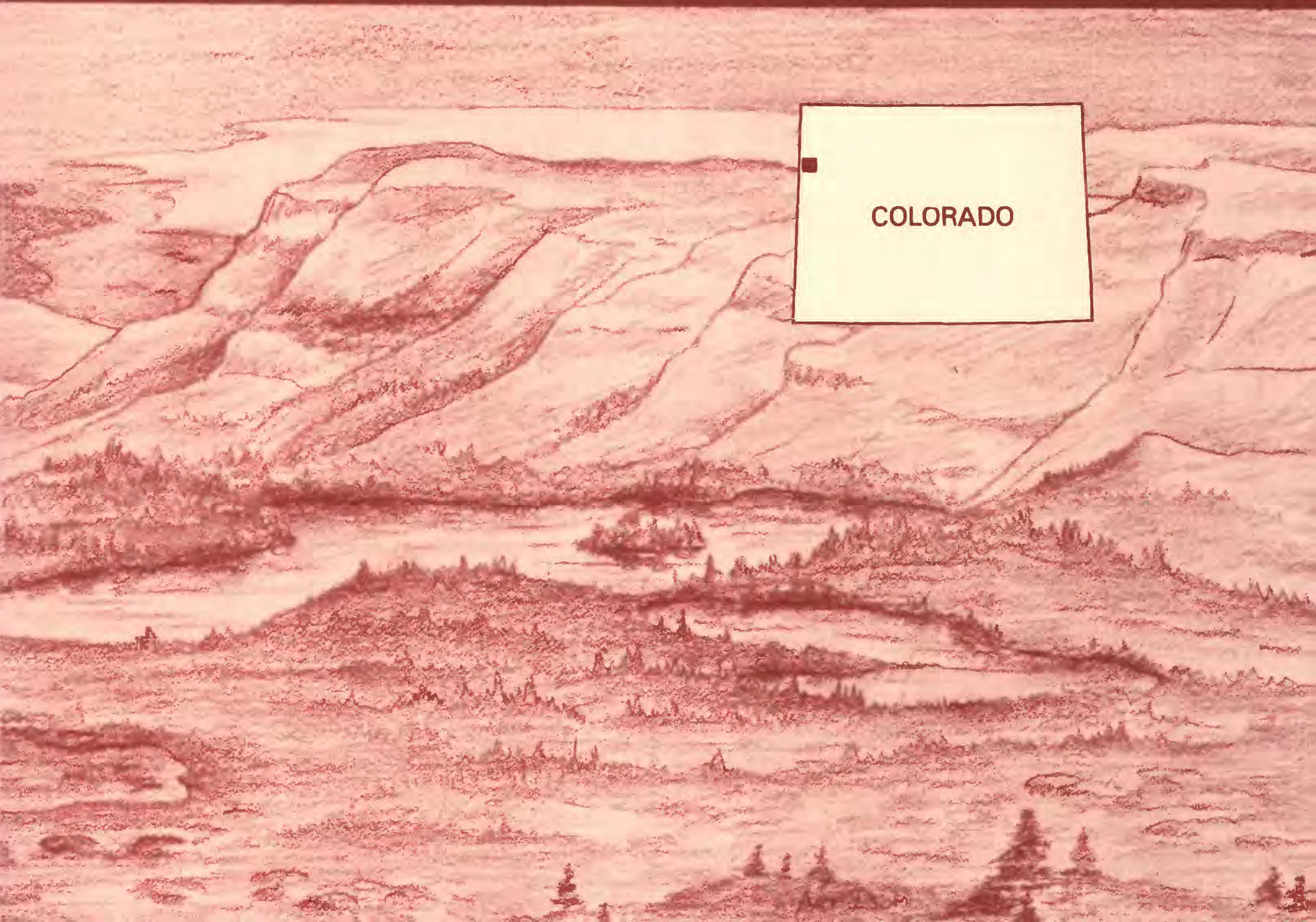
Mineral Resources of the Willow Creek and Skull Creek Wilderness Study Areas, Moffat County, Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 1717–D



Chapter D

Mineral Resources of the Willow Creek and Skull Creek Wilderness Study Areas, Moffat County, Colorado

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MINERAL RESOURCES OF WILDERNESS STUDY AREAS—NORTH-CENTRAL COLORADO

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

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

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STUDIES RELATED TO WILDERNESS

Bureau of Land Management Wilderness Study Areas

The Federal Land Policy and Management Act (Public Law 94–579, October 21, 1976) requires the U.S. Geological Survey and the U.S. Bureau of Mines to conduct mineral surveys on certain areas to determine the mineral values, if any, that may be present. Results must be made available to the public and be submitted to the President and the Congress. This report presents the results of a mineral survey of the Willow Creek (CO–010–002) and Skull Creek (CO–010–003) Wilderness Study Areas, Moffat County, Colorado.

CONTENTS

PLATE

[Plate is in pocket]

FIGURES

Mineral Resources of the Willow Creek and Skull Creek Wilderness Study Areas, Moffat County, Colorado

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ABSTRACT

The Willow Creek Wilderness Study Area (CO-010-002) and the Skull Creek Wilderness Study Area (CO-010-003), which contain 13,368 acres and 13,739 acres, respectively, are in northwest Colorado near the Utah border. There are no identified resources in either of the study areas. The study areas have low resource potential for undiscovered uranium, vanadium, copper, and all other metals; oil and gas; and coal.

SUMMARY

Character and Setting

The Willow Creek and Skull Creek Wilderness Study Areas are located along the southeastern edge of the Uinta Mountains about 15 mi (miles) north of Rangely, Colo. (fig. 2). In this report, unless specific mention is made of one or the other wilderness study areas, both areas will be referred to as the "study areas." The Willow Creek study area, which consists of 13,368 acres, lies west of the Skull Creek study area, which consists of 13,739 acres. The study areas are just north of U.S. Highway 40 between the small towns of Massadona and Dinosaur. Parts of the study areas are visible from this 20-mi stretch of highway. The boundaries of the study areas are defined on the south largely by a legal land net that separates U.S. Bureau of Land Management (BLM) land from private and state land, on the west by a National Park Service road, and on the east and north by secondary roads for the most part. The study areas are separated from each other by a 4-mi-long jeep trail. This trail and most of the other dirt roads around the area serve the ranchers, home owners, and hunters. Land developers have built roads up to parts of the southern and eastern boundary of the study areas. Easy access to either study area is gained from these roads or any number of other secondary roads that lead north off U.S. Highway 40.

Mining, prospecting, and oil and gas exploration activities have been carried out in and near the study areas. Several exploratory oil wells have been drilled in and near the study areas. One was drilled within a mile of the study areas as recently as the spring of 1988, and geophysical surveys were made on parts of the study areas by private companies in the fall of 1988. This activity illustrates the current interest for oil and gas in the region. Uranium and vanadium have been mined nearby, and coal is presently mined from underground workings a few miles south of the study areas. This coal is shipped by railroad to a power plant in Utah. Tourism plays a major role in the region. Dinosaur National Monument is about 10 mi north of the study areas.

The study areas lie along the crest of two east-west-trending anticlines. These anticlines are named after drainages in the respective areas: the Willow Creek anticline and the Skull Creek anticline. These asymmetrical structures closely resemble monoclines. Strata in the northern flanks of the anticlines dip only 2–3° north, whereas strata in the southern flanks dip very steeply 40–50° south. The Willow Creek and Skull Creek anticlines are probably caused by the Willow Creek thrust fault whose surface trace nearly parallels the southern flanks of the anticlines. Asymmetrical folds or monoclines are common in the eastern Uinta Mountains, and they are considered to be formed by movement along thrust faults as older rocks are displaced over younger rocks. The steeply dipping rock along the southern flanks of the

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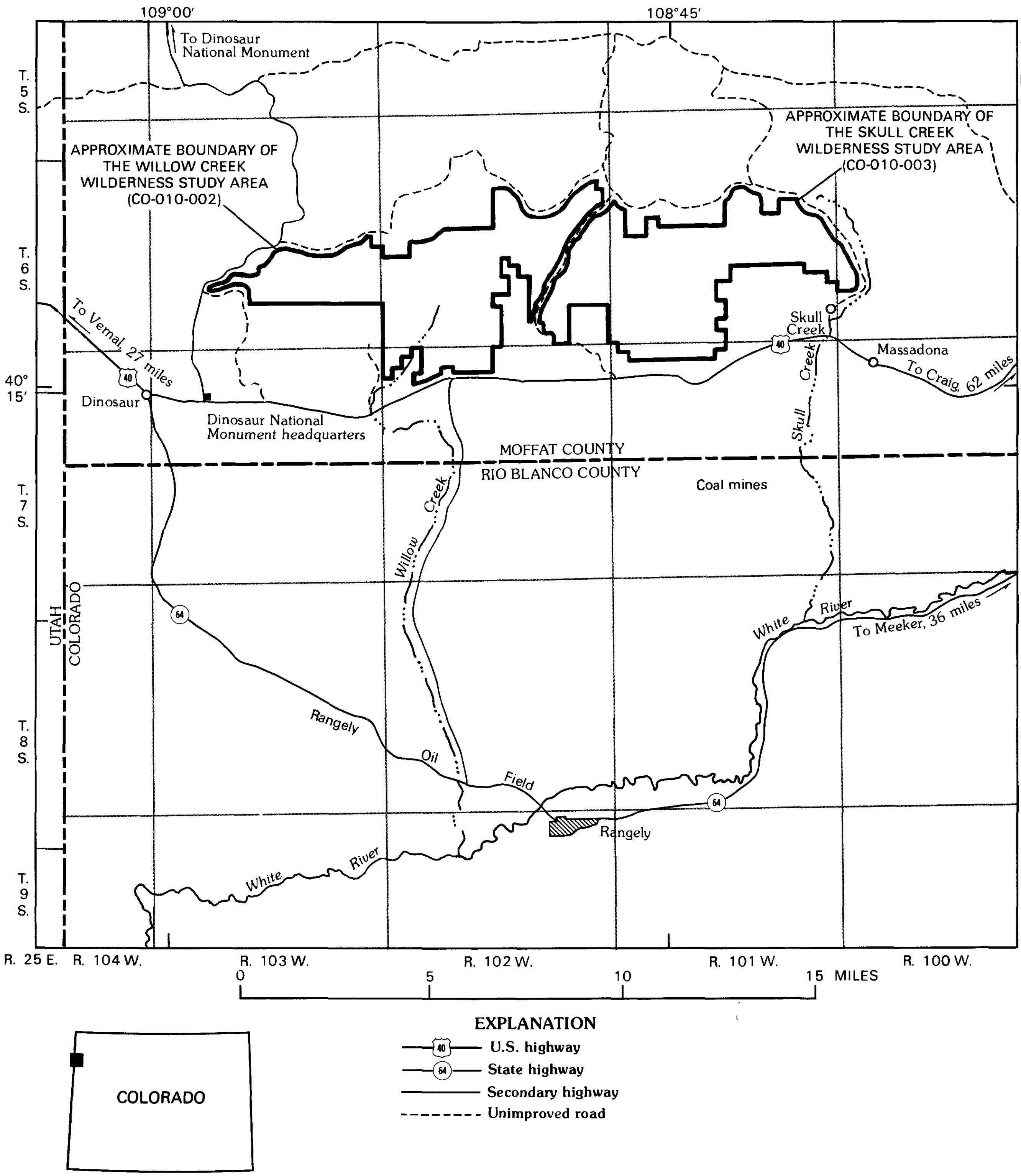


Figure 1. Index map showing location of the Willow Creek and Skull Creek Wilderness Study Areas, Moffat County, Colorado.

anticlines forms hogbacks along the entire east-west length of the study areas. The Skull Creek study area lies near the center of a dome formed by the Skull Creek anticline. The terrain is characterized by a gently dipping erosional surface of sandstone, which is cut by deep canyons. Steep picturesque cliffs of the Skull Creek Rim circle the dome outside the study area. Part of the Willow Creek study area lies in the dome. The terrain in this region rises in elevation from south to north. Elevations at the base of the hogbacks along U.S. Highway 40 are about 5,800 ft (feet), and the elevation along the northern edge of the Willow Creek study area, which is the highest point, is about 8,000 ft.

At least 2,000 ft of Paleozoic rock and more than 20,000 ft of Precambrian rock are probably present in the subsurface of the study areas. These rocks are exposed 5–10 mi north of the study areas.

The stratigraphic units that are exposed in the study areas include more than 3,000 ft of Paleozoic and Mesozoic rock. The oldest rock unit exposed is the Weber Sandstone of Middle and Late Pennsylvanian and Early Permian age. In the Rangely area, the Weber is the principal reservoir rock for oil and gas. Mudstone and siltstone of the Park City Formation of Early Permian age overlie the Weber in exposures that encircle the Skull Creek basin. The Moenkopi Formation of Early and Middle(?) Triassic age overlies the Park City and forms the lower half of Skull Creek Rim, whereas the Chinle Formation of Late Triassic age makes up the upper half of the rim. The Moenkopi and Chinle are primarily a redbed sequence of mudstone, siltstone, and sandstone. The basal conglomerate of the Chinle is uranium bearing in many parts of the Colorado Plateau. The Glen Canyon Sandstone of Early Jurassic age unconformably overlies the Chinle. The Glen Canyon, which is the thickest unit present, is exposed extensively along the crest of the Willow Creek anticline and around the Skull Creek dome. The Carmel Formation of Middle Jurassic age is present in about half of the study areas; where the Carmel is present it is overlain by the Entrada Sandstone of Middle Jurassic age. The Curtis and Redwater Members of the Stump Formation of Middle and Late Jurassic age unconformably overlie the Entrada. The Curtis is a thin and very hard sandstone that forms a series of hogbacks along the southern boundary of the study areas. Mineralization has taken place at the base of the Curtis Member in several locations in and near the study areas. The Morrison Formation of Late Jurassic age overlies the Redwater Member. The Morrison is a thick sequence of sandstone, conglomerate, and variegated claystone and mudstone. Dinosaur bones and petrified wood are common in the conglomerate, and similar stratigraphic horizons host the famous dinosaur quarries to the west in Utah in Dinosaur National Momument. The Morrison contains important uranium deposits throughout the Colorado Plateau in Colorado, Utah, and New Mexico. Minor amounts of oil were produced from the Morrison in the Rangely oil field. The Morrison is overlain by the Lower Cretaceous Cedar Mountain Formation and Dakota Sandstone. The Mancos Shale of Late Cretaceous age is the youngest rock unit in the study areas and consists of the Mowry and Frontier Members and the main body of the shale. The Mowry has been used locally as road metal. Oil has been produced from fractures in the Mancos Shale in the Rangely oil field. Quaternary deposits include dune sands that were derived from the Glen Canyon Sandstone, landslide deposits that developed on the unstable Morrison Formation, terrace gravels and alluvium that were deposited along stream channels, and colluvium that was deposited as slope wash.

Identified Mineral Resources

There are no identified resources in the study areas. Uranium, vanadium, and copper were mined from small workings near the study areas; similar mineral occurrences were explored in the study areas, but none represent a resource. There are no mineral claims within the study area boundaries. Several holes have been drilled for oil and gas in and near the study areas, but none were successful. The study areas are under lease for oil and gas. Sand, gravel, and shale have been quarried near the study areas for use as road metal; similar material occurs in the study areas.

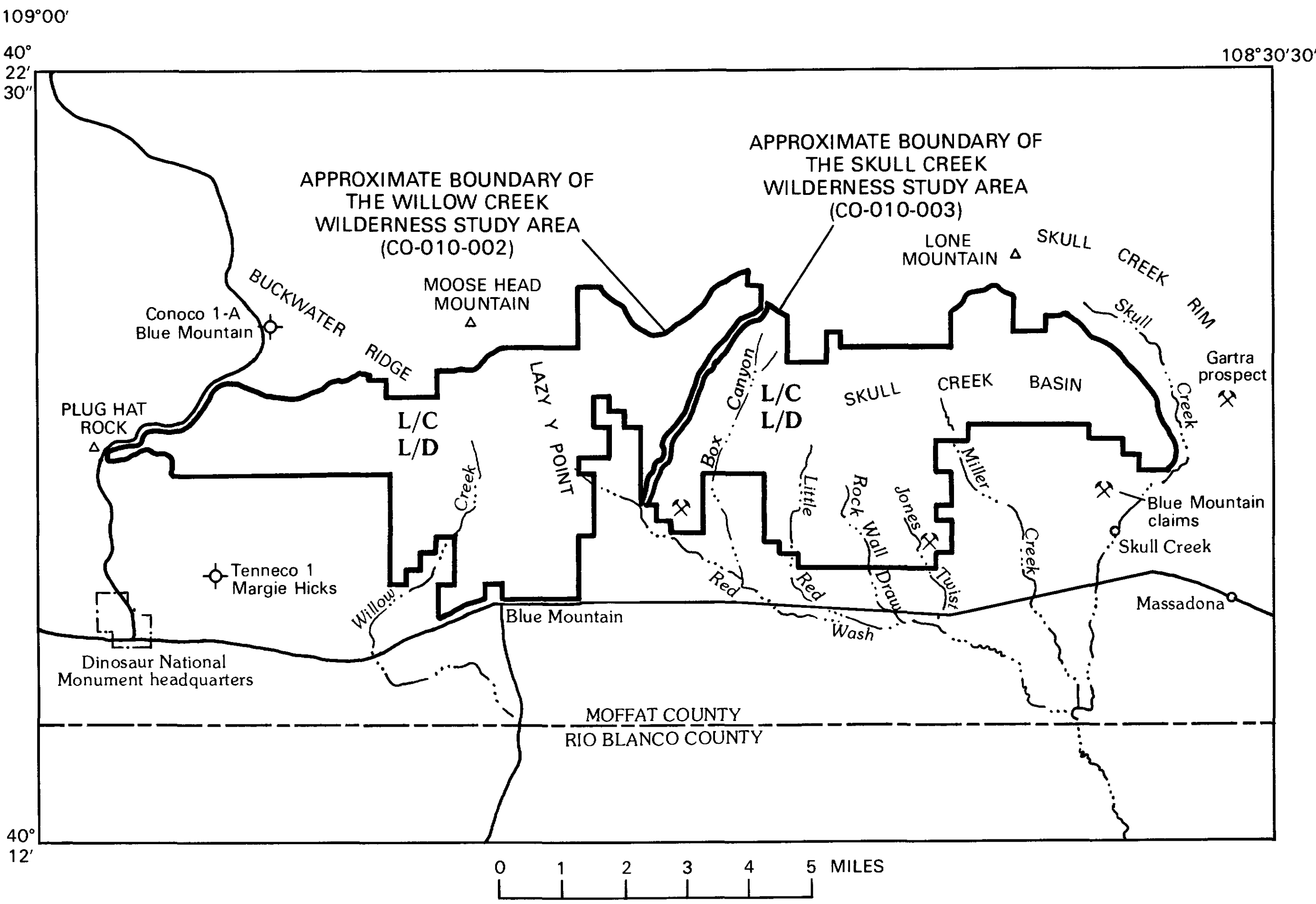
Mineral Resource Potential

The study areas have low mineral resource potential for undiscovered uranium, vanadium, and copper (fig. 2). The Gartra Member of the Chinle Formation and the Curtis Member of the Stump Formation were favorable locally for sandstone-type deposits of uranium, vanadium, and copper. These deposits were mined near the study areas in the past, and similar occurrences, although very small, are present in the study areas. None of the samples collected for the geochemical survey contain these elements or other elements associated with this type of deposit in anomalous concentrations. The organic-rich beds containing plant remains that served as a reductant for deposition at the known occurrences are very thin or absent in the study areas. Anomalous radioactivity that would be expected in the presence of this type of resource was not measured in the study areas.

The study areas have low mineral resource potential for all other metals. Anomalous amounts of several metals are present in altered parts of the Moenkopi Formation, which suggests that the formation was invaded by metal-bearing solutions. However, the mudstone lithologies of the Moenkopi are not a favorable host for mineralization. The low permeability of the mudstones greatly restricts the flow of fluids and limits sites for mineral deposition. Trace amounts of metals are also associated with altered rock in joints and faults, but the low level of concentrations found in the rock and the paucity of metals found in the stream sediments do not indicate the presence of a resource.

The study areas have low resource potential for undiscovered oil and gas. Oil and gas are produced to the south of the study areas in the Rangely oil field, primarily from the Weber Sandstone where oil and gas is trapped beneath the Rangely anticline. A similar structural setting is present in the study areas; however, the anticlines here have been eroded to a much deeper level. The Weber is exposed at the surface, and any oil and gas that may have been trapped there would have escaped. Several wells have been drilled in and around the study areas to test deeper plays, but none have been successful. The resource potential for oil and gas in subthrust traps along the Willow Creek fault beneath the study areas is low. The amount of closure beneath the subthrust is very restricted in extent, and the reservoir rock qualities are poor.

The study areas have low resource potential for undiscovered coal. Cretaceous rocks, which to the south contain rich coal beds, have been eroded from the study areas. Subsurface rocks are not likely to contain coal.



EXPLANATION

L/C Geologic terrane having low resource potential for all undiscovered metals, including uranium, vanadium, and copper, and oil and gas—Applies to both study areas

L/D Geologic terrane having low resource potential for all undiscovered coal—Applies to both study areas

Levels of certainty

C Available information gives a good indication of the level of mineral resource potential

D Available information clearly defines the level of mineral resource potential

Dry hole

Mine or prospect

Figure 2. Map showing mineral resource potential of the Willow Creek and Skull Creek Wilderness Study Areas, Moffat County, Colorado.

INTRODUCTION

This report presents the results of the assessment of the mineral resources of the Willow Creek (CO–010–002) and Skull Creek (CO–010–003) Wilderness Study Areas as requested by the BLM. This assessment, by the U.S. Bureau of Mines (USBM) and the U.S. Geological Survey (USGS) in 1988–89, was of 13,368 acres of the Willow Creek study area and 13,739 acres of the Skull Creek study area. Both study areas are included in this report because they are contiguous and they have similar geologic settings and mineral resources.

The study areas are in Moffat County in northwest Colorado adjacent to U.S. Highway 40 and just east of the Utah border (fig. 1). Rangely, Colo., is about 15 mi to the south of the study areas, and the small town of Dinosaur is 3 mi to the southwest. Dinosaur National Monument is about 10 mi to the north of the study areas. A part of the Park Service road that runs from the Dinosaur National Monument headquarters on U.S. Highway 40 to the monument defines the western boundary of the Willow Creek study area. The Bull Canyon Wilderness Study Area (Soulliere and others, 1987) lies west of and adjacent to the Park Service road just west of the Willow Creek study area. The Willow Creek and Skull Creek study areas consist of an irregularly shaped parcel of BLM land that extends 18 mi east to west and, at its widest, 5 mi north to south. The southern boundary of the study areas is largely a legal land net that divides private and state land from BLM land; U.S. Highway 40 defines part of the southern border. Access to the study area from the south is from U.S. Highway 40 or from any number of county and private roads that head north from the highway. The eastern and northern boundaries follow existing roads for the most part. The study areas are separated from one another by a 4-mi-long northeasterly trending jeep trail. This trail and several other trails north of the study areas are in poor condition. Many roads that lead to the southern part of the study areas cross private land, and some are behind locked gates.

The study areas are along the northern edge of the Colorado Plateau physiographic province where it abuts against the southeasternmost part of the Uinta Mountains of the middle Rocky Mountain province. The study areas lie in the foothills of the Uinta Mountains. Hogbacks, which formed along the south flank of east-west-trending anticlines, characterize the southern part of the study areas. North of the hogbacks the anticlines have been breached, thereby exposing older rock. The northern flanks of the anticlines consist of younger, gently dipping rock. The anticline within the Skull Creek study area is a dome with the Weber Sandstone (Middle Pennsylvanian to Lower Permian) exposed in the core. The erosional surface cut in the Weber supports a very old and mature piñon and juniper forest. The deep canyons that cut into the Weber and the colorful rim of redbeds that surrounds the dome provide spectacular scenery in and around the Skull Creek study area. The core of the Willow Creek study area is made up of canyonlands cut in the Glen Canyon Sandstone (Lower Jurassic). The Willow Creek study area includes a small part of the Skull Creek dome. Some of the prominent landmarks and topographic features in and near the study areas include: Plug Hat Rock, Moosehead Mountain, Lazy Y Point, Lone Mountain, Skull Creek Rim, Skull Creek Basin, Skull Creek, Miller Creek, Rock Wall Draw, Box Canyon, and Willow Creek (fig. 2). Terrain in this region rises in elevation from south to north. The elevation along U.S. Highway 40 at the southern edge of the study areas and at the base of the hogbacks is about 5,800 ft, and the elevation along the northern edge of the Willow Creek study area is about 8,000 ft. The cliffs and steep slopes that surround Skull Creek dome are as much as 600 ft high. All the creeks in the study areas are ephemeral and drain south into the White River near Rangely. Although there are no established trails in the study areas, most of the terrain can be traversed easily on foot. No part of the study areas is more than 3 mi from a road. Ranching is the major industry in and around the study areas. Land developers have divided much of the private land that adjoins the southern and eastern parts of the study areas into lots for building sites. Big game hunting is a popular attraction in the study areas.

Mining, prospecting, and oil and gas exploration activities have had very limited success in the study areas. Several exploratory oil wells have been drilled in and near the study areas, one as recently as the spring of 1988. The study areas are leased for oil and gas (fig. 3). The continued interest in oil and gas here is due to the similar geologic setting of the study areas to that of the oil field at Rangely and to a better understanding of the deep structures in the region that may contain oil and gas. Uranium and vanadium have been mined nearby, and coal is presently mined underground about 2 mi south of the study areas.

This report presents an evaluation of the mineral endowment (identified resources and mineral resource potential) of the study areas and is the product of several separate studies by the USBM and the USGS. Identified resources are classified according to the system of the U.S. Bureau of Mines and U.S. Geological Survey (1980), which is shown in the Appendix of this report. Identified resources are studied by the USBM. Mineral resource potential is the likelihood of occurrence of undiscovered metals and nonmetals, industrial rocks and minerals, and of undiscovered energy sources (coal, oil, gas, oil shale, and geothermal sources). It is classified according to the system of Goudarzi (1984), and is also shown in the Appendix. Undiscovered resources are studied by the USGS.

Investigations by the U.S. Bureau of Mines

BLM records and literature pertaining to the study areas were reviewed for information regarding geologic investigations, patented and unpatented claims, and federal mineral and oil and gas leases in and near the study areas. Two USBM geologists spent 10 days in June 1988 examining the study areas. Two chip samples and one grab sample were taken from a uranium mine outside the southern boundary of the Skull Creek study area; 21 stream-sediment samples, sieved to minus-80-mesh, were taken from the study areas in an attempt to identify extensions of previously known mineralization. The samples were analyzed by Chemex Labs, Inc., Sparks, Nev. All the samples were analyzed by fire assay with atomic absorption spectrophotometry for gold; by inductively coupled plasma-atomic emission spectroscopy for silver, arsenic, copper, lead, vanadium, and zinc; by atomic absorption spectrophotometry for selenium; and by neutron activation analysis for uranium.

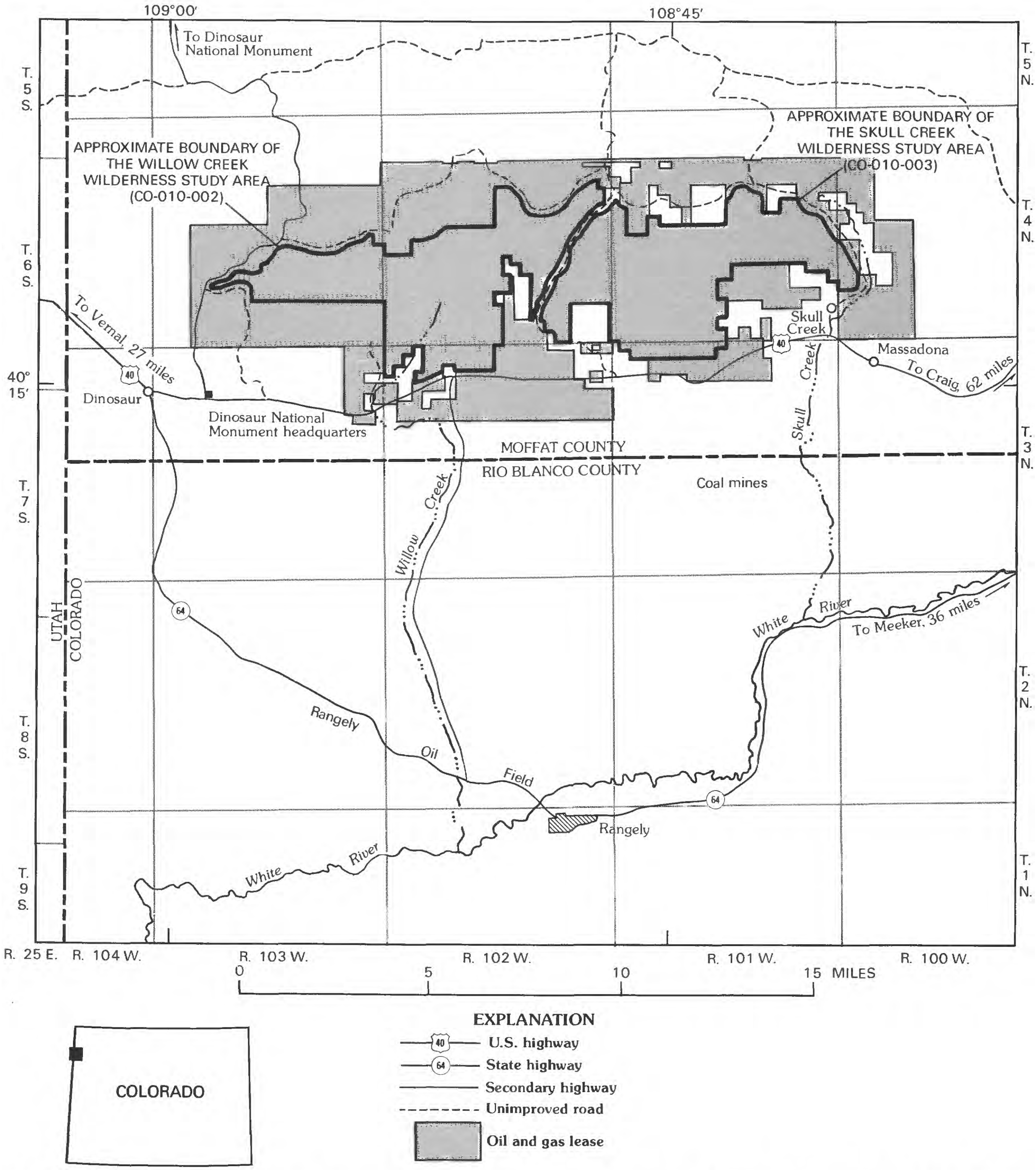


Figure 3. Map showing oil and gas leases in and near the Willow Creek and Skull Creek Wilderness Study Areas, Moffat County, Colorado.

Investigations by the U.S. Geological Survey

The assessment of the potential for undiscovered resources in the Willow Creek and Skull Creek Wilderness Study Areas is based largely on consideration of the geologic setting, results from geochemical sampling, geophysical data, and production history of similar rock formations in the region. Field work for these studies was done in the summer of 1988. Geophysical studies include aeromagnetic and gravity surveys. Some new gravity stations were established, and data obtained from them were used in this report. Eighty-two stream-sediment, 81 heavy-mineral-concentrate, and 10 rock samples were collected and analyzed for the geochemical survey. The analytical data and sample localities are shown in entirety in Folger and Bullock (1990). A geologic map (pl. 1) at a scale of 1:24,000 was prepared using parts of the Lazy Y Point, Skull Creek, Mellen Hill, and Rangely NE 7½-minute topographic quadrangles. The geology for the western part of the Willow Creek study area is taken from the Plug Hat Rock quadrangle by Rowley and Hansen (1979). Radiometric surveys using a hand-held scintillometer were conducted across several formations in the study areas. Mineral and energy resources of the study areas were discussed with BLM personnel in Meeker, Colo., and with Chevron Oil Company personnel in Rangely, Colo. The information used in establishing oil and gas potential is taken largely from Spencer (1983) and Powers (1986).

APPRAISAL OF IDENTIFIED RESOURCES

By Stanley L. Korzeb
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Mining and Mineral Exploration History

The study areas are near an established coal mining district, but they are not included in it or any other mining district. The Skull Creek study area and the region to the north have been prospected for uranium and base metals since the 1870's. In the early 1900's, uranium ore was recovered about 1 mi south of the Skull Creek study area. The deposit was mined from 1917 to 1920 for vanadium, and in the 1950's for uranium. During operations in 1953, this mine was known as the "Blue Mountain Group;" hereafter in this report, it will be called the Blue Mountain claims. Production from early operations at the mine is unknown, but during the uranium boom of the 1950's, it was estimated to be less than 1,000 short tons (Cadigan, 1972, p. 3–4; Isachsen, 1955, p. 124). A uranium prospect was excavated in the 1950's 1 mi east of the Skull Creek study area. Uranium-bearing clay was found around mineralized fossil logs in the Gartra Member of the Chinle Formation, and several sacks of this material were recovered and sold (Cadigan, 1972, p. 4).

At the time of this investigation, there were no mining claims on file with the BLM in or adjacent to the study areas.

The study areas are about 12 mi north of the Rangely oil field where oil is produced from the Weber Sandstone. Several holes have been drilled on the Skull Creek and Willow Creek anticlines in and near the study areas, but none was successful in locating oil or gas (Spencer, 1983, p. E7). The study areas are currently under lease for oil and gas (fig. 3).

Identified Resources

No mineral resources were identified in the study areas; however, traces of mineralization and areas of altered rock do occur. The mineralization was previously explored in prospect pits, and the large area of alteration was studied by Cadigan (1972).

Rock alteration related to possible hydrothermal activity was identified by Cadigan (1972) within the Moenkopi Formation (Lower and Middle? Triassic) along the southern boundary of the Skull Creek area and in the cliffs of Lazy Y Point, adjacent to the eastern boundary of the Willow Creek study area. Trace elements found by Cadigan (1972) in the altered parts of the Moenkopi in this region are greater in abundance than those found elsewhere in the Moenkopi in the Colorado Plateau. Twenty-one stream-sediment samples collected adjacent to known altered rocks were found to contain minor amounts of gold, silver, arsenic, copper, lead, selenium, uranium, vanadium, and zinc (Korzeb, 1989). These metals are probably derived from the altered parts of the Moenkopi, as metal values tend to increase toward outcrops of the altered rock.

Localized areas of rock alteration also occur along faults in the Glen Canyon Sandstone in the Red Wash area. This alteration was explored in several prospect pits. Samples from one of the pits located in sec. 35, T. 4 N., R. 102 W., contained 10 ppm silver, 10,000 ppm arsenic, 100 ppm copper, 300 ppm lead, and 500 ppm zinc. There was no indication on the surface that there may be an extension of this mineralization.

Uranium and vanadium were mined from the Curtis Member (Middle Jurassic) of the Stump Formation (Middle and Upper Jurassic) at the Blue Mountain claims located in sec. 35, T. 4 N., R. 101 W., 1 mi northwest of Skull Creek and just outside the study area (fig. 2). This mineralization was confined to a mudstone bed, about 1 ft thick, that contains abundant carbonized plant remains. Minerals identified from the mine are carnotite, malachite, and minor azurite; several unidentified secondary copper-vanadium and copper-selenium minerals are also present. Two chip samples from the bed of carbonized plant remains contained 172–2,300 ppm uranium, 232–5,010 ppm vanadium, 1,060–1,825 ppm copper, 6 ppm selenium, and 335–645 ppm arsenic (Korzeb, 1989). The Stump Formation extends along the southern boundary of the Skull Creek study area and in the cliffs in the western half of the Willow Creek study area. Mineralization similar to that at the Blue Mountain claims has not been found in the study areas, although several small prospect pits that have been excavated at the base of the Curtis show minor amounts of secondary copper carbonate minerals (azurite and malachite). No anomalous radioactivity was measured in these pits. These pits were probably excavated during the uranium boom of the 1950's.

Uranium-bearing clay and mineralized fossil logs were recovered from a prospect pit in the Gartra Member of the Chinle Formation (Upper Triassic) located 1 mi east of the Skull Creek study area in sec. 20, T. 4 N., R. 100 W. (Cadigan, 1972, p. 4). Petrified wood with anomalous radiation as much as 400 cps (counts per second) above a background count of 25 cps is widely scattered throughout the Chinle Formation, but no resources of uranium were identified in the formation in or near the study areas.

Conglomerate from the Buckhorn Conglomerate Member of the Cedar Mountain Formation (Lower Cretaceous) was quarried within a half mile and adjacent to the southwest boundary of the Willow Creek study area near U.S. Highway 40. The conglomerate was probably used for the reconstruction of U.S. Highway 40, and there is no local market for this material. Sand and gravel in the study areas have no unique or special properties and are not considered a resource. There are voluminous amounts of sand and gravel in the terrace gravels in the flats just south of the study areas. These gravels have been quarried in the past and will probably serve the needs of the region in the future.

ASSESSMENT OF POTENTIAL FOR UNDISCOVERED RESOURCES

By R.E. Van Loenen, H.W. Folger, D.M. Kulik, and W. Anthony Bryant U.S. Geological Survey

Geology

Geologic History

The geologic history of the rocks exposed in the Willow Creek and Skull Creek Wilderness Study Areas began during Middle Pennsylvanian to Early Permian time when the Weber Sandstone was deposited. The Weber is chiefly shallow-marine, intertidal, and eolian sandstone that was deposited in a trough in the ancestral Rocky Mountains. The Front Range and Uncompahgre uplifts of the ancestral Rockies provided sediment to this region during late Paleozoic and part of Mesozoic time. This episode was marked by repeated advances and retreats of seaways accompanied by subaerial erosion and deposition. Thick deposits of the Lower Permian Park City Formation to the west of the study areas accumulated in marine and shelf environments, whereas deposits of the Park City in the study area accumulated in very shallow marine and perhaps fluvial environments. Only the upper part of the Park City is present in this region (Rowley and Hansen, 1979). Lower and Middle(?) Triassic rocks of the Moenkopi Formation are redbeds that represent material deposited on fluvial flood plains under arid conditions and in shallow marine seas. The basal conglomerate of the Upper Triassic Chinle Formation represents material deposited on the eroded surface of the Moenkopi. This coarse material was deposited by high-energy streams and was later covered by the main body of the Chinle, a clastic redbed sequence of silt and sand deposited on fluvial flood plains. Eolian conditions returned to the region during the Early Jurassic as dune sands of the Glen Canyon Sandstone covered the redbeds of the Chinle. During the Middle Jurassic, mud and silt of the Carmel Formation were deposited in shallow-marine conditions over much of the region including about half of the study areas. Dune sands of the Middle Jurassic Entrada Sandstone covered the region before the sea again advanced and deposited the sands of the Curtis Member of the Stump Formation. Deep-water-marine conditions that existed during the Late Jurassic are represented by the Redwater Member of the Stump Formation. The sea again retreated, which exposed a land surface that was covered with continental deposits of the Upper Jurassic Morrison Formation. The Morrison includes fluvial, eolian, and possible lacustrine deposits. Following the Jurassic deposition and periods of erosion, the Cedar Mountain Formation and the overlying Dakota Sandstone represent the first deposits of sediments marginal to the Western Interior Cretaceous seaway. These are largely fluvial deposits that were later covered by thick marine deposits of the Upper Cretaceous Mancos Shale. The Mancos Shale represents the youngest bedrock unit in the study areas. Younger Cretaceous and early Tertiary deposition occurred, but these deposits were eroded from the study areas. Tectonic deformation that began near the end of Cretaceous time is largely responsible for the present geologic setting of the study areas. The large Uinta anticline (of which the study areas are a part) is a product of this period of tectonic deformation, which is known as the Laramide orogeny. Since early Tertiary time, the study areas have remained above sea level and exposed to erosion.

Subsurface Rocks

Most of the rock formations present in the subsurface of the study areas are exposed 5–10 mi to the north (Hansen and Carrara, 1980). These rocks include 2,000 ft of Paleozoic rock that rests on more than 20,000 ft of quartzitic sandstone of the Uinta Mountain Group (Middle Proterozoic). The Paleozoic section consists of 225–280 ft of coarse- to medium-grained sandstone of the Lodore Formation (Upper Cambrian); 600–650 ft of Madison Limestone (Lower Mississippian); 240–300 ft of Doughnut Shale and sandstone, limestone, and shale of the Humbug Formation (Upper Mississippian); 325 ft of Round Valley Limestone (Lower Pennsylvanian); and 1,000 ft of limestone, shale, and sandstone of the Morgan Formation (Middle Pennsylvanian) (Hansen and Carrara, 1980). Powers (1986) reported that the subsurface Paleozoic section of the Willow Creek anticline consists of the Upper Cambrian Ladore Formation; Devonian Chafee Formation; Lower Mississippian Madison Limestone; Pennsylvanian Molas Shale, Belden Shale, and Morgan Formations; Pennsylvanian and Permian Weber Sandstone; and Permian Park City Formation.

Description of Map Units

The following section is a discussion of lithology, ages, and distribution of map units in ascending order as they are shown on plate 1. The lowermost (oldest) rock unit exposed in the study areas is the Middle and Upper Pennsylvanian and Lower Permian Weber Sandstone (PPw). The lower part of the Weber, which is not exposed, commonly contains limestone beds (Hansen, 1965). The exposed part of the Weber consists mainly of light-gray, massive, thick-bedded, fine-grained sandstone. This lithology is consistent through the exposed section except near the top where the sandstone is a pale yellowish brown and slightly calcareous. Large-scale crossbedding and ripple marks are common. The Weber is exposed at the center of the Skull Creek dome. The Weber has been unearthed to only shallow depths, except where several canyons locally expose 500–600 ft of this sandstone. The Weber is 1,000 ft thick 10 mi north of the study areas (Hansen and Carrara, 1980). The Weber Sandstone is the principal reservoir rock in the Rangely oil field, which is located about 10 mi south of the study areas. The Rangely field is Colorado's largest oil field.

The Lower Permian Park City Formation (Ppc) unconformably overlies the Weber Sandstone and consists mainly of a sequence of alternating slope-forming, pale-orange and pale-olive mudstone and harder, ledge-forming yellowish-brown siltstone. Minor amounts of fine-grained lenticular sandstone occur, and all lithologies are calcareous. Strata of this unit that are exposed in the study areas are probably equivalent to the Franson Member, which is the uppermost member of the Park City Formation (Hansen and Rowley, 1980). The Park City is poorly exposed around the Skull Creek dome. Its lower contact with the Weber is marked locally by a 2-ft-thick conglomerate that contains coarse quartz pebbles and angular rock fragments as much as ½ in. across. The thickness of the formation is estimated at 125 ft. Phosphate is being mined from the Park City Formation west of the study areas in eastern Utah, but similar rock is not present here.

The Park City is overlain conformably by the Lower and Middle(?) Triassic Moenkopi Formation (₸m), which is predominately moderate reddish-brown, yellowish-gray, and pale-olive micaceous siltstone with minor amounts of mudstone and very fine grained sandstone. Gypsum is common. The Moenkopi is typically a redbed sequence over much of the Colorado Plateau. However, in the study areas many of the redbeds were apparently subjected to reducing conditions that converted ferrous iron in the rock to ferric iron. Minerals that bear ferric iron impart the green color to the rock. The Moenkopi is well exposed in the cliffs around Skull Creek dome. The contact of the Moenkopi with the underlying Park City, although covered in most places, was mapped below the lowermost reddish-brown siltstone of the Moenkopi. There is a subtle color change from the orangish Park City to the Moenkopi redbeds. The thickness of the Moenkopi Formation ranges from 450 to 600 ft.

The Moenkopi is unconformably overlain by the Upper Triassic Chinle Formation (₸c). The Chinle contains a basal conglomerate known as the Gartra Member. The Gartra is a ledge-forming light-gray coarse-grained conglomeratic sandstone that ranges from 10 to 30 ft thick. It contains heavy-mineral streaks, angular clasts as large as 1 ft, and local petrified wood, and is usually crossbedded. It forms a conspicuous brush-covered bench in the relatively soft red cliffs around the Skull Creek dome. The main body of the Chinle is a slope-forming, moderate-red to moderate-pink siltstone with interbedded very fine grained sandstones of similar color. The Chinle is coextensive with the Moenkopi in the cliffs of Skull Creek dome and ranges from 240 to 280 ft thick. The basal conglomerate of the Chinle is uranium-bearing in many parts of the Colorado Plateau.

The Lower Jurassic Glen Canyon Sandstone (Jg) unconformably overlies the Chinle Formation. It is a massive, thick-bedded, well-sorted, light-gray to grayish-pink, medium- to fine-grained sandstone. The rock is relatively resistant and weathers to rounded buttes. It exhibits medium to very large scale sand-dune crossbedding. The Glen Canyon is exposed extensively along the Willow Creek anticline and around the Skull Creek dome. It ranges from 560 to 760 ft in thickness. Its contact with the underlying Chinle is clearly marked by the color change of the red silt of the Chinle to the light-gray sandstone of the Glen Canyon. The Glen Canyon Sandstone, which in part correlates with the Navajo Sandstone (Lower Jurassic), was thought to be partly Triassic in age. Recent studies by Peterson and Pipiringos (1979) on the basis of palynomorphs and by Padian (1989) on the basis of vertebrate fossils have demonstrated that it is entirely of Early Jurassic age. The Glen Canyon is not known to host mineral deposits.

The Middle Jurassic Carmel Formation (Jca) unconformably overlies the Glen Canyon Sandstone. It is a sequence of slope-forming reddish-brown fine-grained sandstone, siltstone, and mudstone. Rowley and Hansen (1979) reported minor amounts of gypsum and shale. The redbeds of the Carmel display a striking contrast to the light-gray eolian sandstones that lie above and below. The Carmel is well exposed at Plug Hat Rock and on both flanks of the Willow Creek anticline. The Carmel contact with the underlying Glen Canyon is mapped at the color break; however, an unconformity occurs about 10 ft below this break in lithologies similar to the Glen Canyon Sandstone (Pipiringos and O'Sullivan, 1975). The unconformity is marked by a very thin (less than 1 in.) layer of chert pebbles. The Carmel thins from the west to the east. It is 60 ft thick in the western area, thins to zero about 1 mi west of Skull Creek, and is absent eastward from the section. From Red Wash to just west of Skull Creek the Carmel is clearly distinguishable but too thin to show as a map unit. No mineral deposits are known to occur in the Carmel.

The Middle Jurassic Entrada Sandstone (Je) conformably overlies the Carmel; in the absence of the Carmel it unconformably overlies the Glen Canyon. It is a relatively resistant light-gray, fine- to medium-grained, thick-bedded, massive sandstone. It is similar to the Glen Canyon in color, weathering habits, and presence of eolian crossbedding. It contains glauconite in its upper part (Rowley and Hansen, 1979). The Entrada is exposed along both flanks of the Willow Creek anticline and along the southern flank of the Skull Creek dome. Where the Carmel is absent, the Glen Canyon–Entrada contact is inferred and mapped along a topographic low that exists between the two similar sandstones. The Entrada ranges from 90 to 150 ft in thickness. No known resources occur in the Entrada.

The Middle and Upper Jurassic Stump Formation unconformably overlies the Entrada. The Stump is divided into the Curtis Member (Jsc) and the overlying Redwater Member (Jsr). The Middle Jurassic Curtis Member is a light-gray to greenish-gray, fine- to coarse-grained, thin- to medium-crossbedded sandstone. It is a very resistant ledge-forming rock that largely preserves the softer underlying Entrada. It is well exposed and forms flatirons along the southern limb of the anticlines. Glauconite and fossils are common. Trash beds of petrified wood and other plant debris are common at the base of the Curtis. These trash beds may be several feet thick and are locally mineralized. The thickness of the Curtis varies widely from 0 to 30 ft. The Upper Jurassic Redwater Member consists of light-gray and pale-olive glauconitic shale interlayered with siltstone, sandy limestone, coquina, and thin sandstone. The rock unit overall weathers with a greenish cast. Fossils include brachiopods, pelecypods, cephalopods (belemnites are very common), and ammonites. The Curtis-Redwater contact is distinct and occurs between the hard light-gray beds of the Curtis and soft green beds of the Redwater. The Redwater ranges from 85 to 120 ft thick and is usually well exposed at the base of the Curtis flatirons. Mineral resources are not known in the Redwater Member.

The Upper Jurassic Morrison Formation (Jm) unconformably overlies the Stump Formation. The Morrison is a thick sequence of slope-forming variegated pale-olive, dark-red, and reddish-brown siltstone, claystone, and shale with interbedded light-gray to olive-gray, fine- to medium-grained sandstone, conglomeratic sandstone, minor glauconitic sandstone, and argillaceous and nodular limestone. The lowermost fine- to medium-grained sandstone is strongly crossbedded, and just north of Blue Mountain it appears to be of eolian origin. A conglomeratic sandstone that is nearly 30 ft thick occurs near the middle of the Morrison Formation. In several locations in the map area this sandstone contains fragments of dinosaur bones and some teeth. Fossil bones were found weathered out and scattered on dip slopes and were seen in situ in the bedrock of stream beds. Bones may have been removed from workings in an outcrop in Jones Twist just outside the study areas. The Redwater-Morrison contact is at the base of the crossbedded sandstone in the Morrison. There are excellent exposures of the Morrison along the southern flank of the anticline where the formation dips steeply. In contrast, the area between Plug Hat Rock and Moosehead Mountain is entirely landslide deposits that have developed on the Morrison. The Morrison contains bentonitic clays that swell when wet and contribute to slope failure. Large blocks of the overlying Cedar Mountain Formation have been rafted downslope on the Morrison. The Morrison ranges from 560 to 650 ft thick. The Morrison Formation contains important uranium deposits throughout the Colorado Plateau in Colorado, Utah, and New Mexico.

The Lower Cretaceous Cedar Mountain Formation (Kcm) unconformably overlies the Morrison. The lower part (Buckhorn Conglomerate Member) is a ledge-forming thick-bedded medium-gray to light-gray conglomerate and fine- to coarse-grained sandstone; the conglomerate is characterized by black chert pebbles. This resistant rock forms one of the topographic highs along the hogback westward from near Rock Wall Draw. To the east of Rock Wall Draw, the conglomerate is missing from the section. The upper part of the formation consists of slope-forming, pale-olive and purple shales and mudstones with interbedded, thin, fine-grained sandstone and resistant light-brownish-gray limestone with red jasper near the base. The contact with the Morrison is placed below the chert-pebble conglomerate or the red-jasper limestone. The formation thins from about 200 ft at the western part of the map area to about 110 ft near Massadona, Colo. Limestone near Martin Gap and conglomerate in the valley of Willow Creek have been quarried from the Cedar Mountain Formation for use as road metal.

The Lower Cretaceous Dakota Sandstone (Kd) unconformably overlies the Cedar Mountain Formation. The Dakota is a resistant, yellowish-brown to light-gray, medium- to thick-bedded, medium- to coarse-grained sandstone with interbedded conglomerate and minor thin shale. The Dakota weathers rusty and forms a hogback along much of the southern limb of the anticlines. Its contact with the Cedar Mountain is at the base of the rusty sandstone of the Dakota that overlies the soft limestone at the top of the Cedar Mountain. The Dakota ranges from 40 ft thick on Buckwater Ridge (Rowley and Hansen, 1979) to about 100 ft thick near Massadona, Colo.

The Upper Cretaceous Mancos Shale conformably overlies the Dakota Sandstone. The Mancos consists of, from oldest to youngest, the Mowry Member (Kmm), the Frontier Sandstone Member (Kmf), and the main body of the Mancos Shale (Km). The Mowry is a blue-gray to pale-blue fissile shale; locally it contains gypsum. It contains fish bones, fish scales, and some ammonites (Rowley and Hansen, 1979). Recent studies of ammonites from the Mowry Shale in Montana and Wyoming has revised the age of the Mowry (previously considered late Albian, Early Cretaceous) to early Cenomanian, Late Cretaceous (Cobban and Kennedy, 1989). The Mowry is a relatively hard siliceous shale that weathers to chips. In several places along the hogback where it is well exposed it has been quarried for use as road metal. The Mowry ranges from 50 ft thick on Buckwater Ridge to about 90 ft thick near Skull Creek. The lower part of the Frontier is brown and pale-blue fissile shale and siltstone. The upper part of the Frontier Sandstone Member is resistant light-olive-gray, fine-grained calcareous and fossiliferous sandstone. The Frontier is well exposed in the study areas, and it forms the first hogback seen from U.S. Highway 40, along the southern limb of the Willow Creek and Skull Creek anticlines. The Frontier ranges from 180 to 260 ft in thickness. The main body of the Mancos Shale consists of 5,300 ft of soft brownish-gray marine shale with minor interbedded siltstone and very fine grained sandstone (Cullins, 1969). The main body of the Mancos Shale is poorly exposed in the map area at the base of the hogback formed by the Frontier Sandstone Member and in the flats to the south. The first oil discovered in the Rangely field was produced from fractures in the Mancos Shale.

Quaternary Deposits

Eolian deposits (Qd) in the western part of the Willow Creek study area (Rowley and Hansen, 1979) are well-sorted, fine-grained dune sand derived from the underlying Glen Canyon Sandstone. The dunes are partially stabilized by sparse vegetation.

Terrace gravels (Qt) are unconsolidated, poorly sorted sand, gravel, pebbles, and cobbles of mainly quartzite. These deposits rest on Mancos Shale along the southern part of the map area. Terrace gravels were quarried near the Rock Wall Draw water gap for use as road metal.

Landslide deposits (Qls) are poorly sorted debris from the unstable Morrison Formation and overlying rock that has slid on the slopes of Buckwater Ridge and Moosehead Mountain and in areas along the hogback near Blue Mountain. Some blocks of the Cedar Mountain Formation that slid on the Morrison on the slopes of Moosehead Mountain exceed ½ mi in length.

Alluvium and colluvium (Qac) include unconsolidated clay, sand, gravel, and rock fragments that accumulated in and along present stream channels and as slope-wash deposits at the bases of slopes and cliffs around Skull Creek dome. Older alluvial deposits of mainly red clay, silt, and sand occur in and adjacent to the present stream channels. These older deposits are as much as 80 ft thick and are dissected by the present drainage system.

Structure

The major structural feature in the map area (pl. 1) is an asymmetrical, east-trending anticline that crosses both study areas. This anticline extends for more than 30 mi from just west of the Utah-Colorado border to east of Massadona, Colo. (Rowley and others, 1985). The trace of its axis is sinuous. The asymmetrical geometry of the anticline approaches that of a monocline. The northern limb of the anticline dips very gently north at 2–5°, whereas the southern limb dips more steeply south at 25–50°. The western part of this structure is called the

Willow Creek anticline, and the eastern part is called the Skull Creek anticline. Although the axes of these two parts are continuous, Ritzma (1957) considered the Willow Creek anticline to be distinct from the Skull Creek anticline. The surface expression of the Skull Creek anticline forms an ellipsoidal dome with several reentrants around its border; this structure is herein referred to as the Skull Creek dome. The dome is about 5 × 10 mi in size. The Weber Sandstone is exposed at the core, and younger rock is exposed in the surrounding rim. A pronounced system of northeast-trending joints has developed in the Weber and Glen Canyon Sandstones. Most of the drainage, which is from north to south, does not follow the joints or faults but cuts the fractures at acute angles.

The western part of the Skull Creek dome is broken by several northeast-trending faults, which converge to the southwest near the Red Wash reentrant. There, strata in the hogbacks of the south rim show displacement down to the east. One of these faults clearly dissects the north rim of the dome and others may do so also, as there are several springs that discharge along the base of the rim. These faults probably merge as one to the south. If the trend is maintained to the southwest, these faults could link up with a fault shown by Cullins (1969) near Blue Mountain. No evidence was found on the ground that indicates a fault southwest of Red Wash. However, the trace of this inferred fault would be in Mancos Shale, which is a soft, homogeneous, and poorly exposed rock that has overall poor qualities for displaying structures. Rock alteration has occurred along the faults where they pass through the hogbacks near Red Wash. Cadigan (1972) noted alteration and mineralization along joints in Rock Wall Draw.

The reentrant in the rim at Miller and Skull Creeks is a conspicuous structural feature that may be related to stress developed by a thrust fault. Cullins (1969) showed an east-trending thrust fault just south of the Willow Creek study area and nearly parallel to U.S. Highway 40. This fault was encountered at 8,000 ft in a drill hole about 1 mi northeast of Dinosaur National Monument headquarters (Rowley and Hansen, 1979). In this hole the thrust fault, which is known as the Willow Creek fault (Berg, 1962), has placed Precambrian rock over Paleozoic rock.

The Willow Creek and the Skull Creek anticlines are probably caused by the Willow Creek thrust fault. Asymmetrical folds or monoclines are common in the eastern Uinta Mountains (Rowley and Hansen, 1979) and are considered to be formed by movement along thrust faults as older rocks were displaced over younger rock.

Geochemistry

In 1988, a reconnaissance geochemical survey was conducted in the Skull Creek and Willow Creek Wilderness Study Areas to aid in the evaluation of the mineral resource potential. Eighty-two stream-sediment, 81 heavy-mineral-concentrate, and 10 rock samples were collected in the study areas. The stream-sediment samples were collected from first-, second-, and third-order active and intermittent stream beds. Many of the stream beds were dry when the samples were collected. Stream-sediment samples were selected as the primary sample medium for the study because they represent composites of the rocks and soils eroded from within the drainage basins. Heavy-mineral-concentrate samples were collected and analyzed because they may contain minerals that result from ore-forming processes and that are more easily detected when concentrated. Rock samples were collected from mines and prospects to determine the type of mineralization and the suites of elements associated with the mineralization. The analytical data and sample locality maps are in Folger and Bullock (1990).

Methods

The stream-sediment samples were sieved to minus-80-mesh, pulverized, and analyzed by semiquantitative six-step emission spectrography for 35 elements (Grimes and Marranzino, 1968); by inductively coupled plasma-atomic emission (ICP) methods for arsenic, bismuth, cadmium, antimony, and zinc (Crock and others, 1987); and by delayed neutron counting (DNAA) for uranium and thorium (McKown and Millard, 1987). Heavy-mineral-concentrate samples were prepared by removing the low-density minerals (such as quartz, feldspars, clays, mica, and organic matter) by panning, which concentrates the resistate and ore-forming minerals that may be present. The samples were then sieved to minus-35-mesh and passed through a heavy liquid (bromoform, specific gravity of 2.85) to remove any remaining quartz and feldspar. The concentrate was then separated into three fractions based on magnetic properties: (1) magnetite, the strongly magnetic fraction; (2) ferromagnesian silicates and other iron oxides, an intermediate fraction; and (3) accessory minerals such as zircon, apatite, and sphene as well as many ore-related minerals, the nonmagnetic fraction. The mineralogy of the nonmagnetic fraction was determined, and the fraction was then analyzed by semiquantitative six-step emission spectrography for 37 elements. The rock samples were analyzed by emission spectrography for 35 elements; by the ICP method for arsenic, bismuth, cadmium, antimony, and zinc; and by DNAA for uranium and thorium.

The elements that were found and their concentrations were further characterized by factor analysis, which is a statistical method that allows related elements to be grouped according to their occurrence. Specific lithologies or types of ore deposits may be defined by a distinct suite of elements which factor analysis helps to characterize. The technical aspects of this statistical method are more fully described in Davis (1986).

Results

The analytical results from the stream-sediment samples revealed no anomalous concentrations of elements within the study areas. However, the interpretation of factor analysis provided some geologically significant information. The factor scores were plotted on a geologic base map to determine how the factors correlated with specific lithologies and geologic features.

The first factor defines the association of Zn-Ni-U-V-Cu-Fe-Th. High factor scores for this factor correlate well with the Moenkopi and Chinle Formations, which we interpret as a reflection of the geochemical signatures of these rock units. The elements of this factor are similar to those identified in an earlier study of alteration and enrichment of the Moenkopi Formation by Cadigan (1972). The metal association of this factor is similar to the metal suites that are typical of Colorado Plateau sandstone-hosted uranium deposits (Rose and others, 1979).

The second factor defines the association of Ba and Sr. Barium and strontium, the elements with high factor scores, are most commonly associated with sulfate minerals such as barite ($BaSO_4$) and celestite ($SrSO_4$). These minerals were identified in concentrate samples by X-ray diffraction and laser spectrography. Sulfate minerals, especially gypsum, are common in the Moenkopi and Carmel Formations.

The third factor defines the association of Cr-Ga-Ti-B-Cu-Fe. This assemblage of elements is found in common minerals such as chromite, ilmenite, magnetite, tourmaline, and pyrite. The concentration of these elements in stream sediments reflects common placer accumulations of heavy minerals in high-gradient streams.

The fourth factor defines the association of Ca-Mg-Ti-Fe-U-Y. These elements are commonly associated with rock-forming silicate minerals such as pyroxenes, amphiboles, zircon, and garnet. The elevated scores are coextensive with the Weber and Glen Canyon Sandstones and may reflect the accessory-mineral content of the sandstones.

The statistical examination and the element distribution plots for the heavy-mineral-concentrate samples revealed few significant metal anomalies. Minerals identified in the concentrates by use of a microscope or X-ray diffraction include zircon, barite, celestite, anatase, rutile, apatite, amphibole, tourmaline, and pyrite. The isolated samples with high contents of tin and lead may represent contamination from a nearby highway or from people (in particular, hunters) in the area. Metallic lead was observed in one concentrate sample that was collected downstream from the Blue Mountain claims. The boron anomalies in two samples result from the presence of tourmaline. Four concentrates contain elevated amounts of Mo, Ag, Cu, and Ni, and these samples probably reflect localized enrichment in the Moenkopi or Chinle Formations.

Mineralized-rock samples that were collected from two localities in the Curtis Member of the Stump Formation contain the following elements: (1) the Blue Mountain claims (fig. 2) contain 5 ppm Ag, 1,000 ppm As, >20,000 ppm Cu, 1,030 ppm U, >10,000 ppm V, and 300 ppm Zn; and (2) the Jones Twist prospect (fig. 2) contains 50 ppm Ag, 2,000 ppm As, 100 ppm Co, 2,000 ppm Cu, 2,000 ppm Mo, 20,000 ppm Pb, 400 ppm U, and 700 ppm Zn. A sample of silicified fossil wood from a prospect in the Gartra Member of the Chinle Formation (fig. 2) contains 3 ppm Ag, 200 ppm B, 3,000 ppm Cr, 70 ppm Sn, and 5,000 ppm Th. Two samples collected from prospect pits dug in altered rock along faults in the Glen Canyon Sandstone contain (1) 200 ppm As, and (2) 10 ppm Ag, 10,000 ppm As, 100 ppm Cu, 300 ppm Pb, and 500 ppm Zn. These prospects are located in the Red Wash area where faults cut the hogbacks (fig. 2).

The results of the analyses of the stream-sediment and heavy-mineral-concentrate samples reflect the dominant sandstone lithologies and their accessory minerals as well as the slight alteration and enrichment of certain elements in the Moenkopi and Chinle Formations. Rock samples collected from the Blue Mountain claims and the prospect in the Gartra Member exhibit a metal suite that is typical of the Colorado Plateau sandstone-hosted uranium deposits. The high arsenic content and the alteration of the Red Wash samples suggest that the mineralization along the faults may be of hydrothermal origin.

Geophysics

Gravity and magnetic studies were undertaken as part of the mineral resource evaluation of the Willow Creek and Skull Creek Wilderness Study Areas. These studies provide information on the subsurface distribution of rock masses and the structural framework. The gravity and magnetic data are of a reconnaissance nature and are adequate only to define regional features. Magnetic data are from U.S. Department of Energy (1982). Flight lines were flown east-west at 2–5-mi intervals and 400 ft above the ground surface. Parts of two flight lines and one north-south tie line cross the study areas. Residual total intensity aeromagnetic data are shown in figure 4 with a contour interval of 20 nT (nanoteslas). The gravity data were obtained in and near the study areas in 1984, 1987, and 1988, and were supplemented by data maintained in the files of the Defense Mapping Agency of the Department of Defense. The stations measured specifically for this study were established using a Worden gravimeter W–177. The data were tied to the International Gravity Standardization Net 1971 (U.S. Defense Mapping Agency, Aerospace Center, 1974) at base station ACIC 4019–1 at Rangely, Colo., and ACIC 0557–0 at Vernal, Utah. Station elevations were obtained from benchmarks, spot elevations, and estimates from topographic maps at 1:24,000 scale and are accurate to ±20–40 ft. The error in the Bouguer anomaly is less than 2.5 mGal (milligals) for errors in elevation control. Bouguer anomaly values were computed using the 1967 gravity formula (International Association of Geodesy, 1967) and a reduction density of 2.67 g/cm (grams per centimeter). Mathematical formulas are given in Cordell and others (1982). Terrain corrections were made by computer for a distance of 167 km (kilometers) from each station using the method of Plouff (1977). The data are shown in figure 5 as a complete Bouguer gravity anomaly map with a contour interval of 5 mGal.

Aeromagnetics

Magnetic anomalies usually reflect differences in basement lithology or differences in depth to basement rocks. Magnetic anomalies that are clearly of a size and magnitude to be associated with basement sources are associated with surface structural elements in the study areas. This suggests that the surface structures are controlled by underlying basement structures. The region of northwestern Colorado, northeastern Utah, and southwestern Wyoming is characterized by a series of alternating high and low magnetic anomalies that trend generally east-west and arise from contrasts within the basement rocks. The aeromagnetic map (fig. 4) shows a central high anomaly (anomaly 2) that is flanked by low anomalies to the north (anomaly 1) and south (anomalies 4 and 5). The study areas lie on the east-northeast-trending gradient between anomaly 2 and anomaly 1. The gradient extends at least 30 mi to the east-northeast beyond the area shown in figure 4 and may mark the location of one of the bounding faults of the Proterozoic Uinta aulacogen where there is a change in depth to basement rocks and, possibly, a change in basement lithology as well. Rocks of the relatively nonmagnetic sedimentary Uinta Mountain Group are thin south of the gradient where about 2,000 ft of those rocks were penetrated in the Tenneco Gas and Oil Co. 1 Margie Hicks well in the C S½ NW¼SW¼ sec. 3, T. 3 N., R. 103 W. (fig. 2) (Powers, 1986). A similar thickness was penetrated in the Conoco 1–A Blue Mountain Unit well in the NW¼NW¼SW¼ sec. 14, T. 4 N., R. 103 W. (fig. 2) (BLM, written commun., 1988). North of anomaly 1 (fig. 4) the Uinta Mountain Group rocks thicken to as much as 25,000 ft (Stone, 1986) and nonmagnetic Paleozoic rocks are exposed. A magnetic high (anomaly 2, fig. 4) occurs between the study areas and the Rangely anticline where crystalline basement rocks have been uplifted by the thrust fault beneath the Rangely oil field and where Uinta Mountain Group rocks are thin or absent (Stone, 1986). The uplift of crystalline basement rocks in an extension of the Douglas Creek arch (Johnson and Finn, 1986) is suggested by the gravity data as discussed later. This uplift probably contributed to the high magnetic values of anomaly 2 as well as caused the high values at anomaly 3 (fig. 4). Low magnetic anomalies 4 and 5 in the southwest and southeast corners, respectively, of figure 4 are caused by the greater depth to basement of rocks east and west of the crest of the Douglas Creek arch and by the presence of nonmagnetic Tertiary rocks in the Uinta basin to the west and the Piceance Creek basin to the east.

Gravity

The major feature of the gravity map (fig. 5) is a broad high (anomaly A) that appears to have a composite source. The gradient that marks its southwest boundary lies along the thrust fault that underlies the Rangely area (Stone, 1986), and which brings Precambrian crystalline basement rocks near the surface. Anomaly A culminates in an east-northeast-trending lobe that coincides with the partially buried Willow Creek fault block which underlies the study areas. The Willow Creek fault brings high-density Paleozoic rocks to the surface in the Willow Creek–Skull Creek anticline. The fault also carries crystalline rocks, which have been penetrated in the Conoco (Blue Mountain) well described previously. The northern boundary of anomaly A (fig. 5) generally coincides with the Wolf Creek fault and the major magnetic gradient discussed previously. The magnetic gradient, which probably reflects the different thicknesses of Uinta Mountain Group rocks along a bounding fault of the Uinta aulacogen, is much more impressive than the gravity gradient. This suggests that the Uinta Mountain Group rocks are similar in density to the crystalline rocks of the basement. A high-gravity ridge extends south of anomaly A to the Douglas Creek arch, which was identified by Johnson and Finn (1986). The gravity gradient to the southeast of anomaly A marks the boundary between the Douglas Creek arch and the Piceance Creek basin and extends along that boundary

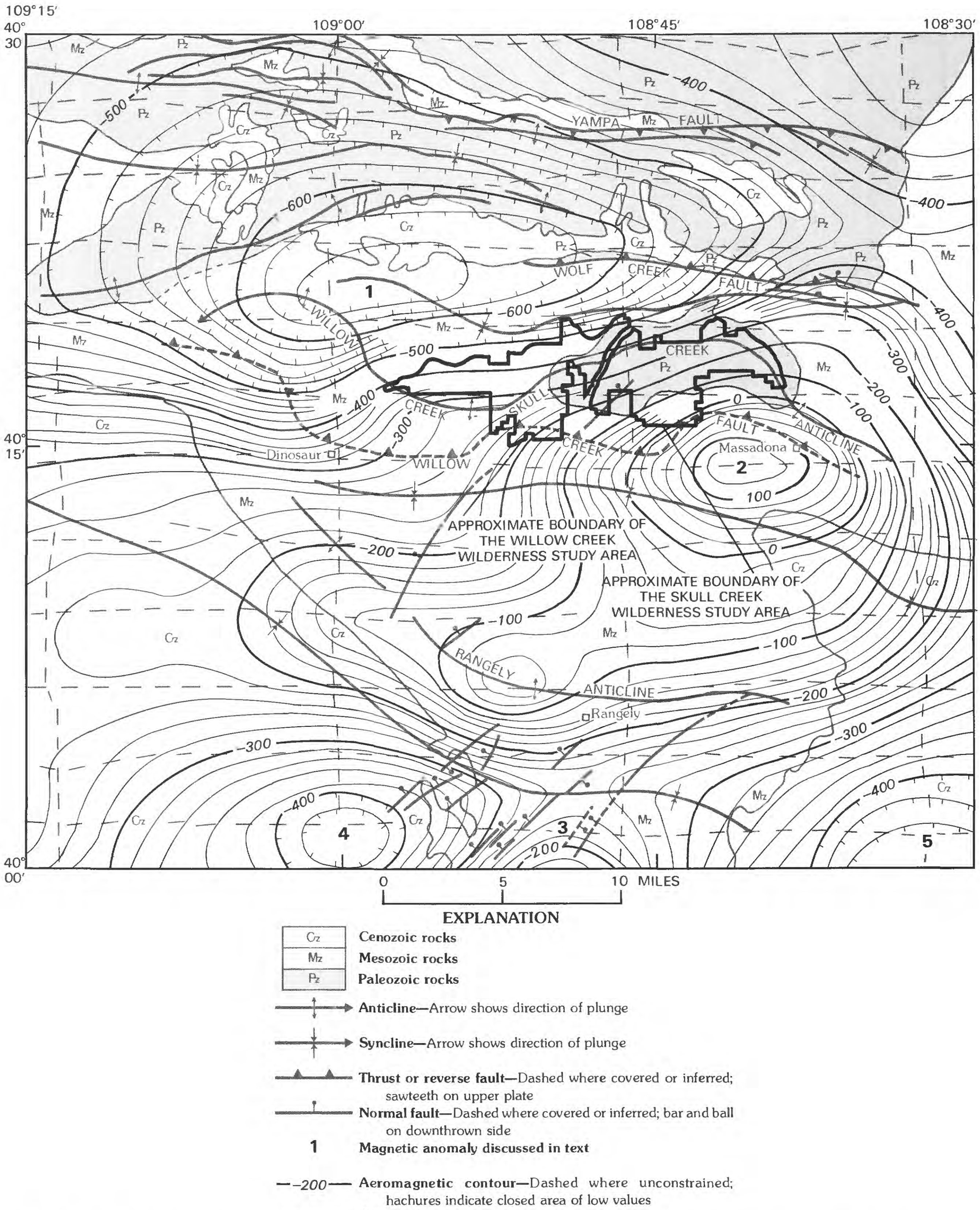
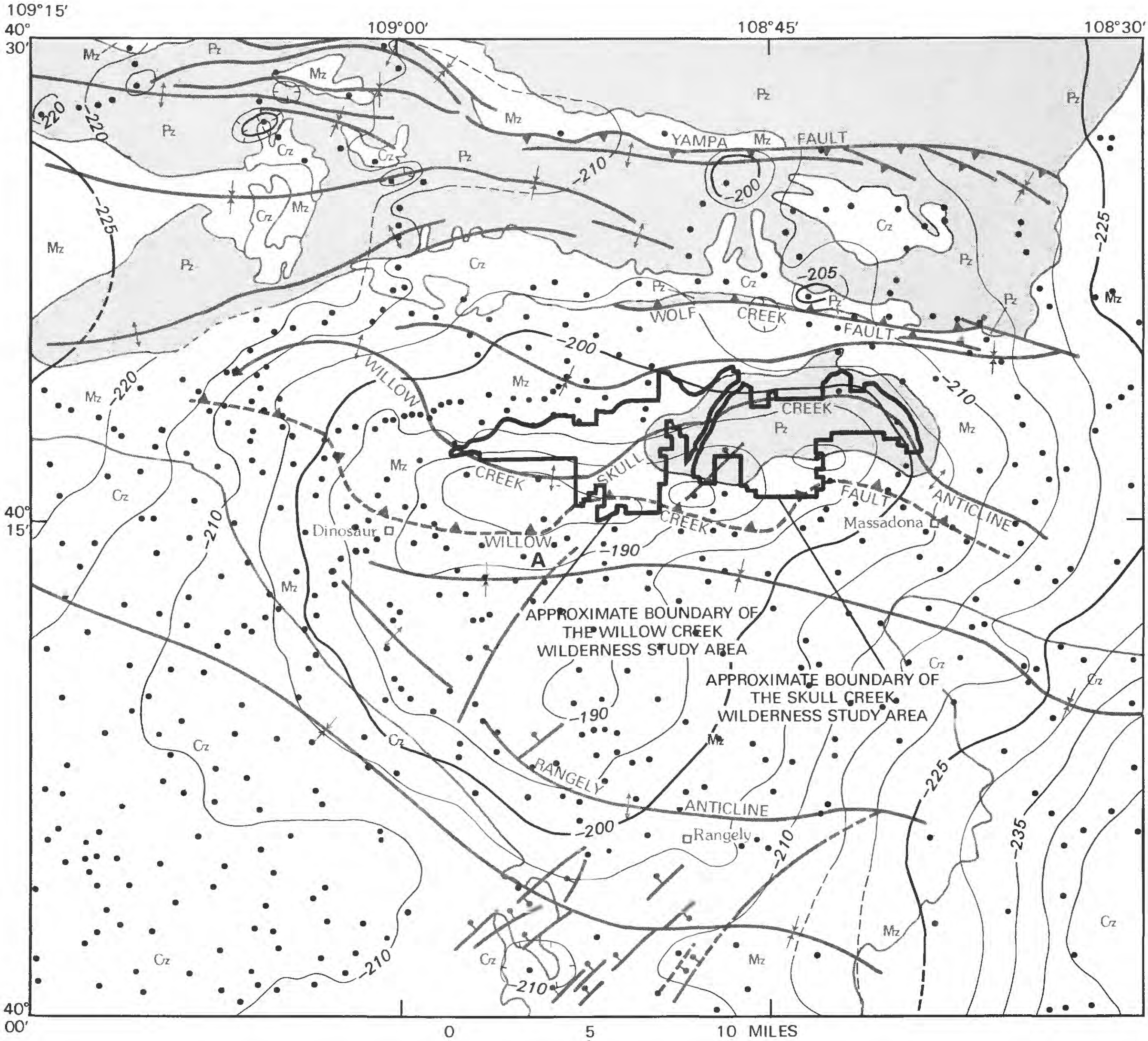


Figure 4. Residual total intensity aeromagnetic and generalized geologic map of the Willow Creek and Skull Creek Wilderness Study Areas. Contour interval 20 nanoteslas. Geology modified from Rowley and others (1985) and Powers (1986).



EXPLANATION

Cz	Cenozoic rocks
Mz	Mesozoic rocks
Pz	Paleozoic rocks

Anticline—Arrow shows direction of plunge

Syncline—Arrow shows direction of plunge

Thrust or reverse fault—Dashed where covered or inferred; sawteeth on upper plate

Normal fault—Dashed where covered or inferred; bar and ball on downthrown side

A **Gravity anomaly discussed in text**

—-200— **Gravity contour**—Dashed where unconstrained; hachures indicate closed area of low values

• **Gravity station**

Figure 5. Complete Bouguer gravity and generalized geologic map of the Willow Creek and Skull Creek Wilderness Study Areas. Contour interval 5 milligals. Geology modified from Rowley and others (1985) and Powers (1986).

for a least another 25 mi south of the area shown in figure 5 (D. Kulik, unpub. data, 1989). The gradient extends northward along the eastern edge of the area shown in figure 5 and continues at least 40 mi in a north-northwest direction. It correlates with saddles in both high and low, east-west-trending magnetic anomalies (U.S. Department of Energy, 1982). The magnitude and slope of the gradient remain remarkably constant while separating diverse rock units at the surface, which suggests that a major basement feature is responsible for the gravity expression. The Douglas Creek arch may be present beneath the eastern Uinta Mountains and may be essentially continuous with the Rock Springs uplift in southern Wyoming. The local gravity anomaly A (fig. 5) and the more generalized configuration of magnetic anomaly 2 (fig. 4) suggest that the bends in the Willow Creek fault are controlled by underlying basement structure.

Mineral and Energy Resources

The available geochemical and geologic data suggests that at least two weak mineralization events took place in the study areas: (1) metals that were deposited during diagenesis in sandstone were later redistributed and concentrated by ground waters, and (2) a possible hydrothermal event locally left traces of metals in altered and fractured rock. The favorable reservoir rock for oil and gas has been exposed by erosion, and the coal-bearing rock that is being mined south of the study areas is not present in the study areas.

Uranium, Vanadium, and Copper

Uranium was mined from a large deposit in the Browns Park Formation of late Oligocene and Miocene age east of Maybell, Colo., which is about 30 mi east of the study areas. This formation is not present in the study areas, but uranium does occur in several other rock formations in and near the study areas. Early-day miners attempted, in at least two localities nearby, to extract ore from the Chinle and the Stump Formations. The occurrence in the Chinle is about 1 mi east of the study area where a small amount of uranium-bearing petrified wood and clay was apparently mined from the Gartra Member (the coarse basal conglomerate) of the Chinle (Korzeb, 1989). The other locality is in the Curtis Member of the Stump Formation near Skull Creek on the Blue Mountain claims; the mine there produced ore that contained uranium, vanadium, and copper. The deposit in the Stump contains several relatively rare secondary oxide minerals that contain arsenic, copper, lead, selenium, uranium, and vanadium; three were identified as new species for Colorado (Brownfield and others, 1986). In addition to the Chinle and Stump deposits, uranium also occurs in low, but detectable, amounts in the Morrison Formation.

Many parts of the Colorado Plateau are rich in uranium that is hosted in sandstone-type deposits, many of which are world class in size. The two principal host rocks are the Chinle and Morrison Formations. Sandstone-hosted uranium deposits result when uranium is precipitated from ground water in a favorable host rock. The important factors that influence the formation of this type of ore deposit are: (1) a permeable host rock such as poorly cemented sandstone, (2) some type of a reducing agent that is contained in or introduced into the host rock, and (3) a uranium source. The uranium is commonly precipitated when uranium-bearing ground waters encounter an environment rich in organic material, which acts as the necessary reducing agent. The uranium is converted to water-insoluble material and is then deposited where it remains in the rock in a stable form.

Favorable depositional conditions existed, at least on a limited scale, at the prospect in the Gartra Member and at the Blue Mountain claims. Beds composed mainly of carbonized plant remains in mudstone and sandstone served as a reductant for uranium, vanadium, and copper at the base of the Curtis Member of the Stump Formation. These beds range from 1 to 3 ft thick at the Blue Mountain claims, but at other locations the organic-rich beds are very thin or absent. Similar mineralization occurs at this stratigraphic interval in several places in and near the study areas. Plant remains also served to localize uranium mineralization at the prospect in the Gartra Member east of the study areas.

The study areas have low mineral resource potential for undiscovered uranium, vanadium, and copper, even though there are deposits or occurrences in and near the study areas. This assessment is based on the following data: (1) None of the more than 80 stream-sediment samples collected for the geochemical survey contain these elements or other elements associated with these types of deposits in anomalous concentrations. These samples characterize the rock formations present in the study areas including those formations that elsewhere are favorable hosts for this type of mineralization. (2) The organic-rich beds that are essential for mineral deposition are either absent or very thin in the study areas. In 1953 the Atomic Energy Commission conducted a drilling program in the vicinity of the Blue Mountain claims, but apparently no extension of that deposit or similar deposits were located (Cadigan, 1972). (3) Radioactivity surveys using a hand-held scintillometer over the Chinle, Stump, and Morrison Formations recorded no anomalous radiation. Measurements over petrified wood fragments, dinosaur bones, and some of the sandstone beds in the Morrison Formation gave readings double that of background; however, these levels of radioactivity are not considered anomalous for the Morrison.

The available data indicate that the study areas have low mineral resource potential for undiscovered uranium, vanadium, and copper, with a certainty level of C.

Other Metals

The Moenkopi Formation exposed in the Skull Creek Rim was the target of extensive geochemical studies by Cadigan (1972). The Moenkopi is typically a redbed sequence throughout the Colorado Plateau; however, some Moenkopi beds in the Skull Creek Rim have been altered to a conspicuous greenish-gray. Cadigan (1972) reported metal enrichment along the interface between the red and green beds in a thin (1 cm thick) zone that contains copper, vanadium, chromium, nickel, cobalt, silver, lanthanum, and boron. In addition, he reported anomalously high amounts of mercury in the altered (green) Moenkopi. Cadigan's (1972) analysis of the data led him to suggest "invasion of the rocks by metal-bearing solutions and alteration of parts of the Moenkopi and an interaction at the contact between the red rock which represent an oxidized environment and the green rocks which represent an invading reducing environment."

Cadigan (1972) also reported traces of arsenic, lead, silver, molybdenum, and zinc in joints in exposures of bedrock in Rock Wall Draw. Trace amounts of silver, arsenic, copper, lead, and zinc occur in altered rock along large faults that dissect the hogbacks to the west of Rock Wall Draw. The altered rock, which is mainly in the Glen Canyon and Entrada Sandstones, was explored in several small prospect pits along the fault.

The weak mineralization in the Moenkopi and in the fractures and joints may represent a single mineralizing event, but it is not clear if this event also deposited metals in the overlying Chinle and Stump Formations. The high arsenic content of the altered rock in fractures and joints, as mentioned above, and the anomalous amount of mercury in the Moenkopi (Cadigan, 1972) suggest a hydrothermal origin for the metals, but nearby magmatic sources are unknown.

The Moenkopi, which is predominantly mudstone, has low permeability, which greatly restricts the flow of fluids and limits the sites for mineral deposition. The Moenkopi is, therefore, an unlikely host for mineral resources. The very thin layer containing copper and other minerals that occurs at the interface of the red and green beds is not an identified resource; furthermore, these occurrences are outside the boundaries of the study areas. The amounts of metals found in the Moenkopi, although anomalous, are too low to suggest that a resource may occur in the study areas. Samples collected along the faults were biasedly selected as high grade, but none contained concentrations of metals that indicate a resource. The area of altered rock along the faults is very limited in size, and there are no indications that these structures, or other similar structures in the study areas, contain resources of base and precious metals. As stated earlier, none of the stream sediments, including those collected downstream from the areas of faulting and rock alteration, contain metals.

The available data indicate that the study areas have low mineral resource potential for all other undiscovered metals, with a certainty level of C.

Oil and Gas

Oil and gas was first discovered in this region in 1933 in the Rangely field about 15 mi south of the study areas. This field became the largest producing oil field in Colorado. The principal oil reservoir rock in the Rangely field is the Pennsylvanian and Permian Weber Sandstone. Minor amounts of oil were also produced from fractures in the Morrison Formation and the upper part of the Mancos Shale. The Rangely field is currently producing (with the aid of CO_2 injection) about 35,000 barrels of oil per day (Robert Ladd, Chevron Oil Co., oral commun., 1988). The average depth of the Weber reservoir is 6,500 ft. Oil is trapped in a large anticlinal structure that dips gently north and steeply south. The Ashley Valley oil field, which is located about 30 mi to the west of the study areas in Utah, has anticlinal structure and reservoir rock similar to that in the Rangely field.

Another type of reservoir for oil and gas in this region is foreland subthrust traps. These traps occur at depth along the margins of uplifts such as in the thrust belt of northeast Utah and southwest Wyoming where oil and gas are currently being produced. These traps may result where older rock, which serves as a cap, has been thrust over younger rock that has reservoir qualities. Complex structures can result when several thrusts repeat the stratigraphic section. Anticlinal closure or updip truncation of plunging structural noses against the main thrust fault, or a combination of the two, may form potential traps (Powers, 1986). Due to the depth of burial and complexity of subthrust structures, identification of favorable oil and gas traps is difficult. Seismic data is the primary exploration method, but interpretation of such records is commonly misleading in the absence of information from drill holes.

The Willow Creek fault, which lies along the southern boundaries of the study areas, has been the target for oil and gas exploration in subthrust traps. Powers (1986) analyzed this foreland subthrust play from seismic data and eight drill holes. Two of these drill holes, which were located within 2 mi of the southwestern border of the Willow Creek study area, had good to excellent shows of oil in Pennsylvanian, Permian, and Triassic rocks, but the wells were abandoned because of poor reservoir rock quality and minimal structural closure (Powers, 1986). Three of the wells did not reach the fault, and the other three wells had poor showings of oil or did not tap the favorable reservoir rock.

The resource potential for oil and gas in subthrust traps along the Willow Creek fault beneath the study areas is low. Oil occurs in this play near the study areas, but the amount of closure beneath the subthrust is restricted in extent and the reservoir rock qualities are poor (Powers, 1986). It is not known if other thrust faults occur beneath the study areas; therefore the potential for oil and gas in subthrust reservoirs separate from the Willow Creek fault is unknown. The gravity and aeromagnetic data prepared for this report do not delineate any such structures.

Although the Weber, Morrison, and Mancos are present in a structural setting similar to that of the Rangely field, the study areas have low resource potential for undiscovered oil and gas. Exploration of the Willow Creek and Skull Creek anticlines by drilling has had little or no success. Several wells have been drilled in both study areas for tests in the Weber and older Paleozoic rock. The anticlines have been breached to much lower stratigraphic levels than the anticline in the Rangely field. Erosion has removed all the Mesozoic and Cenozoic rock from the crest of the Skull Creek anticline, thus exposing the Weber Sandstone and allowing any oil and gas accumulations to escape. The Weber is, however, present at a depth of about 3,000 ft beneath the Willow Creek anticline; the erosional level there exposes the Glen Canyon Sandstone. However, drilling tests were unsuccessful in finding oil or gas in the Weber or deeper rock. With the exception of a very small area near Blue Mountain (pl. 1), the main body of the Mancos Shale has been eroded from the study areas. The Morrison Formation is present in the study areas, but it dips to the north and south in the flanks of the anticlines and any hydrocarbons present could easily escape to the surface. The study areas were given a low resource potential for oil and gas by Spencer (1983).

The available data indicate that the study areas have low resource potential for undiscovered oil and gas, with a certainty level of C.

Coal

Coal is being mined from underground workings in Upper Cretaceous Mesaverde Group rock a few miles to the south, but similar rock has been removed from the study areas by erosion. Older rock exposed on the surface of the study areas does not contain coal and subsurface rocks are not likely to contain coal.

The available data indicate that the study areas have low resource potential for undiscovered coal, with a certainty level of D.

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APPENDIX

DEFINITION OF LEVELS OF MINERAL RESOURCE POTENTIAL AND CERTAINTY OF ASSESSMENT

Definitions of Mineral Resource Potential

LOW mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics define a geologic environment in which the existence of resources is unlikely. This broad category embraces areas with dispersed but insignificantly mineralized rock as well as areas with few or no indications of having been mineralized.

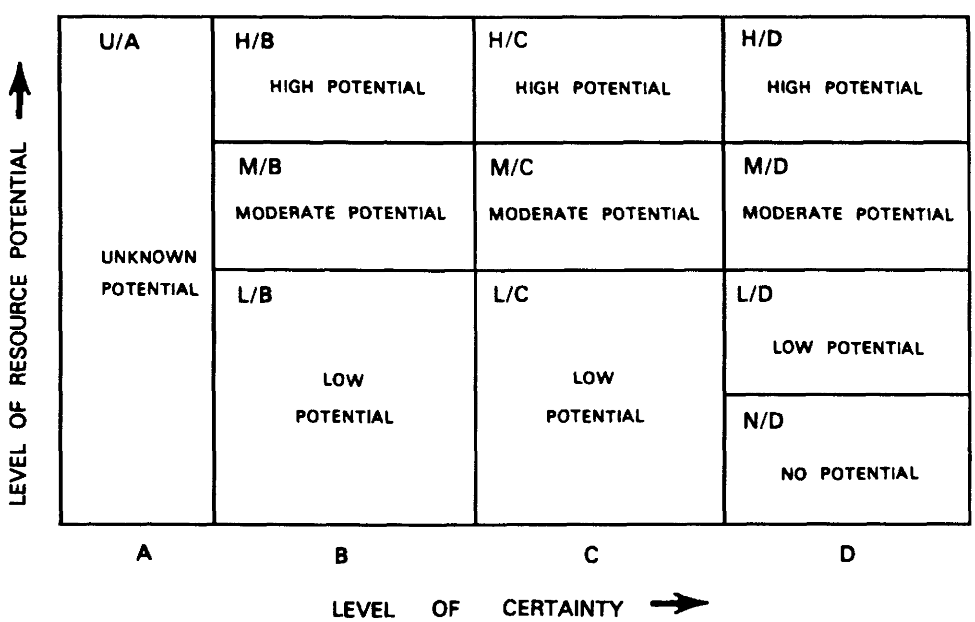
MODERATE mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a reasonable likelihood of resource accumulation, and (or) where an application of mineral-deposit models indicates favorable ground for the specified type(s) of deposits.

HIGH mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a high degree of likelihood for resource accumulation, where data support mineral-deposit models indicating presence of resources, and where evidence indicates that mineral concentration has taken place. Assignment of high resource potential to an area requires some positive knowledge that mineral-forming processes have been active in at least part of the area.

UNKNOWN mineral resource potential is assigned to areas where information is inadequate to assign low, moderate, or high levels of resource potential.

NO mineral resource potential is a category reserved for a specific type of resource in a well-defined area.

Levels of Certainty



A. Available information is not adequate for determination of the level of mineral resource potential.
B. Available information suggests the level of mineral resource potential.
C. Available information gives a good indication of the level of mineral resource potential.
D. Available information clearly defines the level of mineral resource potential.

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RESOURCE/RESERVE CLASSIFICATION

	IDENTIFIED RESOURCES			UNDISCOVERED RESOURCES	
	Demonstrated		Inferred	Probability Range (or)	
	Measured	Indicated		Hypothetical	Speculative
ECONOMIC	Reserves		Inferred Reserves		
MARGINALLY ECONOMIC	Marginal Reserves		Inferred Marginal Reserves		
SUB-ECONOMIC	Demonstrated Subeconomic Resources		Inferred Subeconomic Resources		

Major elements of mineral resource classification, excluding reserve base and inferred reserve base. Modified from McKelvey, 1972, Mineral resource estimates and public policy: American Scientist, v.60, p.32-40, and U.S. Bureau of Mines and U.S. Geological Survey, 1980, Principles of a resource/reserve classification for minerals: U.S. Geological Survey Circular 831, p.5.

GEOLOGIC TIME CHART

Terms and boundary ages used in this report

EON	ERA	PERIOD		EPOCH	BOUNDARY AGE IN MILLION YEARS
Phanerozoic	Cenozoic	Quaternary		Holocene	0.010
				Pleistocene	1.7
		Tertiary	Neogene Subperiod	Pliocene	5
				Miocene	24
			Paleogene Subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	Mesozoic	Cretaceous		Late	96
				Early	138
		Jurassic		Late Middle Early	205
		Triassic		Late Middle Early	~ 240
	Paleozoic	Permian		Late Early	290
		Carboniferous Periods	Pennsylvanian	Late Middle Early	~ 330
			Mississippian	Late Early	360
		Devonian		Late Middle Early	410
		Silurian		Late Middle Early	435
		Ordovician		Late Middle Early	500
		Cambrian		Late Middle Early	~ 570[1]
Proterozoic	Late Proterozoic				900
	Middle Proterozoic				1600
	Early Proterozoic				2500
Archean	Late Archean				3000
	Middle Archean				3400
	Early Archean				3800?
pre-Archean[2]					4550

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

[2] Informal time term without specific rank.

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MANUEL LUJAN, JR., Secretary

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

CONTENTS

[Letters designate the chapters]