UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Leadville $1^{o}x2^{o}$ quadrangle, Colorado:

a pre-assessment

by

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PREFACE

This document presents a proposal and work plan for an evaluation of the mineral resource potential of the Leadville $1^{o}x2^{o}$ quadrangle in west-central Colorado under the Conterminous United States Mineral Resource Assessment Program (CUSMAP).

The authors of the report assembled available published and unpublished information and data germane to the geology, geochemistry, geophysics, and economic mineral deposits in the quadrangle. The team then identified specific topical studies that, when completed and incorporated with existing information, would provide the data necessary to adequately evaluate the mineral resource potential of the Leadville quadrangle. The work plan covers 5 years--4 for data acquisition and 1 for preparation of the final report--as well as a preliminary period of time during which existing data can be evaluated and some new data could be collected.

Owing to the lack of adequate data for resource assessment, this report does not attempt to provide, nor should it be construed to be, a preliminary resource assessment of the quadrangle. However, the available data suggest that the quadrangle has a high resource potential for a number of important commodities.

I. EXECUTIVE SUMMARY

The Leadville $1^{o}x2^{o}$ quadrangle is situated in west-central Colorado in the heart of the southern Rocky Mountains (fig. 1). The area combines a complex geologic setting with an impressively diverse and bountiful resource potential. A Conterminous U.S. Resource Assessment Program (CUSMAP) evaluation of the quadrangle by the U.S. Geological Survey (USGS) would provide an ideal opportunity to refine assessment techniques and increase our scientific understanding of mineral deposits.

The proposed study area is underlain by a lithologically and structurally complex Proterozoic crystalline basement, exposed in deeply incised uplifts, which is overlain by a thick accumulation of Phanerozoic sedimentary rocks. Mesozoic and Tertiary plutons and volcanic rocks are exposed throughout the quadrangle.

Stream sediment samples were collected throughout the quadrangle as part of the National Uranium Resource Evaluation (NURE) and Forest Service and Bureau of Land Management Wilderness programs. The resulting data are in part reflections of known mineralized areas. However, they also identify numerous areas of interest outside of those areas, as well as suggest different model types within recognized districts, which should be evaluated further during a full-scale resource assessment. Unfortunately, molybdenum, which is present in the world-class Climax-type deposits, was not analyzed for during the NURE program.

Geophysical data emphasize the complexity and diversity of the study area. Aeromagnetic and gravity maps suggest that, where covered by Phanerozoic rocks, the crystalline bedrock, where not exposed, is present at relatively shallow depths in much of the eastern half of the quadrangle. In addition, the geophysical data suggest the presence of deep intrusions. Remote sensing and radiometric maps point to regions within the study area where low-temperature ground-water processes could have concentrated minerals.

The Leadville quadrangle contains three of the most productive precious-metal districts in the United States, Leadville, Aspen, and Gilman, as well as Climax, the world's largest molybdenum deposit. More than 39 other districts are present as well (table 1). There are also indications for the possible occurrence of a wide variety of other resources, including syngenetic metal deposits, industrial minerals, and fuels.

Expected Benefits

Scientific

The knowledge of the geologic setting is relatively good, and the quadrangle contains an impressive diversity of mineral deposit types. Within this context, therefore, the Leadville quadrangle offers an exceptional opportunity to actively concentrate on topical studies related to ore deposits and their geologic context. The studies should be interdisciplinary and should incorporate all available facilities and capabilities. Interaction between the CUSMAP study and current and proposed projects would be mutually beneficial to all projects. The scientific products would also fuel future research in the area and region.

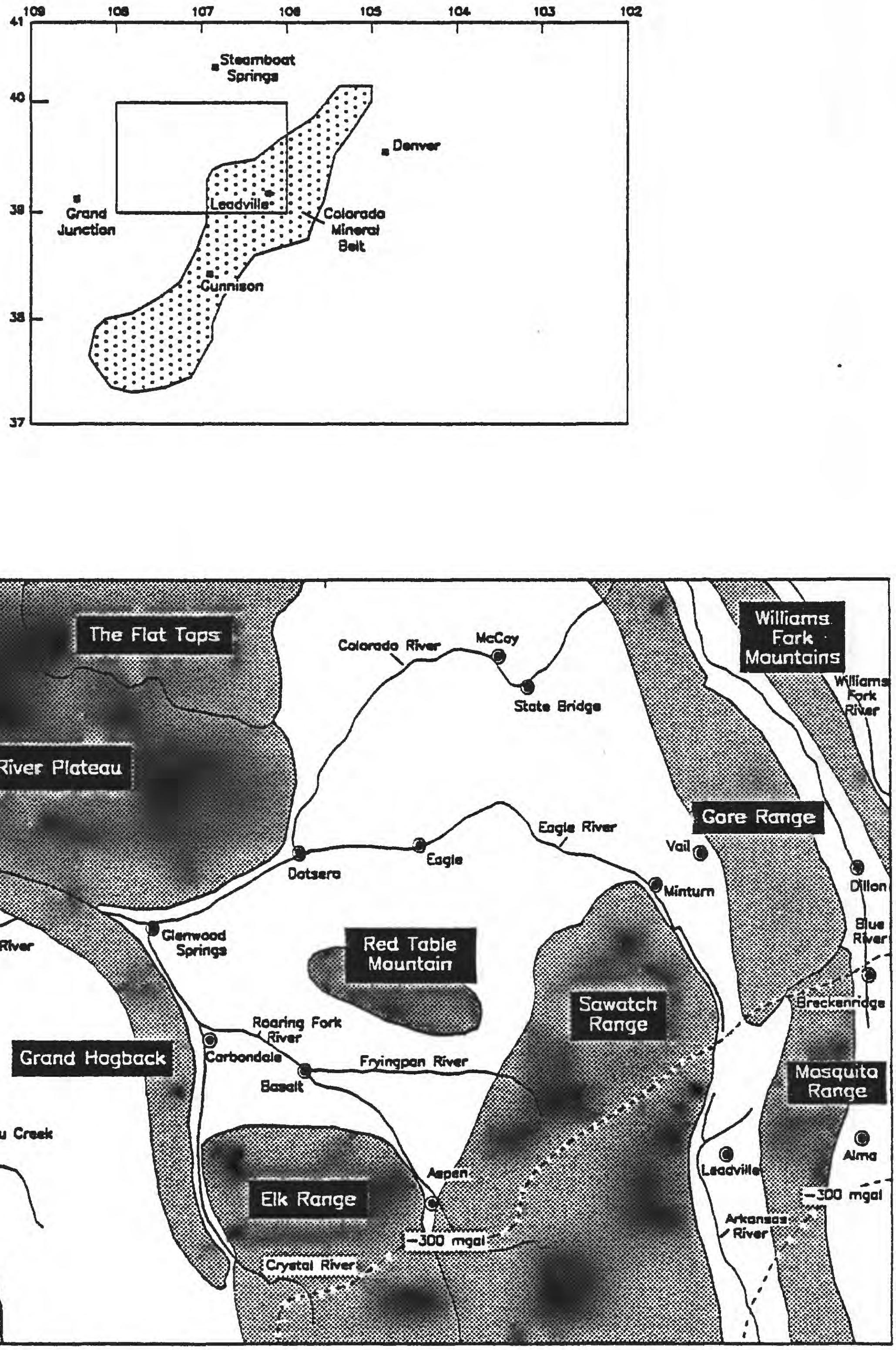

Figure 1. Index map showing the location of the Leadville quadrangle and selected geographic and geologic features. Broken lines in southeast part of quadrangle outline gravity low described by Tweto and Case (1972).

Table 1. Summary of Mining Districts, Leadville Quadrangle, Colorado

DISTRICT	COUNTY	DEPOSIT TYPE
Alicante-Birdseye	Lake	A1
Alma	Park	B1, B2, E
Ashcroft	Pitkin	B2
Aspen	Pitkin	B1, B2
Avalanche	Pitkin	B2
Breckenridge	Summit	A1, A2, B2, D, E
Brush Creek	Eagle	C
Buckskin	Park	A1, B1
Burns-McCoy	Eagle	E
Climax	Lake	A1, A2, D
Consolidated Montgomery	Park	A1
Frisco	Summit	A1
Upper Fryingpan	Pitkin	A1
Fulford	Eagle	A1, B1
Gilman-Redcliff	Eagle	A1, B1, B3
Granite	Chaffee	A1, E
Green Mountain	Summit	A2, B2
Holy Cross	Eagle	A1
Homestake	Eagle	A1
Homestake Peak	Lake	A1
Horseshoe	Park	B1
Independence	Pitkin	A1, A3
Leadville	Lake	A1, A3, B1, E
Lenado	Pitkin	B1, B2
Lincoln Gulch	Pitkin	A3
Mosquito	Park	A3, B1
Richmond Hill	Pitkin	B1
Rifle Creek Vanadium	Garfield	C
Rifle - Elk Creek	Garfield	B1, B2
Rock Creek (Crystal River)	Gunnison	B2
Sacramento	Park	B1
Snowmass	Pitkin	C
St. Kevin - Sugarloaf	Lake	A1
Tenmile	Summit	B2
Tennessee Pass	Lake	A2, B1
Twin Lakes	Lake	A1, A3
Upper Blue River	Summit	A1, B1, B2, E
Weston Pass	Park	B1
Yarmony	Routt	C

Key to Deposit Types:

A1 - Au- and Ag-bearing veins in Precambrian rocks.
A2 - Au-, Ag-, and base-metal veins in Tertiary intrusive rocks.
A3 - Au- and Ag-bearing veins in Tertiary volcanic rocks.
B1 - Ag-Pb-Zn veins in Paleozoic carbonate rocks.
B2 - Base-metal vein and replacement deposits in sedimentary rocks.
C - Sandstone-type deposits in clastic sedimentary rocks.
D - Disseminated porphyry and stockwork deposits.
E - Placer deposits.

Economic

The preliminary mineral resource assessment indicates that the Leadville quadrangle has a high potential for undiscovered resources of a variety of metals and other important commodities. A full-scale assessment would delineate specific areas for known deposit types, and it could possibly identify deposit types heretofore unknown in the area. A CUSMAP resource assessment could make an enormous economic contribution both locally and nationally.

Political

The CUSMAP study would draw upon or interact with other U.S. Geological Survey (USGS) projects and programs. These include:

* More than fifteen Forest Service and Bureau of Land Management (BLM) wilderness areas that have been studied within the quadrangle;

* Projects that are currently in progress or are being proposed that would pertain to resource assessment of the quadrangle; and

* Current DAT projects that include studies of the Leadville district, northern Sawatch Range mineral deposits, and the geochronology of central Colorado intrusive rocks and mineral deposits.

In addition, the strong research interest in various aspects of the quadrangle shown by universities throughout the country invites active interaction with academia.

II. GEOLOGY

The geology of the Leadville $1^{o}x2^{o}$ quadrangle represents more than 1.8 billion years of active tectonism, extensive plutonism, and cratonic sedimentation. During that time, geologic processes created substantial accumulations of mineral and energy resources, some of which have been tapped and others that undoubtedly await discovery. The geology of the quadrangle is shown in Tweto and others (1978); major geographic features are shown on figure 1.

Proterozoic Geology

Metasedimentary and metavolcanic rocks

The metamorphic rocks in the quadrangle include interlayered gneiss, schist, and migmatite. Protoliths include graywacke, shale, basalt, and intermediate to felsic volcanic rocks. The volcanic and volcaniclastic rocks have a strong bimodal affinity, and trace element modeling indicates a mantle-derived source for the basalts and a mixed mantle-crust source for the felsic volcanics (Boardman and Condie, 1986).

Intrusive rocks

Granitic magmas were emplaced into the Early Proterozoic crust at approximately 1.7 and 1.4 Ga (billion years ago). The 1.7 Ga intrusive rocks include the Cross Creek Granite, the Denny Creek Granodiorite, the trondhjemitic Kroenke Granodiorite, and other unnamed granitic to dioritic rocks. The intrusive event was syn- to post-orogenic and related to arc magmatism. Ages range from about 1.71 to 1.66 Ga (Reed, 1986).

The 1.4 Ga intrusive rocks are represented by the peraluminous St. Kevin Granite and possibly by the equivalent Silver Plume Granite. This plutonic event was largely anorogenic, and the melts were derived from metasedimentary rocks in the lower crust (Anderson and Thomas, 1985).

Metamorphism and structure

The Early Proterozoic sedimentary and volcanic rocks were regionally metamorphosed to at least amphibolite grade and complexly deformed prior to and during the emplacement of the 1.7 Ga batholiths. The rocks are cut by numerous faults and shear zones with predominantly north-northwest and northeast trends. Although many of the north-northwest-trending faults initially formed in the Proterozoic, many of them, most notably the Gore fault, were reactivated during the Phanerozoic.

The northeast-trending fault system consists of the Homestake shear zone in the northern Sawatch Range, as well as similar structures in the Gore and Front Ranges (Tweto and Sims, 1963). The zone includes numerous individual faults with textures that range from gouge to mylonites, indicating a wide range of deformational environments, the more brittle of which probably developed during the Phanerozoic.

Paleozoic and Mesozoic Geology

Stratigraphy

Paleozoic and Mesozoic sedimentation in central Colorado responded to episodic epeirogenic and orogenic uplift and related transgressive-regressive marine and nonmarine cycles. The total stratigraphic sequence is more than 13,000 meters thick.

The Lower Paleozoic sedimentary rocks rest unconformably on the Proterozoic basement, and they include Upper Cambrian through Devonian quartzites, dolomitic sandstones, dolomites, and limestones. The Mississippian Leadville Limestone (or Dolomite), a major host for base-metal ores in the quadrangle, was dissected by Mississippian subaerial erosion and karstification.

Fine to coarse clastic sediments and evaporites of Pennsylvanian and Permian age were deposited in the northwest-trending Central Colorado trough, a depositional basin bounded on the northeast by the Ancestral Front Range and on the southwest by the Uncompahgre highland. Clastic sedimentation continued through the Triassic as orogenic activity decreased and erosion of the highlands continued. Jurassic and Cretaceous sediments were deposited during seven nonmarine to marine sedimentary cycles separated by periods of epeirogenic uplift and subsequent erosion.

Structure and tectonics

With the exception of pronounced orogenic uplift in the Late Paleozoic, most of the Paleozoic and Mesozoic sedimentation and erosion in central Colorado was related to regional epeirogenic events. The north-northwest-trending Ancestral Front Range and Uncompahgre highland rose rapidly in the Middle Pennsylvanian, as Proterozoic structures such as the Gore fault were reactivated.

Diapiric flow of Permo-Pennsylvanian evaporites had a pronounced influence on Permian and younger sedimentation and structure (Tweto, 1977; Freeman, 1971a). Some of this activity, which commenced in the Permian, has continued into the Quaternary.

Cenozoic Geology

Cenozoic sedimentation and erosion, igneous and tectonic activity, and mineralization were complexly and intimately related. These geologic events define two major tectonic epochs: (1) the Laramide orogeny (latest Cretaceous through latest Eocene time), and (2) late Cenozoic (Oligocene to present) activity. In addition, three peaks of igneous activity can be identified: separate Laramide and Oligocene subduction-related events, and Oligocene and younger continental (bimodal) activity accompanied by crustal extension.

Laramide structure and stratigraphy

Following the retreat of the Late Cretaceous sea, basement blocks began to rise and orogenic sediments were shed into the adjacent basins. Plutonic and volcanic activity accompanied uplift. The north-trending Sawatch Range was the first of the major uplifts to develop. The Gore and Front Ranges began to form slightly later, reactivating older faults as well as generating new structures, such as the Williams Range thrust fault along the west side of the Williams Fork Mountains.

The White River uplift and the Grand Hogback were the last major Laramide structures to form. The White River uplift, a broad elongate dome, did not develop until early to middle Eocene time. The Grand Hogback marks a west- to south-dipping monocline that forms the western and southern flanks of the White River uplift; it extends southward into the Elk Range where it is cut by a 34.1 Ma (million-year-old) pluton. With the exception of uplift of the White River and Grand Hogback structures, uplift waned in the late Paleocene and Eocene. Erosion and sedimentation gradually degraded the mountainous terrane until the topography was relatively gentle beneath a Late Eocene erosion surface.

In the early to middle Eocene, lacustrine shales and marls and fluvial sandstones of the Green River Formation were deposited in and around a broad, shallow lake in western Colorado and eastern Utah. The Parachute Creek Member is noted for its oil shale reserves.

Laramide and Oligocene igneous activity

Subduction-related igneous rocks were emplaced during Laramide uplift from about 72 to 59 Ma, and again in the late Eocene and Oligocene from about 42 to 30 Ma. Activity was apparently restricted to a northeast-trending zone that is roughly coincident with the Colorado mineral belt. The intrusions form small to large stocks, sills, and dikes in Proterozoic to Cretaceous host rocks. Trace element and isotopic data indicate that the magmas were derived from partial melting from the lower crust with a possible contribution of mantle material. Most of the Laramide plutons in the quadrangle are generally not associated with ore deposits.

Most of the Middle Tertiary (Late Eocene-Oligocene) calc-alkaline igneous rocks are in the eastern and particularly the southern part of the quadrangle. In the Elk Mountains, 34 Ma laccoliths intruded Phanerozoic sedimentary rocks. Volcanic edifices have largely been stripped away by erosion, although volcanic rocks are preserved in the 34 Ma Grizzly Peak cauldron near Independence Pass (Fridrich, 1986).

Late Cenozoic structure and sedimentation

Following a period of late Eocene and early Oligocene tectonic quiescence, uplift disrupted the nearly flat topography. Block faulting reactivated many Laramide and Proterozoic faults, renewing uplift of the Sawatch, Gore/Tenmile, Mosquito, and Front Ranges. Extensional faulting related to the north-northwest-trending Rio Grande rift (Tweto, 1977) longitudinally cut the east flank of the Laramide Sawatch uplift, creating the Mosquito and Sawatch Ranges with the intervening upper Arkansas Valley graben. Major movement along the Mosquito fault and reactivation of older faults generated the Gore/Tenmile Range and basins to the east and west.

Despite late Oligocene uplift in the eastern half of the quadrangle, significant Neogene deformation to the west did not commence until about 10 Ma. Renewed doming of the White River uplift began at this time, and orogenic activity continued in the ranges to the east.

A major period of Quaternary climatic cooling induced glaciation that continued from about 500,000 years ago into the Holocene. During three glacial maxima, ice almost totally covered the higher ranges and the valleys were filled with glaciers; the modern alpine topography with deep U-shaped valleys is largely a product of glacial erosion.

Late Cenozoic igneous activity

With the change in the tectonic regime, igneous activity produced Late Oligocene to Miocene anorogenic granites and Miocene and younger basalts. The high-silica granites range in age from about 29 Ma at Climax to 12 Ma at Treasure Mountain, and many are associated with major molybdenum deposits or prospects. Trace element and isotopic data indicate that the anorogenic granites were derived from partial melting of the lower crust.

Basaltic flows ranging in age from 24 Ma to 4,150 years were erupted throughout the western half of the quadrangle. The basalts are part of a bimodal assemblage that includes small rhyolitic dikes and flows on the east side of the Flat Top Mountains.

Existing Geologic Data

The geologic map of the Leadville quadrangle (Tweto and others, 1978) is a compilation of published and unpublished geologic mapping completed through 1975. The results of additional mapping, primarily wilderness studies, have been published since the map was produced.

Approximately half of the quadrangle has been mapped only at a reconnaissance level as part of producing the Leadville map. In these areas, the distribution of the geologic units is generally known, but the detail necessary for mineral resource appraisal is lacking. In addition, lumping of units during reconnaissance mapping and map compilation obscured important geologic relations. For example, the Leadville Limestone, which is an important ore host throughout the quadrangle, is lumped with either the underlying Devonian rocks or the entire pre-Leadville Paleozoic section. This lack of detail severely constrains mineral resource potential evaluations for Leadville-hosted ore deposits. Therefore, additional mapping in both mineralized and unmineralized (as presently known) areas will be necessary for an adequate resource assessment of the quadrangle.

III. GEOCHEMISTRY

Types, Formats, and Quality of Existing Data

The preliminary geochemical assessment is based almost entirely on data derived from 1,797 stream-sediment analyses which are listed in a National Uranium Resource Evaluation (NURE) report (Planner and others, 1981). The analytical quality of this data is unknown, but plotted localities of anomalous samples are generally correct in that they are located in stream drainages in or near known mining districts. Regardless, the NURE report is the only one which contains geochemical data on a single sample medium for the entire Leadville quadrangle.

Published reports discuss the mineral resource potential of the Flat Tops Primitive Area (Mallory and others, 1966) and the Gore Range-Eagles Nest Primitive Area and vicinity (Tweto and others, 1977). Both reports contain large-scale maps showing sample localities and give analytical data on outcrop samples and stream-sediment samples. In addition, mineral resource appraisal reports by Soulliere and others (1985, 1986, 1987) cover three small BLM wilderness study areas within the Leadville quadrangle; each of these contains analytical information on a limited number of samples from the Hack Lake, Eagle Mountain, and Bull Gulch study areas, respectively. Miscellaneous field studies maps and accompanying texts by Freeman and others (1985), Hedlund and others (1983), Ludington and Ellis (1981), and Theobald and others (1983) describe the mineral resource potential of the Maroon Bells-Snowmass, Buffalo Peaks, Hunter-Frying Pan-Porphyry Mountain, and Vasquez Peak wilderness study areas.

In addition to these published reports, unpublished geochemical sample data on stream-sediment and outcrop samples from the Collegiate Peaks, Mount Massive, and Holy Cross Forest Service Wilderness Areas are contained in the files of the USGS Branch of Geochemistry. The approximate boundaries of these Wilderness and Wilderness Study Areas, for which at least geochemical data on stream sediments now exists, are shown on figure 2.

Geochemical Anomalies

The NURE stream-sediment data were plotted at a scale of 1:250,000 to show the distribution of anomalous concentrations of each of 13 ore and ore indicator elements in the Leadville quadrangle. These elements include: silver, gold, barium, bismuth, cerium, copper, nickel, lead, tantalum, thorium, uranium, vanadium, and zinc. Anomaly thresholds for each element were arbitrarily assigned from inspection of the data, and anomalous concentrations were grouped in three consecutive categories, low, medium, and high (table 2). Several other elements of interest, lithium, antimony, tin,

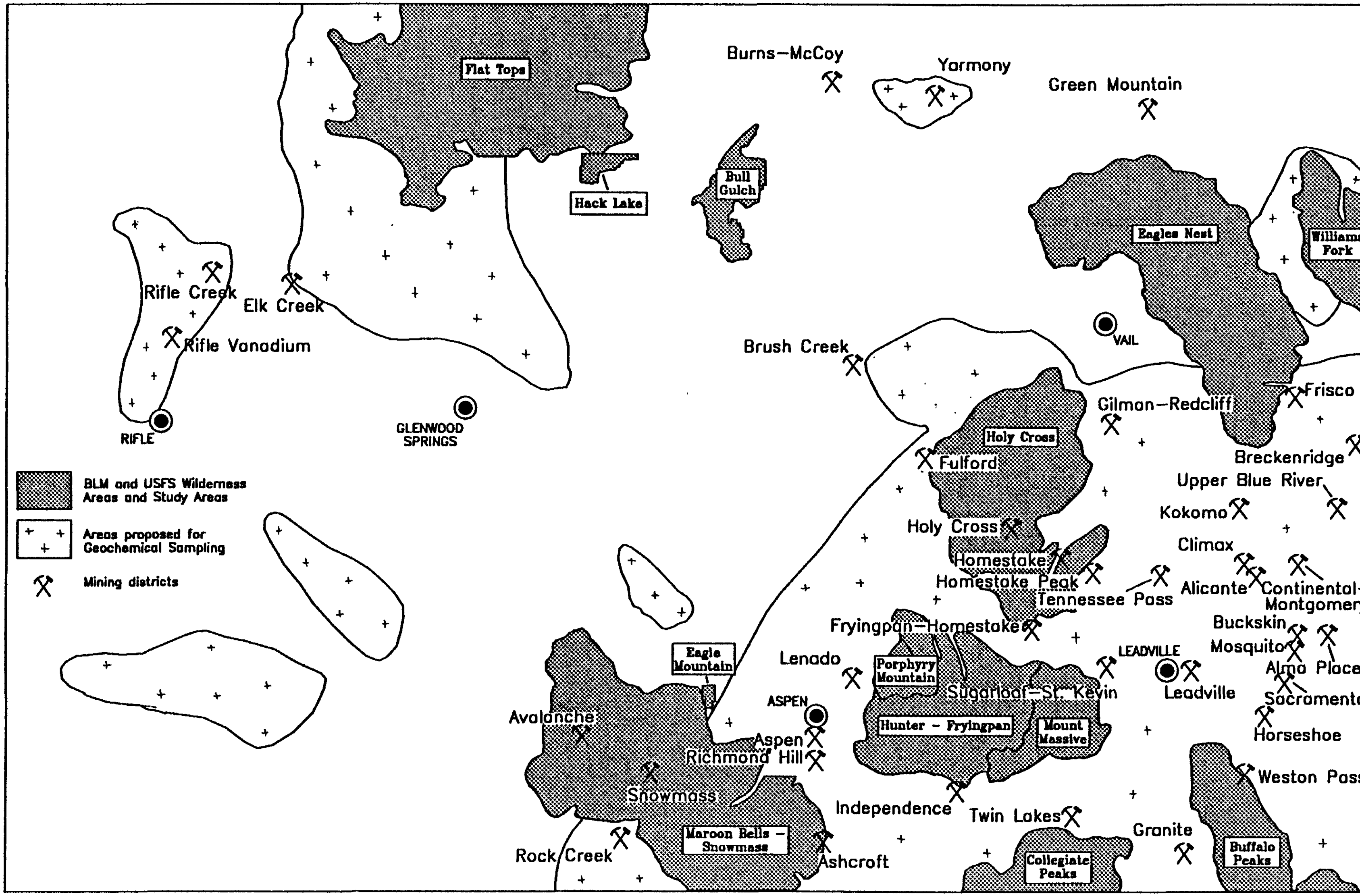

Figure 2. Map showing mining districts, wilderness and wilderness study areas, and tracts for future geochemical sampling.

Table 2. Anamolous concentration ranges and numbers of anomalous samples for ore and indicator elements, NURE stream-sediment data, Leadville Quadrangle, Colorado

ELEMENT	LOW	MEDIUM	HIGH	TOTAL	APPENDIX
Silver (Ag)	5 - <10	10 - <20	≥20		3A
	(26)	(11)	(7)	(44)	
Gold (Au)	0.2 - <0.5	0.5 - <1.0	≥1.0		3A
	(220	(15)	(13)	(50)	
Barium (Ba)	1000 - <2000	2000 - <4000	≥4000		3E
	(29)	(6)	(3)	(38)	
Bismuth (Bi)	10 - <15	15 - <25	≥25		3C
	(62)	(13)	(5)	(80)	
Cerium (Ce)	500 - <700	700 - <1000	≥1000		3E
	(16)	(11)	(8)	(35)	
Copper (Cu)	100 - <400	400 - <800	≥800		3C
	(29)	(7)	(3)	(39)	
Nickel (Ni)	40 - <60	60 - <100	≥100		3C
	(44)	(26)	(9)	(79)	
Lead (Pb)	100 - <500	500 - <1000	≥1000		3B
	(52)	(7)	(16)	(75)	
Tantalum (Ta)	3 - <6	6 - <10	≥10		3E
	(34)	(2)	(2)	(38)	
Thorium (Th)	50 - <100	100 - <200	≥200		3B
	(88)	(21)	(9)	(118)	
Uranium (U)	20 - <40	40 - <80	≥80		3D
	(85)	(10)	(3)	(98)	
Vanadium (V)	--	≥200	--		3D
		(30)		(30)	
Zinc (Zn)	200 - <1000	1000 - <2000	≥2000		3D
	(125)	(28)	(6)	(159)	

Concentration given in parts per million (ppm). Numbers of anomalous samples given in parentheses.

and tungsten, were omitted because fewer than 20 samples yielded concentrations above the limit of detection.

Anomalies for all of these elements except Ba, Ni, Ta, and V are most abundant in streams that drain areas underlain by Proterozoic igneous and metamorphic rocks or plutonic rocks of Laramide and late Tertiary age, and they are also concentrated in the vicinity of known mining districts. Many anomalies for lead, zinc, silver, and barium are also related to outcrop areas of Devonian and Mississippian carbonate rocks which host deposits of these metals in districts such as Alma, Leadville, Gilman, and Aspen. A subsidiary concentration of anomalies is apparent in eastern Mesa County, an area which contains no known mining districts. A brief summary of elemental anomalies is provided in Appendix 2 of this report to show the relation of anomalies to known mineral deposits, bedrock types, and major structural features.

Evaluation of Existing Geochemical Data for CUSMAP Assessment

Although the analytical information on nearly 1,800 stream-sediment samples from the area of the Leadville quadrangle contained in the NURE report provides a general framework as a starting point, it is not adequate for a CUSMAP geochemical assessment of the mineral resource potential of this region. Not only are there no analytical data for molybdenum in this report, there are also no analyses of heavy-mineral concentrates nor of rock or ore samples. The various wilderness study area reports, which do contain adequate geochemical data on a variety of sample media, and maps showing the locations of metal anomalies for selected metals, cover only small portions of the total region.

Consequently, the region covered by the Leadville quadrangle will require a considerable amount of additional geochemical sampling to provide an adequate basis for a CUSMAP mineral resource potential evaluation.

IV. GEOPHYSICS

A variety of geophysical studies have been conducted in the Leadville quadrangle. This chapter summarizes the types and quality of existing data; brief interpretations of the data are provided in Appendix 3.

Gravity and Magnetics

Gravity and magnetic anomalies identified from airborne surveys can be evaluated using measured and theoretical data. Tabulations of limited measured properties of rocks in the Leadville quadrangle are found in reports by Tweto and Case (1972); Isaacson and Smithson (1976); Campbell (1981, 1985); and Campbell and Wallace (1986).

The aeromagnetic coverage of the western half and northern third of the Leadville quadrangle is from the NURE survey flown at 3-mile spacing and 400-ft terrain clearance. Using the industry-wide rule of thumb that an airborne survey can detect point sources in a swath on the ground vertically below the aircraft and up to 45 degrees out to each side, we estimate that less than 5 percent of surface sources and 56 percent of sources at 4,000-ft depth were detected by that survey. Furthermore, the anomaly of a point dipole at 4,000-ft depth has an amplitude only about 0.08 percent as great as if it were at the surface, and so it might go undetected. It definitely would go undetected by the old analog surveys that cover most of the rest of the quadrangle; the pre-digital era recorders used then did not have enough dynamic range to detect both kinds of source. Note, furthermore, that all existing surveys of the quadrangle have sensitivity of at best 1 nT (nanoTeslas), and so cannot be used for modern high-sensitivity (0.1-0.01 nT) purposes such as mapping detrital magnetite horizons in sedimentary basins.

About 2,040 gravity stations have been read in the Leadville quadrangle (about 1 station every 3.8 sq mi, average). More than two-thirds of these stations, however, are in the eastern one-third of the quadrangle.

Aeroradiometrics

A spectrometric-gamma-ray survey of the Leadville sheet was flown by GeoMetrics, Inc. in 1978 as part of the NURE program (U.S. Department of Energy, 1979). The survey was flown by helicopter along east-west lines nominally spaced 3 miles apart and draped 400 ft above mean terrain. Under these specifications, the survey should detect about 5% of the gamma-ray point sources exposed at the surface, but miss the remaining 95% that happen to lie between adjacent lines. The survey, therefore, "sampled" (in a statistical sense) the source populations in the sheet, but it did not inventory all radiometric sources that may be present there.

The survey detected gamma-rays from daughter isotopes of potassium (K), uranium (U), and thorium (Th) that were present within a few feet of the surface of the ground. Using an empirical procedure, the contractor translated the gamma-ray populations he observed into likely amounts at the ground surface of each of the parent elements. Because erosion can conceivably separate parent and daughter isotopes of U and Th, they are reported as "equivalent" U and Th (eU and eTh, respectively). The contractor-interpreted amounts of K (in percent), eU (in ppm), and eTh (in ppm) were contoured at the USGS.

The contractor discussed some 95 eU anomalies identified in the Leadville sheet (U.S. Department of Energy, 1979). "Anomalies" were taken to be places along flight lines where raw eU counts were more than 2 standard deviations above the mean for the whole survey. No similar analysis was done for K or eTh.

Geoelectric

Magnetotelluric (MT) soundings can detect electrical structures to tens of kilometers depth, and audiomagnetotelluric soundings (AMT) can penetrate a depth of several kilometers but with increased resolution of the shallow rock section. They give information on the electrical conductivity of units at depth, and so suggest the presence of conducting materials (e.g.: wet sedimentary rocks, altered zones, black shales, magmas) or resistant ones (e.g.: intrusive bodies, tight sedimentary rocks, metamorphic complexes).

Published accounts of geoelectric work in and near the Leadville quadrangle mention direct current (dc) soundings for ground water or engineering purposes (Harthill, 1969; Dick and Pearl, 1978; Papazian, 1980); electric logs in boreholes (Daniels and others, 1983; Dodge and Bartleson, 1986); and local EM or IP surveys for minerals exploration (Alexander, 1968; Fritz, 1979). Most of the accounts are very sketchy, and none was of use for the preassessment of the Leadville sheet.

Remote Sensing

Limonite Distribution

Limonite mapping from Landsat multispectral scanner (MSS) data provides a first estimate of the location of potential hydrothermal alteration on a regional scale. Landsat thematic mapper (TM) data, with higher spatial resolution and additional spectral bands, provide a means to better characterize potential hydrothermal alteration targets prior to field studies and should be analyzed.

Three scenes of Landsat MSS data have been coregistered to a UTM grid and digitally mosaicked to provide complete coverage of the Leadville quadrangle. These data were used to prepare a band 4 (green)/band 5 (red) ratio for detecting the regional distribution of limonite that might help target areas of potential hydrothermal alteration in the quadrangle. Limonite detection was based on the steep positive slope of the spectral reflectance of iron oxide minerals in the visible part of the spectrum due to strong absorption in the ultraviolet region. The single band data were calibrated to percent reflectance, and an image of the band 4/band 5 ratio was used to measure the slope of the reflectance curve.

Linear Features

Linear features are relatively short, distinct, linear, tonal and textural anomalies on Landsat MSS images that mark linear topographic, structural, and stratigraphic features. Keenan Lee (U.S.G.S. unpublished data) has prepared a Landsat MSS linear features map for the State of Colorado. The linear feature data for the Leadville quadrangle were extracted from his data set and analyzed for prominent trends. The only statistically significant trend is a broad trend composed of several prominent significant spikes between about 40^{o}E and 85^{o}E. Individual significant spikes within the main trend occur at 44^{o}E., $51-65^{o}$E., $69-70^{o}$E., 75^{o}E., and $81-83^{o}$E.

Additional Data Coverage

High-altitude photography: Since October, 1983, high altitude photography has been acquired by the National High Altitude Photography program (NHAP) for the western half of the Leadville quadrangle. The photography includes black-and-white photos at a scale of 1:80,000 covering an area of 11.5 X 11.5 miles and color-infrared photos at a scale of 1:58,000 covering an 8 X 8 mile area. These photos are available from the EROS Data Center, Sioux Falls, South Dakota.

Additional high-altitude photography was acquired for the entire Leadville quadrangle by NASA as part of their aircraft program. Both color and color-infrared photography were taken from a U-2 aircraft flying at approximately 60,000 feet to produce aerial photos in a 10-inch X 10-inch format at a scale of about 1:100,000.

Landsat Satellite Data: The U.S. Geological Survey, Branch of Geophysics maintains a library of Landsat satellite digital tape data, and complete coverage of the Leadville quadrangle with Landsat multispectral scanner (MSS) data is available in this library. Three scenes of MSS data or three scenes of Landsat thematic mapper (TM) data are necessary to provide full coverage of the quadrangle. No TM data for the Leadville has been acquired by the Branch of Geophysics, although high-quality data can be purchased from the EOSAT Corporation.

Side-Looking Radar: Side-looking airborne radar (SLAR) complements regional structural analysis using Landsat data. SLAR imagery of the Leadville quadrangle was acquired by the U.S. Geological Survey radar program in the summer of 1985. The data consist of 1:400,000-scale image strips and 1:250,000 image mosaics of the strips for the quadrangle, flown with both northeast and southeast look directions. The data can be purchased as paper prints or as positive or negative transparencies from the EROS Data Center, Sioux Falls, South Dakota.

V. MINERAL RESOURCE ASSESSMENT

Table 3 summarizes the present state of knowledge of known and undiscovered mineral resources in the Leadville quadrangle. Table 4 describes the attributes of the districts that we infer to have formed by hydrothermal processes. Brief descriptions of each model considered are provided in Appendix 4.

The first column of table 3 refers to occurrence models described in Cox and Singer's (1986) compendium of mineral deposit models. The second column is the name of the deposit type. The third column indicates whether or not deposits or occurrences of the indicated type are known to occur in the quadrangle.

The fourth column indicates the level of assessment (abbreviated LOA) that is possible, now and with the results of a full-scale CUSMAP study. The levels are explained fully below. The fifth column indicates the number of permissive tracts delineated, if any, on figures 3, 4, and 5. Columns 6, 7, and 8 indicate our estimates (for three models only), made by consensus subjective assessment methods, of the expected number of undiscovered deposits in the quadrangle. The ninth column gives the name of a type example from the Leadville quadrangle, if one exists. The tenth (last) column summarizes critical criteria that were either used or potentially could be used to delineate tracts and generate expected numbers of deposits, or to eliminate models from consideration. These criteria are dealt with in more depth in the proposed work plan, where projects to support mineral resource assessment in a CUSMAP study of the Leadville quadrangle are described.

The levels of assessment (LOA) indicated in table 3 indicate how far in the 3-step assessment procedure described by Menzie and others (in press) we were able to proceed. Level 1 indicates a deposit model for which we were able to identify the model, delineate favorable tracts, and make an estimate of the number of undiscovered deposits. This was possible for only three models, Climax-type molybdenum, porphyry copper-molybdenum, and low-F porphyry molybdenum, primarily because of the high level of exploration for these deposit types during the 1960's and 1970's.

Level 2 indicates deposit types for which we were able to delineate tracts, but the level of available information did not justify making estimates of undiscovered deposits. Deposit estimates could be made during a CUSMAP study of the quadrangle, through completion of the projects described in the work plan.

Table 3. Mineral Resources of the Leadville 1°x2° Quadrangle

No.[1]	Deposit Type	Deposits or Occurrences Exist	LOA	No. of Tracts	Percentiles 90th	Percentiles 50th	Percentiles 10th	Example Deposit	Critical Criteria for Tract Delineation
16	Climax Mo	Y	1	1	4	20	38	Climax	gravity low, depth of cover
21a	Porphyry Cu-Mo	Y	1	1	0	0	1	Conundrum Creek	intermediate plutons, depth of cover
21b	Low-F Mo Porphyry	Y?	1	1	0	0	1	Paradise Pass	intermediate plutons, depth of cover
30b	Sandstone Cu	Y	2	2	-	-	-	Yarmony	appropriate host rock
30c	Sandstone U	Y	2	2	-	-	-	Arrowhead claim	appropriate host rock
-	Sandstone V	Y	2	2	-	-	-	Rifle Creek	appropriate host rock
14a	Skarn W	Y?	2	4	-	-	-	Leadville?	carbonate rocks, intrusions
18b	Skarn Cu	Y?	2	4	-	-	-	Leadville	carbonate rocks, intrusions
18c	Skarn Pb-Zn	Y	2	4	-	-	-	Leadville	carbonate rocks, intrusions
18d	Skarn Fe	Y	2	4	-	-	-	Pitkin Co.	carbonate rocks, intrusions
19a	Polymetallic Replacement	Y	2	4	-	-	-	Leadville	carbonate rocks, intrusions
19b	Replacement Mn	Y	2	4	-	-	-	Leadville	carbonate rocks, intrusions
22c	Polymetallic Veins	Y	2	7	-	-	-	Leadville	hypabyssal intrusions
5b	Noril'sk Cu-PGE	N	3	-	-	-	-	-	mafic intrusions + evaporites
6a	Komatiitic Cu-Ni	Y?	3	-	-	-	-	Homestake	komatiitic metavolcanics
12	Diamond Pipes	N	3	-	-	-	-	-	?
31a	Sed. Exhalative Pb-Zn	N	3	-	-	-	-	-	anoxic basins, volcanic rocks
32a	SE Missouri Pb-Zn	Y?	3	-	-	-	-	Weston Pass?	reefs in carbonate sequences
34b	Sedimentary Mn	N	3	-	-	-	-	-	anoxic basins
34c	Upwelling Phosphate	N	3	-	-	-	-	-	anoxic basins
39a	Placer Au-PGE	Y	3	-	-	-	-	Arkansas River	alluvial deposits
-	Massive Sulfide	N	3	-	-	-	-	-	bimodal? metavolcanics
-	Vein U	Y	3	-	-	-	-	Frying Pan claim	?
-	Turquoise	Y	3	-	-	-	-	Turquoise Chief	?
-	Megabreccia Cu-Mo	Y	3	-	-	-	-	Red Mountain	caldera margins
10	Carbonatite REE-Nb	N	4	-	-	-	-	-	alkaline intrusions
15b,c	Vein, Greisen Sn	N	4	-	-	-	-	-	tin-specialized granites
25a	Hot-spring Au-Ag	N	4	-	-	-	-	-	volcanic rocks, little erosion
25d	Sado Veins	N	4	-	-	-	-	-	volcanic rocks over oceanic crust
25g	Epithermal Mn	N	4	-	-	-	-	-	carbonate rocks, intrusions
25e	Qtz-Alunite Au	N	4	-	-	-	-	-	volcanic rocks, little erosion
25h	Rhyolite Sn	N	4	-	-	-	-	-	tin-specialized rhyolites
26a	Carbonate-Hosted Au-Ag	N	4	-	-	-	-	-	argillaceous rocks, felsic dikes
-	Marble	Y	*	-	-	-	-	Marble	pure limestones, intrusions
-	Clay	?	*	-	-	-	-	-	massive alteration, deep weathering
-	Sand and Gravel	Y	*	-	-	-	-	-	?
-	Peat	?	*	-	-	-	-	-	special depositional environment
-	Coal	Y	*	-	-	-	-	-	special depositional environment
-	Oil Shale	Y	*	-	-	-	-	-	special depositional environment
-	Oil and Gas	Y	*	-	-	-	-	-	subsurface structures

* These deposits are not amenable to the classification scheme.

1 Model number from Cox and Singer (1986).

Table 4. Base- and Precious-Metal Mining Areas, Leadville Quadrangle, Colorado

AREA	COUNTY	DEPOSIT TYPES 1	2	3	4	5	6	7	AGE	PRODUCTION
Gilman	Eagle		•		•	•			K	large
Holy Cross	Eagle		•			•			K?	very small
Rifle Creek	Garfield		•						?	small
Climax	Lake		•						T	very small
Leadville	Lake	•	•		•	•	•	•	KT	huge
Turquoise Lake	Lake		•						T	small
Twin Lakes	Lake		•						K?	small
Timberline Lake	Lake	•	•						T	probably not
Aspen	Pitkin		•			•			K	large
Grizzly Caldera	Pitkin		•						T	very small
Lenado	Pitkin		•			•			K	small
Mt. Sopris	Pitkin		•						T	very small
Treasure Mtn.	Pitkin		•			•			T	very small
White Rock	Pitkin		•				•		T	very small
Alma	Park		•	•		•		•	T?	large
Weston Pass	Park					•			P?	moderate
Breckenridge	Summit	•	•		•	•	•	•	KT	large
Frisco	Summit		•						?	very small
Green Mtn.	Summit		•			•			T?	small
Kokomo	Summit		•			•	•		T?	moderate
Upper Blue	Summit		•			•		•	KT	small

KEY TO DEPOSIT TYPES:

1. Gold-bearing epithermal veins.
2. Polymetallic veins.
3. Tungsten-bearing veins.
4. Stockworks and chimneys.
5. Polymetallic replacements.
6. Skarns (all types).
7. Placers.

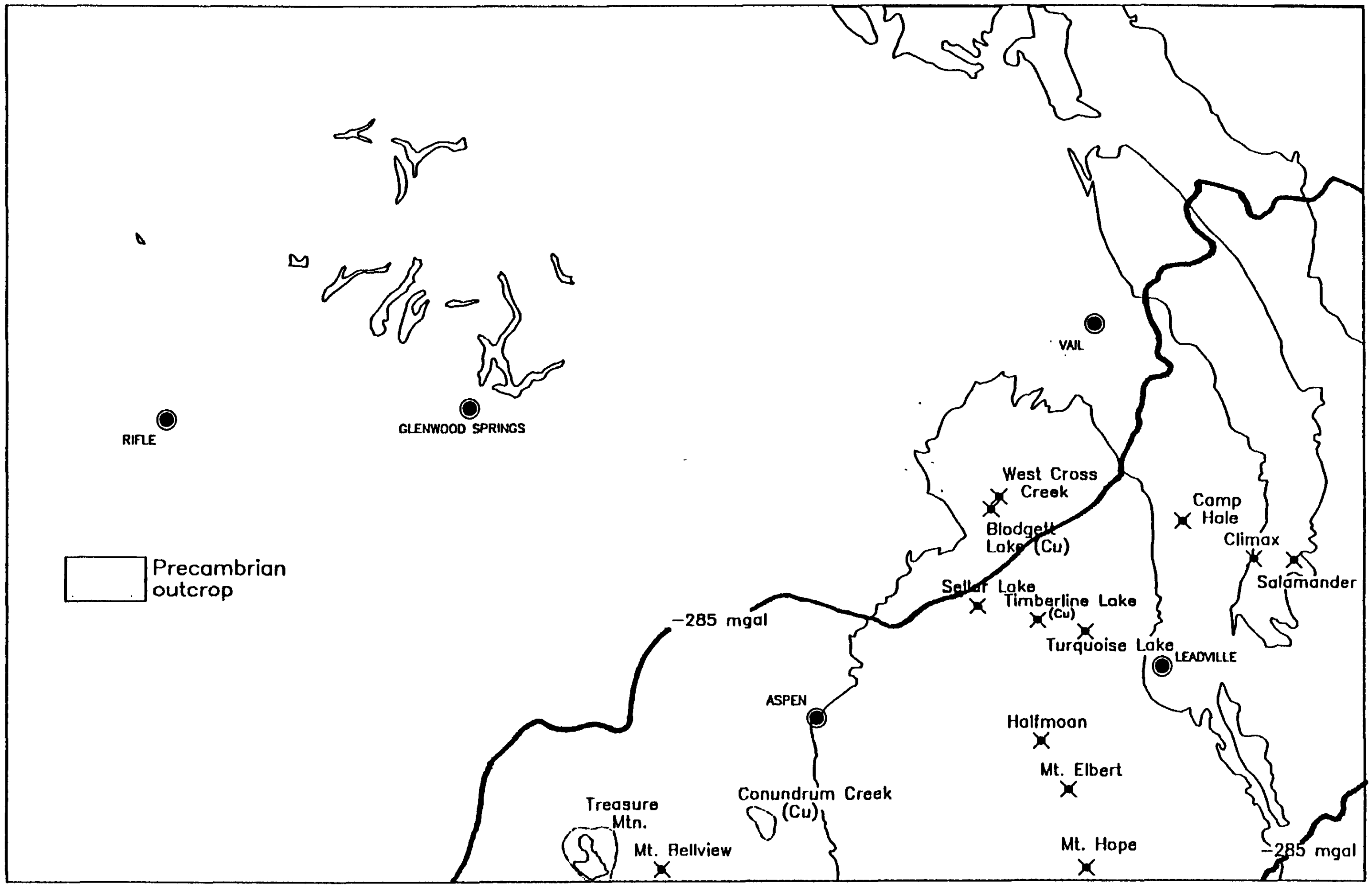

Figure 3. Map showing favorable characteristics for Climax-type molybdenum and porphyry copper-molybdenum deposits. Favorable characteristics include: 1) presence of epizonal felsic plutons, 2) emplacement of stocks near or below the Paleozoic-Precambrian contact, and 3) proximity to the central Colorado gravity low (shown by heavy line). Deposits, prospects, and occurrences are shown by x or by broken line. Copper-molybdenum occurrences are labeled (Cu); all others are Climax-type molybdenum. Solid narrow lines define areas of Precambrian outcrop.

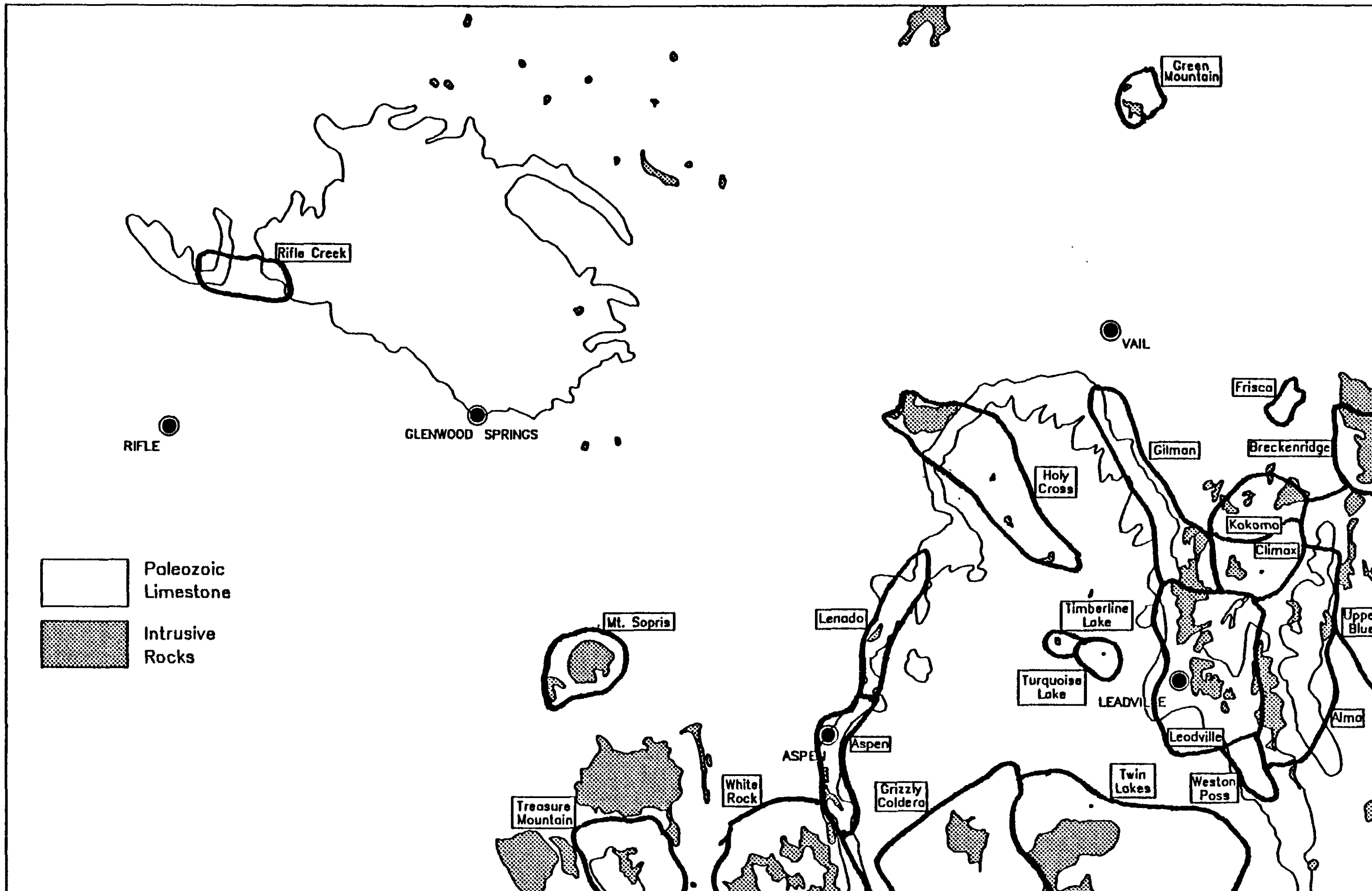

Figure 4. Map showing favorable tracts for polymetallic vein, replacement, and skarn deposits. The critical criteria are outcrop areas of Paleozoic limestone and intrusive rocks. The confluence of these two criteria are particularly favorable. Heavy lines delineate the areas of known epithermal deposits described in table 2.

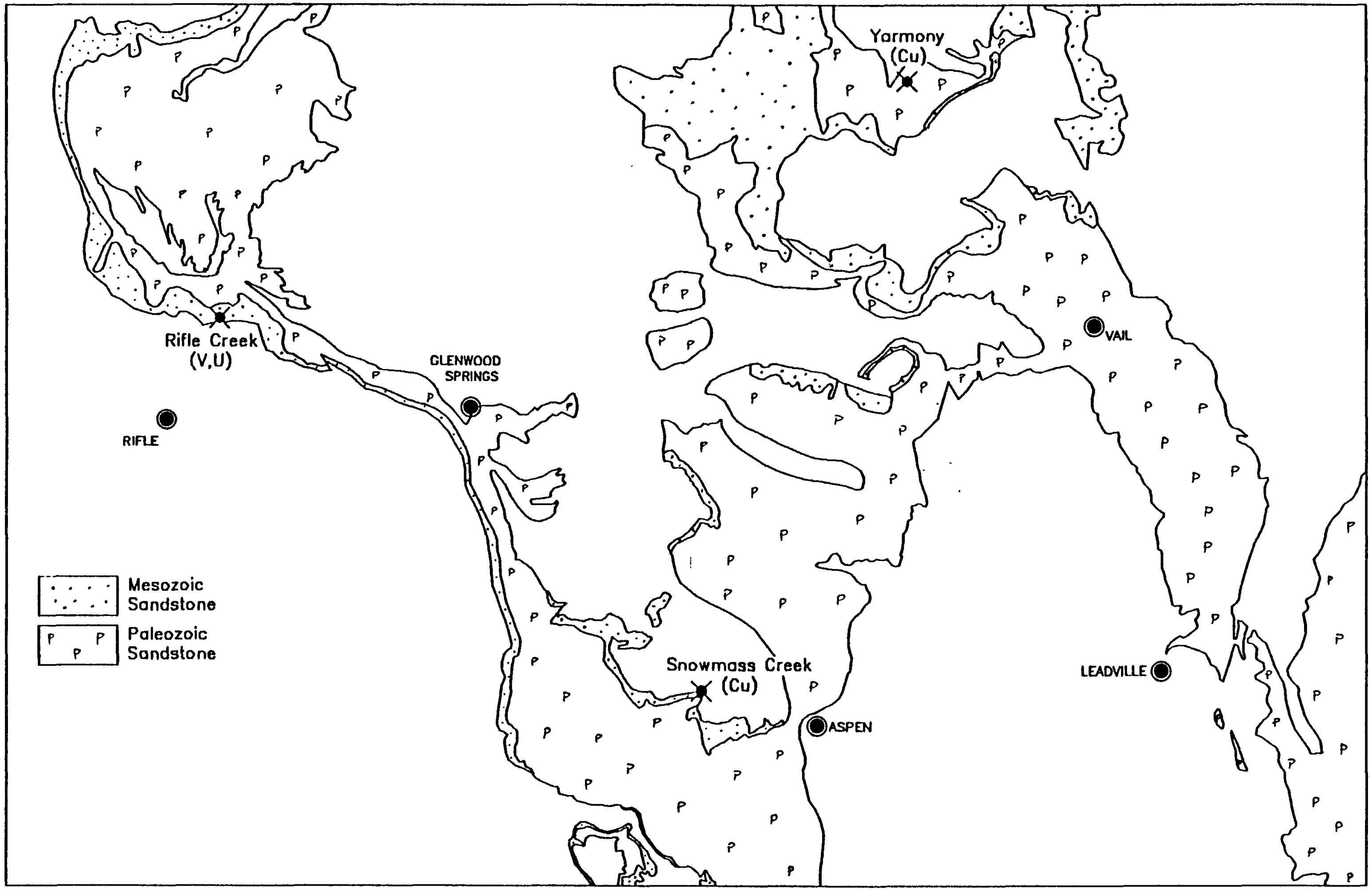

Figure 5. Map showing tracts favorable for sandstone-hosted V, U, and Cu deposits. Paleozoic sandstones host a known Cu occurrence (Yarmony). Mesozoic sandstones host known Cu (Snowmass Creek) and V, U (Rifle Creek) deposits.

Level 3 indicates deposit types for which the amount of information presently available does not justify tract delineation. Tract delineations and deposit estimates could be made during a CUSMAP study of the quadrangle, through completion of the projects described in the work plan. Industrial minerals and fuels were designated level 3 to acknowledge their existence and potential occurrence in the quadrangle. Geologists with special expertise in these areas will be necessary to properly assess these commodities.

A fourth level of assessment (Level 4) is used to indicate deposit types that might reasonably be expected to occur in the quadrangle, and that were considered in some detail in the present assessment, but for which the balance of evidence argues against their occurrence here.

VI. PROPOSED WORK PLAN

Introduction

The mineral resource appraisal of the Leadville quadrangle will be performed by a team of specialist geologists, geochemists, and geophysicists working under a team leader. The work has two objectives:

(1) Improving the fundamental data base for the quadrangle, and
(2) Performing specific tasks to help us evaluate specific mineral deposit types.

This proposal assumes that an operative Geographic Information System (GIS) system will be directly available to all team members, and that they will be able to use that system personally.

Logistics

Road access is reasonably good to most of the area below about 10,000 ft (about two-thirds of the quadrangle), but the rest of the land is much less accessible. Much of the high country is included in Forest Service wilderness areas, and motorized vehicles, including helicopters, are prohibited. However, these lands have already been assessed, and access would be needed largely for topical studies or to assess models not addressed during the wilderness studies. This would most greatly affect projects that require extensive sampling, including large bulk samples for geochronology, and geophysics, mainly specific gravity measurements. Therefore, the majority of access will be by four-wheel-drive vehicles and foot. Helicopters will be used where needed and permitted.

Roughly three-quarters of the quadrangle is public land administered by BLM and the Forest Service. Privately held land is dominated by small towns, agriculture, and patented mining claims.

Fundamental Data

Fundamental data that need to be acquired as a preliminary to resource assessment of the Leadville sheet can be acquired through the following projects: (1) aeromagnetic, (2) gravity, (3) geoelectric methods, (4) remote sensing, (5) geochemical sampling, (6) stratigraphic and structural characteristics of Proterozoic rocks, (7) petrology of the Leadville and related Paleozoic limestones, (8) role of Laramide history, and (9) characteristics of the Rio Grande "Rift".

Aeromagnetic studies

Previous aeromagnetic surveys detected only about 5 percent of the potential magnetic sources in the quadrangle, due largely to the methods used and the level of technology available at the time that the surveys were flown. We recommend that a state-of-the-art aeromagnetic survey be flown of the Leadville quadrangle, with flight lines spaced 0.5 mile apart and draped 1,000 ft above terrain (76 percent coverage of surface sources). Such a survey could be used to detect magnetic units at all scales throughout the quadrangle, to help construct a depth-to-magnetic basement map, to model tectonic and structural geometries, and to search for slightly magnetic horizons within sedimentary piles. Such a survey would give robust regional information, but it stops short of the level of detail needed for prospecting (e.g.: 1/8-mile spacing at 300 ft draping).

Gravity studies

More than two-thirds of the existing gravity stations are in the eastern one-third of the quadrangle, and large tracts in the remainder of the quadrangle are devoid of gravity data. We recommend a helicopter-supported, 2-year-long gravity collection effort in the western two-thirds of the Leadville quadrangle. Elevation control will be by EDM (about 6 inches, relative). With helicopter support, approximately 30 stations can be read each day; about 3,600 new high-quality gravity measurements (1 every 1.4 sq mi, average) would result from the projected 6-month field effort. These data would help to identify buried felsic plutons, and they would provide details on the shape of known intrusive bodies. Data collection should also focus on specific districts and geologic terranes in conjunction with geologic and geochemical studies.

Geoelectric studies

We recommend that both magnetotelluric and audiomagnetotelluric soundings be made at approximately 60 sites in the Leadville quadrangle. Most of these geoelectric soundings would be aimed at elucidating the deep structure of the Rio Grande "rift" (see separate geologic project below). Approximately 20 stations would be used to define electrical stratigraphy of basins and uplift areas in the sheet, and to help calibrate the depth-to-basement map.

Remote sensing

During the early stages of a CUSMAP study, limonite mapping from Landsat multispectral scanner data should be analyzed to provide a first estimate of the location of potential hydrothermal alteration on a regional scale. Similarly, Landsat thematic mapper (TM) data, with higher spatial resolution and additional spectral bands, should be analyzed to better characterize potential hydrothermal alteration targets prior to field studies. The TM data would also be used for regional structural studies and for a GIS base for displaying a number of regional geologic, geophysical, and geochemical data sets. Landsat TM data need to be purchased for the Leadville quadrangle. Three TM scenes will be needed to provide complete coverage.

Side-looking airborne radar (SLAR) complements regional structural analyses using Landsat data and should be purchased and analyzed to complement other investigations.

Geochemistry

Sample Media

For a regional reconnaissance study of this type, where the objective is to delineate areas favorable for the occurrence of mineral deposits rather than discovering such deposits, the most useful sample medium is stream sediments. The -80 mesh size fraction should be utilized, and the bulk samples should be panned to provide heavy-mineral concentrates containing a higher proportion of ore minerals than the fine fraction material. In areas where the upstream drainage basins are largely in rocks that normally do not contain magnetite, such as marine limestone and dolomite or marine evaporites, the magnetic fraction of heavy-mineral concentrates should be recovered and analyzed rather than discarded.

Any mineralized or hydrothermally altered rocks encountered in outcrops, float, or stream cobbles should be sampled. These should not only be chemically analyzed for metals and indicator elements, but also studied with a microscope to determine any ore minerals that may be present. Splits of any anomalous heavy-mineral concentrates should be similarly examined.

Indirect evidence of the existence of concealed deposits may, under favorable circumstances, be provided by ground-water anomalies from wells, drill holes, springs and seeps.

Concealed deposits can also be indirectly identified by collecting and analyzing volatile elements and gases, derived either from soil, gas, or from near-surface atmosphere samples. Radon, thoron, and helium seeping upward from buried uranium and thorium deposits can produce anomalies that are detectable through a hundred feet or more of porous overburden. Anomalous concentrations of such gases as CO_2, H_2S, SO_2, COS, and CS_2 commonly indicate the existence of oxidizing sulfide ore deposits at depth. Mercury may also escape to the surface to produce atmospheric or soil gas anomalies. Most of these volatile element and gas anomalies can be detected in the field with the aid of a portable mass spectrograph. These anomalies are strongly affected by weather and atmospheric conditions. Consequently, an experienced operator is required to estimate optimum field conditions for gas sampling and to interpret the results.

Areas Recommended for Geochemical Sampling

Reconnaissance geochemical sampling for the Leadville CUSMAP mineral resource potential evaluation should include the region within the Colorado mineral belt lying south and east of a line extending from Dillon Reservoir westward to the northwest flank of the Sawatch Range and thence southwest past Ruedi Reservoir to the southern edge of the quadrangle just west of Treasure Mountain. It should also include areas to the north and west of the mineral belt that contain local concentrations of geochemically anomalous stream-sediment samples identified in the NURE report, particularly those which contain favorable host rocks and structure. Areas within the boundaries of previously sampled Wilderness and Wilderness Study Areas can be largely excluded, except where additional sampling is warranted. Known mining districts should be included for three reasons: (1) the actual boundaries of many districts are vaguely defined so that in many places it is difficult to determine whether a specific sample locality falls within them; (2) a knowledge of the distribution of geochemical anomaly patterns related to known mineral deposits will aid in the interpretation of other similar anomalies with an unknown source; and (3) elements of commercial importance, which were not recovered initially, may be associated with ore deposits of more common metals in some of these districts and produce anomalies indicating potentially valuable by-products.

Areas outside the boundaries of the mineral belt which should be included in the geochemical sampling program, either because they contain exposures of favorable host rocks, or concentrations of stream-sediment anomalies, or both, include the following places. (1) The drainage basin of the Williams Fork River in the northeastern part of the region, which is underlain by Proterozoic rocks cut by numerous faults, and also contains NURE-identified stream-sediment anomalies for uranium, thorium, bismuth, and vanadium. (2) A small area to the west extending from west of Yarmony Mountain to the Colorado River and southeast of it, which is covered by sedimentary rocks of middle to upper Paleozoic age, capped by a Tertiary basalt flow; this area contained NURE-identified stream-sediment anomalies for zinc, lead, gold, bismuth, and vanadium. (3) An area extending from Minturn westward to Brush Creek between the Proterozoic rocks of the northern Sawatch Range and the Eagle River, with Paleozoic rocks cut by a Tertiary intrusive near Brush Creek, and overlain to the northwest by sedimentary rocks of Mesozoic age, cut by numerous large faults and containing scattered NURE-identified base-metal and silver anomalies. (4) The large area of the White River Plateau north and northwest of Glenwood Springs in which there are extensive exposures of mid-Paleozoic carbonate rocks, which locally host small lead and zinc deposits. The western part of the Flat Tops area, west of the wilderness boundary and north of the White River Plateau, which is extensively covered by Tertiary basalt flows and also contains some scattered small intrusive plugs, contains a high concentration of nickel anomalies in the stream sediments and should also be included with the White River Plateau geochemical study area. (5) The entire drainage basin of Rifle Creek, in the northwestern part of the Leadville quadrangle, should be sampled as it contains important vanadium deposits on the north side of the Grand Hogback in Jurassic sedimentary rocks, a commercial lead and zinc mine in Mississippian Leadville Limestone a few miles farther north, and a few gold and bismuth stream-sediment anomalies just north of the town of Rifle in lower Tertiary sedimentary rocks. (6) The upper drainage basin of West Divide Creek, in northeastern Mesa County, where both lower Tertiary and upper Cretaceous sedimentary rocks and a Tertiary pluton are exposed, and scattered stream-sediment anomalies for silver, lead, and bismuth are reported. (7) The Plateau Creek-Buzzard Creek drainage basin in Mesa County, north of Grand Mesa, which contains widely scattered stream-sediment anomalies for several ore elements including gold, silver, bismuth, lead, and zinc in an area primarily underlain by early Tertiary sedimentary rocks. (8) A small area south of Basalt and northeast of Mt. Sopris in Cretaceous sedimentary rocks cut by numerous faults, in which there is an isolated cluster of stream-sediment anomalies and copper-silver occurrences. The boundaries of the suggested sampling areas are shown on figure 2.

Geochemical Sampling Program

Stream-sediment samples should probably be collected with an average sample density of one locality per 5 square miles from first-order stream junctions. The total area suggested for sampling covers approximately 3,000 square miles, approximately half of which lies within the Colorado mineral belt. This portion should be sampled first, so that geochemical anomalies related to known deposits can be outlined and interpreted to provide a framework for the interpretation of anomalies that may be encountered elsewhere. The following field season can be used for sampling the other areas, and also possibly for specialized follow-up sampling, such as gas sampling, within the mineral belt. It is extremely important that as much of the regional sampling be completed as early as possible so that the results can be used the plan geologic investigations. Ideally, the first season of sampling should take place the year before the CUSMAP project officially begins.

Wherever possible, portable chemical and spectrographic field laboratories should be used. Although the total number of samples of all kinds is difficult to estimate in advance, it will probably be in the range of 1,000 to 2,000, of which approximately two-thirds will be stream sediment and heavy-mineral concentrates, and the remainder will be rock, ground water, and gas samples. Rock, sediment, and mineral concentrate samples should be analyzed for multiple elements by spectroscopic methods, as well as chemically for specific elements including arsenic, gold, mercury, antimony, thorium, uranium, tungsten, and zinc.

Stratigraphic and Structural Characteristics of Proterozoic rocks

Many of the Cenozoic mineral deposits are hosted by Proterozoic rocks, and Proterozoic structures influenced the localization of plutons and mineral deposits in the Colorado mineral belt. The Proterozoic rocks may also contain stratabound mineral deposits. In order to properly assess the role of these rocks in the mineralizing process, the stratigraphy, plutonic history, and structural relations must be characterized during regional and quadrangle-scale mapping. Mapping should concentrate on major areas of exposed Proterozoic rocks in the Sawatch, Gore, Front, and Mosquito Ranges and the White River uplift. The new data will assist in assessing areas with Proterozoic exposures, and they will also help to evaluate geophysical data and better assess those areas beneath Phanerozoic cover.

Role of Laramide History

Laramide uplift and plutonism drastically influenced concurrent and subsequent mineralization in central Colorado. In order to properly evaluate mineral resources in the quadrangle, we need to characterize the Laramide contributions to structural development and mineral deposits. Quadrangle-scale mapping in and around the major uplifts should evaluate the timing and amount of uplift, including identifying the structures that were integral to this process. In addition, and as part of the concurrent task of characterizing plutonic rocks, the role of Laramide intrusives in the structural and geochemical development of the region must be addressed during mapping studies.

Characteristics of the Rio Grande "Rift"

The Rio Grande "rift" extends into and may end within the quadrangle. Uplift, plutonism, and mineralization, specifically Climax-type molybdenum deposits, are associated with this feature throughout its length. It is essential that we characterize the field and age relations of this economically important major crustal flaw; the current knowledge of its geologic features are insufficient to provide information for resource assessment. Field investigations should identify and focus on specific areas that are known or postulated to have been affected by rifting. Specific field and geochronology studies should evaluate the amount and timing of Neogene uplift in the Sawatch and Mosquito Ranges. Also, field work should concentrate on the northern projection of the rift beyond the upper Arkansas Valley and Climax.

Petrology of the Leadville and Related Paleozoic Limestones

The Mississippian Leadville Limestone (or Dolomite) and other middle Paleozoic carbonate units are the major host rocks for the rich replacement orebodies at Leadville, Gilman-Red Cliff, and Aspen, as well as numerous other smaller districts. Mineralization in large part occurred in the Oligocene, but evidence at all of the districts suggests Laramide or even Mississippian cave-filling mineralization (southeast Missouri Pb-Zn type). The Leadville Limestone is dolomitized in the mineralized areas, most of which are in the southeast part of the quadrangle, and karst-related cave systems and collapse breccias are common in all exposures throughout the study area. In order to evaluate the resource potential for pre-Oligocene southeast-Missouri Pb-Zn-type deposits in carbonate rocks outside of known mineralized areas, particularly in and around the White River Plateau, the distribution and age of solution breccias must be established. In addition, the relations between mineralization and dolomitization, igneous activity, and cave formation should be evaluated as critical criteria for assessment. With these data, tracts outside of known mineralized areas can be more adequately assessed for resource potential.

Studies in direct support of Resource Assessment

To support the accurate assessment of the mineral resources of the quadrangle, we propose the following topical projects to analyze the probabilities that specific deposit types occur in the quadrangle. Together with the fundamental data projects described above, these projects will provide the data necessary for an adequate CUSMAP study of the Leadville quadrangle.

Genetic Characterization of Hydrothermal Mineral Deposits

The first step in any resource assessment is classification of the ore deposits into various deposit models. However, the current state of knowledge regarding the hydrothermal ore deposits of the quadrangle is not adequate for classification. Available models are not adequate to describe either the major districts (Leadville, Gilman, and Aspen) nor most of the minor districts. Table 4 summarizes the information available on the various mineralized areas. Although the factual descriptions of some of the areas are superb, most of the areas have not been studied since World War II, and some have never been adequately described. Specific needs are as follows:

Assemblages and Chemical Signatures

Most of the districts include deposits with multiple origins; veins are superimposed on replacement deposits, which are superimposed on skarn deposits, which are superimposed on possible syngenetic sulfide deposits. An empirical study to catalogue mineral assemblages and trace-element signatures of these multiple episodes will bring order to this chaos.

Intrusive Rocks

For some districts, a particular episode of magmatic activity has been suggested to be "responsible" for the mineralization, certainly as the thermal driving force, and, in some cases, as a possible source of at least some of the metals in the deposits. Extending these designations to all the districts would facilitate the delineation of tracts that may contain similar undiscovered deposits.

Chronology

For many districts, the age of mineralization is unknown. A program of radiometric dating of mineral deposits would provide feedback for the first two portions of this project and inject certainty into the classification.

Designation of Deposits

Especially for the larger districts, the question of where to draw the boundaries for a "deposit" are paramount, and the uncertainty is a major obstacle to resource assessment. Is Leadville one deposit, or twenty? Information in the Mineral Resources Data System (MRDS) for most of the districts is totally inadequate, and quality data can only be created once this problem is addressed.

Belden/Eagle Valley Black Shale-Evaporite Basin

Black shales deposited in a restricted basin, with or without concurrent volcanic activity, have proven to be the source of important metal resources on a world-wide basis. Specifically, sedimentary exhalative lead-zinc, sedimentary manganese, and upwelling phosphate deposits are found in such environments. The extensive Belden Shale and Eagle Valley Evaporite formed in such an environment, and they likely constitute an unrecognized resource in the quadrangle. Specific topics of study include:

Characterization of the formation

Little or no work has been done on identifying facies and depositional environments, and on determining possible volcanic contributions. Field studies would identify facies and areas that correspond to those that have been identified in known mineralized black shales.

Chemical signature and petrologic features

Studies of chemical zoning, metal ratios, thermal maturity, diagenesis, and mineralogy have been successfully applied to metalliferous black shales to identify deposit characteristics. Was the Belden mineralized, and why or why not? If it was, in which facies were the metals deposited? If the mineral deposits have been destroyed, how were they destroyed and where are the metals? Can syngenetic and diagenetic deposits be distinguished from younger epigenetic deposits in the Belden? Geochemical sampling should be concluded at a very early stage to provide data to plan other studies.

Composition of Intrusive Rocks

The concept that the composition of igneous rocks may be a controlling factor in the nature of associated hydrothermal deposits is not new. It has not been adequately tested, but, if true, is potentially the most powerful exploration and assessment tool extant. This hypothesis can now be tested, due to the availability of modern, comprehensive, chemical analytical and geochronological techniques. We propose to assemble a database of major- and trace-element chemistry and radiometric dates for all the major igneous rock groups in the quadrangle. Only with this information at hand can favorable terranes for hydrothermal mineral deposits be extended (or excluded) by analogy into buried and unexplored areas.

Proterozoic Metavolcanics and Massive Sulfides (b4)

Massive sulfide deposits in Proterozoic volcanic sequences are important metal resources in North America in general and Colorado in particular. Deposits have not been recognized in the Leadville quadrangle, although metavolcanic rocks have been mapped. In addition, the Homestake mine (Homestake mining district, fig. 2) contains pentlandite, and it permissively may represent a komatiitic Ni-Cu deposit in a belt of metavolcanic rocks. In order to assess the potential, known metavolcanic rocks in the quadrangle should be physically described and chemically characterized, and any associated sulfide deposits should be similarly examined. Determinations of the physical and chemical properties of the rocks would assist geophysical studies. Tracts of metamorphic rocks should be examined to identify any metavolcanic rocks and possible contained metals. Only by identifying and characterizing the metavolcanic rocks and known massive sulfide occurrences can the potential for buried and unexplored areas be determined.

Noril´sk Cu-Ni Deposits

This poorly known but economically significant deposit type is found where basaltic rocks have been emplaced into and erupted across sulfate-bearing evaporitic sedimentary rocks. In addition to copper and nickel, these deposits have significant amounts of platinum group elements. The quadrangle contains numerous areas that contain both sulfate-bearing evaporites and nickeliferous basaltic rocks, and, based upon our limited understanding of the type deposit, there appears to be a permissive environment for the formation of this type of deposit. In order to properly evaluate the resource potential, the petrology and geochemistry of the basalts and evaporites should be characterized, and the interaction between these two units should be investigated during field studies. Detailed rock property and aeromagnetic studies would be integrated into the final evaluation. The geochemical studies should be completed as early as possible to determine the viability of this study and to delineate areas for more detailed studies.

Sandstone-hosted Deposits

Many of the Phanerozoic rocks in the quadrangle are clastic sedimentary rocks, and many of them are redbeds. Sandstone-hosted metal deposits have been identified in at least two localities, but the vast expanse of clastic sedimentary rocks permissively allows a variety and number of "sandstone-hosted" deposit types. Initially, the formations and facies in which the known deposits occur should be identified and the information integrated into the results of modern sedimentological studies of the units. This would permit specific areas and facies to be targeted for field and geochemical evaluations, using models derived from known deposits.

Placer Deposits

Placer deposits have been exploited in many parts of the quadrangle, and these areas of known placer production should be reevaluated in light of modern placer technology. Work was discontinued on many placers for noneconomic reasons, including environmental constraints. Also, when placer mining was at its zenith, recovery techniques were inferior and little attention was paid to products other than gold. Placer deposits derived from source rocks from Proterozoic to Tertiary in age are likely to occur in the quadrangle. Therefore, consideration should be given to the potential for fossil placers as well as those in modern fluvial systems. Geochronological studies of vein deposits will help delineate areas of potential pre-Tertiary fluvial sediments to be evaluated for placer gold and other products. If the geochronologic study of the vein deposits indicates any older (pre-Tertiary) sources of gold, then pre-Tertiary fluvial sediments should be evaluated for placer gold deposits.

Fuels

The quadrangle contains known deposits of coal, oil shale, and oil and gas that constitute an enormous known resource. The coal and oil shale deposits are contained in specific environments; resource assessment should identify favorable depositional environments and processes, and then apply these data to the known and projected limits of the formations. Oil and gas have been produced from traps in the Piceance Basin. Further studies should identify and evaluate new models, especially those related to structural styles in foreland regions. The models should incorporate commercially available seismic data where financially feasible.

Industrial Minerals

Industrial minerals that have been produced from the quadrangle include marble, sand and gravel, lightweight aggregate, gypsum, limestone, gemstones, and clay. Most of the industrial minerals known to occur in the quadrangle have a local, rather than national, economic importance. As a result, an evaluation of the industrial minerals could take two forms. The first, more exhaustive, form of study would evaluate the environments under which the various commodities formed and apply these data to other areas in the quadrangle. The second, more cursory, form of study would simply catalog the known occurrences and make general predictions regarding potential resources. In both cases, other formations and environments should be evaluated for undiscovered deposits, such as those of nahcolite, dawsonite, and other evaporite-related minerals in the Green River Formation, and rare earths, mica, and feldspar in Proterozoic pegmatites.

APPENDIX 1. BIBLIOGRAPHY

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APPENDIX 2. GEOCHEMICAL ELEMENT ANOMALY DESCRIPTIONS

Gold (Au)

Fifty samples contain gold in concentrations above the detection limit of 0.2 ppm. A value of 0.5-1 ppm was considered highly anomalous and >1 ppm extremely anomalous (table 2). The greatest concentration of these high values is in the upper drainage basin of the South Platte River, from Mosquito Creek northward to Hoosier Pass. Others occur along Lake Creek above Twin Lakes Reservoir, and from the Roaring Fork River between Lincoln Gulch and Aspen, from Iowa Gulch in the Leadville district, from just south of Tennessee Pass, from upper Homestake Creek, from near the head of Halfmoon Creek, from southeast of Twin Lakes Reservoir, from upper Cross Creek, from upper Black Gore Creek, from the Blue River north of Breckenridge, and on the upper South Fork of the South Platte River. Two isolated high grade samples were collected form the upper drainage basin of Buzzard Creek in eastern Mesa County in an area covered by continental clastic sedimentary rocks of early Tertiary age. Other samples containing detectable gold less than 0.5 ppm are widely scattered through the area.

Silver (Ag)

Forty-one silver anomalies range from the detection limit at 5 ppm up to 104 ppm, and they have been classified as anomalous (5-<10 ppm), highly anomalous (10-<20 ppm), and extremely anomalous (≥20 ppm; table 2). Samples in the extremely anomalous category come from the upper Blue River drainage basin northwest of Hoosier Pass, from the head of the Arkansas River south of Climax, from Iowa Gulch in the Leadville district, from the Eagle River at Gilman, and from the Roaring Fork River just below Aspen. Highly anomalous samples occupy a belt extending southwest from the Leadville district, across the Arkansas River to the upper basin of Lake Creek, with another in lower Lincoln Gulch west of the Continental Divide. On the east slope of the Mosquito Range, there is a high silver anomaly on Fourmile Creek east of the London fault, and another where a northeast trending fault crosses the south fork of the South Platte River; there is also one to the north on the Blue River downstream from Dillon Reservoir. Several moderate silver anomalies occur near the old mining districts of Ashcroft, Rock Creek, Granite, Breckenridge, Twin Lakes, Homestake, and Kokomo. One also occurs in eastern Mesa County near Haystack Mountain and another near the mouth of West Lake Creek south of Edwards, which are not related to any known mining districts.

Some of these silver anomalies appear to be related to vein and replacement deposits in carbonate rocks, and others to pyritic gold-quartz veins cutting igneous intrusives and metamorphic rocks.

Copper (Cu)

Copper concentrations of 100 ppm or more were considered anomalous. Thirty-nine such samples were classified as anomalous (100-400 ppm), highly anomalous (400-800 ppm), and extremely anomalous (≥800 ppm; table 2). The three samples in the highest category were taken from the south fork of Lake Creek, from near the head of Lincoln Gulch, and from the Roaring Fork River near Aspen, with another highly anomalous sample just to the south of it. Other highly anomalous samples were obtained from the Crystal River, Twin Lakes, Leadville, Gilman, and Holy Cross districts. Anomalous samples occur also at Holy Cross, Breckenridge, along the east flank of the Mosquito Range in the Alma district, in the Leadville district and in a belt extending from the Sugarloaf-St. Kevin district southwesterly to the Twin Lakes district, and in Lincoln Gulch west of Independence Pass.

Lead (Pb)

There are 75 samples containing more than 100 ppm lead, which have been classified as anomalous (100-500 ppm), highly anomalous (500-1,000 ppm), and extremely anomalous (≥1,000 ppm; table 2). A striking feature of the lead anomaly map is a westerly trending belt of strong anomalies extending from Fourmile Creek through the Leadville district to the Sugarloaf-St. Kevin district west of the Arkansas River, with isolated high anomalies to the south on Box Creek and near the mouth of Lake Fork Creek. High anomalies in the Alma district on Mosquito Creek and Buckskin Gulch are connected with high anomalies near Breckenridge by a northerly trending belt of moderate anomalies. There are also high lead anomalies marking the Kokomo and Gilman districts. A series of three extremely anomalous samples also reflects the Aspen district and a high anomaly to the north on Woody Creek indicates the Lenado district. High lead anomalies near the southern boundary of the Leadville sheet mark the Twin Lakes, Lincoln Gulch, Ashcroft, and Crystal River districts. Moderate anomalies in the 100-500 ppm range are widely dispersed and many of them are unrelated to known mining districts.

Zinc (Zn)

One hundred fifty nine samples contain more than 200 ppm Zn. The range from 200-1,500 ppm was classified as anomalous, 1,000-5,000 ppm highly anomalous, and ≥5,000 ppm extremely anomalous (table 2).

All samples containing 1,000 ppm or more zinc come from streams that drain areas of known base metal mining districts. These include: Four Mile and Mosquito Creek in the Alma district, the Blue River north of Breckenridge, lower Ten Mile Creek and also upper Ten Mile Creek near Kokomo, streams draining the Leadville district, the Sugarloaf-St. Kevin district and the Twin Lakes district west of the Arkansas River and the Eagle River and below Gilman. West of the Continental Divide, there are high zinc anomalies on the Roaring Fork River near Aspen, on Woody Creek near Lenado, and the upper Crystal River in the Rock Creek district. Samples in the lowest category are widely distributed, and most abundant in the southeastern part of the region south of a line extending from Breckenridge to Gilman and southwest to the 39th parallel south of Marble, in the Colorado Mineral Belt. Isolated clusters of zinc anomalies are also present in the Gore Range north of Vail Pass, in a belt extending northeast from near Gypsum to near Yarmony on the Colorado River, and in the northern and western parts of the White River Plateau.

Bismuth (Bi)

Bismuth is a useful tracer element for copper, lead, zinc, and silver deposits, as it is a common minor constituent of ores of these metals. Eighty samples contain 10 ppm or more bismuth. These were classified as anomalous (10-15 ppm), highly anomalous (15-25 ppm) and extremely anomalous (≥25 ppm; table 2). Most of the samples containing more than 15 ppm bismuth are also anomalous in one or more of these four elements, and were collected in or near a known mining district. These include Buckskin Gulch, Alma, Four Mile Creek, Granite, Twin Lakes, Leadville, Kokomo, Ten Mile Creek, Sugarloaf-St. Kevin, and Aspen. A few high bismuth anomalies are not closely related to known mining districts. These include one near the mouth of Willow Creek a few miles north of Dillon Reservoir, one on the south fork of the South Platte River, one about 4 miles west of Turquoise Lake, one on upper Box Creek northeast of Mt. Elbert, and one isolated sample in southeastern Mesa County on the upper east fork of Willow Creek. There are also several widely scattered bismuth anomalies in the 10-15 ppm range in this same region of the upper Buzzard Creek drainage basin north of Grand Mesa. Others are widely scattered on or near the White River Plateau, on the western flank of the Grand Hogback, in the Blue River and Williams Fork River drainage basins in the northern Gore Range, and on the Colorado River east of Yarmony Mountain. However, most of the others are within the boundaries of the mineral belt.

Nickel (Ni)

The frequency distribution of anomalous nickel samples is shown in table 2. Most of them are in the northern part of the map area with a heavy concentration in the northern White River Plateau and the Flat Tops area, where they are associated with Tertiary basalt flows. Other anomalies farther east at Yarmony Mountain and south of Cottonwood Peak are also associated with similar flows. There is an extremely high anomaly southeast of Sheephorn Mountain in the northern Gore Range near a small Tertiary volcanic intrusive cutting Cretaceous sedimentary rocks, and another in Proterozoic rocks of the Williams Fork Mountains on Kaiser Creek. An isolated extreme anomaly to the southwest occurs near the head of West Brush Creek on a west-northwest trending fault that cuts sedimentary rocks of Permo-Pennsylvanian age, and a high anomaly is on upper East Brush Creek near Fulford, with another in Proterozoic rocks on Ten Mile Creek about three miles east of the Dillon Reservoir. An extremely isolated high anomaly near the southern boundary of the Leadville sheet is north of Schofield Pass in the vicinity of a Tertiary intrusive plug in the upper drainage basin of the Crystal River close to the Rock Creek mining district.

Thorium (Th)

One hundred eighteen samples contain 50 ppm or more thorium. These are classified as anomalous (50-$<$100 ppm), highly anomalous (100-$<$200 ppm), and extremely anomalous ($\geq$200 ppm; table 2). These are concentrated in areas of Proterozoic rocks in the eastern part of the region. High thorium anomalies occur in three belts in the southeastern part of the quadrangle; one extends northeast from the crest of the Mosquito Range near the 39th parallel to the south fork of the South Platte River. Another parallel belt to the west runs from south of Twin Lakes Reservoir across the Arkansas River to the upper basin of Big Union Creek, and a third extends northerly from near the head of Box Creek to about 4 miles west of Turquoise Lake; a fourth belt to the west occurs along Hunter Creek from the Williams Mountains to the Roaring Fork River. Isolated high thorium anomalies are also present on the Williams Fork River south of the mouth of Kinney Creek, in the drainage basin of Ten Mile Creek, in the upper drainage basin of the Frying Pan River east of Reudi Reservoir, on the Roaring Fork River near the Independence district, and another near Aspen, and near the head of the Crystal River above Ashcroft, and near the head of Plateau Creek in eastern Mesa County, with moderate anomalies to the north and to the southwest of this locality. Other widely scattered moderate anomalies in the northern part of the region probably have little significance in terms of mineral deposits.

Uranium (U)

Ninety six samples containing ≥20 ppm uranium were classified as anomalous (20-<40 ppm), highly anomalous (40-<80 ppm), and extremely anomalous (≥80 ppm; table 2). Nearly all of the uranium anomalies are in samples from streams that drain areas of Proterozoic igneous and metamorphic rocks in the eastern part of the region. Three strongly anomalous samples mark an easterly trending fault zone in Proterozoic rocks north of Vail Pass in the Gore Range.

In the Ten Mile Range to the south, there is an extremely anomalous sample from an easterly flowing tributary of the Blue River a few miles north of Hoosier Pass, and another in the upper drainage basin of Mosquito Creek about two miles northeast of the London Fault, with three highly anomalous samples in an east-west belt crossing the Mosquito Range about midway between these two localities, in a complexly faulted block of Proterozoic rocks. Another highly anomalous sample is part of a compound anomaly on the upper south fork of the South Platte River where it is crossed by an easterly trending fault; other highly anomalous samples come from the west fork of Ten Mile Creek east of Vail Pass, the Sawatch Range near Homestake Peak, Chapman Gulch southeast of Ruedi Reservoir, and the Roaring Fork River southeast of Aspen. Moderate uranium anomalies are widely scattered in the eastern part of the Leadville $1^{o}x2^{o}$ sheet, chiefly in areas of Proterozoic rocks, but there are none in the north-central and western parts of the region.

Vanadium (V)

The 30 vanadium anomalies are all shown by a single symbol since only two of these contain 200 ppm or more exceed 300 ppm. Most of them are in streams draining areas covered by sedimentary rocks of Paleozoic or younger age. Exceptions are three anomalies along Kaiser Creek in the northeastern corner of the region in Proterozoic rocks, and two samples along Lake Creek west of Twin Lakes Reservoir in an area underlain by a felsic pluton of Laramide age. Sedimentary rocks of Jurassic and Cretaceous age host vanadium anomalies along the Blue River north of Green Mountain Reservoir, west of the Gore Fault on Sweetwater Creek, along the Colorado River northeast of State Bridge, in the area between Castle Peak and Wolcott north of the Eagle River, east of lower Brush Creek south of the Eagle River, north of Basalt Mountain on Cattle Creek, on East Sopris Creek southwest of Snowmass, on the upper Crystal River west of Bellview Mountain, and near the vanadium mines north of Harmony Gap Reservoir, on the north side of the Grand Hogback.

In rocks of middle and upper Paleozoic age, vanadium anomalies occur in the vicinity of Vail Pass, the west flank of Yarmony Mountain, the northern part of the White River Plateau, and west of Carbondale. There are two vanadium anomalies in continental sedimentary rocks of early Tertiary age on Little Rock Creek near Haystack Mountain in eastern Mesa County. Vanadium anomalies are not related to those of uranium or thorium.

Barium (Ba)

Barium in high concentrations in stream sediments is commonly derived from barite gangue associated with vein or replacement base-metal deposits.

Classification of the 38 anomalous barium samples is shown in table 2. Only three samples contain more than 4,000 ppm barium, and these are clustered on the Roaring Fork River near Aspen. In the 2,000-4,000 ppm range, there are two samples on Lincoln Gulch in an area underlain by a mineralized Tertiary quartz monazite pluton, a third from just below the confluence of the Roaring Fork and Frying Pan Rivers. Three more form a cluster near the town of Rifle, two on Rifle Creek north of the town and the third near the mouth of Mamm Creek to the southeast, all in areas covered by clastic sedimentary rocks of early Tertiary age. Samples in the 1,000-2,000 ppm range are widely dispersed, largely in the northern and western parts of the region, although there is one near Leadville, several on Lake Creek, and two on the upper Roaring Fork River, one on the Crystal River near Ashcroft, and two on upper Salt Creek east of the Brush Creek district. The rest are scattered through an extensive area in the northern part of the region except for two on the upper east fork of Lean Creek west of Chalk Mountain in southern Mesa County.

Cerium (Ce)

The classification of the 35 anomalous cerium samples is shown in table 2. The distribution of cerium anomalies bears strong resemblance to that of thorium anomalies. They are largely confined to areas of Proterozoic rock outcrops in the eastern part of the Leadville 2 sheet. Cerium anomaly belts extending northeast from the vicinity of Buffalo Peaks to the south fork of the South Platte River on the east flank of the Mosquito Range, and also northward from Box Creek to west of Turquoise Lake, correspond with thorium anomaly belts. In addition, there are high cerium anomalies in the northeast on the Williams Fork River south of the mouth of Kinney Creek in Proterozoic rocks, on Piney Creek west of Piney Mountain in Permo-Pennsylvanian rocks, on Ten Mile Creek north of the mouth of West Ten Mile Creek in Proterozoic, and at the head of west Ten Mile Creek near Vail Pass in Permo-Pennsylvanian sedimentary rocks. There is one at a fault junction in Proterozoic rocks on the Arkansas River east of Twin Lakes Reservoir, one on Lake Creek west of this reservoir in a mineralized felsic pluton of Tertiary age, one near the head of the Roaring Fork River west of Independence Pass, one on upper Bowman Creek to the southwest on the 39th parallel, one near the head of Hunter Creek, one on the south fork of the Frying Pan River, and one near the junction of Hunter Creek and the Roaring Fork River just north of Aspen.

Tantalum (Ta)

Tantalum, a rare element used in hardening steel, occurs in the mineral tantalite, and in minor amounts in zircon and sphene, most commonly in granite pegmatites associated with niobium. Only 38 samples contain Ta above the detection limit of 8 ppm, and all but 4 of these contain less than 6 ppm (table 2). Most of the samples with detectable Ta come from Proterozoic rocks. Tantalum anomalies occur in an east-northeast trending belt extending from Aspen to north of Leadville where there is a cluster of anomalies south of Chalk Mountain. A shorter northeast trending belt extends from near Homestake Peak, in the Sawatch Range, to Ten Mile Creek, with a strong anomaly just west of Vail Pass. It also forms a short northeast-trending belt in the southern Mosquito Range from north of Buffalo Peak to the south fork of the South Platte River, and a northerly trending belt from near Alma, across Hoosier Pass into the upper drainage basin of the Blue River, with three widely spaced anomalies in the drainage basin of the Williams Fork River in the northeastern part of the Leadville quadrangle. Four widely scattered anomalies, in the southwestern part on Grand Mesa, are suspect because of their geologic setting.

APPENDIX 3. INTERPRETATION OF GEOPHYSICAL DATA

Gravity and Magnetics

Physical Properties

Proterozoic rocks have a wide range in magnetic susceptibility and density. The granitoid rocks tend to be the most magnetic, and metamorphic rocks are generally moderately to weakly magnetic. In some parts of the Sawatch and Gore Range, however, migmatites and biotite gneisses appear to be more magnetic than the granitoid bodies.

Amphibolites are the densest of the common Proterozoic rocks, whereas some granites and felsic metamorphic rocks have relatively low densities. Taken as a whole, the Proterozoic rocks are significantly denser than the Tertiary intrusive rocks. Many Tertiary plutons are magnetic and produce conspicuous positive anomalies, but, where altered, they commonly produce relative magnetic lows or plateaus.

Paleozoic sedimentary rocks have a wide range in density but are in large part nonmagnetic. Densities range from as low as 2.4 g/cm^3 for porous sandstones and siltstone to 2.85 g/cm^3 for limestones and dolomites. Evaporites of the Eagle Valley region may have densities as low as 2.2 g/cm^3, depending on the relative amounts of interstratified clastic and evaporitic material.

The densities of Mesozoic and Tertiary sedimentary rocks in the quadrangle vary widely from 2.3 to 2.5 g/cm^3, based upon comparison with similar rocks to the west and southwest in the central Colorado Plateau. The few measurements of magnetic susceptibility indicate that the rocks are virtually nonmagnetic.

Regional Patterns of Gravity Anomalies

Two major regional gravity anomalies dominate the Leadville quadrangle. The most conspicuous anomaly is a well-known gravity low that trends northeast across the southeastern part of the quadrangle (fig. 1), and which is produced by a low-density batholithic mass that underlies a large part of the Colorado mineral belt. An intracrustal origin for the low has been demonstrated by numerous models, as well as by the isostatic residual anomaly map, on which the large negative anomaly persists through mountainous areas where the crust presumably was isostatically thickened. Local negative anomalies associated with valley fill and with known or interpreted silicic plutons are superimposed on the main low.

The second anomaly, a major relative high of 20-30 mGals or more, trends northwest across the central and northwestern part of the quadrangle. This broad high appears to partly coincide with the White River uplift and, to a lesser extent, with an anticlinal feature at Hardscrabble Mountain. The apparent gravity high may reflect the Pennsylvanian tectonic highland that divided the Eagle Valley evaporite basin into two parts; the high therefore separates lows produced by thick sequences of low-density evaporites.

Several other gravity lows are present within the Leadville quadrangle. A poorly defined low of 10 to 20 mGals is present over the main Eagle basin, presumably caused by low-density evaporites in the basin. Similarly, in the southeast part of the quadrangle, a broad, poorly defined gravity low is present near the Roaring Fork syncline. However, the anomaly, as contoured, crosses the structurally controlled Grand Hogback, suggesting that it may in part be reflecting evaporites of the Paleozoic Eagle basin. Detailed surveys may reveal salt anticlines or domes in the evaporite basins.

Poorly defined gravity highs are present along the western edge of the quadrangle in the Piceance Basin. The cause of these relative positive anomalies is unknown, but dense intrabasement rocks are inferred. Great depth to basement is likely, because the elevation of the base of the Dakota Sandstone is 4,000 to 7,000 ft below sea level at the east-central edge of the adjacent Grand Junction quadrangle to the west. A general gravity high occurs over the northern Gore Range and Williams Fork Mountains, and relative lows are present over intermontane basins along the Blue River and Williams Fork.

General Features of the Magnetic Anomaly Map

Magnetic anomalies are present throughout the quadrangle. The major groups of anomalies will be briefly discussed as they occur from west to east.

In the southwestern part of the map area, short wavelength anomalies are apparently produced by Tertiary basalt flows and associated plugs in the Grand Mesa region. Similarly, basalts of the White River uplift and vicinity produce short wavelength anomalies. Many of these appear to be superimposed on long wavelength anomalies, probably generated by magnetic rocks within the Proterozoic basement. Many negative anomalies are present, perhaps representing intervals of reversed magnetization between about 22 and 4 Ma (based upon potassium-argon age determinations).

A string of northwest-trending magnetic highs of 100 to 300 nT is present along the northwestern edge of the White River uplift, generally just northeast of the Grand Hogback. These may be related to locally exposed Proterozoic units shown on the geologic map (Tweto and others, 1978); these include granitoid bodies, amphibole gneisses, and biotite and felsic gneisses.

Magnetic highs (up to 700 nT) are associated with mid-Tertiary plutons in the Elk Mountains (Campbell, 1985). Magnetic modeling of the White Rock, Snowmass, and Mt. Sopris plutons suggest that they are connected to a main batholithic mass at depth. Northwest-trending "deep-source anomalies" in the nearby Red Table Mountain area may be associated with redbed sequences.

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

None of the major mining districts in the quadrangle have distinct regional magnetic expressions. The Climax and Leadville districts have weak magnetic lows, perhaps related to alteration; a similar argument can be applied to areas in Holy Cross Wilderness Area (Campbell and Wallace, 1986) and a pyritized area in the Maroon Bells-Snowmass Wilderness Area (Campbell, 1985).

Aeroradiometrics

The spectrometric-gamma-ray survey of the Leadville quadrangle detected gamma-rays from daughter isotopes of potassium (K), uranium (U), and thorium (Th) that were present within a few feet of the surface of the ground. Approximately 95 eU anomalies were identified in the Leadville sheet. "Anomalies" were taken to be places along flight lines where raw eU counts were more than 2 standard deviations above the mean for the whole survey. No similar analysis was done for K or eTh. Most of the anomalies were located in upper Paleozoic and Mesozoic sedimentary rocks in the north central part of the Leadville sheet. Others were located on the Sawatch uplift, and they were presumed to be associated with fissures in Proterozoic metamorphic rocks there. Few of the anomalies were in proximity to any of the uranium occurrences reported in the literature for the Leadville sheet, nor did they correlate especially well with certain formations which in the past were widely accepted as uranium host units. The contractor noted the eU high near the Climax Mo mine, but remarked that it did not fall exactly over the open pit workings there and probably was associated with a separate but nearby natural source.

The maps show high concentrations of eTh, and to a lesser extent of K and eU, over the granitic intrusive and metamorphic rocks of the Sawatch uplift. In particular, many eU highs fall over and are presumably related to Middle Proterozoic granitic rocks (Yg in Tweto and others, 1978). In the absence of processes that separate the relatively more soluble U from Th, the ratio eU/eTh in fresh intrusive rocks should be approximately 0.25. The eU/eTh map shows lower values than this (uranium depletion) over parts of the Middle Proterozoic granitic units of the Sawatch Uplift, but higher values (uranium enrichment) over upper Paleozoic and Mesozoic sedimentary units to the north and west. That map therefore suggests that erosional and ground-water processes in the Leadville sheet have moved uranium from primary Middle Proterozoic sources to present-day deposits in sedimentary units of the Eagle and Piceance Basins.

The K map, like those of eU and eTh, shows highs over the Middle Proterozoic map units, but other K highs fall over Early Proterozoic gneissic rocks, particularly in the Gore, Tenmile, Mosquito, and Sawatch Ranges. Tectonic elements such as faults to the west of the Gore and Sawatch Ranges, the Homestake shear zone and its extension to the southwest, the Roaring Fork fault, and the Grand Hogback anticline are evident on this map. (Empirical leveling of flight lines acts to mute features subparallel to those lines, possibly accounting for the missing east-west part of the Grand Hogback.) Some Tertiary igneous units appear to cause K highs. The Tertiary basalt flows at Ralston reservoir south of Dotsero might be such a unit. Middle Tertiary intrusive bodies at Green Mountain and Chair Mountain give rise to K highs, but other such bodies (e.g., the Snowmass stock) do not. The broad K highs over sedimentary units of Grand Mesa and the White River uplift seem to wax and wane without clearly correlating with particular units there.

Remote Sensing

Limonite Distribution

Large areas of limonite are associated with Quaternary alluvial deposits, Tertiary sedimentary rocks, and upper Paleozoic redbeds. These limonite areas can be largely discounted as potential hydrothermal alteration targets based on the limonite occurrence alone. The remaining limonite occurrences are associated with Cretaceous and Tertiary volcanic and plutonic rocks and Proterozoic crystalline rocks. These limonite occurrences delineate areas of potential hydrothermal alteration that must be documented and characterized during full-scale CUSMAP investigations.

Much of the soils and rocks in the western part of the quadrangle are obscured by vegetation cover on the MSS data and cannot be evaluated for limonite. Significant portions of the mountainous terrain in the eastern part of the quadrangle are also obscured by vegetation. The greater resolution afforded by Landsat Thematic Mapper (TM) data should provide a means of better probing these areas for limonite distribution, and the additional spectral bands on TM data will allow additional, more detailed remote sensing characterization of the MSS limonite anomalies as potential hydrothermal alteration targets prior to field investigations.

Linear Features

The linear feature data for the Leadville quadrangle were analyzed for prominent trends. The only statistically significant trend is a broad trend composed of several prominent significant spikes between about 40°E and 85°E. Individual significant spikes within the main trend occur at 44°E., 51-65°E., 69-70°E., 75°E., and 81-83°E.

APPENDIX 4. DEPOSIT MODEL CRITICAL CHARACTERISTICS

The following paragraphs provide the characteristics used in the construction of table 3, and outline the information to be gleaned from the topical studies designed into this preassessment that will bear directly on either making assessment possible or enhancing the assessment that would take place in a full-scale CUSMAP. Only Levels of Assessment 1, 2, and 3 (table 3; Chapter 5) are addressed here.

Climax Mo - The Leadville quadrangle contains the Climax mine, type locality for this deposit type. In addition, at least 11 prospects are known that might fall on the grade and tonnage distributions (fig. 3). The deposit model has three critical characteristics: occurrence within the -285 mgal gravity contour, proximity to Proterozoic rocks, and presence of an epizonal high-silica granitic pluton. Exploration for Climax Mo deposits has been very thorough in well-exposed parts of the quadrangle. At the present state of knowledge, the entire quad is permissive for these deposits, but they are more likely to occur near the large gravity low, and within the Proterozoic outcrop or within a few hundred meters above the contact with overlying rocks. Using consensus subjective methods, we estimate a 90 percent chance of 4 or more, a 50 percent chance of 20 or more, and a 10 percent chance of 38 or more undiscovered deposits. These numbers could be refined using the results of the proposed topical project on the characterization of igneous rocks.

Porphyry Cu-Mo - At least three porphyry Cu-Mo prospects are known in the quadrangle, and one more is immediately adjacent. All are related to intrusive rocks of Oligocene age. Critical criteria for this deposit type are very similar to those for Climax Mo, except that the intrusive rocks that are the source for these deposits are less evolved chemically. We estimate a 10 percent chance of one or more undiscovered deposits. This estimate could be refined on the basis of the results of topical studies of intrusive rocks. At the present state of knowledge, the entire quad is permissive for the occurrence of these deposits. We estimate a 10 percent chance of one or more undiscovered deposits. This estimate could be refined on the basis of the results of the topical project on the characterization of igneous rocks.

Low-F Moly Porphyry - Some of the areas prospected for Cu-Mo porphyries may properly belong to this class of deposits. At the present state of knowledge, the entire quadrangle is permissive. We estimate a 10 percent chance of one or more undiscovered deposits. This estimate could be refined on the basis of the results of topical studies of intrusive rocks.

Sandstone Cu, U, and V - Two areas, shown on figure 5, contain prospects that resemble these deposit types. Topical studies designed specifically to characterize the sedimentary environments favorable for the accumulation of various metals in sandstones are a part of this proposal. At present, the information on sandstone-hosted deposits is too sparse to differentiate the metals, and figure 5 simply shows potential sandstone host rocks for all such deposits.

Skarn Deposits - Skarns may form wherever magmas are emplaced into carbonate rocks. Some of the ore in the Leadville and Breckenridge districts was produced from skarns, and skarns could form a significant component of other districts. In addition, the iron deposit south of Aspen (Pitkin County Iron mine) appears to be an iron skarn developed in limestones of the Belden Formation. By completing the topical project on hydrothermal districts, existing skarns could be identified, and refined tract maps for their potential occurrence could be developed.

Polymetallic replacement - Deposits of this type appear to have been the source of most of the metals produced from those districts developed in carbonate terranes. Completion of the topical study of hydrothermal districts could help document this fact. We do not propose topical research designed specifically to settle the controversy about whether the mineralization at Leadville is primarily polymetallic replacement or remobilized Mississippi Valley-type deposits. Hopefully, the researchers working on this specific problem will have resolved the issue by the time a Leadville CUSMAP is completed.

Replacement Mn - These deposits are known only in districts with major polymetallic replacement deposits. They seem to consist of Mn-rich portions of those deposits, and may not consist of separate deposits. They were exploited primarily by the iron and steel industry.

Polymetallic veins - We know of no districts in the Leadville quadrangle that contain significant polymetallic replacement deposits, but that do not contain significant polymetallic veins. However, the converse is not always true, depending upon host rocks. The primary expected result of the topical project on hydrothermal deposits is to sort out this relationship and to create viable occurrence models for vein and replacement polymetallic deposits.

Noril´sk Copper-Nickel-Platinum Group Elements - The environment is favorable for these deposits over a wide area in the west-central part of the quadrangle, where feeders for the Tertiary Flat Tops basalts have intruded through the Eagle Valley Evaporite basin. A CUSMAP study would examine likely areas for signs of mineralization, and help establish criteria local to the quadrangle that would permit a determination of whether deposits of this type are likely. Because the potential importance of Noril´sk-type deposits is so great, a specific topical study to address the problem has been designed. This study could have important consequences for nickel and PGE evaluations.

Komatiitic Cu-Ni - The Homestake mine, west of Tennessee Pass in a belt of calc-silicate gneisses, contains pentlandite, and it may be a komatiitic Cu-Ni prospect. Nine preliminary tracts were delineated that may contain the appropriate host/source rocks. These designations could be refined, and numbers of undiscovered deposits estimated during execution of the topical project concerning Proterozoic metavolcanic rocks.

Diamond pipes - Small diamond pipes in northern Colorado went undiscovered for decades. The known pipes are of probable Devonian age, and there is no information to suggest that they may not occur in the Leadville quadrangle. They may be exposed in both Proterozoic crystalline rocks and pre-Devonian sedimentary rocks.

Sedimentary Exhalative Pb-Zn - Deposits of this type are not known in the quadrangle, but they may be expected to occur in an environment like that of the Belden-Eagle Valley restricted anoxic basin. Volcanic rocks of the same age may be present in the quadrangle. Thus, a topical project has been designed specifically to evaluate the possibilities for deposits related to this special environment.

SE Missouri Pb-Zn - Stratabound sulfide deposits can occur in carbonate reef units where basin brines have increased porosity and deposited metals in the carbonates. Carbonate reefs are present in the Leadville Limestone and other units, and some may be mineralized. Because the existing information is insufficient to distinguish these deposits from high-temperature polymetallic replacement deposits and skarns, this type of deposit will be evaluated as the various hydrothermal districts are evaluated as outlined in the work plan.

Sedimentary Mn - Deposits of this type are not known in the quadrangle, but they may be expected to occur in an environment like that of the Belden-Eagle Valley restricted anoxic basin. These deposits are very important manganese sources in other parts of the world, and the geochemistry of the Belden Formation is poorly known. Thus, a topical project has been designed specifically to evaluate the possibilities for deposits related to this special environment.

Upwelling Phosphate - Deposits of this type are not known in the quadrangle, but they may be expected to occur in an environment like that of the Belden-Eagle Valley restricted anoxic basin. This type of deposit has produced large amounts of phosphate elsewhere in the world. Thus, a topical project has been designed specifically to evaluate the possibilities for deposits related to this special environment.

Volcanic-hosted Massive Sulfide - Massive sulfides are typically deposited in submarine environments related to generally bimodal volcanic activity. In Colorado, the deposits are of Proterozoic age. Areas in the Leadville quadrangle that may contain metavolcanic rocks will be evaluated during topical studies on the metavolcanic rocks; any occurrences will be assigned to a specific type of massive sulfide model, and tracts and expected numbers of deposits will be generated.

Vein U - A few small occurrences of uranium-bearing veins are found in the east-central part of the quadrangle. Very little is known of these deposits, and they may be genetically related to both connate-hydrothermal and magmatic-hydrothermal deposits elsewhere in Colorado. The deposits should be described during a CUSMAP study, and a determination should be made as to the favorability of other parts of the quadrangle for further similar occurrences.

Turquoise - The Turquoise Chief mine, in the St. Kevin district west of Leadville, is one of the handful of primary turquoise deposits in the United States. No controls on its occurrence are known, and they would be the subject of a CUSMAP study.

Megabreccia Cu-Mo - These deposits are, so far as is known, unique to the Leadville quadrangle. They occur in pervasively-altered megabreccias within the Grizzly Peak Caldera. Large bodies of rock (dimensions of hundreds of meters) are altered to quartz, sericite, and pyrite, and they have copper and molybdenum grades of 0.01 to 0.2 percent. Examples are at Red Mountain and East Red Mountain. A CUSMAP study would provide a comprehensive description of these deposits, and criteria for their recognition elsewhere.

Placer Gold - Placers have been an important source of gold in the quadrangle, and many polymetallic districts were discovered on the basis of downstream gold placers. During the course of a CUSMAP study, known areas of historic production could be reevaluated to define areas of potential new llposits, and the possible importance of platinum group elements could be determined.