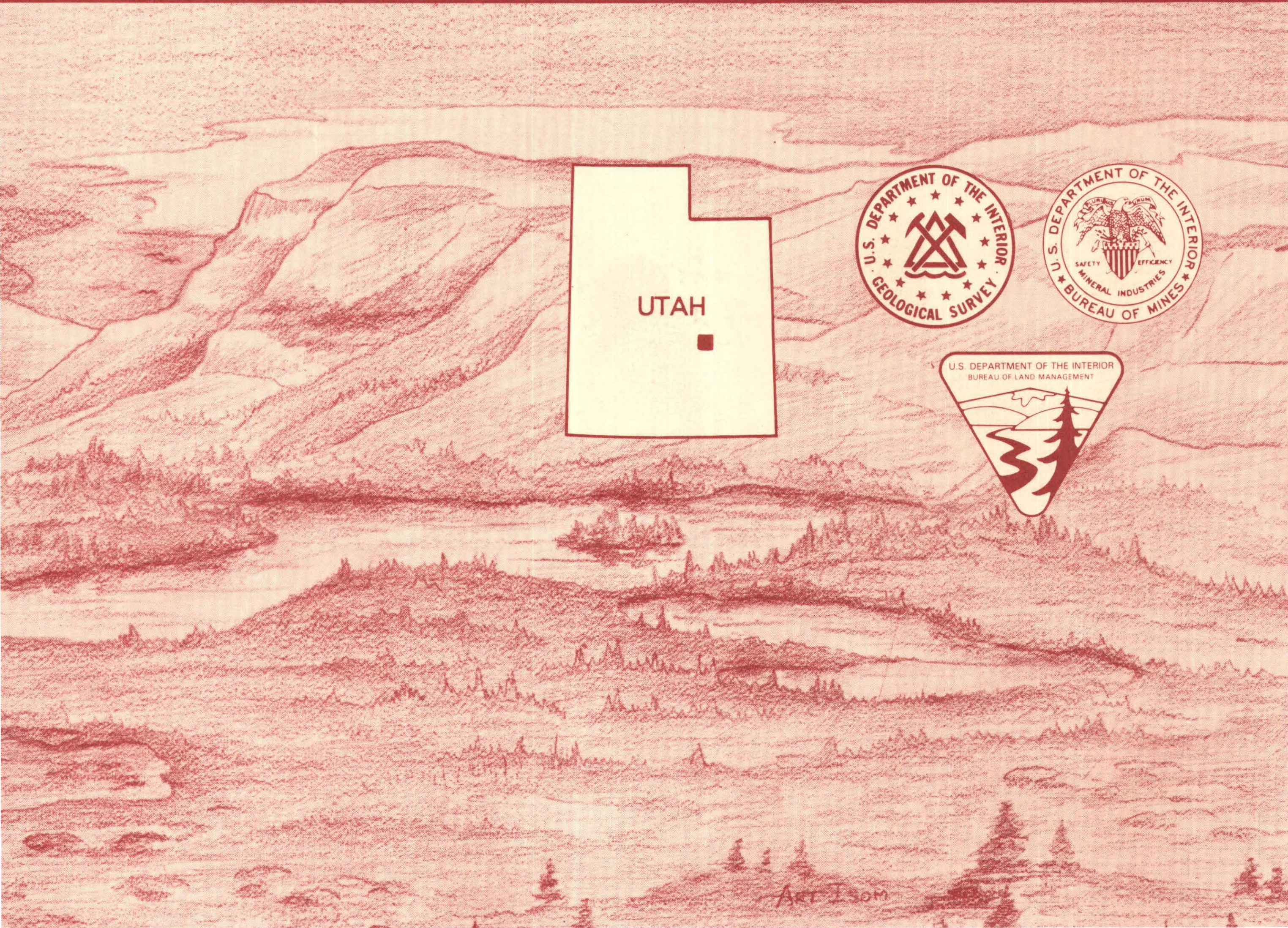
Mineral Resources of the San Rafael Swell Wilderness Study Areas, Including Muddy Creek, Crack Canyon, San Rafael Reef, Mexican Mountain, and Sids Mountain Wilderness Study Areas, Emery County, Utah

U.S. GEOLOGICAL SURVEY BULLETIN 1752



MINERAL RESOURCES OF THE SAN RAFAEL SWELL WILDERNESS STUDY AREAS, INCLUDING MUDDY CREEK, CRACK CANYON, SAN RAFAEL REEF, MEXICAN MOUNTAIN, AND SIDS MOUNTAIN WILDERNESS STUDY AREAS, EMERY COUNTY, UTAH

Landsat Thematic Mapper satellite image (band 7, midinfrared reflectance) of the San Rafael Swell, Utah, taken at noon from 438 mi altitude on Feb. 1, 1989. The San Rafael Swell is an eroded structural dome that is approximately 45 mi long and 25 mi wide, and trends north-northeast. It is part of the much larger San Rafael anticline. The San Rafael Reef, the steeply dipping eastern edge of the structure, is sharply defined as parallel light and dark units and comprises mainly the Chinle Formation and Glen Canyon Group rocks. The San Rafael River flows eastward across the northern part of the swell, and the east-flowing Muddy River cuts the southern tip.

Mineral Resources of the San Rafael Swell Wilderness Study Areas, Including Muddy Creek, Crack Canyon, San Rafael Reef, Mexican Mountain, and Sids Mountain Wilderness Study Areas, Emery County, Utah

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DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

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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 to the Congress. This report presents the results of a mineral survey of the San Rafael Swell wilderness study areas, including Muddy Creek (UT-060-007) Wilderness Study Area, Crack Canyon (UT-060-028A) Wilderness Study Area, San Rafael Reef (UT-060-029A) Wilderness Study Area, Mexican Mountain (UT-060-054) Wilderness Study Area, and Sids Mountain (UT-060-023) Wilderness Study Area, Emery County, Utah.

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Mineral Resources of the San Rafael Swell Wilderness Study Areas, Including Muddy Creek, Crack Canyon, San Rafael Reef, Mexican Mountain, and Sids Mountain Wilderness Study Areas, Emery County, Utah

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Abstract

The San Rafael Swell wilderness study areas, including the Muddy Creek, Crack Canyon, San Rafael Reef, Mexican Mountain, and Sids Mountain Wilderness Study Areas, are in Emery County, south-central Utah. At least 4,100 current and historic mining claims have been located in or near the study areas, primarily for uranium. Vanadium is the most valuable byproduct of uranium mining, although minor copper, silver, lead, zinc, and gold also occur in some deposits. Past production totaled at least 7 million lbs (pounds) of U_3O_8 (uranium oxide) from the entire San Rafael Swell area, and approximately 3 million lbs was mined from within and near the wilderness study areas. Mined ore bodies contained 100–10,000 short tons of ore with an average grade of 0.2 percent U_3O_8 and less than 0.5 percent V_2O_5. Within and near the Crack Canyon Wilderness Study Area is about 221,000 tons of identified subeconomic uranium and vanadium resources (0.05–0.26 percent U_3O_8 and 0.3–0.5 percent V_2O_5). Within the Carmel Formation, inferred subeconomic resources of about 11 million tons of gypsum are in the Muddy Creek Wilderness Study Area, about 680,000 tons in the San Rafael Reef Wilderness Study Area, and about 103 million tons in the Sids Mountain Wilderness Study Area. An identified subeconomic resource of about 20 million tons of gypsum is in the Summerville Formation in the Crack Canyon Wilderness Study Area. Other commodities evaluated include geothermal energy, gypsum, limestone, oil and gas, sand and gravel, sandstone, semiprecious gemstones, sulfur, petrified wood, and tar sand.

The Crack Canyon Wilderness Study Area contains parts of the Delta, Temple Mountain, and Little Wild Horse mining districts. Between 1950 and 1973, about 472 tons of U_3O_8 were produced from 10 mines in districts within or adjacent to the study area, and about 414 tons were produced from 2 mines within the study area.

The mineral resource potential for localized, thin tar sands of variable grade in all wilderness study areas, except the Eardley Canyon area of the San Rafael Reef Wilderness Study Area, is high. The resource potential for gypsum on the surface in the western part of the Muddy Creek Wilderness Study Area, in the eastern and southeastern part of the San Rafael Reef Wilderness Study Area, in the northeastern part of the Mexican Mountain Wilderness Study Area, in the southern and southeastern part of the Crack Canyon Wilderness Study Area, and in the western part of the Sids Mountain Wilderness Study Area is high. The Sids Mountain Wilderness Study Area, Crack Canyon Wilderness Study Area, northeastern part of the Mexican Mountain Wilderness Study Area, eastern and southeastern part of the San Rafael Reef Wilderness Study Area, and western part of the Muddy Creek Wilderness Study Area have high resource potential

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for uranium and vanadium in the Chinle Formation. The resource potential for uranium and vanadium in the Morrison Formation is low in the southern part of the Crack Canyon Wilderness Study Area. The resource potential for oil and gas in all wilderness study areas is moderate. The resource potential for geothermal energy in the wilderness study areas is moderate. The resource potential for carbon dioxide and helium gases in the wilderness study areas is moderate. The resource potential in all wilderness study areas for metals other than uranium and vanadium, including gold and copper, is low. The resource potential for minor, localized sulfur deposits is low in the Mexican Mountain and San Rafael Reef Wilderness Study Areas. The resource potential for bentonite in the Chinle Formation on the surface and in the subsurface is low in the Sids Mountain Wilderness Study Area, Crack Canyon Wilderness Study Area, northeastern part of the Mexican Mountain Wilderness Study Area, eastern and southeastern part of the San Rafael Reef Wilderness Study Area, and western part of the Muddy Creek Wilderness Study Area, and is also low for bentonite with minor zeolite in the southernmost part of the Crack Canyon Wilderness Study Area.

SUMMARY

Regional Setting

In February 1989 the USGS (U.S. Geological Survey) and the USBM (U.S. Bureau of Mines) completed an investigation, at the request of the BLM (U.S. Bureau of Land Management), of 255,589 acres in the San Rafael Swell region, including the Muddy Creek (UT–060–007), Crack Canyon (UT–060–028A), San Rafael Reef (UT–060–029A), Mexican Mountain (UT–060–054), and Sids Mountain (UT–060-023) Wilderness Study Areas, all in Emery County, Utah (fig. 1).

The San Rafael Swell is a structural dome or anticline in which sedimentary rocks ranging in age from Carboniferous to Jurassic (see the geologic time chart in the appendix) are exposed. The rocks of the San Rafael Swell have been uplifted, crossfolded, and involved in pipelike (nearly vertical sided) collapse; most of the rocks are jointed. All of these structural features are potential targets for mineral accumulation. Evidence, including data from subsurface and geophysical information in and adjacent to the swell, suggests that episodes of deformation in the region occurred in Precambrian, Paleozoic, and Mesozoic time. Zones of weakness in the strata may have been sites of recurrent deformation, uplift, intrusion, and faulting throughout this geologic time interval. Paleozoic rocks in this area were formerly predominantly marine, marine-shelf, and eolian sediments that record fluctuating sea levels (especially in late Paleozoic time), whereas the Mesozoic sequences were formerly primarily intertidal, fluvial, eolian, and alluvial sediments that record continental episodes. All units are covered, in places, by younger, relatively thin, surficial talus, terrace, and pediment deposits.

Identified Resources

An inferred subeconomic resource of about 11 million tons of gypsum in the Carmel Formation is in the Muddy Creek Wilderness Study Area. Occurrences of uranium, vanadium, common-variety sandstone, limestone, and petrified wood were also examined. The Crack Canyon Wilderness Study Area contains parts of the Delta, Temple Mountain, and Little Wild Horse mining districts. From 1950 to 1973, 10 mines in these districts that are within or adjacent to the study area yielded 472 tons of U_3O_8 and unknown quantities of V_2O_5 and copper. There are no current patented mining claims or mineral leases. About 221,000 tons of identified subeconomic resources of uranium and vanadium are present at seven mines and prospects within and adjacent to the Crack Canyon Wilderness Study Area. Identified subeconomic resources of gypsum in the Summerville Formation total 20 million tons in the Crack Canyon Wilderness Study Area. Insufficient data were available to determine resources in any of the 22 uranium and vanadium occurrences in parts of the Temple Mountain and Green River mining districts in the San Rafael Reef Wilderness Study Area. Inferred subeconomic resources of gypsum, totalling 680,000 tons, are in the Carmel Formation in the San Rafael Reef Wilderness Study Area. No currently economic resources exist in or near this wilderness study area for gold, semiprecious gemstones, limestone, sandstone, sand and gravel, tar sand, oil and gas, and geothermal energy sources. No identified resources and no production have been recorded from the Mexican Mountain Wilderness Study Area, but nine people hold claims within or near the study area for uranium, copper, and sulfur. The Sids Mountain Wilderness Study Area has five uranium and two copper prospects. No production has taken place, and no uranium, vanadium, or copper resources were identified in the study area. An inferred subeconomic resource of 103 million tons of gypsum is in the western part of the Sids Mountain Wilderness Study Area. Sand and gravel are present along the San Rafael River and most intermittent streams in the study area, but none was identified as a resource.

Mineral Resource Potential

The results of a reconnaissance geochemical survey indicate low-level and isolated geochemical anomalies present in rock and stream-sediment samples, and in heavy-mineral panned concentrates derived from stream-sediment samples from the San Rafael Swell region. The anomalous suite of elements is commonly described as accompanying uranium deposits in the swell and elsewhere (Hawley and others, 1965). The anomalies or elemental enrichments are not considered significant, and any geochemical evidence for near-surface ore deposits or any mineralized system of consequence is absent.

Geophysical studies provided new information on the distribution of altered rocks, trends of lineaments, and the configuration, depth, and lithology of the basement rocks underlying this part of the swell. Gravity and aeromagnetic data primarily express the depth and lateral extent of Precambrian granite that makes up the core of the San Rafael Swell. The data from this study are insufficiently detailed to define specific areas of mineral and energy resources. The remote-sensing analysis identified specific areas of altered rock by compilation of spectral data returned from satellites.

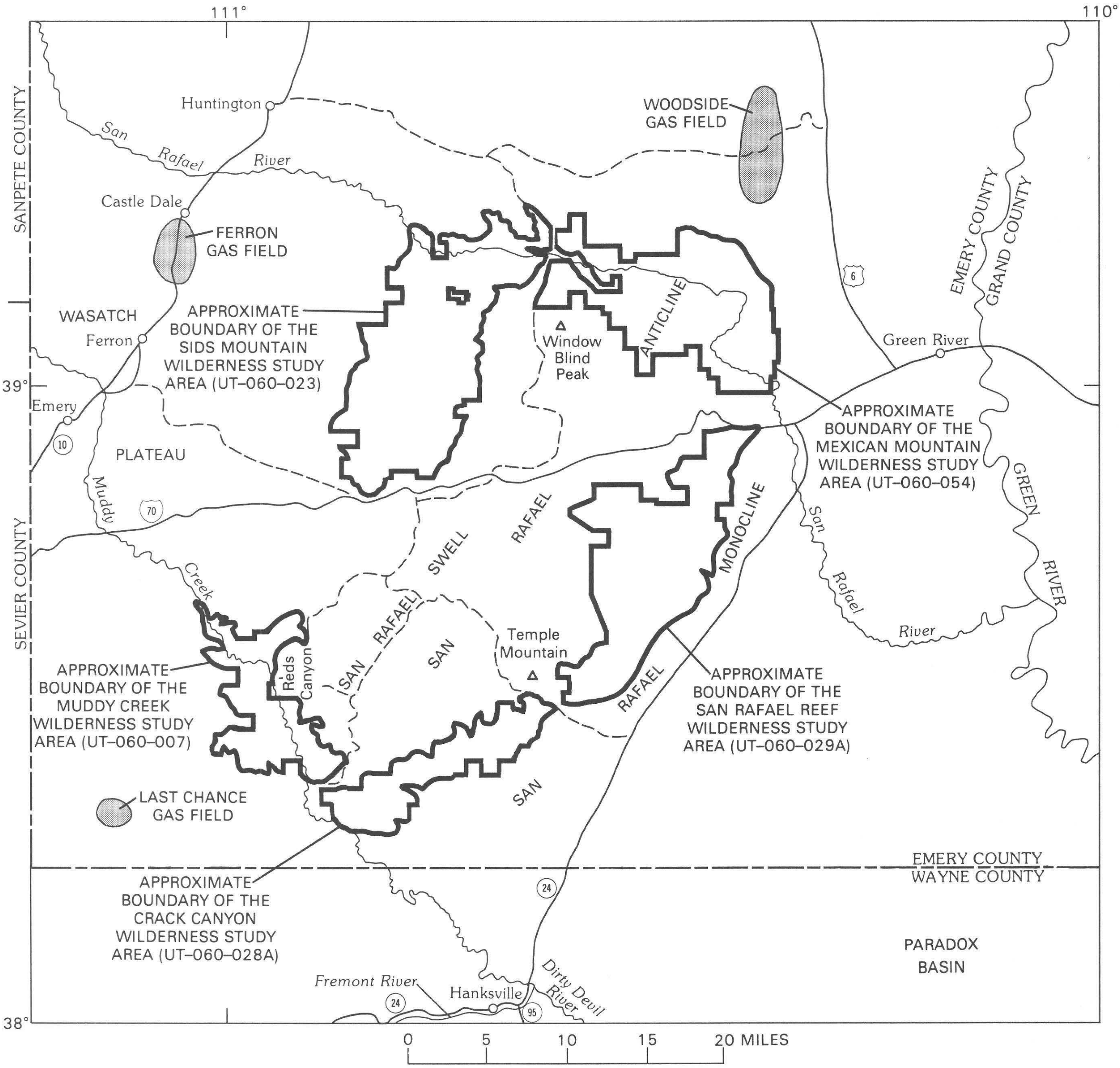

Figure 1. Index map of the San Rafael Swell region showing approximate locations of the five wilderness study areas, Emery County, Utah.

Analysis of linear features suggested areas of probable subsurface collapse structures and areas of possible subsurface crustal breaks, all features that could be associated with subsurface movement of fluids associated with ore or hydrocarbon emplacement.

The Morrison Formation has been eroded from all wilderness study areas except the southern part of the Crack Canyon Wilderness Study Area. Due to its depositional setting, the Morrison Formation has low mineral resource potential for uranium and vanadium deposits on the surface and in the subsurface in the southernmost Crack Canyon Wilderness Study Area. Based on information from depositional models and known occurrences, two broad belts, one in the northern part of the San Rafael Swell and one in the southern part, have mineral resource potential for uranium deposits in the Chinle Formation. All known collapse structures, some of which incorporate geologic units other than the Chinle Formation, also occur within these belts. The Sids Mountain, Crack Canyon, northeastern part of the Mexican Mountain, eastern and southeastern part of the San Rafael Reef, and the western part of the Muddy Creek Wilderness Study Areas have high mineral resource potential for uranium and vanadium in sandstone beds and altered zones along faults and lineaments, on the surface and in the subsurface, in the Chinle Formation (figs. 2–6). Other geologic units both stratigraphically above and below the

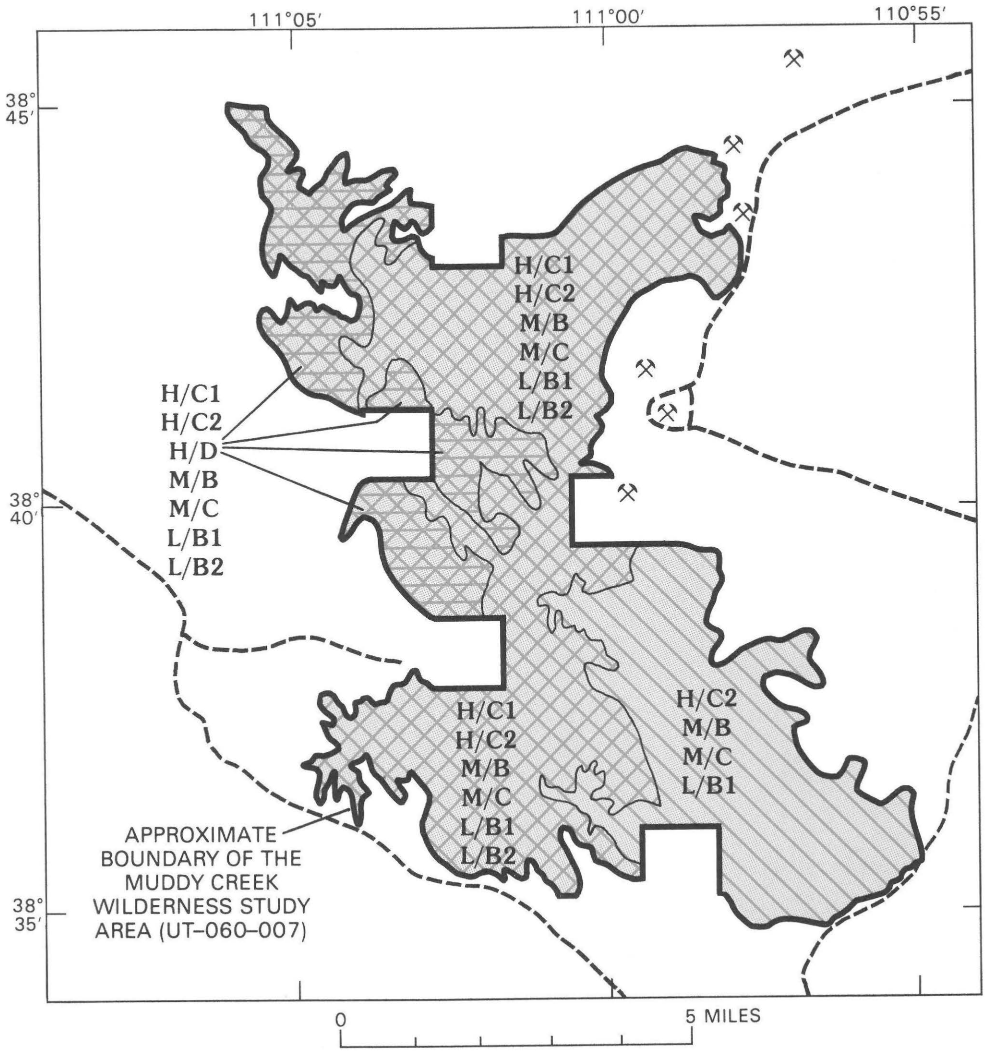

Figure 2 (above and facing page). Mineral resource potential of the Muddy Creek Wilderness Study Area, Emery County, Utah.

Chinle Formation (including the Glen Canyon Group rocks), where collapse structures have formed, may also contain localized uranium and vanadium resources.

Despite favorable attributes of the exposed rocks and shows of oil and gas in Paleozoic strata beneath the surface, no commercial oil and gas resources have been identified. Despite the availability of source rock, reservoir rock, and trapping structures, and the thermal maturity of the rocks in the San Rafael Swell region, geological and exploration evidence shows that the resource potential for oil and gas in each of the study areas can only be rated as moderate.

Localized and lenticular sandstone beds containing tar are exposed at the surface throughout the swell and also are present in wells drilled in the region. The resource potential is high for discontinuous tar-sand deposits of varying grade in the White Rim Sandstone Member of the Cutler Formation, Kaibab Limestone, Moenkopi Formation, Chinle Formation, Wingate Sandstone, Kayenta Formation, Navajo Sandstone, and Page Sandstone, in all wilderness study areas at the surface and in the subsurface except in Eardley Canyon in the San Rafael Reef Wilderness Study Area, where rocks are exposed that are stratigraphically below these units.

Although no evidence for helium and carbon dioxide gases was found in drill-hole information from the San Rafael Swell, the proximity of known reservoirs north of the San Rafael Swell wilderness study areas and the similarity in geologic setting indicate that the resource potential for carbon dioxide and helium is moderate in all wilderness study areas in the San Rafael Swell region.

Bentonite is a constituent of the Chinle Formation and also occurs locally with minor zeolite in the Brushy Basin Member of the Morrison Formation. The mineral resource potential for thin beds (a few inches thick) of bentonite on the surface and in the subsurface in the Chinle Formation is low in the Sids Mountain, Crack Canyon, northeastern part of the Mexican Mountain, eastern and southeastern parts of the San Rafael Reef, and the western part of the Muddy Creek Wilderness Study Areas and is low for thin, localized occurrences with minor zeolite in the lower part of the

EXPLANATION

[The Muddy Creek Wilderness Study Area contains inferred subeconomic resources of gypsum; the Crack Canyon Wilderness Study Area contains identified subeconomic resources of uranium and vanadium in seven mines and prospects in and near the wilderness study area; the San Rafael Reef Wilderness Study Area contains identified subeconomic resources of gypsum; and the western part of the Sids Mountain Wilderness Study Area contains inferred subeconomic resources of gypsum]

H/C1	**Geologic terrane having high mineral resource potential for uranium and vanadium in the Chinle Formation on the surface and in the subsurface, with certainty level C**—Applies to the entire Sids Mountain and Crack Canyon Wilderness Study Areas, the northeastern part of the Mexican Mountain Wilderness Study Area, the eastern and southeastern part of the San Rafael Reef Wilderness Study Area, and the western part of the Muddy Creek Wilderness Study Area
H/C2	**Geologic terrane having high mineral resource potential for tar sand, with certainty level C**—Applies to entire area of all study areas except Eardley Canyon in the San Rafael Reef Wilderness Study Area
H/D	**Geologic terrane having high mineral resource potential for gypsum in the Carmel and Summerville Formations, with certainty level D**—Applies to the western part of the Sids Mountain Wilderness Study Area, the northeastern part of the Mexican Mountain Wilderness Study Area, the eastern and southeastern part of the San Rafael Reef Wilderness Study Area, the southern and southeastern part of the Crack Canyon Wilderness Study Area, and the western part of the Muddy Creek Wilderness Study Area
M/B	**Geologic terrane having moderate resource potential for carbon dioxide and helium gases and geothermal resources, with certainty level B**—Applies to entire area of all study areas
M/C	**Geologic terrane having moderate resource potential for oil and gas, with certainty level C**—Applies to entire area of all study areas
L/B1	**Geologic terrane having low mineral resource potential for metals other than uranium and vanadium, with certainty level B**—Applies to entire study areas
L/B2	**Geologic terrane having low mineral resource potential for bentonite, with certainty level B**—Applies to the entire Sids Mountain and Crack Canyon Wilderness Study Areas, the northeastern part of the Mexican Mountain Wilderness Study Area, the eastern and southeastern part of the San Rafael Reef Wilderness Study Area, and the western part of the Muddy Creek Wilderness Study Area
L/B3	**Geologic terrane having low mineral resource potential for sulfur, with certainty level B**—Applies to the entire Mexican Mountain and San Rafael Reef Wilderness Study Areas
L/C	**Geologic terrane having low mineral resource potential for uranium and vanadium in the Morrison Formation on the surface and in the subsurface, with certainty level C**—Applies to the eastern and southeastern part of the Crack Canyon Wilderness Study Area
⚒	Mine
--------	Unimproved road

Morrison Formation in the southern part of the Crack Canyon Wilderness Study Area.

Geochemical results indicate that no significant metallic-mineral anomalies exist in the region, and, therefore, the mineral resource potential is low for limited occurrences of metals other than uranium and vanadium, including copper and gold, in all wilderness study areas in the San Rafael Swell region.

The mineral resource potential is high for gypsum in isolated deposits as much as 30 ft thick in the Summerville and Carmel Formations on the surface and in the subsurface in the study areas. Thin localized gypsum deposits are also present in the Moenkopi and Curtis Formations, but, because they are relatively insignificant, they are not included in our assessment. Gypsum in the Summerville and Carmel Formations occurs in the western part of the Muddy Creek, the eastern and southeastern part of the San Rafael Reef, the northeastern part of the Mexican Mountain, the western part of the Sids Mountain, and the southern and southeastern part of the Crack Canyon Wilderness Study Areas.

The San Rafael Swell region, because it is a prominent dome with all of the attributes of a sulfur-producing setting, is a favorable area for prospecting for sulfur. The mineral resource potential for minor, localized sulfur deposits near the Kaibab-Moenkopi contact on the surface and in the subsurface is low in the Mexican Mountain and San Rafael Reef Wilderness Study Areas.

Several thermal springs were noted at the Kaibab-Moenkopi contact in the region, and excellent but breached ground-water reservoir rocks are exposed in the swell. Additional porous sandstone and carbonate strata at depth may be potential geothermal sources. Because the occurrence of geothermal resources cannot be ruled out, the potential for geothermal resources in the wilderness study areas of the San Rafael Swell is moderate.

INTRODUCTION

This report presents an evaluation of the mineral endowment (identified resources and mineral resource potential) of five wilderness study areas in the San Rafael Swell region and is the product of several separate studies by the U.S. Bureau of Mines (USBM) and the U.S. Geological Survey (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 were studied by the USBM. Mineral resource potential is the likelihood of occurrence of undiscovered concentrations of metals and nonmetals, industrial rocks and minerals, and of undiscovered energy sources (coal, uranium, oil shale, oil, gas, tar sand, and geothermal sources). Mineral resource potential and the level of certainty are classified according to the system of Goudarzi (1984; see appendix); energy resources are classified according to the system of Miller (1983). The potential for undiscovered resources is studied by the USGS.

The USGS and the USBM studied the San Rafael Swell region at the request of the BLM. These studies were of the Muddy Creek (UT–060–007) Wilderness Study Area, Crack Canyon (UT–060–028A) Wilderness Study Area, San Rafael Reef (UT–060–029A) Wilderness Study Area, Mexican Mountain (UT–060–054) Wilderness Study Area, and Sids Mountain (UT–060–023) Wilderness Study Area, collectively referred to herein as the "San Rafael Swell wilderness study areas" or simply the "study areas".

The study areas are in Emery County in central Utah (fig. 1). They are within the Canyonlands section of

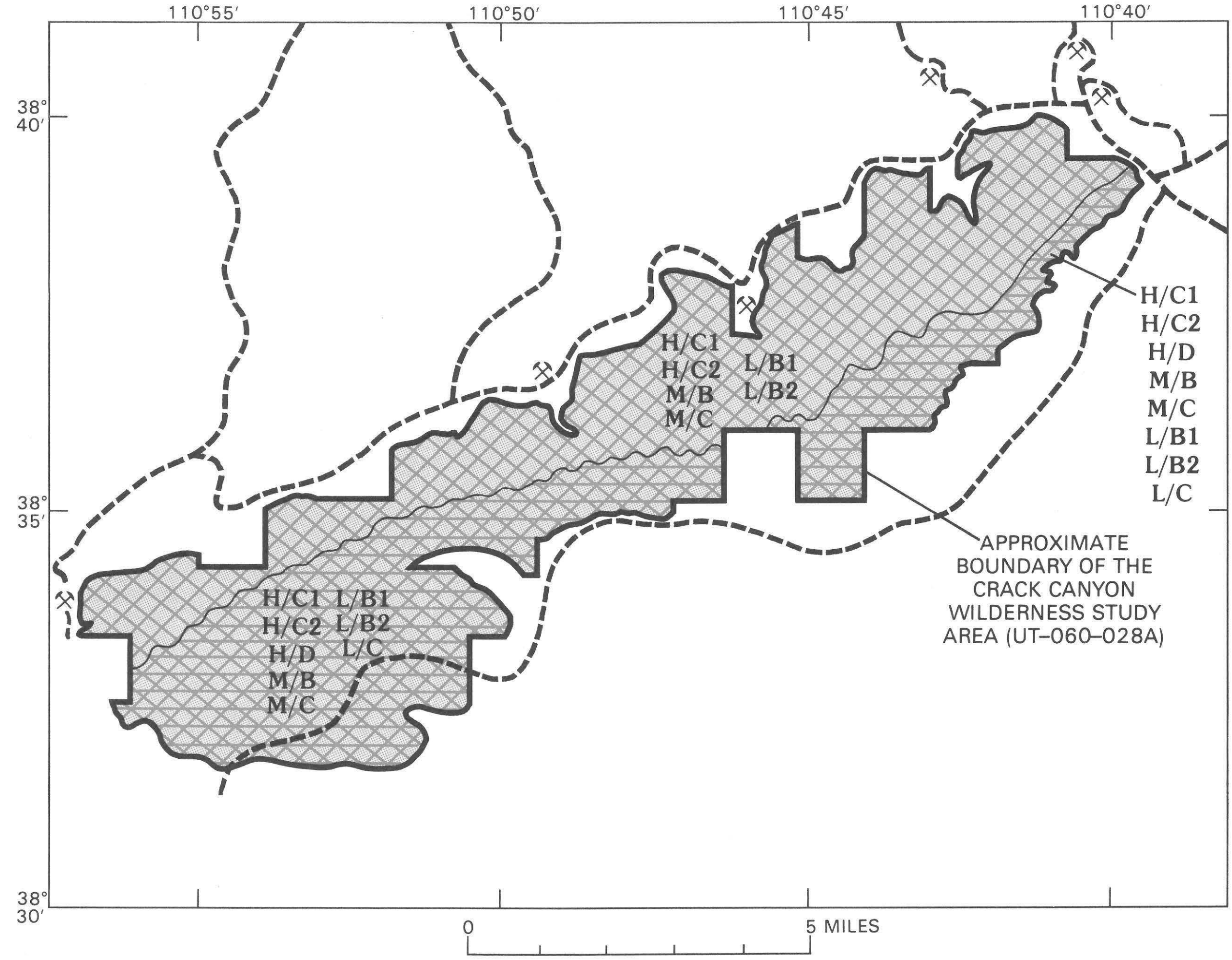

Figure 3. Mineral resource potential of the Crack Canyon Wilderness Study Area, Emery County, Utah. Explanation is on figure 2.

the Colorado Plateaus physiographic province (Thornbury, 1965), and the San Rafael Swell forms a major geomorphic feature in this part of south-central Utah. The study areas total 255,589 acres that are divided as follows: Muddy Creek Wilderness Study Area, 31,400 acres; Crack Canyon Wilderness Study Area, 25,335 acres; San Rafael Reef Wilderness Study Area, 59,170 acres; Mexican Mountain Wilderness Study Area, 59,600 acres; and Sids Mountain Wilderness Study Area, 80,084 acres. The study areas form a nearly continuous ring in the outer, relatively steeply dipping part of the San Rafael Swell. The swell is an eroded, north-northeast-trending structural dome that is approximately 45 mi long and 25 mi wide; it is part of the much larger San Rafael anticline that extends far beyond the swell (Witkind, 1989).

The San Rafael Swell region can be reached via U.S. Interstate Highway 70 (I–70), which crosses the swell in an east-west direction. The study areas are about 15–50 mi west of Green River, Utah. The Sids Mountain and Mexican Mountain Wilderness Study Areas are north of I-70, and the San Rafael Reef, Crack Canyon, and Muddy Creek Wilderness Study Areas are south of I–70. U.S. Highway 6 and Utah Highway 24 are on the eastern border of the San Rafael Swell; Utah Highway 10 parallels the northeastern part of the swell. Many county roads are in the interior and near the outer edges of the swell. These roads and the many four-wheel-drive roads that diverge from them provide access to the study areas. However, only a few roads transect the steeply dipping parts of the swell, and these rugged areas must be traversed on foot through selected cross-cutting canyons.

Folded rocks that dip as much as 70° east and southeast (typically about 30°) are prominent along the eastern and southern margin of the San Rafael Swell; locally the rocks are vertical or overturned (Hawley and others, 1968, p. 29). Strata that make up the northern and western parts of the swell are more gently folded and dip generally less than 10°. The steeply dipping rocks that make up the flanks of the swell are referred to as the "San Rafael Reef." The interior part of the swell, which rises more than 3,000 ft above the San Rafael Desert to

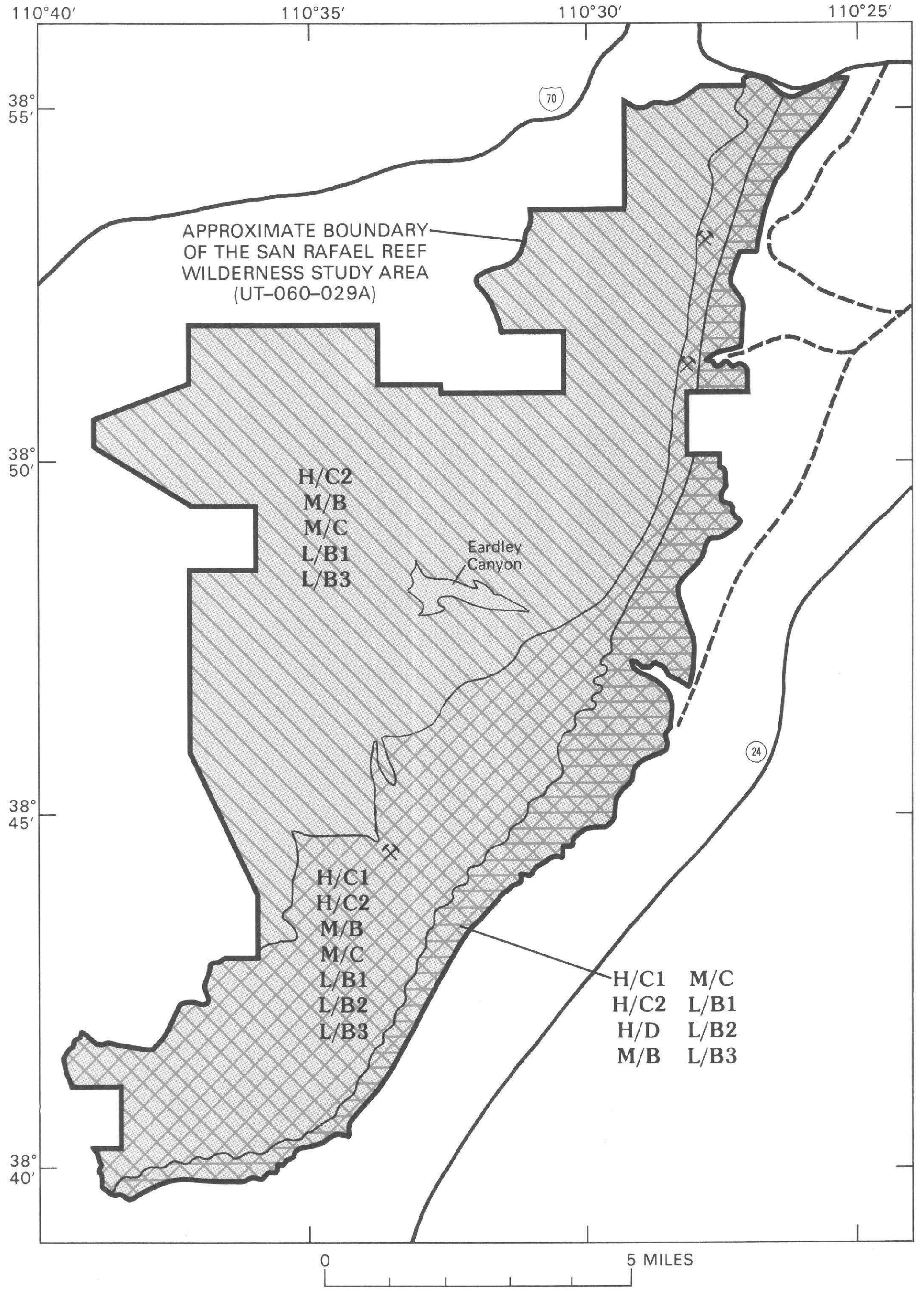

Figure 4. Mineral resource potential of the San Rafael Reef Wilderness Study Area, Emery County, Utah. Explanation is on figure 2.

the east, is deeply incised by intermittent stream channels. This central region of the swell, mostly outside wilderness study area boundaries, is referred to as "Sinbad Country." San Rafael Knob, an erosional remnant and the highest point in the San Rafael Swell at 7,921 ft, is in the west-central part of Sinbad Country.

Two perennial rivers transect the swell. In the northern part, the San Rafael River, with headwaters on the Wasatch Plateau 20 mi west of the study areas, flows from northwest to southeast through the Sids Mountain and Mexican Mountain Wilderness Study Areas, and joins the Green River approximately 15 mi south of the

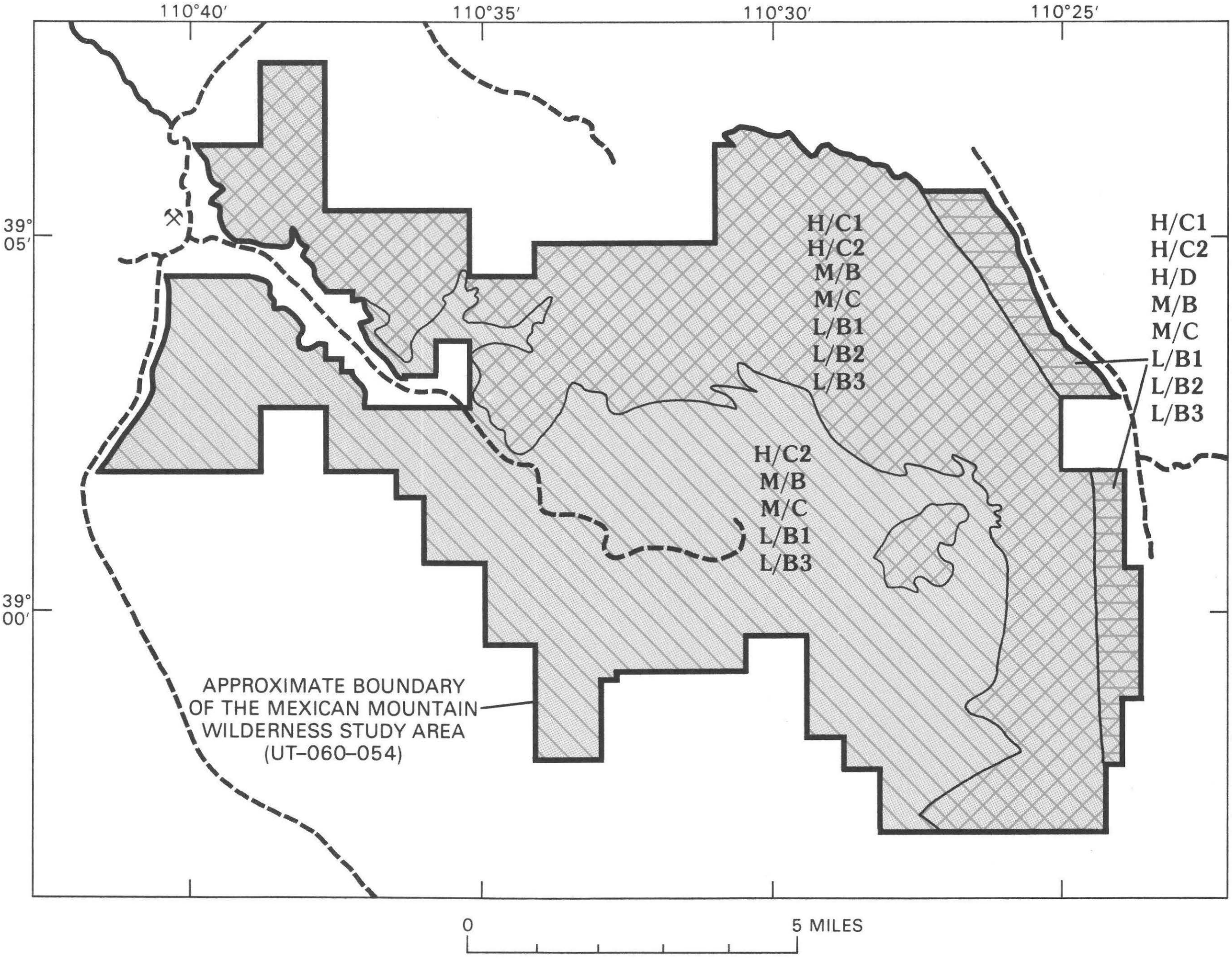

Figure 5. Mineral resource potential of the Mexican Mountain Wilderness Study Area, Emery County, Utah. Explanation is on figure 2.

town of Green River. In the southernmost part of the swell, Muddy Creek winds south and east through the Muddy Creek and Crack Canyon Wilderness Study Areas before joining the Dirty Devil River approximately 4 mi north of the town of Hanksville to the south. The San Rafael Swell area is sparsely vegetated with juniper and piñon and includes expanses of grassland that are utilized by grazing stock. Water is scarce, though springs flow much of the year in some localities; many small cattle tanks have been constructed in the central part of the swell.

Investigations by the U.S. Bureau of Mines

Mineral investigations were conducted by USBM personnel from the Western Field Operations Center, Spokane, Wash., and consisted of research, field work, and report preparation during 1986–89. Prefield studies included a literature search and examination of Emery County mining-claim and leasing records. Historical claim records for 1907–53 were searched, along with the active claim records. USBM, State of Utah, and other mineral property files were searched, and pertinent data were compiled. Attempts were made to contact all current claimants for permission to examine their mines and prospects and to obtain pertinent scientific or historical information for publication. Additional information was found in the libraries and records of the University of Utah, Salt Lake City; U.S. Department of Energy, Grand Junction, Colo.; Bendix Corp., Grand Junction, Colo.; and Hecla Corp., Coeur d'Alene, Idaho.

Field studies included a search for evidence of mining activity and mineralized sites within the study areas. The investigation included the mapping and sampling of mines, prospects, and mineralized areas in and near the study-area boundaries. A total of 912

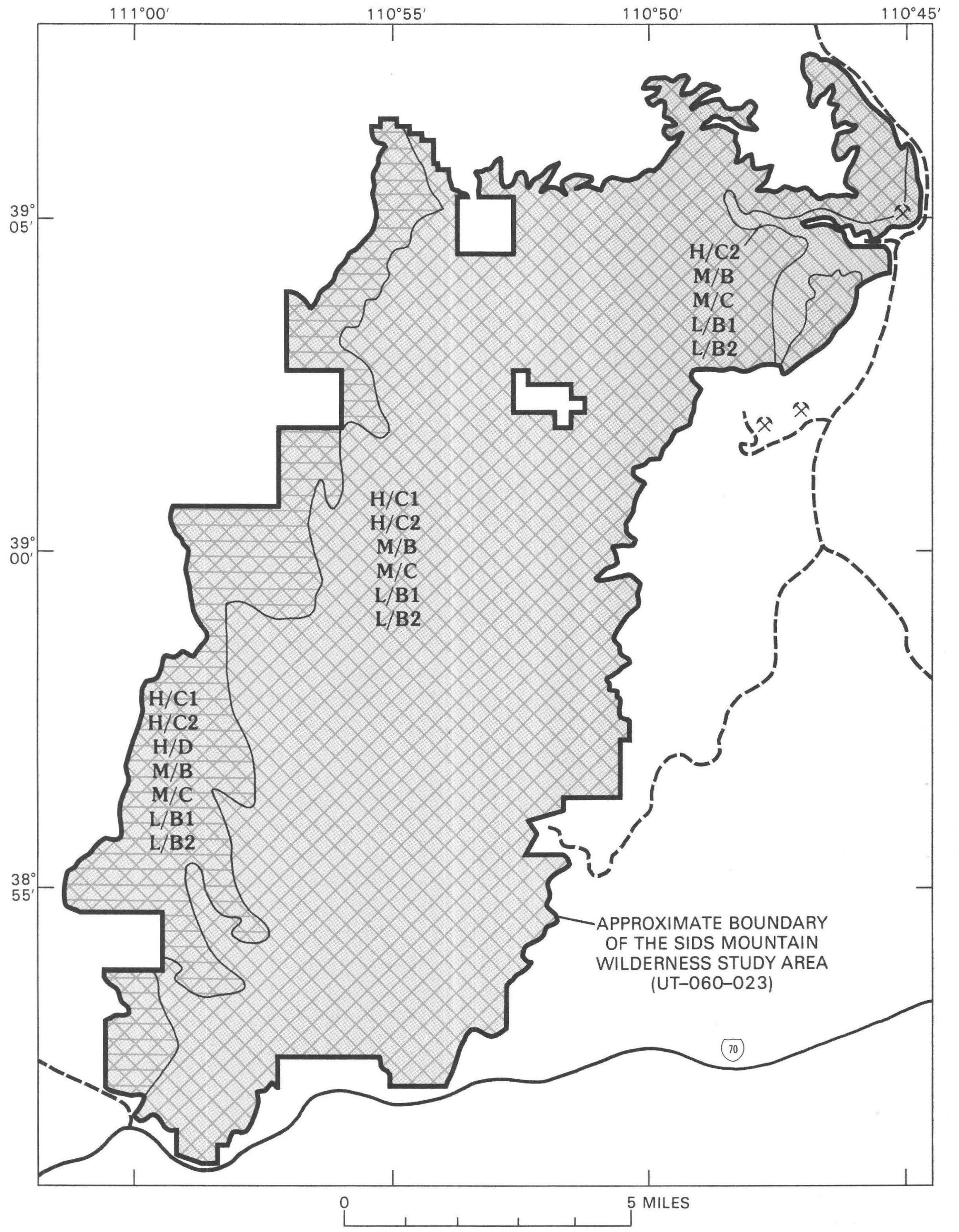

Figure 6. Mineral resource potential of the Sids Mountain Wilderness Study Area, Emery County, Utah. Explanation is on figure 2.

samples were collected by the USBM during the 1987 field season. Foot traverses with a scintillometer were conducted over most of the exposed, known uranium- and vanadium-bearing lower part of the Chinle Formation. Air reconnaissance was undertaken to help locate documented and undocumented workings and altered-rock zones. Details of the sampling procedures and geochemical and statistical analyses of 206 samples were reported by Benjamin (1989), who studied the Mexican Mountain Wilderness Study Area; Close

(1989), who studied the Crack Canyon Wilderness Study Area; Lipton (1989), who studied the Sids Mountain Wilderness Study Area; Munts (1989), who studied the San Rafael Reef Wilderness Study Area; and Neumann (1989), who studied the Muddy Creek Wilderness Study Area. Data including USBM sample analyses are available at the Western Field Operations Center, U.S. Bureau of Mines, Spokane, WA 99202.

Investigations by the U.S. Geological Survey

Field investigation of the San Rafael Swell area by the USGS began in May 1986 and continued intermittently through September 1988. Four-wheel-drive vehicles were used to reach the study areas. Most of the geologic mapping and sampling were done by foot traverses. Geologic information was compiled at 1:62,500 scale and includes new geophysical and geochemical data, subsurface data, and all available previously published geologic reports and maps as of 1988. A bedrock geologic map was prepared (pl. 1).

The geologic information in this report was provided by Susan Bartsch-Winkler and R.P. Dickerson, who conducted field investigations in 1987 and 1988, photogeologic interpretation, compilation of surface and subsurface information from referenced sources, and petrographic examination of selected sandstone samples. Stream-sediment samples, heavy-mineral concentrates derived from stream sediments, and rock samples for geochemical analysis were collected, and interpretations of laboratory data were made by H.N. Barton in May and August 1987 and November 1988. J.S. Duval examined regional aerial gamma-ray data. Gravity and magnetic interpretations are by A.E. McCafferty and V.J.S. Grauch from a gravity survey conducted during September 1987 and June 1988. Hayati Koyuncu and Keenan Lee studied the remote-sensing aspects of the mineral resource appraisal.

Acknowledgments

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APPRAISAL OF IDENTIFIED RESOURCES

By Steven R. Munts, David A. Benjamin, Terry J. Close, David A. Lipton, Terry R. Neumann, and Spencee Willett
U.S. Bureau of Mines

Mining History in the San Rafael Swell Region

The San Rafael Swell region has a long mining history. In 1880, uranium and vanadium prospectors on the Colorado Plateau began to mine deposits in the Morrison Formation at Tidwell Draw (lat 38° 5′ N.; long 115° 18′ W.; pl. 1); in 1904, the deposits at Temple Mountain (fig. 1, pl. 1) were discovered (Cohenour, 1967a, b). In 1912, mining began on the claims of the Radium Company of America in the Temple Mountain area (Miller, 1983), and production of radium began in 1920 (Hintze and others, 1967). Activity was minor until World War II when demand for uranium and vanadium increased. In 1948, the AEC (U.S. Atomic Energy Commission) established a uranium-ore buying program, starting a mining boom that lasted until 1958. During this decade, the Chinle Formation exposed in the San Rafael Swell was extensively explored, and most areas underlain by the Chinle were staked for claims. From 1958 to the early 1970's, mining activity in the area declined along with uranium prices. The 1973 and 1979 oil shortages drove oil and uranium prices upward and precipitated interest in uranium and tar sand in the swell. Since the decline of oil prices during the 1980's, there has been little mining activity. Currently (1989), there are no producing mines in the San Rafael Swell. Because of the decline in the uranium industry, the nearest potential mill for any ore produced from the study area (the Atlas Corp. mill at Moab) closed in 1988. The nearest remaining mill is at Blanding, about 200 mi to the southeast. However, this mill cannot treat the type of ore that comes from many of the study-area mines. The Moab mill would have to be reopened or a new mill with a design specific to the ore from the San Rafael Swell area would have to be built.

U_3O_8 production through 1969 from all of the deposits in the San Rafael Swell totaled almost 7 million lbs. Most of the production came from the Temple Mountain mining district, the Delta mine, and the Lucky Strike mine.

Muddy Creek Wilderness Study Area

Mining in the vicinity of the Muddy Creek Wilderness Study Area began in 1949 when uranium was discovered at the Lucky Strike and Conrad mines in Reds Canyon (fig. 7). Subsequent discoveries at the Dirty Devil mines on Tomsich Butte in 1951 and at the Delta (Hidden Splendor) mine in 1952 spurred prospecting activity in and near the study area. By 1954, several mines adjacent to the eastern boundary of the study area were producing small quantities of uranium ore. Small-scale mining continued through the late 1950's until a decline in uranium prices halted most mining in the area. The only activity in the area in the 1960's was the mining of pillars at the Delta mine in 1962. Interest in mining was renewed in the mid-1970's as uranium prices increased, stimulating exploration and prospect development. New prospects in the The Hondu (arch) area included the Rainbow, Lost Sunday, and Tea For Two properties. During this period, large claim blocks were staked inside the Muddy Creek Wilderness Study Area boundaries by the Phillips Uranium Corp. By the late 1970's, all mining-related activities had ended.

Production from properties within and adjacent to the study area boundaries, including that from the Crossbow, Joshua, Red Butte, Ryan 101, and Standard Ore and Alloys mines (fig. 7) was less than 10,000 lbs U_3O_8 (Neumann, 1989). Production from mines within 2 mi of the study area was approximately 1.65 million lbs of U_3O_8. The largest producers were the Delta mine (about 0.8 million lbs), Lucky Strike mine (about 400,000 lbs), Conrad and Crossbow mines (51,528 lbs), Dirty Devil mines (30,977 lbs), and Green Dragon No. 3 and Bluebird 1–3 mines (about 3,904 lbs) (fig. 7) (Hawley and others, 1968). The Red Butte, Standard Ore and Alloys, Joshua, A&G, Eagle, and Little Susan mines (fig. 7) each produced less than a few hundred pounds of U_3O_8 (unpub. Computerized Resource Information Bank—CRIB (available at the USBM, Intermountain Field Operations Center, Federal Center, Denver, CO 80225); Doelling, 1977). Historically, ore bodies in the area have been from 100 to 10,000 tons in size and averaged about 0.2 percent U_3O_8 and less than 0.1 percent V_2O_5. The Delta mine is the only exception, having had an ore body of about 100,000 tons.

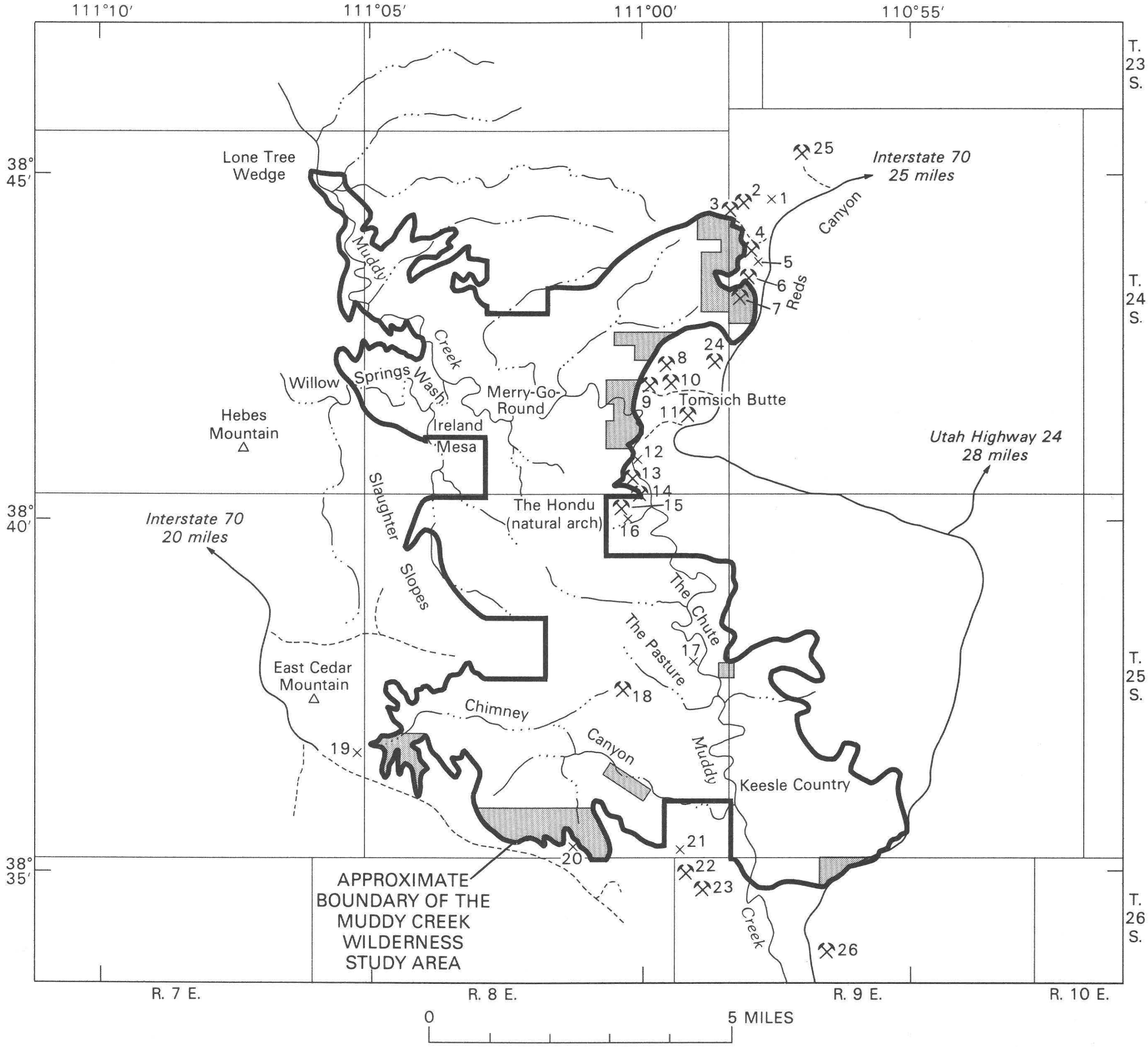
Crack Canyon Wilderness Study Area

A search of the Emery County and BLM records disclosed that many mining claims exist within the Crack Canyon Wilderness Study Area. Since 1910 and especially after 1940, more than 1,000 lode mining claims were located within the study area. All of the uranium mines and prospects within the study area are covered by current (1986) mining claims. The 600 claims held by assessment were owned by individuals. No major mining company was holding claims or was exploring in the Crack Canyon Wilderness Study Area. No patented claims are within the study area. Some early mining claims were petroleum localities in the southwest part of the study area along the San Rafael Reef near the junction of Salt Wash and Muddy Creek (pl. 1). Simmons (1982a) reported that 21 oil and gas leases covered about 75 percent (19,000 acres) of the study area. Most leases were in the northeast part of the area in the Temple Mountain mining district. By 1988, all 21 leases had lapsed. Twenty-two mines and prospects are in and near the study area (fig. 8); 13 of these, including the Delta mine (one of the largest single deposits of uranium in the San Rafael Swell), are inside the study area, and 9 are outside but near the study-area boundary (table 1). Deposits at the Cistern and Little Erma mines (outside the study area) extend into the study area.

San Rafael Reef Wilderness Study Area

Within the San Rafael Reef Wilderness Study Area, the earliest recorded mineral-exploration activity was in 1912 when Royal Swasey located a building-stone placer, and Eb Ring located a gypsum placer. Three uranium lode claims were staked in 1914, and by 1919 a total of 22 lode and 7 lode placer claims had been staked. Between 1920 and 1930, only three additional lode claims were located. From 1940 to 1949, 9 lode and 2 placer claims were filed in and near the study area, and by 1954 another 13 lode and 1 placer claims were filed. A total of 57 claims were filed between 1912 and 1954, excluding the claims located just outside the study area at Temple Mountain, which is a major uranium-producing locality. Currently (1989), more than 1,400 mining claims are located in and near (within 2 mi of) the study area. Between 1948 and 1956, the Temple Mountain district produced more than 261,000 tons of uranium ore that contained approximately 1,287,000 lbs of U_3O_8 and about 3,800,000 lbs of V_2O_5. Large producers included mines of the Calyx group (Calyx 8 and Calyx 3) and the Vanadium King 1 (fig. 9). Smaller mines, including the ATCO, Ferrous, and Cliff Dweller, each produced a few hundred pounds of U_3O_8 (Doelling, 1977). Further information on the history of the Temple Mountain mining district is in Munts (1989).

No significant ore production came from within the San Rafael Reef Wilderness Study Area until 1914. "Union Mines Development Corp. geologists studied the Temple Mountain area for the Manhattan Engineering Project during World War II and concluded that very large tonnages of low-grade ore were present . . . After the war, production from the Temple Mountain deposits began to increase rapidly" (Johnson, 1957, p. 40). "Extensive mining and production began in 1948 and accelerated owing to the development of processes enabling profitable extraction of uranium and vanadium from the asphaltic ores" (Hawley and others, 1965, p. 6). Before 1948, Standard Uranium Co. mined much of the



EXPLANATION

Area of mining claims

2 Mine—Number refers to name in list

×1 Prospect—Number refers to name in list

Gravel road

Four-wheel-drive-vehicle road

MINES AND PROSPECTS

1. Paleface prospect
2. Conrad mine
3. Crossbow mine
4. Red Butte mine
5. Pathfinder prospect
6. Standard Ore and Alloys mine
7. Joshua mine
8. Bluebird 1-3 mines
9. A&G mine
10. Green Dragon No. 3 mine
11. Dirty Devil mines
12. Tea for Two prospect
13. Spanish Trail mine
14. Eagle mine
15. Rainbow mine
16. Lost Sunday prospect
17. Unknown prospect
18. Ryan 101 mine
19. Swell prospect
20. SRAF prospect
21. Freemont prospect
22. Ryan mine
23. Little Susan mine
24. Rio Colorado mine
25. Lucky Strike mine
26. Delta mine

Figure 7. Mines, prospects, and mining claims in the Muddy Creek Wilderness Study Area, Utah.

Temple Mountain district (Miller, 1983). From 1948 to 1951, several operators were active in the district. In 1951, Consolidated Uranium Co. leased all uranium claims except those in the Vanadium King group, and from 1951 to 1956, it was the chief producer in the district. However, in November 1956, Consolidated sold its interest to Union Carbide Nuclear Corp. From 1956 until the early 1970's, production was by Union Carbide

Table 1. Uranium and vanadium resources in and near the Crack Canyon Wilderness Study Area, Emery County, Utah

[Sites are shown on fig. 8. Quantities and grades are from Doelling (1977, a–h); *, mine outside the study area; ppm, parts per million; 1,000 ppm = 0.1 percent; do, ditto]

Site name	Site No.	Quantity (tons)	Resource classification[1]	Grade (ppm)	Commodity
Black Beauty mine	15	200	Subeconomic resource.	2,600 3,000	U_3O_8 V_2O_5
Blue Bird mine...	1*	10,000	do.	2,000	U_3O_8
Cistern mine area	8*	30,500	do.	2,000	U_3O_8
Delta mine.......	3	35,000 70,000	do. do.	2,000 1,000	U_3O_8 U_3O_8
Little Erma mine	10*	17,000	do.	2,000	U_3O_8
Virginia Valley mine.	12*	500	do.	2,000	U_3O_8
Yellow Canary mine.	18*	58,000	do.	500 5,000	U_3O_8 V_2O_5
Grand total..........		221,000			
Wilderness study area total.........		105,200			

[1]The resource classification definitions are from U.S. Bureau of Mines and U.S. Geological Survey (1980). The classification of each deposit is based on the estimate of mining and milling costs.

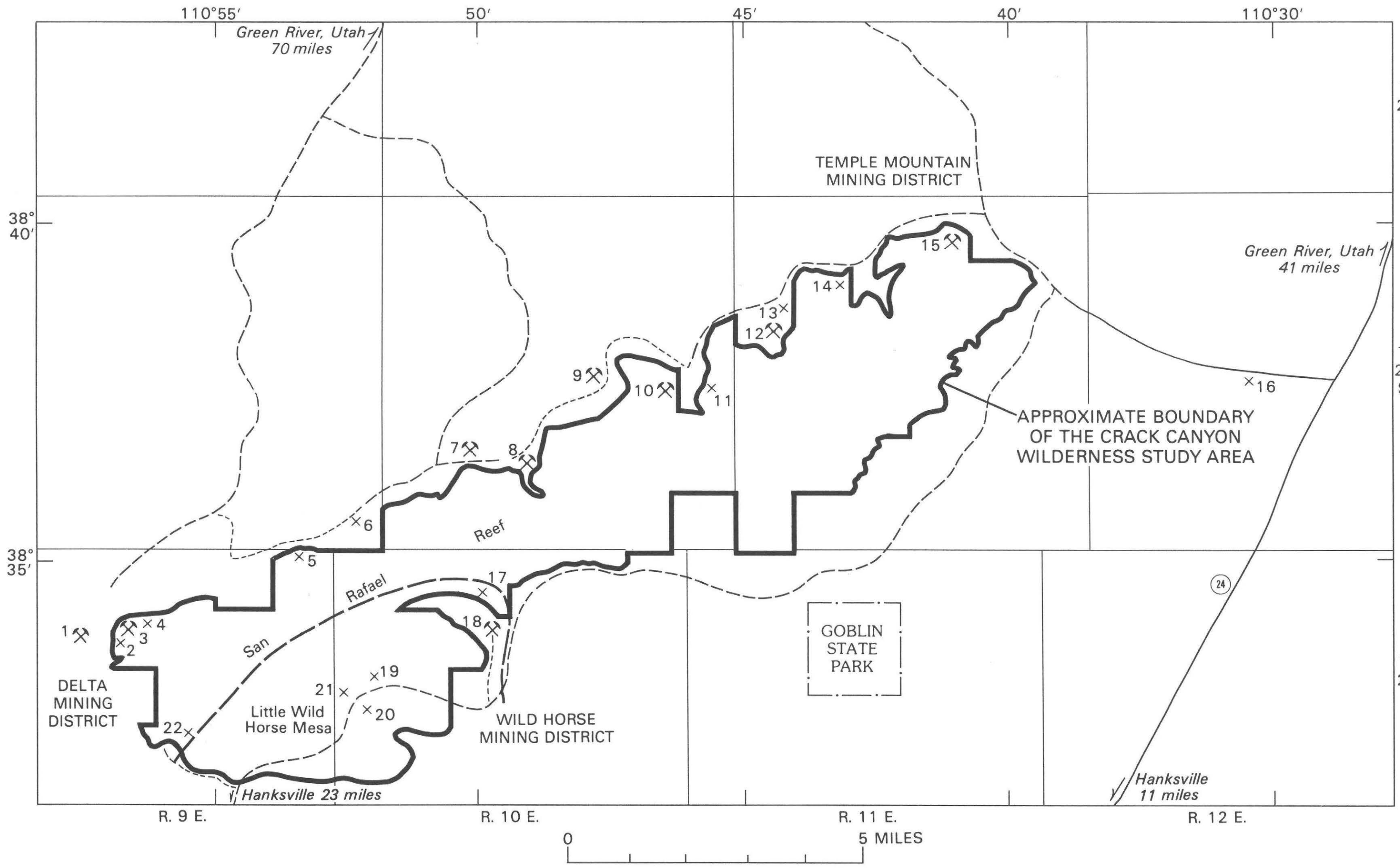
or its lessees. Between 1948 and 1958, several smaller mines northeast of the Temple Mountain district and inside the study area produced uranium. These mines were the Unknown No. 3, Uneva, and the ATCO Nos. 3, 4, and 11, respectively (Munts, 1989).

Mexican Mountain Wilderness Study Area

Examination of Emery County historical records indicates that from 1907 to the late 1940's, only a few scattered claims were located in the Mexican Mountain Wilderness Study Area. However, the 1950's uranium boom produced an increase in claim staking. Field observation of old claim posts indicates that most of the area underlain by the Chinle Formation has been staked at one time or another since the late 1940's. February 1986 BLM claim records indicate that nine persons hold 247 active claims in or adjacent to the study area. These claims are for uranium in the Chinle Formation, for copper and related metals along small shear zones, and for sulfur at warm springs. Until 1984, Pathfinder Mines Corp. and Uranerz USA, Inc., held the R.C. claims (fig. 10) on a collapse structure northeast of Window Blind Peak (fig. 10). No production is recorded from the study area, but the Jasmine No. 1 prospect may have produced a few tons of uranium ore. Four other small prospects were located in or adjacent to the study area: the Bob claims (on a collapse structure) and three small copper prospects known as the Alice and Primrose claims adjacent to the east side of the study area. Details of these claims and prospects are in Benjamin (1989).

Sids Mountain Wilderness Study Area

Mining in the Sids Mountain Wilderness Study Area began in 1898 when Jack Montis opened, from 1899 to 1905, two copper mines, the Sorrel Mule prospect and the ZCMI prospect (McClenahan, 1986). Uranium mining began in 1949 when the Dexter claims were staked (Reyner, 1950). Reyner (1950) reported that about 180 tons of ore was shipped from the area during 1949. In the early 1950's, several other mines on Calf Mesa were opened, including the Lone Tree and Dalton groups, and the Hard Pan and Clifford Smith prospects (Reyner, 1950). The Plymouth Rock and Buckhorn prospects were located in 1950, and the North Cane Group was located in 1975. Production from mines and claims located on Calf Mesa were as follows: the Dexter claims area yielded 2,091 tons of U_3O_8 from 1954 to 1968 and 25 lbs of U_3O_8 in 1972; the Dalton group yielded 46 lbs of U_3O_8 from 1950 to 1976; minor unrecorded and unverified production came from the


110°55′
50′
45′
40′
110°30′
38° 40′
38° 35′
T. 24 S.
T. 25 S.
T. 26 S.
R. 9 E.
R. 10 E.
R. 11 E.
R. 12 E.
Green River, Utah 70 miles
Green River, Utah 41 miles
Hanksville 23 miles
Hanksville 11 miles
TEMPLE MOUNTAIN MINING DISTRICT
APPROXIMATE BOUNDARY OF THE CRACK CANYON WILDERNESS STUDY AREA
DELTA MINING DISTRICT
WILD HORSE MINING DISTRICT
GOBLIN STATE PARK
Little Wild Horse Mesa
San Rafael Reef
24
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
0
5 MILES

EXPLANATION

⚒1 **Mine**—Number refers to name in table

×4 **Prospect**—Number refers to name in table

———— **Paved road**

— — — — — **Gravel road**

- - - - - - - - - - **Four-wheel-drive-vehicle road**

—— —— —— **Boundary of gypsum occurrence**

MINES AND PROSPECTS

[Sites underlined have identified resources; *, site outside the wilderness study area; principal commodities are shown in parentheses; U, uranium; V, vanadium; Cu, copper; Pb, lead; Co, cobalt]

1.* Blue Bird mine (U, V)
2. Queen Ethel prospect (U, V)
3. Delta mine (U, V)
4. Alpha prospect (U, V, Cu)
5. Bullberry Spring prospect (U, V, Cu)
6.* West Great Basin prospect (U, V)
7.* Great Basin mine area (U, V, Cu)
8.* Cistern and Magor mine area (U, V)
9.* Little Wild Horse mine area (U, V, Cu)
10. Little Erma mine (U, V, Cu, Pb, Co)
11. Brown Dog prospect (U, V)
12.* Virginia Valley mine (U, V)
13.* Desolation mine (U, V)
14. Arrowhead prospect (U, V)
15. Black Beauty mine area (U, V, Cu)
16.* San Rafael Desert prospect (U)
17. GG&S prospect (U, V)
18.* Yellow Canary mine (U, V)
19. Rockhound prospect (petrified wood)
20. Pandora prospect (U)
21. Goodluck prospect (U)
22. Little Wild Horse Mesa prospect (gypsum)

Figure 8. Mines, prospects, and mining claims in the Crack Canyon Wilderness Study Area, Utah.

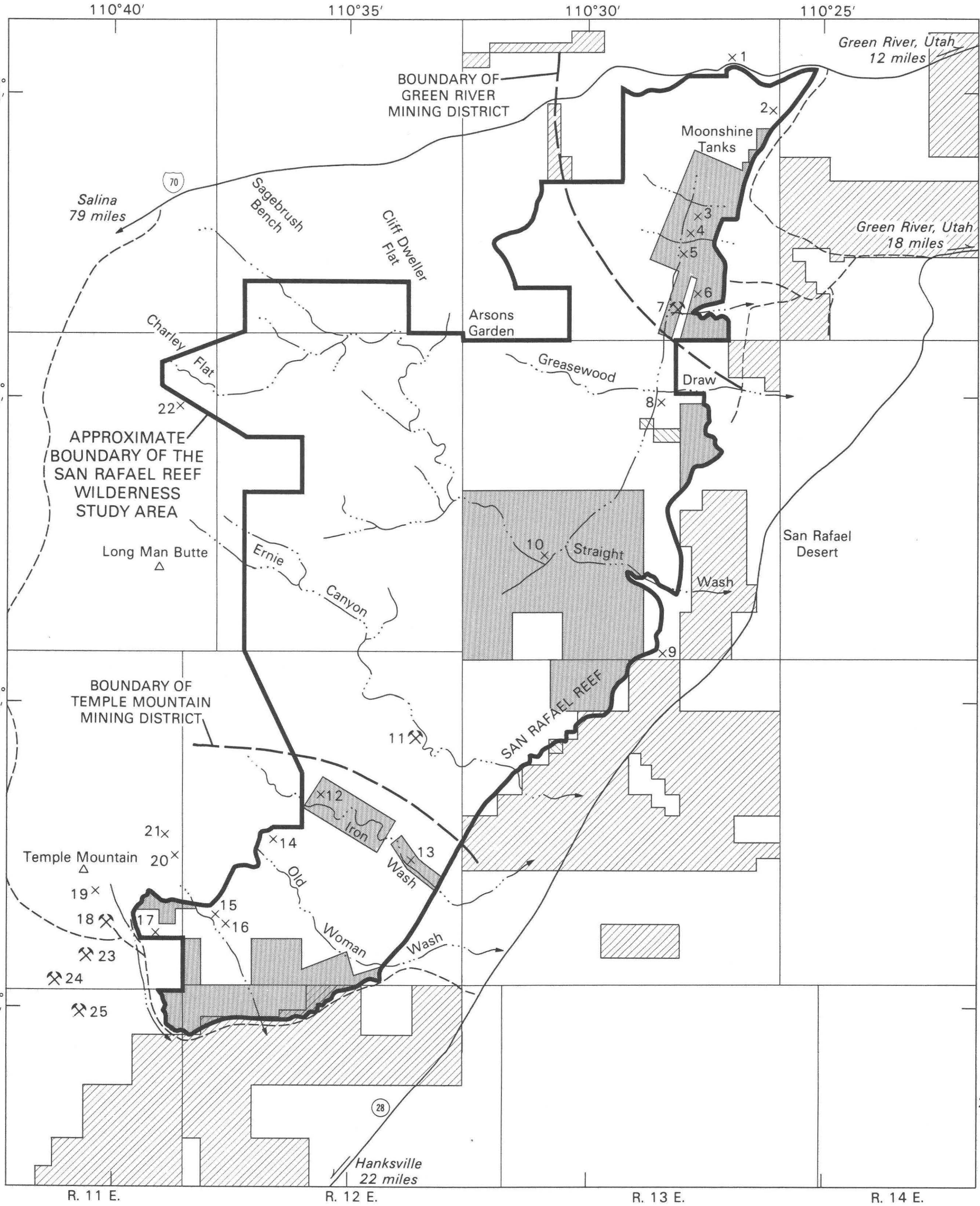


Figure 9 (above and facing page). Mines, prospects, mining claims, and oil and gas leases and lease applications in the San Rafael Reef Wilderness Study Area, Utah.

EXPLANATION

Area of active mining claims

⚒7 Mine—Number refers to name in list

×6 Prospect—Number refers to name in list

Oil and gas lease area

Oil and gas lease-application area

– – – – – Unimproved road

MINES AND PROSPECTS

[*, site outside the wilderness study area]

1.* Unknown No. 1 prospect
2. Unknown No. 2 prospect
3. Unknown No. 3 prospect
4. Uneva prospect
5. Silver Reef prospect
6. Flaming Star prospect
7. Cliff Dweller mine
8. Foly prospect
9.* Copper Chief prospect
10. Ferrous prospect
11. ATCO mine
12. Mellenoid prospect
13. Iron Wash prospect
14. East Pipe prospect
15. Big Cat prospect
16. B No. 1 prospect
17. Twilight prospect
18.* Vanadium King mine
19.* Temple prospect
20.* Golden Cinch prospect
21.* Golden Pipe prospect
22.* Mother Lode prospect
23. Calyx mine group
24. North Mesa mine
25. Camp Bird mine

Douglas prospect, the Lone Tree group, and the Plymouth Rock prospect (Simmons, 1982b).

Mineral Commodities and Appraisal

Uranium and accompanying vanadium are the principal metallic commodities found in the San Rafael Swell region. Gypsum is the chief nonmetallic commodity. The region has occurrences of petroleum, tar sand, copper, sandstone, sand and gravel, semiprecious gemstones, and limestone. Mine-production figures are reported in short tons.

Muddy Creek Wilderness Study Area

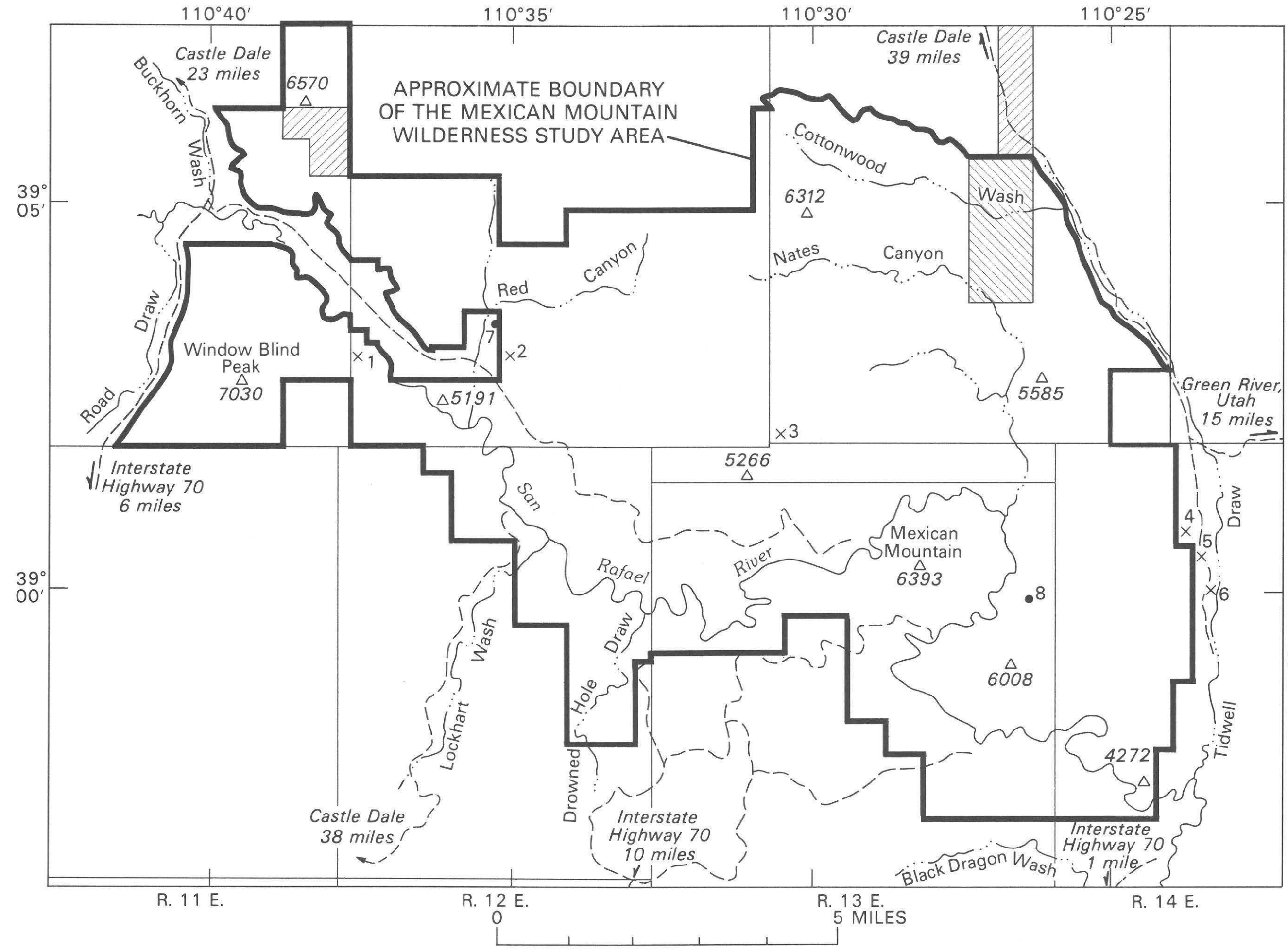
Twenty-three lode properties were examined in the Muddy Creek Wilderness Study Area (fig. 7). The Ryan 101 and Joshua mines and an unknown prospect near The Pasture are in the study area, and 20 mines and prospects adjoin the eastern boundary. The underground workings of the Crossbow, Red Butte, and Standard Ore and Alloys mines appear to extend inside the study-area boundary. Mine workings examined range in elevation from 5,200 ft (Eagle mine) to 5,860 ft (Joshua mine), and include 26 open adits 8–1,100 ft long, 5 inaccessible adits (estimated not to exceed 500 ft long), and many pits and trenches. A summary of all properties is in Neumann (1989).

Since 1949, 303 mining claims covering 6,000 acres have been staked in the study area. Of these, fewer than 100 appear to be current in their assessment. None of these claims has been patented. Most of the claims are in the northeast section of the study area and represent extensions of the main claim group outside the study-area boundary. No drilling or exploration work was seen during the reconnaisance field work. No mineral or oil and gas leases exist in the study area.

Uranium and Vanadium

USBM investigations indicate that uranium, vanadium, gypsum, common-variety sandstone, limestone, and petrified wood occur in the Muddy Creek Wilderness Study Area. The Chinle Formation, which dips beneath most of the study area, crops out along its northeast boundary and extends inside the southeast part of the study area. The Moss Back and Monitor Butte Members of the Chinle Formation have been mined and prospected in the Tomsich Butte-Reds Canyon area (fig. 7) adjacent to the northeast boundary of the study area.

Mines and prospects in the Tomsich Butte-Reds Canyon area are in the southern mineral belt of Hawley and others (1968). The paleoriver channel system is projected to extend north-south through Tomsich Butte, trend northwest into the study area, and northeast through the Joshua and Conrad mine areas. Ninety-eight samples were taken from mines, prospects, and Chinle Formation outcrops in the study area. Only 11 samples of 98 from five mines in the area contained concentrations at or above the historical mining grade of 0.2 percent U_3O_8. Included in these 11 samples are one sample from the Rainbow mine; two from the Green Dragon No. 3 mine; five from the A&G mine; one from the Bluebird 1–3 mines; and two from the Crossbow mine. Only the Crossbow mine samples were from within the study area. Most samples were taken in areas where gamma-ray scintillometer readings were judged to be high (background readings at Chinle Formation outcrops were 50–100 cps (counts per second); high was considered to be greater than 500 cps in mine workings). Chip samples from the area contained 4 ppm to 2.36 percent U_3O_8 and 2 ppm to 2.22 percent V_2O_5. Sample-length weighted averages of analytical data from underground workings



EXPLANATION

×2 Prospect—Number refers to name in table

•8 Mineralized outcrop—Number refers to name in table

Oil and gas lease area

Oil and gas lease application area

— — — — Gravel road

5585 △ Elevation point

[*, site outside wilderness study area; all properties are classified as occurrences]

Map No.	Location or property name	Commodity
1.	R.C. claims	Uranium.
2.	Jasmine No. 1 prospect	Uranium.
3.	Bob claims	Uranium.
4.*	Alice claims prospect	Copper, lead, zinc, silver.
5.*	Primrose claims, north prospect.	Silver.
6.*	Primrose claims, south prospect.	Copper, silver.
7.	Silver-bearing Moss Back Member.	Silver.
8.	Vanadium-bearing Temple Mountain Member.	Vanadium.

Figure 10. Prospects, mining claims, mineralized outcrops, and oil and gas leases and lease applications in the Mexican Mountain Wilderness Study Area, Utah.

ranged from 449 ppm U_3O_8 and 381 ppm V_2O_5 at the Rainbow mine, to 0.47 percent U_3O_8 and 1.58 percent V_2O_5 at the A&G mine. Most sample analyses from underground mines in the area could not be averaged because mineralized lenses were not distinguishable from unmineralized material nearby, so the samples were not comparable. Historical mill records and drill data from mines in the Tomsich Butte area indicate that 2,000 ppm (0.2 percent) U_3O_8 was the ore grade at most mines in the area. Samples taken from Chinle Formation outcrops inside the study area near The Merry-Go-Round averaged 43 ppm U_3O_8 and 317 ppm V_2O_5.

These concentrations indicated no large amount of uranium. The localized, irregularly shaped, nondisseminated nature of the uranium occurrences in and near this area precluded quantitative resource estimations.

Forty samples were analyzed from mines, prospects, and outcrops of the Chinle Formation within a system of paleochannels in the Chimney Canyon area in the southwest part of the study area. Of these 40 samples, concentrations in 4 were at or above the historical mining grade of 0.2 percent U_3O_8; 1 sample was from the Ryan 101 mine, and 3 were from the Little Susan mine. Only the Ryan 101 mine sample was from the study area.

In the Chimney Canyon area at the Ryan 101 mine (fig. 7, no. 18), a paleochannel system is in the Moss Back Member of the Chinle Formation. The property has eight major and seven minor paleochannels. The paleochannels appear to be part of a system that extends from the Ryan 101 property to the Little Susan mine (fig. 7, no. 23) 3 mi to the south. Fourteen samples from mine workings and Moss Back outcrops contained between 1 ppm to 0.28 percent U_3O_8; V_2O_5 content ranged from 29 to 618 ppm. The weighted average of samples from both Ryan 101 adits was 215 ppm U_3O_8. These concentrations are lower by a factor of about 10 than economically significant uranium concentrations. A reconnaisance of Chinle Formation outcrops to the north near The Pasture revealed no paleochannels and no scintillometer readings above background levels. One sample had greater than expected concentrations of silver, arsenic, copper, lead, and zinc.

No economically significant uranium concentrations were identified at the ground surface in the Muddy Creek Wilderness Study Area. However, conditions potentially favorable for uranium deposition are present in the subsurface. The ore-bearing solutions responsible for the Delta mine uranium deposit and other ore bodies in the immediate vicinity could have deposited similar ore in the study area.

The difficulty of exploration for podiform deposits, the historically small size of nearby deposits, the absence of a nearby operating uranium milling facility accepting asphaltitic ore, and the depressed United States uranium industry probably will not encourage searches for new uranium resources in the foreseeable future. Coupled with these factors are the current excess production over demand, cancellation of nuclear-power-plant construction contracts, apparent adequate supplies of known uranium reserves for projected domestic needs, known foreign deposits of higher grade with lower mining costs, environmental concerns about the use and disposal of nuclear fuels in power plants, and the low price of uranium.

Surface exposures of the uranium-bearing Chinle Formation have been explored. Potential uranium deposits may occur in the Chinle Formation underlying the study area. The discovery and delineation of deposits at depth would require close-spaced drilling through thick overburden. A drilling program using 20- to 50-ft centers would be needed in Chimney Canyon at the Ryan 101 mine and in Reds Canyon at the Crossbow mine to fully evaluate uranium potential in the Muddy Creek Wilderness Study Area.

Industrial Minerals

Gypsum

Gypsum occurrences in the Carmel Formation crop out intermittently for about 1.5 mi on a mesa above Willow Springs Wash in the northwest part of the Muddy Creek Wilderness Study Area (fig. 7). A calculated estimate indicates that an inferred subeconomic resource of about 11 million tons of surface-minable gypsum containing 94.48 percent $CaSO_4$ is present in this area. Estimates were based on a 0.57-mi^2 (square mile) area, an average thickness of 10.0 ft, and a tonnage factor of 13.9 ft^3/ton (cubic feet per short ton). The estimate assumes a continuity of gypsum back from the outcrop and is limited to gypsum covered by no more than 100 ft of overburden. The gypsum beds dip 5° west and are interlayered with carbonate beds of various thicknesses. According to BLM records dated February 1986, none of the gypsum in the study area has been claimed.

Examination and sampling of the exposed gypsum occurrences indicate that the gypsum is adequate for use in building materials, fertilizer, cement, and many other products. Gypsum is a low-unit-value, high-bulk commodity, and the most important factors in evaluating a deposit are its proximity to markets and ease of mining. Deposits of commercial size and quality are widespread in the United States, and development depends largely on the accessibility and the demand for gypsum products in the region near the deposit (Appleyard, 1983). Because of the absence of a nearby market and the presence of large minable deposits elsewhere in Utah nearer to markets, the gypsum occurrences in the study area are not likely to be mined now or in the foreseeable future. Because the gypsum is interlayered with carbonates, mining costs would be prohibitive. If mining were to take place, it would likely occur outside of the western boundary of the study area where the gypsum is flat lying and more accessible.

Sandstone

The Navajo Sandstone was evaluated for its value as industrial special-purpose sands, such as foundry and glass sands. Tepordei (1988) stated that most manufacturers establish their own specifications regarding the chemical purity of the sand they use. As a rough guide, foundry-sand specifications require greater than

98 percent SiO_2 (Wilburg, 1983), and first-quality optical-glass specifications require greater than 99.8 percent SiO_2 and less than 0.1 percent Al_2O_3 and 0.02 percent Fe_2O_3 (Mills, 1983). Third-quality flint glass may contain as little as 95 percent SiO_2 and as much as 4 percent Al_2O_3. Analytical data from a sample taken from Navajo Sandstone shows low SiO_2 (92.75 percent) and high impurities (3.0 percent Al_2O_3, 0.26 percent Fe_2O_3), making it unsuitable for foundry sand and the manufacture of glass; Wingate Sandstone is inferred to be similar. The sandstone may be suitable for dimension stone, but because of its remote location and the vast amounts outside the study-area boundary, it cannot be classified as a resource.

Limestone

Limestone suitable for aggregate and agricultural purposes is in the Carmel Formation in the northwest part of the Muddy Creek Wilderness Study Area and in the Kaibab Limestone exposed near The Chute (pl. 1). The limestone is relatively low in $CaCO_3$ (89.29 percent) and is high in SiO_2 (6.22 percent), precluding its use in most limestone-consuming industries (Bowen and others, 1973). The limestone could be crushed and used locally for aggregate or agriculture, but large quantities of similar or higher grade material are readily available closer to markets. Because the limestone in the study area possesses no unique characteristics, its development is highly unlikely.

Petrified Wood

Petrified wood is found in the Moss Back Member of the Chinle Formation on the eastern boundary of the Muddy Creek Wilderness Study Area. Most of the wood is generally not of polishable quality, but in places it has attractive colors and patterns suitable for decorative material. The wood is dark reddish brown and silicified, and has visible growth rings. Large petrified-wood resources are present outside the study-area boundary; petrified wood inside the study area is not unique and is not likely to be mined.

Crack Canyon Wilderness Study Area

Uranium and vanadium are the principal metallic commodities in the Crack Canyon Wilderness Study Area, and gypsum is the primary nonmetallic commodity. A summary of mineral commodities found in the study area is given in Close (1989).

Uranium and Vanadium

The most economically valuable mines and prospects within and adjacent to the Crack Canyon Wilderness Study Area contain uranium, principally within the Chinle Formation. The study area lies within a northwest-trending mineralized belt that conforms to an ancient fluvial system. Uranium deposits in the belt range in size from a few tons to more than 100,000 tons (typically 1,000–5,000 tons); average grade of the ore mined was 0.2 percent (Hawley and others, 1968). Production from 10 mines in and near the study area totaled 945,252 lbs of U_3O_8; production from within the study area totaled 828,261 lbs. Vanadium and copper were recovered from the uranium ore during milling, but the amounts recovered are not known. Identified subeconomic resources of uranium and vanadium within and adjacent to the study area total about 221,000 tons (table 1) and contain 500–2,600 ppm U_3O_8 and as much as 5,000 ppm V_2O_5.

Of 163 samples analyzed by the USBM from deposits in the Chinle Formation in the Crack Canyon Wilderness Study Area, 59 had more than 100 ppm U_3O_8, and 25 had more than 1,000 ppm. Sixteen samples from six mines had more than 0.2 percent U_3O_8, the grade historically suitable for mining. These were samples from the Cistern, Black Beauty, Delta, Great Basin, Little Erma, and Little Wild Horse mines (fig. 8). The three principal uranium mines, in order of relative importance in terms of past production and future mining potential, are the Delta (inside the study area) and the Cistern and Little Erma (both outside the study area).

The Chinle Formation is 600–1,800 ft beneath much of the study area, and access to it must be by underground mining methods. Some smaller and lower grade occurrences are present in the Jurassic Morrison Formation beneath Little Wild Horse Mesa in the southwestern part of the study area. Resources of the Crack Canyon Wilderness Study Area, though they are near minable grade, are not of sufficient size to repay the cost of conventional underground mining and milling or in-place leaching at current (1989) U_3O_8 prices (see Close, 1989, for cost details). Therefore, the deposits in the study area (lat 38° 33′N.; long 110° 50′ W.; pl. 1) are classified as subeconomic resources.

Radiometric surveys followed by drilling are needed to delineate uranium and vanadium reserves and (or) resources in the Chinle Formation. Test mining by leaching would be needed prior to development.

Industrial Minerals

Gypsum

No gypsum has been produced from either the Summerville or Carmel Formations in the Crack Canyon Wilderness Study Area. An identified subeconomic resource of gypsum in the Summerville Formation (the Little Wild Horse Mesa prospect; fig. 8) totals an estimated 20 million tons underlying an area of 18 mi^2, having an average thickness of greater than 9 ft. Limited sampling suggests that the Summerville occurrence contains gypsum that is suitable for manufacturing of all gypsum-based products. However, it is not likely to be minable in the foreseeable future due to its distant location from markets. Gypsum in the Carmel Formation in the study area is in lenses that are too small and scattered to be classified as a mineral resource.

Sandstone, Sand, and Gravel

The rock formations in the Crack Canyon Wilderness Study Area contain large quantities of common, low-value sandstone. Also, small quantities of common sand and gravel occur along the bottoms of the canyons that cross the study area. However, no unique, high-value products could be produced from either material in or near the study area. Also, the development of facilities to produce common silica, sand, gravel, or other related products from the study area is not economic in the foreseeable future, due to lack of nearby markets.

Semiprecious Gemstones

Occurrences of semiprecious gemstones were identified in the Morrison Formation on Little Wild Horse Mesa of the Crack Canyon Wilderness Study Area. Petrified logs containing agate and jasper occur in some paleostream channels. Alabaster may be present in some gypsum beds.

Oil, Gas, and Tar Sand

No oil and gas reserves or resources have been described from the vicinity of the Crack Canyon Wilderness Study Area. Within the study area, oil seeps and asphaltite are in the uranium-bearing rocks, and in the Magor mine, oil forms pools underground. However, the petroleum and tar-sand occurrences in the study area are too small, low-grade, and irregular to be classified as a mineral resource.

Geothermal Energy

There is no evidence of geothermal energy sources in the Crack Canyon Wilderness Study Area.

San Rafael Reef Wilderness Study Area

Twenty-two lode claims or claim groups in and near the San Rafael Reef Wilderness Study Area were examined during the 1987 field study (fig. 9). Fifteen properties are within and seven are near the study area. Those near the study area are primarily to the southwest near Temple Mountain. Complete information on all properties and 216 samples is in Munts (1989).

Approximately 761 claims (57 historic and 704 current), which cover about 15,000 acres, have been located within the San Rafael Reef Wilderness Study Area. A partial review of Emery County courthouse and BLM records indicates that between 1914 and 1957, as many as 47 lode and 10 placer claims (including 3 oil placers) were located in and near the study area. BLM claim-location records (1986) indicate approximately 704 active claims. As many as 736 claims covering almost 14,700 acres have been staked within 2 mi of the study-area boundary. Records indicate that at least 1,400 of these claims were active in 1987; none of the claims in or near the study area has been patented. Many of the current claims are parts of large claim blocks that are both inside and outside the study area, primarily along the eastern and southern boundary. Although drilling and exploration have occurred in and near the study area since the early 1940's, as of 1987 there was no evidence of exploration or drilling activity. BLM records in 1986 indicate that 37 oil and gas leases covered parts of the study area. Although only one oil and gas well was drilled inside the study area and four others were drilled near the study area, none of the leases are held by current exploration or active production (Simmons, 1983a). None of the study area is under geothermal lease (Simmons, 1983a).

Uranium and Vanadium

The Chinle Formation, which crops out along the southern and eastern part of the San Rafael Reef Wilderness Study Area, contains most of the uranium and vanadium mines and prospects in the study area (fig. 9). The Chinle has been eroded from the western part of the study area. All mines and most prospects are near the contact of the Temple Mountain Member with the overlying Moss Back Member (pl. 1). This contact is exposed along most of the 21-mi length of the study area, especially along the east limb of the San Rafael anticline. Although some prospects are upsection from this contact, none of these has reported uranium or vanadium production. Sandstone-hosted and breccia-pipe ore bodies in the study area range in size from a few hundred tons to tens of thousands of tons. Ore bodies within breccia pipes near the study area are small and contain uranium, vanadium, and small amounts of zinc, lead, and molybdenum. Uranium-bearing exposures at the Uneva prospect and in the northern one-third of the study area are part of the northern mineralized belt of Hawley and others (1968).

Geochemical analyses of rock samples from the San Rafael Reef Wilderness Study Area and vicinity are given in Munts (1989). The 22 mines and prospects in and near the study area were divided into those with production (in the southern half of the study area that is part of the Temple Mountain mining district) and those without recorded production (in the northern half of the study area). Seventy samples from mines and prospects in and near the study area were collected and analyzed; of these, 50 were from mines and prospects within the study area. None of these contained historical-average ore-grade uranium or vanadium (0.2 percent). None of the 20 samples collected from prospects outside the study area contained current (1987) ore-grade uranium of 0.2 percent U_3O_8, and only one sample, from the Vanadium King 1 mine, had near-historical-grade vanadium of 1.36 percent. No economically significant uranium and vanadium occurrences were identified in surface exposures within the study area. Possible subsurface occurrences might be found through an extensive drilling program, aided by study of trace-element geochemistry of samples.

Factors that affect mining, processing, and deposit profitability include (but are not limited to) deposit size, grade, hydrocarbon content, distance to suitable mills, access, and support facilities. Assuming current (1989) prices of $12.50/lb U_3O_8, average Temple Mountain mining district ore (0.2 percent U_3O_8) would be marginally economic. Known occurrences within or immediately adjacent to the study area are not presently economic. Either the price or grade must increase by 50 percent above current levels. These calculations do not account for the vanadium content of some ore. If vanadium is considered as a coproduct or byproduct, some occurrences may be marginally economic.

Geologic and geochemical environments may exist for additional uranium and vanadium ore bodies. To determine if any exist, a two-phase program is necessary: (1) a detailed geochemical survey; and (2) a detailed drilling program, epecially in an area extending about 5 mi into the study area between the Vanadium King mine and the ATCO group prospect (Munts, 1989).

Gold and Base Metals

Although some of the earliest claim locations in the San Rafael Reef Wilderness Study Area were for gold in addition to uranium, no uranium mines in or near the study area have reported gold production, and gold has not been found with uranium. To determine if gold anomalies were present in the study area, panned-concentrate samples were analyzed for gold (Munts, 1989). None of the values detected in host-rock samples are economic, but they may indicate that minor amounts of gold may be present and could represent a byproduct from uranium mining. Samples from the ATCO group prospect contained 138 ppm molybdenum. Zinc was an anomalous element in samples from the Mellanoid prospect. None of the gold, copper, molybdenum, or zinc values indicate ore-grade material, but these metals could be byproducts of uranium milling.

Gold anomalies apparently associated with uranium deposits occur in the study area; it is necessary to determine if these anomalies are significant and if they constitute a potential resource for uranium associated with breccia pipes. A study of this type should include additional geologic evaluation, geochemical sampling, and drilling.

Industrial Minerals

Gypsum

Gypsum occurs in a single bed in the Carmel Formation for about 4.5 mi along and within the northeastern edge of the study area. The bed is approximately 4 ft thick. Analytical results for six samples are given in Munts (1989). Although the quality of gypsum is generally consistent, lower grade areas may occur within a bed. Two samples contained greater than 99.9 percent $CaSO_4$ and may be of adequate grade for use in building materials, fertilizer, and cement (Appleyard, 1983). Inferred subeconomic resources are estimated to be approximately 680,000 tons based on a 4-ft thickness, approximately 23,700 ft of strike length, a depth of 100 ft, and a tonnage factor of 13.9 ft^3/short ton. These gypsum occurrences are considered an inferred subeconomic resource based upon analytical results, dip and thickness of bed, difficulty of mining, distance to a processing plant, and distance to market. Although the beds average 4 ft thick, thicker deposits of gypsum occur elsewhere within or near the San Rafael Swell region (Lipton, 1989). Near-vertical beds are more difficult and costly to mine than horizontal beds. The nearest raw gypsum market and processing plants are in Richfield, Utah (Simmons, 1983b), which is approximately 90 mi west of the study area. These plants are currently supplied by gypsum deposits closer to Richfield. Gypsum is a low-density, low-value material, with a low dollar value per ton. Therefore, either freight rates must be low, markets must be nearby, or market prices must increase. Although this occurrence may be of economic grade in surface outcrop, it will probably not be mined in the near future.

Limestone

The Kayenta Formation and the Kaibab Limestone exposed in the study area contain limestone. Kaibab Limestone appears in outcrop to be of lesser quality than the limestone within the Kayenta, and it contains fossils and local interbeds of siltstone and sandstone. Limestone suitable for aggregate or possible agricultural purposes exists within the Kayenta Formation along the eastern edge of the study area. Limestone within the Kayenta is dark blue gray, massive, and fractured, and ranges in thickness from 4 to 12 ft. Analysis indicates a relatively low $CaCO_3$ content. High silica content (7.38 percent) precludes use in most applications (Bowen and others, 1973). Although the limestone could be crushed and used locally for aggregate or agriculture, other sources of equal or better quality are closer to current markets. This occurrence is not likely to be developed in the near future.

Sandstone (Silica)

The Wingate, Navajo, and Entrada Sandstones, and the Kayenta, Carmel, and Morrison Formations all contain sandstone that was evaluated and sampled to determine suitability for use in various industrial applications. Samples were collected from representative outcrops to determine silica content and number and type of impurities present (Munts, 1989). None of the samples collected contained sufficient silica to meet the minimum specifications for any of the sand uses, including glass or foundry sand. Material from surface exposures is useful primarily as dimension stone or aggregate. However, because of the remote location and large quantity of sandstone outside the study area, these occurrences currently are not considered economic resources. If a high-grade zone of sand were discovered within one or more of these sandstone units, and a nearby market was developed, some of the sandstone might be of economic significance in the future. A sample of sandstone collected at the Mother Lode prospect contained negligible uranium but did show low trace-element contamination and minor gold. Sandstone in the subsurface of the study area may contain sand of a suitable grade for glass.

Sand and Gravel

Sand and gravel are along most major intermittent stream channels in the study area. Straight Wash has the largest volume of these commodities. Although certain parts of these deposits appear to be of usable quality for sand and gravel applications, distance to market currently precludes their consideration as an identified economic resource for all but local needs.

Semiprecious Gemstones

Two types of semiprecious gemstones are found at two localities in and near the San Rafael Reef Wilderness Study Area. Both petrified and agatized wood are found in some of the paleochannel deposits of the Chinle Formation. They are most common north of the ATCO group prospect (Munts, 1989); approximately 500 lbs of petrified and agatized wood was observed as float at five locations between the ATCO prospect and Unknown Prospect No. 1. Much of the petrified wood is too soft to polish, but it may be useful as decorative material. The agatized wood could be polished and used to manufacture various decorative items. Although petrified and agatized wood resources exist outside the study area, these occurrences may be of interest to rock hounds and semiprecious gem collectors. Red agatized jasper crops out in the Chinle Formation in the northeastern part of the study area (Munts, 1989).

Oil, Gas, and Tar Sand

Approximately 37 oil and gas leases are active in the San Rafael Reef Wilderness Study Area (Simmons, 1983a). Two oil and gas wells have been drilled in the study area; no oil or gas was found.

Tar-sand occurrences have been reported along the northern edge of the study area (Tripp, 1985). These outcrops of tar sand are in the Moenkopi Formation, but the thickness and extent of tar sand were not determined. Results of tar-sand analyses (Munts, 1989) indicate less than 6 percent of the Athabasca grade; this fact precludes economic exploitation of tar-sand deposits from the study area in the near future.

Geothermal Energy

None of the study area is currently under geothermal lease. The only significant geothermal activity is several low-temperature springs (66–73 °F; Keys and White, 1956) north of the study area. Thus, there are no identified sources of geothermal energy in the San Rafael Reef Wilderness Study Area.

Mexican Mountain Wilderness Study Area

Uranium and Vanadium

Sandstone-hosted uranium and vanadium deposits as well as uranium and vanadium deposits in collapse features occur in the Mexican Mountain Wilderness Study Area. One hundred rock samples were taken to assess uranium and vanadium concentrations. Scintillometer traverses were made over most of the exposed lower part of the Chinle Formation; one carbon-rich sandstone-type prospect, the Jasmine No. 1, was located (fig. 10). The Jasmine No. 1 prospect consists of a 50-ft-long adit and 45-ft drift into the lower part of the Chinle Formation. Azurite, malachite, and hematite are in a bedding-plane lens 1–4 ft thick and 35 ft long. This zone contains anomalous concentrations of uranium, vanadium, copper, and silver. The Lisbon uranium mine, about 60 mi east of the San Rafael Swell area, produced 625 tons per day of 0.2 percent U_3O_8 (Engineering and

Mining Journal, 1986). The source of the ore is the carbon-rich lower part of the Chinle Formation sandstone in a setting similar to the Jasmine No. 1 prospect, but the average grade at the Lisbon mine is 14 times greater than that of the Jasmine No. 1 average assay grade of 142.5 ppm U_3O_8 or 0.01425 percent. Concentrations of vanadium, gold, copper, and silver at the prospect are too low for mining by factors of at least 10. Because of the limited extent of mineralization and the low grade, the Jasmine No. 1 prospect probably will not be mined in the near future. Two collapses were observed, one at the R.C. claims and one at the Bob claims. At the R.C. claims, the east-west-trending collapse feature is about 400 ft long and 150 ft wide. Areas as much as 50 ft in diameter are strongly altered and bleached. No workings are present in the area. None of the four samples analyzed contained anomalous values of U_3O_8 or V_2O_5, or any other elements. At the Bob claims, one 10-ft-long adit, several bulldozer scrapings, and a drill hole are present. The alteration zone is 200 ft long and 75 ft wide. Of six samples analyzed from the Bob claims, only one had an anomalous concentration (8.3 ppm) of U_3O_8, too low to classify as an economic source.

Precious and Base Metals

The Alice claims are outside the Mexican Mountain Wilderness Study Area and consist of two adjacent pits exposing mineralized rock along fractures and bedding planes, and disseminated locally in country rock; minerals include azurite, malachite, and red iron oxides. Analyses of two samples indicate minor low-grade, uneconomic concentrations of copper, lead, zinc, and silver that do not extend into the study area. The Primrose claims north and south prospects, also outside the study area, are in a setting similar to the Alice claims. Analytical data from one sample from the north prospect indicate minor low-grade, uneconomic concentrations of silver that do not extend into the study area. Minerals at the south prospect include azurite, malachite, and chalcocite. Two samples from the south prospect contained 1.4 percent and 1.6 percent copper and 233 ppm and 370 ppm silver; these data indicate minor mineralization insufficient to identify a resource.

Detailed mapping and sampling of a copper-silver prospect (Primrose claims) 0.25 mi east of the study area may be warranted. Two mineralized areas in the Chinle Formation within the study-area boundary should also be sampled and mapped in more detail to determine their significance.

Silver

A surface sample taken from coarse-grained and conglomeratic sandstone in the lower part of the Chinle Formation, about 1 mi north of the Jasmine No. 1 prospect, contained 27.7 ppm (0.8 troy ounce per ton) silver. Copper content was 816 ppm. The silver and copper contents are too low to be mined, and no resources were identified for silver.

Industrial Minerals

Gypsum

Gypsum beds are present throughout the Carmel Formation, but the thickest beds (greater than 3 ft) are only in the upper part of the Carmel, now eroded from the Mexican Mountain Wilderness Study Area. One gypsum sample was taken by the USBM in 1987 in the San Rafael Reef Wilderness Study Area; gypsum beds occur outside but near the study area. Because they are thin and remote from markets, they are classified as occurrences. Gypsum probably will not be mined from the vicinity of the study area in the foreseeable future.

Sand and Gravel

Terrace sand and gravel along the San Rafael River (Oakes, 1982) is moderately well sorted and contains some cobbles about 6 in. in diameter and rare boulders larger than 1 ft in diameter. The average diameter of gravel clasts is about 1 in. Sand constitutes about 60 percent of the material by volume. The maximum thickness of the gravel, which contains sandstone, quartzite, chert, jasper, and limestone clasts, is 20 ft, with an average thickness of about 5 ft. Because of the remoteness and low unit value of the sand and gravel, they are not considered to be an economic resource in the Mexican Mountain Wilderness Study Area.

Silica

The Navajo and Wingate Sandstones (underlying more than half of the Mexican Mountain Wilderness Study Area) are composed of compacted and cemented ancient sand dunes with a high silica (SiO_2) content. During this study, one sample was taken from each of the two formations. As a rough guide to sand quality, first-quality optical glass (high-dollar-value material) must contain 99.89 percent SiO_2, and have a maximum of 0.1 percent Al_2O_3 (aluminum oxide) and 0.02 percent Fe_2O_3 (iron oxide)(Davis and Tepordei, 1985). Sandstone from neither of these formations meets the specifications for industrial use. Third-quality flint glass (low-dollar-value material) may contain as little as 95 percent SiO_2 and as much as 4 percent Al_2O_3. The best quality sand is from the Navajo Sandstone (95.68 percent SiO_2), just adequate for low-value glass. The sandstone is classified as an occurrence, and because of its remote location and low quality, SiO_2 probably will not be mined from the study area in the foreseeable future.

Sulfur (Gas Sulfur Claims)

Approximately 35 percent of domestic sulfur is produced by the Frasch process, whereby hot water is pumped into sulfur deposits formed by hydrocarbon reduction of anhydrite, typically in salt-dome cap rock (Morse, 1985). The hot water melts the sulfur, which is then pumped to the surface. Small amounts of sulfur occur with travertine in the Mexican Mountain Wilderness Study Area. Elemental sulfur content of three samples ranged from less than 0.01 percent to 1.79 percent. These analyses are low when compared with Frasch process production of sulfur with grade in excess of 99 percent. The small, low-grade deposits in the study area are classified as occurrences that probably will never be mined for sulfur.

Oil, Gas, and Tar Sand

The Mexican Mountain Wilderness Study Area has 35,272 acres of oil and gas leases. No leases in the study area are under production or held by established production. Four dry and abandoned oil and gas wells are in the vicinity of the study area.

According to Tripp (1985), gently dipping tar-bearing sandstone in the Cottonwood Draw facies of the Moenkopi Formation consists of two very fine grained, dolomitic, cross-stratified quartz arenite units separated by gypsiferous siltstone. The Cottonwood Draw facies underlies more than half of the study area. Analyses of 84 samples from the quartz arenite units indicate that they contain 0.55–0.75 gallons of hydrocarbon (tar) per short ton. The tar sands are discontinuous. The only tar sands presently being mined in North America are Athabasca tar sands in Alberta, Canada. Syncrude Canada Ltd. operates this mine, which is designed to produce 40 million barrels of oil per year from 85,775,000 short tons of ore (Engineering and Mining Journal, 1986). The average ore grade is 20 gallons per short ton with a stripping ratio of 0.57:1 (waste to ore). The ore zone averages 150 ft thick and is as thick as 200 ft (Fish, 1975). The tar sands in the Mexican Mountain Wilderness Study Area have only 3.3 percent of the average grade and 7.2 percent of the average thickness of the Syncrude deposit. Tar sands in the study area are too low grade to mine in the foreseeable future. The tar-sand samples from the study area were also assayed for 20 elements; two samples contained more gold than expected, 0.018 and 0.029 ppm. No anomalous concentrations of other elements were observed. The analyses indicate that all metal concentrations in the tar sands are too low grade to be mined.

Geothermal Energy

No part of the Mexican Mountain Wilderness Study Area is presently under geothermal lease. Geothermal activity in the area is restricted to several low-temperature springs (66–73 °F; Keys, 1955) at Sulfur Spring in the southern part of the study area.

Sids Mountain Wilderness Study Area

Within the Sids Mountain Wilderness Study Area, eight lode properties were examined; all but the Dexter claims are within the study-area boundary (fig. 11). Workings examined on lode properties consisted of 14 open adits, 1 shaft, 1 inaccessible shaft, and 3 prospect pits. A total of 182 rock samples was collected.

A partial review of Emery County courthouse records indicates that from 1912 to 1953, 10 lode claims and 1 placer claim (for oil) were recorded in the study area. BLM records in 1986 indicate that 975 unpatented lode claims were current in and adjacent to the study area. No patented claims exist, and there is no current mining or exploration activity within the Sids Mountain Wilderness Study Area.

Uranium and Vanadium

Five prospects were located in the uranium-bearing Chinle Formation in the Sids Mountain Wilderness Study Area. Uranium and vanadium assays indicated that samples collected in this study were not of current minable grade of 0.2 percent U_3O_8. The uranium belt and mineralized uranium-bearing paleochannels at Calf Mesa, where high assays at the Dexter claims have been noted, do not appear to extend into the study area. Assays of samples collected at the Buckhorn prospect indicate that the ore cannot be mined economically. The prospect was not sufficiently developed to evaluate all of the uranium-bearing zones. The Plymouth Rock prospect, northeast of the Calf Mesa workings, which include the Dexter claims, was not sufficiently developed to determine resources for uranium or vanadium; however, sample analyses indicate that they are not of economic value. A drilling program initiated by the AEC (U.S. Atomic Energy Commission) (undated map on file at the USBM, Western Field Operations Center, Spokane, WA 99202) on Calf Mesa did not reveal any mineralized rock outside the Dexter claims. Because workings at the Douglas prospect and North Cane group were insufficiently developed, evaluation of resources is incomplete, but assay results did not indicate economic grade. The Douglas prospect is west of the Dexter claims. AEC drill-hole data did not indicate any mineralized rock near the Douglas prospect. The North Cane group lies southwest of the Dexter claims. No AEC holes were drilled in the vicinity.

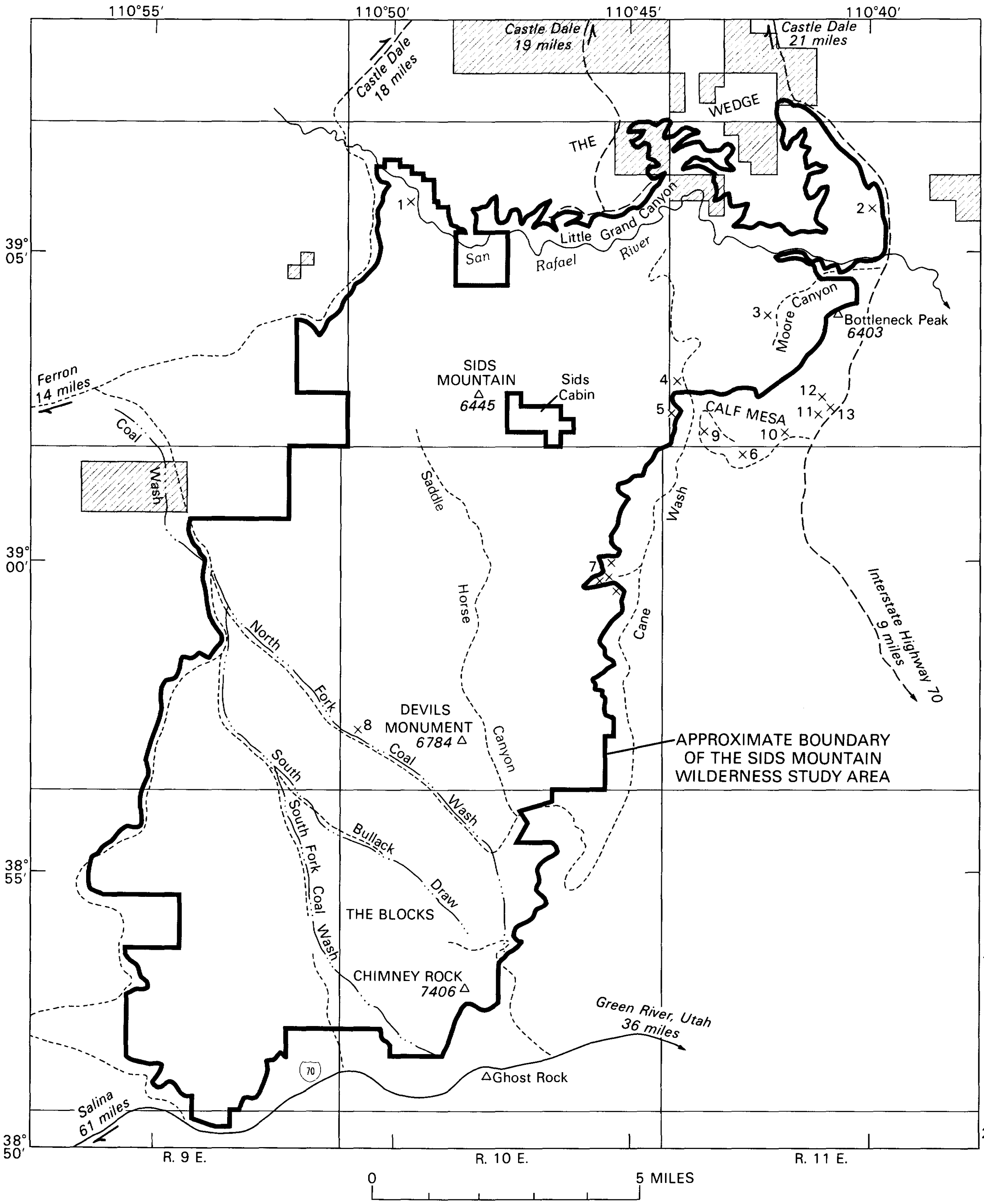


Figure 11 (above and facing page). Prospects and oil and gas leases in the Sids Mountain Wilderness Study Area, Utah.

Foot traverses with a scintillometer were completed on areas of the Chinle Formation that did not contain observable mine workings. A total of 49 samples were taken (Lipton, 1989). Threshold anomalous metal concentrations are given in Munts (1989) (table 1). Only one sample had a U_3O_8 assay above the threshold;

EXPLANATION

×4 Prospect—Number refers to name in list

Oil and gas lease area

——— Gravel road

- - - - Four-wheel-drive-vehicle road

6784 △ Elevation point

PROSPECTS AND CLAIMS

[*, site outside wilderness study area]

1. Sorrel Mule prospect
2. Buckhorn prospect
3. Plymouth Rock prospect
4. Unnamed prospect
5. Douglas prospect
6.* Dexter claims
7. North Cane Group
8. ZCMI prospect
9. Clifford Smith prospect
10. Bluebird prospect
11. Dalton Group
12. Lone Tree Group
13. Hard Pan prospect

the sample contained 69.62 ppm U_3O_8. Another assayed sample contained an anomalous concentration of 707.05 ppm V_2O_5. Three analyses for silver, one for arsenic, one for gold, four for molybdenum, seven for lead, two for zinc, and one for cobalt showed higher contents than those listed in table 2. Only one sample contained anomalous concentrations of three metals, and all other samples contained anomalous concentrations of only one or two metals.

This detailed sampling program could not fully delineate the uranium-bearing zones at the Buckhorn prospect, Plymouth Rock prospect, Douglas prospect, or the North Cane Group, due to a lack of extensive mining and exploration development. A detailed drilling program is needed at these workings to delineate uranium zones both laterally and vertically in the subsurface. Due to the nature of uranium mineralization of paleochannels, this program would have to space drill holes very closely in order to accurately delineate the depositional trend of the ore. However, even if mineralized zones were outlined, the economically depressed uranium market precludes mining of even the more mineralized mines in the southern part of the San Rafael Swell, at today's prices (Neumann, 1989).

Copper

Copper occurrences are present at the Sorrel Mule and ZCMI prospects in the Sids Mountain Wilderness Study Area. At each prospect, fault and shear zones are

Table 2. U.S. Bureau of Mines statistically derived threshold concentrations for selected metals from the Sids Mountain Wilderness Study Area, Utah

Metal	Threshold concentration (ppm)
Ag	0.68
As	89
Au	.012
Cu	176
Mo	25.8
Pb	69.8
Zn	111
Co	28
U_3O_8	40
V_2O_5	408

the primary sites of copper deposits. However, the extent of the copper-bearing zones is only minor, and mining would not be economical in the near future.

Industrial Minerals

Gypsum

Gypsum occurs in the Carmel Formation on the west side of the Sids Mountain Wilderness Study Area. The extent of the gypsum exposure was estimated to be approximately 21 mi long and about 2,000 ft wide in the study area. The average thickness of the gypsum is estimated to be 30 ft (Lupton, 1913). Using a tonnage factor of 13.9 ft^3/ton (Weast, 1988), estimates indicate that 480 million tons of gypsum are exposed in and near the study area, and of this amount, 103 million tons are exposed within the study area. These deposits are classified as an inferred subeconomic resource of gypsum. According to BLM records (February, 1986), most of the gypsum occurring in the study area is part of the HP and San Rafael claim groups (fig. 11); no known mining activity has occurred. Samples of gypsum range from 63.9 to 99.3 percent $CaSO_4$, and interbeds of limestone and shale as thick as 10 ft occur throughout the exposure. Impurities found in the gypsum included iron, chlorite, and manganese. The exposure has been known for many years (Lupton, 1913), but it has not been mined due to its inaccessibility and distance from market. The nearest market would be Richfield, 100 mi west of the study area (Simmons, 1982a). Processing plants there are receiving ore from deposits a few miles away (Pressler, 1985). Nearly three times as much gypsum is estimated to exist outside the study area, and it would probably be utilized first. Producing mines have long-term reserves that are closer to markets compared to exposed gypsum in the study area. Although assays are fairly high for the gypsum, if the deposit were to be open-pit mined, all impurities would be processed along with the gypsum, thus lowering the grade.

Sandstone

Both the Navajo and Wingate Sandstones crop out in the Sids Mountain Wilderness Study Area. Samples were analyzed to determine SiO_2 content and impurities present. Analyses show low SiO_2 content (below 95 percent) and high impurities content (Fe_2O_3 as high as 0.45 percent and Al_2O_3 as high as 4.57 percent), making the sandstone unsuitable for foundry or glass manufacture. Because of the remote location and low quality of the quartz sandstone in the Navajo and Wingate, it is not classified as a resource.

Sand and Gravel

Sand and gravel are found along the San Rafael River and most intermittent streams in the Sids Mountain Wilderness Study Area. The gravels contain sandstone, quartzite, chert, jasper, and limestone clasts. According to Davis and Tepordei (1985), accessibility is a problem for the sand and gravel industry. The high volume and low unit value of sand and gravel require that mining be close to the market. Therefore, these deposits are not considered as economic resources.

Oil, Gas, and Tar Sand

The Sids Mountain Wilderness Study Area contains 29 oil and gas leases that cover approximately 14,160 acres. No leased acreage is currently under production or held by established producers. The True Oil Co. drilled a well 2,440 ft deep outside the study area, but it was plugged and abandoned in 1975.

The tar-bearing Moenkopi Formation does not crop out in the study area. Asphalt does occur in parts of the Chinle Formation. Samples were taken at the Buckhorn prospect and from a tar seep in Saddle Horse Canyon, each from the Chinle Formation. The tar from the seep was liquid tar. Tar-impregnated sandstone occurs at the Buckhorn prospect. Tar does not occur everywhere in the Chinle Formation. No economic appraisal was made on tar sand in the study area.

Geothermal Resources

The Sids Mountain Wilderness Study Area is not under geothermal lease, and no geothermal resources were identified.

ASSESSMENT OF POTENTIAL FOR UNDISCOVERED RESOURCES

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U.S. Geological Survey

Geology

During two expeditions in 1869 and 1872, John Wesley Powell (1875) named many of the physiographic features of the San Rafael Swell. An early work by Boutwell (1905) described the San Rafael River mining area. Emery (1918) was the first to document the general geology of the area. Later work by Gilluly (1929) and Gilluly and Reeside (1928) provided a framework for numerous subsequent studies (referenced herein) on the geology, stratigraphy, regional alteration, structure, and studies of localized areas and unusual features in the swell.

The sedimentary rock sequences that crop out in the region of the San Rafael Swell are laterally continuous and are gently warped into an elongate north-northeast-trending dome with a more steeply dipping eastern and southern flank. This more steeply dipping part of the swell may be termed a "monocline," separating the swell from the Green River basin to the east. The San Rafael monocline forms the northwest edge of the Paradox basin (fig. 1) (Stevenson and Baars, 1987). Monoclines (such as the San Rafael monocline) appear to be ancient reactivated, steeply dipping fault zones thought to reflect Precambrian (basement) faults (Davis, 1984) where, typically, the sense of structural tilting may have been repeatedly reversed (Peterson, 1987). Geologic evidence of movement on the San Rafael monocline is sparse. According to Mahoney and Kunkel (1963), the steeply dipping eastern flank of the swell might have formed during compression, with possible thrust faulting at depth. Seismic, gravity, and magnetic profiles across the east flank indicate thrust faulting, and high-angle thrust faults were discovered in wells on the Farnham dome and a small dome near Huntington (fig. 1) west and northwest of the swell (Equity Oil Co., Peterson, 1954, personal commun., *in* Mahoney and Kunkel, 1963).

The San Rafael Swell is part of the more extensive San Rafael anticline. The sedimentary rocks are cut by many high-angle and bedding-plane faults, typically with minimal offsets, and are distorted by solution collapse features; all of these structures are inferred to have been produced during upwarping and (or) thrust faulting of the swell. The deformation of the rocks on the surface of the San Rafael Swell took place primarily during the Tertiary. The presently exposed northeast-trending structure differs from the subsurface structure. Geophysical evidence and well data indicate that a buried northwest-trending fold formed in Permian(?) and Triassic(?) time and involved rocks as old as Precambrian (Hawley and others, 1968). This older anticlinal feature, the Emery uplift, transects the northern and central part of the San Rafael Swell (Hawley and others, 1968; Witkind, 1989).

Tertiary intrusive rocks invaded parts of the sedimentary stratigraphic sequence along faults and fractures on the southwest flank of the swell; these intrusions may have occurred simultaneously with other intrusive episodes on the Colorado Plateau that took place in Tertiary time.

Structural Elements

The geologic history of the San Rafael Swell is complex, as evidenced by the many structural features present. Two varieties of faults (high and low angle), two generations of folds (primary and subsidiary or crossfolds), and strategically located solution collapse features are described.

Faults

Faulting probably occurred nearly contemporaneously with the arching of the swell, the most recent movement probably taking place during Tertiary time (Witkind, 1989). Faults are characteristically paired, forming a series of horsts and grabens with only minor displacements. The predominant trend of faults in the San Rafael Swell is northwest, though east- and northeast-trending faults also are present (pl. 1). The high-angle faults, because they commonly truncate ore-bearing horizons, may possibly have formed after ore deposition (Trimble and Doelling, 1978). The high-angle faults may be somewhat younger than major and subsidiary folding, collapsing, and bedding-plane slipping. They are probably Tertiary in age (Hawley and others, 1968). Prominent jointing is also present in resistant sandstone and limestone units throughout the swell, with some high-angle faults oriented parallel to joint patterns. Mineralized zones are present locally along joints and high-angle faults. In mineralized areas of the swell, bedding-plane faults are ubiquitous and occur mainly at the Moenkopi and Chinle contact, though displacements are minimal (Hawley and others, 1968). Because the bedding-plane faults are known to be premineralization features, they primarily control alteration patterns and ore deposition (Hawley and others, 1968).

Northwest-striking faults and grabens, prevalent especially in the northern part of the San Rafael Swell, have orientations similar to those in the Paradox basin and the older, underlying, northwest-trending Emery uplift. These structures may have formed, at least in part, during the same time interval (possibly in Mesozoic and Tertiary time) and possibly for similar reasons (Witkind, 1989). Faults and grabens in the Paradox basin clearly resulted from withdrawal or flowage of salt deposits in salt-cored anticlinal structures that have affected Mississippian, Pennsylvanian, and younger rocks (Clem and Brown, 1984). However, according to Stevenson and Baars (1987), the San Rafael monocline defines the northwestern edge of the Paradox basin. North- and northeast-striking faults that are most prevalent on the western side of the swell are similar to structures occurring on the crest of the Wasatch Plateau adjacent to the San Rafael Swell on the west (fig. 1). These structures may also have resulted from withdrawal of salt deposits at depth (Witkind, 1989), though drill-hole evidence in the San Rafael Swell region indicates no remaining salt deposits.

Folds

Numerous small anticlines and synclines with axes normal to the trend of the major axis of the swell probably also formed during the Tertiary episode of deformation. These crossfolds exist near or opposite the major bends in the San Rafael anticline (fig. 12). Two groups of subsidiary folds are present; one in the west-central and the other in the southeast parts of the swell. One of the larger subsidiary folds, the Woodside anticline (fig. 1), is a steep, narrow fold superimposed on the east flank of the north-plunging end of the San Rafael Swell (north of the study area) that has been explored for hydrocarbons and gas.

Above the basement rocks and below the exposed Pennsylvanian sequence, several units of the stratigraphic column at various horizons beneath the swell are missing, suggesting formational pinchouts and intertonguing within the dome (Quigley, 1963). In one well, Precambrian rocks were overlain by Permian rocks, and in other wells stratigraphic variation, formation pinchouts, and intertonguing were found, particularly in Permian, Pennsylvanian, and Mississippian sequences (Quigley, 1963, p. 398). Thus, the San Rafael Swell is inferred to have undergone intermittent episodes of uplift with differential episodes of folding in Pennsylvanian time (Quigley, 1963; Mahoney and Kunkel, 1963). Younger Laramide (Late Cretaceous-early Tertiary) folding did not appreciably affect the lower, previously folded Paleo-

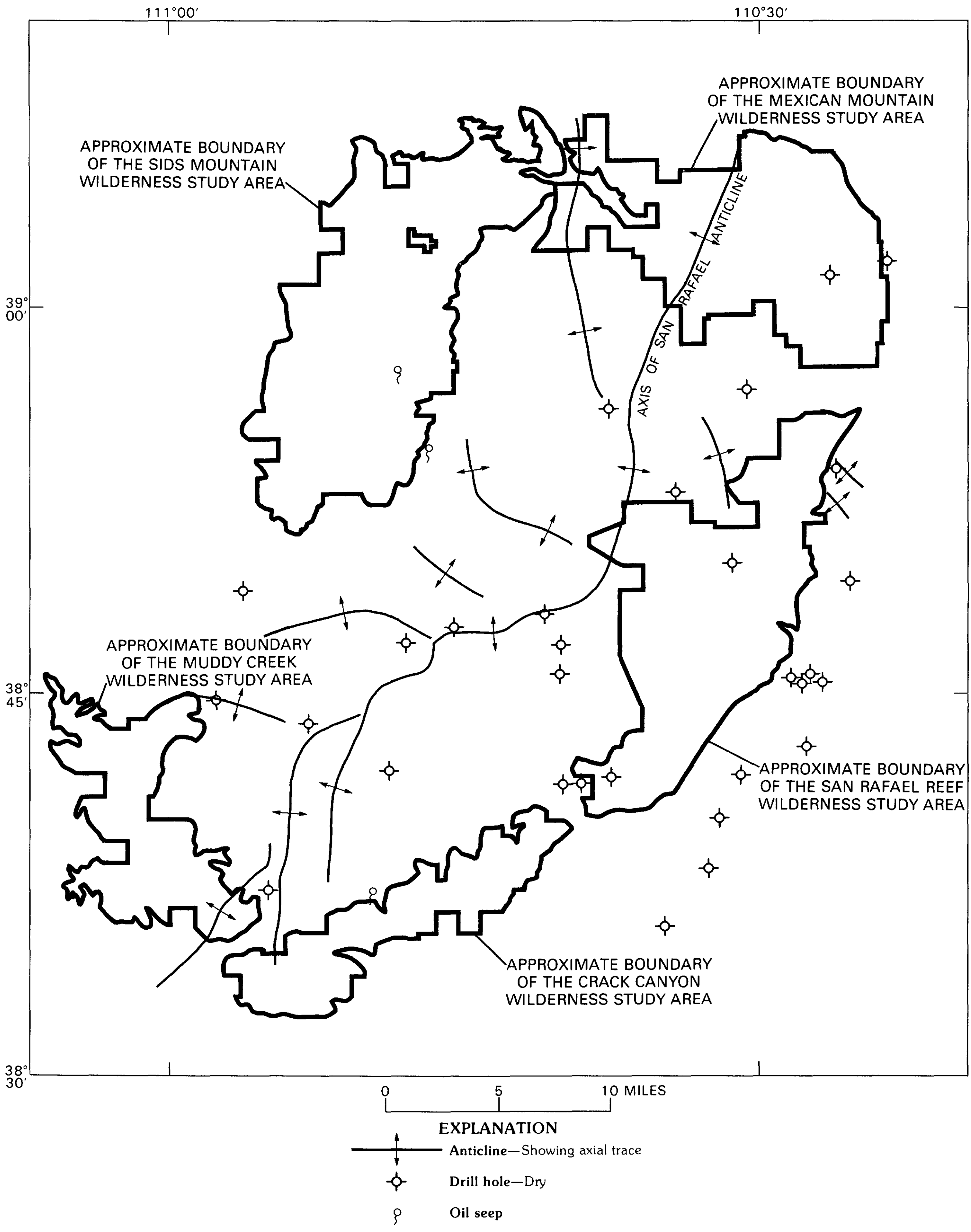

Figure 12. Secondary structures potentially favorable for the accumulation of oil and gas, and locations of drill holes and oil seeps in the San Rafael Swell region, Utah.

zoic sequences; Quigley (1963) has determined that the older structures do not coincide with the Tertiary ones. The older (pre-Laramide) northwest-trending anticlinal fold (the Emery uplift), which extends about 70 mi to the southeast beneath the swell and beyond (McKeown and Orkild, 1958, p. 51, fig. 4; Mahoney and Kunkel, 1963, p. 371; Witkind, 1989), may, like the faults, be related to salt-anticlinal features in the Paradox basin adjacent to the San Rafael Swell to the east and southeast (Wengerd, 1963, fig. 142).

Collapse Structures

Collapse structures occur at several localities in the San Rafael Swell and locally appear to be related to uranium mineralization in some places, especially at Temple Mountain (Hawley and others, 1968; Keys and White, 1956; Kerr and others, 1957). The collapse structures occur in three regions in the swell; (1) at Temple Mountain on the southeast flank of the swell, (2) in Reds Canyon and vicinity on the western flank of the swell, and (3) east of Window Blind Peak near the San Rafael River in the northern part of the swell (fig. 1). These features are ovoid in plan view and are composed of brecciated, contorted, or inwardly dipping sedimentary units ranging in age from Permian to Late Triassic. The exact process of formation of the collapse structures is controversial, but they were initiated by solution of underlying deposits, which created a void into which the overlying rocks subsided. Zones of mineralized rocks possibly were formed at this time. Such features probably formed in early Tertiary time concurrent with development of the San Rafael anticline and formation of the smaller secondary folds (Hawley and others, 1968; Suguira and Kitcho, 1981, p. 42; Witkind, 1989). Of the many collapse features found in the swell, only six are slightly uraniferous; the Temple Mountain collapse is the only one with appreciable uranium-bearing rock (Hawley and others, 1968). These structures are all near areas that have undergone episodes of crosswarping or subsidiary folding.

Intrusive and Plutonic Rocks

Clusters of intrusive rocks occur in the southeastern part of Utah and include large intrusions that invade overlying rocks, forcing them upward into domes. Examples of such features with intrusive cores on the Colorado Plateau east and south of the San Rafael Swell include the Henry, Abajo, and La Sal Mountains. Early workers postulated that such intrusive activity occurred in other uplifted features such as Navajo Mountain near Kaiparowits Basin to the south and the San Rafael Swell. There is little subsurface evidence to support this hypothesis for the San Rafael Swell. Both the stratigraphy in well-exposed areas, such as the Henry Mountains, and the radiometric ages obtained from minerals in bedrock samples suggest a Tertiary age for the intrusive activity in southern Utah.

Surface evidence of intrusive events in the San Rafael Swell can be found in the sills and dike swarms in the southwestern part of the San Rafael Swell near Muddy Creek. The dikes are thin (less than 15 ft thick; Gilluly, 1929) and discontinuous, are composed of analcite-biotite diabase, and are of Tertiary age (Hawley and others, 1968). The phenocrysts in the porphyritic dikes are mainly altered olivine and pyroxene; the groundmass is composed of fine-grained plagioclase, pyroxene, magnetite, biotite, and small amounts of thompsonite and analcite (Gilluly, 1929; Hawley and others, 1968).

The core of the San Rafael Swell, as derived from well evidence, is probably a Precambrian basement block composed of a biotite-rich pink to gray granite with an overlying thin sedimentary deposit rich in granitic clasts (Quigley, 1963). This Precambrian plutonic core, whose lateral extent is well defined by magnetic and gravity data, may have risen at various times during subsequent tectonic episodes (in Cambrian to pre-Late Devonian time) (Quigley, 1963; Stevenson and Baars, 1987). The tectonic reactivations are indicated by a thinning of Cambrian strata over the Emery uplift (Stevenson and Baars, 1987), possibly along an old reactivated fault zone.

Sedimentary Rocks

Sedimentary rocks exposed in the region include Paleozoic carbonate rocks, the Lower Pennsylvanian Molas(?) Formation; the Middle and Upper Pennsylvanian Hermosa(?) Group; the Lower Permian Elephant Canyon(?) Formation of Baars (1962), Organ Rock(?) Tongue and White Rim Sandstone Member of the Cutler Formation (the Coconino(?) Sandstone of early investigators), and Kaibab Limestone (the Black Box Dolomite of Welsh and others, 1979); the Lower and Middle(?) Triassic Moenkopi Formation, the Upper Triassic Chinle Formation; the Lower Jurassic Wingate Sandstone, Kayenta Formation, and Navajo Sandstone of the Glen Canyon Group; the Middle Jurassic Page Sandstone, Carmel Formation, Entrada Sandstone, Curtis Formation, and Summerville Formation of the San Rafael Group; the Upper Jurassic Morrison Formation; the Lower Cretaceous Cedar Mountain Formation; and the Upper Cretaceous Mancos Shale with its marker bed, the Ferron Sandstone Member (Molenaar, 1981, 1987b) and the underlying Tununk Shale Member. Rocks in the subsurface include Precambrian rocks of the basement complex (Hawley and others, 1968) that underlie a thin, presumably Precambrian, sedimentary unit. Stratigraphically above Precambrian basement rocks and beneath the exposed Carboniferous sequence are Cambrian, Devonian, Mississippian, Lower Pennsylvanian, and Permian marine sedimentary rocks, including carbonate sequences (Molenaar, 1987b). Surficial units are generally thin Quaternary eolian, terrace, and pediment deposits, landslides, and stream deposits that mantle bedrock throughout the area. These units were mapped only where they locally obscure large areas of bedrock in the swell (pl. 1). The exposed sedimentary sequence is broken by unconformities above and below the San Rafael Group, above and below the Glen Canyon Group, and between the Moenkopi Formation and the overlying Chinle Formation. A disconformity is present between the Kaibab Limestone and the Moenkopi Formation, and another probably is present between the Lower Pennsylvanian Molas(?) Formation and the Paleozoic carbonate rocks.

Paleozoic Carbonate Rocks

The oldest rocks in the San Rafael Swell are exposed in Straight Wash (Eardley Canyon section; sec. 19, T. 23 S., R. 13 E.) (pl. 1) and include massive, cliff-forming beds of light-gray, fossiliferous, vuggy dolomite and limestone. Near the base of the exposure, the unit contains nodules of chert. The unit was initially assigned by Gilluly (1929) and subsequently by other workers (for example, A.J. Eardley *in* Baker, 1946; Hallgarth, 1962; Mahoney and Kunkel, 1963) to the Middle and Upper Pennsylvanian Hermosa Group. The fossiliferous dolomite has not been dated paleontologically, but lithologically it is similar to the Mississippian Redwall Limestone. The Redwall has been traced in the subsurface on the west side of the the Paradox basin (Franczyk, in press). The carbonate sequence exposed in Eardley Canyon has a minimum thickness of 120 ft.

Molas(?) Formation, Hermosa Group, and Elephant Canyon(?) Formation of Baars, Undifferentiated

The basal exposure in Eardley Canyon in the San Rafael Swell is a thin (about 10 ft thick) unit of pink chert-pebble conglomerate, locally vuggy and crossbedded; these rocks are tentatively correlated herein with the Lower Pennsylvanian Molas(?) Formation. In the San Rafael Swell, exposures of the undifferentiated Lower Permian Elephant Canyon(?) Formation of Baars (1962) and the Middle and Upper Pennsylvanian Hermosa Group show this sequence to be composed of about 260–310 ft of interbedded marine carbonate, siltstone, and sandstone. The unit is buff, light-gray, red, and maroon, poorly to well sorted, finely laminated to parallel-bedded siltstone and massive sandstone that is interbedded with buff, tan, and red, laminated, vuggy, and massive impure limestone and dolomite. These units are oil and gas reservoir rocks.

Lower Permian Organ Rock(?) Tongue, White Rim Sandstone Member of the Cutler Formation, and Kaibab Limestone, Undifferentiated

The basal unit is about 10 ft thick and is composed of a yellow to ochre, well-sorted, limonitic, massive sandstone with interbedded silty limestone, and red siltstone that is only exposed in Straight Wash (Eardley Canyon) in the San Rafael Swell region. The unit is tentatively correlated herein with the Lower Permian Organ Rock(?) Tongue of the Cutler Formation.

The Lower Permian White Rim Sandstone Member of the Cutler Formation, a unit that was mapped in the San Rafael Swell region by earlier workers as the Coconino(?) Sandstone (Gilluly, 1929), is a resistant, typically white to gray and brown, thick-bedded to massive, medium- to coarse-grained quartzose sandstone. Sand grains are typically well rounded and frosted, reflecting their origin in or near an eolian environment in the San Rafael Swell region. However, ripple marks and convoluted bedding suggest that this unit had a subaqueous origin (Baars and Seager, 1970; Baars, 1975). The unit is typically large- to medium-scale crossbedded and friable, weathers rusty red, but is bleached to light tan where it contains asphalt. It is locally cemented and well indurated. The White Rim Sandstone Member, a petroleum reservoir rock, is as much as 600 ft thick (Baars and Molenaar, 1971) near Black Box Canyon and is as much as 880 ft thick in a test well (sec. 28, T. 24 S., R. 10 E.) (Hawley and others, 1968). This unit has also produced carbon dioxide gas as well as oil and natural gas in east-central Utah (Mahoney and Kunkel, 1963).

The Lower Permian Kaibab Limestone is primarily tan to brown, thin- to medium-bedded, even-bedded and resistant, fossiliferous, vuggy limestone that is locally sandy, cherty, and dolomitic. At the base, it includes calcareous sandstone that was reworked from the underlying White Rim Sandstone Member. The Kaibab Limestone is a marine deposit that is 40–80 ft thick; the unit is apparently disconformable on the underlying White Rim (Hawley and others, 1968; Molenaar, 1987a, b). Kaibab Limestone is a petroleum reservoir in much of the Colorado Plateau.

Moenkopi Formation

The Lower and Middle(?) Triassic Moenkopi Formation, a source of oil, gas, and tar sand, has been subdivided into four members in the San Rafael Swell area (Blakey, 1974); these are, in ascending order, the Black Dragon, Sinbad Limestone, Torrey, and Moody Canyon Members. The Moenkopi is typically a green-gray pyritic shale and gypsiferous green and red shale that weathers yellowish brown. The uppermost part is a greenish-gray, locally reddish-brown, thin- to medium-bedded, very fine grained sandstone and shaly siltstone that may contain purple and white bleached or mottled zones (also present in the lower part of the Chinle) and some gypsum. The shale and siltstone of the Moenkopi Formation are typically platy and micaceous, and weather to reddish-, yellowish-, and brownish-tan slopes. Between the Moenkopi Formation and the underlying Kaibab Limestone is a chert-pebble limestone derived from reworking of the Kaibab (Blakey, 1974); the hiatus between the conglomerate and the Kaibab represents the Tr-1 unconformity of Pipiringos and O'Sullivan (1975). The conglomeratic limestone is as much as 42 ft thick and has a prominent wedge-shaped, small-scale cross stratification and a consistent westward dip where it is exposed near Black Dragon Canyon on the San Rafael River (Blakey, 1974). The Sinbad Limestone Member of the Moenkopi Formation, a marine limestone about 200 to 350 ft from the base of the formation, is an important oil and gas source rock. It is yellowish-gray to light-brown, thin- to medium-bedded, crystalline, locally oolitic limestone and dolomite containing the *Meekoceras* fauna and a few thin, shaly siltstone, very fine grained sandstone, and conglomerate beds (Blakey, 1974). The Sinbad Limestone Member forms a resistant cap and long dip slopes in the central San Rafael Swell region. It is as much as 86 ft thick near Muddy Creek (Hawley and others, 1968). The Sinbad contains inflammable gas mixed with carbon dioxide gas and light oil in most wells drilled on Farnham Dome (fig. 1; Mahoney and Kunkel, 1963). In the San Rafael Swell region, this unit typically has a petroliferous odor when struck by a hammer. The Moenkopi Formation ranges from 375 to 935 ft thick and has both marine and nonmarine affinities. The Moenkopi is thinnest in a northwest-trending belt near Straight Wash on the east flank of the swell (Hawley and others, 1968).

Chinle Formation

The Upper Triassic Chinle Formation, a unit that was deposited in broad river systems and lakes, is the major host rock for uranium in the San Rafael Swell. Throughout the San Rafael Swell, the Chinle is composed of four members; in ascending order, they are the Temple Mountain, Monitor Butte, and Moss Back Members, which make up the lower part of the unit, and the overlying Church Rock Member, which makes up the upper part; in the southern part of the San Rafael Swell, the upper unit may also possibly include parts of the Petrified Forest and Owl Rock Members (Stewart and others, 1972, fig. 1). The thickness of the Chinle Formation ranges from 220 to 350 ft, and it is thinnest on the southwest flank of the San Rafael Swell (Hawley and others, 1965, 1968). The lower units vary in thickness and are composed of poorly bedded, mottled, and varicolored red, green, and purple mudstone and siltstone and light-gray to gray, thin- to medium-bedded, crossbedded sandstone, conglomeratic sandstone, conglomerate, and mudstone. The uppermost unit, the Church Rock Member, is reddish-brown to dark-brown, locally light-gray and greenish-gray, thin to medium bedded, cross-bedded, lenticular, and very fine grained sandstone and shaly siltstone and reddish-brown to reddish-orange and spotted light-greenish-gray siltstone with minor, very fine to medium-grained sandstone. Locally the Chinle contains fine-grained, rippled red sandstone and lenses of gray, coarse-grained sandstone and conglomerate, and localized chert-carbonate veins that contain small amounts of sulfide minerals. The lower part of the Chinle forms a cliff and bench and contains much silicified and carbonized wood. The lower units are the principal uranium hosts, and the lowermost beds that may contain carbonized wood or asphaltic material as well as mineralized zones containing uranium and copper, are, in places, altered and mottled purple and white, and excavate into the underlying Moenkopi Formation. According to Mahoney and Kunkel (1963), petroliferous sandstone facies of the Chinle may contain oil on the east flank of the San Rafael Swell; there are many saturated outcrops, and shows of oil are common during drilling. On the Colorado Plateau, abundant amounts of bentonitic clay may occur in the Chinle Formation, and metallic elements associated with this clay include gold, silver, and vanadium, as well as uranium (Stokes, 1963). The Chinle Formation overlies the Moenkopi Formation by a slight angular unconformity (Hawley and others, 1968)—the Tr-3 unconformity of Pipiringos and O'Sullivan (1975).

Glen Canyon Group and Page Sandstone

The Glen Canyon Group is composed, in ascending order, of the Wingate Sandstone, Kayenta Formation, and Navajo Sandstone. The Wingate Sandstone and the Navajo Sandstone are thick eolian units, and the Kayenta Formation is a fluvial unit. Earlier studies indicate that the age of the group is as old as Triassic (Lewis and others, 1961; Wright and Dickey, 1963), but more recent findings indicate that the unit may be Early Jurassic in age (Peterson and Pipiringos, 1979; Litwin, 1986; Padian, 1989). The Page Sandstone, an eolian unit that overlies but is indistinguishable from the Navajo Sandstone, is Middle Jurassic in age (Peterson and Pipiringos, 1979).

Wingate Sandstone

The Wingate Sandstone is a buff to tan, pink, and dark-gray, massive to crossbedded, quartzose, very fine to fine-grained sandstone with a few thin lenses of limestone and beds of calcareous sandstone. The unit forms vertical cliffs and is distinguished by a red stain.

Vertical joints and their attendant talus deposits are abundant in this unit. It ranges from about 300 to 450 ft thick. The J-0 unconformity of Pipiringos and O'Sullivan (1975) separates the Wingate Sandstone from the underlying Chinle Formation.

Kayenta Formation

The Kayenta Formation is a lavender, red-brown, and pale-red, thin- to medium-bedded, irregularly bedded and crossbedded, fine- to coarse-grained sandstone; subordinate interbeds of red and green mudstone and lacustrine limestone are also present. Minor amounts of siltstone occur throughout the unit. It forms broken cliffs in the lower part and shaly slopes in the upper part. Sedimentological evidence suggests it was deposited in a predominantly fluvial environment (Poole, 1961). The unit is conformable and intertongues with the overlying Navajo Sandstone. The Kayenta Formation is from 100 to 250 ft thick.

Navajo Sandstone

The Navajo Sandstone is a very fine to medium-grained, white to buff sandstone unit (with rare pebbles interspersed) that is strikingly crossbedded to massive, indicating predominantly eolian deposition. Rare lacustrine interbeds of shaly, dolomitic, and limy and lenticular pebbly beds also occur in this unit, but none exceed 10 ft in thickness—most are less than 5 ft thick (Doelling, 1975). The Navajo Sandstone, due to strong jointing, is characterized by a checkerboard or "elephant-hide" pattern of erosion. It typically forms sheer cliffs and domes, is mostly without vegetation, and creates scenic box canyons. The Navajo Sandstone is generally interpreted as a predominantly wind-blown deposit, 400–1,000 ft thick, that was deposited in an interior desert environment (Molenaar, 1981, 1987a, b), though other interpretations of its environment of deposition have been presented (Stanley and others, 1971; Freeman and Visher, 1975).

Page Sandstone

The Page Sandstone is an eolian deposit that closely resembles the Navajo Sandstone, from which it was derived; it is included with the Navajo Sandstone on plate 1. According to Peterson and Pipiringos (1979), the Page Sandstone separates the Carmel Formation from the Navajo and is marked at its top by the J-2 unconformity, a discontinuous chert-pebble layer. In the vicinity of the San Rafael Swell, the unit is as much as 100 ft thick, but it pinches out a short distance east of the east flank of the swell (Molenaar, 1981).

The undifferentiated Glen Canyon Group and the Page Sandstone are locally altered and mineralized and, at Temple Mountain, are an important host rock for uranium and vanadium. Minor amounts of copper were found and mined at a bleached zone in the Glen Canyon Group at Copper Globe north of the Muddy Creek Wilderness Study Area. Nonflammable carbon dioxide gas is produced from these units (especially the Navajo and Page Sandstones) at Farnham Dome north of the study areas, on the San Rafael anticline (fig. 1; Mahoney and Kunkel, 1963).

San Rafael Group

According to Pipiringos and O'Sullivan (1975), part of the Middle Jurassic San Rafael Group unconformably overlies the Navajo Sandstone at the J-2 unconformity, a very thin, discontinuous, angular chert-pebble layer; prior to description of this unconformity, the overlying Page Sandstone was not recognized. According to Pipiringos and O'Sullivan (1975), the chert-pebble unconformity is present at Buckhorn Wash in the northern San Rafael Swell. In this report, however, we did not map the unconformity, and the Page Sandstone was not recognized; it is included with the Navajo Sandstone. In this report, the San Rafael Group consists, in ascending order, of the Carmel Formation, the Entrada Sandstone, and the Curtis and Summerville Formations (Craig and Shawe, 1975).

Carmel Formation

The Middle Jurassic Carmel Formation makes a reddish or brownish cap on the undifferentiated Navajo and Page Sandstones. This ledge-forming unit is commonly mottled and streaked and forms broad, intricately dissected slopes. The Carmel is composed of a lower unit of sandstone, limy shale, and fossiliferous limestone, and an upper unit of siltstone, shale, and gypsum. The lower beds are yellowish gray to greenish or orange pink; the fossiliferous limestone may grade laterally into the calcareous, fine-grained sandstone produced, in part, by reworking of the underlying undifferentiated Page and Navajo Sandstones. Gypsum is found in nonresistant beds as much as 20 ft thick (Craig and Shawe, 1975), veinlets, fracture fillings, nodules, or as cement, and, where present, has caused the beds to be brecciated or contorted. The Carmel Formation originated by shallow-water and subaerial deposition near a marine environment. The unit is about 300 ft thick.

Entrada Sandstone

The Middle Jurassic Entrada Sandstone, named for strata at Entrada Point in the northeastern San Rafael Swell by Gilluly and Reeside (1928), is composed of unfossiliferous sandstone, siltstone, and mudstone that may be banded in tints of red, orange, brown, gray, and white. In areas of nonresistant beds, the slopes are earthy and typically covered with sandy soil and vegetation; in areas of resistant sandstone are slickrock areas and elephant-hide cliffs that are grooved on the bedding planes and typically form turrets and isolated buttes. The sandstone is of shallow marine, sabkha, eolian, and fluvial origin. The ledge- and slope-forming sabkha and marine deposits become more predominant in the western part of the Colorado Plateau near the San Rafael Swell (Molenaar, 1987a, b; Peterson, 1988). In the eastern part of the plateau, the Entrada produces natural gas (Mahoney and Kunkel, 1963). The Entrada is about 270 ft thick.

Curtis Formation

The Middle Jurassic Curtis Formation (named by Gilluly and Reeside, 1928, for strata at Curtis Point in the northeastern San Rafael Swell) is composed of fossiliferous grayish-green, glauconitic, flat-laminated and crossbedded sandstone and mudstone. The unit is predominantly marine, but the thin lenses of gypsum indicate minor sabkha conditions at some locations. The Curtis Formation is as much as 225 ft thick (Craig and Dickey, 1956). The unit forms greenish cliffs and ledges that contrast with the reddish units both above and below the Curtis. The unit unconformably overlies the Entrada Sandstone in the vicinity of the San Rafael Swell (Peterson, 1988); this unconformity is the J-3 unconformity of Pipiringos and O'Sullivan (1975).

Summerville Formation

The Middle Jurassic Summerville Formation, named by Gilluly and Reeside (1928) for strata at Summerville Point in the northeastern San Rafael Swell, consists of slope-forming reddish-brown mudstone that has mudcracks and is unfossiliferous, ripple cross laminated, laminated, and locally gypsiferous. Thin beds of pebbly, crossbedded, light-brown sandstone are in the upper part of the unit. The unit has been differentiated by Peterson (1988) on the basis of color and lithology into the chocolate member and the brick-red member; the unit is undifferentiated in this report. The Summerville Formation was deposited in shallow-water (hyposaline) marine, flood-plain, mudflat, and hypersaline environments. The unit is about 100–300 ft thick; it is gradational with the underlying Curtis Formation (Craig and Shawe, 1975).

Morrison Formation

The lower part of the Upper Jurassic Morrison Formation has been differentiated by Peterson (1988) into the Salt Wash (Lupton, 1914), Bluff Sandstone (Gregory, 1938), and Tidwell (Peterson, 1988) Members. The upper part of the Morrison Formation has been differentiated into the Westwater Canyon (Gregory, 1938), Fiftymile (Peterson, 1988), Brushy Basin (Gregory, 1938), and Jackpile Sandstone (Owen and others, 1984) Members (Peterson, 1988). Beds of the Recapture Member (Gregory, 1938) occur in both the upper and lower parts of the Morrison Formation (Peterson, 1988). The members interfinger in the western Colorado Plateau, and only the Tidwell, Salt Wash, and Brushy Basin Members occur in the San Rafael Swell region. Only those members are described herein; the descriptions are from Peterson (1988). Locally, the Morrison Formation rests with slight angular unconformity on the Summerville Formation in the San Rafael Swell area; this is the J-5 unconformity of Pipiringos and O'Sullivan (1975). However, the base of the Morrison is reported as conformable by some geologists (Craig and Shawe, 1975). In the eastern part of the Colorado Plateau, natural gas is produced from sandstone of the Morrison Formation (Mahoney and Kunkel, 1963).

Tidwell Member

The Tidwell Member was named by Peterson (1988) for gray mudstone beds above the basal J-5 unconformity of the Morrison Formation. The member is named for Tidwell Bottoms northeast of Spotted Wolf Canyon and I–70 along the San Rafael River east of the San Rafael Swell. The member is missing on the southwest side of the San Rafael Swell, where the Summerville is overlain by the Salt Wash Member of the Morrison Formation.

The Tidwell Member interfingers with the overlying Salt Wash Member and ranges in thickness from 0 to 292 ft, but typically is 0–98 ft thick in the San Rafael Swell region. The member is composed of grayish-green calcareous mudstone that contains nonswelling clays and thin-bedded, very fine to fine-grained, laminated to massive, light-brown sandstone. White gypsum beds as much as 45 ft thick occur locally at the base. Thin beds of gray, dense limestone, rare occurrences of dark-gray to dark-greenish-gray mudstone containing minute flecks of carbonized plant fragments, minor chert beds, and sparse light-brown pebbly sandstone beds also occur in the Tidwell.

In various places throughout the Colorado Plateau, the Tidwell Member is documented to have been deposited in lacustrine, evaporative, mudflat, and minor fluvial and eolian environments.

Salt Wash Member

Cliff-forming, lenticular sandstone beds of the Salt Wash Member are light grayish brown to light gray, fine to medium grained, and crossbedded to flat laminated.

They are interbedded with minor reddish-brown to light-grayish-green, laminated to very thin bedded mudstone that forms benches, steep slopes, or thin notches between the thick sandstone beds. In some areas of the Colorado Plateau, thin beds of gray to grayish-green, laminated to very thin bedded mudstone with carbonized plant fragments are associated ith tabular sandstone-type uranium-vanadium deposits. Uranium deposits of the adjacent Paradox basin occur in the upper part of the Salt Wash (Molenaar, 1987a, b). The uppermost sandstone beds in the Salt Wash of the San Rafael Swell contain colorful chert pebbles; in the southwestern part of the swell, thick conglomerate beds contain chert and quartzite pebbles, cobbles, and rare boulders.

Brushy Basin Member

The Brushy Basin Member, which typically forms slopes, is at the top of the Morrison Formation throughout most of the Colorado Plateau. The Brushy Basin is composed of reddish-brown and light-greenish-gray, laminated to thin-bedded mudstone with appreciable quantities of swelling clays. Minor light-brown, fine-grained, laminated to very thin bedded or cross-bedded pebbly sandstone and dark-brown crossbedded conglomerate are minor lithologies of the unit. Minor occurrences of red or very light brown bentonite beds, thin beds or lenses of dense gray limestone, and thin zeolite beds are also present.

Though poorly understood, the depositional origin of the Brushy Basin probably was in a mudflat and lacustrine environment, with a small part having been deposited in fluvial and overbank flood-plain environments.

Cedar Mountain Formation

The Lower Cretaceous Cedar Mountain Formation consists of the basal Buckhorn Conglomerate Member and an upper shale member (Stokes, 1944, 1952). The lower unit is a yellowish-gray sandstone that contains granule- to cobble-size clasts. The upper shale, which is thicker than the conglomerate unit, consists of pastel (tints of red, purple, and green) swelling claystone and mudstone, an abundance of limestone nodules, and a few scour-and-fill, yellowish sandstone beds. The shale locally contains light-gray, commonly brown-weathering, fine-grained limestone in beds as much as 1 m thick. Chert occurs mainly as fracture filling or as irregular replacement in limestone. The Buckhorn Conglomerate Member is light-gray to light-greenish-gray and moderate-orange-pink, fine- to medium-grained sandstone, much of which is conglomeratic. The Cedar Mountain Formation is mainly a fluvial and flood-plain deposit derived from the west.

Mancos Shale

The base of the Upper Cretaceous Mancos Shale is marked by an unconformity representing removal of the Upper Cretaceous Dakota Sandstone from the wilderness study areas of the San Rafael Swell. The Mancos is a thick marine shale composed of uniform dark-gray mudstone, shale, and siltstone, containing many zones of impure sandstone and dispersed bentonite as well as limestone concretions; the unit weathers to drab light gray. In the swell, the Mancos includes a marker bed, the Ferron Sandstone Member (Hintze and Stokes, 1964; Williams, 1964; Molenaar, 1981; and Doelling, 1985), a yellow to tan, fine-grained, friable to well-cemented sandstone that forms a conspicuous cuesta or low cliff about 400 ft above the base of the Mancos Shale. The units crop out on the southern edge of the San Rafael Swell. Regionally, the Mancos Shale is about 600 ft thick.

Geochemical Studies

Reconnaissance geochemical studies provide information on low-level and isolated elemental and metallic anomalies that are useful in interpreting the potential for mineral resources.

Sample Media and Collection

Stream sediments, heavy-mineral concentrates derived from stream sediments, and rock chips were selected as the sample media. Stream-sediment samples represent a composite sample of rock and soil exposed in the drainage basin. Their analysis provides information that helps identify those basins containing unusually high concentrations of elements that may be related to mineral occurrences. Chemical analysis of heavy minerals concentrated from stream sediments provides information about the chemistry of certain high-density, resistant minerals eroded from the drainage basin upstream. The removal of most of the rock-forming silicates, clays, and organic material permits the determination of elements in the concentrate that are not generally detectable in bulk stream sediments. Some of these elements can be constituents of minerals related to ore-forming processes rather than rock-forming ones.

A total of 240 bulk stream-sediment and related heavy-mineral-concentrate samples were collected from modern alluvium residing within first- or second-order ephemeral stream channels. Rock samples were collected from 123 sites. Rock samples that appeared unaltered were collected to provide information on background geochemical values. Altered and mineralized samples were collected to determine suites of elements associated with the observed alteration or mineralization.

Stream sediments were sieved to minus-80 mesh and then pulverized to fine powder for analysis. To obtain heavy-mineral concentrates, bulk stream-sediment samples were sieved to minus-10 mesh and then panned to remove most of the quartz, feldspar, and organic and clay-size material. The panned concentrates were separated into light and heavy fractions by flotation in bromoform (specific gravity 2.8). Material of specific gravity greater than 2.8 was then separated on the basis of magnetic susceptibility into three fractions. The nonmagnetic fraction was hand ground to a fine powder for analysis. Rock samples were pulverized to minus-100 mesh prior to analysis.

All samples were analyzed using a semiquantitative emission spectrographic method for the following 37 elements: iron, magnesium, calcium, sodium, phosphorus, titanium, manganese, silver, arsenic, gold, boron, barium, beryllium, bismuth, cadmium, cobalt, chromium, copper, gallium, germanium, lanthanum, molybdenum, niobium, nickel, lead, antimony, scandium, tin, strontium, vanadium, thorium, tungsten, yttrium, zinc, zirconium, palladium, and platinum. In addition, stream-sediment and rock samples were analyzed for arsenic, antimony, bismuth, cadmium, gold, and zinc by specific chemical methods and for uranium and thorium by neutron activation analysis. Analytical data, sample sites, analytical-method references, and a detailed description of the sampling and analytical techniques are given in Bullock and others (1989).

Results of Studies

Anomalous values, defined as those above the upper limit of normal background values, were determined for each element in the various sample media and analysis methods by inspection of the analytical data and by comparison with published crustal-abundance values (Rose and others, 1979) rather than by statistical techniques. Many elements had only a few measurable occurrences. For some elements (Ag, Au, Mo, Sn, W), any occurrence above the detection limit would be anomalous.

Anomalous values in the geochemical data were almost entirely limited to those elements found in the heavy-mineral-concentrate samples where large concentration factors exist, and most of these anomalies were only slight. The anomalies are grouped by anomalous suites of elements and by geographic location into the following seven anomalous zones (fig. 13). The number of sites in each anomalous zone ranges from 1 to 22.

Anomalous zone 1, The Blocks chromium anomaly in the southeastern part of the Sids Mountain Wilderness Study Area, extends approximately 22 mi north from Interstate Highway 70 to near Salt Wash. The zone is about 11 mi from east to west and is approximately centered on longitude 110°52′30″, the boundary of the Sid and Charley and The Blocks 7.5-minute quadrangles (pl. 1). Chromium values in the nonmagnetic fraction of the heavy-mineral concentrate from stream sediments, hereafter called simply the heavy-mineral concentrate, for most of the 22 sites in this area range from 1,000 to 5,000 ppm. Values from other parts of the study area range from less than 20 to 500 ppm. No other elements were found associated with the chromium. A follow-up study of 27 concentrate samples collected from the anomalous zone showed no detectable platinum or palladium at a detection limit of 2 ppm. Stream-sediment samples from this area were not anomalous, containing from less than 10 to 100 ppm chromium, as did samples from the remainder of the Sids Mountain Wilderness Study Area. The source of this low-level anomaly is unknown. Rock samples collected in the area were not anomalous in chromium.

Anomalous zone 2, the Upper Saddle Horse Canyon lead anomaly in the Sids Mountain Wilderness Study Area, specifically in the northeast quadrant of The Blocks 7.5-minute quadrangle (pl. 1), is approximately 2 mi from east to west and 4 mi from north to south. The heavy-mineral concentrate from the six sites in the area contained from 200 to 20,000 ppm lead. No other elements were found to be associated with the lead. Lead was not detectable at 10 ppm in the associated stream-sediment samples.

Anomalous zone 3, the Bottleneck Peak copper anomaly in the Sids Mountain and Mexican Mountain Wilderness Study Areas, is approximately centered on the Bottleneck Peak 7.5-minute quadrangle (pl. 1). Nine of eleven sites in the approximately 5-mi-diameter sample area have slightly anomalous copper values in heavy-mineral concentrates, ranging from 150 to 300 ppm. Two are also slightly anomalous in tin (30 and 70 ppm). Stream-sediment samples are slightly anomalous, ranging from 15 to 50 ppm tin.

Anomalous zone 4, the San Rafael Reef silver anomaly in the San Rafael Reef Wilderness Study Area, extends along the eastern limit of the San Rafael Swell from the third canyon south of Interstate Highway 70 (approximately 3 mi south of the highway) an additional 6.5 mi to Straight Wash. It extends to the west, including tributaries to Straight Wash as far west as Red Draw. Eleven of twelve sites in the area contained detectable silver in the heavy-mineral concentrate, the highest concentration being 7 ppm. Two samples contained arsenic and lead. Sample SR005 contained 1,000 ppm arsenic and 7,000 ppm lead. Sample SR039 contained 10,000 ppm arsenic and 700 ppm lead. No silver was detected in any of the associated stream-sediment samples. Sample sites along the edge of the swell were where drainages emerge from the reef and

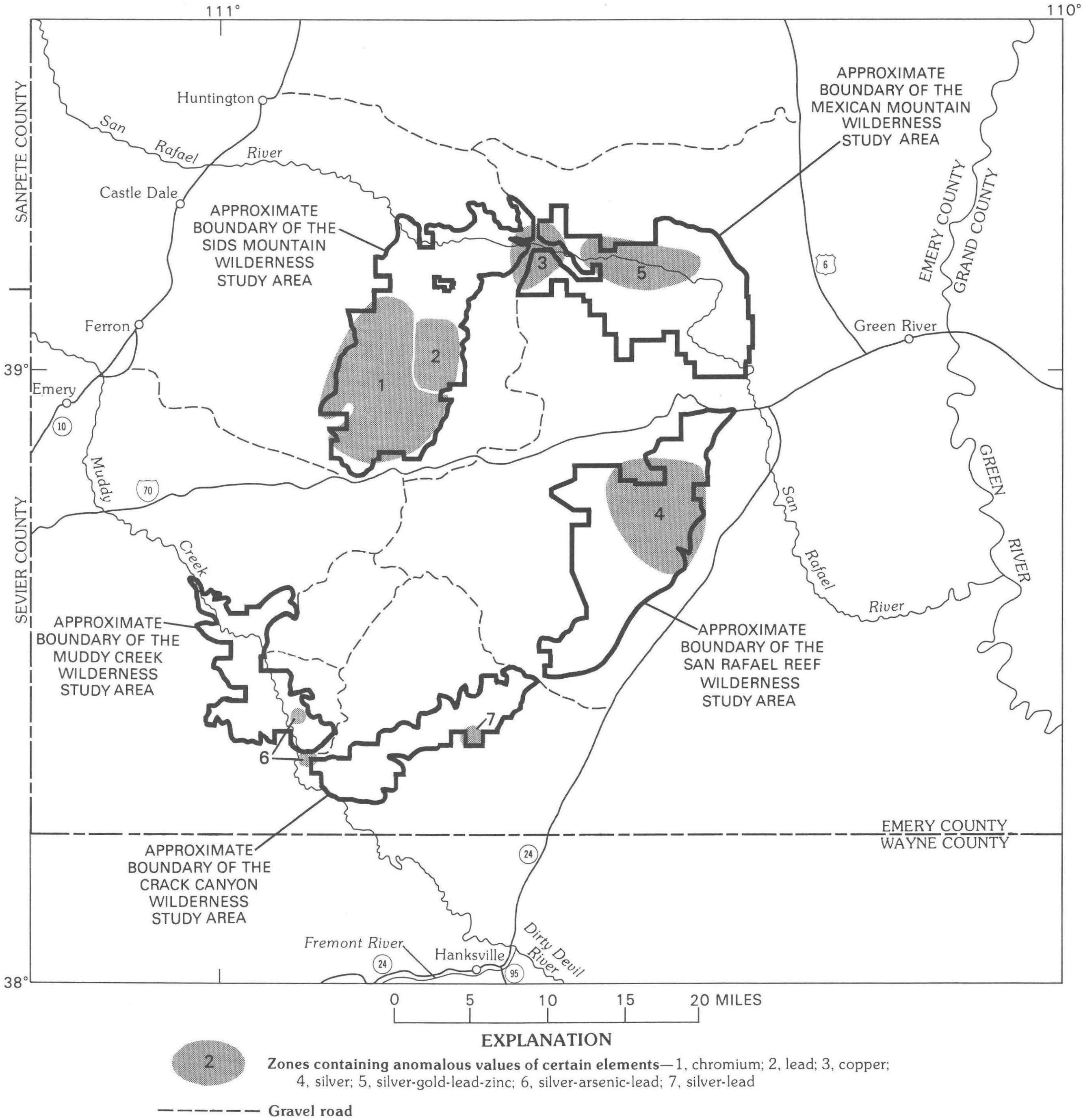

Figure 13. Geochemical anomalous zones in wilderness study areas in the San Rafael Swell region, Utah. 1, chromium; 2, lead; 3, copper; 4, silver; 5, silver-gold-lead-zinc; 6, silver-arsenic-lead; 7, silver-lead.

were stratigraphically above the Carmel Formation. Sites in Straight Wash were stratigraphically as low as the Elephant Canyon(?) Formation.

Anomalous zone 5, the San Rafael River silver-gold-lead-zinc anomaly in the Mexican Mountain Wilderness Study Area, has four anomalous sites interspersed with nonanomalous sites in an area on both sides of the river for approximately 5 mi east of Red Canyon. Two samples contained anomalous gold at 50 ppm, three contained silver ranging from 2 to 7 ppm, three contained lead from 5,000 to 10,000 ppm, and one contained zinc at 700 ppm. The corresponding stream-sediment samples contained no anomalous values.

Anomalous zone 6, the Muddy Creek silver-arsenic-lead anomaly in the Muddy Creek Wilderness Study Area, is on two streams, from the east tributary to the Chute of Muddy Creek between Tomsich Butte and the Delta mine (figs. 7, 13). Sample site MC045, 4.2 mi south-southeast of Tomsich Butte, contained 30 ppm silver and detectable but less than 500 ppm arsenic in the heavy-mineral concentrate. Site MC028, 1.3 mi north-northwest of the Delta mine, contained 1.5 ppm silver, detectable but less than 500 ppm arsenic, and 10,000 ppm lead in the concentrate. The corresponding stream-sediment samples were very slightly anomalous. They contained 72 and 37 ppm arsenic, 0.6 and 0.5 ppm cadmium, and 31 and 27 ppm zinc, respectively.

Anomalous zone 7, the Chute Canyon tributary silver-lead anomaly in the Crack Canyon Wilderness Study Area, is on a tributary drainage from the northeast that joins Chute Canyon outside the San Rafael Reef and approximately 2 mi northwest of Wild Horse Butte (fig. 13). The heavy-mineral concentrate from the single site contained 10 ppm silver, 500 ppm chromium, and greater than 50,000 ppm lead. The corresponding stream sediment contained no anomalous values.

Rock samples taken throughout the San Rafael Swell wilderness study areas showed element concentrations in three general groups: (1) unaltered rock samples of various lithologic units underlying the study area showed background values for all elements of economic interest; (2) rock samples from a prospect on the western side of the swell at Red Canyon, from the Moss Back Member of the Chinle Formation, showed anomalous values for many elements including arsenic, antimony, cadmium, copper, lead, molybdenum, silver, uranium, vanadium, and zinc. These elements are included in the elements stated by Hawley and others (1965) as being enriched in uranium deposits at Temple Mountain, in other areas of the San Rafael Swell, and from throughout the Colorado Plateau; and (3) iron oxide nodules in both sandstone and limestone units from scattered locations throughout the San Rafael Swell area and thin layers of iron-manganese oxide that follow bedding-plane features contain anomalous values of the same suite of elements associated with the mineralized Moss Back Member.

Anomalies of anomalous zones 2–7 are generally isolated and low level. All these anomalous elements are described as accompanying uranium deposits in the swell and elsewhere (Hawley and others, 1965). Guilbert and Park (1986) described similar uranium-vanadium deposits in the Salt Wash Member of the Upper Jurassic Morrison Formation as containing significant uranium, vanadium, copper, silver, selenium, and molybdenum, and erratic amounts of chromium, lead, zinc, arsenic, cobalt, and nickel. The above-mentioned anomalies or elemental enrichments are thought to be related to uranium deposits in the area and are not considered to be significant. Any geochemical evidence for near-surface ore deposits not related to uranium deposits or any undiscovered mineralized system of consequence is absent.

Geophysical Studies

Regional geophysical studies provide information on subsurface lithology and structural features, and new information on the extent and distribution of altered-rock and lineaments. Such geophysical information is useful in interpretation of the potential for mineral and energy resources.

Aerial Gamma-ray Data

Aerial gamma-ray data, which are used to determine the near-surface concentrations of potassium, uranium, and thorium, were examined for the San Rafael Swell only as part of a regional-scale study. A map was compiled and processed by Duval (1983) from surveys flown for the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program in 1975–83.

No significant radioelement anomalies were apparent in any of the study areas on the regional-scale map, even in regions of known uranium mineralization. The lack of anomalies implies that no regional radioactivity occurs in the San Rafael Swell area. The individual areas of uranium mineralized rock are not distinguishable on the regional map due to the wide flight-line spacing of the aerial surveys (commonly 3 mi) and the filtering required to produce the map. The wide spacing limits the coverage of the area, and the filtering lessens the resolution of details. Analysis of individual flight lines is recommended for further study.

Gravity and Aeromagnetic Surveys

Gravity and aeromagnetic data were interpreted for the wilderness study areas. The resolution of the potential field data does not allow a detailed interpretation of the structural and lithologic complexities of the San Rafael Swell. Rather, the geophysical data point out large geologic units that have strong density or magnetic-susceptibility contrasts. The vast majority of these contrasts originate in the crystalline basement rocks and represent abrupt lateral changes in basement lithology and structure. The San Rafael Swell is thought to be early Tertiary in age, a result of reactivation of high-angle fracture zones and faults of Precambrian age as a response to regional compressive stresses during Laramide time. Many of the steep gradients we see in the geophysical data are probably expressions of Laramide structures.

Data

Gravity data compiled for the study area were extracted from the U.S. Department of Defense data bank (available through the U.S. National Oceanic and Atmospheric Administration Data Center, Boulder, Colo.), and McCafferty (unpub. data, 1988). The complete (terrain-corrected) Bouguer gravity field was calculated using a reduction density of 2.67 grams per cubic centimeter, employing standard USGS computer programs (fig. 14). The reduction process and mathematical formulas used to calculate the Bouguer anomaly are given in Cordell and others (1982). Variations in the gravity field reflect contrasts in rock densities associated with changes in geologic structure or lithology.

The total-intensity magnetic field (fig. 15) was compiled from two separate aeromagnetic surveys (Case and Joesting, 1972; Zietz and others, 1976, University of Utah Area #4). The surveys were flown at 2,591 m (8,500 ft) barometric elevation with flight-line spacings ranging from 1.6 to 3.2 km (1–2 mi). The residual aeromagnetic field was obtained by removing the definitive International Geomagnetic Reference Field (Langel, 1988) from each survey after updating to the years in which the surveys were flown (Grauch and Plesha, 1989). The data were then converted to a form equivalent to a vertically incident magnetic field (Hildenbrand, 1983), often referred to as "having been reduced to the magnetic north pole." The result (fig. 15) is a shifted plot of the magnetic field that shows the anomalies centered over their sources.

A gravity high is associated with the San Rafael Swell (fig. 14) and delineates a body of rock denser than the surrounding country rock. The gravity gradient enveloping the swell is steepest to the northeast where it crosses the Mexican Mountain Wilderness Study Area. A northeast-trending magnetic high is over the swell (fig. 15) and extends south of it and, at much lower amplitudes, outside of the swell in several places (east of the swell at about latitudes 39°N, 38°50′N, and 38°35′N).

Description of Gravity and Aeromagnetic Model

In an effort to understand the regional lithology and structure of the crystalline basement rock, a two-dimensional model and associated gravity and aeromagnetic profiles were constructed across the swell (fig. 16). Physical properties of the model are listed on table 3. The profile (*A–A′*, figures 14, 15) was located where data coverage is the most abundant. The depth to crystalline basement was estimated from depths to Precambrian rocks that were extrapolated from drill holes and stratigraphic information (R.W. Scott, Jr., written commun., 1989). Because detailed information on basement geometry was not available, vertical-sided prisms were used in this model in an effort to map only the abrupt lateral changes in density and susceptibility across the swell.

Discussion

A broad gravity high corresponds to the area of the swell (figs. 14, 16). Modeled rock densities increase toward the center of the swell, reaching a maximum of 2.71 grams per cubic centimeter in bodies 3, 4, and 5 (fig. 16, table 3). Although the gravity high also corresponds to the basement structural high, basement relief is not enough to account for the increase in gravity. The model supports the concept of a denser rock body beneath the swell with a different lithology than the surrounding country rock. Gravity effects caused by variations in the overlying sedimentary sequence are not accommodated in this model and are attributed to the 1–3 mGal (milligal) error between the observed and calculated fields.

Coincident with the gravity high over the swell is a positive magnetic anomaly with amplitude exceeding 700 nanoteslas (figs. 15, 16). Magnetic susceptibilities for the model (table 3) indicate that bodies 3, 4, 5, and possibly 7 (fig. 16) represent the source(s) of the magnetic highs. Body 7 probably represents an extension of the same relatively magnetic material represented by bodies 3, 4, and 5, which is most apparent on the magnetic contour map by the high that extends to the east of the swell (fig. 15). However, lack of constraints on the top of the model may have mistakenly produced a somewhat shallower, less magnetic body 7 than would be expected.

As discussed previously in the section on "Intrusive and Plutonic Rocks," Precambrian granite was found in a few drill holes. Depths to the granite generally correspond to relative depths inferred from the geophysical model and maps. Moreover, the modeled densities of 2.71 grams per cubic centimenter for the source of the gravity high support a felsic composition. Therefore, Precambrian granite is the most likely source of the magnetic and gravity highs. The granite is shallowest near the center of the swell and extends outside the swell at deeper levels on the southern and eastern sides, as indicated best by the character of the magnetic anomalies (fig. 15).

Remote-Sensing Analyses

Methods

Remote-sensing data can be used to map altered rocks that may be guides in locating mineral deposits. Landsat Thematic Mapper (TM) imagery data in the form of single-band images, color-infrared (CIR), color-ratio-composite (CRC), and intensity-hue-saturation-classified CRC images, and color-infrared photography

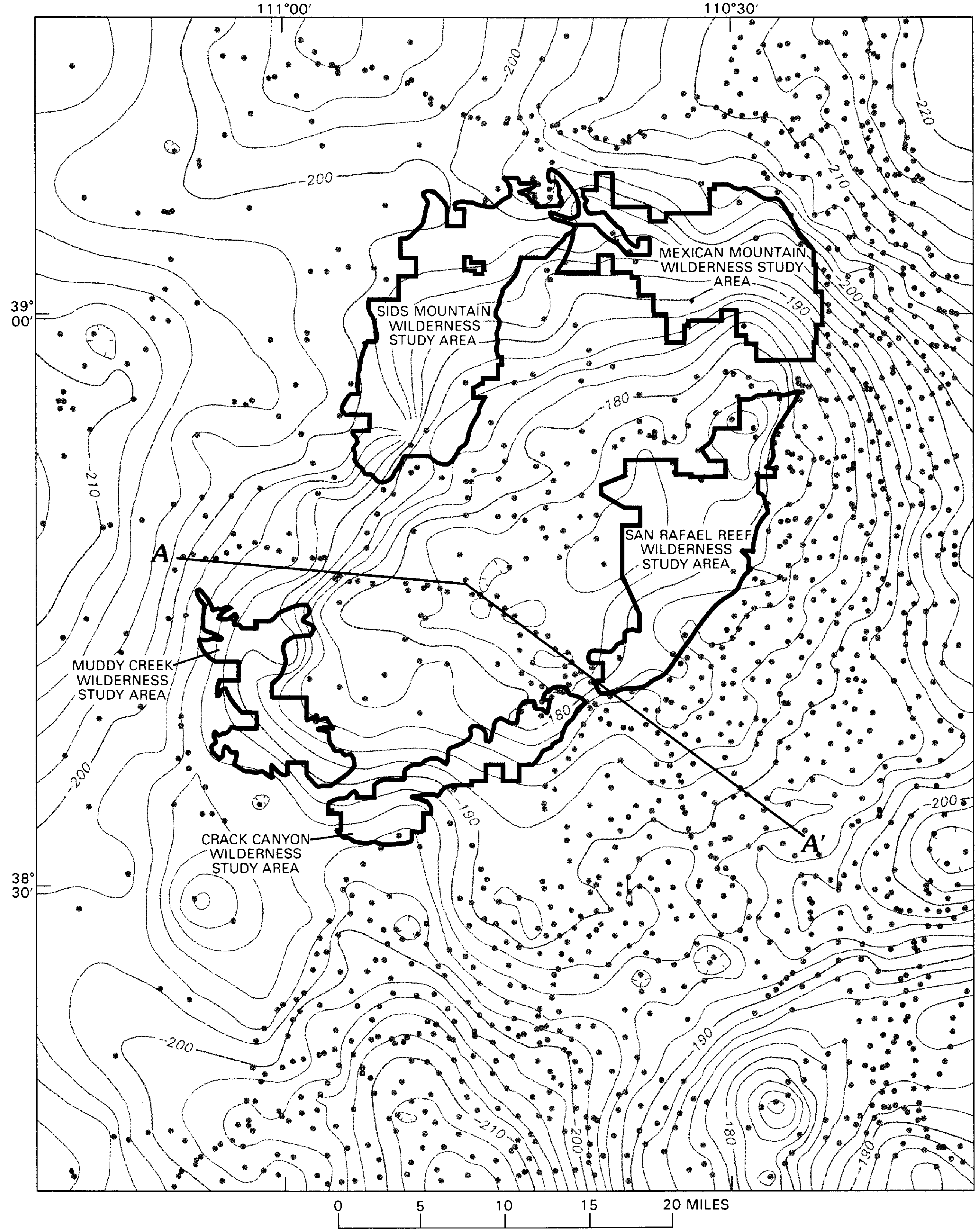

Figure 14. Complete Bouguer gravity anomaly map of the San Rafael Swell region, Utah. Gravity-station locations are shown by dots. Hachures indicate closed areas of lower gravity values. Contour interval is 2 milligals. Line *A–A′* shows location of gravity profile modeled on figure 16.

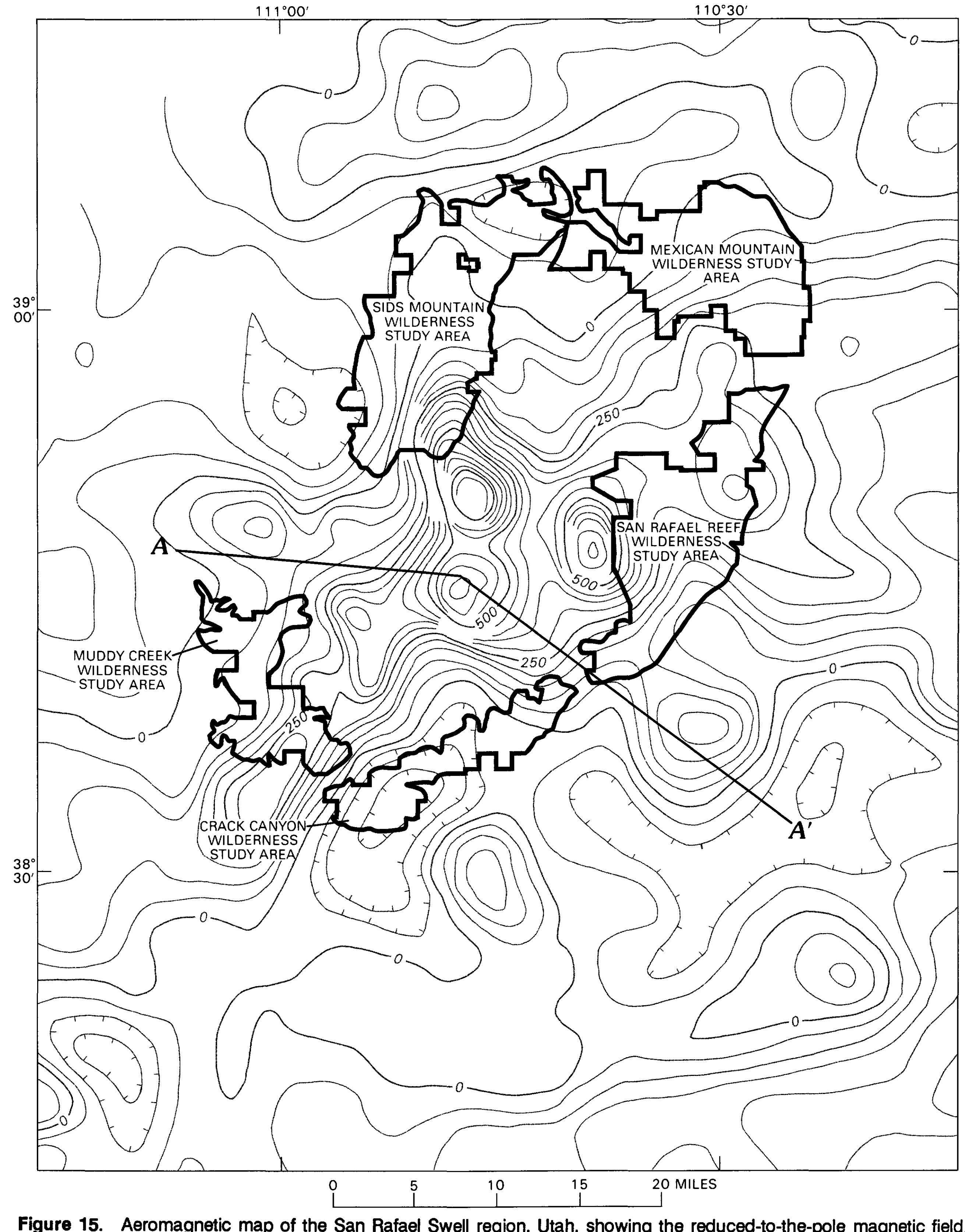

Figure 15. Aeromagnetic map of the San Rafael Swell region, Utah, showing the reduced-to-the-pole magnetic field. Contour interval is 50 nanoteslas. Hachures indicate closed areas of lower magnetic values. Line *A–A′* shows location of magnetic profile modeled on figure 16.

Table 3. Modeled densities and magnetic susceptibilities for the gravity and aeromagnetic model on figure 16, San Rafael Swell wilderness study areas, Utah

Body No.	Density (grams per cubic centimeter)	Magnetic susceptibility (cgs system)
1	2.60	$7.1X10^{-6}$
2	2.62	$17.7X10^{-6}$
3	2.71	$29.0X10^{-6}$
4	2.71	$50.0X10^{-6}$
5	2.71	$33.5X10^{-6}$
6	2.69	$15.1X10^{-6}$
7	2.67	$25.1X10^{-6}$
8	2.64	0.0

at scale 1:80,000 (southern part of the San Rafael Swell region) were used to locate and map altered rocks associated with either uranium mineralization or hydrocarbon seepage and rocks altered by hydrothermal solutions. These data were digitally processed, analyzed, and interpreted to identify the presence and absence of iron oxide, carbonate, and hydroxyl-bearing minerals whose presence might be related to hydrocarbon migration, uranium mineralization, and (or) hydrothermal alteration.

Discrimination of these minerals or mineral groups is possible based on their absorption features (spectral properties) that fall within TM passbands. Band ratios are the most effective and widely used method to extract this information. For this purpose, band ratios were constructed and combined to produce a CRC image on which altered rocks were characterized by color differences. This method effectively discriminates limonitic rocks from nonlimonitic rocks. It also discriminates rocks that contain clays, micas, or carbonates, although an unambiguous identification of which of these minerals is present cannot be made. The CIR and single-band TM images and color-infrared photography were used as an indirect measure of the albedo (brightness) of the rocks associated with potential alteration zones.

A lineament analysis was conducted using contrast-stretched and edge-enhanced TM images. Statistical methods were used to define linear trends, from which lineaments were interpreted.

Results

The rocks of the San Rafael Swell can be classified into three groups according to their oxidation state: (1) syngenetic (depositional) red-bed facies, (2) grayish carbonaceous facies, and (3) epigenetic (post-depositional) altered rocks of the two previous facies.

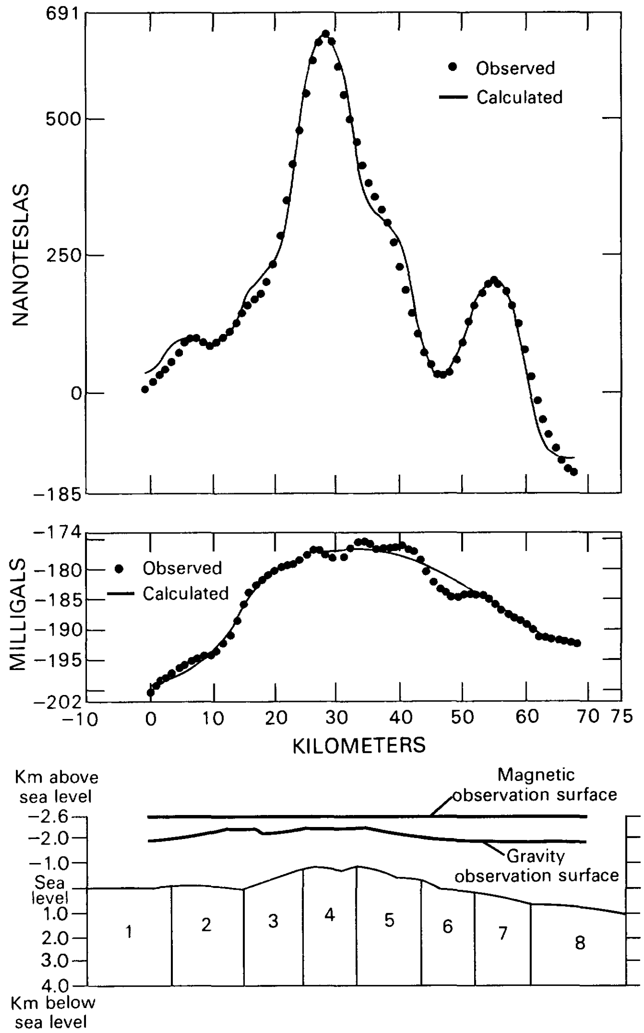

Figure 16. Two-dimensional model showing observed and calculated magnetic and gravity profiles along line *A–A′*, San Rafael Swell region, Utah. Model surface was constructed using extrapolated depth to crystalline basement (R.W. Scott, Jr., written commun., 1989). Vertical exaggeration X4. Numbered blocks in model refer to body values (calculated densities and magnetic susceptibilities) shown in table 3.

Landsat TM imagery data, supported by field and laboratory data, were used to map altered rocks based on their spectral properties and albedo variations (Hayati Koyuncu and Keenan Lee, written commun.,1989). The alteration interpretation map was based on three types of mineralogic anomalies: (1) negative limonite anomalies, (2) clay and (or) carbonate anomalies, and (3) combinations of these anomalies.

Field work and laboratory spectral data show that limonitic areas correspond primarily to outcrops of unaltered red beds. The negative limonitic anomalies correspond to areas of bleached rocks and gray carbonaceous rocks. Oil staining is common in the rocks of this group, and it causes an overall decrease in reflectance. The clay and carbonate anomalies define an introduction or increase in the amount of clay (commonly kaolinite), calcite, and dolomite as a result of alteration caused primarily by: (a) collapse structures, (b) uranium mineralization, and (c) migrating hydrocarbons. The clay and (or) carbonate plus limonitic anomalies were defined as areas where the bleaching of the red beds is not complete or areas where altered rock contained both clay or carbonate and iron oxide minerals.

The data indicate no hydrothermally altered rocks within the San Rafael Swell region. However, negative limonitic anomalies and clay alteration and (or) carbonate anomalies caused by hydrocarbon-induced alteration are present. Altered rocks associated with collapse structures and originally reduced, but epigenetically modified, uranium-bearing sandstones and conglomerates of the Chinle Formation are distinguished.

Field examinations indicated that altered-rock boundaries associated with hydrocarbon migration are generally concordant or planar, although some crosscutting relations occur. Uranium-related altered rock is restricted to preore reduced beds in or near ore deposits and to thin, bleached, and mottled basal rocks of the Chinle Formation.

The lineament analysis defined 27 lineaments (fig. 17) that could be correlated with geological and geophysical data. Intersections of linear features and lineaments suggest the locations of probable buried collapse structures and possible ore deposits associated with the collapses in areas where the terrain is underlain by the thick sandstone units of the Glen Canyon Group.

Mineral and Energy Resources

Uranium and Vanadium

Sandstone-hosted uranium deposits are found in sandstone beds that typically are generally flat bedded, feldspathic or tuffaceous, of Devonian or younger age, and in a stable platform or foreland-interior basin setting (Turner-Peterson and Hodges, 1986). According to Turner-Peterson and Hodges (1986), the microcrystalline uranium and vanadium oxides and silicate ores form during postdepositional alteration of fine- to medium-grained permeable sandstone beds within shale and mudstone sequences, and are later redistributed by ground water; some of these metallic oxides are concentrated at an oxidation-reduction boundary. Further, the interbedded mudstone or shale in some instances provides the source for ore-related fluids; carbonaceous material typically reacts with these fluids to precipitate the uranium and vanadium. Fluvial channels, braided-stream deposits, continental-basin margins, and stable coastal plains are the most characteristic settings for uranium and vanadium deposits (Turner-Peterson and Hodges, 1986).

According to Wood and Grundy (1956), uranium and vanadium deposits in the Chinle Formation are commonly associated with: (1) bottoms and sides of fluvial channels; (2) poorly sorted, argillaceous, arkosic sandstone or conglomerate interbedded with mudstone and clay lenses; (3) irregular channels with steep, narrow cross sections; (4) carbonaceous material and clay lenses; (5) a thickened bleached zone in the underlying Moenkopi Formation; and (6) the following combinations of metals in adjacent rocks: copper sulfides, sulfates, and carbonates; iron sulfides, sulfates, and hydrous oxides; and cobalt arsenate. Uranium and vanadium, commodities produced within the Colorado Plateau, are found typically in the Upper Triassic Chinle Formation and in the Upper Jurassic Morrison Formation of northern New Mexico, southwestern Colorado, and southeastern Utah (Finch, 1959, 1967; Doelling, 1975; U.S. Department of Energy, 1979). The primary host in the San Rafael Swell region is the fluvial units at the base of the Chinle Formation. The ore is concentrated along peneconcordant basal beds of the Chinle Formation exposed at the surface in the San Rafael Swell and in the subsurface to the west. These deposits are in channel sandstone in scours in the uppermost part of the Moenkopi Formation and are associated with carbonized and petrified wood and asphaltic material. Uranium and vanadium are also present in the permeable Glen Canyon Group in the Temple Mountain collapse structure, where the ore occurs along the flanks of the collapse primarily as roll deposits.

Uranium and vanadium also are commonly associated with collapse features elsewhere on the Colorado Plateau, most notably in northern Arizona (Finch, 1959, 1967). According to Wenrich (1985), Paleozoic sedimentary rocks on the Colorado Plateau in Arizona host hundreds of breccia pipes similar to the one at Temple Mountain but involving rocks ranging from the Mississippian Redwall Limestone to the Upper Triassic Chinle Formation. In Arizona, the features result from solution-collapse within the Redwall Limestone and stoping of the overlying strata that took place from Mississippian to Triassic time; in no places in Arizona has collapse been observed in strata younger than Triassic (Wenrich, 1985). Mineralization took place in Mesozoic time, but the origin of the mineralizing fluids is not known. Indications are that the fluids were low-temperature types, although heated in excess of normal geothermal gradient on the Colorado Plateau (Wenrich, 1985). In the Arizona collapse features, the suite of elements in the mineralized rock includes silver, arsenic, barium, cadmium, cobalt, chromium, cesium, copper, mercury, molybedum, nickel, lead, antimony, selenium,

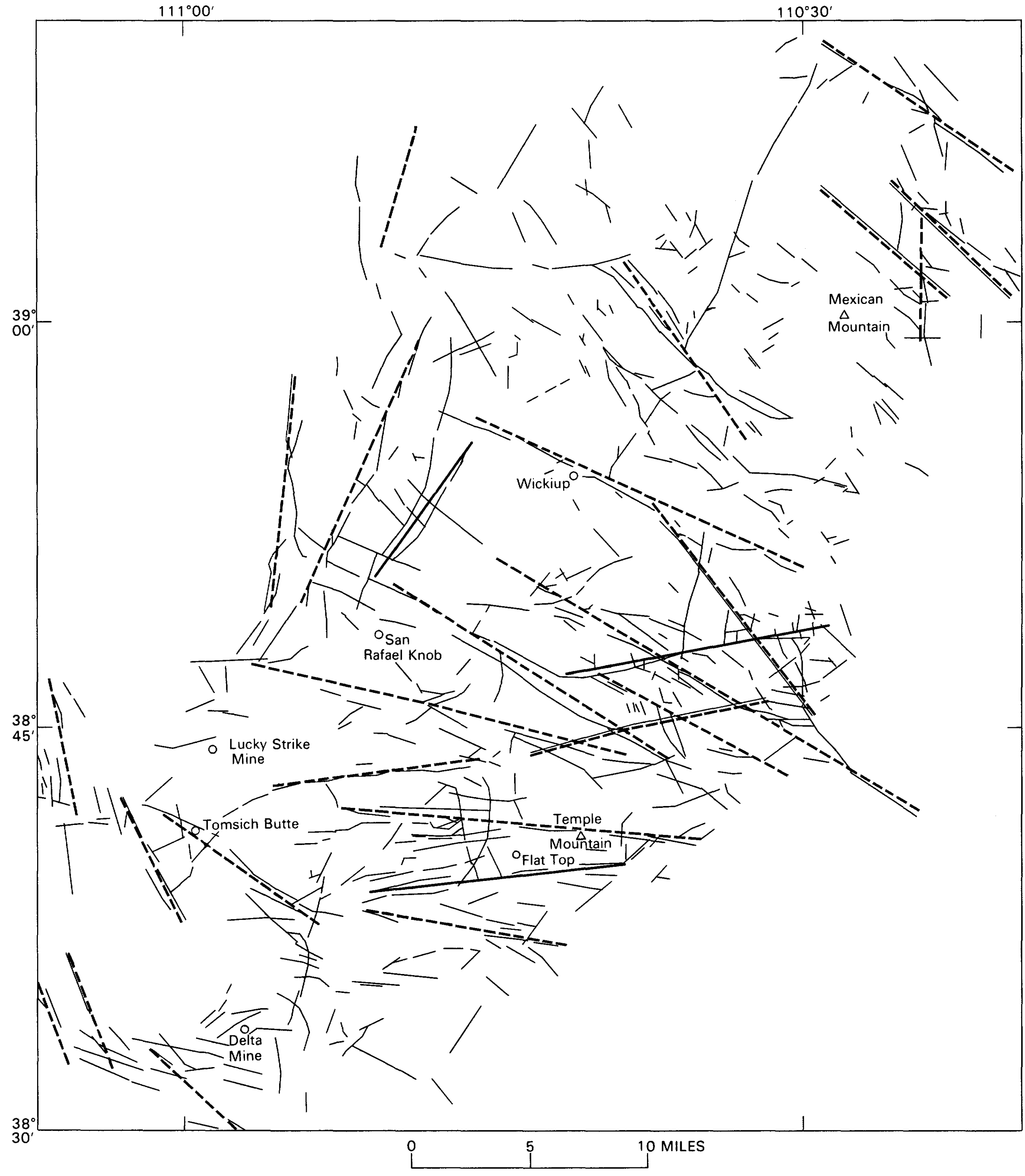

Figure 17. Lineament map of the San Rafael Swell region, Utah, showing linear features mapped from contrast-stretched and edge-enhanced Landsat Thematic Mapper images. Short dashed lines are lineaments interpreted from analysis of the smaller linear features shown as thin continuous lines.

uranium, vanadium, zinc, and the rare-earth elements, with copper, lead, zinc, silver, and particularly arsenic being the best geochemical indicators of mineralization (Wenrich, 1985).

The process of ore formation in the Temple Mountain collapse structure of the San Rafael Swell is not fully understood. In this belt, some investigators conclude that the uranium was already hosted in sandstone beds predating the collapse, and secondary solutions penetrating the collapse remobilized and concentrated the uranium into deposits within the collapse.

Location, Alteration, and Origin of the Uranium-Vanadium Deposits

The part of the San Rafael Swell region that contains rocks of the Chinle Formation was rated as being favorable for uranium and vanadium mineralization by Lupe and others (1982) and Campbell and others (1982). The most favorable environment for concentration of uranium minerals is in proximal and distal braided stream channels that contain carbonaceous matter and where the channels are incised into relatively impermeable rocks that are overlain by mudstone (fig. 18; Lupe, 1977; Campbell and others, 1982). In the San Rafael Swell area, the Chinle Formation was deposited in such a reducing environment by predominantly southeast-to-northwest flowing streams in three fining upward sequences. In this area, two Chinle fluvial sandstone systems merged, increasing the sandstone-to-mudstone ratio and increasing the likelihood of uranium and vanadium concentration.

Several belts in the San Rafael Swell region have been regarded as favorable for uranium mineralization in the Chinle Formation, and these are in the southeastern, southwestern, and northwestern parts of the swell (Hawley and others, 1968) near Temple Mountain, Tomsich Butte, and Calf Mesa, respectively. According to Witkind (1989), the northwestern belt near the Calf Mesa area apparently follows the northeastern flank of the older northwest-trending fold that is concealed beneath the San Rafael anticline. The southeastern belt near the Temple Mountain mining district is adjacent to a large collapse feature that may have provided a conduit for uraniferous solutions. Some workers (Campbell and others, 1982) suggested that ground water could transport the uranium as far as 20 mi from source rocks. In the southern part of the San Rafael Swell, the upper part of the Chinle Formation contains bentonitic siltstone and mudstone derived from volcanic material; these units also may have been a source for the uranium. A further consideration is the role of collapse structures as conduits for mineralizing fluids furnishing uranium and other metals from sources below the Chinle Formation.

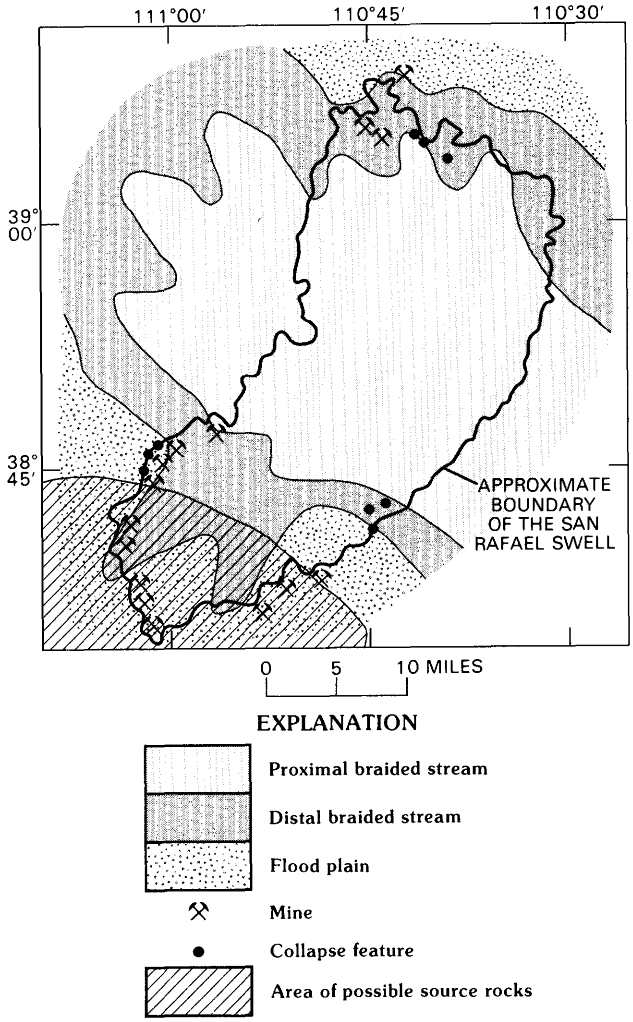

Figure 18. Distribution of depositional environments in the lower part of the Chinle Formation, San Rafael Swell region, Utah, and location of collapse features, mines and possible uranium source rocks in the upper part of the Chinle Formation. Modified from Lupe (1977).

Uranium Deposits in Fluvial Settings

Most of the uranium deposits in the Chinle Formation in the swell are in sandstone beds interbedded with conglomerate, siltstone, and mudstone; according to some workers, the ore may cut across bedding and assume the shape of a roll deposit (Lupe and others, 1982). The largest fluvial channel in the Chinle Formation in the San Rafael Swell is in the vicinity of Tomsich Butte. The channel is as wide as 1 mi and can be traced both on the surface and in the subsurface from the southeast flank of the swell, through Tomsich Butte, and northward through the Lucky Strike mine area. A smaller but major Chinle channel occurs near the Delta mine in the southern part of the San Rafael Swell. Both channels contain large amounts of uranium ore, the larger channel contributing the greatest amount of mined ore in the San Rafael Swell (Hawley and others, 1968).

The upper part of the Salt Wash Member of the Morrison Formation in the San Rafael River mining area on the northeast flank of the swell also contains uranium and vanadium in thick channel-sandstone deposits that contain carbonaceous material (Trimble and Doelling, 1978); however, in much of the San Rafael Swell region, the upper part of the Salt Wash Member is coarser grained, containing cobbles, pebbles, and rare boulders. Mineralization in the San Rafael River mining district paralleled northeast-trending point-bar, levee, crevasse-splay, and channel-bottom deposits or gentle northeast-trending folds (Trimble and Doelling, 1978).

Ore minerals in the Chinle and Morrison Formations contain oxidized and unoxidized uranium, copper, vanadium, zinc, lead, iron, and minor amounts of nickel, arsenic, molybdenum, silver, and cobalt. Unoxidized minerals are uraninite, coffinite, minor pyrite, sphalerite, tetrahedrite-tennantite, chalcocite, galena, chalcopyrite, bornite, marcasite, molybdenite, and montroseite. Oxidized minerals include carnotite, autunite, tyuyamunite, zippeite-like minerals, meta-zeunerite, pascoite, corvusite, malachite, and azurite (Hawley and others, 1968; Lupe and others, 1982; Campbell and others, 1982; Trimble and Doelling, 1978).

Uranium in Collapse Structures

Of the three areas in the San Rafael Swell that contain collapse structures, the Temple Mountain and Reds Canyon areas locally contain copper-uranium deposits in and near the collapse structures. These deposits also exist within several miles of the collapse structures near Window Blind Peak (Hawley and others, 1965, 1968). The most significant uranium deposits in collapse structures are at Temple Mountain, where some of the oldest mines on the Colorado Plateau are located. Six individual collapse structures are in the Temple Mountain mining district, and all but one has been mineralized. The collapse structures on Temple Mountain itself contain uranium ore in vertical pipes, veins, roll-like masses, and breccia zones. Altered blocks of sandstone in the collapse structures also contain sulfide minerals, native arsenic, and asphaltite, whereas unaltered blocks contain only asphaltite. At Temple Mountain, crosscutting relationships indicate that emplacement of oil occurred before collapse but that emplacement of uranium and other metals occurred after collapse. Apparently there is a pattern of zoning in the secondary metals associated with uranium deposits around the collapse structures at Temple Mountain. The concentration of vanadium and arsenic is greatest in the collapse structures, decreasing away from them, and concentrations of copper, lead, and zinc have opposite trends, though somewhat less systematically (Hawley and others, 1965; Finch, 1967). Possibly, some uranium and other metals were introduced into this district via the collapse structures from sources beneath the Chinle Formation. Of the three collapse structures in the Reds Canyon area on the southwest side of the swell, two are slightly uraniferous; all contain minor amounts of copper. None of the collapse structures east of Window Blind Peak in the northern part of the swell are known to be uraniferous (Hawley and others, 1968).

The Morrison Formation has been removed from all wilderness study areas except the southernmost Crack Canyon Wilderness Study Area. Due to its depositional setting, the Morrison Formation is not considered favorable for uranium deposits in the San Rafael Swell region outside of the San Rafael River mining district (Lupe and others, 1982).

Based on depositional models and known occurrences, there are two broad belts, one in the north and one in the south of the San Rafael Swell, that have favorable terrane for uranium deposits in the Chinle Formation. All known collapse structures also occur within these belts. Favorable source rocks for uranium exist in the upper part of the Chinle Formation in the southern belt. In exploration holes drilled to test the Chinle Formation for uranium on the western flank of the swell, anomalous levels of uranium were found in 2 of 22 (U.S. Department of Energy, 1979). Both holes are in the northern belt just west of the Sids Mountain Wilderness Study Area. The Sids Mountain Wilderness Study Area, the Crack Canyon Wilderness Study Area, the northeastern part of the Mexican Mountain Wilderness Study Area, the eastern and southeastern part of the San Rafael Reef Wilderness Study Area, and the western part of the Muddy Creek Wilderness Study Area have high mineral resource potential for small, localized uranium and vanadium deposits in sandstone beds and in altered zones along faults and lineaments, in the Chinle Formation (table 4) with certainty level C. Where collapse structures have formed, other geologic units both stratigraphically above and below the Chinle Formation (including the Glen Canyon Group) may also have high mineral resource potential for localized uranium- and vanadium-bearing sandstone. The Salt Wash Member of the lower part of the Morrison Formation outside the San Rafael River mining district (the southern part of the Crack Canyon Wilderness Study Area) has low mineral resource potential for sandstone-hosted uranium and vanadium with certainty level C.

Oil, Gas, and Tar Sand

Exploration for oil and gas in this part of central Utah began about 1900, with many discoveries of small fields in subsidiary structures along the axis and flanks of the San Rafael anticline. In 1934, gas was discovered in the Moenkopi Formation in the Last Chance anticline 10 mi southwest of the swell. In 1957, gas was discovered in the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale on the western flank of the swell near Ferron, Utah (fig. 1). In 1961, oil was discovered in the Moenkopi Formation on the Grassy Trail anticline about 20 mi north of the wilderness study areas (Preston, 1961; Mahoney and Kunkel, 1963).

The most favorable formations targeted for oil and gas exploration in south-central Utah are the

Table 4. Summary of mineral resource potential, San Rafael Swell wilderness study areas, Utah

Wilderness study area (figs. 2-6, pl. 1)	Resource potential	Level of potential/ Level of certainty (See appendix for explanation of symbols)	Commodities	Location in wilderness study area
Muddy Creek	High........	H/C	Tar sand.......	Entire area.
	High........	H/D	Gypsum.........	Western part.
	High........	H/C	Uranium and vanadium.	Western part.
	Moderate....	M/C	Oil and gas....	Entire area.
	Moderate....	M/B	Geothermal resources.	Entire area.
	Moderate....	M/B	CO_2 and He.....	Entire area.
	Low.........	L/B	Metals.........	Entire area.
	Low.........	L/B	Bentonite......	Western part.
Crack Canyon	High........	H/C	Tar sand.......	Entire area.
	High........	H/D	Gypsum.........	Southern and southeastern part.
	High........	H/C	Uranium and vanadium.	Entire area (Chinle Formation).
	Low.........	L/C	Uranium and vanadium.	Southern part (Morrison Formation).
	Moderate....	M/C	Oil and gas....	Entire area.
	Moderate....	M/B	Geothermal resources.	Entire area.
	Moderate....	M/B	CO_2 and He.....	Entire area.
	Low.........	L/B	Metals.........	Entire area.
	Low.........	L/B	Bentonite......	Entire area.
San Rafael Reef	High........	H/C	Tar sand.......	Entire area except Eardley Canyon.
	High........	H/D	Gypsum.........	Eastern and southeastern part.
	High........	H/C	Uranium and vanadium.	Eastern and southeastern part.
	Moderate....	M/C	Oil and gas....	Entire area.
	Moderate....	M/B	Geothermal resources.	Entire area.
	Moderate....	M/B	CO_2 and He.....	Entire area.
	Low.........	L/B	Metals.........	Entire area.
	Low.........	L/B	Bentonite......	Eastern and southeastern part.
	Low.........	L/B	Sulfur.........	Entire area.
Mexican Mountain	High........	H/C	Tar sand.......	Entire area.
	High........	H/D	Gypsum.........	Northeastern part.
	High........	H/C	Uranium and vanadium.	Northeastern part.
	Moderate....	M/C	Oil and gas....	Entire area.
	Moderate....	M/B	Geothermal resources.	Entire area.
	Moderate....	M/B	CO_2 and He.....	Entire area.
	Low.........	L/B	Metals.........	Entire area.
	Low.........	L/B	Bentonite......	Northeastern part.
	Low.........	L/B	Sulfur.........	Entire area.

Table 4. Summary of mineral resource potential, San Rafael Swell wilderness study areas, Utah—Continued

Wilderness study area (figs. 2-6, pl. 1)	Resource potential	Level of potential/ Level of certainty (See appendix for explanation of symbols)	Commodities	Location in wilderness study area
Sids Mountain	High........	H/C	Tar sand.......	Entire area.
	High........	H/D	Gypsum.........	Western part.
	High........	H/C	Uranium and vanadium.	Entire area.
	Moderate....	M/C	Oil and gas....	Entire area.
	Moderate....	M/B	Geothermal resources.	Entire area.
	Moderate....	M/B	CO_2 and He.....	Entire area.
	Low.........	L/B	Metals.........	Entire area.
	Low.........	L/B	Bentonite......	Entire area.

Mississippian Redwall Limestone (Kunkel, 1965; Oakes and others, 1981), the Middle and Upper Pennsylvanian Paradox and Honaker Trail Formations (Oakes and others, 1981), the Lower Permian Cedar Mesa and White Rim Sandstones and Kaibab Limestone (Kunkel, 1965; Oakes and others, 1981), and the upper part of the Lower and Middle(?) Triassic Moenkopi Formation (Peterson, 1973; Doelling, 1975, p. 91–96; Oakes and others, 1981).

The San Rafael Swell is a breached anticline that exposes Carboniferous to Jurassic rocks containing petroliferous and tarry sandstone and siltstone. Other reservoir rocks occur in the subsurface, and some workers postulate that thrust faulting might have occurred during the evolution of the swell, producing potential structural traps for oil and gas (Mahoney and Kunkel, 1963). Also, according to Mahoney and Kunkel (1963), structural and stratigraphic traps probably occur along the south and east flanks of the swell. These potential traps resulted from subsurface discontinuities between the underlying structure in the northern part of the swell and the overlying structure that is manifest on the surface, coincident with lateral facies changes in Pennsylvanian and Permian rocks on the western shelf of the Paradox Basin. Later fracturing and faulting has created the potential for increased permeability and porosity in the rocks.

Surficial evidence of tar sand or asphaltite deposits is in the White Rim Sandstone Member of the Cutler Formation, Kaibab Limestone, Moenkopi Formation, and Chinle Formation; asphalt-based oil also permeates the Triassic Chinle and Moenkopi Formations and the Jurassic Wingate Sandstone, Kayenta Formation, Navajo Sandstone, and Page Sandstone in the Temple Mountain mining district (Hawley and others, 1965). Oil staining, tar sand, and oil seeps are found in the Moenkopi Formation and are especially notable in the Sinbad Limestone Member. Exploration wells drilled into the swell document that oil staining and live oil also occur in rocks of the Kaibab Limestone and the White Rim Sandstone and Cedar Mesa Sandstone Members of the Cutler Formation (Baars, 1987; Witkind, 1989). Natural gas occurs in the Entrada Sandstone and in the Morrison Formation.

Secondary folds that may entrap hydrocarbons, and oil-seep and oil-well locations in the San Rafael Swell region are shown on figure 12. Many test wells have been drilled in the San Rafael Swell, mostly in the central, southern, and eastern parts (fig. 12). Although there has been no production from any of the wells, shows of oil and gas are in the Chinle and Moenkopi Formations, Kaibab Limestone, White Rim and Cedar Mesa Sandstone Members of the Cutler Formation, and the Hermosa Group, units that are exposed on the flanks and in the center of the swell. Although these rocks may have poor porosity and permeability in some areas, they probably form good reservoirs because they are secondarily fractured (Papulak, 1963; Witkind, 1989).

Oil and gas resources in Utah have been appraised by Molenaar and Sandberg (1983), and the San Rafael Swell area is designated as having moderate resource potential for oil and gas. The complex structural history of the swell increases the potential for stratigraphic and structural traps; fracturing of the rocks augments the reservoir potential. Oil seeps occur in some areas of the swell. Exploration has taken place on structural anticlines in the swell, and, despite favorable attributes of the exposed rocks and the shows of oil and gas in Paleozoic strata beneath the surface, no commercial oil and gas resources have been identified. Available drill-hole and structural information from the San Rafael Swell region indicates only limited future prospects for oil and gas. Two active oil seeps are present in and near the Sids Mountain Wilderness Study Area (fig. 12), but these are not currently being exploited. Thus, despite the availability of source rock, reservoir rock, trapping mechanisms, and thermal maturity of the rocks in the San Rafael Swell setting, geological and exploration evidence indicates that the resource potential for oil and gas in the wilderness study areas can be rated as moderate, with certainty level C (table 4). Tar sand is exposed on the surface and occurs in wells drilled into the swell. The potential for discontinuous tar-sand deposits of varying grade in the White Rim Sandstone Member of the Cutler Formation, Kaibab Limestone, Moenkopi Formation, Chinle Formation, Wingate Sandstone, Kayenta Formation, Navajo Sandstone, and Page Sandstone in all wilderness study areas of the San Rafael Swell except in Eardley Canyon in the San Rafael Reef Wilderness Study Area is rated as high with certainty level C (table 4).

Carbon Dioxide and Helium Gases

Carbon dioxide and helium may accumulate as gases in petroleum reservoirs; helium is a known component of and is commonly extracted from natural gas. Both gases are rated as strategic and critical gases.

Carbon dioxide is used in oil-recovery-enhancement techniques like those used in West Texas oil fields. Because carbon dioxide is miscible with oil, it acts as a solvent, displacing enough water to mobilize oil in water-invaded reservoirs that would otherwise be unrecoverable. The largest carbon dioxide gas reservoirs are the McElmo Dome and Doe Canyon fields near the Four Corners area of Colorado, and the host rock is the Leadville Limestone of Mississippian age. Presumably, carbon dioxide gas was created in this carbonate reservoir when the water-filled formation was subjected to high pressure and temperature alteration during deep-seated volcanism.

Helium, a unique elemental gas, has many useful properties; it is chemically inert, has a simple chemical structure, a very low specific gravity, a low density, and is thought to be a byproduct of radioactive decay (U.S. Bureau of Mines, 1980).

The Woodside anticline on the northeastern flank of the swell (fig. 1) was drilled in the 1920's and thought to contain a large reservoir of helium and carbon dioxide (Gilluly, 1929). The reservoir, in the White Rim Sandstone Member of the Cutler Formation (the Cedar Mesa Sandstone of Mahoney and Kunkel, 1963), produced 6–10 million cubic feet per day (Mahoney and Kunkel, 1963, p. 371) and was set aside as a national helium reservoir. In the adjacent Paradox basin to the east and southeast of the San Rafael Swell, and in the Woodside anticline to the northeast and Farnham dome about 3 mi east of Wellington and about 30 mi north of the San Rafael Swell, nonflammable carbon dioxide gas was recovered from the Glen Canyon Group and the White Rim Sandstone Member. In some places, the Sinbad Limestone Member of the Moenkopi Formation also contains minor amounts of carbon dioxide gas. Though no evidence for these gases has been found in drill-hole information from the San Rafael Swell, the proximity of these reservoirs to the San Rafael Swell wilderness study areas and the similarity in geologic setting indicate that the resource potential for carbon dioxide and helium gas in the study areas is moderate, with certainty level B (table 4).

Gypsum

Gypsum commonly originates as a chemical precipitate in inland-sabkha (salt-flat) and desert-lake basins with limited rainfall and high evaporation rates (Reineck and Singh, 1975). Gypsum typically occurs as evaporite deposits or as extensive beds interstratified with limestone, shale, and clay. The Carmel Formation, exposed along the outer flanks of the swell and overlying the Navajo and Page Sandstones, contains alternating beds of gypsum and siltstone, especially in the upper part of the unit. Gypsum deposits in the Carmel Formation in the northeastern part of the swell in the San Rafael River mining district are as much as 8 ft thick (Trimble and Doelling, 1978), and on the west side of the Sids Mountain Wilderness Study Area they are as thick as 30 ft. Here the gypsum is not of uniform thickness; it is a massive and relatively pure crystalline alabaster, and it makes up as much as 50 percent of the rock mass (Trimble and Doelling, 1978). On the west side of the Sids Mountain Wilderness Study Area, gypsum as thick as 30 ft occurs in the Carmel Formation, and where the Summerville Formation crops out in the study areas, isolated beds and minor occurrences of gypsum are present in veinlets or fracture fillings, nodules, and cement. Gypsum beds also occur in the Tidwell Member of the Morrison Formation and in the Moenkopi and Curtis Formations as localized beds, lenses, fracture fillings, and bedding-plane nodules. Because they are relatively insignificant, the gypsum in these units was not included in this assessment.

The mineral resource potential for possibly thick, but isolated, gypsum deposits in the wilderness study areas of the San Rafael Swell region in the Summerville and Carmel Formations on the surface and in the subsurface is high, with certainty level D (table 4). These areas include the western part of the Muddy Creek, eastern and southeastern parts of the San Rafael Reef, northeastern part of the Mexican Mountain, the southern and southeastern parts of the Crack Canyon, and the western part of the Sids Mountain Wilderness Study Areas.

Bentonite

"Bentonite" is a term applied to various colloidal or plastic clays, or swelling clays. These clays are able to absorb water or organic liquids between their structural layers, as well as to exchange cations readily (Deer and others, 1966).

Bentonite is formed by in-place alteration of volcanic ash; the deposits containing bentonite may be either marine or nonmarine. Deposits of bentonite are typically less than 1 ft thick, but there are rare occurrences of beds as thick as 50 ft. Generally, several tens of thin bentonitic beds separated by clastic or tuffaceous units occur in a formation (Blatt and others, 1972). The chemical composition of bentonite is complex and variable, though calcic montmorillonite (with small amounts of magnesium) is the most common bentonite clay in the Western United States and Canada (Blatt and others, 1972; Dana, 1963).

Bentonitic clay is a minor constituent of the rocks of the Chinle Formation and occurs locally with minor zeolite in the Brushy Basin Member of the Morrison Formation. Elements associated with bentonite in the Chinle Formation include gold, silver, and vanadium. Bentonitic clay beds are typically less than a few inches thick in the swell and are dispersed throughout the Chinle Formation and in the Brushy Basin Member of the Morrison Formation.

Because the bentonitic clay beds are thin and dispersed, the mineral resource potential for bentonite in the lower part of the Chinle Formation on the surface and in the subsurface of the Sids Mountain Wilderness Study Area, the Crack Canyon Wilderness Study Area, the northeastern part of the Mexican Mountain Wilderness Study Area, the eastern and southeastern part of the San Rafael Reef Wilderness Study Area, and the western part of the Muddy Creek Wilderness Study Area, and in the Brushy Basin Member of the Morrison Formation in the southernmost Crack Canyon Wilderness Study Area is low, with certainty level B (table 4).

Native Sulfur

About 90 percent of the world's native sulfur reserves formed by natural chemical reduction of calcium sulfate minerals (gypsum and anhydrite) to hydrogen sulfide and free sulfur (Blatt and others, 1972). The reduction process seems to be primarily the result of the activity of the bacteria *Desulphobibrio Desulphuricans*.

Interdisciplinary geological studies indicate that sulfur may form from sedimentary sulfate minerals in areas of salt doming where there is a nonevaporite-bearing limestone caprock, where oil associated with the sulfur deposits supplies the carbon dioxide in a reducing process, and where sulfate-reducing bacteria are the reducing agents (Blatt and others, 1972). Sedimentary sulfur deposits are always associated with evaporite deposits containing gypsum or anhydrite, and they also commonly occur in limestone of nonevaporitic origin. Some evidence suggests that the world's largest deposits occur in zones of porosity associated with old oil traps; dead oil and oil staining are common (Blatt and others, 1972). The sulfur was possibly released from hydrogen sulfide emanating from oil. The largest economic deposits of native sulfur in the United States are associated with salt domes along the coast of the Gulf of Mexico. There sulfur is concentrated at the contact between gypsum and limestone beds. In West Texas, where very large domestic sulfur deposits are, secondary sulfur occurs in gypsite deposits formed from disintegrated and weathered gypsum and in alluvial conglomerate, clay, sand, and caliche that mantles the surface of those deposits (Blatt and others, 1972). Sulfur may fill seams, cavities, or fissures, or may be disseminated, only rarely occurring in a continuous bed.

The San Rafael Swell region, because it is a prominent dome with all of the attributes of a sulfur-producing setting, is a favorable area for prospecting for sulfur. One small occurrence of sulfur is in the Mexican Mountain Wilderness Study Area where it is deposited by warm springs issuing from the Kaibab-Moenkopi contact along the San Rafael River (see the following section on "Geothermal Sources"). Because the units potentially favorable for sulfur occurrence are adjacent to salt deposits of the Paradox basin, and there is one known sulfur locality in the region, the mineral resource potential for small, localized sulfur deposits in the Mexican Mountain and San Rafael Reef Wilderness Study Areas is low, with certainty level B (table 4).

Metals

Mineral deposits, excluding uranium and vanadium, include copper, silver, and rare gold and occur in the San Rafael Swell region in the Chinle Formation and the Glen Canyon Group. Small mineralized areas typically occur along low-angle (bedding-plane) faults, with lesser concentrations along high-angle faults and joints, or at their junctions. Collapse features like those at Temple Mountain, Reds and Sulfur Canyons, and Window Blind Peak, are important mineral-bearing structures in the region.

Results of geochemical analyses indicate that no significant metallic mineral anomalies exist in the San Rafael Swell region. Therefore, the mineral resource potential for metallic mineral deposits, excluding uranium and vanadium, is low, with certainty level B (table 4).

Geothermal Energy Sources

Geothermal sources are typically lacking within the Colorado Plateau, except where volcanic rocks crop out. The only known hydrothermal convection system on the Colorado Plateau is near the San Juan Mountains in southwestern Colorado. The plateau has low overall heat flow, but young volcanic features are promising areas for exploration (Brooks and others, 1979). In the Muddy Creek Wilderness Study Area in the southwestern part of the San Rafael Swell, Tertiary basaltic dikes intrude Mesozoic sedimentary rocks (pl. 1). Moreover, in the north-central part of the San Rafael Swell area, several thermal (warm) springs with temperatures ranging from 60 to 73 °F (Hawley and others, 1968) emerge at the Kaibab-Moenkopi contact along the San Rafael River; these springs are anomalously radioactive, with radioactivity counts of twice background level (Hess, 1913; W.S. Keys, *in* Hawley and others, 1968). The springs emit hydrogen sulfide and carbon dioxide gas and have formed local travertine deposits. Locally, copper sulfate and cobalt- and iron-bearing sulfates coat nearby vegetation (Hawley and others, 1968). Many springs and seeps, some associated with limited amounts of oil, were noted elsewhere in the San Rafael Swell. No other warm springs were noted. Excellent aquifers are present in the Glen Canyon Group exposed throughout the swell; because they are breached, the water table is lowered in the area. Nevertheless, because of the evidence for intrusive activity in the southwestern part of the swell and the porous sandstone and carbonate sequences at depth, potential for the occurrence of geothermal energy sources cannot be ruled out. On the basis of these criteria, the potential for geothermal energy sources in the wilderness study areas of the San Rafael Swell is moderate, with certainty level B (table 4).

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APPENDIX

DEFINITION OF LEVELS OF MINERAL RESOURCE POTENTIAL AND CERTAINTY OF ASSESSMENT

LEVELS OF RESOURCE POTENTIAL

H 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.

M 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 reasonable likelihood for resource accumulation, and (or) where an application of mineral-deposit models indicates favorable ground for the specified type(s) of deposits.

L 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 permissive. This broad category embraces areas with dispersed but insignificantly mineralized rock, as well as areas with little or no indication of having been mineralized.

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

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

LEVELS OF CERTAINTY

A Available information is not adequate for determination of the level of mineral resource potential.
B Available information only 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.

LEVEL OF RESOURCE POTENTIAL →

<table>
<tr><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr><td rowspan="4">U/A
UNKNOWN POTENTIAL</td><td>H/B
HIGH POTENTIAL</td><td>H/C
HIGH POTENTIAL</td><td>H/D
HIGH POTENTIAL</td></tr>
<tr><td>M/B
MODERATE POTENTIAL</td><td>M/C
MODERATE POTENTIAL</td><td>M/D
MODERATE POTENTIAL</td></tr>
<tr><td rowspan="2">L/B
LOW POTENTIAL</td><td rowspan="2">L/C
LOW POTENTIAL</td><td>L/D
LOW POTENTIAL</td></tr>
<tr><td>N/D
NO POTENTIAL</td></tr>
</table>

LEVEL OF CERTAINTY →

Abstracted with minor modifications from:

Taylor, R.B., and Steven, T.A., 1983, Definition of mineral resource potential: Economic Geology, v. 78, no. 6, p. 1268-1270.
Taylor, R.B., Stoneman, R.J., and Marsh, S.P., 1984, An assessment of the mineral resource potential of the San Isabel National Forest, south-central Colorado: U.S. Geological Survey Bulletin 1638, p. 40-42.
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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 by the U.S. Geological Survey in this report

EON	ERA	PERIOD		EPOCH	AGE ESTIMATES OF BOUNDARIES (Ma[1])
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	~ [2]570
Proterozoic	Late Proterozoic				900
	Middle Proterozoic				1600
	Early Proterozoic				2500
Archean	Late Archean				3000
	Middle Archean				3400
	Early Archean				
		3800?			
pre-Archean[3]					4550

[1]Millions of years prior to A.D. 1950.

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

[3]Informal time term without specific rank.

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