

STUDIES RELATED TO WILDERNESS

PRIMITIVE AREAS

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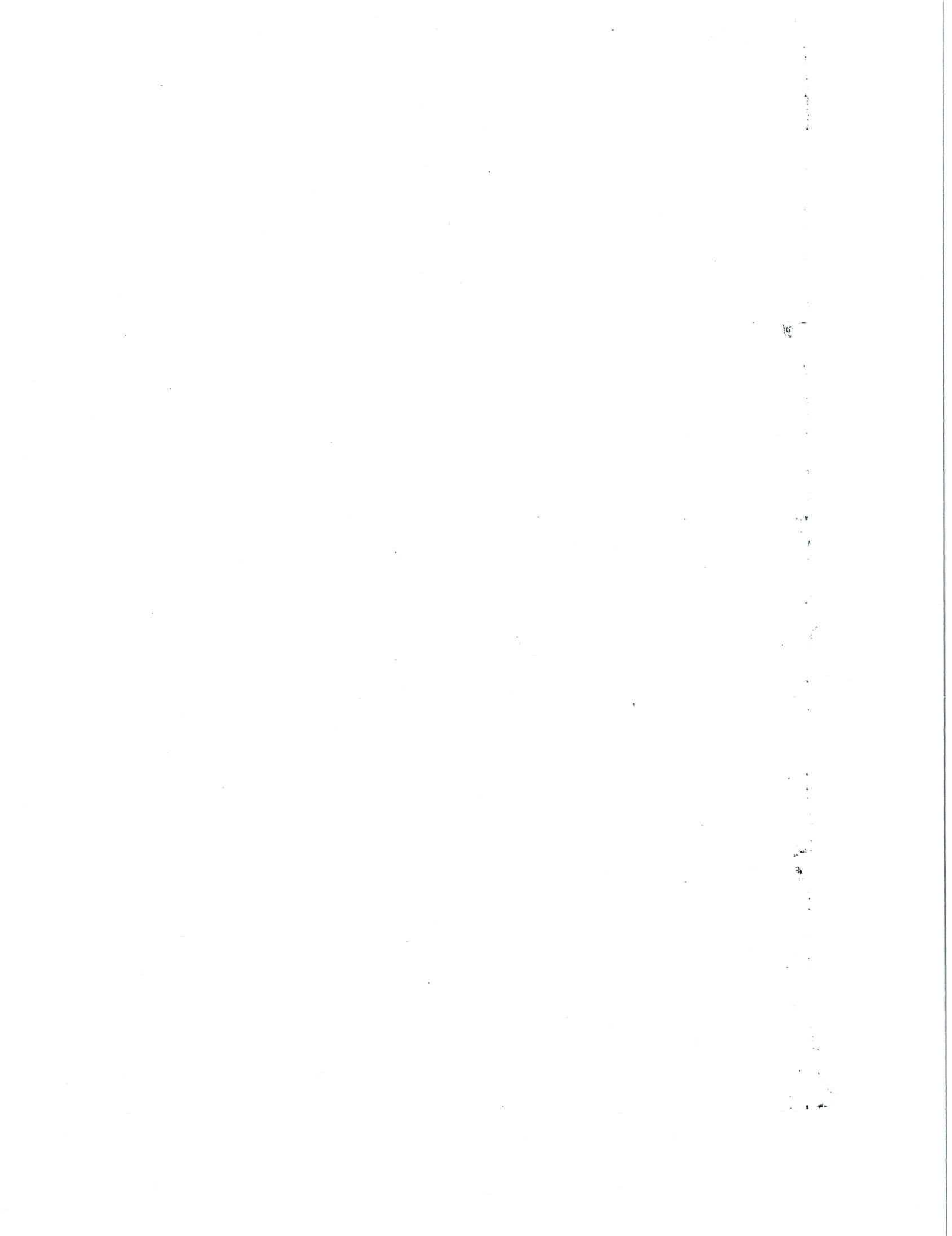


AREAS CONTIGUOUS TO THE  
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SOUTHWESTERN COLORADO

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Mineral Resources of Study Areas  
Contiguous to the  
Uncompahgre Primitive Area,  
San Juan Mountains,  
Southwestern Colorado

By T. A. STEVEN, P. W. LIPMAN, F. S. FISHER,  
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*With a section on*  
INTERPRETATION OF AEROMAGNETIC DATA

By PETER POPENOE and R. G. LUEDKE, U.S. GEOLOGICAL SURVEY

STUDIES RELATED TO WILDERNESS—PRIMITIVE AREAS

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GEOLOGICAL SURVEY BULLETIN 1391-E

*An evaluation of the mineral  
potential of the area*



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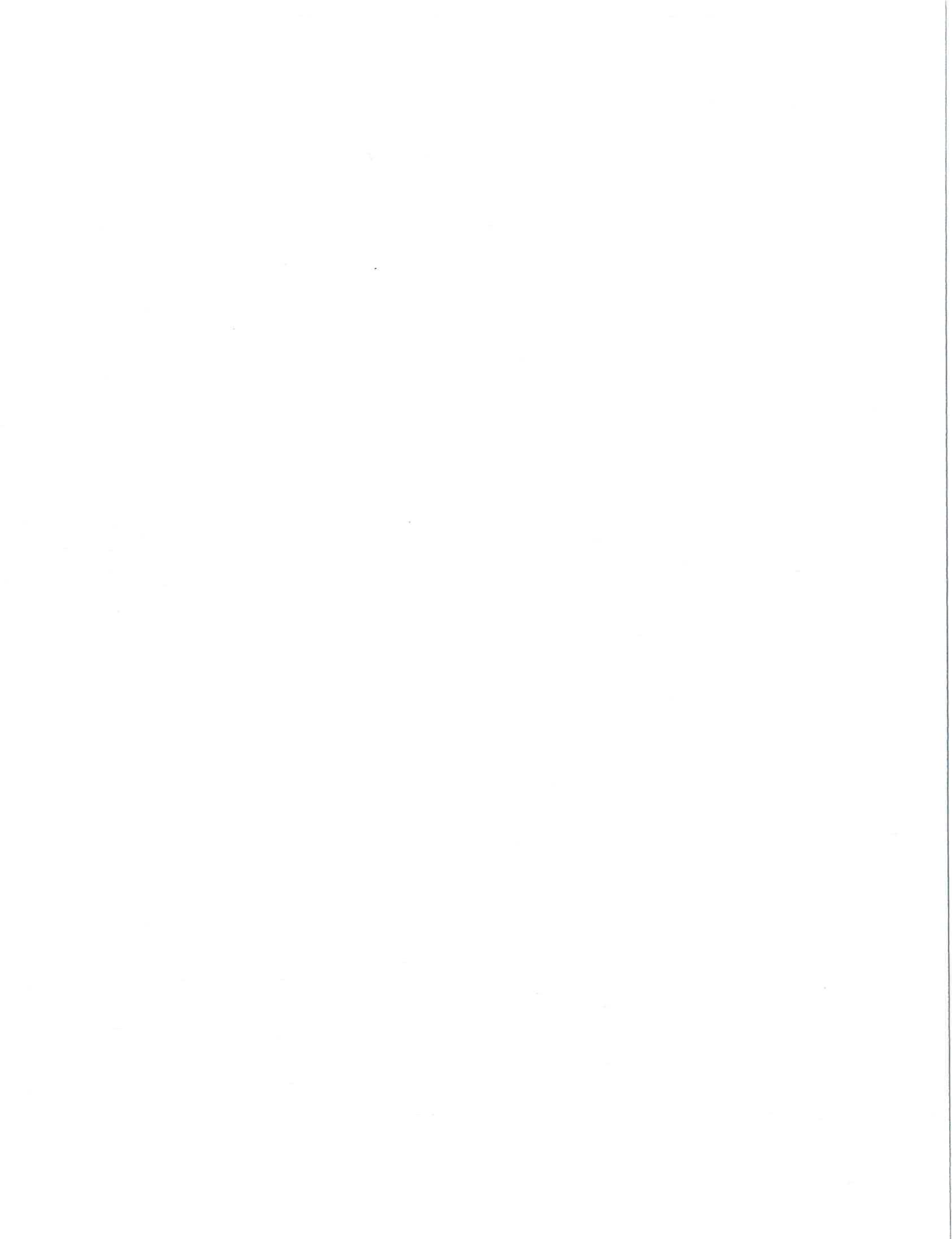
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## STUDIES RELATED TO WILDERNESS PRIMITIVE AREAS

In accordance with the provisions of the Wilderness Act (Public Law 88-577, Sept. 3, 1964) and the Conference Report on Senate bill 4, 88th Congress, the U.S. Geological Survey and the U.S. Bureau of Mines are making mineral surveys of wilderness and primitive areas. Areas officially designated as "wilderness," "wild," or "canoe" when the act was passed were incorporated into the National Wilderness Preservation System. Areas classed as "primitive" were not included in the Wilderness System, but the act provided that each primitive area should be studied for its suitability for incorporation into the Wilderness System. The mineral surveys constitute one aspect of the suitability studies. This bulletin reports the results of a mineral survey of study areas contiguous to the Uncompahgre Primitive Area, San Juan Mountains, southwestern Colorado, and some adjoining national forest lands that may come under discussion when the area is considered for wilderness designation.



## CONTENTS

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	Page
Summary.....	E1
Introduction.....	3
Previous investigations.....	4
Present investigations.....	5
Acknowledgments.....	6
Geologic appraisal, by T. A. Steven, P. W. Lipman, and F. S. Fisher.....	7
Regional geology.....	7
Paleozoic geology.....	8
Mesozoic geology.....	11
Telluride Conglomerate.....	14
Volcanic geology.....	14
Early intermediate volcanics.....	15
Ash-flow tuffs and associated rocks.....	15
Glacial deposits.....	19
Mineral resources.....	19
Late Cretaceous mineralization.....	20
Middle Tertiary mineralization.....	20
Geothermal energy.....	21
Fossil fuels.....	22
Western contiguous area.....	24
Geology.....	24
Stream-sediment samples.....	25
Vein deposits.....	25
Central contiguous area.....	27
Geology.....	27
Stream-sediment samples.....	28
Vein and replacement deposits.....	28
Eastern contiguous area.....	30
Geology.....	30
Stream-sediment samples.....	31
Matterhorn Creek.....	31
Yellowstone Gulch.....	32
El Paso Creek.....	32
Southern and southeastern streams.....	33
Northeastern and northern streams.....	34
East Fork Cimarron River.....	34
Middle Fork Cimarron River.....	35
Mineralization associated with early intermediate volcanic centers.....	35
Larson center.....	36
Cimarron center.....	36
Mineralization associated with intracaldera intrusions.....	37
Matterhorn center.....	38
Capitol City mining area.....	39
Altered area at Iron Beds.....	40

	Page
Geologic appraisal—Continued	
Eastern contiguous area—Continued	
Mineralization associated with intracaldera intrusions—Continued	
Veins along Henson Creek .....	E41
Mineralization associated with rhyolite intrusions .....	41
Geochemical data .....	42
Economic significance .....	45
Interpretation of aeromagnetic data, by Peter Popenoe and R. G. Luedke.....	47
Magnetic susceptibility measurements.....	47
Western Uncompahgre Primitive Area and western contiguous study area.....	51
Central Uncompahgre Primitive Area and central contiguous study area.....	52
Eastern Uncompahgre Primitive Area and eastern contiguous study area.....	53
Economic appraisal, by C. L. Bieniewski and H. C. Meeves.....	55
Mining claims.....	55
Sampling.....	56
History and mineral production .....	56
Leasing act minerals.....	58
Mines, prospects, and mineralized areas.....	58
Western contiguous area .....	59
Plummer Gulch.....	59
Moonshine Park .....	61
Forceman Creek.....	61
Corbett Creek.....	61
Cornet Creek-Pack Basin-Mill Creek basin .....	62
San Miguel River .....	64
Hayden Peak.....	66
Whipple Mountain.....	66
Last Dollar Mountain .....	66
Coal Creek .....	67
Beaver Creek .....	67
Wilson Creek .....	67
Blue Lakes .....	70
Central contiguous area .....	70
Cow Creek .....	71
Dexter Creek .....	72
Carbonate Hill.....	74
Cutler Creek.....	76
Crooked Tree Gulch.....	79
Eastern contiguous area .....	79
Henson Creek .....	80
Uncompahgre Peak-Nellie Creek-Larson Creek .....	83
Matterhorn Peak.....	85
Silver Jack mine area .....	85
Porphyry Basin.....	86
References cited.....	86
Index .....	123

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## ILLUSTRATIONS

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[Plates are in a separate case]

- PLATE    1. Geologic maps of study areas contiguous to the Uncompahgre Primitive Area, southwestern Colorado.



CONTENTS

VII

	Page
PLATE	
2. Sample-localities maps of study areas contiguous to the Uncompahgre Primitive Area, southwestern Colorado.	
3. Maps showing mines, prospects, mining claims, and sample localities of study areas contiguous to the Uncompahgre Primitive Area, southwestern Colorado.	
FIGURE	
1. Map showing location of the study areas contiguous to the Uncompahgre Primitive Area and calderas in the San Juan volcanic field, southwestern Colorado .....	E8
2. Geologic map of the western San Juan Mountains showing the Uncompahgre Primitive Area and contiguous study areas .....	10
3. Aeromagnetic map of the Uncompahgre Primitive Area and eastern, central, and western contiguous areas .....	48
4-10. Maps showing:	
4. The Millersburg middle adit .....	60
5. The Plummer Gulch adit .....	60
6. Main underground mine workings in and near the southeastern part of the western contiguous area .....	63
7. Adit at head of Cornet Creek .....	64
8. Adit in Pack Basin .....	64
9. Adit in Mill Creek basin .....	65
10. The Cowboy adit .....	68
11. Aerial view of Blaine Basin .....	68
12. Map of the Blaine mine .....	69
13. Map of the Hidden Silver adit .....	71
14. Map of the New York adit .....	72
15. Aerial view of the northern end of Bighorn Ridge .....	73
16. Map showing major underground mine workings of the Carbonate Hill area .....	74
17. Photograph of Carbonate Hill from Little Gem mine area .....	75
18. Map of the Army-Navy adit .....	76
19. Map of the Sunbeam workings .....	77
20. Photograph showing prospects in Wanakah Formation on north side of Cutler Creek .....	78
21. Map of the Portland adit .....	79
22. Underground mine workings of the Ute-Ulay, Hidden Treasure, and Pelican mines in and near the southern part of the eastern contiguous area .....	81

TABLES

[Tables 5-8, 11 follow "References Cited"]

	Page
TABLE	
1. Paleozoic sedimentary rock units in western San Juan Mountains...	E9
2. Mesozoic sedimentary rock units in western San Juan Mountains...	12
3. Major ash-flow sheets of the western San Juan Mountains .....	17
4. Selected chemical data from vein samples, western contiguous area .....	26
5. Analyses of stream-sediment samples from the eastern contiguous area .....	92
6. Analyses of rock samples from altered areas, eastern contiguous area .....	96

	Page
TABLE 7. Analyses of rhyolite intrusive rocks and associated wallrocks, eastern contiguous area .....	E100
8. Uranium, thorium, fluorine, and radioactivity in rhyolite intrusives and associated rocks .....	106
9. Magnetic measurements of intrusive rocks, Uncompahgre Primitive Area and surrounding areas.....	50
10. Magnetic measurements of volcanic flows, breccias, and welded tuffs, Uncompahgre Primitive Area and surrounding areas.....	51
11. Analyses of samples from study areas contiguous to the Uncompahgre Primitive Area.....	108
12. Chemical analysis of limestone (sample 390) from the Pony Express Limestone Member, Wanakah Formation.....	56
13. Analyses of coal from west of San Miguel.....	57

STUDIES RELATED TO WILDERNESS—PRIMITIVE AREAS

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**MINERAL RESOURCES OF STUDY AREAS  
CONTIGUOUS TO THE UNCOMPAHGRE  
PRIMITIVE AREA,  
SAN JUAN MOUNTAINS,  
SOUTHWESTERN COLORADO**

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By T. A. STEVEN, P. W. LIPMAN, and F. S. FISHER,  
U.S. Geological Survey, and  
C. L. BIENIEWSKI and H. C. MEEVES, U.S. Bureau of Mines

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SUMMARY

A mineral survey was made by the U.S. Geological Survey and the U.S. Bureau of Mines of three areas contiguous to the Uncompahgre Primitive Area in southwestern Colorado; the three areas have been proposed for inclusion in the National Wilderness Preservation System. The combined area covers about 215 square miles (550 square kilometres), or about 137,000 acres (55,500 hectares) of rugged terrain in the western San Juan Mountains. The mineral resource potential of these areas was investigated in 1972 by two field teams from the U.S. Geological Survey and one team from the U.S. Bureau of Mines. Existing geophysical data covering the three areas were analyzed and were interpreted by the U.S. Geological Survey.

The western San Juan Mountains, including the three contiguous areas studied, consist of a deeply dissected volcanic plateau built in middle Tertiary time on a platform of slightly deformed Paleozoic, Mesozoic, and local lower Tertiary sedimentary rocks. Intrusive igneous rocks were emplaced in latest Cretaceous time, and at several times during accumulation of the volcanic rocks in middle Tertiary time. Mineralization took place during both periods of igneous activity in the Late Cretaceous and in the middle Tertiary.

Within or adjacent to the three areas studied there are 525 patented claims and 4,300 unpatented claims. Of these, 93 patented claims and approximately 3,000 unpatented claims are within the contiguous areas. All mine and prospect workings that could be found within or near the contiguous areas were examined, and most were sampled.

Important mineral deposits of several ages have been exploited at many places in the western San Juan Mountains, including the originally studied Uncompahgre Primitive Area. Although the three contiguous areas—western, central, and eastern—considered here are largely outside the more productive mining areas, some evidence exists for metallic mineralization near the margins of the areas. The potential for significant fossil fuel resources within the contiguous areas is low, although coal conceivably may exist in local structural basins beneath the northwestern part of the eastern contiguous area and oil and gas accumulations are possible beneath the northern part of the central area and northwestern part of the eastern area. Geothermal energy potential seems low, although this conclusion is based on sketchy data.

A large quantity of "moss rock" for decorative purposes is readily available in talus piles in the western part of the western contiguous area, and it is a significant mineral resource. Stone, sand, and gravel for construction purposes could be obtained from many parts of the contiguous areas, and limestone in the Pony Express Member of the Wanakah Formation has been used for chemical purposes and is a potential resource in the central and western contiguous areas, but these commodities also occur in large volume in adjacent, readily accessible areas, where they can be obtained more economically.

The southeastern part of the western contiguous area is cut by numerous veins. Some of them are the northwestern ends of major veins that have produced significant precious and base-metal ore in the major mining area a few miles southeast, and mine maps indicate some underground workings within the western contiguous area. Other shorter veins extend into the western contiguous area from the Stony Mountain-Mount Sneffels stock which lies just to the east; some of them may contain significant metallic resources at depth. The several veins cutting the volcanic rocks between Whipple Mountain and Hayden Peak in the western part of this contiguous area indicate widespread hydrothermal activity, but the low metal concentrations measured at the surface and the weak vein structures suggest only a moderate to low economic potential.

Surface indications of hydrothermal activity are weak within the central contiguous area, but an important potential exists for buried mineral deposits. The middle Tertiary volcanic rocks at the surface unconformably overlie productive Upper Cretaceous deposits exposed along the Uncompahgre River valley near Ouray, where only the western part of a mineralized intrusive center has been uncovered by recent erosion. If the eastern side of the center is mineralized comparably to the western side, a significant potential exists under the volcanic cover between the Uncompahgre River and Cow Creek. Much of this area is in the original Uncompahgre Primitive Area and south of the central contiguous area, but productive veins are known in the Dexter Creek drainage along the southwest side of the central contiguous area, and similar veins almost certainly exist under the adjacent volcanic cover to the northeast. Other intrusive centers, possibly with related mineral deposits, may exist elsewhere beneath the volcanic cover in the central contiguous area. Such deposits would be difficult and expensive to find; thus, they may not be economic at this time. The probability that they exist is sufficiently good, however, to postulate a significant resource potential.

The intrusive center cutting volcanic rocks on Bighorn Ridge along the northern margin of the Uncompahgre Primitive Area southeast of the central contiguous area is locally altered and some samples contain anomalous concentrations of copper. This center potentially might contain a disseminated "porphyry-type" copper deposit.

Several mineralized areas occur along the southern periphery of the eastern contiguous area. These areas are in part marked by aeromagnetic lows that may be related to hydrothermally altered rock and may have economic significance. The Matterhorn volcanic center, Iron Beds altered area, and Capitol City mining area are all just outside the southwestern margin of the contiguous area; these altered and mineralized areas are associated with monzonitic intrusive bodies, and all of them have a good potential for the discovery of economic mineral deposits. Base- and precious-metal veins are known in lower Henson Creek along the south side of the eastern contiguous area, and at least two of these approach and may extend into the contiguous area. Several of these veins have produced significant metal in the past and probably contain significant undiscovered resources. The potential for future discovery of mineral deposits, however, is largely south of the eastern contiguous area, and, except for veins exploited by the Ute-Ulay, Hidden Treasure, and Pelican mines, little evidence for related mineral deposits was seen in adjacent areas to the north.

The Cimarron volcanic center in the East Fork Cimarron River drainage is partly within the eastern contiguous area. The intrusive core and adjacent wallrocks are irregularly altered, but evidence for mineral deposits is sparse. The potential for disseminated copper or molybdenum deposits within the intrusive core seems better than for significant vein deposits, but available evidence does not favor the discovery of economic deposits of either type.

Anomalously radioactive rhyolite intrusions, which extend eastward across the southern part of the eastern contiguous area, contain at least three areas with small concentrations of secondary uranophane in fracture zones, and a few tons of uranium ore have been mined from one of these areas. Other similar concentrations may exist, and some of them may be of sufficient size to be of economic interest. Most rock appears somewhat depleted in uranium, however, and the potential for major deposits is judged to be low.

The remainder of the eastern contiguous area, embracing most of the area north of the Henson Creek drainage and east of the East Fork Cimarron River, shows only local evidence of hydrothermal activity and virtually no indication of economic mineral deposits.

## INTRODUCTION

Contiguous areas aggregating 137,000 acres (55,500 ha (hectares)) or about 215 square miles (550 km<sup>2</sup> (square kilometres)) along the north, west, and east sides of the Uncompahgre Primitive Area, southwestern Colorado, were studied as possible additions to the National Wilderness Preservation System. Part of this acreage in the drainage basins of Cow Creek and the Middle and West Forks Cimarron River was included as a marginal study area in the original investigation of the mineral potential of the Uncompahgre Primitive Area by the U.S. Geological Survey and U.S. Bureau of Mines (Fischer and others, 1968, pl. 1). During the present investigation some additional data on this area were collected by the U.S. Bureau of Mines, but no further work was done by the U.S. Geological Survey. The remaining three areas covering about 110,000 acres (45,000 ha) or about 170 square miles (430 km<sup>2</sup>) were studied by both the U.S. Geological Survey and the U.S. Bureau of Mines during 1972; these areas form the primary focus of this report and will be referred to as the western, central, and eastern contiguous areas (figs. 1, 2; pls. 1-3).

Much of the terrain of the contiguous areas is extremely rugged, and altitudes range from about 7,400 feet (2,225 m (metres)) near the Uncompahgre River to over 14,000 feet (4,300 m) on Uncompahgre Peak, with at least three-fourths of the area above 10,000 feet (3,050 m). Access to the peripheries of these areas ranges from excellent along all-weather highways that follow the San Miguel, the Uncompahgre, and the Lake Fork Gunnison Rivers to fair or poor along secondary roads and jeep trails that extend along some secondary drainage systems. Within the contiguous areas, good trails follow most of the larger streams in the eastern area, but trails are rare and commonly poor in the central and western areas. Many of the higher ridges can be traversed only with great difficulty and considerable hazard.

Summers in the high mountains are short and cool, and thunderstorms are common. The winters are long and cold, and deep snow commonly covers the intermediate and higher areas.

The western contiguous area covers slightly more than 45 square miles (115 km<sup>2</sup>) in the shape of a distorted U, enclosing the high, sinuous, and commonly knife-edged ridge along the county line between Ouray and San Miguel Counties. Several spur ridges extend out from the main ridge

and are separated by deep, steep-walled, glaciated canyons. The higher ridges are above timberline, and consist largely of bare or lichen-covered rock with local patches of grassy tundra. The high ridges are generally flanked by great banks of talus, and spectacular rock glaciers extend down the heads of many of the north-facing canyons. Lower slopes are covered by dense stands of spruce, pine, and aspen, broken locally by open grassy parks.

The central contiguous area in Ouray County consists of 25 square miles (64 km<sup>2</sup>) of tree-covered rounded mountains. Steep-walled canyons and valleys enclose Dexter, Cutler, and Cow Creeks, but the interfluvial areas are more subdued than the high mountains in the Uncompahgre Primitive Area to the south. Most of the central area lies between 9,000 and 10,500 feet (2,700 and 3,200 m) in altitude, and none extends above timberline, which is about 11,800 feet (3,600 m) altitude in this area.

The eastern contiguous area includes somewhat more than 100 square miles (255 km<sup>2</sup>) of a highly dissected volcanic plateau lying between the Middle Fork Cimarron River and the Lake Fork Gunnison River in Hinsdale and Gunnison Counties. Steep-walled glaciated valleys flank major north-flowing streams in the northern three-quarters of this study area. Intervening ridges range from serrated, knife-edged crests in the Cimarron River drainage area to elongate flat-topped ridges between the Little Cimarron and the Lake Fork Gunnison Rivers. Within the study area most ridge crests extend above timberline, and in the southern part they include several high and spectacularly rugged mountains. The ridges diminish in altitude northward, and in the northeastern parts of the area they are densely covered by spruce forest. Open grassy parks occupy large parts of the glaciated valley bottoms.

The southern part of the eastern contiguous area is drained by numerous short precipitous south-flowing streams tributary to Henson Creek. Relief is great, and the altitudes range from near 9,000 feet (2,700 m) along Henson Creek to 14,309 feet (4,400 m) on Uncompahgre Peak, the highest point along the divide a few miles north. The area above timberline is bare rock or grassy tundra, whereas the steep rocky slopes below are covered by patchy and commonly sparse spruce and aspen forest.

Commercial activities in the western San Juan Mountains include logging, grazing of sheep and cattle, recreational uses, and mining. The contiguous areas are near and partly within one of the most intensely mineralized regions of the United States, and numerous mines and prospects are present in adjacent areas and a few are within the study areas.

### PREVIOUS INVESTIGATIONS

The geology of the widely mineralized western San Juan Mountains has been studied intensively for nearly a hundred years, and numerous

maps and articles have been published. The first important summary of economic geology within the areas considered here was by Purington (1898) of the U.S. Geological Survey, who studied the ore deposits in the Telluride area near the western contiguous area. This work was followed shortly by a remarkable series of geologic folios by the U.S. Geological Survey (Cross and Purington, 1899; Cross and others, 1905; Cross and others, 1907) which established the basic geologic framework of the area. Irving and Bancroft (1911) extended the study of the ore deposits into the Lake City area to the east, near the southern margin of the eastern contiguous area.

Detailed study of the western San Juan Mountains progressed into a broader study of the whole volcanic field, directed first by Whitman Cross and later by E. S. Larsen, Jr. The results of these studies have been summarized by Cross and Larsen (1935) and Larsen and Cross (1956). Since about 1930, W. S. Burbank and several associates have studied the detailed geology of many of the more intensely mineralized areas in the western San Juan Mountains (Burbank, 1940, 1941, 1947; Burbank and Luedke, 1964, 1966, 1968, 1969; Luedke and Burbank, 1962, 1968; Kelley, 1946). The western part of the western contiguous area is within the Grayhead quadrangle that was mapped by Bush, Bromfield, Marsh, and Taylor (1961).

The mineral resource potential of the Uncompahgre Primitive Area, covering some of the most intensely mineralized area in the western San Juan Mountains, was studied in 1966 and 1967 (Fischer and others, 1968). The geology of the Wetterhorn Peak quadrangle, largely between the central and eastern contiguous areas, was mapped (Luedke, 1972) as a partial outgrowth of that study. Concurrent work in the central and eastern San Juan Mountains by T. A. Steven and P. W. Lipman established regional geologic relations (Lipman and others, 1970) that have had direct bearing on recent reinterpretations of the geologic history of the western San Juan Mountains (Lipman and others, 1973). These reinterpretations have been incorporated into the present report.

### PRESENT INVESTIGATIONS

The mineral resource potential of the three areas contiguous to the Uncompahgre Primitive Area was studied by the U.S. Geological Survey and U.S. Bureau of Mines in 1972. Some additional information was collected by the U.S. Bureau of Mines on a study area previously covered (Fischer and others, 1968), but this is incorporated here in discussions of either the central or the eastern contiguous area. All pertinent published data were reviewed and the areas were studied and were sampled in the field. Data on patented mining claims were taken from records of U.S. Bureau of Land Management, and data on unpatented mining claims from records in the courthouses of Hinsdale, Gunnison, Ouray, and San Miguel Counties.

The extent of previous study differs widely for each of the three contiguous areas, and somewhat different approaches were taken in appraising the mineral resources of each area. Studies by the U.S. Geological Survey in the western and central contiguous areas were made by F. S. Fisher, assisted by R. R. Kern. The areas were largely covered by previously published geologic maps of good quality (Bush and others, 1961; Luedke and Burbank, 1962; Burbank and Luedke, 1966; Luedke, 1972), and only minor fringe areas needed to be mapped during the current investigation. Stream sediments were sampled along all the main streams, and all altered and mineralized areas were examined and were sampled in the field.

Existing geologic maps in the eastern contiguous area, on the other hand, are all reconnaissance studies made early in the century and were inadequate for the purposes of this mineral appraisal. In consequence, the entire area was remapped by P. W. Lipman, T. A. Steven, and D. A. Johnston. Concurrently, stream-sediment samples were collected along all the major streams, largely by Kimball Goddard and David Dennison, and all mineralized or potentially mineralized areas discovered in the course of geologic mapping were examined and were sampled under the direction of Steven.

All U.S. Geological Survey samples from the three contiguous areas were analyzed in Survey laboratories. Spectrographic analyses were by J. M. Motooka and J. H. Reynolds. Chemical and instrumental analyses were by C. M. Bunker, C. A. Curtis, E. J. Fennelly, W. H. Ficklin, R. L. Hutchens, A. L. Meier, J. B. McHugh, José de Mello, H. T. Millard, J. M. Negri, S. H. Truesdell, and E. P. Welsch.

U.S. Bureau of Mines studies were conducted by C. L. Bieniewski and H. C. Meeves, assisted by A. G. Hite and R. A. Van Horn. All available claim records were examined and the locations plotted where possible. All old mines or significant prospects were examined in the field, and most were sampled. Analyses were made by U.S. Bureau of Mines laboratories at Reno Metallurgy Research Center, Reno, Nev.

Only the analytical data pertinent to specific areas of special geologic interest or containing anomalous concentrations of metals are tabulated in the present report. All analytical data obtained by the U.S. Geological Survey, both tabulated and untabulated, have been placed on magnetic computer tape (Steven and others, 1973) and are available through the National Technical Information Service (NTIS), U.S. Department of Commerce, Springfield, Va. 22161, at the expense of the user. The samples are identified by the field numbers shown on plate 2; in coding and retrieval, each of these numbers carries a prefix of 72, indicating the year the sample was collected.

#### ACKNOWLEDGMENTS

The cooperation of the U.S. Forest Service and U.S. Bureau of Land



Management and many county officials, mining company personnel, and local residents is gratefully acknowledged. Special thanks are extended to Gene Adams, Dave Calhoun, Adolph Jordan, J. N. Mayor, Frank Mendenhall, Joel Swank, and Lowell Swanson for valuable information about the location and history of mines and prospects, and to Harley Greiman of the U.S. Forest Service for information on mining and prospecting activity. Art Pansze and John Longshore of Exxon Corp., Ed Hughes of Hughes Mining Co., and Bob Larsen of Baumgartner Oil Co. provided valuable information on exploration activities by their companies.

### GEOLOGIC APPRAISAL

By T. A. STEVEN, P. W. LIPMAN, and F. S. FISHER, U.S. Geological Survey

Tertiary volcanic rocks predominate within the three study areas contiguous to the Uncompahgre Primitive Area and form part of the great San Juan volcanic field of southwestern Colorado (fig. 1). Some Paleozoic and Mesozoic sedimentary rocks underlying the volcanic plateau are exposed in the lower parts of the western and central areas. Hypabyssal intrusive rocks were emplaced in Late Cretaceous and middle Tertiary time, and mineral deposits are associated with intrusive centers of both ages.

The rocks exposed in the individual study areas represent only fragments of the geologic history of the area, and a coherent picture of the geology cannot be presented by considering only the specific areas studied. Instead, the general geology of the whole western San Juan Mountains area is first described, and the specific geology and mineral resources of the individual study areas are then considered within this framework.

The volcanic history of the western part of the San Juan volcanic field has recently been reinterpreted by Lipman, Steven, Luedke, and Burbank (1973) in part as a result of investigations leading to this report. Thus, the sequence of volcanic events we present here differs in certain aspects from most previously published accounts, including the report considering the mineral resource potential of the Uncompahgre Primitive Area proper (Fischer and others, 1968).

### REGIONAL GEOLOGY

The western San Juan Mountains (fig. 2) have had a complex geologic history extending from Precambrian to Holocene times. No Precambrian rocks are exposed in the three study areas, and the early phases of this history will not be discussed. Paleozoic sedimentary rocks are exposed along the lower slopes above the Uncompahgre River near Ouray, along the San Miguel River near Telluride, and in small areas along Cow Creek northeast of Ouray. Mesozoic sedimentary rocks overlie the Paleozoic rocks in all these places and generally are more extensively

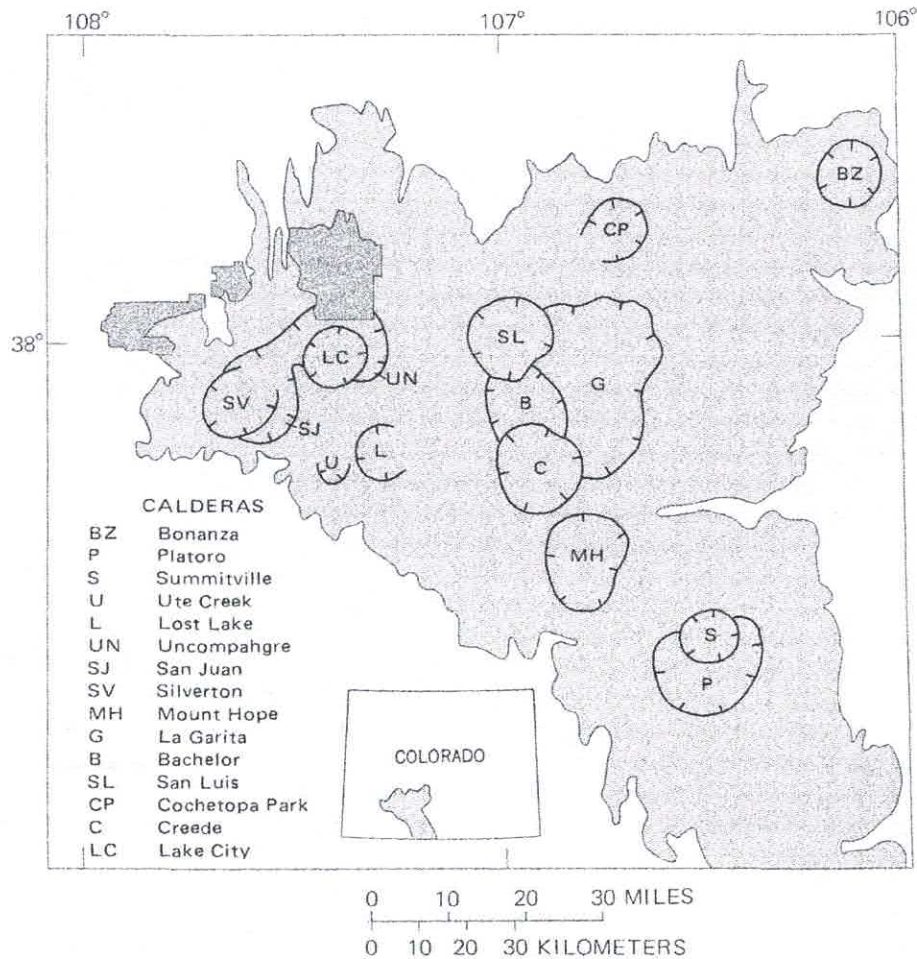


FIGURE 1.—Location of the study areas contiguous to the Uncompahgre Primitive area (black) and calderas in the San Juan volcanic field (stippled), southwestern Colorado.

exposed. Intrusive rocks emplaced during latest Cretaceous time cut both the Paleozoic and Mesozoic sedimentary rocks near Ouray and along Cow Creek to the northeast. Telluride Conglomerate of early Eocene age unconformably overlies the sedimentary and intrusive rocks in places near Ouray, and much more widely between Ouray and Telluride. A thick pile of middle Tertiary volcanic rocks overlies the sedimentary and early intrusive rocks and, together with related intrusive rocks, constitutes the great bulk of the San Juan Mountains. Mineralization took place during the two periods of igneous activity, the Late Cretaceous and middle Tertiary.

#### PALEOZOIC GEOLOGY

The Paleozoic sedimentary rocks in the western San Juan Mountains have been described in detail by Burbank (1930, p. 157-169), and more

recent stratigraphic usage is given by Luedke and Burbank (1962) and by Fischer, Luedke, Sheridan, and Raabe (1968, p. C7-C8). Although the Paleozoic rocks are shown as a single unit on the geologic map (pl. 1A), several formations are exposed near Ouray. The oldest of these, the Elbert Formation, is overlain successively by the Ouray Limestone, Leadville Limestone, Molas Formation, Hermosa Formation, and Cutler Formation (table 1). Of these, only the Mississippian Leadville Limestone and the Permian Cutler Formation are exposed in the central contiguous area. No rocks of Paleozoic age crop out in the eastern or western contiguous areas.

TABLE 1.—*Paleozoic sedimentary rock units in western San Juan Mountains*  
[Taken largely from Fischer, Luedke, Sheridan, and Raabe (1968) and Luedke and Burbank (1962)]

Formation	Age	Thickness		Lithology
		(feet)	(metres)	
Cutler Formation	Permian	0-2,000	0-610	Red shale, siltstone, sandstone, and conglomerate.
		Conformable		
Hermosa Formation	Pennsylvanian	1,450	440	Greenish-gray or red shale, sandstone, and conglomerate with some limestone.
		Conformable		
Molas Formation	Pennsylvanian	40-60	12-18	Red, gray, or green calcareous shale, sandstone, and conglomerate.
		Unconformity		
Leadville Limestone	Mississippian	180-235	55-70	Massive dolomitic limestone.
		Conformable		
Ouray Limestone	Devonian	70	21	Thin-bedded dolomitic limestone with shaly partings.
		Conformable		
Elbert Formation	Devonian	30-50	9-15	Green, buff, or gray calcareous shale, sandy limestone, and sandstone.

The Leadville Limestone is a blue to brownish-gray fine- to coarse-grained massive dolomitic limestone. Locally, it contains thin cherty and sandy layers. In the central contiguous area it crops out only in a small area along Cow Creek (Luedke, 1972), but it ranges in thickness from 180 to 235 feet (55-70 m) near Ouray.

The Cutler Formation is well exposed along the Uncompahgre River valley, where it is as much as 1,200 feet (370 m) thick. The lower parts of the Cutler consist of interbedded red, brown, and gray fine- to coarse-grained sandstone, siltstone, and shale. In most places the beds are calcareous and in some places conglomeratic. The upper parts of the Cutler are red, pink, and gray sandstone with lesser amounts of siltstone and shale. Lenticular conglomerate beds as much as 40 feet (12 m) thick are scattered throughout. Clasts in the conglomerates are primarily Precambrian quartzite and other metamorphic rocks.

In late Paleozoic time the Paleozoic rocks in the western San Juan Mountains area were folded, and the area east of the Uncompahgre River was broadly uplifted and was eroded. Most Paleozoic sedimentary rocks were removed east of a sinuous, generally north-trending line that passes 1-2 miles (1.6-3.2 km (kilometres)) south and east of Ouray (Fischer and

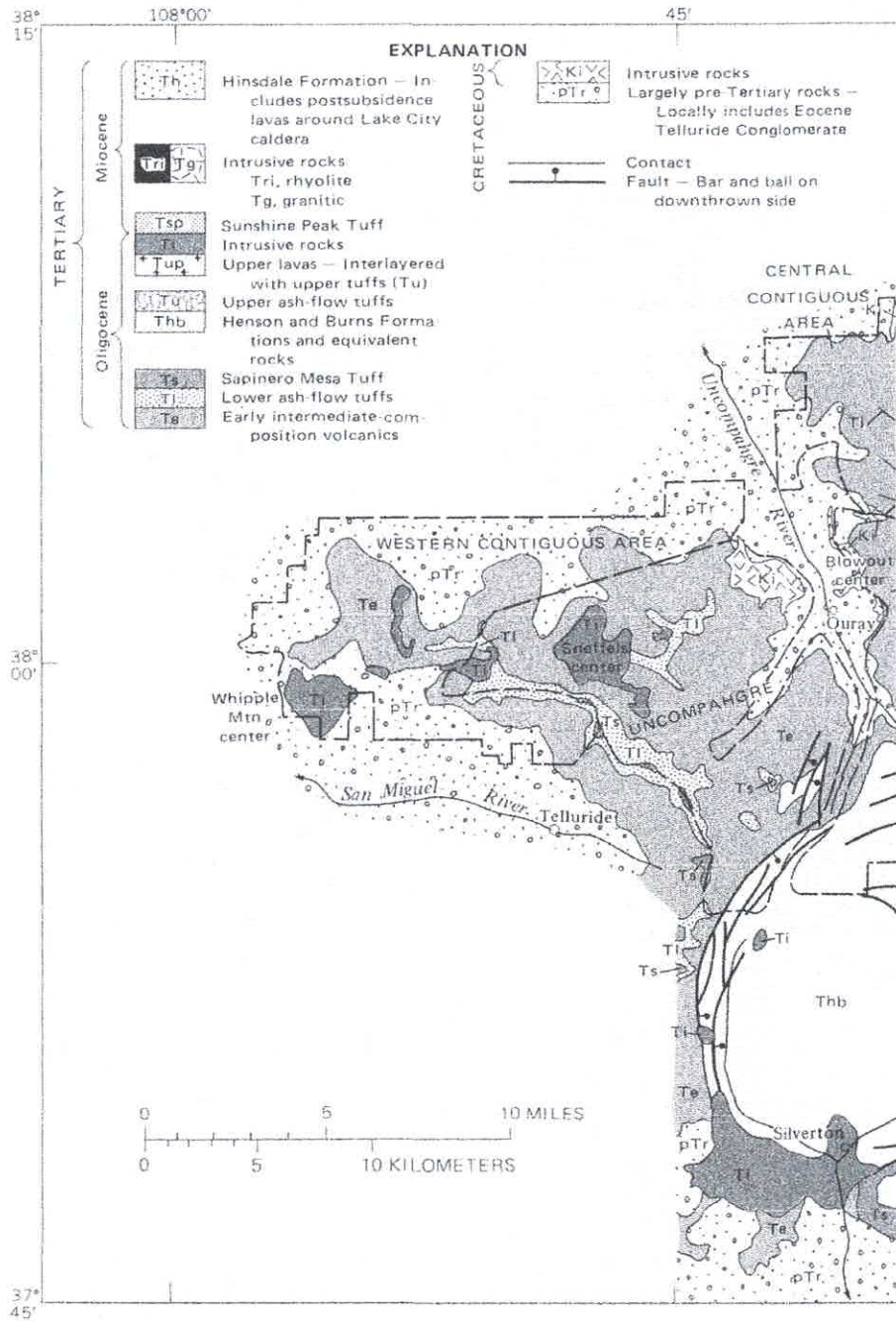
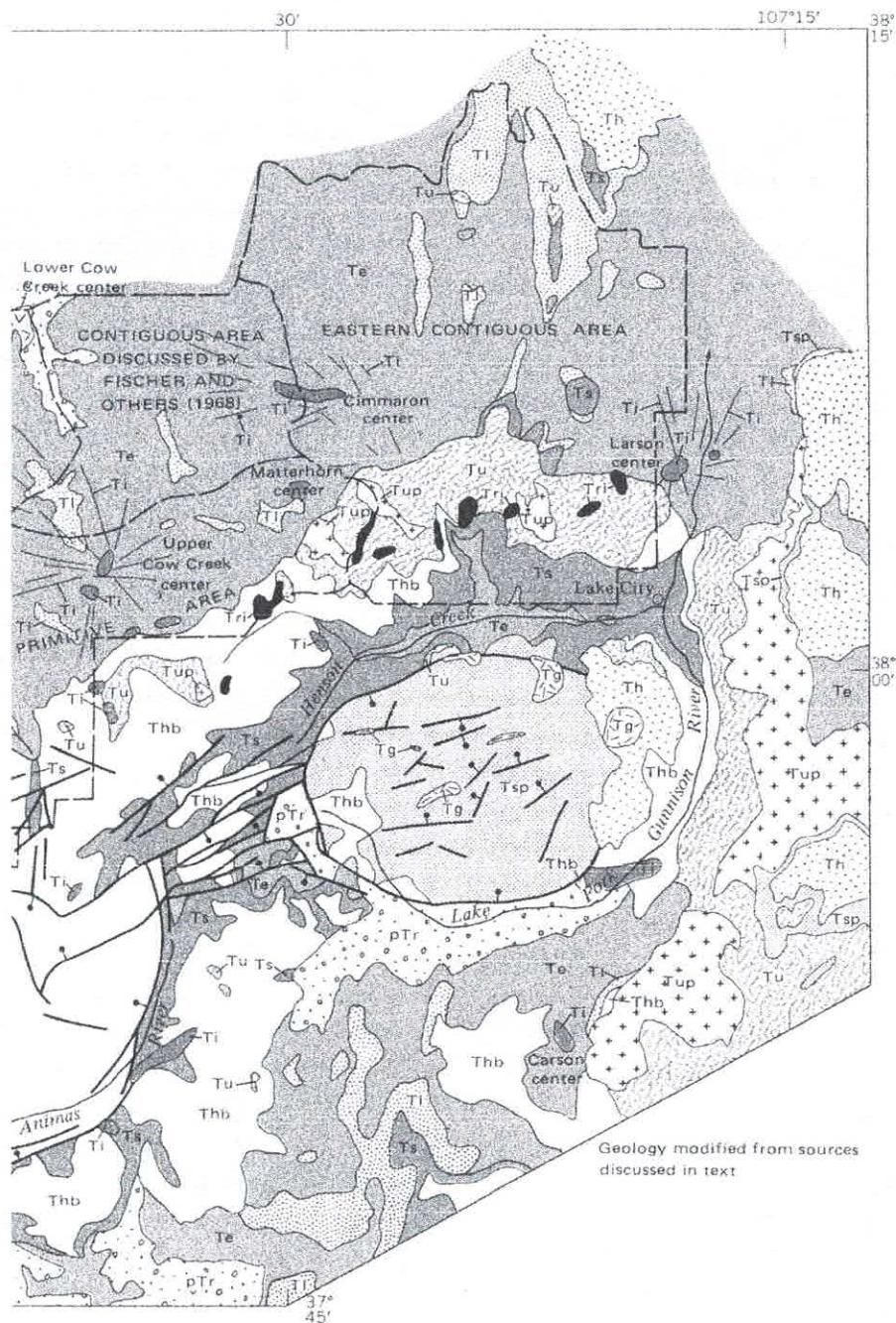


FIGURE 2.—Geologic map of the western San Juan Mountains

others, 1968, fig. 2). Thus, a complete section of Paleozoic strata probably underlies the western contiguous area and the western part of the central area. The units are erosionally truncated under the eastern part of the central area and probably are absent under the eastern area.



showing the Uncompahgre Primitive Area and contiguous study areas.

MESOZOIC GEOLOGY

The western San Juan Mountains area was once covered by a thick blanket of Mesozoic sedimentary rocks that ranged in age from Late Triassic to Late Cretaceous (table 2). Mesozoic rocks are now exposed only

TABLE 2.—*Mesozoic sedimentary rock units in western San Juan Mountains*  
 [Taken largely from Fischer, Luedke, Sheridan, and Raabe (1968) and Luedke and Burbank (1962)]

Formation	Age	Thickness		Lithology
		(feet)	(metres)	
Mancos Shale.....	Late Cretaceous.....	0-1,000	0-305	Gray to black shale.
		Conformable		
Dakota Sandstone.....	Late and Early (?) Cretaceous.	40-175	12-53	Thin- to thick-bedded sandstone with interbedded shale.
		Unconformity		
Morrison Formation.....	Late Jurassic.....	620-750	190-230	Brushy Basin Member, which is predominantly variegated mud- stone with subordinate sand- stone and limestone, is under- lain by the Salt Wash Member, which is predominantly sand- stone and lesser mudstone and limestone.
		Unconformity		
Wanakah Formation.....	Late Jurassic.....	85-125	26-38	
Marl Member.....		40-75	12-23	Reddish-brown calcareous mud- stone.
Bilk Creek Sandstone Member.....		14-25	4-8	Greenish-gray to buff fine- grained silty sandstone.
Pony Express Limestone Member.....		1-70	0.3-21	Porous breccia derived by partial leaching of gypsum from a mixed assemblage of gypsum, limestone, and shale beds. Lower 1-5 ft is fine-grained dark limestone.
		Conformable		
Entrada Sandstone.....	Late Jurassic.....	45-80	14-24	Crossbedded sandstone.
		Unconformity		
Dolores Formation.....	Late Triassic.....	80	24	Brownish-red mudstone and sand- stone.

in the central and western contiguous areas. Upper Cretaceous intrusive rocks invade the Paleozoic and Mesozoic sedimentary rocks.

The Dolores Formation of Late Triassic age consists of thin-bedded to massive mudstone and fine- to coarse-grained sandstone with some thin layers of limestone and conglomerate; it typically forms steep brownish-red slopes and cliffs. In the central contiguous area, the Dolores is exposed along the Uncompahgre River valley and along Cow Creek; it is not exposed in the western or eastern contiguous areas.

The Entrada Sandstone of Late Jurassic age is exposed only in steep cliffs and slopes in the central contiguous area along the Uncompahgre River valley and along Cow Creek. It is a white to buff thick-bedded fine-grained commonly crossbedded calcareous sandstone, which ranges in thickness from 45 to 80 feet (14-24 m).

The Wanakah Formation of Late Jurassic age consists of three lithologic units: a lower, dark-colored limestone with interbedded gypsiferous shales (the Pony Express Limestone Member); a middle, greenish-gray to buff silty to very fine grained calcareous sandstone (the Bilk Creek Sandstone Member); and an upper, thin-bedded reddish-brown limy mudstone and siltstone (the marl member). The entire formation is about 100 feet (30 m) thick. It is exposed only in the central contiguous area along the Uncompahgre River valley and in small areas along Cow Creek.

The Morrison Formation of Late Jurassic age crops out on steep slopes and cliffs along the Uncompahgre River valley, Cutler Creek, and Cow Creek in the central contiguous area, and along Mill Creek in the western contiguous area. It is about 700 feet (210 m) thick; the lower half of the formation consists of lenticular light-colored sandstone with interbedded red mudstones and a few thin limestone beds, and the upper half is mainly varicolored mudstone with some thin sandstone and limestone beds.

The Dakota Sandstone of Early(?) and Late Cretaceous age is 40-175 feet (12-53 m) thick and varies locally from one to three units. The upper and lower units consist of interbedded sandstone and shale; these rocks commonly are absent or are not exposed. The middle unit is a thin- to thick-bedded light-colored fine- to coarse-grained sandstone containing some thin shale and mudstone layers and some conglomerate lenses. The formation is exposed in the central contiguous area along Cow Creek and in the Uncompahgre River valley and in the western contiguous area along Mill Creek.

The Mancos Shale of Late Cretaceous age crops out along many of the stream valleys in the western contiguous area, and in small areas along the Uncompahgre River valley and Cow Creek in the central contiguous area. The Mancos consists predominantly of gray to black shale that ranges in thickness from 0 to 1,000 feet (0-305 m) owing to erosion in early Tertiary time.

The area east of Ouray was again domed in latest Cretaceous (Laramide) time (Dickinson and others, 1968, p. 144-145). This renewed uplift in part reactivated older structures, but the main marginal monoclinical flexure is 2-4 miles (3.2-6.4 km) northwest of the late Paleozoic monocline (Luedke and Burbank, 1962). Erosion during Late Cretaceous and early Tertiary time removed the sedimentary rocks from the higher parts of the dome. The truncated edge of Mesozoic strata forms an irregularly north-northeast-trending line that passes a few miles southeast of Telluride and Ouray and crosses the trend of the pinchout of Paleozoic rocks near the north margin of the Uncompahgre Primitive Area (Fischer and others, 1968, fig. 2). Mesozoic strata underlie all the western contiguous area, most of the central area, and at least the northwestern corner of the eastern area.

Intermediate-composition magma invaded the slightly deformed Mesozoic and Paleozoic strata in latest Cretaceous time, about 67 m.y. (million years) ago (Dickinson and others, 1968, p. 142). The largest intrusive bodies are exposed along the flanks of the Uncompahgre River valley just north of Ouray (Luedke and Burbank, 1962), and smaller bodies are known to the northeast in the drainage basins of Cow Creek and Cimarron River (Dickinson and others, 1968, fig. 2). The intrusive center of Late Cretaceous age north of Ouray consists of a crosscutting

central stock at The Blowout, less than a mile north of town, surrounded by laccolithic and sill-like concordant sheets and by numerous smaller discordant dikes.

Dickinson, Leopold, and Marvin (1968) have shown that the Cimarron Ridge Formation exposed between the Uncompahgre and Cimarron Rivers north of the primitive area is part of a volcanoclastic apron of the same age as these intrusives. This apron was deposited north of its probable volcano source in the Ouray area. Before the Telluride Conglomerate was deposited in this area in early Eocene time, erosion removed all the near-source volcanic rocks that overlay the intrusive center near Ouray.

#### TELLURIDE CONGLOMERATE

Erosion of the Late Cretaceous dome in the western San Juan Mountains area stripped the sedimentary cover from this highland, and in early Eocene time (Steven and others, 1967, p. D49) an apron of coarse fluvial deposits of the Telluride Conglomerate was deposited around the flanks of the dome. Only discontinuous tongues of coarse channel-filling deposits represent the Telluride Conglomerate near Ouray, where the marginal apron wedges out against the flanks of the dome (Luedke and Burbank, 1962). Farther from the dome near Telluride (Burbank and Luedke, 1966), however, the apron is a nearly continuous sheet, generally 100–500 feet (30–152 m) thick, of conglomerate, with interbedded sandstone, siltstone, and shale. Clasts in the Telluride Conglomerate are largely mixed Precambrian rocks with some Paleozoic and Mesozoic sedimentary rocks. The poorly sorted sandy matrix is arkosic and generally is cemented by iron-oxide stained calcite. The formation was clearly deposited before the beginning of the mid-Tertiary volcanic activity that built the overlying San Juan volcanic field.

#### VOLCANIC GEOLOGY

The broad aspects of the evolution of the San Juan volcanic field were summarized by Lipman, Steven, and Mehnert (1970). Volcanic activity began in latest Eocene or earliest Oligocene time, and during the interval 35–30 m.y. ago numerous widely scattered andesitic to rhyodacitic central volcanoes were built throughout south-central Colorado (Steven and Epis, 1968). The San Juan Mountains constitute the largest erosional remnant of this formerly extensive field. Between 30 and 26 m.y. ago, dominant activity in the San Juan Mountains area was voluminous quartz latitic and rhyolitic ash-flow eruptions, with associated caldera collapses at most of the eruptive centers. During the period of ash-flow eruptions, mafic-intermediate lavas and breccias continued to be erupted in reduced volume from local central volcanoes and more silicic lavas were erupted in and adjacent to the calderas. In early Miocene, about 25 m.y. ago, volcanic activity shifted from the andesitic and derivative rocks,



which characterized the Oligocene eruptions, to a bimodal assemblage of basalt and high-silica alkali rhyolite, which was erupted intermittently through Miocene and Pliocene time. These later rocks formed a widespread but relatively thin cover of predominantly basaltic rocks, with local accumulations of rhyolite. Most of the rhyolite masses are small, but one large-volume ash-flow sheet was erupted from the Lake City caldera source (fig. 1) in the western San Juan Mountains.

#### EARLY INTERMEDIATE VOLCANICS

The western San Juan Mountains, in the vicinity of the Uncompahgre Primitive Area and contiguous areas, were the site of a cluster of andesitic central volcanoes (Lipman and others, 1973). Near the individual vents, these volcanoes consist of complex assemblages of lavas and breccias that stood topographically above the surrounding terrane. The near-source lavas and breccias (near-source facies) (pl. 1) intertongue laterally with widespread coalescing volcanoclastic aprons of mudflow and conglomerate debris (volcanoclastic facies) (pl. 1) derived from the central volcanoes. The surface of the outflow apron formed a widespread constructional plain, surmounted by local hills that generally represented thick local lava flows, and incised here and there by stream channels.

Diverse formational names have been assigned to different parts of these generally equivalent early intermediate volcanic rocks. Most of the outflow sheet has been assigned to the San Juan Formation, although some similar rocks to the east have been included in the Lake Fork Formation (Larsen and Cross, 1956, pl. 1). Vent-facies lavas and breccias north of Lake City form the bulk of the Lake Fork Formation (Larsen and Cross, 1956); these were derived from two adjoining central volcanoes; one west of the Lake Fork Gunnison River about 3 miles (4.8 km) north of Lake City, and the other about 6 miles (9.7 km) farther northeast. The center north of Lake City is along lower Larson Creek, just outside the eastern contiguous area (pl. 1A).

At least two other early intermediate volcanoes, defined by thick local near-source accumulations, were centered near the head of Wetterhorn Creek and in the upper drainage basin of the Cimarron River (pl. 1A). A volcanic neck that may mark the core of the Cimarron Volcano (Lipman and others, 1973) extends from the East Fork Cimarron River at the Silver Jack mine west across a high ridge into Porphyry Basin, tributary to the Middle Fork Cimarron River. Numerous dikes cut the complex vent-facies lavas and breccias surrounding this center. Present data permit an alternative interpretation, however, that these intrusions mark the roots of a younger volcano superimposed on the flank of Cimarron Volcano (D. A. Johnston, written commun., 1973).

#### ASH-FLOW TUFFS AND ASSOCIATED ROCKS

Initial large-volume ash-flow eruptions in the western San Juan Mountains area deposited the Ute Ridge and Blue Mesa Tuffs (Lipman and

others, 1973; Olson and others, 1968), which spread widely over the early intermediate volcanoclastic constructional plain. These units are as much as 600–1,000 feet (180–300 m) thick in places, and they originally had minimum volumes on the order of 100 cubic miles (400 km<sup>3</sup>) (table 3). They wedge out laterally against the volcanic highlands formed by the clustered early intermediate central volcanoes. The sources for both the Ute Ridge and Blue Mesa Tuffs were in the upper Rio Grande drainage basin, about 15 miles (24 km) southeast of the Uncompahgre Primitive Area—the Ute Ridge came from the Ute Creek caldera south of the Rio Grande, and the Blue Mesa came from an inferred source in the Lost Lake caldera north of the Rio Grande (fig. 1). Lipman, Steven, and Mehnert (1970, table 3, No. 10) gave a somewhat discordant age of 28.4 m.y. for the Ute Ridge Tuff (which they called tuff of Storm King Mountain); the younger Blue Mesa Tuff was erupted shortly thereafter, as several other ash-flow sheets intervene between it and the 27.8-m.y.-old Fish Canyon Tuff (Lipman and others, 1970, table 3; Lipman and others, 1973, table 2).

Ash-flow eruptions from the vicinity of the Uncompahgre Primitive Area and contiguous areas began with the Dillon Mesa Tuff (Olson and others, 1968), which appears to have been derived from the Uncompahgre caldera areas west of Lake City. The Dillon Mesa Tuff was deposited widely in the northwestern San Juan Mountains, but it is generally less than 100 feet (30 m) thick—commonly less than 30 feet (9 m) thick—and it is nearly an order of magnitude less voluminous than the Ute Ridge and Blue Mesa Tuffs (table 3). Indirect evidence suggests that eruption of the Dillon Mesa Tuff may have caused initial collapse of the Uncompahgre caldera (Lipman and others, 1973).

The Sapinero Mesa Tuff had an original volume of more than 250 cubic miles (1,000 km<sup>3</sup>) and when emplaced it covered most of the western and northern parts of the San Juan volcanic field. Its eruption resulted in major collapse of both the Uncompahgre and San Juan calderas (figs. 1, 2), which localized most subsequent volcanic and related activity in the western San Juan Mountains. The mineralization that deposited most of the ores that have been mined from this highly productive area was controlled largely by structures initiated during this cycle of caldera development.

Outflow Sapinero Mesa Tuff is generally 200 feet (60 m) thick or less, and it wedges out laterally against the flanks of the early intermediate-composition central volcanoes centered in upper Cimarron River drainage and areas to the south. The intracaldera Eureka Member of the Sapinero Mesa Tuff, on the other hand, is locally as much as 2,000 feet (610 m) thick and covers irregular topography on top of vent-facies, early intermediate-composition rocks. Lithic debris is common in the Eureka Member, and landslide debris interleaves marginally near the steep caldera walls. These relations are interpreted (Lipman and others, 1973) to indicate accumulation concurrent with caldera subsidence, in which

TABLE 3.—Major ash-flow sheets of the western San Juan Mountains  
[Leaders (...), not determined]

Unit	Caldera source (fig. 1)	Phenocryst content and composition	Estimated initial volume		K-Ar age (m.y.) <sup>1</sup>
			cubic miles	km <sup>3</sup>	
Sunshine Peak Tuff	Lake City	Crystal-rich rhyolite	50-75	200-300	22.5
Nelson Mountain Tuff	San Luis	Crystal-rich quartz latite	170-200	700-800	26.4
Wason Park Tuff	Creede area	Crystal-rich rhyolite	50-75	200-300	26.7
Carpenter Ridge Tuff	Bachelor	Crystal-poor rhyolite	300-400	1,200-1,600	26.7
Crystal Lake Tuff	Silverton	...do	6-12	24-48	.....
Fish Canyon Tuff	La Garita	Crystal-rich quartz latite	750+	3,000+	27.8
Sapinero Mesa Tuff	San Juan and Uncompahgre	Crystal-poor rhyolite	250+	1,000+	.....
Dillon Mesa Tuff	Uncompahgre(?)	...do	12-25	48-100	.....
Blue Mesa Tuff	Lost Lake	...do	100+	400+	.....
Ute Ridge Tuff	Ute Creek	Crystal-rich quartz latite	75+	300+	28.4

<sup>1</sup>From Lipman, Steven, and Mehnert (1970) and H. H. Mehnert (written commun., 1971).

two calderas collapsed within an area of clustered early intermediate-composition central volcanoes.

After caldera collapse, the subsided areas were filled with a complex accumulation of intermediate lavas, breccias, and volcanic sediments. Within the San Juan caldera, these rocks are subdivided into the Burns Formation, consisting of thick porphyritic rhyodacitic to rhyolitic lava flows and minor sediments, and into the overlying Henson Formation, consisting of abundant sedimentary rocks in association with more mafic andesites and rhyodacites. These distinctions have not been recognized within the Uncompahgre caldera. Equivalent mudflow breccias and local interlayered lavas overlie the outflow Sapinero Mesa Tuff east and southeast of the San Juan caldera (Lipman and others, 1973), but they have not been recognized elsewhere around the periphery of the calderas.

The Uncompahgre and San Juan calderas were resurgently domed together, apparently over an extended period of time beginning shortly after subsidence and continuing during and after accumulation of the Burns and Henson Formations and equivalent caldera-filling rocks (Lipman and others, 1973). A broad, low dome extends from the east side of the Uncompahgre caldera near Lake City, across the septum of Precambrian rocks between the calderas, to the west side of the San Juan caldera northwest of Silverton. A northeast-trending apical graben formed along the crest of the dome and involves rocks from the Burns and Henson Formations and from some of the younger ash-flow units.

Beginning with eruption of the Fish Canyon Tuff (table 3), the central San Juan Mountains became a major source area for ash-flow deposits. The distal parts of four ash-flow sheets from the central San Juan Mountains extend into the caldera area in the western San Juan Mountains, where they were in part confined to the moat around the resurgently domed core. Present remnants occur only around the eastern and northern margins of the Uncompahgre caldera and northeastern margin of the San Juan caldera. The oldest of these units is the Fish Canyon Tuff, derived from the La Garita caldera source 35 miles (55 m) southeast of the study area, which has been well-dated as 27.8 m.y. old (Lipman and others, 1970, table 1). This is overlain successively by the Carpenter Ridge Tuff from the Bachelor caldera, the Wason Park Tuff from a postulated source beneath the Creede caldera (Ratté and Steven, 1967, p. H34), and the Nelson Mountain Tuff from the San Luis caldera. All these units are older than the Fisher Quartz Latite of the Creede area, which has been dated as 26.4 m.y. (Steven and others, 1967).

The Crystal Lake Tuff, which intervenes locally between the Fish Canyon and Carpenter Ridge Tuffs, appears to have been erupted from the Silverton caldera, nested within the older San Juan caldera (figs. 1, 2) (Lipman and others, 1973). Ring fractures active at this time offset the Burns and Henson Formations and bound a tilted, trapdoor-style subsided block that sank 2,000 feet (610 m) or more on its south and southeast

sides, but the block had virtually no displacement along its northern margin. Numerous intrusive bodies, ranging from minor dikes and plugs to a large monzonite stock, were emplaced along the late ring-fracture zone (fig. 2).

Local accumulations of intermediate-composition flows, breccias, and minor sedimentary rocks are interlayered at one place or another between all units in the late ash-flow sequence. The largest of these in the vicinity of the eastern contiguous area underlies Uncompahgre Peak and adjacent areas where a succession of thick intermediate-composition flows as much as 1,300 feet (400 m) thick intervenes between the Carpenter Ridge and Nelson Mountain Tuffs (p. 14). These rocks are believed to represent marginal accumulations erupted late in the cycle of development of the Uncompahgre caldera.

The Sunshine Peak Tuff, the youngest major ash-flow sheet in the San Juan volcanic field, was erupted about 22.5 m.y. ago from a source in the Lake City caldera area (Mehnert and others, 1972). The Sunshine Peak Tuff is a high-silica alkali rhyolite and is a typical silicic member of the bimodal basalt-rhyolite suite that characterizes Miocene and Pliocene volcanics in the San Juan field and elsewhere in the Western United States (Christiansen and Lipman, 1972).

The Sunshine Peak Tuff is more than 3,200 feet (1 km) thick within the Lake City caldera, where it contains abundant andesitic lithic rock fragments and interleaved andesitic landslide breccia derived by caving of the caldera walls concurrently with deposition of the ash. Remnants of the outflow sheet, in contrast, are generally less than 150 feet (45 m) thick and contain few fragments. These remnants are now limited to the south and east sides of the Lake City caldera, where they have been protected from erosion by hard overlying basalt flows.

The core of the Lake City caldera was resurgently domed, and coarsely porphyritic quartz latitic lavas were erupted in places around the periphery. A northeast-trending chain of rhyolite porphyry plugs, dikes, sills, and laccoliths that closely resemble the Sunshine Peak Tuff in composition were emplaced north of the structural boundary of the Lake City caldera, across the southern part of the eastern contiguous area.

#### GLACIAL DEPOSITS

Glaciers occupied all the main stream courses in the western San Juan Mountains during Quaternary time, and all the larger valleys in and near the three contiguous areas are in part floored by glacial drift or related sand and gravel deposits. Postglacial alluvium is restricted in most places to narrow strips adjacent to the modern streams.

#### MINERAL RESOURCES

The western San Juan Mountains area has been a prolific source of valuable minerals, and at present it is among the most active mining areas

in Colorado. Metallic mineral deposits formed during periods of igneous activity in the Late Cretaceous (Laramide) and middle Tertiary, and several separate episodes of mineralization have been recognized within the latter period. Hot springs are present at several places in the San Juan Mountains and may indicate some potential for a thermal energy resource. Significant deposits of coal exist just north of the Uncompahgre Primitive Area and contiguous study areas, and oil or gas accumulations are possible within the same general area.

#### LATE CRETACEOUS MINERALIZATION

The intrusive center (The Blowout) of Late Cretaceous age north of Ouray (fig. 2) was a major center of mineralization. Some of the intrusive bodies are intensely altered and are pyritized, and fractures cutting the surrounding Paleozoic and Mesozoic strata contain base and precious metals (Burbank, 1940). The ore deposits formed in part as fracture-filling veins in the harder sandstone units, and in part as replacement bodies in the more reactive rocks adjacent to such fractures. Mesozoic rocks, particularly those in the Pony Express Limestone Member of the Wanakah Formation and in the Dakota Sandstone, are hosts for the larger ore bodies developed to date. Total production to 1940 was about \$12 million (Burbank, 1940, p. 193); an estimated \$1 million has been produced since then.

#### MIDDLE TERTIARY MINERALIZATION

At least three episodes of mineralization can be recognized in the Tertiary volcanic sequence of the western San Juan Mountains. The oldest of these is associated with the intrusive cores of two or three early intermediate-composition volcanoes around the periphery of the Uncompahgre caldera. Of these, the Larson and Cimarron centers are north of the caldera (fig. 2) and are either in or immediately adjacent to the eastern contiguous area. The third center is at the old mining camp of Carson (Larsen, 1911), south of the caldera, where production in the early days of mining is estimated to have been about \$200,000 (Vanderwilt, 1947, p. 115). The Larson and Cimarron centers are widely altered and are prospected, but little if any production has been recorded. Geochemical sampling connected with the present study disclosed only weak anomalies around the Larson and Cimarron centers.

Ores deposited in fractures initiated during the San Juan, Uncompahgre, and Silverton caldera cycles (Steven and others, 1974) have supplied most of the production from the western San Juan Mountains. Numerous intermediate to silicic intrusive bodies cut the caldera fills, and they are especially abundant along the ring-fracture zone of the Silverton caldera (figs. 1, 2). Many of these intrusive bodies are altered and are mineralized, and nearby fractures commonly contain metalliferous veins. The Red Mountain district in the south-central part of the Uncompahgre

Primitive Area (Fischer and others, 1968, p. C25) was the center of especially intense alteration and mineralization, and a series of persistent major veins extends northwestward across the western part of the primitive area toward Mount Sneffels. These veins have been the most productive in the western San Juan Mountains area, and the veins supply most of the ore currently being mined in the area (Fischer and others, 1968, p. C24). The distal parts of some of these veins extend into the western contiguous area. Other veins deposited in and near the Uncompahgre Primitive Area occur along the crest of the resurgent dome that jointly uplifted the cores of the Uncompahgre and San Juan calderas late in the caldera cycles. Local intrusive centers emplaced within and adjacent to the northern parts of the Uncompahgre and San Juan calderas also were more or less latered and are surrounded by mineralized areas containing metalliferous veins along fractures. The veins are most abundant in the Engineer Mountain-Red Mountain Creek area within the Uncompahgre Primitive Area (Fischer and others, 1968, p. C29) and along the north side of the Uncompahgre caldera between Henson Creek and the south boundary of the eastern contiguous area (pl. 1A). The Matterhorn intrusive center, within the eastern contiguous area (fig. 2), is the locus of intense hydrothermal alteration, and stream-sediment and bedrock samples contain anomalous concentrations of several metals.

Alteration and mineralization associated with the Lake City caldera are represented by Red Mountain, an intensely altered quartz latite lava dome that passes downward into a volcanic neck. This dome was emplaced along the eastern ring fracture of the caldera, about 3-4 miles (4.8-6.4 km) south of Lake City; it is younger than the Sunshine Peak Tuff, and older than adjacent quartz latitic lavas in the moat of the Lake City caldera, both of which have been dated as about 22.5 m.y. old (Mehnert and others, 1973). In addition, many of the distentional fractures cutting Sunshine Peak Tuff in the resurgently domed core of the Lake City caldera are extensively altered, and sulfide-bearing veins follow some of these. The east-trending chain of rhyolite intrusives emplaced north of Henson Creek following the Lake City caldera cycle are anomalously radioactive, and in places contain small concentrations of supergene uranium minerals.

#### GEOHERMAL ENERGY

Thermal springs are widely scattered through the San Juan Mountains (Pearl, 1972, p. 18-23). The best known near the Uncompahgre Primitive Area and contiguous study areas are the Radium (Ouray) Hot Springs at Ouray (temperatures 60°-82°C), and the Orvis (Ridgway) Hot Spring 2 miles (3.2 km) west of the northwest corner of the central contiguous area (temperature 54°C). Other thermal springs in adjacent parts of the western San Juan Mountains are the Cebolla (Powderhorn) Hot Springs, 15 miles (24 km) northeast of the eastern contiguous area (temperatures

9°–46°C), and the Lemon Hot Springs at Placerville, 5 miles (8 km) west of the western contiguous area (temperature 34°C). As reported by Pearl (1972, p. 12, 44), a heat-flow measure made at Ouray by E. R. Decker in 1969 was 3.7 heat-flow units (a heat-flow unit is  $1.0 \times 10^{-6}$  cal/cm<sup>2</sup> sec); this measurement is the highest that has been reported from interior of the earth of 1.5 heat-flow units. These springs thus reflect somewhat higher than normal heat flow beneath the San Juan region, and possibly a potential source of geothermal energy.

Most areas of developed geothermal energy utilize natural steam, or very hot water capable of flashing into steam on release of pressure. These areas occur in regions of late Tertiary or Quaternary igneous activity where abnormally hot volcanic or intrusive rocks lie close to the surface (White, 1965, p. 10; Godwin and others, 1971, p. 7). Permeable reservoir rocks also are essential to permit ready transfer of heat by circulating fluids rather than by conduction through rock. An impermeable cap above the reservoir favors retention of heat and permits buildup of pressures; therefore, supercritical conditions can exist. Very hot but dry rocks near the surface are a potential energy source if proper technology is developed to utilize the heat.

None of these favorable conditions is known to exist in the western San Juan Mountains. Precambrian crystalline rocks underlie well-compacted Paleozoic and Mesozoic sedimentary rocks at fairly shallow depths, so the capacity of potential reservoirs is limited. The general requirement of hot near-surface rocks is generally met in areas where igneous activity took place within the last few million years, but in the western San Juan Mountains the most recent volcanic activity that has been dated is about 18 m.y. old (H. H. Mehnert, written commun., 1972). Thus, it would seem that the geothermal energy resource potential of the Uncompahgre Primitive Area and contiguous study areas is low, although present data are too sparse for a definite statement to be made.

#### FOSSIL FUELS<sup>1</sup>

The Tongue Mesa coal field underlies the general Cimarron Ridge area from about 5 miles (8 km) northwest of the northwestern corner of the eastern contiguous area, northward for about 15 miles (24 km). The coal is in the lower 200 feet (60 m) of the Fruitland Formation, which overlies the Pictured Cliffs Sandstone and Mancos Shale and underlies the Kirtland Shale, all of Late Cretaceous age. The coal is subbituminous, and its aggregate thickness is as much as 40–50 feet (12–15 m) in places. It has been widely drilled in recent years, and commercial development is contemplated.

<sup>1</sup>Data supplied largely by R. G. Dickinson, U.S. Geological Survey.



The coal field is terminated on the south by the Ridgway fault, which crosses the Uncompahgre River 10 miles (16 km) north of Ouray and swings northeast to pass 5 miles (8 km) northwest of the northwestern corner of the eastern contiguous area. The uplifted block south of the fault is widely covered by younger volcanic rocks and by glacial and landslide debris; thus, geologic relations are obscure. Most scattered exposures are of Mancos Shale, but widely different faunal zones are juxtaposed in such a manner as to suggest that the area is complexly faulted. Two small areas of probable Fruitland Formation are exposed through the widespread landslide and glacial drift cover in the Cimarron River valley southeast of the Ridgway fault, indicating the possibility that some coal may exist in local fault blocks in this area as well. One of these exposures is only 2 miles (3.2 km) from the northwest corner of the eastern contiguous area.

Inasmuch as this faulting took place during the Laramide orogeny in latest Cretaceous and early Tertiary time, the surface geology of the mid-Tertiary volcanic rocks exposed in the eastern contiguous area gives no clue to the buried structure that might control the distribution of coal-bearing rocks. Available evidence does not indicate the presence of any coal beneath the eastern study area, but on the other hand, if suitable downdropped blocks are present in the pre-Tertiary basement, buried areas containing significant resources of coal could well exist.

The Dakota Sandstone is a common reservoir rock for oil and gas accumulations throughout the Southern Rocky Mountains region. This formation underlies most of the western and central contiguous study areas and at least the northwestern part of the eastern contiguous area. Any area within or adjacent to the study area underlain by Mancos Shale or by the Fruitland Formation would in all probability be underlain by Dakota Sandstone as well. The probable faults indicated by juxtaposed faunal zones in the Mancos Shale just northwest of the eastern contiguous area would offset the underlying Dakota Sandstone.

Small quantities of natural gas have been discovered in the Dakota Sandstone in the Ridgway field (Parker, 1962, map 1 in pocket) on the east side of the Uncompahgre River valley, 2.5 miles (4 km) north of the northwest corner of the central contiguous area. Depending on the presence of suitable structural or stratigraphic traps to retain hydrocarbons, concentrations of oil or gas in potentially economic quantities could well exist at one place or another in any area underlain by the Dakota Sandstone. Possible exceptions are areas near the igneous centers exposed at many places in and near the contiguous areas, where heat and metamorphism accompanying intrusion would make accumulation of oil or gas unlikely.

No resources of oil and gas within the study areas contiguous to the Uncompahgre primitive Area can be postulated from known data, but the possibility that such resources may exist must be recognized.

## WESTERN CONTIGUOUS AREA

## GEOLOGY

The western study area contiguous to the Uncompahgre Primitive Area (pl. 1B) consists largely of a high ridge of volcanic and intrusive rocks set on a platform of low-dipping Mesozoic sedimentary rocks. A layer of Eocene Telluride Conglomerate at the base of the ridge intervenes between the older sedimentary rocks and the volcanic rocks. Great landslides form the northern flank of the ridge, and over most of the area they cover the contact between the volcanic and sedimentary rocks.

The sedimentary platform beneath the western contiguous study area is capped nearly everywhere by the Mancos Shale, which forms smoothly rounded topography above the more precipitous slopes on the harder, underlying Dakota Sandstone. Dips in the sedimentary rocks are low, generally 5° or less, along the western and northern margins of the western contiguous area. On the south side, dips steepen to 20°-30° W. on the limb of a monocline in the vicinity of Mill Creek but flatten to near 5° W. farther east near Telluride. The Mancos Shale is structurally weak and was a favored host for concordant and semiconcordant sills and laccolithic intrusives.

The arkosic Telluride Conglomerate unconformably overlies the Mancos Shale. It is a hard, resistant unit that commonly stands as steep slopes and cliffs. Significant bodies of base- and precious-metal replacement ore are being mined in the Telluride Conglomerate in the highly productive mining area a few miles east of the western contiguous area (Mayor and Fisher, 1972).

The San Juan Formation is a local outflow volcanoclastic apron that surrounded the clustered early intermediate-composition volcanoes in the western San Juan Mountains. The San Juan Formation forms the main part of the volcanic ridge in the western contiguous area and stands as rubbly cliffs as much as 2,000 feet (600 m) high. Great banks of talus at the base of the cliffs commonly obscure relations with underlying rocks. The formation consists mainly of mudflow breccias, water-laid tuffs, and conglomerates that were derived from the central volcanoes. Near the San Juan caldera these rocks were intensely propylitized, and the originally fragmental unit was converted into a more uniform, compact greenish rock that acted as a competent host for the fracture-filling veins that to the east of this study area have supplied much of the metal production.

Ash-flow units form a thin, discontinuous cap to the high volcanic ridge in the western contiguous area. Many veins and dikes cut these rocks, but the tuffs have not been hosts for economic ore deposits farther east.

Intrusive rocks cut the sedimentary and volcanic rocks at many places in the western contiguous area. A large, semiconcordant body of granodiorite was emplaced in the northeastern part of the western

contiguous area in Late Cretaceous time. This floored laccolithic body was injected westward from the intrusive center at The Blowout, north of Ouray, into the sedimentary section just above the contact between the Dakota Sandstone and Mancos Shale. It was unroofed by erosion in early Tertiary time, and it was covered unconformably by the San Juan Formation in Oligocene time.

Intrusions emplaced during middle Tertiary volcanism are common in the western contiguous area; these range in composition from rhyolite to gabbro, but porphyritic andesite and granodiorite predominate. A major stock of this age centers on Mount Sneffels within the original Uncompahgre Primitive Area (fig. 2), and several similar discordant bodies cut the volcanic ridge farther west. A major laccolithic body was emplaced in the Mancos Shale at Whipple Mountain at the west end of the high ridge. Many thin sills were injected into the Mancos Shale adjacent to the laccolith at Whipple Mountain, and numerous steeply dipping dikes cut the sedimentary and volcanic rocks throughout the western and southern parts of the western contiguous area.

#### STREAM-SEDIMENT SAMPLES

Stream-sediment samples were taken along all the main streams draining the western contiguous area (pl. 2B). Because of the difficulty of access, the streams were best sampled near the margins of the study area, but the streams are short and precipitous and the samples collected should reflect in some measure the headwaters areas as well. Analytical results from these samples were largely negative and are not tabulated.

Except for streams draining areas with known mines and mineralized veins (samples F178 and F181 from Wilson Creek, and F276 from a tributary to Mill Creek in Pack Basin, pl. 2B), most analytical results indicate background metal concentrations only. The most significant exception was a widespread, relatively low anomaly (5-10 ppm) of molybdenum in samples collected near the contiguous area boundary where the streams flow through Mancos Shale. Dark shales in general are slightly enriched in many metals (Vine and Tourtelot, 1970), and the Mancos Shale probably supplied most of the molybdenum detected in these samples.

One sample (F112) from a tributary of Coal Creek contained 300 ppm (parts per million) zinc, and another (F288) from a tributary of Alder Creek contained 0.5 ppm silver. No other elements in either sample were present in anomalous concentrations, and no other samples nearby had more than background concentrations. In the absence of more supporting data, the significance of these scattered anomalous values cannot be assessed.

#### VEIN DEPOSITS

All veins seen in the western contiguous area are of middle Tertiary age. The most highly mineralized of these, along the volcanic ridge near

Greenback Mountain and Mount Emma (pl. 1B), are the distal ends of major radial veins that trend northwest out of the Silverton and San Juan calderas (Burbank and Luedke, 1968), and they extend into the southeastern part of the western contiguous area. Several of these veins, such as the Smuggler-Union, Liberty Bell, Terrible, and Humboldt (Burbank and Luedke, 1966), were the source of significant base- and precious-metals production in the major mining area just southeast of the contiguous area. Samples from some of these veins (F216–F226, table 4), taken along the crest of the volcanic ridge (pl. 2B), contain anomalous concentrations of silver, arsenic, gold, copper, mercury, molybdenum, lead, antimony, and zinc, although no ore-grade material was indicated. The grade and tonnage of mineralized rock at depth along these veins beneath the western contiguous area cannot be estimated from present exposures, but the surface evidence for mineralization and the known existence of ore at depth to the southeast suggest that ore-grade material may be present.

TABLE 4.—Selected chemical data from vein samples, western contiguous area  
[See pl. 2B for sample localities. ppm, parts per million; N, not detected; L, detected but below lower limit of measurement. Number in parentheses below element symbol is the usual lower limit of determination]

Sample	Semi-quantitative spectrographic analyses (ppm)		Chemical analyses (ppm)						
	Ag (0.5)	Mo (5)	As (10)	Au (0.05)	Cu (5)	Hg (0.02)	Pb (5)	Sb (0.5)	Zn (5)
F216	N	10	120	N	5	0.12	35	N	20
F217	N	N	100	N	L	.4	25	N	5
F220	L	N	10	N	5	N	20	.5	20
F221	L	N	1,000	N	5	.02	5	1	10
F223	200	200	12,000	.7	130	2.0	4,500	15	2,500
F226	L	10	L	N	N	.04	10	8	5
F263	.5	700	140	.05	5	.08	10	3	5
F264	N	20	20	N	10	.34	10	.5	15
F268	L	50	140	.05	5	L	20	4	60
F269	N	N	N	N	5	.26	15	2	90

Other veins in the southeast part of the western contiguous area are radial to the stock that forms Stony Mountain and Mount Sneffels just east of the contiguous area (Burbank and Luedke, 1966), and the veins appear related to this more local source. These relatively short veins extend only about 1 mile (1.6 km) from the core intrusive. Many of these veins are mineralized, and anomalous metal concentrations were detected on several. No ore-grade material was seen at the surface, but local ore bodies could exist at depth. These local veins, together with the major northwest-trending radial veins, indicate that the southeastern fringe of the western contiguous area is extensively mineralized and may have significant potential for vein-type base- and precious-metal resources at depth.

Several veins cut the high ridge of volcanic rocks between Whipple Mountain and Hayden Peak, in the western part of the western contiguous area (pl. 1B). Dikes of intermediate composition are abundant near the veins, and larger intrusive masses are located just south and east of the mineralized area. The veins consist largely of calcite, pyrite, and altered rock at the present levels of exposure. Samples (F263, F264, F268, and F269, table 4) contained anomalous concentrations of metals similar to those in the veins near Greenback Mountain just discussed. Although no ore-grade material was seen, the character and intensity of alteration and mineralization suggest that more careful study might outline deeper exploration targets. However, the veins are not large, and it seems unlikely that major metallic resources exist.

#### CENTRAL CONTIGUOUS AREA GEOLOGY

The central contiguous area also consists of a high ridge of volcanic rocks set on a platform of low-dipping Paleozoic and Mesozoic sedimentary rocks (pl. 1A). Numerous granodioritic intrusive bodies were injected into the sedimentary rocks in latest Cretaceous time, and many of these were exposed by early Tertiary erosion before the Telluride Conglomerate was deposited in local channels in early Eocene time. Most of the volcanic rocks and related intrusives were emplaced in Oligocene time.

The unconformity beneath the Telluride Conglomerate and volcanic rocks is largely the stripped top of the Dakota Sandstone, with irregular patches of overlying soft Mancos Shale and local paleohills marking the tops of Upper Cretaceous intrusive bodies. Mancos Shale is especially abundant along the north margin of the central contiguous area, where the weak shales have made the overlying volcanic rocks particularly susceptible to landsliding.

Upper Cretaceous intrusive bodies are exposed near the southwest and northeast corners of the central contiguous area. A major sill was injected northward from the intrusive center at The Blowout, about 1 mile (1.6 km) north of Ouray (Luedke and Burbank, 1962). This sill is largely in the lower part of the Mancos Shale, just above the contact with the Dakota Sandstone; it extends into the Dexter Creek drainage where it wedges out northward under the southwest part of the central contiguous area. Numerous crosscutting igneous and clastic dikes fill fractures in the adjacent sedimentary rocks, and some also cut the sill. Another igneous center is exposed on both sides of Cow Creek near the northeast corner of this study area. Most of the exposed intrusive rock is part of a crosscutting stock that marks the intrusive center, but part forms a semiconcordant sheet injected southward along the contact between the Mancos Shale and Dakota Sandstone. Thin dikes and sills cut the sedimentary rocks in nearby parts of Cow Creek canyon; most of these are too small to be shown

on plate 1A. The Blowout center, lower Cow Creek center, and Spruce Ridge center (Dickinson and others, 1968) are arranged in a north-northeast-trending line 10 miles (16 km) long; the area between The Blowout and Cow Creek is almost completely covered by younger volcanic rocks. Other concealed intrusive centers could well exist along this trend.

Most of the volcanic rocks in the central contiguous area are outflow volcanoclastic sediments of the San Juan Formation. These rocks have weathered to smooth steep slopes over much of the central contiguous area, and to sheer rubbly cliffs adjacent to Cow Creek. Most of the San Juan Formation has been weakly to moderately propylitized, and it is much more compact and uniform than the fragmental rock that was originally deposited. The top of the high ridge along the southeast side of the central contiguous area is capped by Ute Ridge Tuff, the oldest widespread welded ash-flow sheet in the western San Juan Mountains.

Numerous intermediate-composition dikes radial to an intrusive center in upper Cow Creek (Luedke, 1972) extend northwestward into the central contiguous area (pl. 1A). These dikes cut both the San Juan Formation and Ute Ridge Tuff and were emplaced relatively late in the local sequence of igneous events.

#### STREAM-SEDIMENT SAMPLES

Stream sediments were sampled along all the main streams draining the central contiguous area (pl. 2A). Of these, only the samples from Dexter Creek and its tributaries, which drain an area of known mines, mine dumps, and mineralized veins, showed consistently anomalous concentrations of lead, zinc, silver, molybdenum, and copper. Examples are samples F1, F5, and F14 (pl. 2A). In addition, one sample from Bear Gulch contained 0.5 ppm silver; the significance of this lone anomalous value is not known.

#### VEIN AND REPLACEMENT DEPOSITS

Productive mines near the central contiguous area were all developed on veins and replacement bodies related to the Upper Cretaceous intrusive bodies associated with The Blowout center north of Ouray; total production has been about \$13 million in gold, silver, copper, lead, and zinc. As described by Burbank (1940, p. 200–201):

Deposits that are definitely correlated with this [Late Cretaceous] period of mineralization extend from the vicinity of Ouray northward to Cutler Creek, a distance of 4 or 5 miles, and eastward from the Uncompahgre Valley for at least 2 or 3 miles. A fringe of deposits extends along the west side of the valley, but the intensity of mineralization decreases more abruptly westward than eastward. The deposits that extend for about 2 miles southward from the intrusive axis on both sides of the Uncompahgre Valley have not been so productive as those of the northern area. The central productive area represented by several large groups of deposits, such as those of the American Nettie and Bachelor mines, covers about 4 or 5 square miles northwest of the intrusive axis and east of the Uncompahgre Valley.

On the basis of their metal content the ores may be divided into four groups: (1) magnetite-pyrite ores containing a little copper and gold; (2) pyritic ores containing copper and gold; (3) pyritic base-metal ores containing native gold, with gold and silver tellurides; (4) siliceous and baritic ores containing silver, lead, and zinc, but commonly little gold. The gross productivity of the different groups increases in about the order named, but perhaps group 3, because of its relatively rich deposits, has returned the most on small investments. Individual mines producing from the richer silver veins of group 4 have had the highest gross productivity.

These ore deposits are zonally arranged with group 1 the central and group 4 the outer zones; they extend into the Dexter Creek area where some of the most productive mines exploiting the outer mineral zone (Burbank, 1940, p. 201) have been developed. The edge of the overlying middle Tertiary volcanic rocks extends across the zonal pattern described by Burbank, and the outer zone containing his group 4 deposits projects beneath volcanic cover in the central contiguous area northeast of Dexter Creek. Some of the known veins extend beneath the volcanics, and others undoubtedly exist in adjacent areas to the northeast.

The Upper Cretaceous intrusive mass along lower Cow Creek near the northeast corner of the central contiguous area (fig. 2; pl. 1A) showed little evidence of hydrothermal activity, and only a few small veins were seen in the poorly exposed adjacent sedimentary rocks. A few samples (F84, F85, F102, pl. 2A) of the Morrison Formation along Cow Creek contained 20-60 ppm arsenic, and other samples (F84, F93, F102, F273, pl. 2A) contained 3-6 ppm antimony. The significance of these values is uncertain; they may mark original concentrations in the Morrison shales, or they may reflect halo concentrations around the exposed lower Cow Creek intrusive center or some similar center now buried by the younger volcanic rocks. Samples of the small veins did not contain significant concentrations of valuable metals.

Other Upper Cretaceous intrusive centers may exist beneath the volcanic cover between The Blowout center and the lower Cow Creek center. Favorable host rocks for mineralization underlie the volcanics along this trend (Fischer and others, 1968, fig. 2), and these might contain vein, replacement, or porphyry-type ore bodies, similar to those peripheral to The Blowout center. Surface exposures give no indication of any such buried Upper Cretaceous mineral deposits, and exploration would have to depend on geophysical or other indirect methods of study and on extensive physical exploration.

Several veins that cut the San Juan Formation along Cow Creek in the southeastern part of the central contiguous area were deposited during the middle Tertiary mineralization. These veins are within the area cut by dikes radial to the upper Cow Creek intrusive center (fig. 2), and the veins probably are also related to that center. The veins are poorly exposed and are very inaccessible, so their lateral extent is not known. Conceivably, they occupy fissures similar to those followed by the radial dikes, which extend for several miles.

The veins at the surface contain only sparse visible base-metal sulfides, but three samples collected from one of these veins (taken at localities F98, F99, and F101, pl. 2*A*), contain low but anomalous concentrations of arsenic (20–80 ppm), antimony (5–10 ppm), and mercury (0.65–1 ppm) as determined by chemical analyses. The vertical extent of mineralization would be difficult and expensive to determine because of the extremely rugged and hazardous terrain. Concentrations greatly above those determined would be required to constitute significant potential mineral resources.

#### EASTERN CONTIGUOUS AREA GEOLOGY

The eastern contiguous area (pl. 1*A*) is most readily discussed in terms of rocks that predate and postdate formation of the Uncompahgre caldera: an older assemblage consisting of andesitic to rhyodacitic lavas and breccias of the early intermediate-composition volcanoes and overlying older ash-flow tuff units that were erupted prior to collapse, and a younger assemblage of lavas, breccias, and ash-flow tuff units that filled the caldera. The Sapinero Mesa Tuff, whose eruption was accompanied by collapse of the caldera, occurs both as a thin sheet capping the older assemblage and as a thick accumulation within the caldera. The topographic wall of the caldera which separates the two assemblages extends generally westward across the southern part of the eastern contiguous area where the complex accumulations of early intermediate-composition lavas and breccias are unconformably overlapped on the south by a mixed assemblage of younger intermediate-composition lavas and breccias and more silicic ash-flow tuffs (pl. 1*A*).

The topographic wall of the Uncompahgre caldera flares outward from the buried ring-fracture zone that marks the structural margin of the caldera. This structural margin is everywhere covered by caldera-fill, and its position can only be conjectured from the general structure and morphology of the caldera. It should be near the base of the topographic wall of the caldera and outside any early intermediate-composition volcanics exposed by recent erosion within the subsided block. Experience elsewhere in the San Juan volcanic field (T. A. Steven and P. W. Lipman, unpub. data) indicate that generally the structural margin marks the outer edge of the domed cores of resurgent calderas. By these criteria, the northern structural margin of the Uncompahgre caldera should be just north of the exposures of early intermediate-composition lavas along Henson Creek and its tributaries (pl. 1*A*) and in part beneath the line of younger rhyolite intrusives that extends across the southern part of the eastern contiguous area. This same zone appears to have localized monzonitic intrusives that cut the caldera-filling lavas and ash-flow tuffs along North Fork Henson Creek and Matterhorn Creek near the southwest corner of the eastern contiguous area. These and similar



intrusives may have fed the intermediate-composition lavas and breccias that are interlayered with the younger ash-flow tuff units at many places around the Uncompahgre caldera.

Three obvious environments for potential mineral deposits exist within the geologic framework of the eastern contiguous area: (1) the cores of hydrothermally altered and mineralized early intermediate-composition volcanoes that are exposed in or adjacent to the eastern study area; (2) the altered and mineralized monzonitic intrusives cutting the caldera fill above the postulated structural margin of the Uncompahgre caldera, and related metalliferous veins exposed near Henson Creek along the southern margin of the study area; and (3) the young rhyolite intrusives, emplaced largely along the postulated trend of the structural margin of the Uncompahgre caldera that are anomalously radioactive and locally contain secondary concentrations of supergene uranium minerals.

These environments were examined as carefully as time permitted. In addition, routine stream-sediment samples were collected throughout the eastern study area to detect any other less obvious concentrations of valuable minerals that might exist.

#### STREAM-SEDIMENT SAMPLES

Stream sediments were sampled along all the drainage systems of the eastern contiguous area (pl. 2A), and all the samples were analyzed spectrographically and chemically for selected elements. Anomalous metal contents were found only in drainage basins that contain known mineralized areas. The results of the stream-sediment sampling program are summarized, according to drainage basin, in the following paragraphs.

#### MATTERHORN CREEK

Matterhorn Creek is tributary to North Fork Henson Creek, largely within the original Uncompahgre Primitive Area and just west of the eastern contiguous area. It drains two overlapping areas of hydrothermally altered rocks, and several patterns of metal anomalies can be discerned in the stream-sediment analyses.

Matterhorn Creek heads in patchily altered rocks that fringe both the altered and mineralized Matterhorn volcanic center, in the headwaters of the East Fork Cimarron River, and an altered area at the Iron Beds to the southeast. The influence of the Matterhorn center is clearly shown by the distinctly higher molybdenum and lead values in samples S48-S52 (table 5) collected near the head of the drainage basin. Metal values diminish below this area and remain generally low to near the mouth of Matterhorn Creek where zinc increases sharply in samples S60-S65 collected from the main stream and from an eastern tributary draining the southeastern part of the altered area at the Iron Beds. The behavior of copper is

particularly instructive: spectrographic analyses which measure total copper show little variation throughout the drainage basin; chemical analyses, measuring the copper extracted in cold HCL solutions (CxCu test) and probably largely the copper held loosely by adsorption on clay fractions, show a sharp increase in samples from lower Matterhorn Creek in direct confirmation of the spectrographic zinc anomaly. Total heavy metal content extracted in cold citrate solutions (CxHM test)—largely zinc and copper—expectably parallels the zinc-copper anomaly just described.

Both the molybdenum-lead anomaly near the head of Matterhorn Creek and the copper-zinc anomaly near the mouth are sufficiently distinctive to indicate areas worthy of further exploration. The specific source areas of the anomalous stream sediments are just outside the eastern contiguous area, but adjacent fringe areas within the contiguous area might be of economic interest as well.

#### YELLOWSTONE GULCH

Yellowstone Gulch is a short tributary to lower North Fork Henson Creek, just southwest of the eastern contiguous area. Several veins in the Capitol City mining area were developed within this drainage basin, and some of the mine dumps extend to the bottom of the gulch. As expected, the stream sediments are strongly anomalous. Silver ranges from below detection levels (0.5 ppm) to 20 ppm, copper from 20 to 1,500 ppm, molybdenum from less than 5 to 30 ppm, lead from less than 10 to 2,000 ppm, and zinc from less than 200 to 2,000 ppm. No gold was detected.

#### EL PASO CREEK

El Paso Creek is tributary to Henson Creek, and its drainage basin includes the eastern part of the altered area at the Iron Beds, several young rhyolite intrusive bodies, and an area containing metalliferous veins near its mouth. All three of these geologic environments are reflected in analyses of the stream-sediment samples.

Samples J51-J57 and J59 (table 5) were collected near the head of El Paso Creek (pl. 2A) in an area of patchily altered rocks on the east side of the altered area at the Iron Beds. Chemical analyses (table 5) show CxCu to be generally above background and CxHM to be spottily above background. Spectrographic analyses, measuring total metal contents, are less discriminating, and, although the copper and lead may average slightly higher in these samples than in the nonanomalous samples collected from middle El Paso Creek, the distinction is not clear.

The influence of the young rhyolite intrusives is shown largely by spectrographic analyses. Beryllium constitutes 7-15 ppm and niobium 20-50 ppm of most of the rhyolite, and these elements, especially beryllium, were widely detected in sediment samples taken near and below such intrusive bodies. Beryllium was not detected in the head-

waters of El Paso Creek above the level of the rhyolite intrusives, but 19 samples from between the intrusion and the mouth of El Paso Creek analyzed 1-1.5 ppm beryllium. Niobium was detected (20 ppm) in sample J60 taken adjacent to one of the largest rhyolite intrusive bodies in the drainage basin.

Lower El Paso Creek, from the boundary of the eastern contiguous area to Henson Creek, contains anomalous metal contents as indicated by both the CxCu and CxHM chemical tests (table 5). This part of the drainage basin, adjacent to Yellowstone Gulch in the Capitol City mining area, is cut by related mineralized veins. Some of the anomalous metal might be derived from the eastern fringe of the altered area at the Iron Beds drained by upper El Paso Creek, but the relatively low metal values obtained from samples taken along the middle course of the stream suggest a more local origin.

#### SOUTHERN AND SOUTHEASTERN STREAMS

Samples from streams draining the southern and southeastern parts of the eastern contiguous area east of El Paso Creek contained little or no anomalous metal other than beryllium derived from the young rhyolite intrusives. The drainages sampled are Pole, Nellie, Modoc, Ute, and Crystal Creeks, Neoga Mountain area, the landslide area below Crystal Lake, Larson Creek, and Independence Gulch. A few random samples contained one constituent or another in slightly anomalous concentrations, but these were too few and too widely scattered to indicate local areas of potential economic interest. Beryllium in concentrations of 1-1.5 ppm was widely detected, however, and in some streams, such as Nellie Creek, it was present in almost every sample taken. Niobium is generally less than the limit of measurement by spectrographic methods (10 ppm), although in places its presence was detected but not measured. The close association of detectable beryllium in stream sediments with the rhyolite intrusive bodies is especially well shown along Larson Creek. In 16 samples taken above a prominent rhyolite plug, beryllium either was not detected or if detected was present in concentrations too small to be measured. Of the 17 samples taken from the rhyolite plug to the mouth of Larson Creek, beryllium was detected in all but 1 and constituted 1-2 ppm in 7 samples.

The lack of base-metal anomalies in stream sediments from the southern part of the eastern study area is significant. Scattered veins are exposed along Henson Creek, just south of the eastern contiguous area, from the Capitol City district to Lake City (pl. 1A). Most of these veins are short, but one group, developed by the Ute-Ulay mine (fig. 22), extends more than 1 mile (1.6 km) in strike length and may project into the southern part of the study area. Similar veins in the Capitol City area are reflected by distinct metal anomalies in stream-sediment samples, such as those taken from Yellowstone Gulch and lower El Paso Creek. The lack of

similar anomalies to the east suggests that most of the veins are limited to the lower slopes above Henson Creek, and probably few extend into the eastern contiguous area which covers the headwaters and middle courses of the streams sampled.

The lower course of Larson Creek is about one-fourth mile (0.4 km) south of and parallel to the southern margin of an irregular intermediate-composition intrusive body that marks the core of the Larson volcanic center (pl. 1A). Numerous satellite dikes from this intrusive body extend southward at least to the creek, and one old prespecting tunnel half a mile (0.8 km) from the mouth of Larson Creek was driven northwest from creek level along an altered fracture zone. Spectrographic analyses of samples from this locality did not disclose anomalous metal contents, but samples G303–G305, taken near the mouth of the creek, contained CxCu and CxHM values slightly above background. Most of the intrusive body and all the weakly anomalous sample localities are outside the eastern contiguous area.

#### NORTHEASTERN AND NORTHERN STREAMS

Stream-sediment samples collected from the northeastern and northern drainage of the eastern contiguous area contain no anomalous metal concentrations. Drainage basins discussed here are Bill Hare and High Bridge Gulches, Elk Creek, Soldier Creek, Big Blue Creek, Fall Creek, Firebox Creek, and the Little Cimarron River. All these streams drain the north flanks of the clustered early intermediate-composition volcanic centers of the western San Juan Mountains, and no major intrusives are located within their drainage systems. A few dikes and minor plugs on the east side of the Cimarron volcanic center extend into the headwaters of Big Blue Creek, and radial dikes extending northward from the Larson center cross Bill Hare and High Bridge Gulches, but, apparently, there is no significant related mineralization. Outflow welded ash-flow tuff sheets cap some of the high ridges, but these are far from their sources and no known mineral concentrations accompanied their emplacement.

If Independence Gulch, with its very minor anomalous beryllium concentrations, is included, the drainage basins discussed here embrace nearly three-fourths of the eastern study area. Neither geologic mapping nor chemical analyses of stream sediments indicated mineral concentrations of potential economic interest anywhere within this part of the study area.

#### EAST FORK CIMARRON RIVER

The East Fork Cimarron River cuts through altered and mineralized intrusive cores of two intermediate-composition volcanoes and extends across the volcanoclastic apron on the north side of the volcanic complex. Stream-sediment samples clearly show the influence of the altered areas, particularly in the widespread anomalously high copper content, and less prominently in the zinc content.

Stream-sediment samples S4–S11 (table 5), collected between about

three-fourths mile (1 km) below the highly altered Matterhorn center and the Cimarron center (pl. 2A), have copper contents of 15-30 ppm by spectrographic methods and 2-10 ppm (average 4.4 ppm) by CxCu methods. Sporadic anomalous zinc concentrations are indicated by spectrographic analyses but not clearly by the CxHM analyses.

Samples S12-S18 from within or adjacent to the Cimarron center ranged from 8 to 15 ppm (average 8.7 ppm) copper by the CxCu method and from 15 to 20 ppm by the less discriminating spectrographic method. The nearly twofold increase in average copper determined by the CxCu method is interpreted to reflect contributions from the altered and mineralized rocks of the Cimarron center.

Downstream from the Cimarron center the copper content of stream sediments drops off somewhat to the range of less than 1 to 10 ppm (average about 5.4 ppm) copper by the CxCu method. Total copper in the samples as indicated by spectrographic analyses averages about 20 ppm, about the same as samples higher in the drainage basin. Sporadic anomalous zinc values were detected throughout the drainage area by both spectrographic and CxHM analyses.

Compared with the background of samples from streams draining similar rocks to the east, the samples from the East Fork Cimarron River drainage are slightly but distinctly anomalous in copper and zinc. The higher copper content in samples near the altered Cimarron center pin-points one probable source, and the even more altered and mineralized Matterhorn center at the head of the drainage is another obvious source. Both areas will be considered individually later in this report.

#### MIDDLE FORK CIMARRON RIVER

A short segment of the Middle Fork Cimarron River borders the eastern contiguous area. Samples taken along this segment showed no clear-cut metal anomalies by spectrographic methods, although the copper (15-20 ppm) may average somewhat higher than the background established by samples from streams farther east (generally 5-15 ppm). However, chemical analyses by the CxCu method show 2-7 ppm loosely held copper, definitely above background, which is generally 1 ppm or less.

These values show no significant variation within the area sampled and are generally comparable to values obtained well below the altered volcanic centers on the East Fork Cimarron River. The western end of the Cimarron volcanic center extends into Porphyry Basin, tributary to the Middle Fork several miles upstream from the sampled area, and might well be the source of the anomalous copper values.

#### MINERALIZATION ASSOCIATED WITH EARLY INTERMEDIATE VOLCANIC CENTERS

During early intermediate-composition volcanic activity, 35-30 m.y. ago, a clustered group of volcanoes formed in the western San Juan

Mountains area. Many of these volcanic centers have since collapsed into the Uncompahgre and San Juan calderas and have been covered by younger deposits, but a few centers outside the collapsed area are now marked by near-source lavas and breccias surrounding intrusive cores. Two of these centers are just outside the north wall of the Uncompahgre caldera (figs. 1, 2): the Larson center between the east margin of the eastern contiguous area and the Lake Fork Gunnison River and the Cimarron center, largely on the ridge between the East and Middle Forks Cimarron River. All these centers have been altered and mineralized.

A similar early intermediate intrusion south of the Uncompahgre caldera at the old mining camp of Carson is hydrothermally altered, and the surrounding lavas and breccias are cut by numerous small metaliferous veins. An estimated \$200,000 worth of metals have been produced from the Carson Camp (Vanderwilt, 1947, p. 115).

#### LARSON CENTER

The Larson center is marked by an irregular intrusive plug exposed on the ridge between lower Larson Creek and Independence Gulch (pl. 1A). Numerous dikes radiate from this center; some extend as far as 3 miles (5 km) north into Bill Hare and High Bridge Gulches. The intrusive center is irregularly altered, and a few small prospect pits have been dug.

Little mineralized material except for some irregularly hydrothermally altered rock was seen. Samples of the dump of an adit along Larson Creek taken by the U.S. Bureau of Mines were not encouraging. Stream-sediment samples taken along Larson Creek adjacent to the intrusive center contained slightly anomalous metals by CxCu and CxHM analyses, but samples from Independence Gulch to the north were virtually at background levels.

Most of the intrusive center and all the anomalous samples are outside the eastern contiguous area. This distribution and the weak evidence for mineralization indicate that the eastern contiguous area near the Larson center has little economic potential.

#### CIMARRON CENTER

An elongate monzonite intrusion extends from near the Silver Jack mine, on the East Fork Cimarron River, west across a high ridge into Porphyry Basin, tributary to the Middle Fork Cimarron River (pl. 1A). Numerous dikes cut the surrounding lavas and breccias. This intrusive center appears to mark the core of a relatively young volcano within the early intermediate-composition assemblage of volcanics, although the field relations do not preclude a possibility that the intrusions are younger than the early intermediate near-source accumulation. The lower slopes of the ridge are mostly outflow-facies mudflow breccias from older sources to the south, but the upper parts of the ridge consist largely of near-source lavas and breccias that formed the volcanic edifice around

the Cimarron center. The main intrusion cuts both the mudflow breccias and the overlying near-source lavas. Most rocks near the Cimarron Volcano were propylitically altered, and disseminated pyrite is widespread. This pervasive alteration probably resulted from reactions with hot carbonate-bearing water that permeated the volcano and underlying rocks late in its development.

Subsequent to the propylitic alteration, the main intrusion was in part hydrothermally altered to red and yellow argillized and silicified rocks with abundant disseminated pyrite. Similarly altered fractures that cut the surrounding volcanics are followed by some of the associated dikes. Many of these fractures were extensively prospected, particularly in Porphyry Basin and near the Silver Jack mine. Mudflow breccias near the Silver Jack mine are cut by numerous dikes and altered fractures, which contain local concentrations of sulfides, largely pyrite. Most prospect pits and short adits were dug along altered dikes that localized the late mineralized shears and veins.

Some analyzed samples (table 6) are representative of the altered rock in general, but others were taken from the apparent highest grade parts of the exposed veins. Many of these latter samples contained slightly anomalous silver, arsenic, copper, molybdenum, lead, antimony, tellurium, or zinc by either or both spectrographic or chemical analyses, but only one (S86H) was strongly anomalous in more than one metal. Even this sample did not approach ore grade. The most anomalous samples commonly contained limonite and may reflect some secondary concentration of metals. These largely negative results indicate a low potential for vein deposits.

Veins also occur in Porphyry Basin near the western end of the intrusive mass. These deposits are outside the eastern contiguous area and were not examined by the U.S. Geological Survey. U.S. Bureau of Mines personnel sampled the area, however, and their results indicate anomalous concentrations of copper, lead, and molybdenum, but no ore-grade material.

Two sample traverses were made across the irregularly altered central intrusion of the Cimarron Volcano. Ten samples of the intrusion and altered wallrocks were taken along the lower slopes just west of the East Fork Cimarron River (S85A-J, table 6), and seven additional samples were collected along the ridgecrest between the East and Middle Forks (S170-S175, table 6). A few samples contained slightly anomalous quantities of silver, arsenic, copper, molybdenum, lead, antimony, tellurium, or zinc, but anomalies are so scattered and so slightly above background that only a low economic potential is indicated for the central intrusion.

#### MINERALIZATION ASSOCIATED WITH INTRACALDERA INTRUSIONS

Monzonitic intrusions cut the Uncompahgre caldera fill at several places within, south, and southwest of the eastern contiguous area (pl. 1).

These bodies probably were emplaced late in the Uncompahgre caldera cycle, and in part they may represent feeders for the intermediate-composition lavas and breccias that are interlayered with the younger ash-flow units and fill the northern caldera moat. The intrusions are commonly altered and locally have metalliferous veins associated with them.

#### MATTERHORN CENTER

An elongate monzonite intrusion, about 5,000 feet (1,500 m) long and 1,000 feet (300 m) wide, cuts early intermediate-composition lavas and breccias on the north slope of Matterhorn Peak in the headwaters of the East Fork Cimarron River (pl. 14). The intrusion and adjacent wallrocks are widely altered. Prospect pits and trenches have been dug, and bulldozer roads cut.

The Matterhorn center probably is the core of an intracaldera-age volcano. The halo of intensely argillized and pyritized rock along the south side of the intrusive appears to extend up into propylitically altered Ute Ridge Tuff, although the argillization and pyritization of the older rocks in places greatly exceeds that in the younger Ute Ridge Tuff. On the south side of Matterhorn Peak, the altered area centered on the Iron Beds area to the southeast overlaps the altered area related to the Matterhorn center.

This intrusive center is just west of the eastern contiguous area, but stream sediments containing anomalous concentrations of metals derived from this area were collected along both Matterhorn Creek and the East Fork Cimarron River (table 5), and the eastern fringe of the alteration halo around the center closely approaches the western boundary of the study area. In consequence, the intrusive center was examined briefly and 21 samples of altered and mineralized rock were analyzed (table 6). In the 21 samples silver, arsenic, copper, molybdenum, lead, zinc, and tellurium were widely but irregularly detected in anomalous concentrations. Particularly significant are widespread anomalous copper, molybdenum, lead, and arsenic, which indicate pervasive mineralization centered on the altered intrusive plug. Stream-sediment samples from the head of Matterhorn Creek, which is within the alteration halo around the Matterhorn center, also contain anomalous molybdenum and lead. Scattered altered rock samples from the upper Matterhorn Creek area, not tabulated, are anomalous in the same elements as those from the intrusive center to the north.

All rock samples taken in and near the Matterhorn intrusive center were from surface exposures where leaching by acidic meteoric water probably has reduced the metal content and obscured the anomalies. This probability receives some support from unverified reports of visible molybdenite in the shallow workings along the East Fork Cimarron River. The presence of molybdenum at the Matterhorn center has also



been indicated by Clark (1972, figs. 3, 4) but the source of his information was not given.

The widespread anomalous metal values and the pervasive alteration and pyritization centered on the core intrusive indicate a possible exploration target. Veins are obscure around the center, and the potential seems much better for a disseminated "porphyry-type" deposit containing copper or molybdenum, or both. The shallow volcanic environment now exposed is above the deeper volcanic or subvolcanic environment in which most porphyry-type deposits are found, and extensive deep drilling probably would be required to test the mineral potential adequately.

#### CAPITOL CITY MINING AREA

The Capitol City mining area, 1-2 miles (1.6-3.2 km) southwest of the eastern contiguous area near the confluence of Henson Creek and its North Fork, is centered on several monzonitic intrusions. The intrusions and adjacent country rock are widely but irregularly altered and are cut by numerous small metalliferous veins that produced significant precious metals in early mining (Irving and Bancroft, 1911). Veins of the Capitol City mining area occur on both slopes adjacent to lower North Fork Henson Creek (pl. 1A). All the veins are just outside both the original Uncompahgre Primitive Area and the eastern contiguous area. However, the ore deposits are typical of what might be expected at depth beneath the altered area at the Iron Beds to the north, so some stream-sediment and altered-rock samples were taken for comparison purposes.

The mineral deposits and mines in the Capitol City area have been described in detail by Irving and Bancroft (1911, table 2, p. 72-81). The veins consist largely of quartz, galena, and sphalerite, with lesser pyrite, chalcopyrite, and tetrahedrite. Minor gangue minerals are barite, sericite, and rare fluorite. The veins are generally less than 1,000 feet (300 m) long, and most are only 1-2 feet (0.3-0.6 m) wide. Ore shoots within the veins are generally much more restricted and in places form only a small part of the associated vein. The fissures filled by the veins show little evidence of significant displacement and appear largely to be discontinuous fractures.

The exploited veins are largely around the northern periphery of a highly altered area containing numerous small monzonitic intrusions. This altered area extends south from North Fork Henson Creek, across the east flank of Sunshine Mountain, Henson Creek, and up the south wall of Henson Creek canyon to be cut off abruptly by the bounding fault of the younger Lake City caldera. Stream-sediment samples from Yellowstone Gulch, within the area of developed mines, are highly anomalous. Ten samples of altered rock from the south side of North Fork Henson Creek (not tabulated) contain highly anomalous concentrations of silver, copper, molybdenum, lead, zinc, antimony, and arsenic, as well as local

gold, as expected within an area of developed mines. Nine additional samples of altered rock from the lower slopes south of Henson Creek (not tabulated) show distinctly anomalous silver and molybdenum and somewhat anomalous arsenic and antimony.

This reconnaissance sampling suggests that the whole eastern flank of Sunshine Mountain might warrant study to determine whether disseminated mineralization might be associated with the Capitol City intrusive center. This area extends south under a broad flat valley of Henson Creek where it is covered by alluvium and glacial drift; geophysical methods and drilling would be required to test the mineral potential here. The samples taken along the south side of the valley were not nearly as anomalous as those to the north, but they are still sufficiently so to encourage study.

#### ALTERED AREA AT THE IRON BEDS

The altered area at the Iron Beds is high on the slopes east of Matterhorn Creek and extends into the El Paso Creek drainage to the east and the East Fork Cimarron River drainage to the north. Most of the altered area is in the original Uncompahgre Primitive Area and is just west of the eastern contiguous area (pl. 1A). A wide variety of rocks are altered, including intermediate-composition lavas in the Henson and Burns Formations and the volcanics of Uncompahgre Peak and ash-flow tuffs in the Fish Canyon, Crystal Lake, and Carpenter Ridge Tuffs. In detail, the alteration was controlled in part by lithology, but the altered area seems localized near a cluster of small monzonitic intrusive bodies. Some of these are shown on plate 1A in the headwaters of Matterhorn Creek, but others were too small to be shown or were too altered to be mapped in the time available. The rocks are irregularly argillized, silicified, bleached, and oxidized. Pyrite is abundantly disseminated throughout the area. Much of the pyrite has been removed from the near-surface rocks, and supergene leaching of metals probably has occurred.

Stream-sediment samples from lower Matterhorn Creek and upper El Paso Creek contain anomalous metal concentrations that seemingly were derived from the altered area at the Iron Beds. Twenty-three bedrock samples (G328A-G3285, S164A, S167-S169), largely from altered rocks in the central part of the altered area, also indicate local anomalous metal concentrations (table 6). Silver was detected and was, therefore, anomalous in two of the samples; copper and lead were erratically anomalous by both spectrographic and chemical analyses, as were zinc, arsenic, antimony, and tellurium by chemical analyses; and six of the samples contained anomalous molybdenum.

These results, in conjunction with stream-sediment-sample analyses, indicate that the altered area at the Iron Beds contains widespread slightly anomalous metal concentrations. The sample coverage was too uneven to establish distribution patterns for the different metals or to pinpoint local exploration targets.

## VEINS ALONG HENSON CREEK

Scattered veins are exposed along the lower slopes on both sides of Henson Creek from the Capitol City area 8 miles (13 km) east to Lake City (pl. 1A). The largest groups of veins are near the mouth of El Paso Creek, just east of Ute Creek, and on the lower south slope of Neoga Mountain. The veins are very similar to those in the Capitol City area except for the local occurrence of rhodochrosite as a major gangue mineral (Irving and Bancroft, 1911, table 2, p. 81-99). Most veins are fairly short, generally less than 1,000 feet (305 m) in length, but the group developed by the Ute-Ulay and Hidden Treasure mines extends for more than 3,300 feet (1 km) from Henson Creek northeast to near and perhaps across the southern boundary of the eastern contiguous area. As in the Capitol City area, there is little evidence for significant displacement along these veins, and even the longer ones do not appear to offset geologic contacts or local flows appreciably. One monzonitic intrusive, Sugarloaf Rock, cuts the caldera fill on the south slope of Neoga Mountain, but none of the veins appears closely related to it.

Of the known veins, only those developed by the Ute-Ulay, Hidden Treasure, and Pelican mines extend near and perhaps into the eastern contiguous area. Only the veins near the mouth of El Paso Creek extend across a major drainage, and these were clearly reflected in the anomalous concentrations of metals in stream-sediment samples collected along lower El Paso Creek. The lack of similar anomalies in the other streams draining the southern part of the contiguous area suggests that few if any of these veins exist within their middle or upper drainages. However, brief examinations made at mines south of the eastern contiguous area suggest that worthwhile targets for exploration may well exist along some of the veins. The vein system developed by the Ute-Ulay and Hidden Treasure mines in particular appears favorable.

## MINERALIZATION ASSOCIATED WITH RHYOLITE INTRUSIONS

An east-northeast-trending line of rhyolite intrusions cuts the caldera fill near the northern wall of the Uncompahgre caldera. These intrusions extend from the Mary Alice Creek tributary of North Fork Henson Creek, west of the eastern contiguous area, across the southern part of the study area to Larson Creek, near the east margin of the area (pl. 1A). The intrusions range from oval-shaped plugs and irregular small cross-cutting masses to concordant and semiconcordant sills and wedge-shaped laccolithic bodies. The sills and laccoliths were generally injected along local sedimentary units between lava flows or ash-flow sheets in the caldera fill and appear to have been fed from the crosscutting plugs. The main bodies mapped are: a stubby irregularly branching dike at Broken Hill and upper El Paso Creek, local small plugs and sills between El Paso and Pole Creeks, a major wedging sill or laccolith between the east and west forks of Nellie Creek that extends west of the west fork of Nellie

Creek, an oval-shaped plug along the east fork of Nellie Creek, and an elongate plug in the Larson Creek drainage.

The rhyolite is a distinctive siliceous rock (76–77 percent  $\text{SiO}_2$ ) with abundant quartz and sodic sanidine and sparse biotite phenocrysts set in a white to light-gray devitrified groundmass. Hydrated vitrophyres occur locally along the margins of some crosscutting bodies. Part of the devitrified rhyolite is distinctly vesicular and locally contains a fibrous cavity-filling mineral that is possibly a zeolite. Small euhedral topaz crystals and powdery purple fluorite occur in some vesicles and along minor fractures. Megascopically the rock appears fresh and unaltered, and the wallrocks show minor evidence of baking but none of hydrothermal alteration. No veins were seen either in the intrusive bodies or in the wallrocks.

All the intrusive rhyolite is anomalously radioactive, and scintillator field measurements are commonly twice or more those of the wallrocks. Three local areas were seen where the rhyolite contains secondary yellow uranophane along fractures near the contacts with wallrocks. Since 1968, several exploration programs by industry have tested the economic potential of several of these rhyolite plugs. As a result, the rhyolite intrusive bodies were examined carefully, were sampled extensively, and were analyzed chemically by several methods (tables 7, 8).

Sediment samples were taken along all the streams draining the area containing the rhyolite bodies as part of the general sampling program. In addition, all the main intrusive bodies were examined in more detail, radioactivity was measured, and the rock was sampled along traverses planned to obtain maximum coverage in the time available. Limited time did not permit extensive petrographic study of the rocks.

Representative samples were analyzed spectrographically, and some were also analyzed chemically (table 7). The equivalent uranium (eU) content of 40 samples was checked by the beta-gamma scaler method, and the uranium and thorium contents were measured by the delayed neutron method (table 8). The uranium and thorium contents of one sample, L47, were determined by gamma-ray spectrometry as well; its values (table 8) are similar to those obtained by the delayed neutron method. These data show the distribution of many of the elements of possible economic significance and permit interpretation of their behavior during intrusion and subsequent cooling of the rhyolite.

#### GEOCHEMICAL DATA

High-silica alkali rhyolite magmas like those that formed the intrusions in the eastern contiguous area are enriched during magmatic differentiation in many minor constituents, including beryllium, fluorine, molybdenum, niobium, tin, thorium, uranium, and tungsten (Nockolds and Allen, 1953; Turekian and Wedepohl, 1961). Not all these elements, however, are comparably enriched in all alkali rhyolites, and each local area generally has its own characteristic assemblage and

relative concentrations. Because many of these elements are mobile, they may be variably enriched or depleted locally in an intrusion during cooling and crystallization. The extensive analytical work during this investigation provides data bearing on these postemplacement processes.

Attention will be focused chiefly on the behavior of fluorine, uranium, thorium, beryllium, molybdenum, niobium, and tin in the rhyolite and wallrocks. Six samples of marginal vitrophyre were collected: four (S47F, S106B, S110A, and L47) were from the northern and eastern margin of the plug along the east fork of Nellie Creek, and two (G324J and G324K) were from the body on Broken Hill. These samples are assumed to represent the least modified part of the original rhyolite magma available, and the analytical results are compared with those from the devitrified parts of the intrusions and the wallrocks.

Fluorine was determined by specific-ion analyzer on most samples of rhyolite that were chemically analyzed, and, in addition, on a few samples that were tested for radioactivity only. Values ranged erratically from below the limit of detection (50 ppm) to 1,300 ppm. The highest value was from a marginal vitrophyre (G324K), but other measurements on vitrophyres ranged from less than 50 to 700 ppm fluorine. Similar erratic results were obtained from devitrified rhyolites, although most of these were only a few hundred parts per million fluorine or less. The scattered high values, along with local occurrence of topaz in vesicles and fluorite along fractures, probably indicate that the original magma contained significant fluorine; the erratic but generally low values in devitrified rhyolite are interpreted to indicate general expulsion of fluorine during cooling and crystallization. Loss of fluorine during crystallization of rhyolitic magmas has also been documented by Noble, Smith, and Peck (1967) and by Lipman, Christiansen, and Van Alstine (1969).

The distribution of uranium and thorium in the samples is particularly instructive. Analyzed marginal vitrophyres (S110A and L47, table 8) contain about 40 ppm uranium, 55-63 ppm thorium, and have a thorium/uranium ratio of 1.4-1.6; these concentrations are among the highest measured except for samples taken near obvious secondary uranophane. Field scintillator determinations for all the sampled vitrophyres (tables 7, 8) confirm this conclusion. Wallrock samples generally contain appreciably less uranium and thorium, and the field radiometric readings were distinctly lower. Sample S108 is not consistent with this conclusion, and analytical results do not agree with field readings. A misidentified sample is suspected.

Most devitrified rhyolite appears to be significantly depleted in uranium and considerably less depleted in thorium. The core of the plug along the east fork of Nellie Creek (table 8) contains only about half as much uranium (22-25 ppm) as the marginal vitrophyres, whereas the thorium is not appreciably different. The thorium/uranium ratios for

devitrified rock are 2-2.6 in contrast with 1.4-1.6 for vitrophyres, also indicating relative depletion of uranium. The devitrified rock from the sill between the east and west forks of Nellie Creek and west of the west fork of Nellie Creek contains even less uranium, and the thorium is also somewhat less; the relatively greater depletion of uranium is reflected by the many thorium/uranium ratios greater than 2. Devitrified rock from the rhyolite plug along Larson Creek, in general, contains the least uranium measured (10-20 ppm), and the rock has consistently high thorium/uranium ratios, indicating relative depletion. The small intrusions in the upper El Paso Creek area, on the other hand, have more uranium (26-37 ppm) and have lower thorium/uranium ratios (1.3-2.1) than any of the rhyolite other than the marginal vitrophyres, indicating significantly less removal of uranium from these bodies.

One El Paso Creek sample (G325C, table 8), from a small prospect where secondary uranophane was locally concentrated along minor fractures in the rhyolite, expectedly contains high uranium and thorium as a result of secondary enrichment. The relatively uniform uranium and thorium concentrations in the other samples, in comparison with this obviously enriched specimen, accord with the postulated general depletion of uranium in most devitrified rocks. Depletion of uranium from crystallized volcanic rocks, in comparison with glassy parts of the same units, has also been carefully documented by Rosholt and Noble (1969).

Beryllium is generally high in all intrusive rhyolite bodies and was commonly detected in stream-sediment samples taken below outcrops of the rhyolite. Comparison of concentrations of beryllium in the six marginal vitrophyre samples (mostly 15-20 ppm, with one of 7 ppm) with those in the other rhyolite samples also indicated depletion in the devitrified rock. Most samples of devitrified rock from the Nellie Creek basin contained 7-15 ppm beryllium, and samples from the core of the plug along Larson Creek contained only 7 ppm beryllium. This relative depletion closely parallels the behavior of uranium, with devitrified rock in the Nellie Creek basin showing intermediate loss and in the Larson Creek basin the greatest loss. Significantly, samples from the Broken Hill body and the small intrusives in upper El Paso Creek, which showed little depletion in uranium, also contained nearly as much beryllium as the samples of marginal vitrophyre.

Molybdenum shows the same general pattern as uranium and beryllium. Molybdenum was detected in all but one of the vitrophyre samples, and it was as high as 15 ppm in two samples (both from the plug along the east fork of Nellie Creek). It was erratically detected (generally 5-7 ppm) in some devitrified samples from the plug along the east fork of Nellie Creek, but only in a very few samples from the sill between the east and west forks of Nellie Creek, or from the Broken Hill dike. Molyb-

denum was below detectability in samples from the sill west of the west fork of Nellie Creek and from the plug along Larson Creek. It was detected in most samples from the small intrusives in upper El Paso Creek where it commonly is present in quantities comparable with those in the marginal vitrophyres. The broad parallelism with the behavior of uranium and beryllium is apparent, with greatest depletion in the plug along Larson Creek and least depletion in the small El Paso Creek intrusive bodies.

These patterns closely parallel those discovered by Haffty and Noble (1972), who clearly showed depletion of molybdenum from peralkaline silicic volcanic rocks during crystallization. In contrast with our data, Haffty and Noble found no comparable depletion in beryllium but suggested that this fact may have been due to the peralkaline composition of their rocks.

Niobium concentrations are 20-50 ppm in most samples of intrusive rhyolite and, locally, are as much as 80 ppm. No pattern of distribution was discerned between marginal vitrophyre and devitrified rock, or from place to place within an intrusive body. The plug along Larson Creek and the sill west of the west fork of Nellie Creek average somewhat lower than the other bodies, but the significance of this is not known. No regular pattern of depletion or enrichment comparable to those interpreted for uranium, beryllium, and molybdenum is apparent.

Tin was widely but erratically detected in all rhyolite intrusive bodies except the plug along the east fork of Nellie Creek. In most samples the concentration was not sufficient to be measured; thus, comparisons cannot be made. Tin was widely detected both in the Larson Creek plug, where uranium, beryllium, and molybdenum showed greatest depletion, and in the small intrusive bodies in El Paso Creek, which show the least depletion in these elements. Tin was detected in only one vitrophyre sample. These data suggest that tin was neither depleted nor enriched comparably with uranium, beryllium, and molybdenum during crystallization.

#### ECONOMIC SIGNIFICANCE

Except for local areas containing small concentrations of secondary uranophane in the rhyolite, no evidence for economic deposits was seen in or near the rhyolite intrusive masses. The relatively high concentrations of fluorine, uranium, thorium, beryllium, molybdenum, niobium, and tin in samples are typical of high-silica alkali rhyolites and result largely from normal magmatic differentiation. Careful review of the geochemical data indicates that the devitrified rhyolite comprising the bulk of those bodies is actually somewhat depleted in fluorine, uranium, beryllium, and molybdenum compared to the original magma, as best represented by local marginal vitrophyres. No concentrations of any of

these depleted metals were detected in wallrocks adjacent to the intrusive bodies, although all exposures of these rocks near the intrusives were examined carefully and were checked extensively for radioactivity.

The timing of this depletion is critical to interpretation of the economic potential of the rhyolite intrusive masses. Seemingly, the intrusions could have been depleted during cooling and crystallization, when many minor elements and volatile constituents, such as water and the halogens, that did not fit well into lattices of the rock-forming minerals were expelled. On the other hand, the depletion might have taken place much later owing to leaching by downward-percolating ground water; this hypothesis was tentatively favored by Rosholt and Noble (1969) in their study of the loss of uranium from crystallized volcanic rocks. Under the first alternative, the depleted elements would probably have been expelled upward and out of the now-exposed environment; under the second alternative, they would have entered the ground-water regime and have been dispersed outward into the surrounding rocks where some may have been deposited locally in significant concentrations.

Several lines of reasoning favor expulsion during cooling and crystallization: (1) the pattern of distribution of many elements reflects vitric versus devitrified rock; (2) no difference was noted between dense devitrified rock and more permeable vesicular devitrified rock that might have channeled ground water; (3) each intrusive body appears to have characteristic concentration patterns; and (4) the depleted elements are a related group that are mobile during cooling and crystallization of silicic igneous rocks. Fluorine appears to be a key element: uranium, beryllium, and molybdenum are all readily mobile as halogen complexes, and, inasmuch as fluorine and probably chlorine were expelled, they may have scavenged uranium, beryllium, and molybdenum from the crystallizing magma and carried them out of the local system. No evidence was seen for nearby precipitation, and the emanations probably traveled upward toward a near-surface thermal spring or fumarolic environment associated with the local igneous centers. Conceivably, the depleted rhyolite bodies could represent sources similar to those that supplied the near-surface fluorite-bertrandite deposits at Spor Mountain, Utah (Staatz, 1963; Staatz and Griffiths, 1961), or the shallow fluorite deposits at Northgate, Colo. (Steven, 1960), and elsewhere in the Western United States. Such levels of possible precipitation have all been eroded from above the exposed rhyolite intrusives in the southern part of the eastern contiguous area.

The local areas containing secondary uranophane represent local ore-grade concentrations that conceivably have economic potential. All the uranophane deposits seen are in rhyolite and are concentrated in fractures near contacts with wallrocks. The fractures appear to be minor shears that developed in the solidified margins of concordant bodies during intrusion. Observed fracture zones are apparently too limited in extent to localize large ore bodies. No secondary concentrations of uranium were



detected in adjacent wallrocks, and in particular the local sedimentary units that localized most of the sills and laccoliths appear devoid of uranium concentrations. Significant concentrations of secondary uranium may exist somewhere in association with the rhyolite bodies, but these would be controlled by conditions not observed during this investigation, and, therefore, are not predictable from present data.

### INTERPRETATION OF AEROMAGNETIC DATA

By PETER POPENOE and R. G. LUEDKE, U.S. Geological Survey

An aeromagnetic survey of a region in southwestern Colorado that includes the Uncompahgre Primitive Area and the three contiguous study areas was flown by the U.S. Geological Survey in 1969 as part of a wilderness investigation program. Traverses spaced about 1 mile (1.6 km) apart were flown in an east-west direction at a barometric elevation of 14,500 feet (4,400 m), and the total intensity magnetic field was recorded with fluxgate magnetometer. The aeromagnetic map of the primitive and contiguous areas is shown in figure 3.

The regional magnetic high associated with the San Juan Mountains volcanic field is best seen on the aeromagnetic map of Colorado by Zietz and Kirby (1972) and the aeromagnetic map of the Ridgeway-Pagosa Springs area, southwestern Colorado (U.S. Geol. Survey, 1972). Regional aspects of the aeromagnetic and gravity fields associated with the volcanic field have been discussed by Plouff and Pakiser (1972) who have interpreted the regional gravity low and magnetic high in the area as reflecting a near-surface batholith genetically related to the caldera complex and volcanic field. Model studies of the anomalies show that the top of this concealed batholith ranges from 0.5 to 1.75 miles (0.8–2.8 km) below the surface and is nearest the surface in the area of the Lake City caldera located south of the western contiguous area.

A preliminary interpretation of the aeromagnetic pattern of the Uncompahgre Primitive Area was released in August 1970 (Popenoe and Luedke, 1970). However, recent reinterpretations of the volcanic stratigraphy and caldera-collapse structures within and near the primitive area (Lipman and others, 1973) necessitate a reinterpretation of the local aeromagnetic pattern of the original primitive area and the three contiguous areas.

#### MAGNETIC SUSCEPTIBILITY MEASUREMENTS

Measurements of magnetic susceptibilities were made for 54 samples of rocks from the Uncompahgre Primitive Area and surrounding areas. These samples are listed individually with locations in Popenoe and Luedke (1970) and summarized herein on the basis of reclassification with the geologic units used in this report.

Although only a few of the rock units were measured for magnetic susceptibilities in the Uncompahgre Primitive Area and surrounding areas, the validity of the results is borne out by observation of the expression of these units on the magnetic map. The Upper Cretaceous intrusive rock

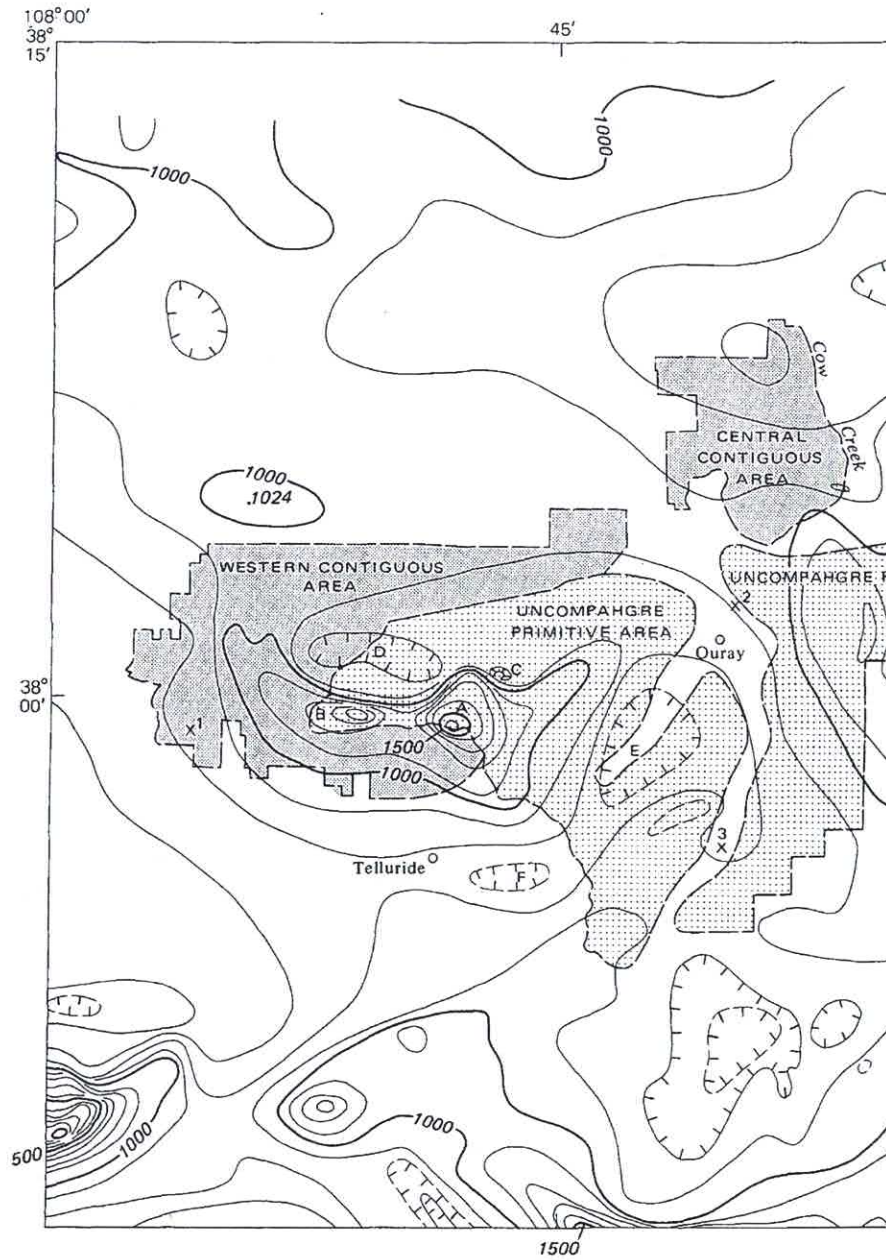
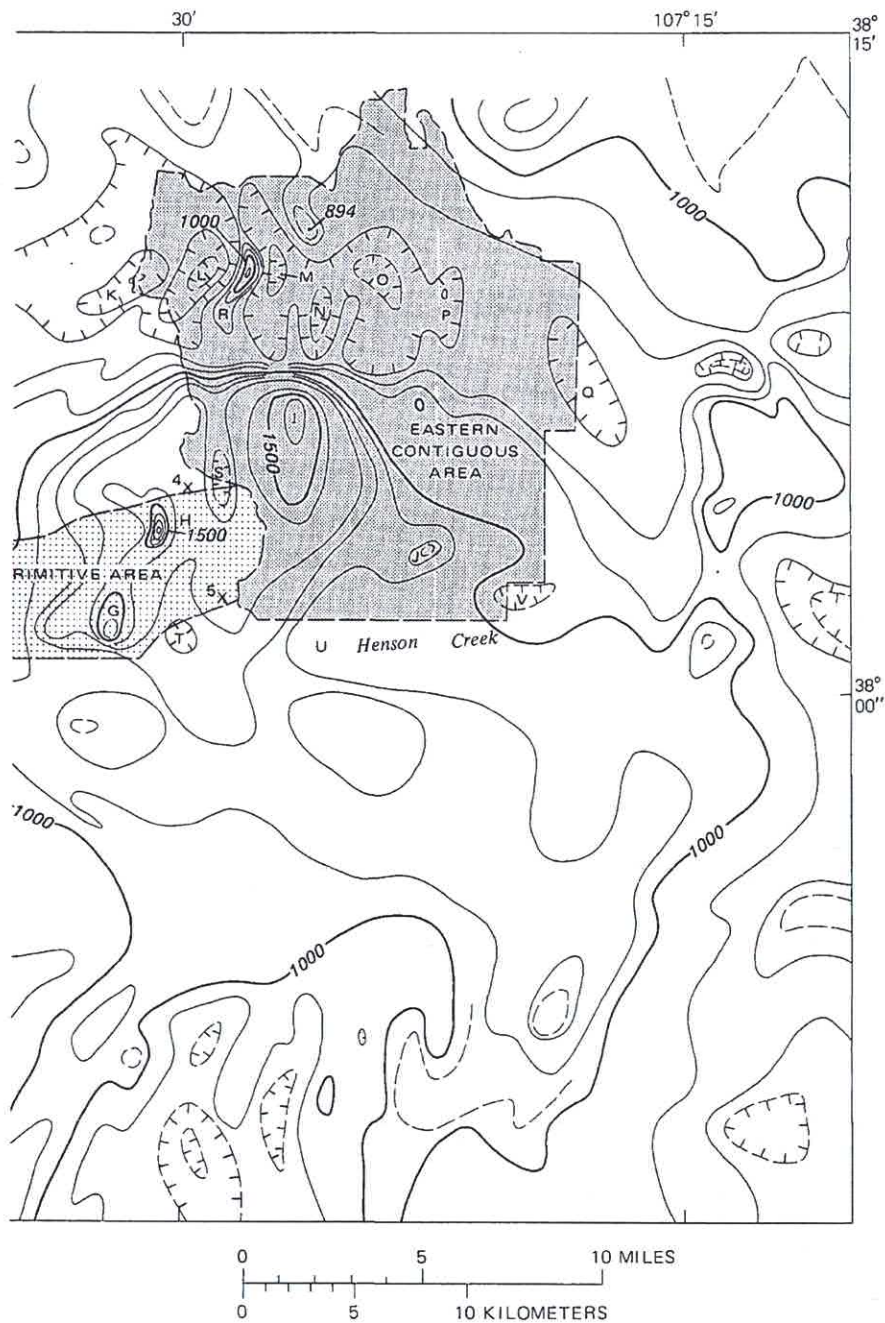


FIGURE 3.—Preliminary aeromagnetic map of the Uncompahgre Primitive Area and eastern, central, and western contiguous areas. Contours show total intensity magnetic field of the earth in gammas relative to arbitrary datum; hachures indicate

CONTIGUOUS AREAS, UNCOMPAHGRE PRIMITIVE AREA, COLO. E49



closed areas of lower magnetic intensity. Selected measured maximum or minimum intensities, in gammas, are also shown. Points of reference: 1, Whipple Mountain; 2, The Blowout; 3, Ironton; 4, Matterhorn Peak; 5, Iron Beds. A through V represent anomalies discussed in text.

from a laccolith along Cow Creek showed an intermediate susceptibility of  $1.4 \times 10^{-3}$  emu/cm<sup>3</sup> (table 9), and on the aeromagnetic map the Upper Cretaceous intrusives at Cow Creek and at The Blowout and vicinity near Ouray show no aeromagnetic expression even though they are surrounded by nonmagnetic sedimentary rocks. This finding is explained by the intermediate susceptibility of the intrusives, their low topographic position remote from the detector, and their occurrence mainly in relatively thin sills and laccoliths that form most of the intrusive bodies. The discordant stock at The Blowout is highly altered suggesting that this stock has a very low magnetic susceptibility owing to destruction of magnetite by leaching solutions.

TABLE 9.—Magnetic measurements of intrusive rocks, Uncompahgre Primitive Area and surrounding areas

Rock type	Number of samples	<sup>1</sup> K × 10 <sup>-3</sup>	
		Range	Mean
Miocene rhyolite intrusives .....	3	0.1-0.9	0.6
Middle Tertiary intermediate-composition intrusives .....	11	3.6-10.9	6.1
Cretaceous intrusives .....	1	1.4	1.4

<sup>1</sup>K=apparent volume magnetic susceptibility in emu/cm<sup>3</sup> (electromagnetic units per cubic centimetres) measured with an induction-type apparatus.

Most middle Tertiary intrusives of intermediate composition have high magnetic susceptibilities. The granodioritic to gabbroic intrusive rocks ranged in magnetic susceptibility from  $3.6 \times 10^{-3}$  to  $10.9 \times 10^{-3}$  emu/cm<sup>3</sup> indicating a magnetite content of 1.3 percent by volume (Lindsley and others, 1966). The high susceptibility of the measured samples is verified by the aeromagnetic highs observed over the Mount Sneffels intrusive (anomalies A and B, fig. 3) and other intrusives marked by the large amplitude anomalies shown in the southwest corner of figure 3. Some of the monzonite intrusives exposed within the Uncompahgre Primitive Area and contiguous study areas, such as the altered plug at Matterhorn Peak, have a lower aeromagnetic expression than the intermediate intrusive rocks mentioned above. The monzonites do not contrast significantly with the surrounding ash-flow units and are difficult to recognize on the aeromagnetic map.

Three samples of the Miocene rhyolite intrusives measured for magnetic susceptibility indicate a moderate susceptibility with a mean of about  $0.6 \times 10^{-3}$  emu/cm<sup>3</sup>. This moderate susceptibility is evident on the aeromagnetic map as the rhyolite intrusives exhibit no magnetic contrast where they are surrounded by tuffaceous rocks, but they cause aeromagnetic lows when contrasted with near-vent intermediate-composition flows.

Within the primitive area, the early intermediate-composition near-