jarosite, and alunite; supergene processes often produce higher grade deposits.

Geochemical signature.—Higher in the system, the geochemical association is Au+As+Sb+Hg; at other levels in the mineralized system, Au+Ag+Pb+Zn+Cu, Ag+Pb+Zn, and Cu+Pb+Zn are typical elemental associations. Base metal is generally higher grade in deposits with silver; W + Bi may be present.

ASSESSMENT CRITERIA

1. The limiting criteria for identifying areas that fit model 25b (Cox and Singer, 1986) include: (a) dominantly hosted by felsic volcanic rocks, (b) structural preparation of the potential site (including calderas, horsts and grabens, ring faults, doming), (c) presence of a metallic signature, (d) appropriate volume of rock; districts that fit model 25b are large (~20 mi^2 in area) and have vertical extents that range from a few hundred to a maximum of about 3,000 ft.
2. Pertinent criteria for applying grade and tonnage model 25b (Cox and Singer, 1986) include: (a) Gold grade is correlated with zinc grade. (b) Areas published as districts in the literature are the units of the grade and tonnage model; each unit includes all fracture systems developed around an intrusive center. (c) Median size = 1.4 million tons of 0.16–1.1 percent Cu, 2.5 percent Pb, 1.7 percent Zn, 130 g/ton Ag, 1.5 g/ton Au.

DISCUSSION

Silver and base-metal epithermal veins occur throughout the Forest in intermediate to felsic volcanic rocks of the Tertiary volcanic terrane (fig. 14). Because these deposits fit the descriptive and grade and tonnage models for Creede epithermal veins, model 25b (Cox and Singer, 1986), quantitative estimates are calculated.

Favorable areas identified within the permissive terrane include:

Silverton area.—This favorable area has the appropriate volcanic rocks, structural setting, and a strong metallic signature (fig. 44, G1). A maximum of one model 25b deposit (Cox and Singer, 1986) could be contained in the area given its size. The site is on the eroded western edge of the San Juan volcanic field. The area has been heavily prospected and contains a number of older small mineralized areas, mines, prospects, and occurrences with minor to moderate mining activity (Burbank and Luedke, 1968; Varnes, 1963). Mining was small scale, and much lower amounts of metal production have been reported than are typical of districts used to create model 25b. This area abuts four world-class epithermal vein mining districts, deposit type G (Telluride, Red Mountain, Eureka, and Animas), and a high potential exists for finding additional mineralized veins, fissures, and faults; however, the potential for discovering a new district equivalent in richness to the aforementioned districts is considerably lower.

Crater Lake/Quartz Creek.—This favorable area (fig. 44, G2) has the appropriate volcanic rocks and contains faults radial to the Platoro and Summitville calderas (fig. 23). Some veins with characteristic sulfide minerals occur in the area (Steven and Ratté, 1960; Lindquist, 1985). The site is approximately on the Forest boundary, and we estimate that, at most, one deposit of type 25b could be contained within the Forest. However, the area has been prospected intermittently since 1882 and drilled by several mining scompanies. It is within a few miles of the gold deposit at Summitville (deposit type H), and small mines and occurrences are known throughout the area.

Mt. Wilson.—A small amount of Tertiary volcanic rock rims the Wilson Peak stock (fig. 44, G3) (Bromfield, 1967).

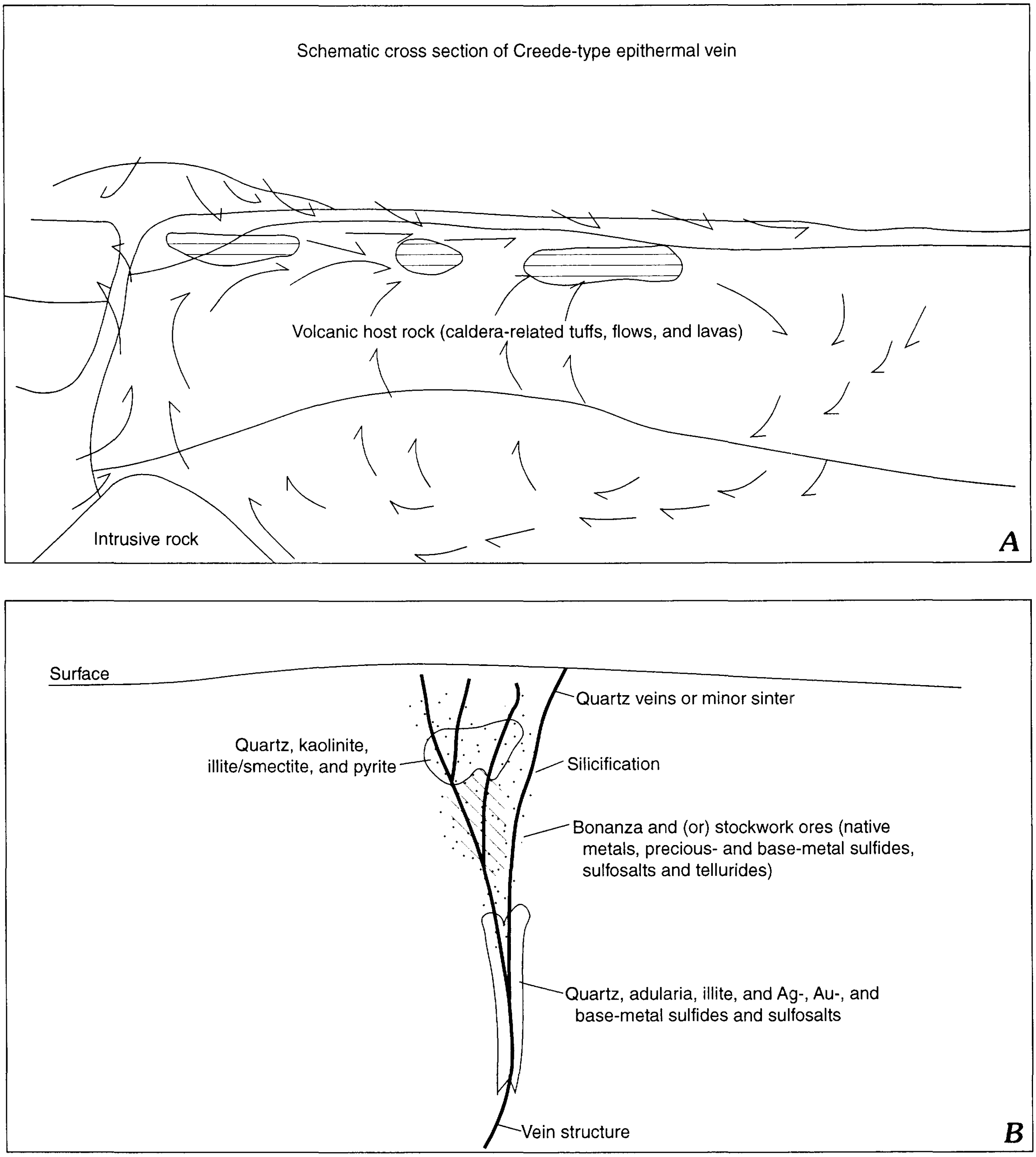


Figure 43. Schematic cross sections of Creede-type volcanic-hosted polymetallic deposit (deposit type G). *A*, geologic and structural setting; *B*, alteration and vein mineralogy. (Figure from Cox and Singer, 1986.)

The stock consists of granodiorite, granogabbro, and quartz monzonite. It is equigranular and coarse grained, contains clots of chalcopyrite (but no molybdenite), and has quartz-rich chalcopyrite, pyrite, and arsenopyrite in veins. Thus, the depth of exposure of this area is probably below that which typically hosts ores of deposit type G (Bromfield, 1967).

Piedra Peak.—This favorable area has the appropriate volcanic rocks and structural setting (fig. 44, G4) (Steven and others, 1969). It occurs on the thin, eroded, western edge of the San Juan volcanic field, on the southwestern side of the newly recognized (Lipman and Sawyer, 1988) South River caldera (fig. 14). A metallic signature is not well developed at the site (Ag = 0; Au = 0.1–0.16 ppm), although metallic anomalies do exist to the west in the area of Piedra Peak (fig. 14)—these anomalies may or may not be related. No mines or occurrences are found in the area. A maximum of two deposits of model

25b (Cox and Singer, 1986) could be contained in the area, given its size. However, the area has been prospected, and the extensively altered area has been mapped and studied. Potential for near-surface deposits appears to be almost nil; potential remains for undiscovered ores in the deeper volcanic to subvolcanic environment.

ECONOMIC SIGNIFICANCE

Although the northern boundary of the San Juan National Forest area is within a few tens of miles of six classic volcanic-hosted epithermal deposits, only a minor amount of production has come from within the Forest itself. This production is mainly from parts of the Animas and Red Mountain districts within the northern bounds of the Forest.

These districts tend to be relatively large, although individual veins and deposits are small, localized, and can be rich. The veins generally have higher combined metal grades than other deposit types, and, if substantial amounts of gold or silver are present, they can be very valuable even in a small volume. The vein-related character of the ores and spacing generally requires underground mining rather than bulk mining methods.

ASSESSMENT

The model 25b (Cox and Singer, 1986) Creede epithermal veins in the permissive tract are shown in table 2 by the mean number of deposits, the mean tonnages of each metal, and the total tonnages estimated using MARK3. The program calculated that a combined deposit tonnage of 3 million tons of rock, containing mean tonnages of 4,100 tons of Cu, 7.3 tons of Au, 63,000 tons of Zn, 810 tons of Ag, and 34,000 tons of Pb metal remain within the quantifiable areas of the Tertiary volcanic terrane.

DEPOSIT TYPE H: EPITHERMAL QUARTZ-ALUNITE GOLD DEPOSITS IN THE TERTIARY VOLCANIC TERRANE

DESCRIPTION

This deposit type consists of gold, pyrite, and enargite in vuggy veins and breccias in zones of high-alumina alteration related to felsic volcanism (fig. 45).

A classic example of this type of deposit occurs at Summitville, immediately east of the Forest (fig. 23); this deposit was used to construct the descriptive model of epithermal quartz-alunite Au (acid sulfate)—model 25e (Cox and Singer, 1986). Other deposits of this type occur at Masonic, Mohave, and Stedman districts, California; and at Goldfield, Nevada; El Indio, Chile; and Iwato, Japan.

COMMODITIES

Commodities include silver and gold.

HOST ROCKS

Volcanic hosts include dacite, quartz latite, rhyodacite, and rhyolite in hypabyssal intrusions or domes.

ORE CONTROLS

Ore controls include through-going fractures (keystone graben structures, ring fracture zones, normal faults, fractures related to doming, joint sets) and centers of intrusive activity (fig. 45). Ore may also occur in the upper and peripheral parts of porphyry copper systems and also within the volcanic edifice, in ring fracture zones of calderas, or in areas of igneous activity with sedimentary evaporites in basement.

AGE

The age of this deposit type is generally Tertiary, but it may be any age.

ORE GUIDES

Ore guides include weathering to abundant yellow limonite, jarosite, and goethite; white argillization with kaolinite; fine-grained white alunite veins; and hematite.

Geochemical signature.—Higher in system, the geochemical signature includes Au+As+Cu; base metals increase in abundance at depth. Te and, rarely, W may be present.

ASSESSMENT CRITERIA

1. Limiting criteria for identifying favorable areas within the volcanic terrane that fits model 25e include: (a) dominantly hosted by felsic volcanic and subvolcanic rocks; (b) structural preparation of the potential site (doming, small intrusions, faulting, etc.); (c) presence of a distinctive metallic signature of Au and ± enargite and intense quartz-alunite

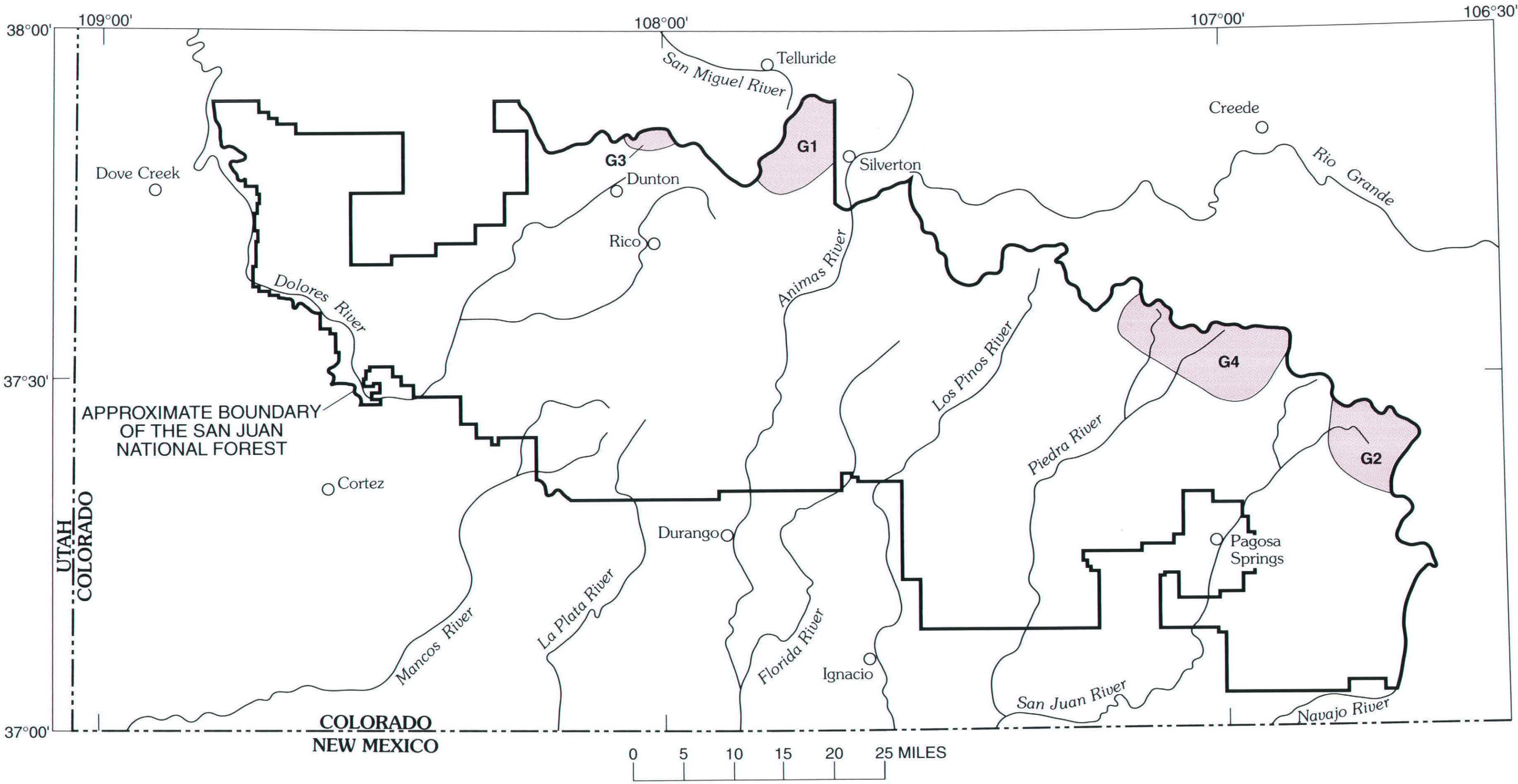


Figure 44. Map showing areas favorable for Creede-type epithermal veins hosted in Tertiary volcanic terrane (deposit type G) in the San Juan National Forest.

alteration; (d) appropriate volume of rock (districts that fit model 25e are very small; they generally are about 1 mi^2 in area; (e) these deposits generally do not cluster—all known occurrences are isolated.

2. Pertinent criteria for applying grade and tonnage model 25e include: median size = 1.6 million tons of 8.4 g/ton Au, 18 g/ton Ag, 0.05–5.0 percent Cu.

DISCUSSION

Gold-bearing epithermal veins may occur within the Forest in intermediate to felsic volcanic rocks of the Tertiary volcanic terrane (fig. 14). Because the volcanic-hosted gold vein occurrences within the Forest may fit the descriptive and grade and tonnage model for epithermal quartz-alunite Au (acid sulfate), model 25e, quantitative estimates are calculated for this deposit type.

Crater Lake/Quartz Creek.—This area (fig. 46, H1) has the appropriate volcanic host rock, structural setting, distinctive signature (Au and alunite), and the area is large enough to contain at least one district of model 25e (Steven and Ratté, 1960; Lindquist, 1985). However, the area has been prospected since the 1870's, and the Summitville district is within a few miles. The favorable area in the Forest is near the ring of the older Platoro caldera, whereas Summitville is on the ring fault of the nested Platoro-Summitville caldera complex (figs. 46, 23). Geophysical techniques were unable to limit the focus to specific sites within the favorable area. The formation mechanism of the alunite is not known.

Piedra Peak.—This area (fig. 46, H2) has the appropriate volcanic host rock, structural setting (located a few miles south and west of the South River caldera (fig. 14)), distinctive alteration signature (alunite associated with extensive surface alteration), and the area is large enough to contain at least one district (Steven and others, 1969). The geologic setting is similar to that at Summitville. The area has been extensively mapped and sampled for geochemistry; anomalies for most metals (Ag, Au, Cu) are not present. Red Mountain (fig. 14) may be an older intrusive and has only local quartz-alunite pods, indicating less extensive alteration. Piedra Peak (fig. 14) has extensive quartz-alunite alteration. The area outside of the Forest has been extensively prospected without much success. Potential for near-surface deposits appears to be almost nil; potential remains for undiscovered ores in the deeper, volcanic to subvolcanic environment.

Calico Peak (3 mi west of the Rico district).—Volcanic rocks have been eroded away in the area of Calico Peak (McKnight, 1974) in the Rico district (fig. 46, H3), but other factors indicate possible mineralization. The possible host rock consists of a Tertiary hornblende-latite porphyry and biotite-hornblende-latite porphyry dikes and plugs that contain alunitic alteration and a geochemical signature of Au, Cu, Bi and ± Mo. Free gold and enargite are present at the Johnny Bull mine (Ransome, 1901) (fig. 17), but the deposit was reportedly mined out by 1882. The area is covered with landslides, and old workings are caved, making the area difficult to examine. However, the favorable area has been heavily prospected, especially in the late 1800's, and more recently (1970–80's) as part of studies of the Rico mining district.

ECONOMIC SIGNIFICANCE

These deposits tend to be relatively small and rich. They generally have substantial amounts of gold or silver, and they can be very valuable even in a small volume. The character of the ores generally allows for large-scale bulk mining methods, although cyanide heap-leaching (the most popular of these methods) involves considerable environmental and engineering problems.

ASSESSMENT

Quantitative estimates of undiscovered resources for model 25e epithermal quartz-alunite Au veins are shown in table 2 by the mean number of deposits, the mean tonnages of each metal, and the total tonnages estimated using MARK3. The program calculated that a combined deposit tonnage of 840,000 tons of rock containing mean tonnages of 5,800 tons of Cu, 6.7 tons of Au, and 40 tons of Ag metal that remain within the quantifiable areas of the Tertiary volcanic terrane.

DEPOSITS GENETICALLY RELATED TO ROCKS OF THE PALEOZOIC CLASTIC TERRAIN

DEPOSIT TYPE I: SANDSTONE URANIUM

Uranium deposits of the Salt Wash Member of the Upper Jurassic Morrison Formation (Shawe and others, 1959; Thamm and others, 1981) are typical of the sandstone uranium deposits in the region that includes the Forest. Deposits of this type form during diagenesis in locally reduced environments in fine- to medium-grained sandstone beds. Fluvial channels and braided-stream deposits of lower parts of sea- or lake-margin sedimentary aprons are the most characteristic depositional settings for the uranium deposits.

Deposits usually occur as massive and tabular ore bodies, nearly concordant with gross sedimentary structures of the host sandstone (fig. 47). A variant is the "roll-type"

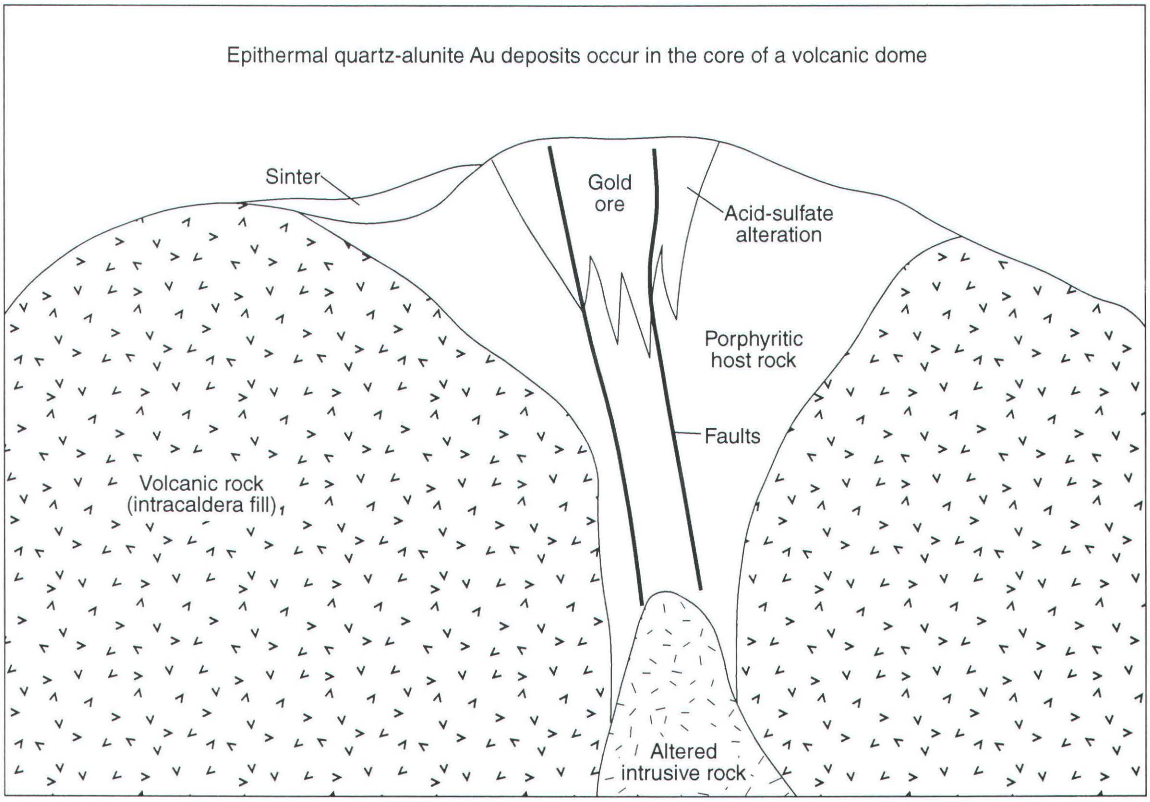


Figure 45. Schematic diagram of epithermal quartz-alunite Au deposits (deposit type H).

deposit in which the ore zone freely transgresses bedding (fig. 47, insert).

Chief uranium ore minerals are uraninite and coffinite. Vanadium minerals are montroseite, roscoelite, and vanadium clays. Principal secondary minerals, found in oxidized portions of the deposits, are the uranyl vanadates, carnotite and tyuyamunite. Ore minerals are deposited in locations where reduction rather than oxidation of uranium and vanadium has occurred. Contemporaneous felsic volcanism or eroding felsic plutons are considered to have been the source of the uranium. The source rocks for ore-related fluids are commonly overlying and underlying mudstone beds.

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include uranium, vanadium, and copper.

HOST ROCKS

Host rocks are mostly feldspathic or tuffaceous sandstone deposited in an onshore environment. In the Forest, the units that could contain types of uranium deposits related to those of the Salt Wash Member of the Morrison Formation are, besides the Salt Wash itself, the Rico and Cutler Formations, and the Moss Back Member of the Chinle Formation.

AGE

Deposits of this type range in age from late Paleozoic to early Mesozoic.

ORE CONTROLS

Structural.—The degree of structural control within the Forest is unknown. To the north, in the Slick Rock–Uravan area (fig. 16), Salt Wash deposits tend to occur on the east side of the crests of the salt anticlines (fig. 8).

Stratigraphic.—Deposits are concentrated in the lower part of the Rico Formation (Theis and others, 1981, Appendix C), the upper part of the Cutler Formation, the lower part of the Moss Back Member (Wood, 1968), and the lower part of the Salt Wash Member of the Morrison Formation.

Lithologic.—In the Salt Wash, deposits occur in fluvial sandstones near bodies of a particular "favorable" type of

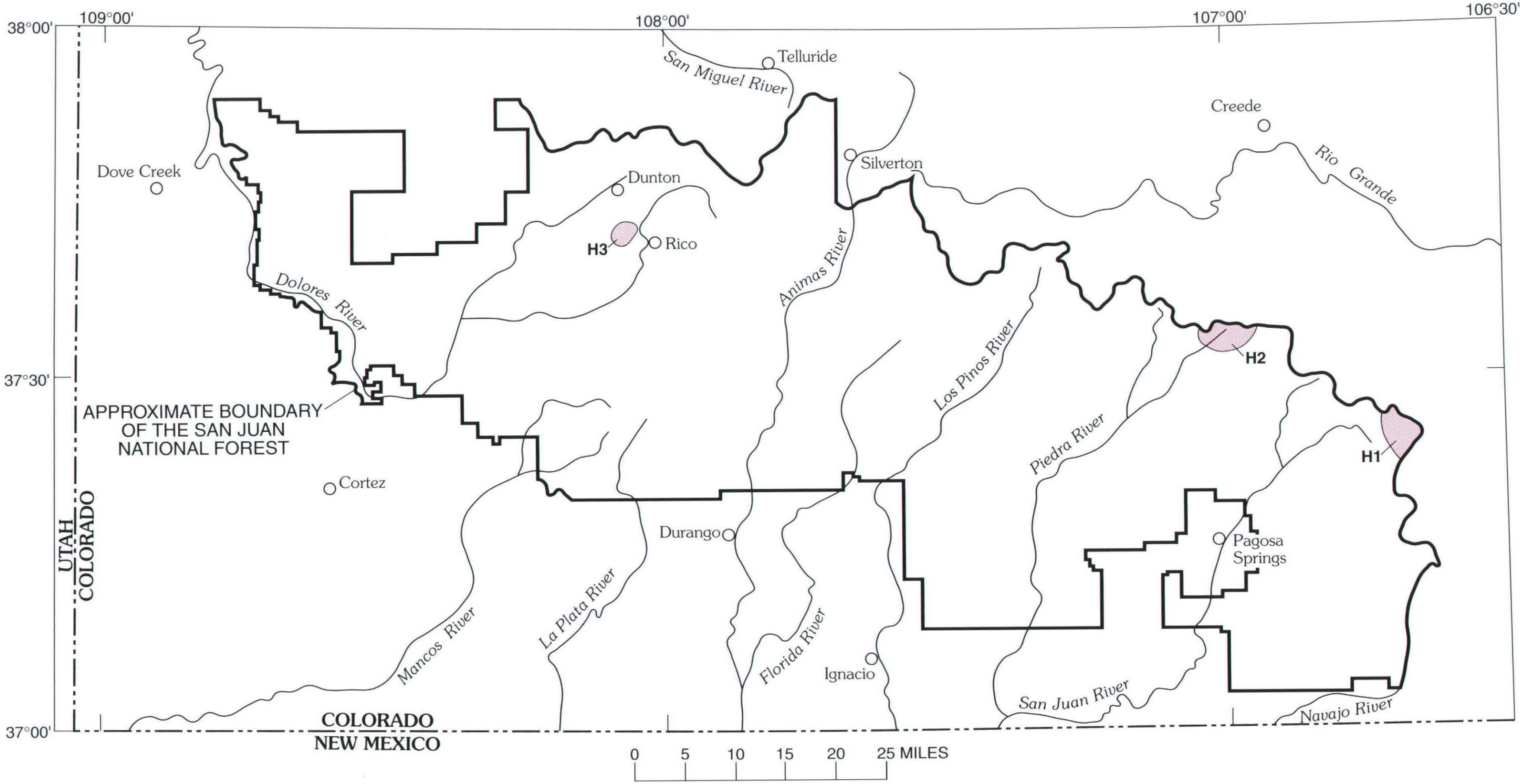


Figure 46. Map showing areas favorable for epithermal quartz-alunite Au deposits (deposit type H) in the San Juan National Forest.

gray mudstone, which is rich in swelling clays and lacks fossils of the green lacustrine alga *Botryococcus* (Campbell and others, 1982).

Depositional.—Deposits tend to occur along the distal fringe of a depositional apron where fluvial facies are mingled with lacustrine facies (Salt Wash) or marine facies (Rico and Cutler Formations).

ORE GUIDES

Geologic.—In the Salt Wash, geologic ore guides include alteration of detrital magnetite and ilmenite, presence of favorable (non-*Botryococcus*-bearing, bentonitic) gray mudstone.

Geochemical.—Geochemical ore guides include anomalous concentrations of U, V, Se, and, locally, Cu.

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

ASSESSMENT CRITERIA

Criteria used to identify favorable areas include: (a) the presence of the Rico Formation, Cutler Formation, Moss Back Member of the Chinle Formation, or Salt Wash Member of the Morrison Formation, (b) location in the distal "wet" apron facies of the sedimentary unit, (c) proximity to uranium-producing areas, (d) structural and sedimentary continuity with, or similarity to, nearby uranium-producing areas.

DISCUSSION

In general, sandstone uranium deposits related to those of the Salt Wash Member accumulate as microcrystalline oxides of uranium and vanadium. The deposits of the Cutler Formation, in which uranium and vanadium are mostly found associated with iron oxides, are the exception. In the Rico Formation and Salt Wash Member, deposit size is relatively small, with typical ore bodies a few feet thick by a few tens of feet wide by a few hundreds of feet long. Commonly, such a deposit contains a few thousand tons of ore with a grade of 0.2–0.25 percent. Deposits in the Cutler Formation are larger—as much as 3 ft thick, a hundred or more feet wide, and as much as a mile long—and are typically about 0.3 percent uranium.

The extreme northwestern corner of the Forest lies in an area inferred to be favorable for uranium deposits (I1, fig. 48) in the Salt Wash Member of the Morrison Formation by Campbell and others (1982). It is just across the Dolores River from the Spud Patch Camp mining area and a few miles south of uranium-producing areas in the vicinity of Slick Rock (fig. 16) and could be underlain by the same favorable facies of the Salt Wash Member. However, the area lies entirely outside the Uravan mineral belt, an east-arcuate tract, 2–9 mi wide, near the Colorado-Utah border that is defined by a notable concentration of uranium deposits in the Morrison Formation (fig. 48) (Butler and Fischer, 1978).

Encompassing the part of the Forest that Campbell and others (1982) inferred to be favorable for uranium deposits in the Morrison is an area of the Forest larger than shown on figure 48 (I1) that these authors inferred to be favorable for uranium deposits in the Cutler Formation. This area is about 30 mi southeast of the nearest known Cutler uranium deposits in Lisbon Valley, Utah, but offers a similar structural and facies environment. Shawe (1969) suggested the possibility of uranium deposits in the Moss Back Member of the Chinle Formation in part of tract I1.

In the area north of Durango and west of the Animas River, sandstone of the Rico Formation is host to two known uranium deposits (fig. 48, I2). The Lucky Lepracon mine (fig. 48) produced 8 tons of ore (Nelson-Moore and others, 1978, p. 205). No production is known from the Tripp Gulch mine (fig. 48).

ECONOMIC SIGNIFICANCE

Uranium deposits in sandstone have yielded most of the uranium produced in the United States and an additional large quantity of by-product vanadium. Although Colorado has produced considerable quantities of uranium from the Salt Wash deposits of the Uravan mineral belt north of the Forest, there has been no production within the Forest. The current price of uranium provides no incentive for exploration for Salt Wash-type deposits.

ASSESSMENT

Uranium deposits of Salt Wash and related types could be present in the subsurface in the northwestern part of the Forest (fig. 48, I1). However, no deposits are known to occur nor are any strongly indicated. Accordingly, this part of the Forest is judged to be only moderately favorable for such deposits.

In an area north of Durango and west of the Animas River, uranium deposits occur in sandstone of the Rico Formation (fig. 48, I2). Only two such deposits are known, and these are widely separated and have had no significant production. This area is judged to be no more than moderately favorable for sandstone uranium resources.

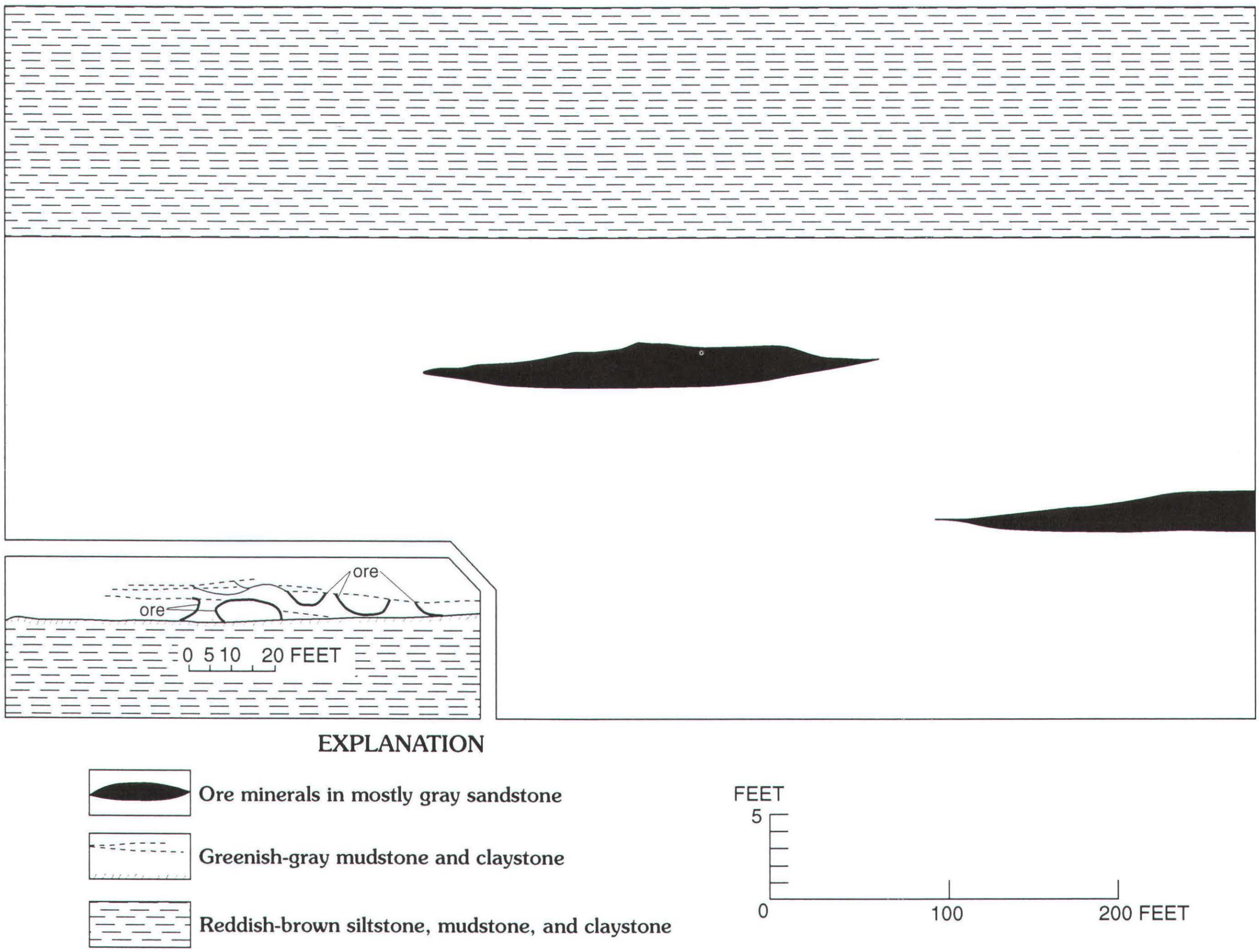


Figure 47. Diagrammatic sections of sandstone uranium deposits (deposit type I). Main figure shows near-concordant deposits in plane parallel to sedimentary trends. Insert, modified from Shawe and others (1959), is of a roll-type deposit in section taken perpendicular to sedimentary trends—and deposit elongation—in order to show maximum convolution of ore zone. Vertical exaggeration: 10× for main figure; inset, vertical and horizontal scales same.

DEPOSIT TYPE J: SANDSTONE VANADIUM-URANIUM

DESCRIPTION

Sandstone vanadium-uranium deposits of the Forest are of the type described from Placerville (fig. 1) (Fischer, 1942; Bush and others, 1959). Deposits consist of sandstone impregnated with vanadium and uranium minerals. Roscoelite, a vanadium mica, is the principal ore mineral and occurs as minute flakes coating sand grains, filling pore spaces, and where mineralization is intense, replacing silica cement and sand grains. Secondary minerals include carnotite and tyuyamunite.

Dark, fetid limestone is closely associated with deposits of this type. Sills of felsic igneous rock are associated with the deposits in the favorable area east of Rico (fig. 50, area J1) but not elsewhere.

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include vanadium and uranium.

HOST ROCKS

Host rocks are clean, fine- to medium-grained quartzose sandstone of the Middle Jurassic Entrada Sandstone.

AGE

Deposits of this type are Middle Jurassic in age.

ORE CONTROLS

Stratigraphic.—Deposits are in the upper part of the Entrada Sandstone (fig. 49).

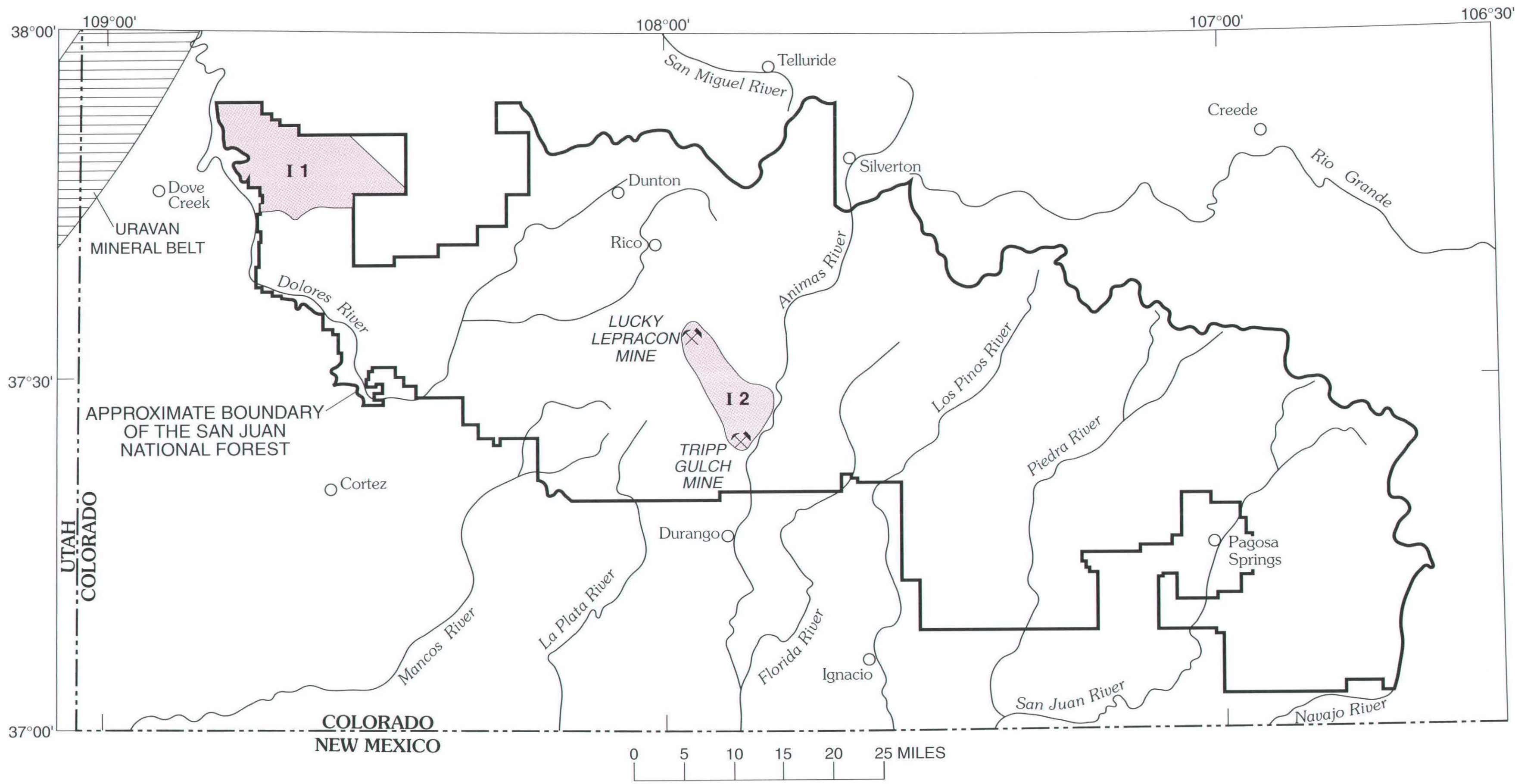


Figure 48. Map showing areas favorable for sandstone uranium deposits (deposit type I) in the San Juan National Forest.

Depositional.—Deposits occur in what may be remnants of a formerly continuous belt (Bush and Bryner, 1953) that is approximately 1.5 mi wide and trends north-south roughly along the 108th meridian (fig. 50). The belt is evidently related to the westward depositional pinchout of the Pony Express Limestone Member of the Wanakah immediately overlying the Entrada Sandstone (fig. 49). At nearest approach, the belt lies from one-quarter to one-half mile east of the limestone pinchout.

ORE GUIDES

Geologic.—Geologic guides to ore include the gray-green mineralized color of otherwise buff to white sandstone and the occurrence of deposits in nearly straight-line belts that trend approximately north-south.

Geophysical.—The geophysical guide to ore is anomalous radioactivity.

ASSESSMENT CRITERIA

Assessment criteria include (1) the presence of Entrada Sandstone and (2) a location 0.25–0.5 mi east of the westward pinchout of the Pony Express Limestone Member.

DISCUSSION

Roughly stratiform deposits occur in the upper part of the Entrada Sandstone, 0–25 ft below the contact with the overlying Pony Express Limestone Member of the Wanakah Formation (fig. 49). Deposits consist of sandstone impregnated with vanadium and uranium minerals.

The mineralized zone is mostly only a few inches thick but locally thickens into orebodies as much as 20 ft thick and a few hundred feet across that contain many thousands of tons of ore. Grade of ore was 2–3 percent V_2O_5 and 0.05–0.1 percent U_3O_8.

Dark, fetid limestone of the Pony Express Limestone Member of the Wanakah Formation, a correlative of the Todilto Limestone Member of the Wanakah of Arizona and New Mexico, is closely associated with all deposits of this type. A local association is with sills of felsic igneous rock.

Roscoelite deposits within the Forest occur in the southward extension of a continuous belt of mineralized Entrada Sandstone that parallels the pinchout of the Pony Express Limestone Member in the area of Placerville (fig. 1). Within the Forest, the belt is overlain on the north side of the Dolores River by as much as 3,500 ft of younger rocks. At the south end of the continuous belt is a tract favorable for undiscovered roscoelite deposits (fig. 50, J1). South of Rico, the mineralized belt is interrupted by outcrops of older strata, and only remnants of it are preserved.

A small area of preservation of the mineralized belt of Entrada Sandstone is indicated around the Bear Creek claims in the Cape of Good Hope district about 12 mi south of Rico (fig. 50). This area is not considered favorable for vanadium-uranium deposits.

The mineralized belt is also preserved in the Lightner Creek drainage about 8 mi northwest of Durango (fig. 50, J2). This area is known to contain a number of small vanadium-uranium roscoelite (vanadium-bearing mica) deposits. Southward from the Lightner Creek area, the host Entrada Sandstone is buried beneath younger strata.

ECONOMIC SIGNIFICANCE

At present, vanadium is extracted profitably only from rich deposits or as a by-product of other commodities such as iron, phosphorus, or uranium. Uranium, present only as a by-product in these deposits, is currently in little demand.

ASSESSMENT

Area J1 of figure 50, at the south end of the continuous belt of mineralized Entrada that extends down from the northern boundary of the map, includes the Graysill, Barlow Creek, and Spanish King mines (fig. 50). It has high potential for vanadium and uranium in additional roscoelite deposits. The small area around the Bear Creek claims south of Rico is poorly known but is considered to have low potential for roscoelite deposits. The southernmost area of occurrence of roscoelite deposits around the Lightner Creek mine (fig. 50, J2) has moderate resource potential.

DEPOSITS RELATED TO THE QUATERNARY SURFICIAL TERRANE

DEPOSIT TYPE K: PLACER GOLD

DESCRIPTION

This deposit type consists of a mechanical concentration of gold particles by natural processes in a fluvial environment. Products of weathering of gold-bearing rock are deposited along with free gold in selected parts of placer gravels. Gravels, when used in describing placers, can be any size from silt to boulders.

COMMODITIES AND BY-PRODUCTS

Commodities and by-products include gold and silver. Gold usually contains some silver.

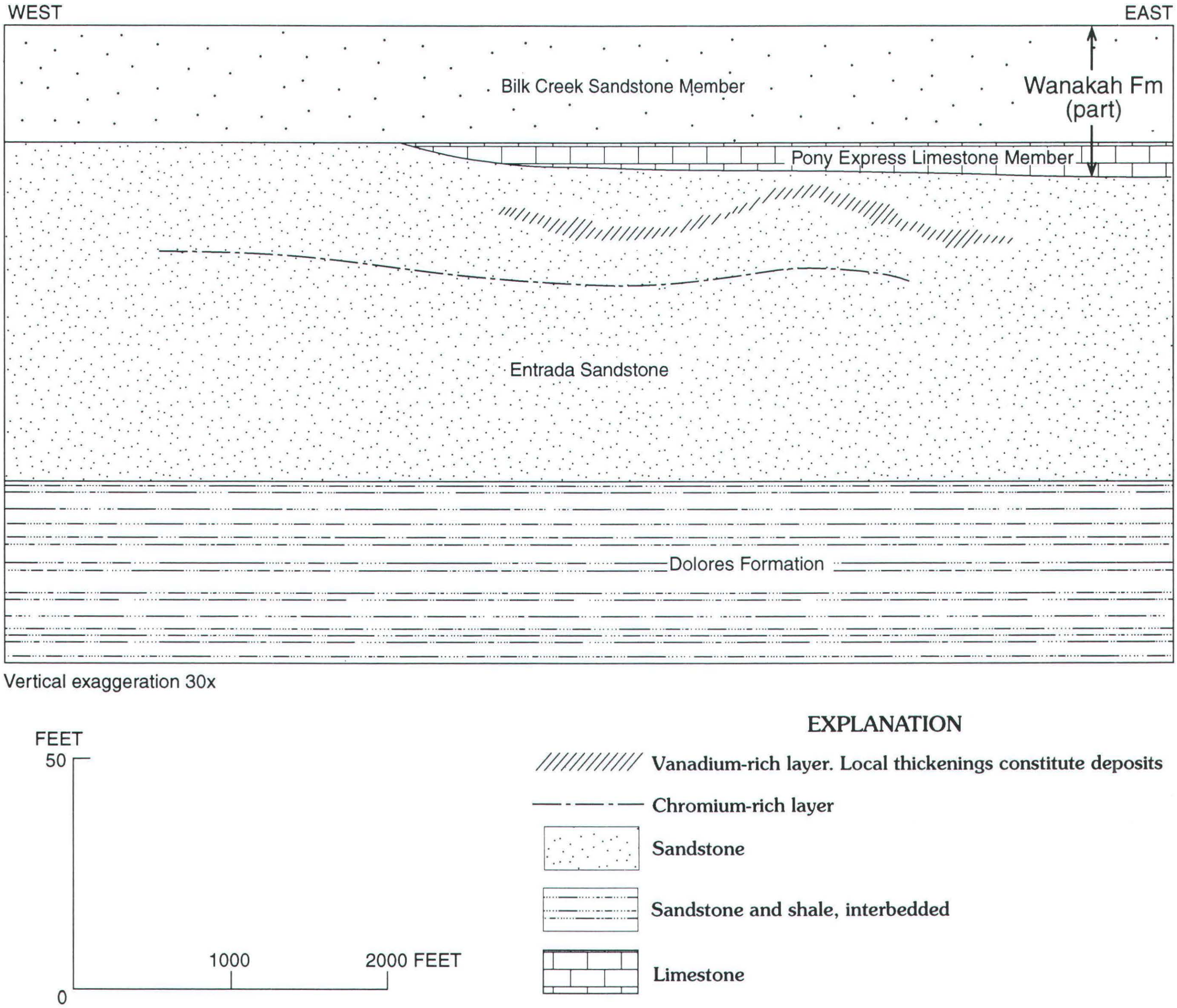


Figure 49. Schematic diagram of sandstone vanadium-uranium deposits (deposit type J). Figure adapted from Fischer (1942) and Bush and others (1959).

HOST ROCKS

Host rocks are Quaternary alluvial gravels.

ORE CONTROLS

Structure and stratigraphy have no direct bearing on the formation of placer deposits. Placers are formed downstream from lode deposits in modern stream-bed gravels. Paleoplacers in older glacial deposits may be reworked and deposited in modern stream beds. Placers form in a high-energy fluvial environment where stream flows are irregular and abrupt changes in gradient occur. Gold is commonly deposited in traps at the base of gravels in depressions or cracks in bedrock, at the base of waterfalls, along the inside of meanders, and below boulders.

AGE

Deposits of this type are Tertiary and Quaternary in age.

ORE GUIDES

Geochemical signature.—Regional stream-sediment geochemistry provides no direct evidence of placers. Concentrations of heavy minerals in gravels indicate that a mechanical separation of heavy and light material has occurred but does not indicate that gold is present.

Geophysical Signature.—Regional geophysical surveys provide no useful information. Under certain conditions, special-purpose metal detectors are used to locate nuggets, and magnetometers employed directly over stream

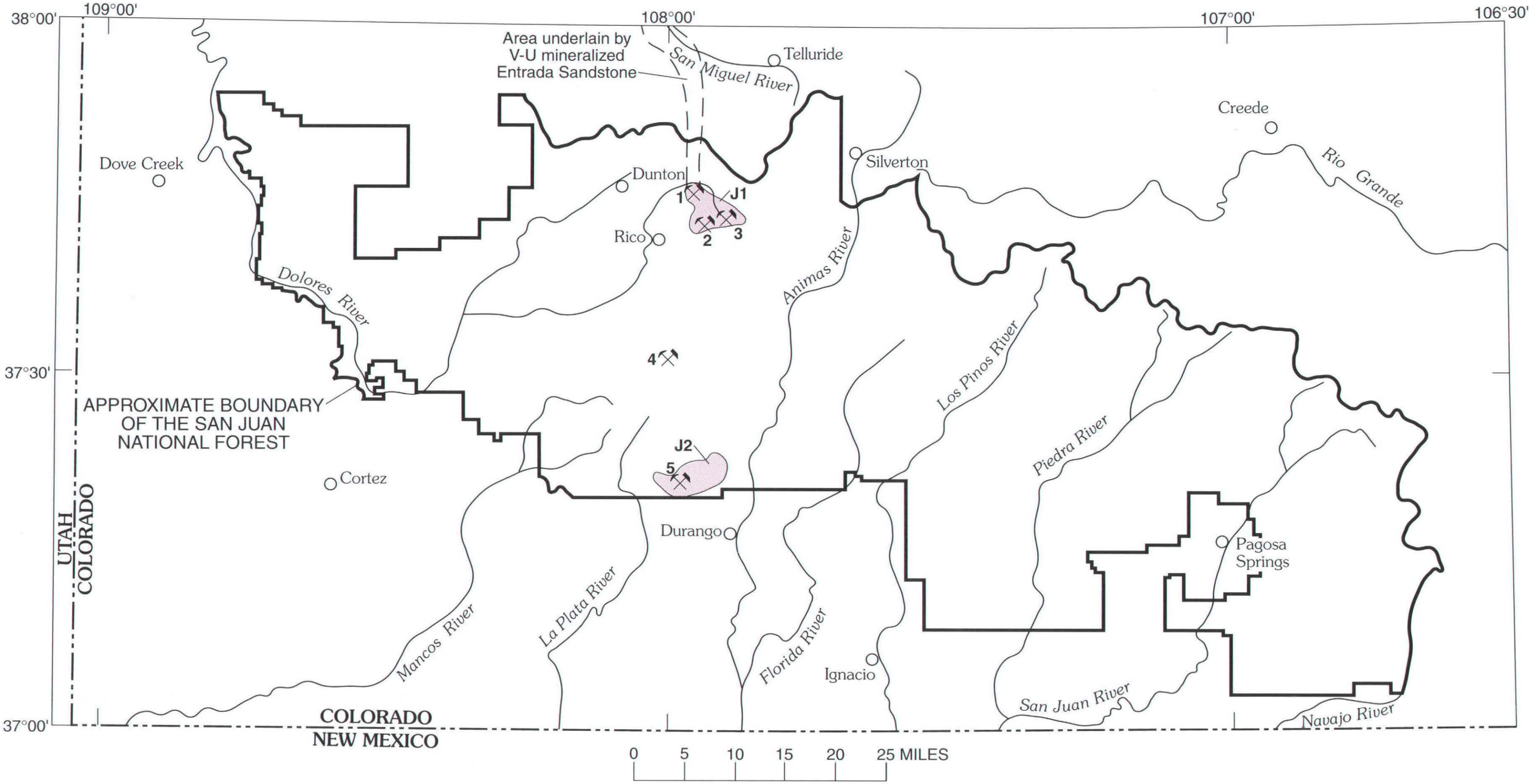


Figure 50. Map showing areas favorable for vanadium-uranium deposits (deposit type J) in the San Juan National Forest. Numbered localities: 1, Barlow Creek mine; 2, Spanish King mine; 3, Graysill mine; 4, Bear Creek claims; and 5, Lightner Creek mine.

gravels could detect black sands (concentrations of magnetite along with other heavy minerals).

ASSESSMENT CRITERIA

Limiting criteria for identifying favorable areas for gold placers include the presence of: (a) alluvial deposits downstream from known lode deposits that contain gold, (b) gold in alluvial gravels, and (c) placer mining activity.

DISCUSSION

The amount of gold produced from placers in the San Juan National Forest is negligible compared to other placer areas of Colorado. Only about 700 ounces of gold have been recovered from placers in the Forest, whereas the total production from all Colorado placers is nearly 2 million ounces (Parker, 1974).

The known Au-bearing placers in the Forest (fig. 51) are (K1) the upper Dolores River placers downstream from the Rico mining district, (K2) the West and East Forks of the Mancos River and the La Plata River placers downstream from the La Plata mining district, and (K3) the Bakers Bridge placers on the Animas River downstream from the Silverton and Needle Mountains mining districts (Parker, 1974).

The Dolores River placers start about 2 mi south of Rico and extend for about 7 mi downstream. Several terrace gravels and the modern river bed gravels contain minor amounts of gold. A serious effort to work these placer during the 1930's yielded about 18 ounces of gold (Parker, 1974). Gold in these placers is probably derived from eroded lode deposits upstream in the Rico mining district.

Gravels along the East and West Forks of the Mancos River and the La Plata River contain placer gold derived from eroded parts of ore deposits in the La Plata mining district. The upper part of Junction Creek, which drains the eastern part of the La Plata district, contains trace amounts of gold in placers, but this gold is thought to have been lost from milling operations upstream (Eckel, 1949).

The Animas River placers are about 10 mi north of Durango, just below Bakers Bridge. The Animas Valley, starting from near Silverton and extending to Bakers Bridge, is a narrow gorge which offers few sites for placer deposits. Weathering of ore deposits in both the Silverton and Needle Mountains mining districts must have shed gold into the Animas drainage, but for nearly 45 mi there was little or no deposition of gravels. However, near Bakers Bridge the gorge opens into a valley nearly a mile wide where gravels were deposited over a large area. These gravels and placer gold are derived in part from reworked older glacial moraines deposited below Bakers Bridge.

ECONOMIC SIGNIFICANCE

The paucity of placers and their relatively low grade are well illustrated in historical accounts of placer mining in the Forest (Parker, 1974). Although only small amounts of gold were taken from the placers, these discoveries often led to the discovery of lode gold deposits.

Small placer operations continue to work gravels in a few areas of the Forest. Gold placers at Golconda, near the upper reaches of the North Fork of the Mancos River, are worked seasonally (Neubert and others, 1992). The placer deposits on the Animas River north of Durango will probably never be mined because they are on prime real estate that is rapidly being developed for housing. The high cost of placer mining due to environmental regulations, large volumes of water required, and land reclamation will most likely exceed the value of gold gained from a placer deposit in the Forest.

The real value of placers today in the San Juan National Forest is their recreational value. Tourists and placer-mining hobbyists will continue to pan for gold in the stream gravels throughout the Forest. Commercial guided tours of the Forest commonly include gold-panning instructions.

ASSESSMENT

The areas shown on figure 51 and plate 2 (K1, K2, and K3) are favorable for additional gold placer deposits. The potential for placers in the Forest is not high because of (1) extensive glaciation, which is not conductive to placer formation, and (2) the nature of the gold in the original lode deposits. Much of the lode gold occurs as Au-Ag-Te minerals, which tend to weather into very fine flour gold (Eckel, 1949). Placers containing flour gold tend to be diluted and far removed from the gold source. It is doubtful that any significant undiscovered gold placers exist in the Forest. Although the Forest was thoroughly explored during the gold-placer era of the late 1800's, available data are insufficient to evaluate every stream gravel in the Forest.

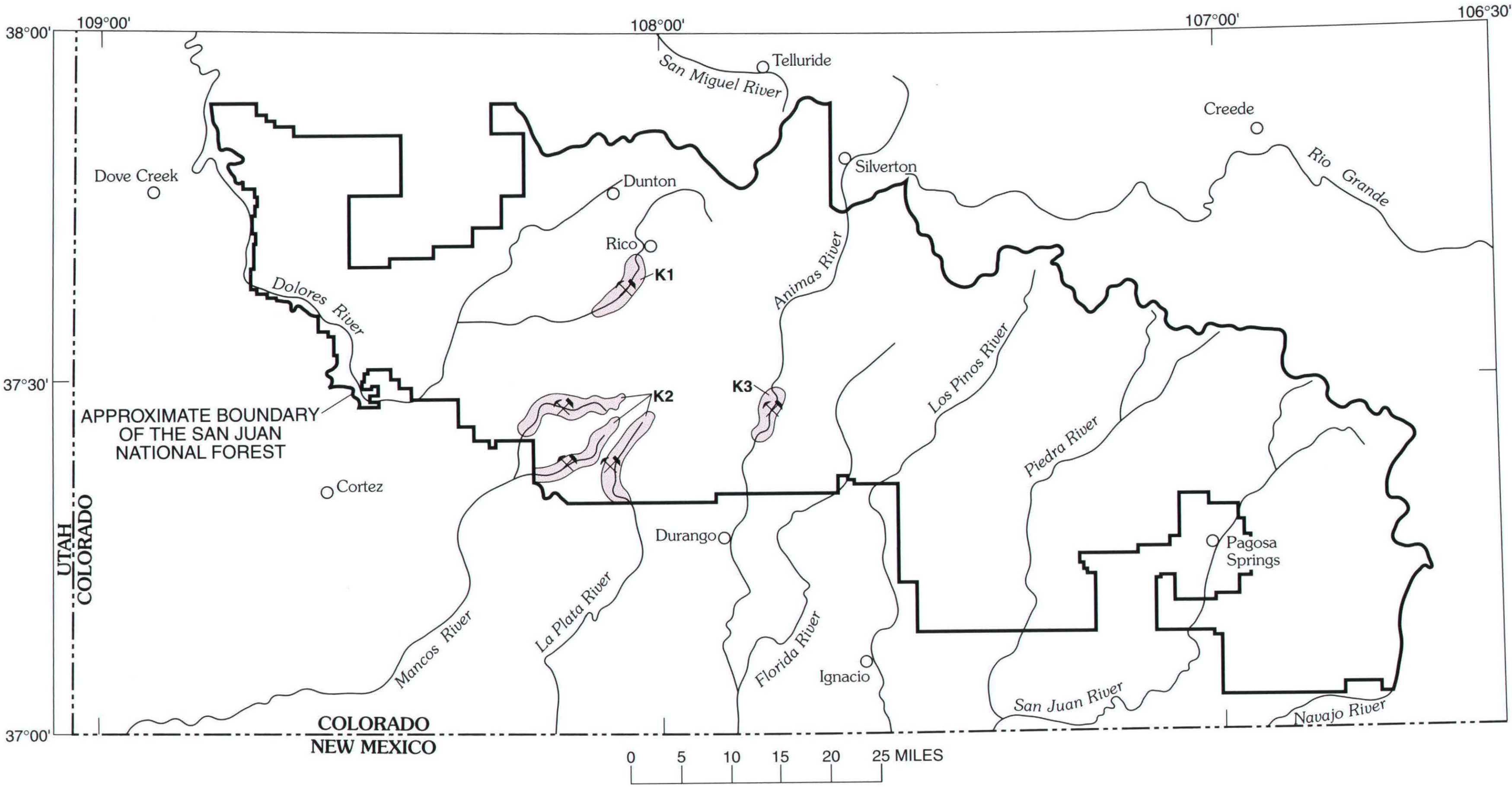


Figure 51. Map showing areas favorable for placer gold deposits (deposit type K) in the San Juan National Forest.

MINERAL RESOURCE POTENTIAL—LEASABLE MINERALS (ENERGY RESOURCES)

COAL GEOLOGY AND RESOURCES

By John W. M'Gonigle *and* Laura N. Robinson Roberts

INTRODUCTION

The San Juan National Forest contains coal in sedimentary rocks of Cretaceous age. Some of these coals have been mined within the Forest area on a small scale for more than a century, and, currently, various companies are exploring for and extracting methane from some of the coal beds and associated sedimentary rocks. The coal is both a source and a reservoir for methane, as is discussed more fully in the following section, Coal-Bed Gas Resources. The purpose of this chapter is to summarize the coal geology of the Forest area as described in the literature in previous studies and to present new resource calculations for coal in that part of the Forest where exploration for coal methane is underway.

CRETACEOUS ROCKS

Over the past century, Cretaceous rocks have been assigned various formation names by geologists as an aid in description, mapping, and stratigraphic studies of deposits. The sedimentary rock units are of both continental and marine origin, and they show that, during Late Cretaceous time, the western shoreline of an epicontinental sea, which trended north-south across North America, advanced toward the southwest and retreated toward the northeast several times across Colorado and adjacent areas in response to varying sediment supply and rate of subsidence of the ocean basin (Sears and others, 1941; Pike, 1947; Molenaar, 1983; Molenaar and Baird, 1991; Aubrey, 1991). Figure 52 shows a generalized geometric configuration of the stratigraphic succession and the names applied to the coastal, marine, and continental deposits that accumulated during these marine oscillations. In any one place, a vertical section in outcrop or drill hole would show the various stratigraphic units stacked upon each other; only in a regional section, such as shown in figure 52, can the geometry and interrelationships of the units be discerned. It is apparent from the figure that the formations rise stratigraphically and are younger to the northeast.

STRATIGRAPHY

The basal Upper Cretaceous unit, the Dakota Sandstone, was laid down across fluvial rocks of the Lower Cretaceous Burro Canyon Formation during the initial advance of the sea into this area. The Dakota Sandstone, about 200 ft thick in the Forest area, is fluvial at the base and deltaic to marine shoreface in upper parts and includes sandstone, conglomerate, and subordinate interbedded lenticular claystone, carbonaceous mudstone, and coal (Pike, 1947; Zapp, 1949; Wood and others, 1948; Barnes, 1953; Haynes and others, 1972; Aubrey, 1991).

The Upper Cretaceous Mancos Shale, which conformably overlies the Dakota Sandstone, is about 2,000 ft thick in the Forest area (Barnes, 1953) and consists of dark-gray, sparsely fossiliferous marine shale containing a few thin limestone beds (Cross and Purington, 1899; Zapp, 1949; Haynes and others, 1972). Aubrey (1991) discussed a regional unconformity within the unit and pointed out that limestone development was a function of distance from shore.

The Mancos Shale intertongues with the Upper Cretaceous Mesaverde Group (Holmes, 1877; Wanek, 1959), members of which were named the Point Lookout Sandstone, Menefee Formation, and the Cliff House Sandstone by Collier (1919). The Mesaverde Group thins eastward across the area to where individual members are not resolvable; it is about 1,200–1,500 ft thick in the area around the Mesa Verde National Park (Wanek, 1959) (figs. 5, 54), about 325–365 ft thick in eastern exposures in the southern part of the San Juan National Forest, and merges into marine shales to the northeast (Steven and others, 1974; Barnes, 1953; Wood and others, 1948).

The Point Lookout Sandstone of the basal Mesaverde Group has a maximum thickness of about 400 ft in the Forest area; the lower part is made up of thin sandstone and interbedded shale, and the upper part is made up of massive sandstone (Zapp, 1949). It was deposited in a variety of shoreline environments during the "R-4 regression" of Molenaar (1983) of

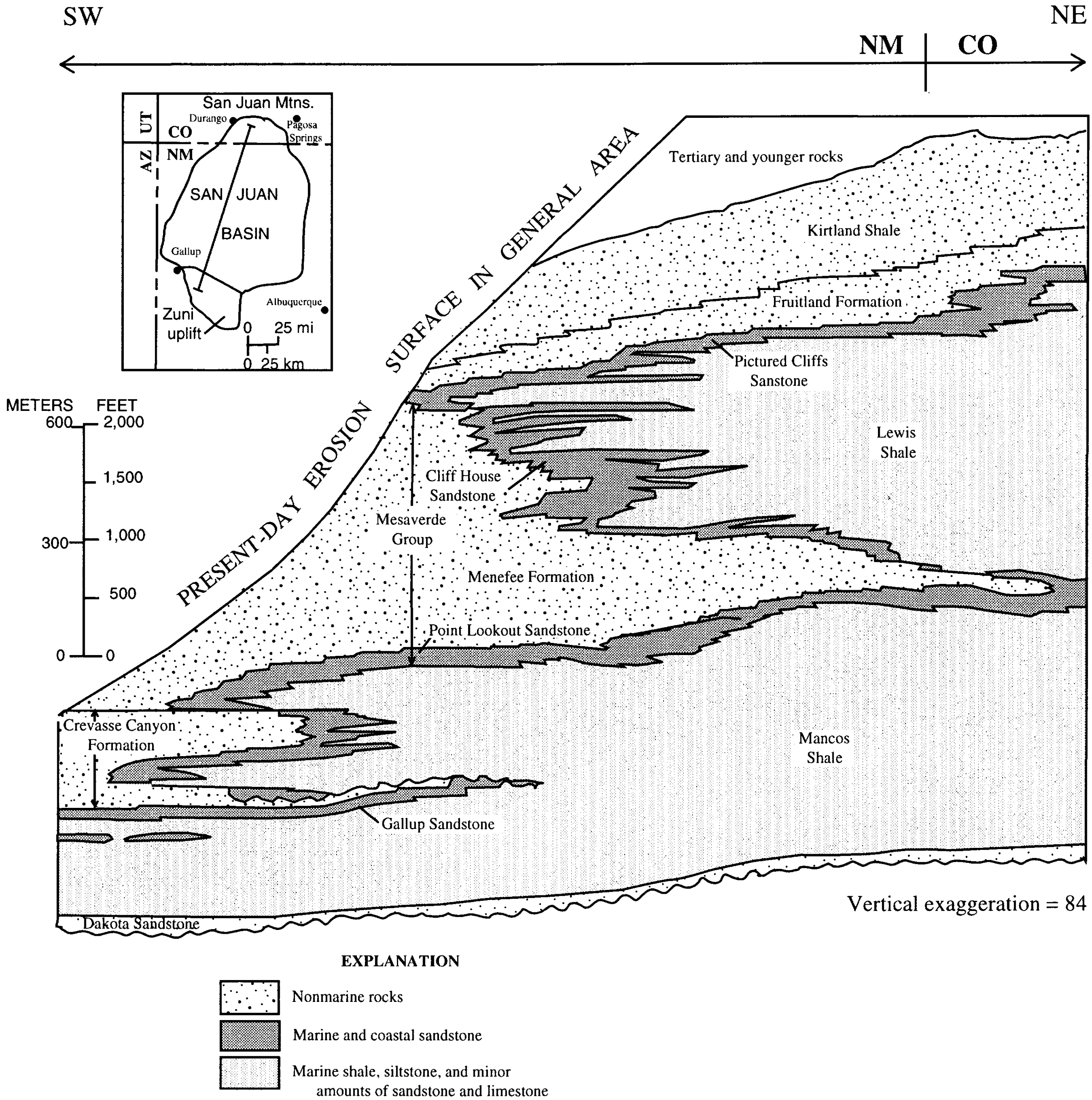


Figure 52. Generalized stratigraphic cross section showing Upper Cretaceous rocks across the San Juan Basin, New Mexico and Colorado. Modified from Molenaar and Baird (1991).

the epicontinental sea toward the east and is transitional with the underlying Mancos Shale (Aubrey, 1991).

The Menefee Formation of the Mesaverde Group formed to the west or landward of the Point Lookout and the Cliff House Sandstones. It is a complex assemblage of sandstone, siltstone, shale, and coal measures formed in fluvial, estuarine, and littoral environments and is characterized by extreme irregularity or lenticularity of individual beds. Coals in the Menefee Formation usually are concentrated near the top and base (Pike, 1947; Barnes and others, 1954; Aubrey, 1991). In the northern part of the Mesa Verde National Park area, the Menefee is about 340 ft thick (Wanek, 1959), but it thins to the east, and the thickness of the unit in the Forest area is generally 100 ft or less.

The Cliff House Sandstone is a transgressional shallow marine, fine- to medium-grained sandstone that forms cliffs separated by shaly sandstone and siltstone units; it becomes more shaly eastward in the Forest area (Zapp, 1949). It was formed during the "T-5 transgression" of Molenaar (1983), largely in shoreface environments along a barrier-island beach front (Aubrey, 1991). The sandstone interfingers laterally and vertically with overlying Upper Cretaceous Lewis Shale and the underlying Menefee Formation.

The Lewis Shale is a dark-gray to black marine shale that varies from about 1,800 to 2,400 ft in thickness in the Forest area (Zapp, 1949; Wood and others, 1948). It contains a few interbeds of fine-grained sandstone, limestone, calcareous concretions, and bentonite (Aubrey, 1991) and, similar to the Mancos Shale, represents fairly deep water marine sediments.

The Upper Cretaceous Pictured Cliffs Sandstone is a well-sorted, medium-grained sandstone with shaly beds in the lower part. The thickness of the unit is about 214 ft on the east side of the Animas River; it thins to the east and is absent on the San Juan River northeast of Pagosa Springs (Wood and others, 1948; Zapp, 1949). The Pictured Cliffs Sandstone was laid down during the final retreat of the sea from the area (known as the "R-5 regression" of Molenaar (1983) and represents deposits made along a prograding shoreline (Roberts and Uptegrove, 1991). Rises or northwest-trending benches of the Pictured Cliffs Sandstone, combined with thickness increases, represent temporary stability of the shorelines when sediment supply balanced marine subsidence (Fassett and Hinds, 1971). In most places, the Upper Cretaceous Fruitland Formation directly overlies the Pictured Cliffs, but in the southeastern part of the basin, the Pictured Cliffs Sandstone is thin or absent and the Fruitland Formation locally overlies the Lewis Shale. This implies either nondeposition of the Pictured Cliffs Sandstone or perhaps uplift and erosion of the Pictured Cliffs Sandstone prior to deposition of the Fruitland Formation (Aubrey, 1991).

The Fruitland Formation and Upper Cretaceous Kirtland Shale are continental deposits laid down landward of the sea as it made its final retreat to the northeast. The sedimentary rock types indicate that the sedimentary environments were similar to those of the Menefee Formation.

The Fruitland Formation in the Durango area is about 300 ft thick (Zapp, 1949), and, along the Los Pinos River, it is as much as 390 ft thick; farther east, the Fruitland Formation and the Kirtland Shale thin rapidly (Wood and others, 1948). Aubrey (1991) described a thinning of the two formations from the northwest to the southeast part of the San Juan Basin and stated that their local absence in the southeast could be the result of either depositional thinning onto a structurally positive area or pre-Tertiary uplift and erosion. By definition, the Fruitland Formation is coal bearing, whereas the Kirtland Shale is not—the Fruitland is the most important coal-bearing formation in the San Juan Basin (Fassett, 1988). An irregularly bedded sequence of sandstone, shale, and coal beds (Zapp, 1949; Barnes, 1953) or, more specifically, interbedded sandstone, siltstone, carbonaceous shale, carbonaceous siltstone, carbonaceous sandstone, coal, and thin pelecypod-shell limestone comprise the Fruitland Formation (Aubrey, 1991; Roberts and Uptegrove, 1991). The thickest coal beds are in the lower part of the formation and form a fairly continuous coal-bearing interval or zone, although the individual coal beds are lenticular and cannot be traced far (Barnes and others, 1954; Fassett and Hinds, 1971; Roberts and Uptegrove, 1991). Fassett and Hinds (1971) noted that the thickest Fruitland coal deposits of the San Juan Basin trend toward the northwest parallel to, but southwest of, pronounced stratigraphic rises of the Pictured Cliffs Sandstone. The coal beds and associated strata represent coastal-swamp, lagoon, alluvial, and lacustrine deposits inland from the shoreline (Barnes and others, 1954; Aubrey, 1991; Roberts and Uptegrove, 1991; Roberts and McCabe, 1992).

The Kirtland Shale is about 1,200 ft thick near Durango (Zapp, 1949) and thins eastward, as mentioned above. Bauer (1916) subdivided the formation into a lower and an upper shale member, which are separated by a middle sandstone unit, the Farmington Sandstone Member. The formation is considered to be an alluvial deposit, with siltstone and mudstone beds formed as overbank floodplain deposits and sandstones formed as stream-channel deposits (Aubrey, 1991). Barnes and others (1954) thought that the large quantities of feldspar and ferromagnesian minerals and coarse clastic material in the upper member indicated deeper erosion of uplifted source areas, perhaps reflecting the beginning of the Laramide orogeny.

The Cretaceous rocks are overlain by Tertiary clastic deposits (Baltz, 1953; Barnes and others, 1954; Baltz and others, 1966). The Animas Formation (Upper Cretaceous and Paleocene) is the principal Tertiary sedimentary unit in the Forest area, although the Nacimiento (Paleocene) and San Jose (Eocene) Formations also occur not far south of the Forest boundary (plate 1). These Tertiary formations contain large amounts of andesitic and other volcanic material (Zapp, 1949; Barnes and others, 1954). Source areas for andesitic material in the Animas Formation probably included the La Plata Mountains to the north. Metamorphic and granitic material source areas probably included the San Juan and Needle Mountains to the northwest and the Brazos–Sangre de Cristo uplift to the northeast (Aubrey, 1991). Baltz (1967), Baltz and others (1966), and Smith and others (1985) discuss the stratigraphy and origin of these Tertiary units at length.

DISTRIBUTION OF CRETACEOUS STRATA

At least 5,000 ft of Cretaceous strata once blanketed the region of southwestern Colorado and adjacent States (Atwood and Mather, 1932; Shoemaker, 1956; Molenaar, 1983).

These Cretaceous units are well preserved in the San Juan Basin, the northern part of which lies in the San Juan National Forest area. In most places in the Forest, the preservation of Cretaceous rocks is not so complete for several reasons. Since Cretaceous time, a number of tectonic events have taken place in the region, both modifying preexisting structures and sedimentary basins (e.g., the Uncompahgre uplift and the Paradox Basin) and creating new ones (e.g., the San Juan uplift and the San Juan Basin) (Shoemaker, 1956; Kelley, 1955, 1956). The successive overstepping of the Animas, Nacimiento, and San Jose beds on the northwest edge of the San Juan Basin near the Colorado–New Mexico border suggests that the San Juan Basin was outlined in Late Cretaceous time and mostly formed in Paleocene time (Baltz, 1953; Kelley, 1955; Fassett and Hinds 1971; Fassett, 1985). Figure 53, modified from Shoemaker (1956) and Kelley (1955), shows some of the more prominent structural and volcanic features of the area around the San Juan National Forest. Many of the features formed at the end of the Cretaceous and in the early Tertiary, a series of events collectively termed the Laramide orogeny. Erosion of rocks in some places and deposition of sediments in others occurred during and since the Laramide events. This, in combination with extensive intrusion and extrusion of Tertiary magmas over older rocks and strata, has had a net effect of considerably reducing the coverage and exposure of Cretaceous rocks in the Forest area. Figure 54 is a generalized map showing the present configuration of Cretaceous rock units and other selected rock units in the Forest. These units are depicted with greater detail on plate 1.

COAL GEOLOGY

An inspection of figure 54 and plate 1 shows that the Burro Canyon Formation and Dakota Sandstone (combined) is the most widespread unit in the Forest, exposed widely in the west and in the southeast. Coal-bearing strata are present in the Dakota Formation, but coal beds are generally thin, impure, and discontinuous; the lenticularity makes lateral correlation of coal beds difficult (Landis, 1959). Dakota Sandstone coals are generally noncoking, high-volatile bituminous in rank, containing 7–10 percent ash, 0.9 percent sulfur, and heating values of about 12,500 Btu/lb (Kelso and Rushworth, 1988).

The Menefee Formation in the Mesaverde Group does not contain minable coal east of the Florida River (figs. 5, 54, and plate 1), according to Gardner (1909), Barnes (1953), and Landis (1959), and, hence, only a very small exposure of the Menefee Formation containing coal is inside the San Juan National Forest boundary (location A, fig. 54). Menefee coals in the general area are generally high-volatile bituminous and somewhat higher in rank than Fruitland Formation coals (Barnes and others, 1954). Most Menefee coal occurring within 6 mi of Durango could probably be coked (Zapp, 1949).

The Fruitland Formation, shown in combination with the Kirtland Shale on fig. 54 and plate 1, contains a considerable amount of coal in the Forest area. The Fruitland coals are high- to medium-volatile bituminous and tend to be much thicker than those in the Menefee, but they are of poorer quality as they have a much higher ash content (Zapp, 1949; Barnes, 1953; Fassett and Hinds, 1971; Sandberg, 1990). Roberts and Uptegrove (1991) reported that analyses of 153 samples of Fruitland coal in the Southern Ute Indian Reservation, south of the Forest area, showed the coal to be high-volatile B bituminous with an average sulfur content of 0.75 percent, an average ash content of 21 percent, and average gross calorific value on a moist, mineral-matter-free basis of 13,570 Btu/lb. Fruitland coal types include bright and boney coal with numerous shale, siltstone, and clay partings, some of which are altered volcanic ash layers (Roberts and Uptegrove, 1991).

The Fruitland crops out in a sinuous band below the Kirtland Shale along the southern boundary of the Forest (Zapp, 1949; Barnes 1953; Wood and others, 1948). A few meters of the Fruitland are also locally exposed beneath the Upper Cretaceous and Paleocene Animas Formation and Tertiary volcanic rocks on the north and south sides of the San Juan River and U.S. Highway 160 in the eastern part of the Forest in R. 1 E. and R. 1 W., T. 35 and 36 N. (plate 1; Steven and others, 1974; and location B, fig. 54). This area is northeast of Pagosa Springs and has been called the Pagosa Springs coal field (Landis, 1959). These exposures represent remnants of the Fruitland Formation, eroded prior to the deposition of the overlying Animas Formation. The geology and coal in the Fruitland in this area was described by Gardner (1909), Cross and Larsen (1935), Landis (1959), and most recently by Brock and Gaskill (1985) and Lindquist (1985). The rank of the coal in this area is probably high-volatile bituminous B or C (Landis, 1959; Lindquist, 1985).

MINING

Zelten (1992) has produced the most recent discussion of the history of coal mining activity within the San Juan National Forest and in nearby areas in a Bureau of Mines report, to which the interested reader is referred. Only mining highlights will be discussed here because no newer information is available than is in the Bureau of Mines publication.

Coal in the Dakota Sandstone has been locally mined in the past, and it was mined as a coking coal for a time on the east and west sides of the Dolores River north of Rico (fig. 5). The coal beds mined were about 100 ft above the base of the Dakota Sandstone (Hills, 1893; Purington, 1898). Apparently, little Dakota coal has been mined elsewhere in the Forest (Landis, 1959; Zelten, 1992), probably because of the thin and discontinuous nature of the coal beds and their unpredictable occurrence.

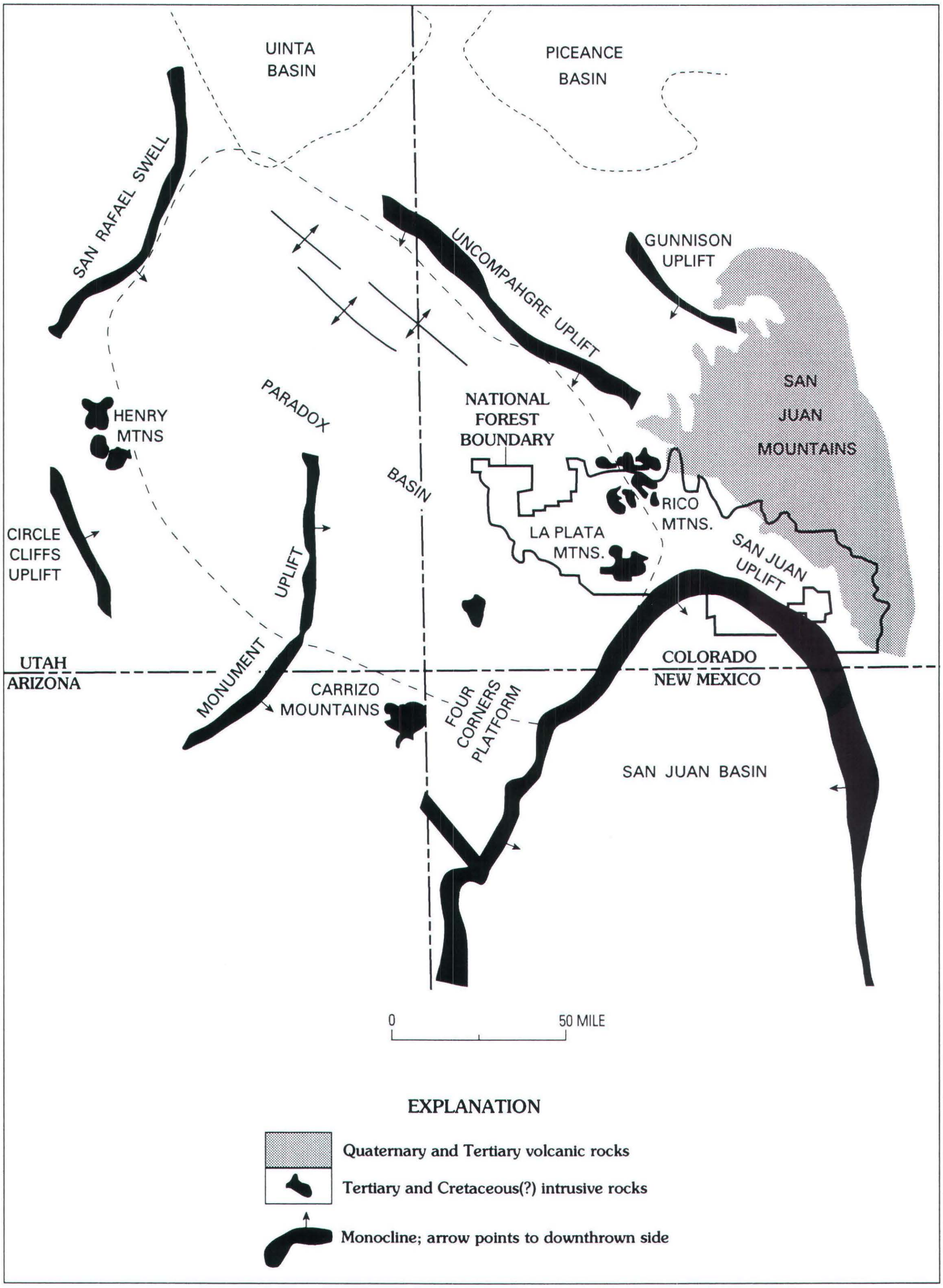


Figure 53. Map showing major structural features of the Four Corners region. Modified from Shoemaker (1956) and Kelley (1955).

Menefee coals, mined in the Durango and Mancos areas, are largely lacking in the Forest area. Zelten (1992) reports there were a few mines northeast of Mancos inside the Forest, but we could find no references supporting this information. East of Bayfield (fig. 54), the Menefee Formation of the Mesaverde Group apparently contains little coal, and no mines in these units are shown on the maps by Barnes (1953) and by Wood and others (1948).

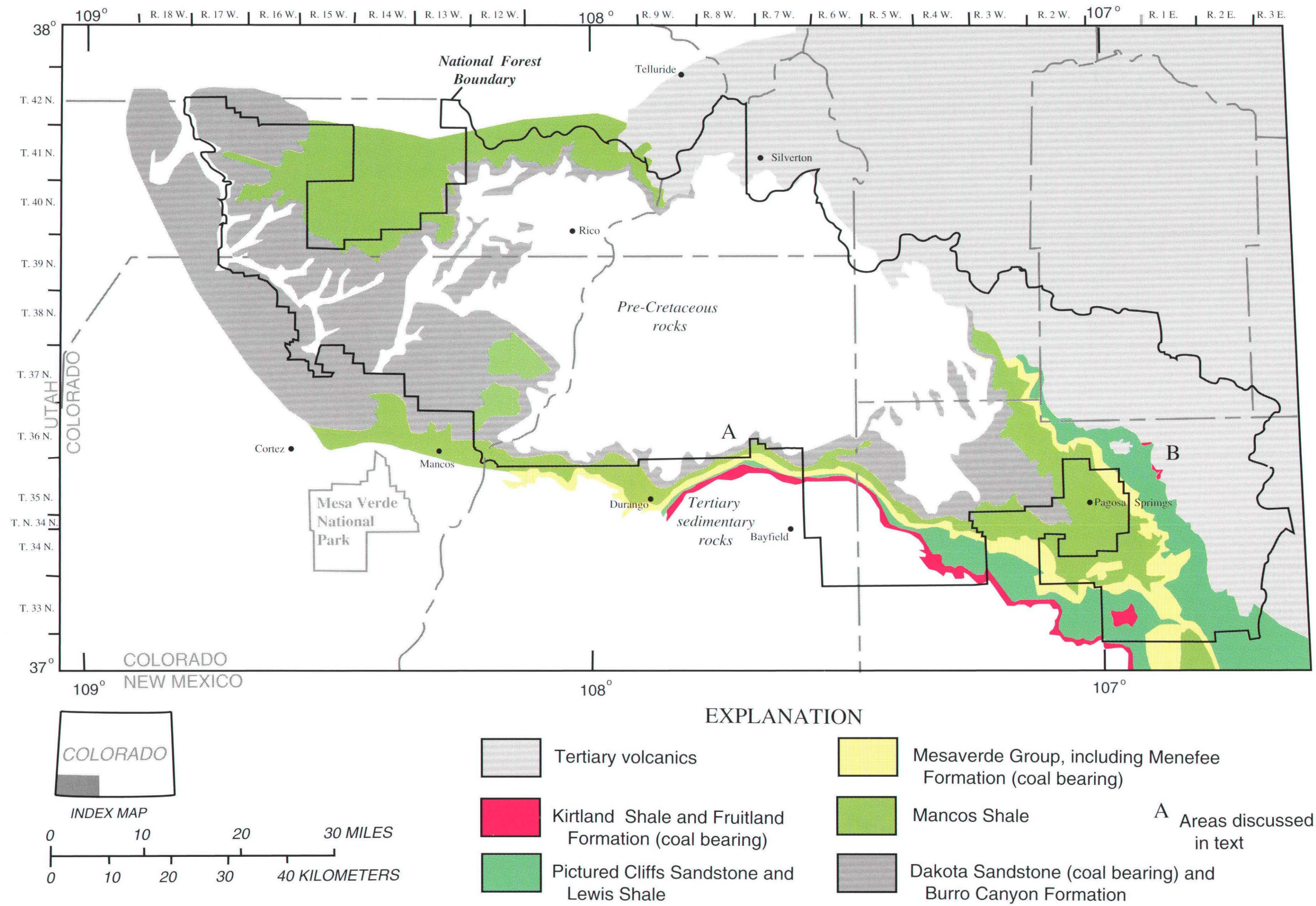


Figure 54. Generalized geologic map showing distribution of Upper Cretaceous stratigraphic units, San Juan National Forest.

Table 3. Location data for drill holes shown in figure 55.

[The designation "N34 N." is used to differentiate between two townships that are both designated "T. 34 N." on topographic maps of the area. Twp, Township; Rng, Range; Sec, Section; Prod., Production]

Well	Location			Company, well name, and number
ID	Twp	Rng	Sec	
01	35 N.	7 W.	NW¼SE¼, 24	Amoco Prod. Co. Wommer Gas Unit A 1
02	35 N.	7 W.	NW¼SE¼, 25	Amoco Prod. Co. Robert S. Dulin Gas Unit A 1
03	35 N.	7 W.	NW¼NW¼, 36	Amoco Prod. Co. State of Colorado AW 1
04	35 N.	7 W.	NE¼SE¼, 36	Amoco Prod. Co. State of Colorado AW 2
05	35 N.	6 W.	SE¼SE¼, 19	Amoco Prod. Co. Magoon Federal Gas Unit B 1
06	35 N.	6 W.	SW¼SE¼, 20	Amoco Prod. Co. Feinberg Gas Unit B 1
07	35 N.	6 W.	SW¼SE¼, 21	Amoco Prod. Co. Miller Gas Unit 1
08	35 N.	6 W.	NE¼SW¼, 22	William Perlman Albright 22-1
09	35 N.	6 W.	SE¼NW¼, 30	Amoco Prod. Co. Robert Dulin Gas Unit C 1
10	35 N.	6 W.	NE¼NW¼, 29	Amoco Prod. Co. Magoon Federal Gas Unit 1
11	35 N.	6 W.	NW¼NW¼, 28	Amoco Prod. Co. Feinberg Gas Unit C 1
12	35 N.	6 W.	NE¼SE¼, 30	Amoco Prod. Co. Parry Land Company B 1
13	35 N.	6 W.	NE¼NE¼, 31	Amoco Prod. Co. Los Pinos Water Disposal 1
14	35 N.	6 W.	NE¼NE¼, 31	Amoco Prod. Co. Evelyn Payne C 1
15	35 N.	6 W.	SW¼SE¼, 29	Amoco Prod. Co. Evelyn Payne E 1
16	35 N.	6 W.	SE¼NW¼, 31	Amoco Prod. Co. Evelyne Payne C 2
17	35 N.	6 W.	NE¼SE¼, 31	Amoco Prod. Co. Evelyn Payne Gas Unit D 1
18	35 N.	6 W.	E½NW¼, 32	Natomas North America Inc. Jones 1-32
19	35 N.	6 W.	SE¼NW¼, 32	Amoco Prod. Co. Evelyn Payne Gas Unit A 1
20	35 N.	6 W.	NW¼SE¼, 32	Amoco Prod. Co. Evelyn Payne Gas Unit F 1
21	35 N.	6 W.	SE¼NW¼, 33	Amoco Prod. Co. Albright-Trimble G.U. 1
22	35 N.	6 W.	NW¼SE¼, 33	Amoco Prod. Co. Albright Federal Gas Unit 1
23	35 N.	6 W.	NE¼NW¼, 34	Amoco Prod. Co. Sauls Creek 1
24	35 N.	6 W.	SW¼SE¼, 27	Amoco Prod. Co. Sauls Creek 3
25	35 N.	6 W.	NE¼SE¼, 34	Amoco Prod. Co. Sauls Creek 2
26	35 N.	6 W.	SE¼NE¼, 25	William Perlman Federal 25A-1
27	35 N.	5 W.	NW¼SW¼, 30	Amoco Prod. Co. USA Amoco Com AC 1
28	N34 N.	7 W.	NW¼SE¼, 1	Amoco Prod. Co. Taliaferro Trust Gas Unit A
29	N34 N.	7 W.	SW¼SE¼, 12	Amoco Prod. Co. Ludwig Gas Unit 1
30	N34 N.	7 W.	SW¼NW, 13	Amoco Prod. Co. Snooks Gas Unit A 1
31	N34 N.	7 W.	NE¼NE¼, 13	Lama Corporation Sitton 1
32	N34 N.	6 W.	NW¼NE¼, 6	Amoco Prod. Co. Beaver Creek Gas Unit 1
33	N34 N.	6 W.	NE¼NW¼, 5	Amoco Prod. Co. Evelyne Payne Gas Unit 1
34	N34 N.	6 W.	NE¼NW¼, 3	Amoco Prod. Co. Fischer Mark Federal B 2
35	N34 N.	6 W.	NE¼SE¼, 6	Amoco Prod. Co. K G Trust Gas Unit 1
36	N34 N.	6 W.	SE¼SE¼, 4	Amoco Prod. Co. Fisher-Mark Federal 1
37	N34 N.	6 W.	NW¼SE¼, 3	Amoco Prod. Co. Lee Federal Gas Unit 1
38	N34 N.	6 W.	NW¼SW¼, 2	William Perlman Federal 21-1
39	N34 N.	6 W.	SE¼NW¼, 7	Amoco Prod. Co. Luter Federal Gas Unit 1
40	N34 N.	6 W.	NW¼NW¼, 9	Amoco Prod. Co. Fisher-Mark Federal 1
41	N34 N.	6 W.	SW¼NW¼, 10	Amoco Prod. Co. Merry Federal Gas Unit 1
42	N34 N.	6 W.	NE¼SE¼, 7	Amoco Prod. Co. Morrison Federal Gas Unit B 1
43	N34 N.	6 W.	SE¼SE¼, 8	Amoco Prod. Co. Morrison Federal Gas Unit 1
44	N34 N.	6 W.	SW¼SE¼, 9	Amoco Prod. Co. Archuleta Dix Gas Unit
45	N.34 N.	6 W.	SW¼SE¼, 10	Amoco Prod. Co. Frahm Federal Gas Unit 1
46	N34 N.	6 W.	NW¼SE¼, 18	Amoco Prod. Co. Beaver Creek Gas Unit B 1
47	N34 N.	6 W.	SW¼NE¼, 18	Amoco Prod. Co. Bayfield Disposal 1
48	N34 N.	6 W.	SW¼NE¼, 17	Amoco Prod. Co. Hubert Morrison G.U. A 1
49	N34 N.	6 W.	NW¼NE¼, 16	Lama Corporation Ivers 1-16
50	N34 N.	6 W.	SE¼NW¼, 15	William Perlman Frahm 15-1

Table 3. Location data for drill holes shown in figure 55—*Continued.*

Well ID	Location Twp	Rng	Sec	Company, well name, and number
51	34 N.	7 W.	NW¼NW¼, 12	J. Magness Inc. Echols-Ute 1-12U
52	34 N.	7 W.	NE¼SW¼, 12	J. Magness Inc. Ute 2-12U
53	34 N.	7 W.	SW¼SE¼, 13	Natomas North America Inc. Harper 1-13U
54	34 N.	7 W.	NW¼SE¼, 23	William Perlman Southern Ute 23-2
55	34 N.	7 W.	NW¼NW¼, 25	Amoco Prod. Co. Gary Beebe Gas Unit A 1
56	34 N.	7 W.	SW¼NW¼, 36	Amoco Prod. Co. Kenner G. U. A no. 1
57	34 N.	6 W.	SE¼SW¼, 18	Natomas North America Inc. Harper 1-18U
58	34 N.	6 W.	NW¼SW¼, 17	Natomas North America Inc. Glaser 1-17 u
59	34 N.	6 W.	NW¼NE¼, 14	Amoco Prod. Co. Pargin Mountain Unit 2
60	34 N.	6 W.	SE¼NW¼, 19	Natomas North America Inc. Wright 1-19
61	34 N.	6 W.	SW¼NW¼, 20	Natomas North America Inc. Smith 1-20
62	34 N.	6 W.	SW¼SE¼, 19	Amoco Prod. Co. Boone Gas Unit 1
63	34 N.	6 W.	SE¼NW¼, 30	Natomas North America Inc. Pine River Unit 1-30
64	34 N.	5 W.	NW¼SW¼, 29	Natomas North America Pine River Unit 2-29
65	34 N.	6 W.	SE¼NE¼, 32	Natomas North America Inc. Pine River Unit 4-32
66	34 N.	6 W.	SW¼SE¼, 31	Natomas North America Inc. Pine River Unit 3-31
67	34 N.	6 W.	SW¼SW¼, 32	Empire State Drilling Corporation Daniels 1
68	34 N.	5 W.	NE¼NW¼, 9	William Perlman Federal 9U-1A
69	34 N.	5 W.	SW¼NW¼, 10	William Perlman Federal 10U A-1
70	34 N.	5 W.	SE¼SE¼, 14	Big Horn-Powder River Schamburg 1
71	34 N.	5 W.	NW¼NE¼, 34	Amoco Prod. Co. Pargin Mountain Unit 10
72	34 N.	5 W.	SW¼SE¼, 32	Amoco Prod. Co. Pargin Mountain Unit 4
73	34 N.	5 W.	SE¼NW¼, 34	Amoco Prod. Co. Pargin Mountain Unit 11
74	34 N.	5 W.	NE¼SE¼, 34	Amoco Prod. Co. Pargin Mountain Unit 9
75	34 N.	5 W.	SE¼SW¼, 35	Amoco Prod. Co. Bull Creek Federal 1
76	34 N.	4 W.	SE¼SW¼, 32	William Perlman Federal 32A 1
77	33 N.	7 W.	SE¼SE¼, 1	William Perlman Southern Ute 1-1
78	33 N.	6 W.	NE¼NW¼, 6	Lama Corporation Powell 1-6
79	33 N.	6 W.	NW¼NE¼, 6	Consolidated Oil and Gas Superior-Ute 1-6
80	33 N.	6 W.	NW¼NW¼, 4	Consolidated Oil and Gas Superior-Ute 2-4
81	33 N.	6 W.	NW¼NW¼, 3	Amoco Prod. Co. Southern Ute Tribal B 1
82	33 N.	6 W.	NW¼NW¼, 3	Amoco Prod. Co. South Ute Tribal B 3
83	35 N.	5 W.	NW¼SW¼, 33	Measured section 30 (Barnes, 1953)
84	N34 N.	5 W.	S½, 4	Measured section 1 (Wood and others, 1948)
	N34 N.	5 W.	SE¼, 4	Measured section 1 (Wood and others, 1948)

The Fruitland Formation coal within the Forest area was formerly mined on a modest scale, mostly along the outcrop exposures between Bayfield and Piedra (fig. 55, table 3). Individual mines are located on maps by Barnes (1953) and Wood and others (1948). Zelten (1992) reports that eight of these mines or mine groups produced between 3,000 and 11,000 short tons of bituminous coal each during the period 1928–56. The Chimney Rock mine, in sec. 29, 30, T. 34 N., R. 4 W., was the only coal mine in the Forest under Federal coal lease as of 1990. It produced 1,359,000 short tons of coal between 1947 and 1985, when it became inactive (Zelten, 1992). Gardner (1909) reported that there had been some mining in the Pagosa Springs field, and Lindquist (1985) reported that at least several thousand short tons of Fruitland coal were produced from mines there during the period 1923–40.

COAL RESOURCES

Resources for the Dakota and Menefee Formations were not calculated for this report because sufficient data for making these calculations are lacking for the Forest area.

The greatest amount of coal accessible/amenable to mining in the Forest is in the Fruitland Formation, and currently there is also much interest in the potential for methane production from these coal beds (e.g., see U.S. Forest Service and Bureau of Land Management, 1991). For the coal field northeast of Pagosa Springs (location B, fig. 54), Lindquist (1985) calculated that, on the basis of one 4.9-ft-thick bed that was well established in mine workings and in outcrop exposures, an indicated reserve base of 8 million short tons of bituminous coal was present. An additional 36 million short tons could be inferred to exist (Lindquist, 1985). Landis

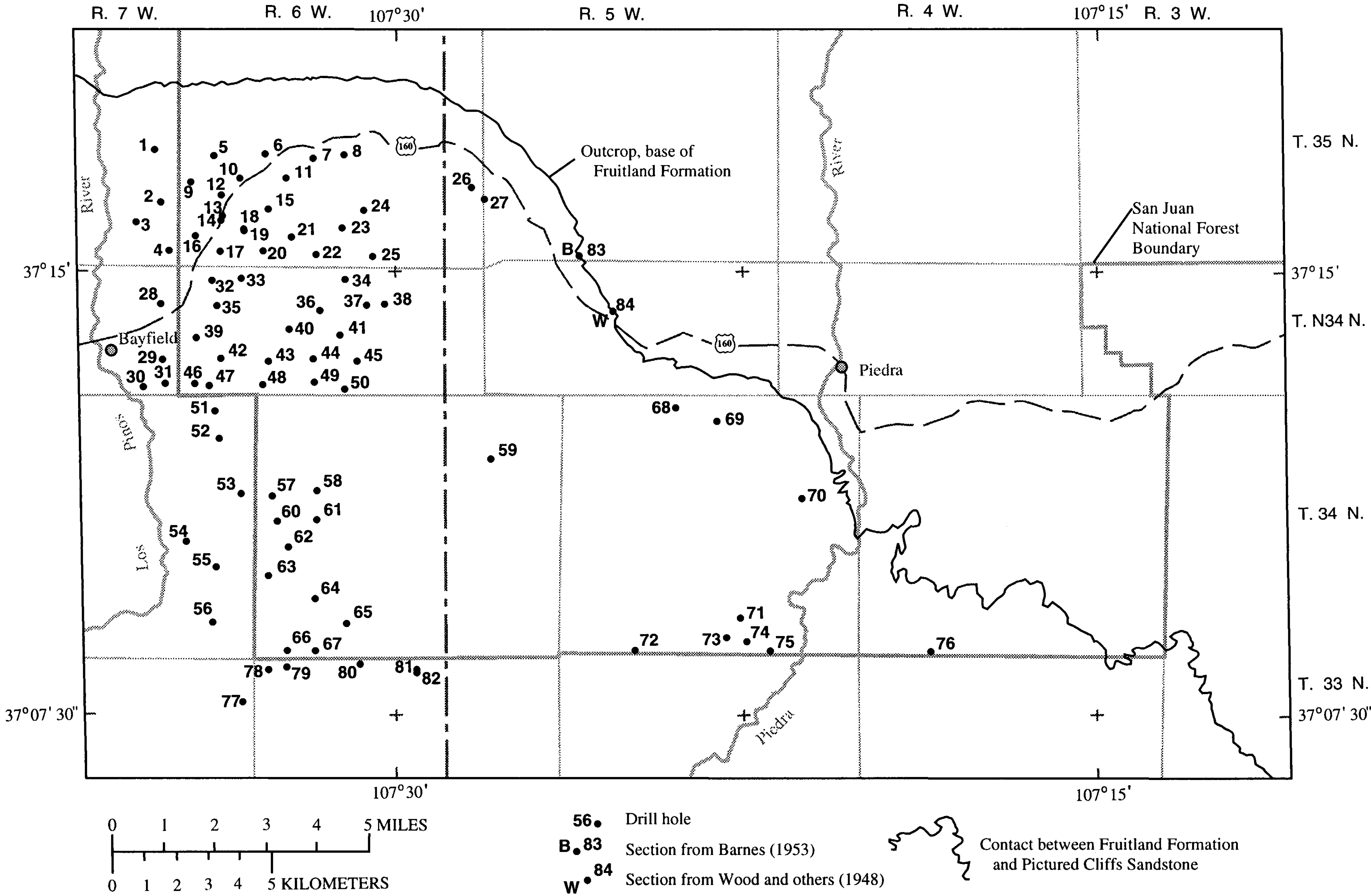


Figure 55. Location of drill holes and measured sections delineating coal resources, south-central part of San Juan National Forest. Numbers are keyed to well names and locations shown in table 3. The designation T. N34 N. is used to differentiate between two townships that are both designated T. 34 N. on topographic maps of the area.

(1959) had calculated that 10 million short tons of bituminous coal were originally present in a 1-mi^2 area in the field.

For this report, new calculations were made of the coal resources in the Fruitland Formation for that part of the Forest east of Bayfield and southwest of Pagosa Springs (figs. 54, 55), in T. 35 N., R. 5 and 6 W., T. N34 N., R. 5 and 6 W., and T. 34 N., R. 4, 5, and 6 W. Information from 82 geophysical logs of drill holes showing coal beds and from two measured sections along the outcrop of the Fruitland Formation in the area was used in the calculations (table 3 and fig. 55). The designation T. N34 N. is used to differentiate between two townships that are both designated T. 34 N. on topographic maps of the area. The two measured sections are from Barnes (1953) and from Wood and others (1948). Other measured sections in these reports were not used in final calculations because many were incomplete, and it was not certain that all of the coal in the Fruitland Formation had been measured in the rest of the sections.

Each geophysical log used provided information on the elevation of the ground surface, depth to the highest Fruitland Formation coal bed, thickness of coal beds, and depth to the Pictured Cliffs Sandstone. Coal beds were measured on each well log in four standard thickness categories for bituminous coal. The percent of total coal measured in the wells in the study area in the four categories was: 1.2–3.5 ft, 5 percent; 3.5–7 ft, 10 percent; 7–14 ft, 16 percent; and greater than 14 ft, 69 percent. The lenticular nature of Fruitland Formation coal beds precludes consistent correlation of individual beds between wells; therefore, it was not practical to calculate resources for individual beds. Consequently, the coal-bearing interval of the Fruitland Formation was treated as a coal zone, and the total coal in beds greater than 1.2 ft thick in the zone at each data point was used for the resource calculations in this report. Fassett and Hinds (1971) and Sandberg (1990) discussed such coal zones in the Fruitland Formation in the San Juan Basin. The coal zone used in this study corresponds to Sandberg's upper coal zone. Two lower zones that she recognized do not extend into the study area.

The coal beds measured undoubtedly include some ashy material, but no corrections for ash content, such as those made by Sandberg (1990), were attempted by us to change the measurements. In the area studied, no core or analyses were available to us to make any such corrections less subjective. In any case, ashy coal beds still contribute to the methane resources of the coal zone (Fassett, J.E., editor's note *in* Sandberg, 1988, p. 43).

Calculations were made with the aid of the Interactive Surface Modeling (ISM) and Interactive Polygon Operations (IPO) computer programs developed by Dynamic Graphics, Incorporated.

A well and outcrop location map was made with the ISM program (fig. 55). Map plots made from the location map and well-log data include those showing structure contours on the top of the highest Fruitland coal (fig. 56), as well as one showing isopachs of total coal in the Fruitland Formation (fig. 57). A digital elevation model of the topography of the west half of the Durango 1:250,000-scale quadrangle was used in conjunction with well data on the depth to the top of the highest coal in the Fruitland Formation to produce an isopach map of the overburden (fig. 58). These data were combined by means of the computer programs with coal thickness data and zones of reliability around each data point to calculate measured, indicated, inferred, and hypothetical resources of coal in the Fruitland Formation in the study area.

The procedures followed were those described by Wood and others (1983). Measured, indicated, inferred, and hypothetical categories of coal resources are those measured within 0.25 mi, 0.25–0.75 mi, 0.75–3.0 mi, and greater than 3.0 mi radii from each data point, respectively. Depth categories used were those bounded by 500-, 1,000-, 2,000-, 3,000-, and >3,000-ft depths below the surface from each data point. The resources are listed by township and range in table 4 and for the general area in table 5. As much as 6 billion short tons of bituminous coal in the Fruitland Formation are estimated to be present in this area of the San Juan National Forest.

DISCUSSION

Although the Fruitland coal resource area discussed here is a small part of the San Juan Basin, thickness trends of total coal seemingly are consistent with those made by Fassett and Hinds (1971) for the whole basin. Differences are probably due to the much larger drill-hole database available to us than was available to Fassett and Hinds for this small part of the basin and because Fassett and Hinds (1971) used most of the outcrop data from Barnes (1953) and Wood and others (1948) as part of their calculations, whereas we did not. The outcrop information implies a rapid thinning of coal from nearby drill holes all along the Fruitland outcrop line. Our projections from the drill-hole data across the outcrop line (fig. 57) are thicker, and so the indicated and inferred resource estimates to a 1,000-ft depth, shown in table 4, may possibly be overestimated if these thickness projections are inaccurate. Coal thicknesses projected from drill holes 1, 5–8, 26, 27, and 68–70 to the Fruitland Formation outcrop line (figs. 55, 57) constitute the suspect data. However, the remainder (more than 85 percent) of the resource estimates in the study area are thought by us to be very well founded.

A few of the wells used for this study were also used by Sandberg (1990). We measured greater thicknesses of coal in these well logs than did Sandberg, apparently because we included coal beds she excluded, based on her estimate of their high ash content (Sandberg, 1990). Our greater resource numbers for T. 34 N., R. 4, 5, 6 W. (table 4) over

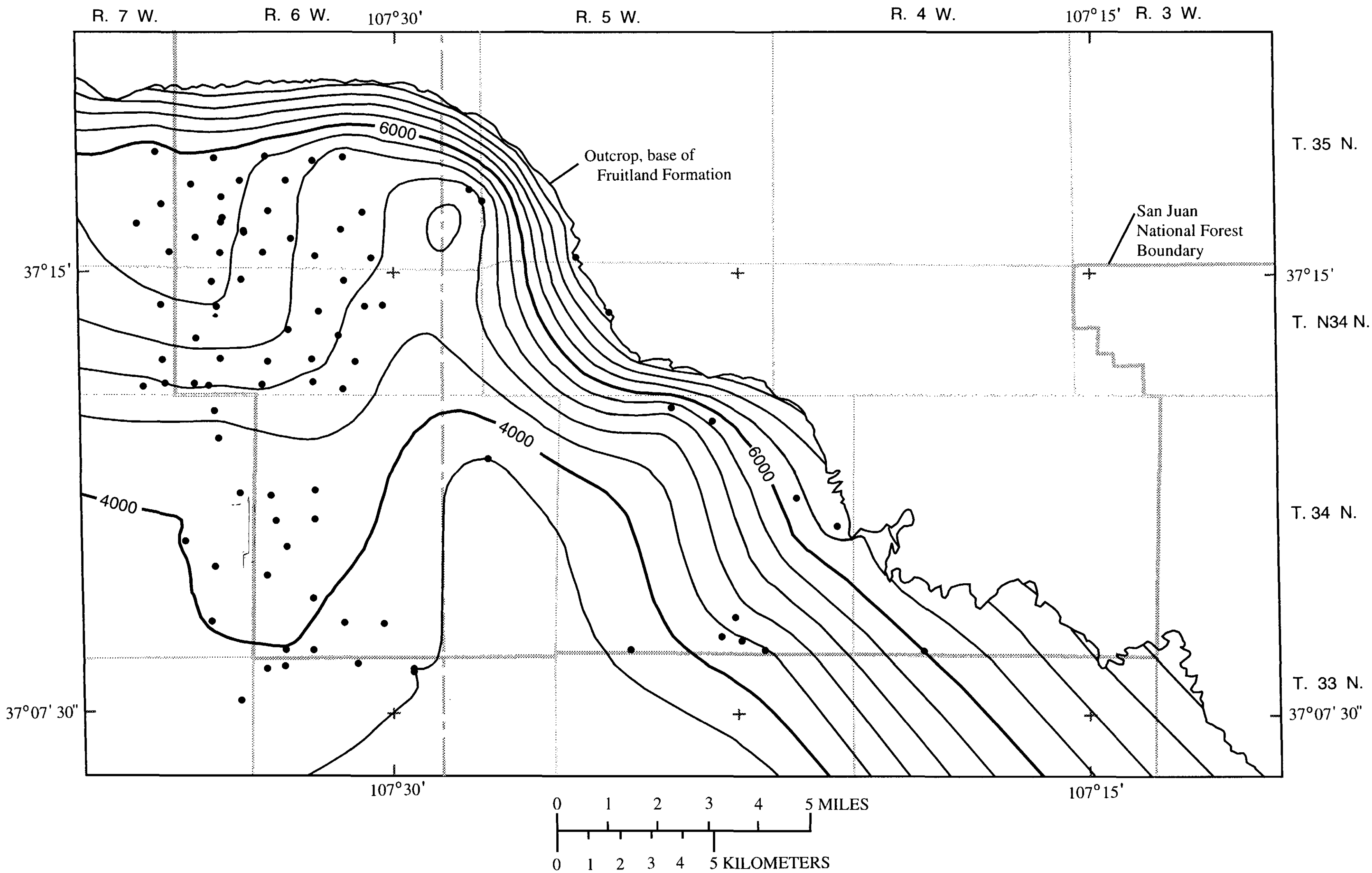


Figure 56. Structure contours on top of highest Fruitland Formation coal bed, south-central part of San Juan National Forest. Contour interval 400 ft. Contour elevations in feet. The designation T. N34 N. is used to differentiate between two townships that are both designated T. 34 N. on topographic maps of the area.

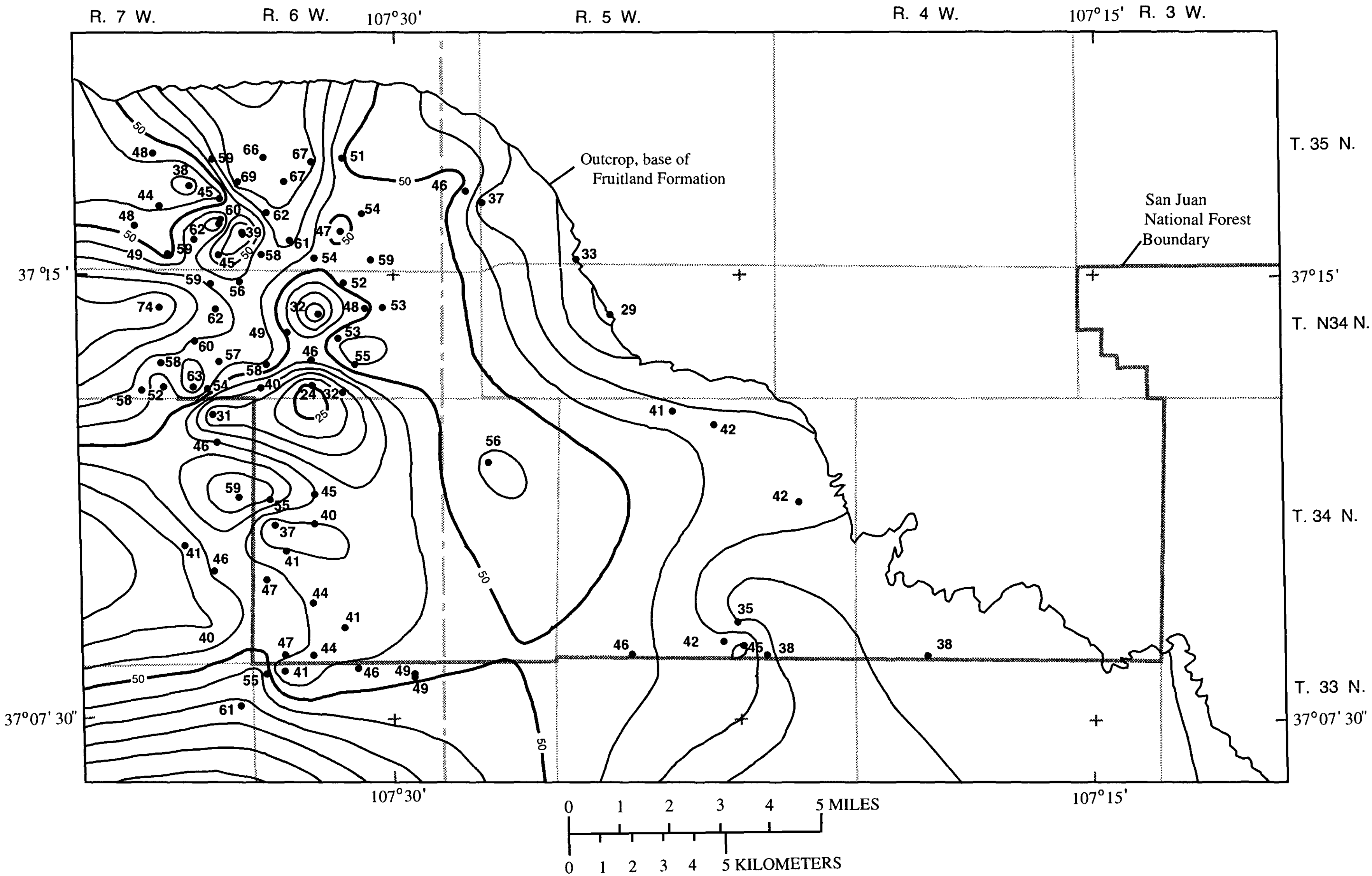


Figure 57. Isopach map of total coal in the Fruitland Formation, south-central part of San Juan National Forest. Numbers represent total coal, in feet, at data point. Contour interval 5 ft. The designation T. N34 N. is used to differentiate between two townships that are both designated T. 34 N. on topographic maps of the area.

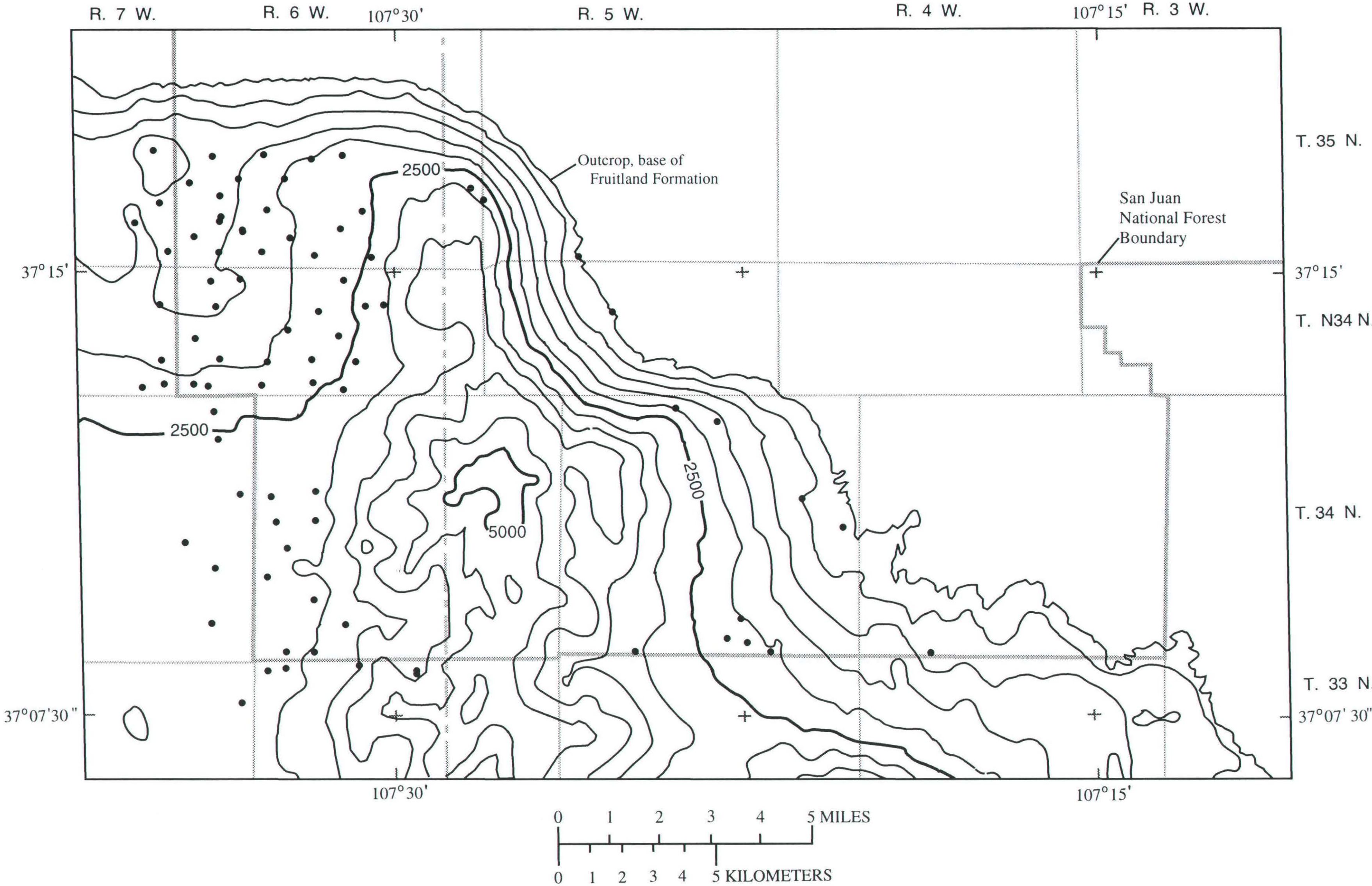


Figure 58. Overburden thickness to top of first Fruitland Formation coal bed, south-central part of San Juan National Forest. Isopach interval 500 ft. The designation T. N34 N. is used to differentiate between two townships that are both designated T. 34 N. on topographic maps of the area.

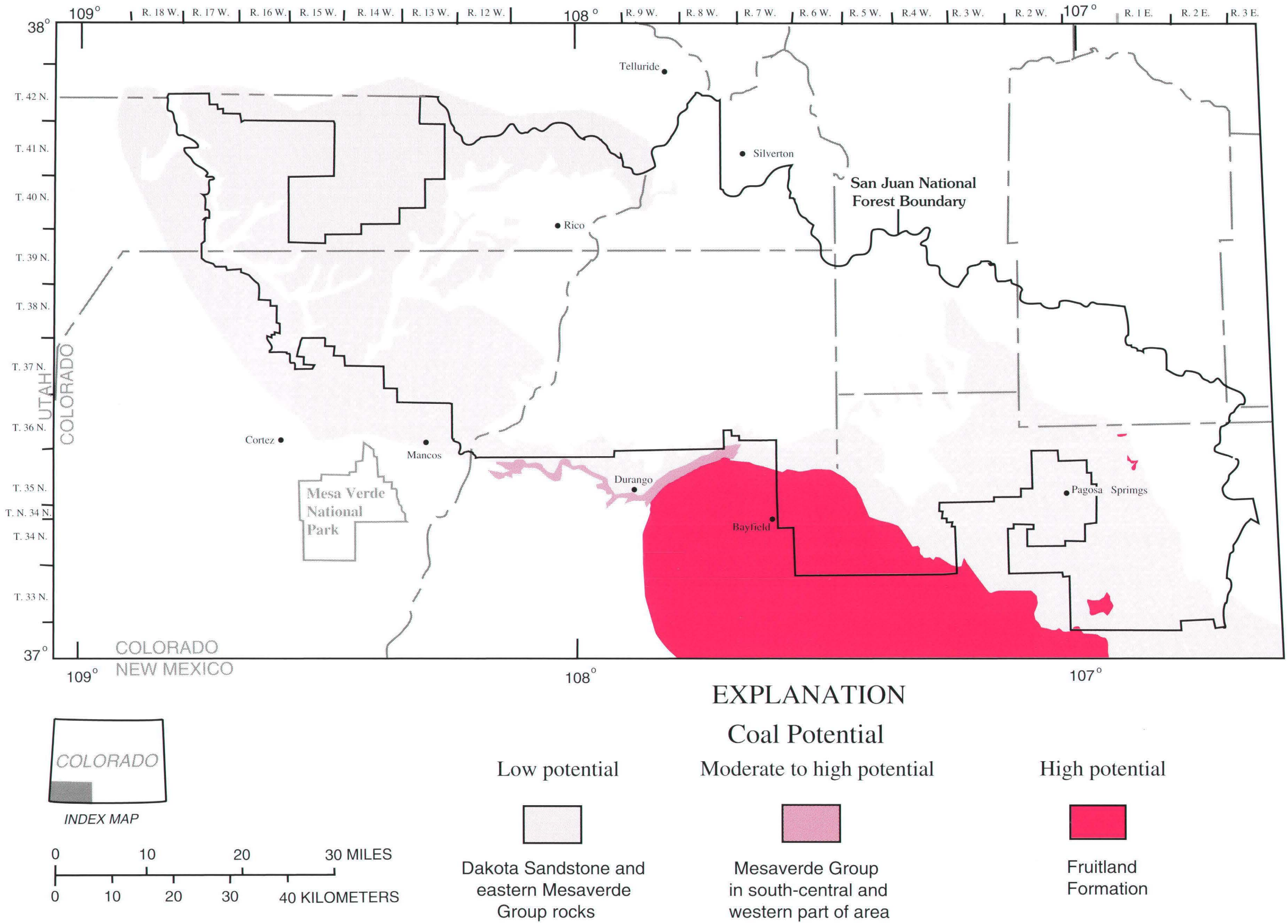


Figure 59. Map showing coal resource potential of areas underlain by coal-bearing Upper Cretaceous stratigraphic units, San Juan National Forest. The designation T. N34 N. is used to differentiate between two townships that are both designated T. 34 N. on topographic maps of the area.

those made by Sandberg (1991) apparently reflect these differences in measurements.

COAL RESOURCE POTENTIAL

The potential for recoverable coal resources in the Forest is variable. Our qualitative assessment of high, medium, and low coal resource potential in various areas of the Forest is based upon the general geology, past and current mining operations, and the known distribution, thickness, quantity, and quality of coal in stratigraphic units. The Dakota Sandstone, which covers large areas of the Forest, has a low potential for recoverable coal; the Menefee Formation of the Mesaverde Group, although it lies mainly outside the Forest, has a moderate to high potential; and the Fruitland Formation, which covers a significant part of the Forest, has a high potential. Figure 59 shows resource potential for recoverable coal in various areas of the Forest and vicinity, based on the distribution of the three formations. Plate 3 shows area of the Forest favorable for coal in the Fruitland Formation.

COAL-BED GAS RESOURCES

By Dudley D. Rice

INTRODUCTION

The part of the San Juan National Forest in the northern part of the San Juan Basin (fig. 53) is considered to have significant potential for coal-bed gas resources in the Upper Cretaceous Fruitland Formation, with coal beds serving as both the reservoir and source rock (figs. 54, 61). The regional geologic framework and coal-bed gas potential of the Fruitland Formation in the San Juan Basin are presented by Choate and others (1984), Fassett (1988), Kelso and others (1980), Kelso and Rushworth (1988), Kelso and others (1988), and Ayers and others (1991). Although coal beds are present in the Upper Cretaceous Menefee Formation of the Mesaverde Group, they are not evaluated in this study because of the thinness of the coal beds and because no commercial production has been established. However, Menefee coals are considered to be the probable source for some of the gas in adjacent low-permeability sandstone reservoirs of the Mesaverde Group.

CHARACTER OF COAL AND COAL-BED GAS

Coal beds are widespread in the lower part of the Fruitland Formation throughout most of the San Juan Basin. The following data are from M'Gonigle and Roberts in the preceding section of this report on coal resources. In the San Juan National Forest, the total thickness of Fruitland coal beds individually greater than 1.2 ft thick ranges from about 35 to 50 ft. The coal resources are estimated to be about $6{,}170\times10^6$ short tons (table 5). In the Forest, the Fruitland coal beds generally dip steeply to the southwest along the Hogback monocline into the main part of the basin (fig. 56). The coal beds crop out along the northeastern flank of the basin and occur at depths of as much as 5,000 ft (fig. 58), their deepest present-day depth of burial in the basin. The rank of the Fruitland coals in the Forest increases to the southwest from high-volatile A bituminous to medium-volatile bituminous (vitrinite reflectance (R_0) values of 0.8 to 1.2 percent) (Rice, 1983; Law, 1992). The area of highest rank does not coincide with the area of maximum present-day depth of burial.

Regional trends suggest that the coal-bed gases in the Forest are composed mainly of methane (gas wetness (C_{2+}) values less than 3 percent) with some carbon dioxide (less than 6 percent) (Rice and others, 1989; Scott and others, 1991). The molecular and isotopic composition of the gases indicates that the coal-bed gases are mainly thermogenic with mixing of some relatively recent biogenic methane and carbon dioxide associated with ground-water flow (Scott and others, 1991; Rice, in press).

FACTORS AFFECTING THE DEVELOPMENT OF COAL-BED GAS RESOURCES

Three factors—present-day depth of burial of coals, water, and topography—will influence the development and production of the coal-bed gas resources in the San Juan National Forest. Although most of the Fruitland coal beds will contain significant quantities of commercial gas at depths greater than about 500 ft, commercial production of the gas will depend on the development of permeability that occurs mainly in the cleat (fracture) system. This cleat-associated permeability is strongly influenced by in situ stress or depth of burial, such that there is a general decrease in permeability with increasing depth of burial (McKee and others, 1988). Current production of Fruitland coal-bed gas in the San Juan Basin extends to depths of about 3,000 ft. The effect of an additional 2,000 ft of overburden (total of 5,000 ft) in the southern part of the San Juan National Forest (fig. 58) on permeability of the coals, and thus economic production of coal-bed gas, is unknown.

The Fruitland coals are aquifers in the San Juan National Forest and are in an area of recharge characterized by the influx of high amounts of relatively fresh water, as indicated by low total dissolved solids (TDS) and low chlorinity (Kaiser, Ayers, and others, 1991). This recharge is probably the result of high rainfall in the La Plata and San Juan Mountains to the north and tectonically enhanced cleats in relatively continuous coals, which crop out in this area.

Table 4. Estimated original coal resources of the Upper Cretaceous Fruitland Formation, by township, for total coal in beds greater than 1.2 ft thick in the San Juan National Forest, Colorado

[Resources given in millions of short tons. Leaders (--) indicate no resources in that category. The designation "T. N34 N." is used to differentiate between two townships that are both designated "T. 34 N." on topographic maps of the area]

Overburden (ft)	Measured	Indicated	Inferred	Hypothetical	Subtotal
		T. 35 N., R. 6 W.			
0–500	--	--	161.9	--	161.9
500–1,000	--	22.7	113.5	--	136.2
1,000–2,000	175.5	320.9	66.2	--	562.6
2,000–3,000	77.3	229.7	58.0	--	365.0
>3,000	3.8	42.0	95.3	--	141.1
Subtotal	256.6	615.3	494.9	--	1,366.8
		T. 35 N., R. 5 W.			
0–500	3.1	6.1	27.9	--	37.1
500–1,000	--	10.2	27.0	--	37.2
1,000–2,000	--	24.4	24.7	--	49.1
2,000–3,000	5.9	13.0	12.4	--	31.3
>3,000	0.7	6.5	10.6	--	17.8
Subtotal	9.7	60.2	102.6	--	172.5
		T. N34 N., R. 6 W.			
0–500	--	--	--	--	--
500–1,000	--	--	--	--	--
1,000–2,000	79.6	213.4	2.6	--	295.6
2,000–3,000	120.5	197.7	7.3	--	325.5
>3,000	3.2	42.7	208.9	--	254.8
Subtotal	203.3	453.8	218.8	--	875.9
		T. N34 N., R. 5 W.			
0–500	5.2	35.1	31.4	--	71.7
500–1,000	--	28.6	19.4	--	48.0
1,000–2,000	--	9.6	86.1	--	95.7
2,000–3,000	--	--	80.1	--	80.1
>3,000	--	--	88.2	--	88.2
Subtotal	5.2	73.3	305.2	--	383.7
		T. 34 N., R. 6 W.			
0–500	--	--	--	--	--
500–1,000	--	--	--	--	--
1,000–2,000	--	--	--	--	--
2,000–3,000	85.9	237.8	49.3	--	373.0
>3,000	29.0	238.4	970.3	--	1,237.7
Subtotal	114.9	476.2	1,019.6	--	1,610.7
		T. 34 N., R. 5 W.			
0–500	2.0	25.5	82.9	--	110.4
500–1,000	7.5	48.8	90.1	--	146.4
1,000–2,000	20.4	104.0	168.5	--	292.9
2,000–3,000	33.0	91.2	249.7	--	373.9
>3,000	7.0	36.0	491.2	--	534.2
Subtotal	69.9	305.5	1,082.4	--	1,457.8
		T. 34 N., R. 4 W.			
0–500	--	1.8	141.8	14.0	157.6
500–1,000	7.1	31.0	84.1	0.4	122.6
1,000–2,000	--	7.6	15.9	--	23.5
2,000–3,000	--	--	--	--	--
>3,000	--	--	--	--	--
Subtotal	7.1	40.4	241.8	14.4	303.7

Table 5. Summary table, estimated original coal resources for total coal in beds greater than 1.2 feet thick in the Upper Cretaceous Fruitland Formation in the San Juan National Forest, Colorado.

[Resources given in millions of short tons. Leaders (--) indicate no resources in that category]

Overburden (ft)	Measured	Indicated	Inferred	Hypothetical	Subtotal
0–500	10.3	68.5	445.9	14.0	538.7
500–1,000	14.6	141.3	334.1	0.4	490.4
1,000–2,000	275.5	679.9	364.0	--	1,319.4
2,000–3,000	322.6	769.4	456.8	--	1,548.8
>3,000	43.7	365.6	1,864.5	--	2,273.8
Subtotal	666.7	2,024.7	3,465.3	14.4	6,171.1

The southward flow of ground water into the basin has resulted in artesian overpressuring and production of large amounts of water from the coal beds in the northern part of the basin (Kaiser, Swartz, and Hawkins, 1991). The disposal of this produced water affects the economical development of the coal-bed gas resources and poses an environmental concern. Under the control of Federal, State, and local agencies, most of the produced water in the northern San Juan Basin is disposed of in underground injection wells (Zimpler and others, 1988). In addition, the water from individual wells must also be transported to these injection wells by truck or pipeline.

As much as 2,500 ft of relief is present in that part of the San Juan National Forest with potential for coal-bed gas. The lower elevations are mainly in the drainage areas of the Los Pinos and Piedra Rivers, where most of the development of coal-bed gas has taken place to date. The highest elevations are present in the area of Pargin Mountain, about 10 mi east of Bayfield in central part of the area of coal-bed-gas potential (plate 3). Development of coal-bed gas resources, including siting and drilling of wells and construction of roads and pipelines, will probably be restricted in forested areas with steep slopes. In addition, the topographically high areas coincide with areas of maximum burial depths of the Fruitland coal beds. As stated earlier, this increased depth has the effect of reducing both permeability and gas production rates.

Coal-bed gas wells commonly exhibit a distinctive production history because of the relation between gas and water production (Kuuskraa and Brandenberg, 1989) (fig. 60). In general, the early stage of production from a well, the dewatering stage, is characterized by large volumes of water and small volumes of gas. As the coal-bed reservoir is depressurized by dewatering, increasing amounts of gas begin to desorb, diffuse through the matrix, and flow through the cleats to the wellbore. A "negative decline" curve for water is maintained during the dewatering and stable production stages, whereas the decline stage for gas begins at the end of the stable production stage. Some drilling and production of coal-bed gas have already taken place in the southeastern part of San Juan National Forest; about 45 wells have been completed in Fruitland coals, and two wells have commingled production from the underlying Pictured Cliffs Sandstone and Fruitland coals. Possible trends can be predicted from production histories of four coal-bed gas wells in the eastern part of the Forest (secs. 31 and 32, T. 35 N., R. 6 W.) producing at depths of about 1,500–2,000 ft. Three of the wells are distinguished by increasing gas production rates (as much as about 900,000 cubic feet (900 MCF) per day) and decreasing volumes of water production (less than 300 barrels per day) over a period of about 4 years (1989–92). The wells are, at present, in the stable production stage; their production histories are typical of coal-bed gas wells, as illustrated by figure 60. During the same period, the other well produced large amounts of water (more than 1,000 barrels per day) and smaller amounts of gas (about 300 MCF per day). This well may be draining water from the area of the other three wells, or the Fruitland coals in this well may be characterized by high permeability. The line pressure for these wells was reduced in May 1992, resulting in reduced water and increased gas production rates (J. McAnear, Amoco Production Co., oral commun., 1992). Wells completed in more deeply buried coals are expected to have lower production rates for both gas and water because of reduced permeability.

COAL-BED GAS RESOURCE ESTIMATES

Estimates of in-place gas resources in the Fruitland coal beds in the San Juan Basin have been made using information on thickness, areal extent, density/rank, and gas content of the coal beds (Choate and others, 1984; Kelso and others, 1988). The most recent in-place estimate of Fruitland coal-bed gas for the basin is about 50 trillion cubic feet (TCF) (Kelso and others, 1988). Using information on coal resources by depth increments (table 4), gas contents versus depth and rank from Kelso and others (1988) and unpublished data, as well as rank data from Rice (1983) and Law (1992), the most likely in-place resources of coal-bed gas in the Fruitland coal beds in the Forest (fig. 61 and area M, plate 3) are estimated to be about 1.5 TCF at depths greater than 500 ft. The low estimate of coal-bed gas in place is in the range of 1 TCF, and the high estimate is about 3.5 TCF. The range of values reflects the uncertainty of coal resources in undrilled areas and the variability of gas content with rank

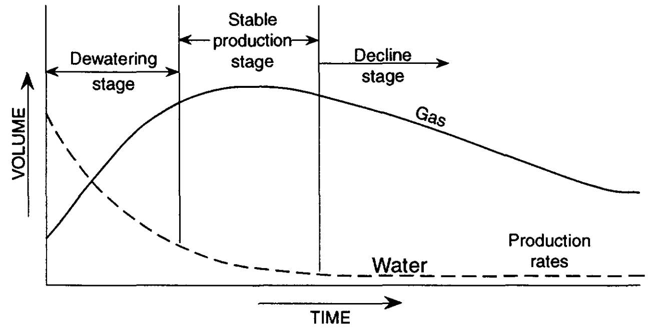


Figure 60. Generalized gas- and water-production curves for a typical coal-bed gas well. From Kuuskraa and Brandenberg (1989).

and depth, especially at depths below 3,000 ft where few data are available.

TIGHT GAS RESOURCES

By Charles W. Spencer *and* Craig J. Wandrey

INTRODUCTION

Tight gas (very low permeability) reservoirs are present in a small area of the San Juan National Forest in eastern La Plata and western Archuleta Counties (fig. 5). The part of the Forest with tight gas potential lies within the San Juan Basin (figs. 53, 62). The rocks containing tight gas comprise the Dakota Sandstone, the Juana Lopez Member ("Sanostee" of industry usage) of the Mancos Shale, the Mesaverde Group, and Pictured Cliffs Sandstone—all of Late Cretaceous age. This chapter provides a brief review of the character of tight gas reservoirs and their resource potential within the San Juan National Forest.

The compilation of data for this assessment of the Forest was done in several steps: (1) retrieval was made of all wells drilled in and near the Forest using the Petroleum Information Corp. Well History Control System (WHCS) computer file, (2) a review was made of selected well logs and operator reports, (3) the regional stratigraphy and structure were reviewed, and (4) the production history of San Juan Basin gas wells in and adjacent to the Forest was compiled. This compilation included annual gas production from 21 Dakota Sandstone and three Mesaverde Group producing wells.

TIGHT GAS RESERVOIR CHARACTERISTICS

Tight gas reservoirs are very low permeability gas-bearing rocks. In the Forest and adjacent areas they comprise mostly sandstone and siltstone. The reservoirs have an in-situ permeability to gas of 0.1 millidarcy (mD) or less. Gas production rates and recovery are strongly dependent on the presence of natural fracturing. These reservoirs characteristically produce little or no water with the gas and do not have gas/water contacts. Spencer (1989) provides a detailed review of tight gas reservoir characteristics.

The U.S. Geological Survey has been conducting detailed studies of tight gas (also termed "unconventional") reservoirs in many Rocky Mountain basins since 1978. Much of this work was done in cooperation with the U.S. Department of Energy, and references to more than 260 of these publications are reported in Krupa and Spencer (1989).

Most of the tight gas reservoirs, here and elsewhere, require artificial hydraulic fracturing in order to produce economic quantities of gas. Hydraulic fracturing was developed by the parent company of Amoco Production Company in the late 1940's. The first extensive use of this technique was to stimulate production from Upper Cretaceous rocks in part of the San Juan Basin in New Mexico. Hydraulic fracturing consists of injecting a proppant (usually sand) and a carrying gel (mostly water) into a formation at a downhole pressure sufficiently high to "crack" the formation and drive the sand and gel mixture along artificially created fractures some distance into the reservoir. The sand proppant helps to prevent the fractures from closing, which allows formation gas access to the wellbore. Commonly, the wells will produce some gel water early in their production history, and this amount decreases with time. If the volume of water increases with time, it usually indicates that formation (connate) water is being produced. Typically, conventional (not tight gas) reservoirs will yield large volumes of water late in their production history.

As a general rule, most shallow (less than 5,000 ft) reservoirs are conventional and produce from mappable structural and stratigraphic traps. Tight gas sandstone reservoirs in Cretaceous basins in the Rocky Mountains generally are found at depths greater than 5,000 ft and usually occur deeper than 6,000–8,000 ft, depending on the depositional and thermal (diagenetic) history of a given basin. In the San Juan Basin, most designated tight gas reservoirs are deeper than 5,000 ft, although some wells less than 5,000 ft in the Upper Cretaceous Pictured Cliffs Sandstone have been certified as "tight" in the New Mexico part of the basin. Structure contours on figure 56 are drawn on top of the "highest" Upper Cretaceous Fruitland Formation coal. This coal is about 5,000 ft shallower than the Dakota Sandstone and about 2,500 ft shallower than the Mesaverde Group in the part of the Forest prospective for tight gas. The map (fig. 56) serves to crudely show structure on the deeper rocks. It is an approximation only because the "highest" coal varies with Fruitland stratigraphy. The relationships among the Dakota Sandstone, Mesaverde Group, and Fruitland Formation, and associated Cretaceous rocks are well shown by Molenaar and Baird (1991). A cross section, shown on fig. 52, extends into

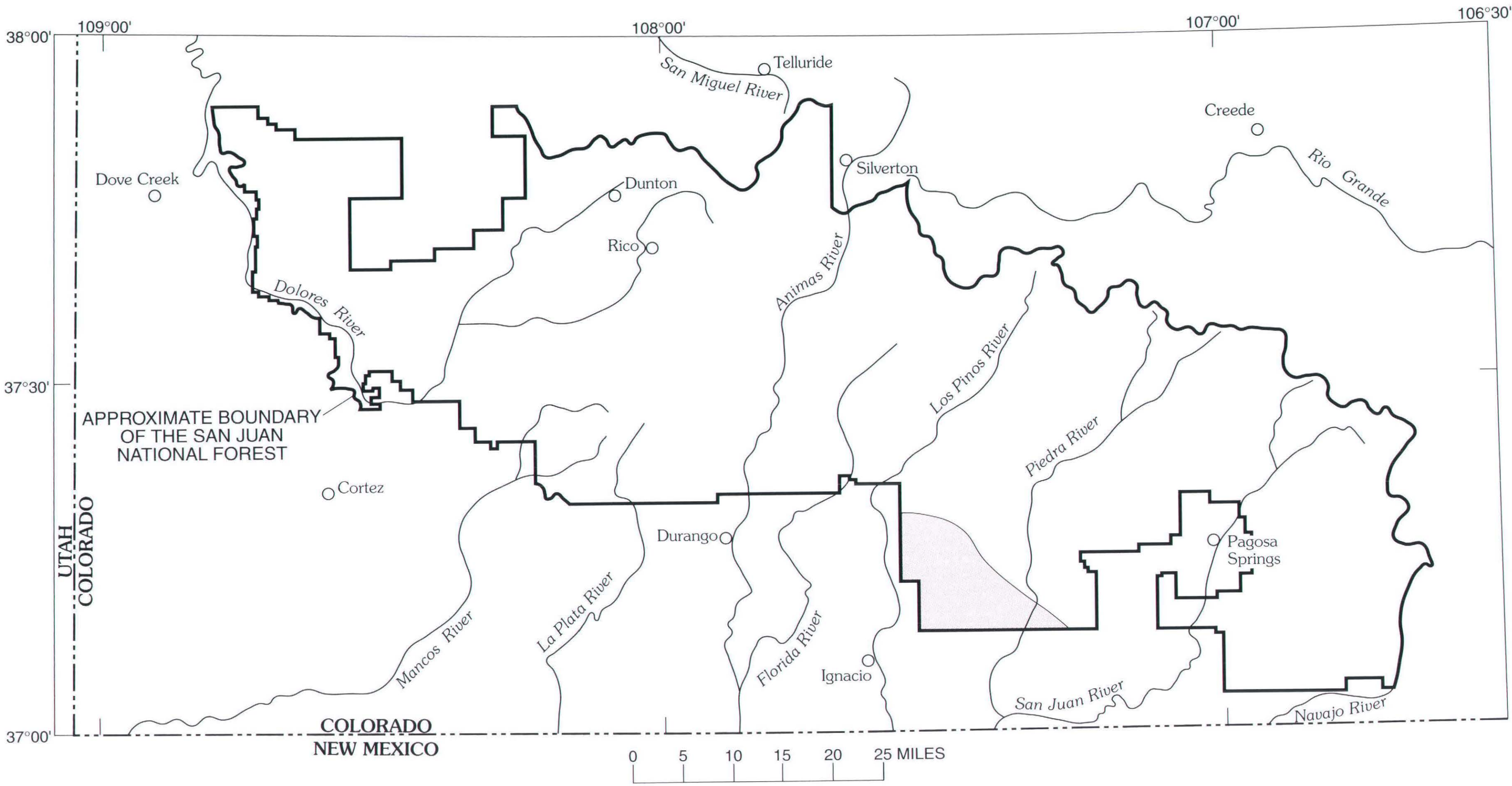


Figure 61. Map showing area favorable for coal-bed gas in the San Juan National Forest.

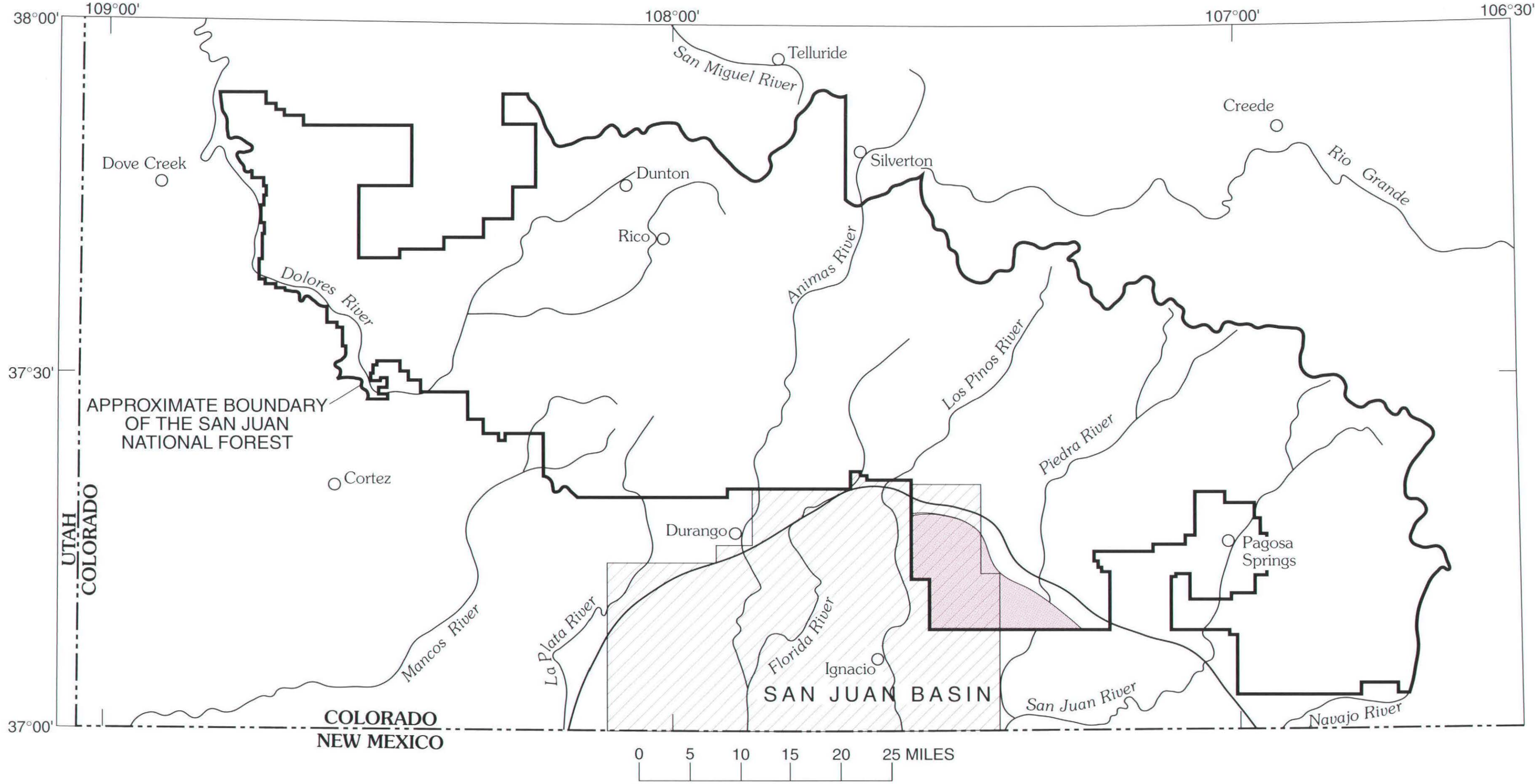


Figure 62. Map showing area favorable for tight gas resources in the San Juan National Forest. Tight gas area designated by the Federal Energy Regulatory Commission (FERC) is shown by cross-hatch pattern.

the Forest to a 6,995-ft-deep well in sec. 32, T. 35 N., R. 6 W., La Plata County, Colorado.

The San Juan Basin has produced gas from Cretaceous rocks for more than 40 years. Most of this production came from near-tight (1.0 to 0.1 mD) rocks, commonly called sweet spots. Many other wells were never completed, or they were abandoned, because of low gas prices. The gas shortages of the 1970's caused the U.S. Congress to authorize incentive (higher) prices for gas from certain qualified tight gas reservoirs. A surplus of gas in the mid to late 1980's caused prices to decline, and interest in new drilling for tight gas waned until introduction of a tax of 52 cents per MCF for gas produced after December 31, 1990, from qualified wells. Both incentive policies (price and tax) resulted in certain areas (formations and wells) being "qualified" by the Federal Energy Regulatory Commission (FERC) as tight gas areas. To date, about 70 percent of the area in the Forest with tight gas potential has been certified as "tight" for tax-credit purposes, but only a few deep (>5,000 ft) wells have been drilled in the San Juan Basin part of the Forest. Figure 62 shows the tight gas designated area within and adjacent to the Forest. Tight gas designations are requested by oil and gas lessees, and, if not requested by a lessee, no designations are made by FERC. FERC only approves those areas that meet specific criteria for demonstration of rock low permeability.

PRODUCTION AND POTENTIAL

Dutton and others (1993) provide a summary of San Juan Basin tight gas reservoirs from both Colorado and New Mexico and ultimate recoveries from them. They note that about 17,000 oil and gas wells have been drilled in the basin. They also estimate that all tight gas reservoirs in the basin will ultimately produce more than 22 TCF (Dutton and others, 1993, p. 270) from 13,549 tight gas completions (as of 1988) in five Upper Cretaceous formations. Only two of these formations, the Dakota Sandstone and the Mesaverde Group, are believed to have potential for significant tight gas production in the Forest. Of these, the Dakota has the better potential.

Production records in Petroleum Information's PetroROM production data file were compiled by well and by year for most wells adjacent to the Forest. This file also identified wells that have received a tight gas certification by FERC. This retrieval did not find any tight gas designated wells with production in the Forest; however, some wells drilled after June 1991 may not have been included in the data file.

Gas and water production was analyzed for 19 Dakota and 3 Mesaverde tight gas designated wells and 2 conventional Dakota wells near the Forest. Generally, the conventional (not tight) Dakota Sandstone wells have produced gas in economic quantities. The few producing Mesaverde wells near the Forest are poor. Many of the tight gas designated wells that produce from the Dakota appear to be marginally commercial or uneconomic at 1993 gas prices of $2.00 per MCF or less.

On the basis of well histories, log analysis, and other factors, tight gas reservoirs are present in a small portion of the Forest (fig. 62 and area N, plate 3). The area with potential for gas contained in "tight" reservoirs in the Forest covers about 70 mi^2. We estimate that, most likely, there are 36 well locations in the Forest that would produce about 0.5 billion cubic feet (BCF) each for a most likely recoverable resource of 18 BCF. The most likely probability will result in a recoverable volume of gas from the Forest of 6 BCF (95 percent probability) and a least likely (5 percent probability) of 40 BCF.

CONVENTIONAL OIL AND GAS RESOURCES

By A. Curtis Huffman, Jr. *and*
Cornelius M. Molenaar

INTRODUCTION

The San Juan National Forest includes parts of two major petroleum provinces, the San Juan Basin in the east and the Paradox Basin in the west (fig. 53). Estimates of undiscovered oil and gas resources in the Forest are derived from the 1989 National Assessment of undiscovered oil and gas resources (in U.S. Geological Survey and Minerals Management Service, 1989), which used a methodology based on analysis of petroleum exploration plays. A play is a set of oil or gas accumulations that are geologically, geographically, and temporally related and that exist by virtue of identical or similar geological conditions. The oil or gas accumulations may be known to exist or may be completely hypothetical and may be discovered or undiscovered. Such geological characteristics as reservoir lithology, timing and migration, trapping mechanisms and source rock are taken into consideration in the definition and evaluation of each play. In order to assess the potential oil and gas resources of San Juan National Forest land, play analysis methodology and the same plays that were defined and evaluated for the 1989 National Assessment were used (Powers, 1993; Huffman, 1987; U.S. Geological Survey and Minerals Management Service, 1989; Peterson, 1989). In addition to the conventional resources treated here and in the National Assessment, two unconventional reservoir types, tight gas sands and coal-bed gas, are evaluated in preceding sections of this report.

Most of the Forest has been very sparsely tested for petroleum resources, resulting in a wide spread between the high and low probability estimates. According to the 1989 National Assessment, the most likely estimates of 16 MMBO (million barrels of oil) and 26 BCF of gas indicate a rather low potential for undiscovered conventional petroleum resources. Most of these resources will be distributed in small- to moderate-size accumulations rather than concentrated in a few large ones. Much of the favorable area (figs. 63, 65, and 66) will be gas prone because of burial depths, source rock type, proximity to intrusive rock heat sources, or various combinations of these (fig. 64). The eastern side of the Forest, east of the Animas River, has a higher potential for oil and some associated gas, whereas the western side has a greater potential for nonassociated gas. Devonian and Mississippian rocks on the west side of the Forest were not assessed even though both probably have some potential. The reason for this was the uncertainty involving the presence and percentage of CO_2 in the natural gas and the likelihood of increased CO_2 percentages in the vicinity of Laramide-age and younger intrusives (see plate 1). We could not assign a probability to the occurrence of CO_2 as opposed to natural gas.

DAKOTA SANDSTONE PLAY

The southeastern part of the San Juan National Forest lies within the northern part of the Dakota Oil and Gas Play of the San Juan Basin (fig. 63 and area O, plate 3). This play is in shallow marine sandstone and continental fluvial sandstone units, primarily within the transgressive Upper Cretaceous Dakota Sandstone. In the basinal portion, it is a gas play in which the traps are dominantly stratigraphic and the reservoirs are tight; on the flank of the basin, it is an oil and gas play in which the traps are typically both stratigraphic and structural and the reservoirs are conventional. The basin flank part of the play includes a portion of the southeastern part of the Forest. In the San Juan Basin area, reservoir quality within the Dakota producing interval is highly variable. Most of the marine sandstones within the Dakota of the central part of the basin are considered "tight," having porosities ranging from 5 to 15 percent and permeabilities generally less than 0.1 mD (see preceding section on tight gas reservoirs). Fracturing, both natural and induced, is essential for effective development. In contrast, a conventional reservoir such as the Gramps field (fig. 64), on the northern basin flank adjacent to the Forest, has an average reservoir porosity of 13 percent and permeability of about 100 mD. Permeabilities elsewhere may be as high as 400 mD. Source beds for Dakota oil and gas are in the marine shales of the overlying and intertonguing Mancos Shale and carbonaceous shale and coal of the Dakota Sandstone.

Most of the oil production from the Dakota Sandstone is from structural or combination traps on the flanks of the San Juan Basin. Some are located on faulted anticlinal structures, and the seal is commonly provided by either marine shale or paludal (marshy) carbonaceous shale and coal. Most of the basin-flank oil fields are small, that is, less than 1 MMBO, but approximately 30 percent of the fields have an estimated ultimate recovery exceeding 1 MMBO; the largest is Gramps field (fig. 64), which is estimated at just over 7 MMBO (Huffman, 1987). About 15 BCF of associated gas has been produced through 1990. Reservoir depths commonly range from 1,000 to 3,000 ft.

Within the San Juan National Forest, the Dakota is 150–200 ft thick. In depth it ranges from the surface outcrop at the basin flank to about 6,000 ft. The Gramps field is on the faulted crest of an asymmetrical anticline and has produced almost 6 MMBO from the Dakota at a depth of about 1,100 ft. Other significant shows noted in drilling associated with the field occur in the Upper Cretaceous Bridge Creek Limestone Member of the Mancos Shale and the Middle Jurassic Entrada Sandstone and Upper Jurassic Morrison Formation. Dakota oil at the Gramps field is characterized as intermediate paraffinic with an API gravity of 31.4° and a 60° pour point (Donovan, 1978).

The easternmost part of the San Juan National Forest is covered by the San Juan volcanic field of the San Juan Mountains and includes part of the San Juan Sag Play of Gries (1985) (fig. 64). This industry play was based on traps, primarily in Cretaceous rocks, below the volcanic cover. Oil seeps and staining in surface igneous rocks and in mining company cores in the sag area (fig. 64), which have been known for many years, caught the attention of petroleum geologists in the oil-boom years of the early and middle 1980's. About 12 tests were drilled by industry in this play in the last 8 or 10 years; the last one was drilled in 1990. All the wells were drilled east of the San Juan National Forest; most of the wells were along the eastern foothills of the San Juan Mountains in the Del Norte area. The main objective of most tests in the San Juan Sag Play was the Dakota Sandstone, although the thick eolian Middle Jurassic Entrada Sandstone and Upper Jurassic Junction Creek Sandstone were secondary objectives. Many of the tests had good oil and gas shows in igneous sills and fractured Cretaceous shales. For a few months, one was a marginal producer from a fractured igneous sill in the Mancos Shale before it was abandoned. Hydrocarbon shows encountered in many of the wells in the area, as well as several surface indications of oil in igneous rocks and the oil found in igneous rocks in some mining company cores, indicate that there are mature hydrocarbon source rocks in the system. The source rocks are undoubtedly in the lower part of the Mancos Shale. Therefore, it seems reasonable to assume that the area has potential for oil and gas accumulations. Prior to the inception of the industry's San Juan Sag Play, Ryder (1985) discussed the petroleum potential of South San Juan Mountains Wilderness Area (fig. 6), which covers much of the easternmost San Juan National Forest area.

Although the area of the San Juan sag and the easternmost part of the Forest has fair to good potential for

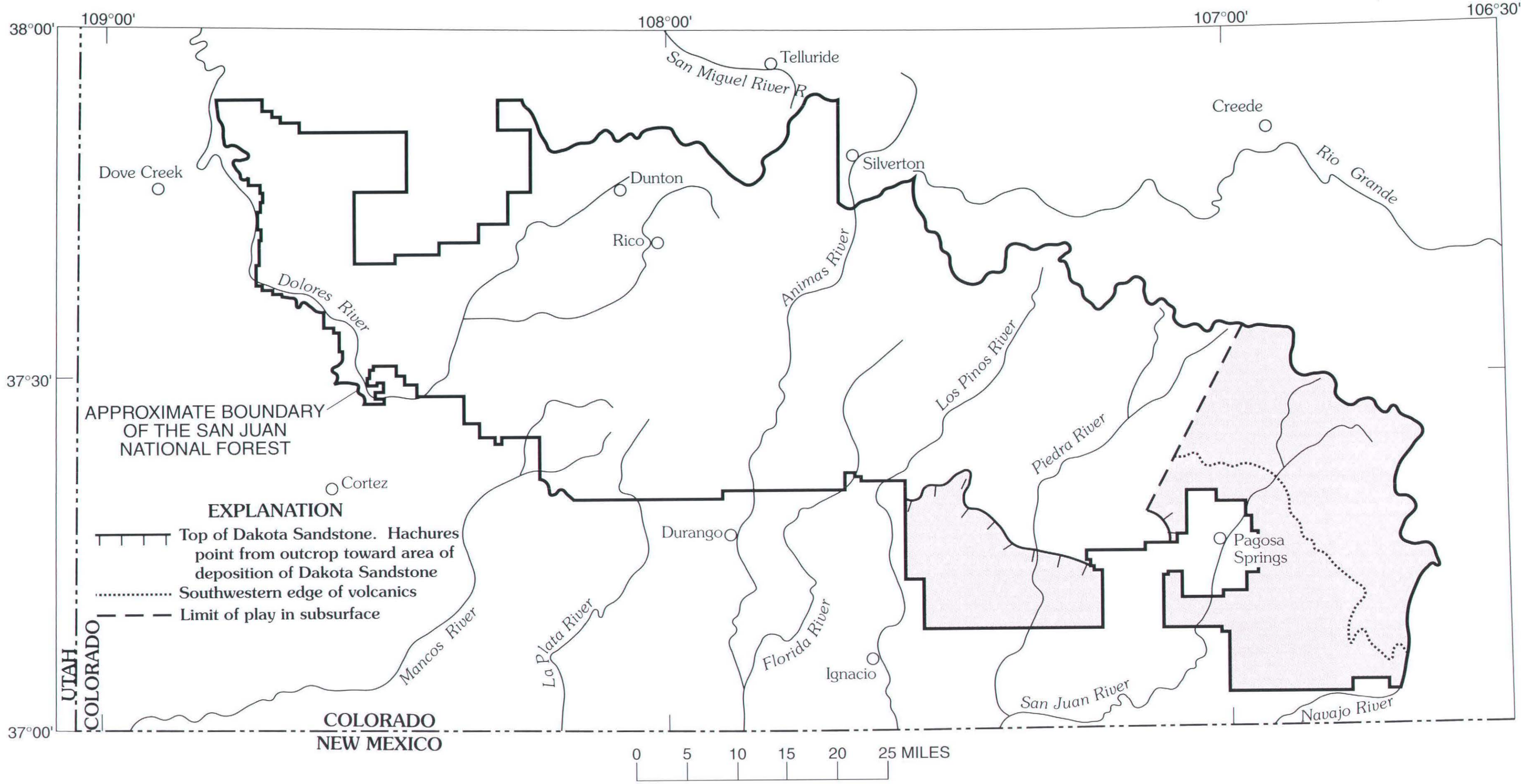


Figure 63. Outline of Dakota Oil and Gas Play within the San Juan National Forest.

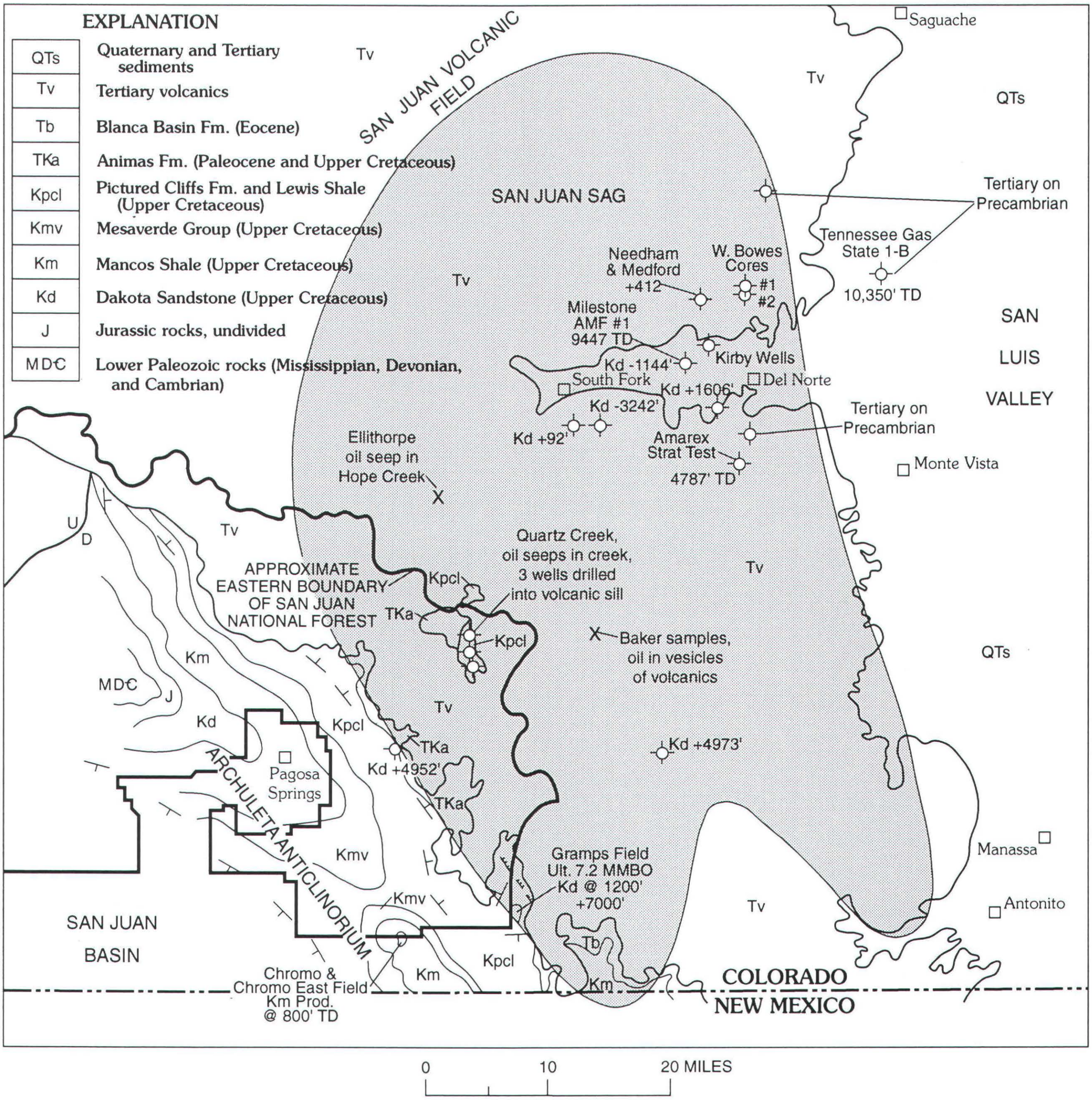


Figure 64. Index map showing significant wells, oil shows, and production in the vicinity of the San Juan volcanic field and San Juan sag. Modified from Gries (1985). Numbers near wells are subsurface elevations (in feet referenced to sea level) of top of Dakota Sandstone.

containing hydrocarbon accumulations, the favorable factors are offset by the difficulties in finding the traps. Some of the problems in this high-risk area are:

1. The high rugged terrain makes seismic surveying very difficult and expensive. Many of the seismic surveys are conducted with helicopters, and costs are $40,000 to $50,000 per line mile.
2. The quality of the seismic data is poor. As the thickness of volcanics increases in the mountains, the seismic quality decreases.
3. The many igneous sills in the area are difficult or impossible to detect on seismic data. The last Amoco well, the Beaver Mountain Unit No. 1, encountered a 600-ft-thick sill that was intruded into the Dakota Sandstone. It had about the same seismic velocity as the Dakota.
4. The igneous activity has locally baked the adjacent shales into hornfels. Maturation of the source rocks ranges from the oil-generating range to super mature.
5. The area of the San Juan sag seems to be highly faulted under the volcanic cover. Note the variations of the elevation of the top of Dakota between wells

(fig. 64). Note especially the 3,334-ft relief between the wells 2 mi apart south and southeast of South Fork (fig. 64).

In summary, the Dakota Play in the southeastern part of the San Juan National Forest, in the rugged San Juan Mountains, has fair to good potential for containing hydrocarbon accumulations. However, finding them would be costly and difficult. The 10 or 12 tests in the comparatively easier-to-explore eastern foothills of the Del Norte area had oil shows, but no commercial discoveries so far. The structure, maturity, and proximity of shows and production from the Dakota Play make the likelihood of an occurrence similar to Gramps field very high, and there is a possibility of several similar accumulations being present under volcanic rocks along the eastern side of the Forest. A most likely value of 10 MMBO and 9 BCF of associated gas distributed between two or more fields is assigned to this play (fig. 63 and area O, plate 3).

FRACTURED MANCOS SHALE PLAY

In the 1989 San Juan Basin assessment, the Fractured Mancos Shale Play as used here was included in the Tocito-Gallup Play (Powers, 1993) because the New Mexico Oil and Gas Commission, for record-keeping purposes, considers all producing zones from the top of the Bridge Creek Limestone Member of the Mancos Shale (formerly Greenhorn Limestone Member) to the base of the Mesaverde Group as the Gallup interval. With the exception of the several fields producing from fractured Mancos Shale, nearly all production from this thick and rather nebulous interval has been, more specifically, from the Tocito Sandstone Lentil of the Mancos Shale and the Torrivio Member of the Gallup Sandstone. These sandstone reservoirs are all in the central and southern parts of the San Juan Basin and do not occur in the San Juan National Forest. In the northern part of the basin, the lithology of this interval, which is about 1,800 ft thick, is dominantly dark-gray marine shale. Hence, in the northern part of the basin and in the Forest, we are calling this the Fractured Mancos Shale Play (fig. 65 and area P, plate 3). Actually, much of the upper part of the lower half of the interval contains thin-bedded, very fine grained, dolomitic or calcareous sandstone or siltstone, which is the part that comprises the potential fractured reservoir.

Several fields, including Puerto Chiquito on the east and Verde on the west side of the San Juan Basin of New Mexico, have been developed in fractured Mancos Shale. The Mancos Shale contains 1–3 weight percent organic carbon and produces a sweet, low-sulfur, paraffin-base oil that ranges from 38° to 42° API gravity in the Verde field (8 MMBO), and from 34° to 40° API gravity in the Puerto Chiquito East (4.5 MMBO), Puerto Chiquito West (9 MMBO), and Boulder (2 MMBO) fields. The Mancos Shale of the central part of the San Juan Basin reached thermal maturity for oil generation in the late Eocene and for gas in the Oligocene.

All of the fractured shale fields are on or adjacent to monoclinal or anticlinal structures that form the structural boundary of the central part of the San Juan Basin. The same type of structures occupy much of the San Juan National Forest between Durango and Pagosa Springs, and similar conditions are likely to exist in this area. Dips of 10°–15° do not appear to be too steep; much of the production in the Verde and Boulder fields is from shale dipping at similar angles. Nearby, the Chromo field (fig. 64) indicates that conditions favorable for the occurrence of oil do, in fact, extend into the southeastern part of the San Juan National Forest.

It is very likely that an oil and gas field similar to the Boulder field (2 MMBO) exists within the San Juan National Forest, and it is possible that a Puerto Chiquito-size field (9 MMBO) is present. We therefore have assigned a most likely value of 3 MMBO and 3 BCF of associated gas to this play (fig. 65 and area P, plate 3), based on the presence of favorable structures and source rocks. There is a higher likelihood that oil and gas would be distributed between two or more smaller fields than in a single large field.

SILVERTON DELTA PLAY

Along the east flank of the Paradox Basin (fig. 53) in the western part of the San Juan National Forest, the Hermosa Group of Middle and Late Pennsylvanian age contains an easterly derived clastic facies known as the Silverton fan delta (Spoelhoef, 1976). The delta is made up of numerous depositional cycles, each of which includes a prodelta facies of dark marine shale. The prodelta units are believed to be correlative with the black organic-rich shales of the carbonate-evaporite cycles in the Paradox Basin to the west. Isopach maps of individual black shale units indicate that many of them thicken significantly in the vicinity of the delta complex (Peterson, 1989).

Limited subsurface data are available on the potential sandstone reservoirs of this play. However, some of these rocks crop out in the San Juan Mountains south of Silverton, where the delta-front sandstones have been described as well sorted, fine to medium grained, and arkosic (Spoelhoef, 1976). The arkosic and calcareous nature of much of the clastic section may be detrimental to consistently good porosity and permeability, but the variable energy regime of the deltaic depositional environment should enhance reservoir characteristics in many sandstone units. Although similar deposits occur in the eastern part of the Forest, they appear to be more arkosic and thus poorer reservoirs (Peterson, 1989).

Dark-gray or black marine shales of potential source-rock quality intertongue with the marine and delta-front sandstone facies along the western margin of the play area. These rocks are organic rich in the central

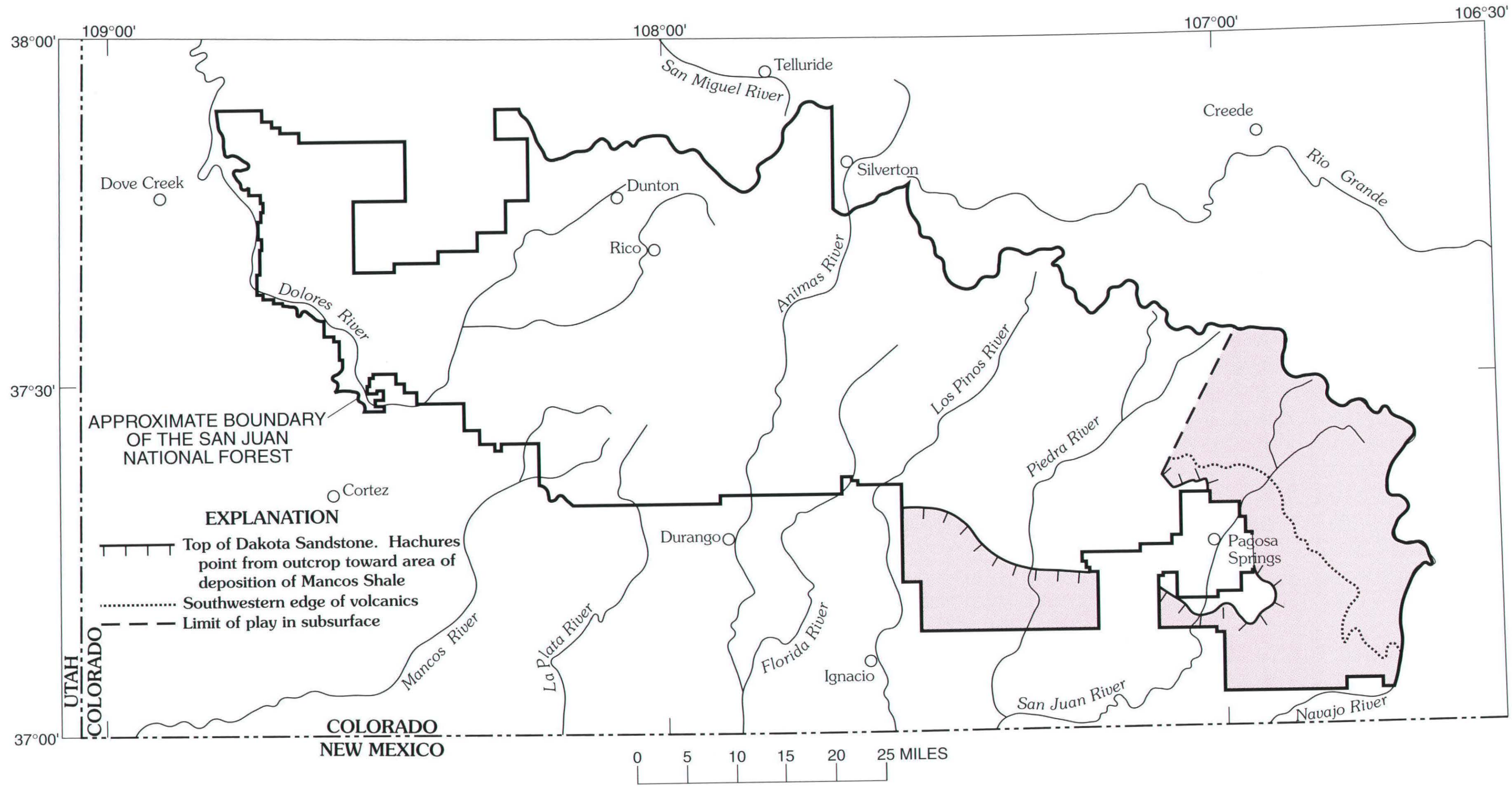


Figure 65. Outline of Fractured Mancos Shale Play within the San Juan National Forest.

Paradox Basin region and probably become more humic in character in the deltaic complex, where land-derived organic matter is more prevalent. The presence of large igneous intrusions (Rico, San Miguel, and La Plata Mountains, plate 1) suggests that greater maturation levels may be expected in parts of the area. The probability of type-III kerogen plus higher heat flow indicate that the Silverton delta area will be gas prone.

This play is speculative, and drilling density in the area is very low. At least one well on the northwest margin of the play had significant gas shows in sandstones of the Hermosa Group, which are probably part of the Silverton fan-delta complex. Many of the potential reservoir rocks crop out updip from the play area, increasing the probability of trap leakage and flushing of reservoirs by ground-water recharge, thus reducing the favorability of this play.

Traps should be a combination of structural and stratigraphic on folded and faulted structures of variable size. The presence of distributary, delta-fringe, and longshore sand bodies within the deltaic complex offer potential stratigraphic trap possibilities.

This play will remain highly speculative until more data are available, but we think there is at least some potential for small accumulations of nonassociated gas. The most likely estimate of 2 BCF assigned to the play (fig. 66 and area Q, plate 3) reflects our low confidence level but also a conviction that it should not be overlooked entirely.

CARBONATE BUILDUP PLAY

The most important petroleum production in the Paradox Basin province is from stratigraphically controlled carbonate reservoirs in the southern part of the Paradox Basin, most of which is well west of the Forest. This play, termed Carbonate Buildup Play (fig. 66, area R, plate 3), is predominantly oil bearing and contains only moderate amounts of associated gas. Reservoirs occur in a series of depositional cycles in the carbonate facies of the Hermosa Group of Middle and Late Pennsylvanian age (plate 1). The cycles of the carbonate facies pass laterally into evaporite cycles of the Middle Pennsylvanian Paradox Formation deeper in the basin. Organic-rich black shales or shaly carbonates of the "Chimney Rock and Gothic shales" of local usage are the main source rocks in this play, along with intertonguing organic-rich and shaly carbonates adjacent to the mound buildups. Crude oil from the Hermosa Group is low sulfur and 40°–43° API gravity. Accumulations occur primarily in isolated carbonate buildup belts that may or may not be associated with mapped structures. Structural closure is commonly influenced to varying degrees by draping over algal mound buildups. Lateral facies changes from porous biogenic reservoir rock to nonporous argillitic or anhydritic carbonate and shale aid in trapping. Seals are commonly black, organic-rich, high-carbonate shales or shaly carbonates and anhydrites. Basinal algal mound buildups, much smaller than those in the Aneth area west of the Forest, are usually sealed by overlying anhydrite beds.

This play is moderately to well explored, but use of high-resolution seismic techniques and detailed stratigraphic studies probably will result in discovery of small- to medium-sized new fields or new pool accumulations, primarily in stratigraphic traps.

The nearest production from this play is at the Dove Creek (1 BCF) and Papoose Canyon (5.8 MMBO/36 BCF) fields, which are approximately 15 mi west of the San Juan National Forest. Favorable conditions probably extend into the Forest (fig. 66 and area R, plate 3), but the source rocks become poorer and more gas prone to the northeast. If the belt of mounds in the upper part of the Paradox Formation does continue into the Forest, the fields will probably be small, 1 MMBO or less, but with a high gas-to-oil ratio, becoming entirely gas toward the east side of the play. Our assessment indicates most likely values of 3 MMBO and 12 BCF of both associated and nonassociated gas.

HYDROTHERMAL RESOURCES

By Anthony B. Gibbons

Widely separated areas of the Forest contain one or more thermal springs or artesian wells (fig. 67). Characteristics of the spring waters are given in table 6. Except for the town of Pagosa Springs, where hot water from the springs is currently used to heat buildings and public sidewalks, the thermal springs are at present either undeveloped or are developed for recreational and therapeutic uses in private and public pools.

Isograds of the geothermal gradient (fig. 67) show a relationship between high geothermal gradient and the occurrence of thermal springs. Most of the Forest lies in an area of relatively high geothermal gradient. Only in the extreme western part, which lacks thermal springs, does the gradient approximate the "Earth-normal" value of about 14°F per 1,000 ft of depth. The relationship between gradient and hot springs is a very general one, however. More definite ties are to intrusions and eruptions of igneous rock, as sources of heat, and to systems of faults and fractures as conduits for thermal waters.

Most of the thermal springs in the Forest are believed to be related to geologically young volcanic or intrusive events. The heat-supplying intrusion may be distant from the thermal springs. McCarthy and others (1982) infer that the Tripp, Trimble, and Stratten thermal springs in the Animas River valley (no. 5, fig. 67 and table 6) derive heat and at least some water from the La Plata Mountains area of igneous intrusions about 10–12

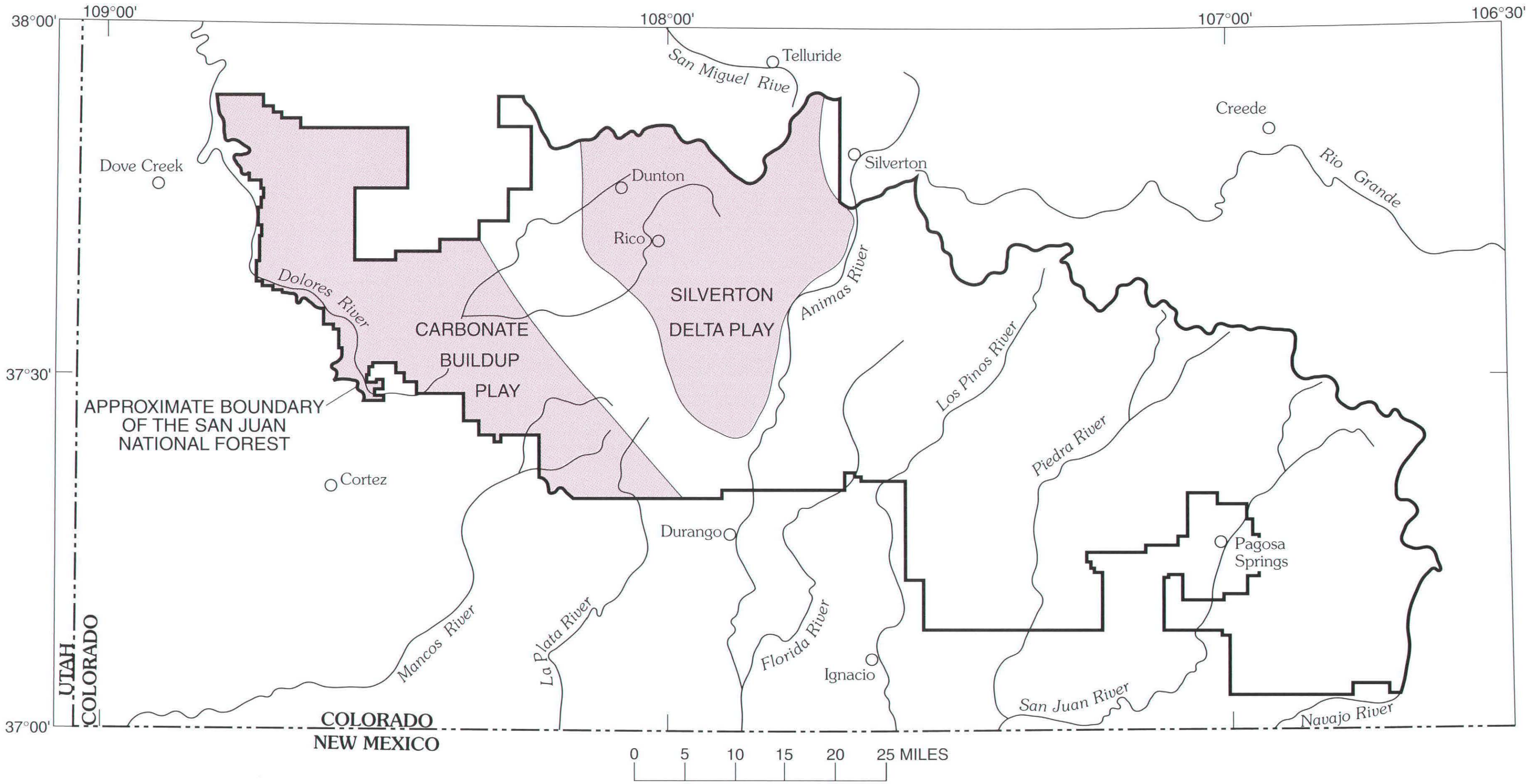
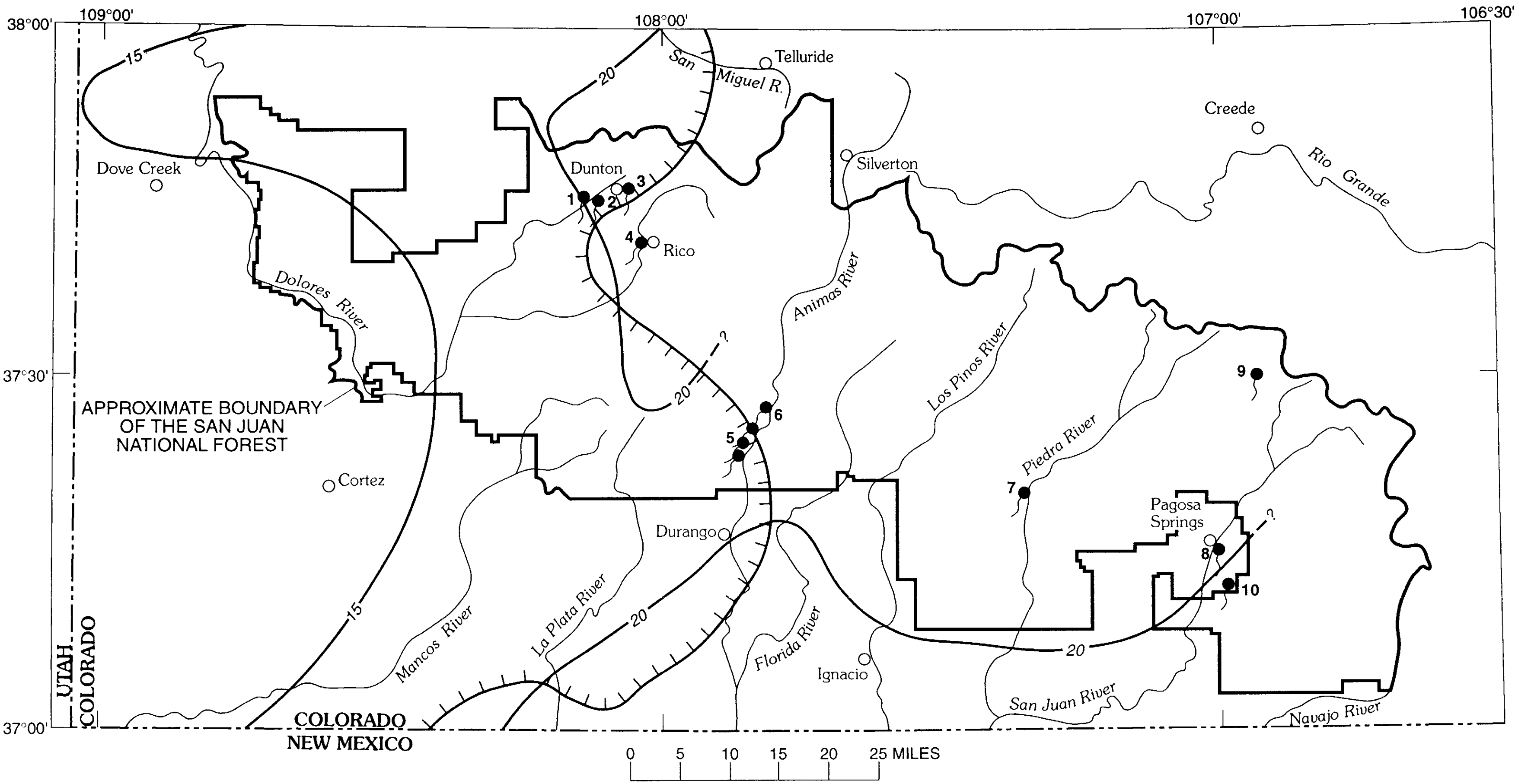


Figure 66. Outline of Silverton Delta and Carbonate Buildup Plays within the San Juan National Forest.



EXPLANATION

Boundary of area underlain by salt-bearing strata of the Paradox Formation— Teeth on salt side. (Peterson, 1966)

Thermal spring or artisian well or group of such springs or wells— Number keyed to table 6.

20 **Isograd, geothermal gradient, in °F per 1,000 feet of depth—** Recontoured from metric contours of Repplier and Fargo (1981)

Figure 67. Locations of thermal springs and artesian wells in and near the San Juan National Forest.

Table 6. Characteristics of thermal springs and artesian wells in and near the San Juan National Forest.

[Data from Pearl (1979) and McCarthy and others (1982). "Number" corresponds to locations shown on figure 67]

Number	Area	Spring or spring group	Temperature (°F)	Chemical character	Total discharge (gallons/minute)	Bedrock aquifer
1.	Dunton	Dunton	108	Calcium bicarbonate	25	Dolores Formation
2.	Dunton	Geyser	82	Sodium bicarbonate	25–200	Dolores Formation
3.	Dunton	Paradise	40–46	Sodium chloride	26–34	Dolores Formation
4.	Rico	Rico (4 artesian wells)	34–44	Calcium bicarbonate, calcium bicarbonate–calcium sulfate	54	Uncertain
5.	Animas River Valley	Tripp, Trimble, and Stratten	82–111	Calcium sulfate, calcium-sodium sulfate	≥11	Hermosa Group
6.	Animas River Valley	Pinkerton (4 springs)	79–91	Sodium-calcium chloride-bicarbonate	130	Leadville Limestone
7.	Piedra River Valley	Piedra River	108	Not available	50	Leadville Limestone
8.	Pagosa Springs	Pagosa Springs (1 spring, 2 wells)	129–136	Sodium sulfate	226–265	Dakota Sandstone
9.	West Fork, San Juan River	Rainbow	104	Sodium bicarbonate	45	Tertiary volcanic rocks
10.	Southeast of Pagosa Springs	Eoff artesian well	102	Not available	50	Uncertain

mi to the west. The Pinkerton group (no. 6) of hot springs in the Animas valley may be from the same source area (McCarthy and others, 1982). However, faults identified at the Pinkerton springs trend northwest in the direction of the Rico and Dunton areas of intrusives in the drainage of the Dolores River (fig. 67). All of the thermal springs of the Animas valley have water that is rich in sodium chloride, suggesting an origin to the west in the area underlain by the salt-bearing Paradox Formation (fig. 67). Pagosa Springs (no. 8), with the highest water temperatures of any springs in the region, have no known relation to an intrusive body, although they occur in an area of moderately high geothermal gradient.

Geyser Spring (no. 2), in the Dunton area, is Colorado's only geyser. Eruptions, at approximately half-hour intervals, are marked by fountaining to a height about 1 ft above the resting level of the geyser pool. Evolution of gas is continuous, greatly increasing during eruptions. The gas, analyzed by Gary Landis (unpub. data, 1993), comprises carbon dioxide (70 percent), oxygen (5 percent), nitrogen (16 percent), argon (0.3 percent), and water vapor (9 percent). Hydrogen sulfide, recognizable by its odor during geyser eruptions, was not detected in the analysis of the gas—probably because it decomposed completely into products that dissolved into the water taken with the gas sample.

The potential for significant further development of known hydrothermal resources and the presence of undiscovered hydrothermal resources in the area encompassing the Forest seems to be slight. Most of the thermal springs yield only moderately hot water in relatively small quantities. Moreover, most are remote from markets. Only three springs, Geyser, Piedra, and Rainbow, are on public land. A scheme for heating State-owned buildings in Durango with water piped in from thermal springs in the Animas River valley was found to be uneconomic (Meyer and others, 1981). There are no geothermal leases held in the San Juan National Forest today, although large tracts were applied for but withdrawn in 1974 and 1980 (Neubert and others, 1992, p. 284).

MINERAL RESOURCE POTENTIAL—SALABLE MINERALS

By Andrew G. Raby *and* John S. Dersch, U.S. Forest Service

Salable minerals are defined as those minerals that may be acquired from the U.S. Government only by purchase. Such minerals include petrified wood, common varieties of sand and gravel, some varieties of dimension stone, pumice, volcanic cinders (including scoria), and some varieties of clay. These materials were removed from acquisition by either location or lease in the Federal Materials Act of 1947, as amended by the Multiple Surface Use Act of 1955. Not included in the salable category are block pumice, perlite, and some forms of dimension stone such as travertine and high-quality marble. Determination that a particular mineral is salable must be reviewed on a case-by-case basis in light of past legal decisions and U.S. Forest Service (USFS) regulations. Salable commodities generally have low unit value (value per short ton); their exploitation is dependent on easy access to transportation, and generally they are used near the site of production. Any further mention of dimension stone applies only to the salable variety, which is sandstone or igneous in composition.

This part of the report and its accompanying plate 4 define areas, within and near the Forest, that are favorable for containing specified salable minerals (gravel deposits, aggregate, and dimension stone). Raby (1992) addressed identified or known industrial minerals (including salable minerals) within the San Juan National Forest, described sites that have had production, and estimated reserves in selected sites. Many of the sites are within the favorable areas delineated on plate 4. Some sites that do not fall within favorable areas are isolated geological features too small or discontinuous to map; others reflect historical development more favored by nearness to roads or specific project needs than favorable geological conditions. As noted below, there are sources of gravel and dimension stone throughout the Forest, not only within the favorable areas.

Favorable areas for currently marketed salable minerals shown on plate 4 are Quaternary alluvium, colluvium, and glacial drift, which are sources of sand and gravel (only some of these Quaternary units are shown on plate 1); talus slopes of Late Cretaceous to Tertiary igneous rock, which contain material for crushing, lightweight aggregate, and dimension stone; Late Cretaceous and Tertiary intrusives, which contain dimension stone and large aggregate; and Cretaceous sedimentary rock, which contain dimension stone and aggregates. About 150 sites have been quarried at some time; of these, there are about 15 sites that are active or have had recent production (Raby, 1992).

Gravel deposits are abundant throughout the Forest, and they are used almost entirely for road construction and maintenance, with other minor uses on an intermittent basis. Most quarries are small and are used intermittently or one time only; however, the deposits themselves tend to be widespread and sizable (thousands of cubic yards).

Dimension stone has been collected across the Forest, mostly from the Dakota Sandstone and other Cretaceous sedimentary rock units, with lesser amounts from volcanic and intrusive rock talus. Potential quarries containing Tertiary intrusive rock dimension stone are located in the Rico area and near the head of Taylor Creek about 5 mi southwest of Rico. Rock from these intrusives is being considered for decorative and construction use in the Aspen (fig. 1) area. Similar intrusive rock occurs in the La Plata Mountains and in the mountains southwest of Summitville. Most dimension stone is used locally for small construction projects and landscaping by homeowners and local contractors.

Boulders, which are used for river-channel stabilization and fisheries habitat improvement, are in growing demand. The source of the boulders is from river terraces and conglomerate outcrops. Petrified wood and vertebrate fossils occur in the Morrison Formation, Lewis Shale, and Pictured Cliffs Sandstone (plate 1). Calcite (spar) was quarried from the Mancos Shale during World War II for military use (U.S. Geological Survey, 1971). Pottery clay has been collected since pre-Columbian times from Mancos and Lewis Shales. Paleozoic limestones are potential sources of nonchemical- and metallurgical-grade limestone (Raby, 1992). Except for industrial limestones, these materials do not occur in sufficient quantities to be considered a resource.

Middle Paleozoic limestones are exposed throughout the central San Juan National Forest (see units ℙh, MD, plate 1). Industrial limestone potential has been identified (Raby, 1992), but no production has occurred. A potential use for these limestones is in scrubbers for power plant waste-gas emissions (as limestone or as lime). Scrubber lime sources are the Upper and Middle Pennsylvanian Hermosa Group in the Animas River drainage, as well as the Upper Devonian Elbert Formation, Upper Devonian Ouray Limestone, and Lower Mississippian Leadville Limestone in the Animas

River Valley about 15 mi north of Durango (Jesco, 1973; Roberts, 1974).

RESOURCE POTENTIAL

The following is an evaluation of the mineral resource potential for salable gravel and dimension stone. Income from the sale of these commodities will vary according to accessibility, unit value and cost, and the amount produced. Environmental consequences (such as ground disturbance caused by bulk mining) and transportation costs have not been considered in this assessment.

GRAVEL

Gravel (containing sand- to clay-size components) used in road construction and surface maintenance, for both public and private use, is available across the Forest in amounts adequate for anticipated needs. Major sources of gravel are the alluvial and glacial-drift deposits along the major drainages of the San Juan Mountains (plate 4). Most Cretaceous sedimentary bedrock weathers to form alluvial deposits that contain adequate sand to be useful as road material. Gravels from weathered volcanic rocks, Cretaceous shales, and Paleozoic limestones (exposed mainly in canyons along the major drainages) generally contain too much clay-size material for road use, but the clay could be washed away if the gravels were needed. A detailed map of the different gravel-bearing units cannot be shown adequately at 1:250,000 scale, but the general distribution of Quaternary alluvium, colluvium, and glacial drift deposits are combined and shown as a single map unit (plate 4, but not on plate 1). Gravel is most likely to be found in abundance in this favorable area. However, isolated sources exist outside of the favorable areas as well.

DIMENSION STONE

Dimension stone, both of sedimentary and igneous origin, occurs throughout the Forest. Factors that affect the value and use of dimension stone are its appearance, strength, weathering characteristics, ease of quarrying, and shape and size of individual blocks.

Most dimension stone is found in and below weathered outcrops of Dakota Sandstone and the Mesaverde Group and other sandstone layers in the Jurassic and Cretaceous sedimentary strata outcropping along the edge of the San Juan Basin. These stones are primarily valued for their colors, texture, and the encrusting lichen and moss. Surface weathering of these sandstone outcrops will yield 1 to 5 short tons of dimension stone per acre (Raby, 1992).

Dimension stone is also collected from weathered exposures of igneous rock. This material collects in rock glaciers and talus slopes in the higher elevations in the Forest around Groundhog Mountain, the La Plata Mountains, Graysill Mountain, and Jackson Mountain, and along the canyons and drainages of the southeastern San Juan Mountains (plate 4). Latite porphyries with a distinctive speckled appearance are a potential source of dimension stone for markets in Aspen and other nearby developing areas. These stones weather from igneous sills that are as much as 100 ft thick in the mountains around Rico (Pratt and others, 1969). Similar stones are also found nearby at Taylor Creek. Reliable reserve estimates are not available, but float and large areas of exposures indicate a good supply of dimension stone in the areas shown as favorable for resource potential (Raby, 1992).

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APPENDIX I. QUANTITATIVE ASSESSMENT OF MINERAL RESOURCES

METHODOLOGY OF QUANTITATIVE ASSESSMENT

Quantitative assessments completed by the U.S. Geological Survey follow the methodology outlined by Menzie and Singer (1990). The approach involves three steps and a computer simulation. The three steps are described below:

1. Identify known and possible mineral occurrences in the area and categorize each on the basis of a mineral deposit model.
2. Produce a mineral resource assessment map—a geologic terrane map—based on the geological, geophysical, and geochemical data utilized in step 1. If possible, define possible target areas for specific mineral deposit models.
3. Estimate the number of undiscovered deposits of each type in each terrane.

Steps 1 and 2 are straightforward and follow standard geologic techniques for qualitatively assessing the geologic attributes of an area. Step 3 advances the qualitative assessment by assigning subjective numerical estimates based on a combined geologic knowledge of the area, of the deposit type, and of grade and tonnage relationships for each deposit type. The estimate of the number of undiscovered mineral deposits is reported in the form of a probability distribution with estimates of the number of undiscovered deposits given for the 10-percent, 50-percent, and 90-percent confidence levels.

The estimated number of undiscovered deposits is converted to estimates of metal values using a computer simulation program called MARK3 (Root and others, 1992). MARK3 uses a Monte Carlo random number generator procedure. This statistical approach is documented in Root and Scott (1988) and Drew and others (1986), as well as in extensive literature on statistics. The program combines the estimates of probabilities of number of deposits of each type with the distribution of grade and tonnage for each mineral deposit as characterized in Cox and Singer (1986) to give estimates of the quantities of metals that remain to be discovered at various grades. Because MARK3 uses grade and tonnage models as published in Cox and Singer (1986) and Bliss and others (1992), at the present time quantitative assessments can only be made for deposits that both fit those descriptive models and for which grade and tonnage models exist (table 7).

Table 7. Metal-by-metal estimates of undiscovered resources in the San Juan National Forest.

[Calculation of totals is done by random number (Monte Carlo) method and is based on actual numbers estimated to be present at different degrees of probability]

Deposit type[1]	Deposit model[2]	Favorable area or areas	Mean (average) number of deposits	Amounts (metric tons)						
				Metals						Ore
				Cu	Au	Zn	Ag	Pb	Mo	
A	16	all	0.0562						31,000	18,000,000
B	17	all	0.0304	120,000	0.9		16		2,900	16,000,000
C	19a	all	0.4485	6,600	2.1	160,000	560	150,000		2,900,000
G	25b	all	0.3801	4,100	7.3	63,000	810	34,000		3,000,000
H	25e	all	0.1816	5,800	6.7		40			840,000
Totals for metals and ore				136,500	17	223,000	1,426	184,000	33,900	40,740,000

[1]This report (see table 1).
[2]Cox and Singer (1986).

APPENDIX II. GEOLOGIC TIME CHART

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

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

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

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

††Informal time term without specific rank.

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