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Mineral resource potential of the Richfield $1^{o}x2^{o}$ quadrangle, west-central Utah

By

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ABSTRACT

The geology of the Richfield quadrangle is highly varied and developed over a long span of time. The oldest rocks comprise small patches of early Proterozoic gneiss and schist that crop out along the west side of the Mineral Mountains. Sedimentation during the latest Precambrian, Paleozoic, and Mesozoic deposited a thick sequence of sedimentary rocks now exposed in the northern part of the quadrangle. These rocks were broadly deformed during the Sevier orogeny in late Cretaceous time when allochthonous Precambrian and Paleozoic rocks were thrust eastward across Mesozoic and Paleozoic strata in the autochthon along the sinuous Sevier orogenic belt that trends diagonally southwest across the quadrangle. In early Tertiary time, erosion of highlands west of the orogenic belt produced a wide variety of debris that accumulated in basins east of the highland. Volcanism in Oligocene and early Miocene time formed an east-northeast-trending belt of calc-alkalic volcanoes across the southern half of the quadrangle; these rocks range in composition from mafic andesite to low-silica rhyolite. In early Miocene, about coincident with inception of extensional tectonism throughout much of the Western U.S., the composition of volcanic rocks changed to a bimodal assemblage of mafic rocks and high-silica alkali rhyolite that erupted episodically throughout the remainder of Cenozoic time. Extensional tectonism culminated in late Miocene-Pliocene time when the present basin-range topography formed through block faulting. The resulting mountain areas were eroded rapidly to supply debris which was deposited in the lower parts of nearby basins.

Known and inferred mineral resources in the Richfield quadrangle are both syngenetic and epigenetic. Syngenetic types include limestone and dolomite, silica-rich sandstone and quartzite, metalliferous black shale, evaporite deposits, zeolite deposits, pumice, cinders and scoria, perlite, and different materials deposited in playa environments. The carbonate and silica resources are virtually inexhaustible, but are generally unfavorably located with respect to markets. The other syngenetic resources need to be discovered, or to have extraction or fabrication technologies developed to utilize them.

Epigenetic resources are largely of volcanogenic-hydrothermal origin. Mineralization took place many times and in many different places, and deposits can be grouped by geologic association. The earliest mineralization was related to calc-alkalic igneous centers of Oligocene age, which formed an east-northeast-trending belt across the full length of the quadrangle. Associated resources are predominantly base- and precious-metal deposits (Cu, Pb, Zn, Au, and Ag) that occur in a wide variety of types zoned around core intrusions. During Miocene and younger times, many local rhyolite fields developed along the axis of the older belt of calc-alkalic centers. Resources or possible resources of lithophile elements (Mo, W, U, Be, Sn, and F) as well as base and precious metals (Pb, Zn, Au, and Ag) occur in association with many of the rhyolite centers.

Except for a few of the mineralized areas associated with calc-alkalic centers near the middle of the quadrangle, where erosion has cut down to the level of the core intrusions, most of the mineralized areas expose only the upper, near-surface parts of the different hydrothermal systems. This means that most of whatever mineral deposits formed in these areas still exist and await discovery. Our conclusion is that many of the mineralized areas have excellent possibilities for the occurrence of significant mineral resources, and that the Richfield quadrangle may be a storehouse of resources awaiting development.

INTRODUCTION

The Richfield 1°x2° quadrangle in western Utah has been studied as part of the U.S. Geological Survey CUSMAP (Conterminous United States Mineral Appraisal Program) program in which multidisciplinary studies are used to evaluate the mineral resource potential of selected quadrangles throughout the nation. This CUSMAP appraisal is limited to metallic and nonmetallic resources; coal, oil and gas, and geothermal energy resources were not considered. The Richfield quadrangle was chosen for study because preliminary data indicated that parts of the area had high mineral resource potential, and because modern geologic studies, focussing in part on mineral resources, had already been begun in several local areas. By expanding and integrating these local studies, and by bringing to bear other earth science disciplines, it has been possible to identify many areas favorable for mineral resources. In addition, basic geological, geophysical, and geochemical parameters of important segments of the intersecting Cordilleran overthrust belt and younger Pioche-Marysvale igneous and mineral belt have been determined.

Many of the preliminary results of this study or of directly tributary precursor studies, as well as much of the basic data, have been published or released in open file as the studies progressed. More than 140 of these products had been made available to the public by the end of 1983. This report, assessing the mineral resource potential of the Richfield quadrangle, is thus one of many products; it uses a series of geological, geophysical, geochemical, and remote sensing maps of the quadrangle as the basis for evaluating the mineral resource potential of the area. Other reports to follow will summarize and interpret in more detail selected aspects of the combined studies. These follow-up reports will focus in part on local mineralized areas, and in part on subjects of interest to other segments of earth science.

To anticipate some of the conclusions reached later in this appraisal, it is our opinion that the full resource potential of the Pioche-Marysvale mineral belt, and particularly of that part of it within the Richfield quadrangle, has not been fully recognized. The general level of erosion is sufficiently shallow that only the near-surface manifestations of many mineralized areas are exposed. Whatever mineral resources originally were deposited within these areas still largely exist and await discovery. These near-surface indications are sufficiently encouraging over wide areas to suggest that a bountiful cornucopia of mineral resources exists, to be tapped by future discovery and development.

CUSMAP PRODUCTS

The intent of the CUSMAP program is to present a series of maps at 1:250,000 and 1:500,000 scales showing geologic, geochemical, geophysical, and remote-sensing data on the quadrangles studied, and to use these data to appraise the mineral resource potential of the quadrangles. These maps, listed below, provide only a part of the data base we have used in appraising the potential of the Richfield quadrangle. Project studies have produced numerous byproduct reports which have looked in greater detail at many aspects bearing on the resource potential. Those products directly attributable to the CUSMAP program are:

Steven, T. A., and Morris, H. T., 1983, Geologic map of the Richfield 1°x2° quadrangle, west-central Utah: U.S. Geological Survey Open-File Report 83-583, scale 1:250,000.

Miller, W. R., Motooka, J. M., and McHugh, J. B., 1980, Distribution of molybdenum in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-A, scale 1:500,000.

______in press a, Maps showing distribution of arsenic in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-B, scale 1:500,000.

______in press b, Maps showing distribution of barium in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-C, scale 1:500,000.

______in press c, Maps showing distribution of beryllium in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-D, scale 1:500,000.

______in press d, Maps showing distribution of bismuth in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-E, scale 1:500,000.

______in press e, Maps showing distribution of copper in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-F, scale 1:500,000.

______in press f, Maps showing distribution of lead in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-G, scale 1:500,000.

______in press g, Maps showing distribution of silver in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-H, scale 1:500,000.

______in press h, Maps showing distribution of thorium in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-I, scale 1:500,000.

______in press i, Maps showing distribution of tin in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-J, scale 1:500,000.

______in press j, Maps showing distribution of tungsten in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-K, scale 1:500,000.

______in press k, Maps showing distribution of zinc in heavy-mineral concentrates, Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1246-L, scale 1:500,000.

Cook, K. L., Adhidjaja, J. I., and Gabbert, S. C., 1981, Complete Bouguer gravity anomaly and generalized geology map of Richfield $1^{o}x2^{o}$ quadrangle, Utah: Utah Geological and Mineral Survey Map 59, scale 1:250,000.

Mabey, D. R., and Virgin, Vicky, 1980, Composite aeromagnetic map of the Richfield $1^{o}x2^{o}$ quadrangle, Utah: U.S. Geological Survey Open-File Report 80-242, scale 1:250,000.

Price, Don, 1980, Map showing general chemical quality of surface water in the Richfield quadrangle, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1234, scale 1:250,000.

______1981, Map showing general chemical quality of ground water in the Richfield quadrangle, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1374, scale 1:250,000.

Podwysocki, M. H., Segal, D. B., Jones, O. D., and Nelson, M. G., in press a, Map showing the distribution of hydrothermally altered rocks, Richfield, Utah, $1^{o}x2^{o}$ quadrangle: U.S. Geological Survey Miscellaneous Investigations Series Map I-____, scale 1:250,000.

______ in press b, Image map of limonitic rocks, Richfield 1°x2° quadrangle, Utah, U.S. Geological Survey Miscellaneous Investigations Series Map I-1574, scale 1:250,000.

OUTLINE OF GEOLOGY

The geology of the Richfield quadrangle, as illustrated by a 1:250,000-scale compilation by Steven and Morris (1983a), which has been generalized for use on plates 1 and 2 of this report, is highly varied and moderately complex. The oldest rocks comprise small patches of early Proterozoic gneiss and schist that crop out along the west side of the Mineral Mountains. Sedimentation during the latest Precambrian, Paleozoic, and Mesozoic deposited a thick sequence of sedimentary rocks now exposed in the northern part of the quadrangle. These rocks were broadly deformed during the Sevier orogeny in late Cretaceous time when allochthonous Precambrian and Paleozoic rocks in the northwestern two-thirds of the quadrangle were thrust eastward on a series of flat décollement faults that extend across Mesozoic and Paleozoic strata in the autochthon. The resulting sinuous Sevier orogenic belt trends diagonally southwest across the quadrangle. In early Tertiary time, erosion of highlands in the allochthonous part of the orogenic belt produced a wide variety of debris that accumulated in basins east of the highland. Volcanism in Oligocene and early Miocene time formed an east-northeast-trending belt of calc-alkalic volcanoes across the southern half of the quadrangle; these rocks range in composition from mafic andesite to low-silica rhyolite. In the early Miocene, about coincident with inception of extensional tectonism throughout much of the western U.S., the composition of volcanic rocks changed to a bimodal assemblage of mafic rocks and high-silica alkali rhyolite. These rocks were erupted episodically throughout the remainder of Cenozoic time. Extensional tectonism culminated in late Miocene-Pliocene time when the present basin-range topography formed through block faulting. The resulting mountain areas were eroded rapidly to supply debris which was deposited in the lower parts of nearby basins.

OLDER PRECAMBRIAN ROCKS

The oldest rocks in the Richfield quadrangle are exposed in isolated outcrops of banded amphibolite gneiss, sillimanite schist, and quartzite that formed by regional metamorphism of quartzo-feldspathic and argillaceous deposits during early Proterozoic time, about 1.7 Ga (Aleinikoff and others, in press; Nielson and others, 1978). These rocks probably are equivalent in age to the Farmington Canyon or Little Willow Complexes of north-central Utah. The sparse small areas of outcrop occur only on the west side of the Mineral Mountains in the central part of the Richfield quadrangle (pl. 1; Steven and Morris, 1983a).

PRE-OROGENIC SEDIMENTARY ROCKS

The chief period of sedimentation in the Richfield quadrangle began in latest Precambrian time and continued with brief interruptions until middle Mesozoic time. The resulting rocks form a thick, generally conformable sequence of sandstone (quartzite), shale, and carbonate rocks separated in places by disconformities indicating local erosion or nondeposition that resulted from mild epeirogenic uplift. Deposition in the western part of the Richfield quadrangle was in a miogeosynclinal environment and is dominated by carbonate strata. These rocks grade eastward and southeastward into a more clastic-rich continental shelf facies in the southeastern part of the quadrangle.

The latest Proterozoic sedimentary rocks in the Richfield quadrangle comprise a thick sequence of weakly metamorphosed sandy, shaley, and limy strata that are exposed only in the Wah Wah-Frisco thrust plate (the highest major thrust plate in the Sevier orogenic belt). Similar rocks probably underlie Paleozoic strata in at least some other parts of the area. The exposed late Proterozoic strata are 1,600-2,000 m thick, and probably correlate with part of a similar sequence of sedimentary rocks that crops out in southeastern Idaho and north-central Utah (Crittenden and others, 1971). All these strata apparently accumulated in a generally north-trending depositional trough that was cut by one or more of the great Sevier thrust faults during the Late Cretaceous and displaced eastward many tens of kilometers (Morris, 1983). The late Proterozoic stratified sequence is generally conformable with the overlying Paleozoic sequence, and in places the uppermost Proterozoic unit appears to merge into the lowermost Cambrian unit.

Paleozoic sedimentary rocks exposed in the Richfield quadrangle range in age from Cambrian through Permian, and include strata that were deposited during all periods of the Paleozoic Era. These rocks have an aggregate thickness of 6,000 to 8,000 m. More than three-quarters of the Paleozoic sequence consists of limestone and dolomite; quartzite and sandstone are next in abundance, and shale is least abundant. In some parts of the sequence, disconformities indicate periods of erosion or at least nondeposition during episodes of uplift or crustal warping. However, the absence of strong, widespread, unconformable relationships indicate that these events were epirogenic and not related to significant tectonic activity. The Paleozoic strata also are cut and displaced by Cretaceous thrust faults, and differences in thickness and lithology between rocks of the same geologic age across the major thrust faults are crude indications of the magnitude and directions of displacement of the various thrust plates.

Cambrian strata make up about 40 percent of the total thickness of the Paleozoic rocks. These strata are thickest and best exposed in the Wah Wah-Frisco thrust plate (the youngest and highest plate) where their aggregate thickness is about 3,700 m; they are only about half this thick in the underlying Blue Mountain-Pavant plate, and their thickness in the autochthon is unknown but probably quite thin. Ordovician strata are 1,000-1,400 m thick and also are predominantly carbonate rocks. Silurian rocks are represented by 300-400 m of medium-gray dolomite that is remarkably uniform in thickness and lithology in all the thrust plates. Devonian strata consist mostly of dolomite with some shale and quartzite, which are about 1,500 m thick in the Wah Wah-Frisco thrust plate, but are only about 850 m thick in the Blue Mountain-Pavant thrust plate and the underlying autochthon. In part, this difference in thickness is the result of a local unconformity within the thinner sections.

Mississippian rocks show the greatest differences in thickness and lithologic character from one thrust plate to another of any of the Paleozoic systems. In the Wah Wah-Frisco thrust plate, the Mississippian strata are about 700 m thick and consist largely of shale with some limestone. The underlying Blue Mountain-Pavant thrust plate contains little Mississippian shale, and limestone predominates along with subordinate sandstone and quartzite. This latter sequence thins eastward across the quadrangle from about 800 m to about 400 m. In the autochthon in the eastern part of the quadrangle all the Mississippian strata are included in a single limestone unit 175-400 m thick.

The Pennsylvanian strata also are dissimilar from one thrust plate to another. In the Wah Wah-Frisco thrust plate, Pennsylvanian rocks consist of about 500 m of medium-bedded cherty limestone. In the Blue Mountain-Pavant thrust plate and in the autochthon the Pennsylvanian strata consist of 300-600 m of limestone interlayered with beds of sandstone. Permian strata in the Wah Wah-Frisco thrust plate consist of 1,000-1,500 m of limestone and sandstone, whereas in the underlying Blue Mountain-Pavant plate, the aggregate thickness of Permian limestone and sandstone is only 300-600 m. The thinnest Permian sections occur in the autochthon in the eastern part of the Richfield quadrangle where only about 300 m of Permian beds are recognized. The contact of Permian strata with overlying Mesozoic strata is abrupt and probably represents a disconformity of regional extent.

Strata of Triassic and Jurassic age occur in both the Blue Mountain-Pavant thrust plate and in the autochthonous area of the eastern part of the Richfield quadrangle, but all Mesozoic strata have been eroded from the area of the Wah Wah-Frisco plate in the western part of the map area. Triassic strata in the quadrangle are predominantly fluviatile or lacustrine, red- to brown-weathering siltstone with some rather thick beds and zones of light-gray limestone, varicolored sandstone, and red conglomerate. Lower Triassic strata are 300-700 m thick, and the Upper Triassic strata a few meters to about 250 m thick. The great variation in thickness of the Upper Triassic rocks is the result of erosion which preceded deposition of the overlying Jurassic strata. Jurassic rocks include the 500- to 600-m-thick, crossbedded, pink to white Navajo Sandstone, and the overlying incomplete Carmel Formation, about 175 m thick. Northeastward in the autochthon, the dominantly limy Carmel probably merges with the lower part of the Arapien Shale, but the area of transition is concealed by Tertiary volcanic deposits.

SEVIER ORGENY

Extensive sedimentation in the Richfield quadrangle and adjacent areas from Late Precambrian through Jurassic times was terminated during the Cretaceous by the Sevier orogeny (Armstrong, 1968, from Harris, 1959), which produced regional uplift, major thrusting, and major and minor folding. The resulting Sevier orogenic belt is a broad zone characterized by overlapping thrust plates of large breadth and displacement that extends from southeastern California northeasterly through southern Nevada and western Utah, and thence northerly through southeastern Idaho, western Wyoming and Montana, into Canada. In Utah, the zone within which thrust faults crop out is about 160 km wide. The origin of the thrust plates and their mode of eastward transport are not well known, but they appear to have developed in response to broad upwarps of the present border lands of Utah and Nevada and areas farther to the west that caused large plates of stratified rocks to become detached and move eastward under the influence of gravity across autochthonous strata, commonly Jurassic rocks. Locally along the east edge of the orogenic belt, the thrust plates also overrode thick deposits of penecontemporaneously accumulating coarse conglomerate and other clastic debris. These synorogenic coarse clastic deposits were first dated broadly by Spieker (1946; 1949) as medial to late Montana in age, and more precise recent studies by Fouch and others (1983) indicate that the oldest are late Cenomanian, and the youngest latest Campanian or early Maestrichtian, thus refining but in general confirming Spieker's estimates. The general absence of Lower Cretaceous strata, with the possible exception of some minor sandstone and conglomerate units in peripheral areas, suggests, however, that the initial uplift of the precursory Sevier arch (Harris, 1959) may have taken place somewhat earlier than Cenomanian time, perhaps during the Albian to late Neocomian stages.

In the Richfield quadrangle the principal tectonic units within the Sevier orogenic belt are the older Blue Mountain-Pavant thrust plate and the younger Wah Wah-Frisco thrust plate. Essentially contemporaneous secondary thrusts include the Red Ridge thrust fault, which lies in the lower part of the Blue Mountain-Pavant thrust plate, and the Beaver Lake Mountains thrust fault, which forms the sole of a secondary plate underlying but probably related to the Wah Wah-Frisco thrust plate. A fifth thrust plate, here named the Paxton thrust from the Paxton oil test hole, apparently underlies the Blue Mountain-Pavant thrust plate in the northeastern part of the quadrangle but it is totally concealed and is known only from interceptions in the Paxton and possibly other drill holes.

The Blue Mountain-Pavant thrust typically emplaces Cambrian limestone or quartzite over Jurassic sandstone, and the asociated thrust plate also contains a virtually complete sequence of Paleozoic and Lower Mesozoic strata at one place or another. In contrast, the Wah Wah-Frisco thrust shows relations that vary widely from place to place, but in general Cambrian or Precambrian strata at the base of the thrust plate overlie middle Paleozoic strata below the thrust. The upper part of the Wah Wah-Frisco thrust plate has been irregularly eroded so that only partial sections of Paleozoic rocks are present in most places.

No direct estimates of the magnitude of displacement across either of the major thrust faults can be made on the basis of evidence at hand. However, the strong contrasts in thickness and lithology of contemporaneous units, particularly in those of Mississippian age, across the thrusts suggests displacements on the order of 100 km.

At the time of their emplacement, the thrust plates were remarkably coherent. The Wah Wah-Frisco plate was warped into broad folds cut by a few high-angle faults, but the Blue Mountain-Pavant plate formed a relatively simple broad homocline.

The eastern margin of the Sevier orogenic belt extends south-southwestward into the northeastern corner of the Richfield quadrangle, bends abruptly westward across the center of the quadrangle, and then swings back south-southwestward to exit in the southwestern part of the quadrangle. This bend was named the Black Rock Offset by Crosby (1973, p. 31-32), who ascribed its origin to right-lateral strike-slip faulting. Careful examination of all exposed segments of the main thrust faults in this area, however, did not disclose the presence of any of the tear faults suggested by Crosby (op cit., p. 31). We believe instead that the structural dislocation is a result of regional doming of a broad area in the east-central part of the quadrangle, possibly resulting from the emplacement of the Mineral Mountains batholith, and subsequent erosion of the thrust plates from the uplifted area.

SYNOROGENIC AND POST-OROGENIC SEDIMENTARY ROCKS

The debris resulting from the accelerated erosion of the uplifted area of the Sevier orogenic belt spread eastward to be deposited in sedimentary basins along its eastern margin. Late Cretaceous deposits consist mostly of coarse clastics deposited in front of the rising Sevier orogen, and locally were involved in the deformation. Latest Cretaceous and early Tertiary rocks, on the other hand, consist of continental strata forming a number of formations that were deposited in piedmont areas and younger sedimentary basins both within and east of the then inactive orogenic belt.

Upper Cretaceous conglomerate, coarse to fine sandstone, siltstone, and shale aggregating a few meters to 1,800 m in thickness crop out in the northeastern part of the Richfield quadrangle, where they were deposited in north-trending eastward-opening troughs contemporaneously with or just after the Sevier orogeny. The deposits overlap westward onto the eroded edge of the Blue Mountain-Pavant thrust plate, and are covered to the south by Tertiary volcanic rocks of the Marysvale volcanic field.

The several broad sedimentary basins east of the Sevier orogenic belt continued to receive sediments in early Tertiary time (Paleocene-Oligocene) after tectonism ceased. One of these basins extends into the northeastern corner of the Richfield quadrangle and contains more than 1,600 m of these early Tertiary strata, and another basin south of the eastern part of the quadrangle contains as much as 300 m of equivalent rocks. Both fluviatile and lacustrine and deposits are represented and range from conglomerate, sandstone, and shale, to widespread units of fresh-water limestone. The youngest two of these sedimentary formations, of probable Oligocene age, contain volcanic debris, indicating that volcanism in the nearby Marysvale volcanic field had begun while these formations were still being deposited.

VOLCANIC ROCKS

Volcanism in the Richfield quadrangle began in early Oligocene time and has continued episodically nearly to the present; the oldest volcanic rocks dated by radiometric methods are about 35 Ma, and the youngest are less than 0.5 Ma. Two general assemblages of rocks have accumulated in this span of time: an earlier assemblage of generally intermediate-composition (andesitic to rhyolitic) calc-alkalic rocks erupted between early Oligocene and early Miocene times, and a later bimodal assemblage of mafic rocks and high-silica alkali rhyolite erupted between early Miocene and late Pleistocene times. The calc-alkalic assemblage accumulated during a virtually anorogenic interval, whereas the bimodal assemblage during extensional basin-range tectonism in later Cenozoic time.

CALC-ALKALIC IGNEOUS ROCKS

In early Oligocene time, scattered volcanoes began to erupt along the east-northeast-trending Pioche-Marysvale belt which extends from southeastern Nevada into central Utah. These volcanoes increased in number with time and by the early Miocene, volcanic rocks covered all the Richfield quadrangle but the higher parts of the hilly northwest quarter. The volcanic rocks are especially thick in the eastern part of the quadrangle where an arbitrary segment of the volcanic area about 120 km across is called the Marysvale volcanic field. Except for an isolated source area in the northwest part of the quadrangle (pl. 1) volcanic sources were largely confined to the southern two-thirds of the Richfield quadrangle where volcanic rocks still predominate at the bedrock surface. These source areas also contain most of the known volcanogenic mineral occurrences in the quadrangle (pls. 1 and 2).

Early Oligocene (pre-30 Ma) andesitic to rhyodacitic stratovolcanoes formed across the Richfield quadrangle from the southern Needle (Indian Peak) Range on the west through the central Wah Wah Mountains, the southern San Francisco Mountains-Shauntie Hills area, to the northern Tushar Mountains and southern Pavant Range on the east. Two isolated centers of about the same age were active in the northwestern part of the quadrangle where a cluster of rhyolitic volcanic domes formed at one center, and pyroclastic eruptions caused a small caldera to collapse at another. The outer flanks of some of these Oligocene volcanoes consist of volcaniclastic and pyroclastic deposits that wedge out laterally to thin discontinuous aprons over adjacent areas.

In middle Oligocene time (30-28 Ma), voluminous pyroclastic eruptions broke out in the southern corner of the Richfield quadrangle, and the resulting ash flows spread outward many kilometers in all directions to deposit the several formations of the Needles Range Group (M. G. Best and S. K. Grant, written commun., 1983). The Wah Wah Springs Formation, the most widespread formation in the Group, extends beyond the northern boundary of the quadrangle in the Confusion Range area, and to the eastern boundary of the quadrangle in the Sevier Plateau. The great Indian Peak caldera complex, exposed in part in the southern Needle (Indian Peak) Range, formed by collapse of the source area of the eruptions.

Late Oligocene and earliest Miocene andesitic to rhyodacitic volcanoes were most abundant in the eastern part of the Richfield quadrangle where clustered volcanoes with contrasting lithologies formed the thick volcanic pile of the Marysvale volcanic field (Rowley and others, 1979). Prominently porphyritic rhyodacitic rocks were erupted from volcanoes in the central part of the field. Concurrently active volcanoes in the southern part of the field erupted mostly finely porphyritic andesitic and dacitic rocks, and others in the northern and northeastern parts of the field erupted widespread flows of mafic andesite and basaltic andesite. More silicic rocks were erupted episodically during the same interval, particularly in association with the more centrally located rhyodacitic volcanoes, to form bulbous volcanic domes and widespread pyroclastic deposits. Some of the pyroclastic eruptions resulted in caldera collapse of the source areas (Steven and others, in press). The clustered volcanoes were surrounded and partly buried by a coalescing volcaniclastic apron that filled saddles between volcanoes and spread outward many kilometers, particularly to the south. The final result was a great volcanic pile that is 1-2 km thick near the source volcanoes, and diminishes to a featheredge at the outer limits of the field.

Late Oligocene-early Miocene andesitic volcanoes in the western part of the Richfield quadrangle were widely scattered, and formed isolated accumulations in the Shauntie Hills and southern Wah Wah Mountains and Needle (Indian Peak) Range. Most of the later calc-alkalic rocks that accumulated in these areas consist of thin welded ash-flow tuff sheets, in part derived from local vents and in part from distant sources, particularly to the southwest.

Of especial interest with regard to mineral resource potential is an eastward-younging belt of intrusive rocks (pl. 1) that extends easterly across the center of the Richfield quadrangle from the central Wah Wah Mountains where the intrusive rocks are 35-32 Ma (Lemmon and others, 1973), through the southern San Francisco Mountains-Beaver Lake Mountains, Rocky Range, and Star Range (29 Ma, Lemmon and others, 1973), Mineral Mountains (25 Ma, Aleinikoff and others, in press), northern and central Tushar Mountains (27-22 Ma, Steven and Morris, 1983b; Steven and others, 1979) to the eastern edge of the quadrangle in the northern Sevier Plateau (22-21 Ma, Steven and others, in press). The belt also contains all the known calderas in the Marysvale volcanic field (Steven and others, in press), which are also manifestations of shallow intrusive bodies. Within the Marysvale volcanic field, the belt of intrusions and calderas is closely confined to that part of the field underlain by the centrally located porphyritic rhyodacitic volcanoes. Most all volcanogenic mineral occurrences known to be associated with calc-alkalic igneous rocks are located within this belt, and apparently formed in association with the intrusive activity.

BIMODAL IGNEOUS ROCKS OF MIOCENE AGE

The change from calc-alkalic to bimodal mafic-silicic volcanism in the Richfield quadrangle took place in early Miocene time, during the same interval that extensional basin-range tectonism began in the area. The change was not everywhere coincidental, however, as potassium-rich mafic lavas and silicic ash-flow tuff of the bimodal Blawn Formation began to be erupted in the southwestern part of the quadrangle about 23 Ma while major calc-alkalic eruptions were still taking place in the Marysvale volcanic field in the eastern part of the quadrangle. Mafic lavas in the Marysvale field began to be erupted about 22 Ma, and silicic lavas and pyroclastic rocks nearby about 21 Ma. The distal edges of 24-19 Ma calc-alkalic ash-flow tuff sheets derived from distant sources to the southwest (Rowley and others, 1979, p. 11) were emplaced into the southern part of the Richfield quadrangle or the area just to the south several million years after local bimodal volcanism had begun.

The earliest mafic volcanic rocks in the bimodal suite in all parts of the Richfield quadrangle characteristically contain exceptionally high potassium contents (2-4 percent K_2O) (Best and others, 1980). Concurrently erupted silicic rocks are closely associated with these mafic rocks in the western part of the quadrangle where the contrasting rock types are interlayered (Abbott and others, 1983). In the eastern part of the quadrangle, however, the mafic and silicic end members form adjacent but separate accumulations that are only partly contemporaneous (Cunningham and others, 1983). Mafic flows that were erupted later in Miocene time generally contain less than 2 percent K_2O (Best and others, 1980), and include some flows that are closely associated with coeval silicic volcanic rocks and others that are widely scattered in both time and space.

Silicic rocks of Miocene age in the Richfield quadrangle form five local accumulations (pl. 1). Each local accumulation formed separately in both time and area of distribution, but in the aggregate, by the end of Miocene time, they had formed a nearly continuous cover of rhyolitic rocks along the axial part of the composite Pioche-Marysvale igneous belt. Thus, the source areas of the older calc-alkalic suite and younger silicic member of the bimodal suite broadly coincided. Some hydrothermal activity took place at one place or another in association with each of the Miocene silicic accumulations, and some centers have high potential for mineral resources.

The oldest silicic accumulation in the bimodal suite is in the Blawn Formation (23-18 Ma) (M. G. Best, written commun., 1983) in the southwestern part of the Richfield quadrangle. Small intrusive bodies and associated hydrothermally altered rocks of Blawn age occur in the Shauntie Hills, but the main area of exposure of the formation is in the southern Wah Wah Mountains and southern Needle (Indian Peak) Range 5-45 km north of the quadrangle boundary. Silicic rocks in the lower part of the Blawn are mostly ash-flow tuffs, which are interlayered with lava flows of potassium-rich mafic rocks. Rhyolite lava flows predominate in the upper part of the formation. The silicic rocks were erupted from many local centers within the area of occurrence of the Blawn Formation. These centers are most abundant in the southern Wah Wah Mountains where many intrusive bodies or associated hydrothermally altered rocks have been identified. The subvolcanic intrusive center at Pine Grove localized intense hydrothermal alteration with associated deposition of replacement lead-zinc ores in the higher levels, and a disseminated molybdenum-tungsten ore body at depth (see later sections).

Silicic volcanism related to the bimodal suite began in the eastern part of the Richfield quadrangle about 21 Ma and continued intermittently until about 14 Ma. The resulting accumulation of lava flows, volcanic domes, and ash-flow tuff, called the Mount Belknap Volcanics, is a composite pile at least 50 km across that erupted from two source areas in the Tushar Mountains and adjoining Antelope Range (Cunningham and Steven, 1979a). Igneous activity at the eastern source area continued throughout the 7 million years that the Mount Belknap Volcanics was accumulating, whereas the western source area was active briefly but violently 19 Ma when the Joe Lott Tuff Member was erupted and the Mount Belknap caldera collapsed, and perhaps again about 16 Ma when a postulated intrusion was emplaced. Many of the Mount Belknap igneous centers show evidence of extensive hydrothermal activity and associated mineralization. The resulting mineral deposits may be the most important in the eastern part of the Richfield quadrangle.

The Steamboat Mountain Formation near the southwest corner of the Richfield quadrangle, like the adjoining older Blawn Formation, consists of both silicic and mafic volcanic rocks (Best and Davis, 1981). The silicic rocks are mostly rhyolite lava flows, with lesser associated ash-flow and air-fall tuff and water-reworked tuff, distributed over an area more than 20 km across. The lava flows locally contain lithophysae and vugs lined with quartz and topaz crystals deposited from a vapor phase. All available radiometric ages indicate that the Steamboat Mountain silicic rocks were erupted 13-12 Ma (M. G. Best, written commun., 1983). The Steamboat Mountain Formation was derived from many local centers, and some of these centers have been extensively altered by hydrothermal activity and appear to have significant potential for containing concealed mineral resources.

The rhyolite of Gillies Hill (9.3 Ma) at the north end of Beaver Basin, and equivalent rhyolitic rocks on the west flank of the Mineral Mountains (the rhyolite of Corral Canyon, 7.9 Ma), and in the northern Black Mountains (the rhyolite of Thermo Hot Springs, 10.3 Ma, and the rhyolite of Blue Ribbon Summit, 7.4 Ma) were erupted in late Miocene time from a number of local sources just east of the center of the Richfield quadrangle (Evans and Steven, 1982: Rowley and others, 1978; Mehnert and others, 1978). Porphyritic to aphanitic rhyolite plugs and dikes were emplaced in earlier intrusive rocks of the Mineral Mountains batholith complex at about the same time. The area containing rocks of this age is about 50 km across, about equivalent to the area covered by the older Mount Belknap Volcanics just to the east; the younger rhyolites, however, are much less voluminous than the older, and probably formed a number of isolated local volcanoes surrounded by small volcaniclastic aprons. Significant hydrothermal activity related to the Gillies Hill period of igneous activity seems to have been limited largely to the fault zone marking the boundary between Beaver basin and the Tushar Mountains where alunite dated as about 9 Ma has been found at two places, and small prospects and mines have been developed in mineralized areas nearby (Steven and others, 1979; Cunningham, Steven, and others, 1984).

The youngest Miocene rhyolitic activity in the Richfield quadrangle took place in the vicinity of Kingston Canyon in the Sevier Plateau near the southeastern boundary of the quadrangle (Rowley and others, 1981). Silicic volcanism here spanned the period of intense basin-range faulting during which the major uplifts and basins of the present topography developed. Lava flows and volcanic domes of the rhyolite of Forshea Mountain were erupted about 7.6 Ma (about the time when the rhyolite of Blue Ribbon Summit was being erupted) and spread over an area of more than 45 km^2 of relatively flat topography before uplift of the Sevier Plateau and cutting of Kingston Canyon. Overlying lava flows and volcanic domes in the rhyodacite of Dry Lake were deposited on an eroded fault scarp, but in turn are cut by other faults, indicating eruption during the period of intense basin-range faulting. The rhyolite of Phonolite Hill, on the other hand, consists of a pyroclastic cone containing an endogeneous volcanic dome emplaced 5.4 Ma (Rowley and others, 1981) at the bottom of a steep-walled canyon, indicating that the adjacent Sevier Plateau had been uplifted and an ancestral Kingston Canyon cut between 7.6 and 5.4 Ma. Small areas of hydrothermally altered rock are associated with the rhyolite of Phonolite Hill.

BIMODAL ROCKS OF PLIOCENE AND PLEISTOCENE AGE

Mafic and silicic volcanic rocks of Pliocene and Pleistocene age occur together in a belt that extends from north-central Beaver basin northward to beyond the northern boundary of the Richfield quadrangle (pl. 1; Steven and Morris, 1983a). Bimodal volcanism within this belt began about 3 Ma, and continued episodically until about 0.3 Ma. Mafic rocks range in composition from basaltic andesite to olivine tholeiite, whereas the silicic rocks are mostly high-silica alkali rhyolite (Lipman and others, 1978; Crecraft and others, 1981; Clark, 1977).

Earliest bimodal volcanism of Pliocene age began in the Coyote Hills-Twin Peaks area where silicic lava flows and volcanic domes were erupted 2.7-2.4 Ma (Evans and others, 1980; Crecraft and others, 1981). Mafic lava flows were erupted during this same interval in the adjoining area to the south and east (Crecraft and others, 1981; Steven and Morris, 1983b). Soft lacustrine marls underlie the Pliocene silicic rocks at several places in this area, and similar soft marls to hard limestones overlie the silicic rocks and are interlayered with and overlie the mafic rocks in many places (Steven and Morris, 1983b). Both the rhyolites and mafic rocks were erupted through and marginal to a lake of considerable extent that was confined within a major down-faulted block along the eastern margin of the Great Basin.

In Pleistocene time, mafic rocks were erupted along a north-trending belt that extends through the area of Pliocene volcanic rocks. Many of the lava flows of this assemblage were erupted about 1 Ma (Best and others, 1980; Crecraft and others, 1981), but related eruptions continued until about 0.3 Ma. The only silicic rocks associated geographically with these mafic flows form a small 0.4-m.y.-old rhyolite flow near the northern boundary of the quadrangle. A 1 Ma mafic flow east of the Black Rock siding on the Union Pacific Railroad was erupted onto an eroded surface cut on Pliocene lacustrine marls, indicating that the Pliocene lake had disappeared in this area by middle Pleistocene time.

Silicic rocks dated as 0.8-0.5 Ma (Lipman and others, 1978) were erupted along the crest of the central Mineral Mountains where volcanic domes and thick lava flows of viscous rhyolite heaped up above local vents, and an ash-flow tuff (the tuff of Ranch Canyon) spread over adjacent areas. The Roosevelt Hot Spring geothermal area at the west base of the Mineral Mountains (currently being developed for the production of electrical power) is believed related to a magma chamber that fed these silicic extrusive rocks (Lipman and others, 1978).

MINERAL MOUNTAINS BATHOLITH

The Mineral Mountains are carved from a highly uplifted structural block that includes the largest composite batholith exposed in Utah (Nielson and others, 1978). Sibbett and Nielson (1980) consider this block to be an igneous diapir that has raised plutonic intrusive rocks to the present level of erosion. The different plutons are the same ages as the volcanic rocks exposed farther east in the Marysvale volcanic field (Aleinikoff and others, in press; Steven and others, in press). Early intrusive rocks (about 25 Ma) equivalent to the calc-alkalic volcanic rocks comprise scattered small plutons of dioritic to quartz monzonitic composition. Many of these plutons are only a few kilometers across, and have contrasting lithologies and mineralogies. Rocks equivalent in age to the Mount Belknap Volcanics, on the other hand, consist of quartz monzonite or granite that form large plutons of uniform lithology as large as 6 by 10 km across; in aggregate these plutons form a coherent composite batholith that makes up most of the Mineral Mountains.

BASIN-RANGE TECTONISM AND SEDIMENTATION

The change from calc-alkalic igneous activity to bimodal mafic-silicic igneous activity in early Miocene time coincided in a broad way with a change from earlier tectonic quiet, to extensional tectonism that ultimately resulted in basin-range block faulting throughout the Great Basin area. Extensional tectonism still persists along the intermountain seismic belt which crosses the eastern half of the Richfield quadrangle (Smith and Sbar, 1974; Anderson and Bucknam, 1979). Early Miocene faulting has been detected at a number of places in the southern Wah Wah Mountains and southern Needle (Indian Peak) Range (M. G. Best, written commun., 1983). Most of these faults trend northeast and either localized eruption of early Miocene volcanic rocks, or influenced their accumulation. Vertical displacements of as much as 1,500 m have been recognized, but generally the offsets are much less. Although evidence for northeast-trending faults of early Miocene age can be recognized over wide areas, the pattern of fracturing is generally open and most displacement apprently took place along major fault zones, such as the Bible Spring zone in the southern Needle (Indian Peak) Range, where numerous close-spaced fractures developed and in the aggregate achieved major structural offsets. The northeast-trending faults were most active before the Steamboat Mountain Formation was erupted about 13-12 Ma.

Faulting in the eastern part of the Richfield quadrangle appears to have been minor in early to middle Miocene time. Tectonism here developed broad uplifts and basins, with attendant erosion of the higher areas and deposition of the Sevier River Formation in the lower areas. Ash beds near the bottom and top of the formation near the type section have been dated radiometrically as respectively about 15 and 7 Ma (Steven and others, 1979). Major faulting in the eastern part of the Richfield quadrangle took place in late Miocene time after the 7 Ma ash bed was deposited near the top of the type section of the Sevier River Formation. This section is strongly tilted, and cut by basin-range faults that formed during development of the present mountains and basins. Farther south in the Kingston Canyon area, uplift of the Sevier Plateau has been closely dated as having taken place between 7.6 and 5.4 Ma (Rowley and others, 1981). Although the general trend of mountains and basins formed during the brief period of highly active tectonism in latest Miocene time is north-south, this is only a crude average of many individual normal faults that range in strike from northwest to northeast. Major fault zones bound the mountain and basin blocks, but the blocks in turn are cut by innumerable lesser faults which divide the bedrock into smaller slices or rhombic to polygonal blocks.

The basins resulting from late Miocene basin-range faulting were the sites of rapid sedimentation, in part by streams and in part in lakes. Initially, many of the basins were closed and trapped all the sediment derived from adjacent highlands. With time, streams were progressively integrated so that much of southwestern Utah now drains to ultimate sumps in the Escalante and Sevier Deserts in and adjacent to the central part of the Richfield quadrangle. Most of the eastern half of the quadrangle now drains to Sevier Lake, a broad playa in the north-central part of the Richfield quadrangle and in adjacent parts of the Delta quadrangle to the north. The western half of the quadrangle in part drains to local closed basins in the Wah Wah, Pine, and Hamlin Valleys, and in part to lower closed basins in adjacent areas to the west and south. None of the water falling on or passing through the Richfield quadrangle reaches the ocean, nor has it done so since late Miocene time.

An extensive lake formed in late Cenozoic time in the major composite basin in the central part of the Richfield quadrangle now occupied by Sevier Lake, Sevier Desert, and Escalante Desert. It is not known just when this lake became established, except that it occupied the lower part of the topography developed by intense basin-range block faulting in late Miocene time. The lake clearly was in existence in middle Pliocene time inasmuch as clayey marls deposited in it underlie 3-Ma rhyolite lava flows (Crecraft and others, 1981) along the west side of Coyote Hills. Other carbonate sediments ranging from soft marls to hard limestone deposited in the same lake are interlayered with and overlie 2-Ma rhyolite and basalt lava flows there and in the Twin Peaks-Cove Creek area to the east (Best and others, 1980; Crecraft and others, 1981; Steven and Morris, 1983b). The Huckleberry Ridge ash bed derived from the Yellowstone Park area about 2 Ma is interlayered with the upper part of the lake bed sequence along Highway 257 about 7 km north of Black Rock (Izett and Wilcox, 1982). By middle Pleistocene, however, the lake no longer existed in the Black Rock area where a 1-Ma basalt lava flow (Best and others, 1980) rests on eolian sands which covered the bottom of a broad shallow valley cut several tens of meters into the lacustrine marls.

SURFICIAL DEPOSITS

Except for the Beaver basin (Machette, 1982; Machette and others, 1984), surficial deposits in the Richfield quadrangle have been accorded scant attention. In the High Plateaus subprovince in the eastern part of the quadrangle, Tertiary basin-fill deposits (Sevier River Formation) have been mapped separately from Quaternary deposits, but in the Basin-Range province occupying the western two-thirds of the quadrangle, all basin-fill sediments but the Pliocene-early Pleistocene lacustrine beds in the north-central part of the quadrangle have been mapped together (Steven and Morris, 1983a). These undivided fill deposits also include marl, gravel, and sand deposited in glacial Lake Bonneville in the north-central part of the quadrangle.

MINERAL RESOURCES

Known and inferred mineral resources in the Richfield quadrangle span a wide spectrum of types from syngenetic (including diagenetic) to epigenetic (largely volcanogenic-hydrothermal). Within this framework, many geologic environments favorable for the occurrence of mineral resources have been recognized, ranging from those where a strong presumption exists for the occurrence of valuable deposits, to those where only a broad possibility for such occurrence exists. Although we are able to recognize many of these environments, the nature and extent of our knowledge almost nowhere permits us to assess them in terms of quantity or quality of specific mineral commodities contained. Thus, this appraisal (pl. 2) will deal largely with mineral resource potential (likelihood of occurrence of mineral deposits), wherein a high potential indicates that characteristics favorable for the occurrence of mineral deposits are known to be present, or where geologic models favorable for ore accumulation are strongly supported, and evidence indicates that mineralization has taken place; moderate potential indicates that characteristics favorable for the occurrence of mineral deposits are known or can be reasonably be interpreted to be present, but evidence is less clear cut; and low potential indicates that characteristics are unfavorable for the occurrence of mineral deposits or available data do not support geologic models favorable for resource occurrence (Taylor and Steven, 1983). Inadequate knowledge will be indicated by the category of unknown potential. The size or grade of the resource being considered does not enter into this classification; these aspects will be treated in the discussion that follows.

SYNGENETIC AND DIAGENETIC MINERAL RESOURCES

Syngenetic mineral resources are those that formed as integral parts of the host rocks with which they are associated. Diagenetic resources formed as the result of processes that modified original constituents of these host rocks shortly after deposition, but without significant addition of materials from an external source. Very few deposits are truly syngenetic inasmuch as virtually all show some post-depositional modifications. The distinction is largely arbitrary and meaningless for assessment purposes, and this discussion will make no attempt to separate the types. The 1:250,000 geologic map of the Richfield quadrangle compiled by Steven and Morris (1983a) will be especially helpful in following this discussion.

LIMESTONE AND DOLOMITE

Many of the stratigraphic units within the thick and extensive Paleozoic carbonate sequence exposed in the Richfield quadrangle are chemically similar to rock quarried elsewhere in Utah for highly varied uses in industry and agriculture. These materials are so common and so widely distributed that only those strata suitably close to transportation facilities can be considered as possibly economic to extract at the present time. A plant for processing carbonate rock in the Cricket Mountains in the north-central part of the quadrangle was under construction when this investigation was being made, but had not reached production in 1982.

Virtually inexhaustible resources of limestone and dolomite are known in the Richfield quadrangle. The chief constraints on their development are economic factors such as transportation costs and competition with more advantageously located and already established pits and quarries. [Resource potential--High]

QUARTZITE AND SANDSTONE

Silica-rich quartzite and sandstone deposits are so abundant in the Richfield quadrangle that they also constitute a virtually inexhaustible source of silica. Formations of interest as possible sources are the Caddy Canyon, Prospect Mountain, Eureka, Watson Ranch, and Cove Fort Quartzites, and the Navajo Sandstone. Of these, the richest beds are believed to occur in the Eureka Quartzite, which commonly contains 95-99 percent SiO_2 in many of its exposures in eastern Nevada and western Utah (Ketner, 1973, p. 578). The deposits in the Richfield quadrangle are disadvantageously located with respect to most possible markets, however, and only those exposures located close to transportation facilities can be considered even remotely economic at the present time. [Resource potential--High]

METALLIFEROUS BLACK SHALE

The Chainman Shale of Late Mississippian age crops out in narrow sinuous belts in the northern Needle (Mountain Home) Range and Burbank Hills in the northwestern part of the Richfield quadrangle. The Chainman consists mainly of organic-rich shale containing anomalous quantities of several metals; in particular, silver (and lesser As, Zn and Cu) was widely detected in reconnaissance geochemical surveys of stream sediments that were sampled during the present CUSMAP investigation (Miller and others, 1980; unpub. data). In most places reexamined in the field, these anomalous silver values are associated with exposures of organic-rich shale units near the base of the Chainman Shale, although some higher beds also contain anomalous silver.

Variations in trace-element concentrations in the Chainman Shale have been studied by Drewes (1967, p. 37-40) and J. D. Vine and coworkers (written commun., 1982). In general, these studies indicate that metals are only moderately enriched in most of the Chainman over typical noncarbonaceous shale. As for the content of silver, Drewes (1967, table 5) shows a range of 0-1.5 ppm in 20 samples collected across the full thickness of the formation in White Pine County, Nev. One additional sample contained 20 ppm silver; this is probaby the same silver-rich sample that was reported by Davidson and Lakin (1961, p. C329-C331), and which also contains 20 times as much zinc, chromium, and vanadium as other samples collected during the same study. In the exposures of the Chainman Shale in the western Delta $1^o x 2^o$ quadrangle, a short distance north of the exposures in the Richfield quadrangle, Vine and his coworkers (written commun., 1982) determined the silver content of about 40 samples also collected across the full thickness of the formation to range from 0-7 ppm, and to average about 1.5-2 ppm. One sample from exposures on Conger Mountain in the Delta quadrangle contained 10 ppm silver, and also was enriched in other metals. The two samples containing relatively large contents of silver may have come from stratigraphically restricted zones characterized by high metal values, or they may reflect local enrichments of some kind that have no widespread significance.

From these data it appears that the Chainman Shale as a whole is only moderately enriched in silver over other less carbonaceous shales. These general values may mean little, however, with respect to restricted stratigraphic zones within the formation that seem especially enriched in metalliferous constituents, as suggested by isolated samples with high metal contents, and by the stream-sediment samples collected in connection with the CUSMAP investigation of the Richfield quadrangle. The resource potential for any such restricted zones cannot be assessed until much more work has been done to identify these zones, and determine their specific thicknesses, distributions, and metal contents. [Resource potential--Unknown]

PRE-TERTIARY EVAPORITE DEPOSITS

Bedded evaporite deposits of pre-Tertiary age occur in both the central and extreme northeastern parts of the Richfield quadrangle. In the Star Range near Milford, beds of gypsum are present in the Permian Pakoon Dolomite, Toroweap Formation, and Kaibab Limestone. In general, the gypsiferous horizons are not large and commonly are interlayered with discontinuous beds of medium-gray limestone. The thickest gypsum beds occur near the top of the Kaibab, where some lenses are as much as 10 m thick. Despite extensive prospecting, no commercially viable gypsum-producing mines have been developed. [Resource potential--Low]

In the extreme northeastern part of the Richfield quadrangle, northeast of the community of Richfield, extensive exposures of the Upper Jurassic Arapien Shale contain thick beds of high-grade gypsum and separate deposits of halite. Near Sigurd, about 13 km northeast of Richfield, gypsum that is 96-99 percent $CaSO_4 \cdot 2H_2O$ is mined from a bed as much as 30 m thick and is utilized in the manufacture of wallboard and other products. Near Redmond, 35 km northeast of Richfield, halite has been mined on a small scale for many years from a zone more than 60 m thick, also in the Arapien Shale. This rock salt generally averages about 96 percent NaCl, 2 percent SiO_2, 2 percent $CaSO_4 \cdot 2H_2O$, and other minor impurities. Much of it is used as block salt by local cattle and sheep ranchers. The Arapien halite deposits are small to moderate in size and are disadvantageously located with respect to major population centers compared to those being mined in many parts of the United States. Any industry developed to increase the exploitation of these deposits will be constrained by these same factors. [Resource potential--High]

No potassium-bearing beds have been reported in either the Permian or Jurassic evaporite deposits in the Richfield quadrangle. The present investigation made no effort to look for any such deposits. [Resource potential--Unknown]

OLIGOCENE EVAPORITES

In studying cuttings and core from the Gulf Oil No. 1 Gronning oil test hole drilled 12 km northwest of Delta, Utah, and 47 km north of the Richfield quadrangle, Lindsey and others (1981) identified anhydrite-bearing strata of late Oligocene age interlayered with sedimentary rocks consisting dominantly of volcanic detritus. Anhydrite is present at places through the lower kilometer of the hole, between depths of 1,481-2,458 m. Deposition appears to have been in an extensive saline lake contained in a broad closed basin, during a time when the climate in the area was arid to semi-arid. Volcanism in the Marysvale volcanic field to the south (Steven and others, 1979) and in the Tintic volcanic field to the northeast (Morris and Lovering, 1979) was essentially contemporaneous with the lake and provided the volcanic debris interlayered with the evaporite beds. The basin may have formed by tectonic warping or by damming of drainage by volcanic rocks.

A nearby oil test 11 km northeast of the Gulf Oil well, the Argonaut Energy Corporation No. 1 Federal, encountered a Tertiary evaporite section between 778-2,349 m that consists predominantly of halite with some anhydrite (Mitchell, 1979). A 7.3-m interval within the evaporite section consists of clay with some volcanic debris and the evaporites are underlain by conglomerate containing some volcanic clasts. Deposition in a saline lake during the span of Tertiary volcanism seems indicated. Diagenetic potassium feldspar, illite, smectite, and clinoptilolite derived from alteration of volcanic ash in the saline lake has been reported by Lindsey and others (1981).

The evaporite sections in the two test wells are probably broadly correlative as suggested by both Mitchell (1979) and Lindsey and others (1981). Likely, a major saline lake in which mainly evaporite minerals were deposited toward the center and a mixed evaporite beds and volcanic sedimentary beds toward the margins probably existed in the vicinity of Delta, Utah, in late Oligocene time. The extent and configuration of the Oligocene lake cannot be determined from available data. The lake was in existence before basin-range tectonism, so the present topographic arrangement of mountains and basins would have had no influence on its extent. Whether this lake extended south into the area of the Richfield quadrangle is not known. No evaporite beds were reported in another oil test, the Cominco-American No. 1 Federal, south-southwest of Delta and about 4 km north of the Richfield quadrangle boundary (Lindsey and others, 1981, p. 252-253), which may indicate that the lake did not extend this far south in this local area. The southern extent elsewhere seems unconstrained.

The existence of a saline lake between two penecontemporaneous volcanic fields provides an environment favorable for the occurrence of several types of potentially valuable mineral deposits. The halite and anhydrite reported from the two test wells probably have minimal value because the same materials are available in quantity in near-surface deposits in the Jurassic Arapien Formation in nearby parts of west-central Utah. However, other evaporite minerals of greater potential value could exist within the evaporite section and not have been detected because of inadequate sampling or logging techniques used on what were primarily wildcat oil tests. The presence of at least some diagenetic feldspar, smectite, illite, and clinoptilolite, as reported by Lindsey and others (1981, p. 255, 258), indicates that possibly other diagenetic minerals, especially zeolites, could have formed by alteration of volcanic ash in a saline lake. Lithium or other relatively soluble elements derived from penecontemporaneous volcanic activity in adjacent areas also may be adsorbed on clays within the lacustrine sequence. However, no firm evidence is now known that would indicate the presence of such materials, let alone their aggregation into possibly commercial concentrations. Even if such concentrations exist, they may be totally restricted to an area north of the Richfield quadrangle. [Resource potential in Richfield quadrangle--Unknown]

ZEOLITE RESOURCES

Clinoptilolite was identified in a number of scattered localities in the Richfield quadrangle in the course of CUSMAP investigations. Most of these occurrences are in diagenetically altered nonwelded ash-flow tuff units. Inasmuch as all of these units accumulated subaerially, alteration probably was under what Sheppard (1973) has classified as open-system conditions by reaction of vitric tuff with ground water. Steven and Cunningham (1979) estimated that several billion tonnes (metric tons) of clinoptilolite exists at three different locations in the Tushar Mountains, and much of this is readily available for open-pit mining. Other occurrences of clinoptilolite were noted in passing in the southern Wah Wah Mountains and southern Needle (Indian Peak) Range, but no estimates of resource potential were made.

None of the so-called closed-system zeolite deposits (Sheppard, 1973) that formed by alteration of silicic volcanic ash in saline, alkaline lakes was seen in the Richfield quadrangle, although favorable geologic environments probably existed at many places in Miocene and younger times. Closed system zeolite deposits are commonly zoned laterally from clinoptilolite formed in relatively fresh waters near the margin of a lake, through a sequence of different zeolite minerals whose type and distribution were controlled by local chemistry of increasingly alkaline and saline waters, to authigenic potassium feldspar at the center of many lakes.

The basin-fill deposits in the Richfield quadrangle have the best possibility for occurrence of closed-system type zeolite deposits. Modern playa lakes exist there, and comparable lakes probably formed many times in different places since inception of extensional tectonism in early Miocene time. A large saline lake penecontemporaneous with volcanic activity in the Marysvale volcanic field existed just north of the Richfield quadrangle in late Oligocene time (see previous section), and may have extended south into the area of concern here. A Pliocene-early Pleistocene lake of varying salinity existed in the north-central part of the Richfield quadrangle where it was in part contemporaneous with both mafic and silicic volcanic activity. Exposures are poor in all these areas, and the potential for closed-system type zeolite deposits can be established only by physical exploration--chiefly by extensive deep drilling in many of the basins. [Resource potential--High for clinoptilolite, Unknown for closed-system zeolites]

PUMICE DEPOSITS

Pumice has been mined from a frothy rhyolite lava flow of Pliocene age at the Cudahy mine in the Coyote Hills, and considerable pumice still remains in the unmined part of the flow. None of the other rhyolite lava flows exposed in this vicinity is nearly as vesiculated as the one developed by the Cudahy mine, and it is impossible to predict if hidden pumiceous flows exist without physical exploration. [Resource potential--Unknown]

PLAYA DEPOSITS

Playa lakes (locally called hardpans in the Richfield quadrangle) occupy low parts of many closed basins in western Utah. In the Richfield quadrangle, the Pine Valley Hardpan, Wah Wah Valley Hardpan, and Sevier Lake are the most prominent present-day playa lakes, although deposits from former playas probably exist in many places and at different depths within the sedimentary fill in these and other basins in the western part of the quadrangle. Inasmuch as virtually all drainage effluent from the volcanic terrain and its many mineralized areas in the southern part of the quadrangle has been trapped in these developing basins since early Miocene time, the various playa lakes of different ages would seem to represent ultimate repositories of soluble elements not sorbed onto clay or zeolite minerals or otherwise dispersed through the basin-fill sediments.

Very little data is available on which to judge the resource potential of playa deposits in the Richfield quadrangle, and those available are not encouraging. Whelan (1969) reported analytical results from samples of sediments and brines collected from three shallow holes, 6-15 m deep, drilled along the west side of Sevier Lake. The brines from these holes contained 165-204 g/l dissolved solids, a content about five times that of sea water but somewhat less than that of Great Salt Lake brines. Of special interest, the average Li content of Sevier Lake brines (about 28 ppm) is considerably higher than that of average sea water (0.1 ppm), but less than that of Great Salt Lake brines (51-63 ppm). The content of dissolved solids in the brines is different from place to place both vertically and laterally, and it is uncertain how far the data obtained can be extrapolated in assessing the potential of Sevier Lake playa deposits as a whole. The unknown influence of evaporative pumping in forming near-surface concentrations of soluble salts in the Sevier Lake playa, shown by Glanzman (1977) to be effective in the Great Salt Lake Desert to the north, adds uncertainty to extrapolations. Sediment samples from the holes contained about 12 percent soluble salts, mostly consisting of Na, Ca, Cl, and SO_4, and with negligible Li. Whelan (1969) concluded that the Sevier Lake brines represent a possible exploitable resource, and Whelan and Peterson (1976) calculated a minimum resource of 450-540 tonnes of Li; in view of the uncertainties noted above, these figures should be used with caution.

In considering the distribution of uranium in playa deposits in the Great Basin, Leach, and others (1980) analyzed samples obtained from 3 to 290 m depths in a hole drilled in Sevier Lake. U contents ranged from 1.7 to 7.8 ppm, with a median concentration of 3.8 ppm. These contents are comparable with or lower than contents of other playa lake sediments they sampled. Uranium contents in Sevier playa brines are low, only 3.7-14.1 ppb. Li contents of brines in seven samples taken between 96 and 195 m depths also are low, ranging from 1.5 to 1.9 ppm. A relatively high Li content (100 ppm) was found in sediment samples from the top 1.5 m of the Sevier Lake playa fill by Glanzman (1977), but in the same study, similar near-surface concentrations farther north in the Great Salt Lake Desert were found to result from evaporative pumping.

The relatively low contents of Li and U in the Sevier Lake sediments and brines seem surprising inasmuch as the two main drainage systems tributary to Sevier Lake, the Sevier and Beaver Rivers, drain extensive volcanic areas with the known Li and U source rocks (Steven and others, 1981). However, Glanzman and Meier (1976) show that the Sevier River contains 1.8 mg/l Li where it passes through the Marysvale volcanic field between Kingston Canyon and Salina, but that this concentration is greatly diluted downstream toward the Sevier Lake playa. The long transit distance also allows for sorption onto clays or zeolites as well as dilution by water and sediment containing little lithium, which would lead to dispersal rather than concentration. As Leach and others (1980) point out, playas are complex dynamic systems that are not well understood. For uranium, at least, they show clearly that analytical data obtained from playa sediments do not reflect the presence of known uranium occurrences within the related drainage basin.

The many seeming contradictions in published data and interpretations dealing with the Sevier Lake playa probably reflect inadequate or nonrepresentative sampling. These contradictions must be resolved and a vastly larger data base established before the economic potential of the playa environment in the Richfield quadrangle can be assessed. This will require extensive physical exploration, which is beyond the scope of the present investigation. [Resource potential--Unknown]

LAKE BONNEVILLE RESIDUES

Glacial Lake Bonneville occupied the lower parts of basins in the north-central part of the Richfield quadrangle, from Fillmore, Utah, on the east to the mountain front west of Sevier Lake on the west. Sand and gravel occur in bars, spits, and deltas around the margin of the former lake, and fine-grained impure marl covers much of the former lake bottom. Wind locally has sculpted the marly blanket and developed dunes. In places, particularly a few kilometers southwest of the town of Fillmore, the wind has winnowed the fine marl and left a lag residuum of gypsum crystals that form local sandy concentrations pure enough to have been mined and sold for agricultural purposes. No large resource of this material exists, but the gypsum dunes are easily mined and are convenient to transportation facilities, and probably will serve as an intermittent source for many years. The conventional sand

and gravel deposits are extensively used on a local basis. [Resource potential--High]

CINDERS AND SCORIA

Basaltic cinder cones of Pliocene and Pleistocene age occur widely in the belt of young basaltic and rhyolitic volcanoes that extends from the low hills at the north end of Beaver basin northward to the north boundary of the Richfield quadrangle 12-24 km west of Fillmore. Cinders and scoria for gravel, roofing granules, and ornamental stone have been produced episodically from several of these cinder cones, and large reserves still exists. These resources probably will be tapped intermittently in the future to meet demands as they arise. [Resource potential--High]

PERLITE

Perlite has been reported from the central Mineral Mountains (Bell, 1953; Whelan, 1973) from an area where it most likely occurs as glassy bases on Pleistocene rhyolite lava flows and volcanic domes. These glassy zones are only irregularly hydrated, and most are still unhydrated obsidian. These deposits were not studied in detail. Glassy flow margins consisting of unhydrated obsidian nodules (apache tears) in perlitic matrices also were noted in Pliocene-Pleistocene rhyolite lava flows in the Coyote Hills north of the Mineral Mountains; these deposits also were observed in only the most cursory manner. [Resource potential--Unknown]

EPIGENETIC MINERAL RESOURCES

Epigenetic deposits form by introduction of material into a host rock by one or more processes not related to the development of that host. Hydrothermal ore deposits are typical of the epigenetic class; roll-front uranium deposits also are members of the class, as are other deposits not genetically related to the rocks that enclose them. Most of the known or anticipated epigenetic deposits in the Richfield quadrangle formed by volcanogenic-hydrothermal processes. Possible mineral deposits introduced into basin-fill sedimentary rocks by water draining adjacent volcanic areas also are discussed here.

Epigenetic mineralization in the Pioche-Marysvale igneous belt took place many times and in many different places (pl. 1). These episodes can be separated according to geologic association, beginning with mineralization related to calc-alkalic igneous centers in Oligocene time, and progressing through successive periods of Miocene and younger bimodal intrusion, extrusion, and mineralization. Some hydrothermal activity is still in progress in the Cove Fort-Sulphurdale area. The different geologic associations containing known or postulated mineral resources are outlined and identified by capital letters on plates 1 and 2. Specific areas discussed in the following sections are identified on these illustrations by number combined with the capital letter indicating geologic association: for example, Locality A1 represents the Sawtooth Peak area (1) in the southern Needle (Indian Peak) Range where mineralized rock is near and is probably associated with a large area of calc-alkalic igneous rocks (A).

MINERAL RESOURCES ASSOCIATED WITH OLIGOCENE AND EARLY MIOCENE CALC-ALKALIC IGNEOUS CENTERS

Oligocene to early Miocene dioritic to quartz monzonitic intrusions cut sedimentary units and calc-alkalic volcanic rocks in many places in the Pioche-Marysvale igneous belt within the Richfield quadrangle, and evidence for associated hydrothermal activity is widespread. Intrusions of this association in the southern Needle (Indian Peak) Range in the southwest corner of the quadrangle (Area A, pls. 1 and 2) formed by emplacement of resurgent magma working its way up into the roots of the Indian Peak caldera (M. G. Best and S. K. Grant, written commun., 1983). Farther east, most exposed calc-alkalic intrusive bodies and associated mineralized rocks occur in an eastward-younging belt (Area B) extending across the middle of the Richfield quadrangle from the central Wah Wah Mountains to the eastern boundary of the quadrangle in the norther Sevier Plateau (Steven and others, in press).

Most of the known mineral deposits associated with these areas of calc-alkalic intrusive rocks are small to moderate in size, and available evidence gives no encouragement that undiscovered mineral deposits of this association are any larger. This tentative conclusion is somewhat disappointing when it is considered that in middle Tertiary igneous belts farther north in Utah, mineralized areas of similar age and association include such giant districts as Bingham Canyon, Park City, and Tintic. No satisfactory explanation for this apparent disparity in magnitude of mineral resources between the different igneous belts has yet been proposed, although Butler (1915, p. 119) has suggested that it may in part be related to depth of erosion of the associated plutons which has exposed mineralized rock in some areas but has cut below the level of mineralization in others.

SOUTHERN NEEDLE (INDIAN PEAK) RANGE

A number of scattered areas showing evidence of hydrothermal activity related to igneous activity responsible for erupting the middle Oligocene Needles Range Group have been recognized in the southern Needle (Indian Peak) Range. Two of these mineralized areas are associated with quartz monzonitic intrusions emplaced during resurgent stages of the Indian Peak caldera cycle, and one formed during a later stage of Needles Range magmatism. Other mineralized areas in this vicinity are associated with younger rhyolites emplaced during the period of bimodal mafic-silicic igneous activity, and will be discussed later in this report. Mineralized areas most clearly associated with calc-alkalic intrusions are the Sawtooth Peak area and Miners Cabin Wash area along or near the northern margin of the Indian Peak caldera and in the Arrowhead mine-Bob Leroy Peaks area within the resurgently domed core of the caldera. Scattered samples of stream sediments show weakly to moderately anomalous Ag, As, Bi, Ba, Cu, Th, and W in and near these areas (Miller and others, 1980; unpub. data).

In the Sawtooth peak area (Locality A1), highly faulted Ordovician carbonate rocks and overlying Tertiary volcanic rocks contain small masses of iron oxide-stained limestone and ferruginous jasperoid along some of the fractures. These masses have been widely prospected, but the only production seems to have been small quantities of siliceous iron ores shipped as flux to smelters near Frisco, Utah, near the beginning of the 20th century. No base- or precious-metal ore minerals were seen on any of the dumps of the scattered prospect pits. [Resource potential--Low (plate 2)]

The Miners Cabin Wash area (Locality A2) on the west side of the southern Needle (Indian Peak) Range embraces part of the margin of the Indian Peak caldera, where small bodies of granodiorite and quartz monzonite intruded along or near the structural margin of the caldera cut faulted lower Paleozoic carbonate strata and overlying Oligocene volcanic rocks (Best and others, 1979). Most of the mineralized rock is in discontinuous zones of skarn and marble along intrusive contacts, or in minor replacement bodies and veins in breccia zones along faults that cut nearby carbonate strata. Ore minerals include chalcopyrite and bornite (in part altered to malachite, azurite, and other secondary minerals) in the skarns, and limonitic ocher carrying local galena and secondary lead minerals in the veins and replacement bodies. Small reefs of silicified limestone (jasperoid) occur in the general area of the skarns and mineralized breccias; these have recently (1983) been the focus of industry exploration for precious metals. Total production from the Miners Cabin Wash area was probably no more than a few thousand tonnes of lead-silver ore.

The generally small size and sparse occurrence of known ore bodies in the Miners Cabin Wash area do not offer much hope for the discovery of major base-metal resources in this area. Associated bodies of hydrothermally altered rock, including jasperoid, are only small to moderate in size and intensity of alteration, again suggesting limited potential for undiscovered ore in these areas. [Resource potential--Moderate]

At the Arrowhead (Calumet) mine and nearby mines in the southern Needle (Indian Peak) Range (Locality A3), known mineral deposits are largely confined to Paleozoic sedimentary strata. Peripheral volcanic rocks to the south, including mostly rocks in the Oligocene Needles Range Group, are in part silicified, argillized, and pyritized, probably during the same period of hydrothermal activity, so a middle Oligocene age is presumed for the known ore deposits as well.

The Arrowhead (Calumet) area produced about 5,000 tonnes of base- and precious-metal ore during intermittent periods of operation between 1916 and 1946. Gross value of the gold, silver, copper, lead, and zinc produced probably was less than a quarter of a million dollars. The Arrowhead area is within the resurgent core of the Indian Peak caldera, but alteration affected younger rocks in the Needles Range Group and probably is younger than the caldera. The exposed rocks consist of highly faulted and hydrothermally altered Paleozoic strata surrounded and overlain by Tertiary volcanic rocks. Some intrusive rocks are reported to have been exposed in mine workings. The altered zones are in part localized by faults, and in part form thick masses of dark jasperoid replacing Paleozoic carbonate rocks and prevolcanic conglomerate and regolith along the contact between sedimentary and volcanic rocks. In the volcanic rocks, alteration was most intense in the Ryan Spring Formation and Lund Tuff, which are strongly silicified and at least weakly argillized and pyritized in places.

The ore deposits that have been mined consist of tabular and pod-shaped masses that replace carbonate strata along fractures. Primary ore consists of argentiferous galena, sphalerite, pyrite, and minor tetrahedrite in a gangue of jasperoid, dolomite, and barite; most of the ore is oxidized and converted to a wide variety of secondary minerals. Ore bodies are generally small in size, and are sparsely distributed. The possibility for hidden intrusions seems good; some of these may have buried mineral deposits associated with them.

The large masses of jasperoid are reported to contain precious-metal values and are currently (1983) being explored by industry. The geochemical survey made in connection with this CUSMAP investigation, however, was not sufficiently detailed to contribute much toward assessing the resource potential of the jasperoid. [Resource potential--Moderate to High]

CENTRAL WAH WAH MOUNTAINS

Wah Wah Pass in the central Wah Wah Mountains is a low divide that was eroded along the trend of a cluster of igneous intrusions consisting predominantly of diorite and lesser rhyolite (Locality B1). The igneous rocks and adjacent sedimentary rocks are irregularly altered and are less resistant to erosion than the unaltered sedimentary rocks that comprise most of the adjacent Wah Wah Mountains. The altered rocks have attracted considerable prospecting interest, and numerous prospect pits and small adits have been dug on hematite-filled fissures and replacement deposits (Bullock, 1970).

The Wah Wah Pass area consists of an east-dipping homocline of Paleozoic sedimentary rocks overlain to the northeast by Oligocene (about 33 Ma, Lemmon and others, 1973, p. 24-25) pyroclastic deposits and flow rocks assigned by Hintze and others (1981) to the dacite of Wah Wah Cove and the andesite of Kelly's Place. The dioritic plutons in the pass area probably mark the sources of the volcanic rocks (Erickson, 1966, p. 9); they range in size from small plugs and dikes to stocks as much as 3,500 m long and 1,500 m wide, and crop out within an east-trending zone about 8 km long and 1-2 km wide extending nearly the full width of the range. Adjacent sedimentary rocks consist locally of marble and skarn, and the volcanic units are weakly pyritized and argillized.

The contact-metamorphosed and hydrothermally altered rocks in the intrusive area at Wah Wah Pass show little evidence for the occurrence of associated ore deposits. No sulfide minerals other than pyrite were recognized in either the sedimentary or volcanic wall rocks, and geochemical sampling results indicate only scattered weak anomalies in a number of elements (Miller and others, 1980; unpub. data). Small gossanlike bodies of iron oxides in the Cambrian carbonate rocks appear to contain only hematite, limonite, and manganese oxides. No production has been recorded, and no significant amounts of ore minerals were recognized on mine dumps (Erickson, 1966, p. 12-13). Some of the Tertiary rhyolitic plutons in the western part of the intrusive area resemble Miocene molybdenum-bearing intrusive bodies in other parts of the Richfield quadrangle (see later sections), but a 250- to 300-m hole drilled in one of these bodies in 1981 did not cut any mineralized rock of economic interest. [Resource potential--Low]

SOUTHERN SAN FRANCISCO MOUNTAINS AND ADJACENT AREAS

A tract nearly 30 km across, west and northwest of Milford, Utah, contains many mineralized areas associated with calc-alkalic igneous intrusions of quartz diorite, granodiorite, quartz monzonite, and granite (Whelan, 1973; Lemmon and Morris, 1979a and 1979b; Hintze and others, 1981; Lemmon and Morris, 1984). These mineralized areas have supplied the great majority of mineral products produced so far in the Richfield quadrangle. Major base-metal anomalies were detected by the CUSMAP reconnaissance stream-sediment sampling program (Miller and others, 1980; unpub. data). This area contrasts with other mineralized areas in the quadrangle by depth of erosion, which here has cut to the lower volcanic or upper subvolcanic levels, exposing the tops and central parts of hypabyssal intrusions and their associated mineral deposits so that they could be discovered and developed relatively easily. Equivalent levels in most other mineralized areas in the Richfield quadrangle are still largely buried and the associated mineral deposits hidden. The widely exposed mineralized areas west of Milford were discovered early in the history of mining in western Utah, mostly in the 1870's, when numerous local mining districts were organized; these are the Pruess (Locality B2) and San Francisco (Locality B3) districts in the southern San Francisco Mountains, the Beaver Lake district (Locality B4) in the Beaver Lake Mountains, the Rocky district (Locality B5) in the Rocky Range, and the North and South Star districts in the Star Range (Locality B6).

Mineralized rock in core plutons has been mined mainly at the Cactus mine in the Cactus stock in the southern San Francisco Mountains (Pruess district), and the OK mine in the Beaver Lake district (Butler and others, 1920). Both of these mines developed copper-precious metal ores in tabular to pipelike masses of breccia. The Cactus ore body was a tabular body as much as 400 m long, 90 m wide, and 300 m deep. The origin of the breccia (whether tectonic or a breccia pipe) has not been solved satisfactorily, but the texture and mineralogy of the ore (open spaces in breccia filled by pyrite, chalcopyrite, quartz, siderite, tourmaline, hematite, and anhydrite, with minor tetrahedrite, bornite, galena, and barite) suggest affinity to breccia pipe processes. A total of about 19 million kg of copper with byproduct gold and silver was produced at the Cactus mine. The OK mine, on the other hand, was developed on a nearly vertical pipelike mass of breccia 60-65 m across in which pyrite, chalcopyrite, and molybdenite are disseminated through crackled quartz monzonite surrounding a silicified core. The texture and mineralogy of the OK deposit are similar to those found in "porphyry copper"-type deposits. It produced about 7 million kg of copper with minor gold and silver.

Skarns commonly formed in carbonate strata adjacent to plutons in the San Francisco Mountains and adjacent areas. Many of these skarn bodies contain ore minerals and numerous mines and prospects are located along intrusive contacts in all the mineralized areas. Most of the skarn ore that has been mined, however, has been taken from the Rocky district (Whelan, 1982) where about 12 million kg of copper and byproduct magnetite, tungsten, gold, and silver has been produced. Most of the ore in the Rocky district has come from contact zones between the different intrusions and the Toroweap Formation. The main mines in the Rocky district are the Bwana, Old Hickory, Montreal, Maria, and Hidden Treasure.

Vein and replacement ore bodies containing largely lead, zinc, silver, gold, and minor copper also are widely distributed in sedimentary and volcanic rocks peripheral to the intrusive bodies. These deposits are especially important in the San Francisco and North and South Star districts. The Horn Silver mine and adjacent King David mine in the San Francisco district exploit a replacement deposit of silver-lead-zinc-copper-gold ore that is unique among known ore deposits in the Richfield quadrangle in size and richness (Butler and others, 1920; Heyl, 1963; Stringham, 1967). Past periods of mining activity have produced about 735,000 tonnes of ore containing approximately 510 kg gold, 525,000 kg silver, 4,500 tonnes copper, 175 tonnes lead, and 30,000 tonnes zinc; a large reserve of oxidized zinc ore remains unmined (Heyl, 1963). The Horn Silver deposit replaced carbonate strata adjacent to the north-trending Horn Silver fault, which has a hanging wall of Tertiary volcanic rocks adjacent to a footwall of thrust-faulted Paleozoic sedimentary rocks. The deposit is confined to a short segment of the main fault a few hundred meters long between cross faults, and it bottoms out between the 1,000- and 1,600-ft levels of the mine. The main Horn Silver fault seemingly formed by uplift of the roof of the Cactus stock in middle Oligocene time. The fault dies out about a kilometer south of the Horn Silver deposit and is obliterated by the Cactus stock about the same distance north of the deposit.

Other mines exploiting vein and replacement ores in and adjacent to the southern San Francisco Mountains are the Beaver Carbonate mine in the Beaver Lake district; the Indian Queen, Blackbird (New Years), Comet, Belmont, and Golden Reef mines in the Pruess district; and the Washington, Cupric, and King David mines in the San Francisco district.

The ore deposits in the Star Range (North and South Star districts) are largely replacement and fissure-filling deposits localized along fractures cutting sedimentary rocks near small igneous intrusions. The geology of the Star Range is broadly an eastward-dipping homocline of Paleozoic and Mesozoic sedimentary rocks (Baer, 1973) overlain locally by Tertiary volcanic rocks and invaded by many small quartz monzonitic to granitic plutons. The homocline is highly broken by many minor faults of diverse trend. The ore bodies are generally small and consist of podlike to tabular replacement bodies and fissure-filling veins of oxidized material localized along fractures cutting thin- to medium-bedded arenaceous limestone and dolomite units. Some of the larger ore bodies are 1-10 m across and 150-200 m long (Butler and others, 1920; Baetcke, 1969). Total production from the Star Range area is estimated (Whelan, 1973) to have been about 225,000 tonnes of ore containing 130 kg gold, 66,000 kg silver, 1,050,000 kg copper, 25,000,000 kg lead, and 3,175,000 kg zinc, plus a significant (but unknown) quantity of fluorspar. The largest producing mines are the Moscow, Harrington-Hickory, Red Warrior, Wild Bill, and Cedar-Talisman.

The mineral resource potential of the southern San Francisco Mountains and adjacent areas ranges widely, depending on the environment. The core intrusions exposed in all the mineralized areas seem to have a low potential. The upper parts of these bodies where "porphyry-type" mineralization commonly takes place are widely exposed in the Pruess, Beaver Lake, and Rocky districts, and only two small- to moderate-sized and somewhat atypical breccia pipe or porphyry-type ore bodies have been discovered. No zonal pattern of rock alteration was noted in these districts that might suggest that hidden ore bodies of these types exist below the levels now exposed. The buried pediment and basin areas nearby seem no more favorable for the occurrence of ore than the areas now exposed. The ore deposits in the Star Range, on the other hand, are largely of vein and replacement types found in the peripheral parts of mineralized centers, and in the Star Range, levels exposed in the other districts to the north and northwest are still largely hidden at depth. Whether blind plutons carrying disseminated ore deposits in their carapaces exist here also is problematical; the small intrusions that are exposed show no indication that "porphyry-type" mineralization took place, and analogy with the other nearby districts is certainly not encouraging.

The potential for undiscovered skarn-type, and vein- and replacement-type mineral resources is considered high. Some skarns, most of which carry at least some ore minerals, have been recognized in all districts, and the possibility that higher grade mineralized rock occurs in especially favorable stratigraphic units seems excellent. All known deposits of this type are small to moderate in size, however, and no reason is known to indicate that the undiscovered deposits are of greater magnitude.

The undiscovered vein- and replacement-type mineral deposits are most likely to occur in the San Francisco and North and South Star districts where the peripheral parts of mineralized districts are widely exposed. These levels in the Pruess, Beaver Lake, and Rocky districts have largely been eroded from above the presently exposed parts of the districts, but could still exist in part in outlying areas now covered by pediment gravels and basin-fill sediments. The size of the undiscovered vein- and replacement-type deposits probably will be small to moderate, comparable to most of the nearby known deposits.

The Horn Silver deposit seems unique in size and geologic occurrence. On the basis of presently available data, there seems little liklihood that another deposit of similar magnitude and grade exists in the southern San Francisco Mountains and adjacent areas.

All the known mineralized districts are bounded in part by younger sediment-filled basins, and some, like the Beaver Lake and Rocky districts, are nearly surrounded. Buried ore deposits could exist in peripheral parts of these districts, as well as in totally hidden mineralized centers. [Resource potential--High]

MINERAL MOUNTAINS AREA

The Mineral Mountains consist primarily of intrusive rocks that form a composite batholith consisting of numerous individual intrusive bodies emplaced during three different episodes of igneous activity. The oldest activity took place in latest Oligocene and earliest Miocene time (about 25 Ma, Aleinikoff and others, in press) when numerous small dioritic to quartz monzonitic intrusions were emplaced. These rocks are time equivalent to the Bullion Canyon Volcanics widely exposed in the northern Tushar Mountains to the east. Mineralization associated with this early period of igneous activity is discussed in this section. Mineralized rock related to early, intermediate-composition, intrusive rocks has been recognized in the Antelope district at the north end of the mountains, in the Fortuna mine area along the east margin of the batholith, and in the Bradshaw and Lincoln districts at the south end of the mountains.

The Antelope district (Locality B7) in the northern Mineral Mountains has been prospected sporadically from 1871 until recent times. No reliable records of production are available, but there is scant evidence that more than a small amount of ore has been shipped. Values apparently were largely in lead and barite. Weak to moderate geochemical anomalies in Ag, As, Pb, Cu, and Zn, and moderately strong anomalies in Ba were detected by the CUSMAP geochemical survey (Miller and others, 1980; unpub. data).

The rocks of the Antelope district consist of thrust-faulted Cambrian quartzite and carbonate strata cut by many high-angle faults. These rocks are cut off on the south by a body of hornblende granodiorite belonging to the early assemblage of intrusive rocks in the Mineral Mountains batholith (Sibbett and Nielson, 1980). The ore bodies consist of small pods and stringers of relatively soft and incoherent lead ore that occur adjacent to bedding planes and steep faults cutting the Cambrian limestones. Hypogene minerals include galena, pyrite, barite, and calcite. Virtually all the larger ore bodies are strongly oxidized, and consist of nodules of galena, cerusite, and anglesite embedded in a vuggy matrix of porous ochre. Locally barite and lamellar calcite are abundant in the oxidized ore.

Although exploration has been minimal, the small record of production and general absence of extensive zones of hydrothermally altered rock in the Antelope district indicate that the potential for resources in large concealed ore deposits is low. In the southern part of the district, abundant massive to disseminated tremolite occurs in skarn near the contact with the hornblende granodiorite pluton (Crawford and Buranek, 1942). Much of this material is too coarsely crystalline to serve as fibrous asbestos. Small bodies of vermiculite are located along the same intrusive contact; all those bodies observed are too small to be of commercial interest. [Resource potential--Low]

The Fortuna mine area (Locality B8) (Butler and others, 1920, p. 558) is in the low hills between the Mineral and Tushar Mountains at the north end of the Beaver basin, where a 1- to 2-km-wide belt of propylitically altered intermediate-composition lava flows is exposed for nearly 8 km along the eastern margin of the Mineral Mountains batholith. In places the rocks are intensely altered and are cut by east-trending fissure zones marked by pyrite-bearing quartz veins and argillically altered rock. Butler and others (1920, p. 558) report native gold occurring in the oxidized parts of the veins. Numerous prospect pits have been dug on these fissure zones, and a few small workings have been developed, probably in areas showing low-grade gold values. Evidence for stoping is minimal, however, and total production probably did not exceed a few hundred tonnes of rock. Geochemical samples taken near the vein zones contained only sparse anomalous metal values. In all probability, only small pockets of low-grade gold ore exist in this area. [Resource potential--Low]

The Bradshaw mining district (Locality B9) is located in the southwestern part of the Mineral Mountains along Cave Canyon and the west face of Bradshaw Mountain (Butler and others, 1920, p. 530-531). Since the district was organized in 1875, total production is estimated to have been about 10,000 tonnes of ore containing 96 kg Au, 9,400 kg Ag, 1,760 kg Cu, 450,000 kg Pb, and 2,500 kg Zn (Earll, 1957, p. 90). Some of the ores mined in early years were very rich, returning as much as $500-$800 per short ton in silver, gold, and lead. Moderate to strong geochemical anomalies in a wide variety of elements were detected near the known mineralized area (Miller and others, 1980; unpub. data).

The geology of the Cave Canyon-Bradshaw Mountains area consists of a moderately east-dipping sequence including the Redwall Limestone, Pakoon and Callville Limestones, undivided, and the Talisman Quartzite. These rocks are cut and displaced eastward along a high-angle fault that follows east-trending Cave Canyon. In the lower reaches of the canyon, several plutons of the composite Mineral Mountains batholith cut out the fault, and it is in the wall rocks of these intrusions that the mineralized rock occurs. The intrusion nearest the mineralized area consists of hornblende diorite; farther east up Cave Canyon the intrusive rock is a leucocratic granite. Several small dikes and plugs of intrusive rock occur in the mineralized area.

Most production from the Bradshaw district came from the Cave mine on the west face of Bradshaw Mountain. The ore here consists of pulverulent limonitic ochre containing grains and nodules of cerussite, minor anglesite, and galena (Earll, 1957). All the ores contain important amounts of gold and silver. Minor secondary copper and zinc minerals are present locally. The ore partly fills a series of large and small caves localized along obscure, east-trending fissures in limestone. Some of the ore-bearing caves are isolated, but several are connected by stringers of ore or limonitic material. These ore bodies and caverns seem to have originated through intense oxidation and leaching of sulfide ore bodies which also contained either calcite gangue or a high proportion of limestone breccia. Several other small limestone replacement deposits are known in the Bradshaw district.

The first metallic ore produced in the original Territory of Utah was from the Lincoln district (Locality B10), from the Rollins (Rawlins), since renamed Lincoln, mine near the south end of the Mineral Mountains (history summarized in Butler and others, 1920, p. 530). This and other nearby mines near the mouth of Lincoln Gulch have produced an estimated 7,000 tonnes of ore containing at least 11 kg Au, 910 kg Ag, 5,800 kg Cu, 114,000 kg Pb, and 170,600 kg Zn. The principal producing properties were the Lincoln, Creole, Harriet, and Croff mines. Moderate to strong geochemical anomalies in many elements were detected near the mines (Miller and others, 1980; unpub. data).

The general geology of the Lincoln district consists of a north-trending, east-dipping faulted monocline exposing strata ranging from the Permian and Pennsylvanian Pakoon and Callville Limestones, undivided, to the Jurassic Carmel Limestone. These rocks are intruded by the Lincoln quartz mozonite stock and several small satellitic bodies. Near the intrusions the carbonate rocks are commonly bleached and marbleized and locally are converted to skarn.

The main ore deposits of the Lincoln district consist of small tabular and podlike replacement bodies in the Kaibab Limestone. Minor ore occurrences also have been explored in the adjacent Pakoon Limestone, Talisman Quartzite, and possibly in the Moenkopi Formation. The great majority of these ore bodies appear to be localized by bedding plane faults and minor fissures, and none to date has been found within the strong, crossbreaking faults. One of the most productive zones of mineralized rock is the uppermost part of the Kaibab Limestone immediately below the overlying Moenkopi Formation.

The principal ores from the Lincoln district consist of a rather soft and vuggy mixture of calcite and iron oxide with local concentrations of secondary lead, zinc, and copper minerals. Sulfide ores containing pyrite, sphalerite, galena, and chalcopyrite are common in the deeper workings (Earll, 1957, p. 88). In the Creole mine, tungsten-bearing ore consisting of scheelite crystals scattered through irregular bodies of porous limonite was mined during World War II (Hobbs, 1945, p. 110).

The small size and nonpersistent character of the known ore bodies in the Bradshaw and Lincoln districts suggest little chance for large concealed ore bodies, although a moderate, and perhaps good possibility exists for undiscovered ore bodies of the type and size already mined. [Resource potential--High]

TUSHAR MOUNTAINS AREA

Monzonite and quartz monzonite intrusive bodies cut the intermediate-composition rocks of the Bullion Canyon Volcanics at many places in the central and northern Tushar Mountains, and most seem to have been emplaced relatively late in the period of calc-alkalic igneous activity. Several of these intrusions have been dated geologically as having been emplaced between 27 and 23 Ma (Steven and Morris, 1983b), and altered rock associated with one of the intrusions has been dated as about 23 Ma (Steven and others, 1979). The volcanic wallrocks around some of these bodies have been extensively propylitized, and locally the rock has been further converted to argillic assemblages. Pyrite-bearing quartz-carbonate veins occur in some of the altered rocks, and in places these veins carry spotty gold and silver values which have encouraged widespread prospecting.

The only area of altered rock associated with calc-alkalic intrusive bodies that has had significant production is the Kimberly district (Locality B11) in the north-central part of the Tushar Mountains. This area yielded about 3,600 kg gold and 13,000 kg silver (recalculated from data given by Callaghan, 1973) during episodic mining between 1892 and 1937. Silver is strongly anomalous and molybdenum and lead somewhat less so in stream sediments in the Kimberly area (Miller and others, 1980; unpub. data). The ores produced came chiefly from the oxidized parts of two persistent vein zones, the Annie Laurie (Lindgren, 1906, p. 87-90) and the Sevier (Butler and others, 1920, p. 555), cutting propylitized quartz monzonitic intrusive rock. Descriptions by Callaghan (1973) suggest that metal values probably drop off significantly in unoxidized ores in the lower levels of the old mines. The mineralized area is cut off on the south by the topographic wall of the younger Mount Belknap caldera, and on the north by an even younger basin-range fault that juxtaposes the post-mineral Joe Lott Tuff Member of the Mount Belknap Volcanics against the mineralized intrusive rock. Unmined mineralized rock in the Kimberly area apparently is most likely to occur at depth along the two known vein zones. [Resource potential--High]

Other areas in the northern and central Tushar Mountains where gold- and silver-bearing quartz-carbonate veins in propylitically (and locally argillically) altered Bullion Canyon Volcanics were noted are the Deer Flat area (Locality B12) north of Lower Deer Creek, the Butler-Beck mine area (Callaghan, 1973, p. 29) in the headwaters of Deer Creek and east of the Kimberly district, a small area a few kilometers southeast of Sulphurdale (Locality B13), the Rob Roy mine (Locality B14) (Butler and others, 1920) near the mouth of Indian Creek Canyon, and the Cork Ridge area (Locality B15) south of the Mount Belknap caldera, (Cunningham, Steven, and others, 1984). In all of these places the quartz veins appear to form small pods or lenses along fissure zones; unverified oral reports suggest that although local pockets of rich ore occur in places, most gold and silver values are low. Butler and others (1920, p. 558) noted a reported occurrence of tungsten (in wolframite) near Cork Ridge. Whereas there is probably a moderate potential for more small and generally low-grade gold and silver deposits to be found in this environment, the total resources of these metals in the Tushar Mountains exclusive of the Kimberly district is probably not great. [Resource potential--generally Moderate to Low]

MONROE PEAK CALDERA AREA

The Monroe Peak caldera in the east-central part of the Richfield quadrangle is a major volcanic collapse structure 17 by 26 km across that formed during eruption of the Osiris Tuff about 23 Ma (Steven and others, in press). The roots of the caldera were widely invaded by quartz monzonitic magma shortly after collapse, and volcanic rocks adjacent to and overlying some of the cupolas of intrusive rock were locally intensely altered to argillic and advanced argillic mineral assemblages. Most of the replacement alunite deposits north and northeast of Marysvale, which have been the focus of intermittent exploration and development interest for many decades (Callaghan, 1973), were formed at this time.

An igneous cupola called the Central Intrusive (Locality B16) (Kerr and others, 1957), exposed in the southern Antelope Range in the western part of the Monroe Peak caldera, is virtually surrounded by a series of replacement alunite deposits that mark the cores of many hydrothermal convection cells. Alunite from two of these deposits has been dated as about 23 Ma (Steven and others, 1979). As described by Cunningham, Rye, and others (1984), these alunite deposits are interpreted to have formed in a near-surface environment above the buried margin of a cooling pluton that underlies and fed the Central Intrusive cupola. Reaction of the pluton with evaporite minerals in its walls supplied sedimentary sulfur to convecting hydrothermal cells localized along the marginal cooling gradient. Near-surface reaction of this sulfur with atmospheric oxygen led to the strongly acidic alteration of volcanic rocks, with development of alunite and related products. The broad zonal pattern of the altered areas consists of propylitically altered rocks which formed below permanent water table, overlain by alunite-kaolinite deposits formed just above water table, grading upward through jarositic and then hematitic rocks to a highly siliceous cap deposited at and just beneath the paleoground surface.

By this model, a whole series of potential environments in which ore deposits might exist is identified. The core pluton shows little evidence of any zonal pattern of altered rocks that might indicate the presence of porphyry-type deposits. The evidence for reaction of the pluton with adjacent evaporite strata suggests that nearby carbonate strata could well have been converted to skarn, perhaps containing metallic constituents. The different convecting hydrothermal cells located above the margin of the pluton conceivably could have deposited replacement-type metal deposits in a zone outside the contact-metamorphic aureole, and fissure vein deposits may have formed in fractures cutting either sedimentary or volcanic rocks even farther out in the system. Precious-metal deposits could be associated with the near-surface parts of the hydrothermal systems. Geochemical sampling of the altered areas showed only weak and sporadically distributed anomalous metal values, which has discouraged exploration of shallow levels. The strength and intensity of the hydrothermal activity, as well as its wide distribution, leaves ample opportunity for deeper level deposits to exist, however, and a good chance exists for vein, replacement, or skarn deposits at depth.

Other areas affected by advanced argillic alteration are exposed farther east in the northern Sevier Plateau (Callaghan, 1973, p. 111-117), near the center of the caldera, as exemplified by the Marysvale Peak and Manning Creek alunite deposits (both indicated by Locality B17) and the Box Creek kaolinite (fire clay) deposit just east of the Richfield quadrangle. Large masses of densely silicified rock are exposed near these deposits, particularly near Box Creek, and by analogy with the pattern of altered rocks discerned farther west, these may be underlain by alunitic or kaolinitic zones. Samples of altered surface rocks and of stream sediments from the central part of the Monroe Peak caldera, however, are nearly devoid of anomalous metal values. The mineral resource potential of this area can be judged using the same logic applied to the altered areas around the Central Intrusive, except that our data are less detailed and thus the interpretations are even more tentative. The post-caldera intrusive body beneath the center of the caldera apparently has cut out the sedimentary strata in this vicinity, so little likelihood exists for replacement or skarn deposits.

Alunite has periodically been proposed as a possible source of potash (during World War I), alumina (World War II), and more recently for combined potash, alumina, and sulfuric acid. The Monroe Peak caldera area obviously has a high potential for alunite resources, both within the many exposed bodies of altered rock, as well as at depth beneath the highly silicified rock bodies near Box Creek. [Resource potential--High for alunite and kaolinite; Moderate for hidden vein, replacement, or skarn-type deposits]

MINERAL RESOURCES ASSOCIATED WITH EARLY MIOCENE AND YOUNGER SILICIC ROCKS

From early Miocene time to the present, magmatism in the Pioche-Marysvale belt has been characterized by bimodal mafic-silicic igneous activity. This bimodal activity was broadly synchronous with late Cenozoic basin-range extensional tectonism that affected much of Western United States (Christiansen and Lipman, 1972). Mafic volcanic rocks were erupted widely but generally in low volume throughout this span. The silicic rocks, on the other hand, formed a sequence of local accumulations that developed now here, now there, across the earlier calc-alkalic volcanic field. In the aggregate, the silicic rocks formed a nearly continuous cover over those parts of the earlier volcanic field characterized by abundant shallow calc-alkalic igneous intrusions and associated mineral deposits. In all, six separate silicic volcanic accumulations of different ages have been recognized; significant hydrothermal activity is known to have accompanied emplacement of the oldest four of these, and numerous areas of high to moderate mineral resource potential have been identified. The separate silicic accumulations and their known or postulated resources will be discussed in historical sequence in the following sections.

MINERALIZED AREAS ASSOCIATED WITH THE BLAWN FORMATION

Silicic rocks in the Blawn Formation (23-18 Ma) (M. G. Best, written commun., 1983) are exposed over a northeast trending lens-shaped area least 70 km long and as much as 35 km wide that extends from the Indian Peak area in the southern Needle (Indian Peak) Range to the vicinity of the San Francisco mining district at the south end of the San Francisco Mountains. These rocks include dikes and intrusive plugs and stocks, thick lava flows, and widespread ash-flow tuff sheets; in part these rocks are interlayered with potassium-rich mafic lava flows. The widespread occurrence of intrusive bodies and locally derived lava flows indicates widely distributed igneous sources, and associated hydrothermal activity took place in all major areas of exposure of the Blawn Formation.

The Shauntie Hills (Locality C1) in the south-central part of the Richfield quadrangle consist primarily of Oligocene and early Miocene calc-alkalic volcanic rocks surrounding a few isolated exposures of sedimentary rocks marking the tops of prevolcanic hills. Some silicic volcanic rocks belonging to the Blawn Formation are exposed in the western part of the Shauntie Hills, and small intrusive bodies of Blawn age have been identified as far north as the abandoned mining camp of Frisco.

A belt of extensively altered rocks 2-4 km wide extends about 12 km east from the western margin of the southern Shauntie Hills, across and several kilometers beyond a prominent hill of sedimentary rocks called White Mountain. The altered rocks in places have been converted to large masses of alunite and kaolinite, which locally contain small deposits of uranium and native sulfur. Alunite from one locality has been dated by K-Ar methods as 22.5 Ma (H. H. Mehnert, written commun., 1983), which indicates that alteration took place during the Blawn volcanic episode. Despite the intensity of the rock alteration that affected this area, geochemical samples show only strong barium and weak copper anomalies (Miller and others, 1980; unpub. data).

The largest development prospect in the Shauntie Hills is at a uranium occurrence within a small patch of altered volcanic rocks overlying silicified limestone and prevolcanic rubble about 3 km east-southeast of the top of White Mountain. Here, small quantities of secondary uranium minerals occur within argillized and silicified lava flows, but the quantity of mineralized rock is low and probably no more than a few hundred tonnes of uranium ore has been produced. A second area of extensive prospecting lies 6.5 km west of the top of White Mountain where intensely acid-leached rock consisting mostly of a network of residual silica contains scattered crystals of native sulfur. In addition, large masses of alunitized and kaolinitized rock crop out east and west of White Mountain; estimates based on data given by the U.S. Bureau of Land Management (1977) indicate that the area west of White Mountain may contain 80 million tonnes of alunitic rock containing 14.5 percent Al_2O_3 and 3.15 percent K_2O.

All these areas of altered and mineralized rock are typical of those that form in near-surface solfataric environments where hypogene H_2S reacts with atmospheric oxygen to form sulfuric acid (Cunningham, Rye, and others, 1984). The type of alteration products now exposed probably formed largely above the paleoground-water table, and thus should have limited vertical extent. Enough alunitic rock is indicated by surface exposures to constitute a major resource if an economically viable technology is developed to treat them. The potential for other types of mineral resources deposited under much different conditions deeper within the hydrothermal systems is more difficult to assess. Assuming intrusive igneous roots for the hydrothermal systems, a whole gamut of deposit types can be envisaged, from porphyry-type deposits near the tops of the postulated intrusions, to skarn, replacement, and vein types progressively outward and upward. All bodies of silicified rock, whether jasperoid associated with carbonate strata or highly silicified volcanic rocks formed in the near-surface solfataras, are possible hosts for precious metals. Major hydrothermal systems bearing large quantities of sulfur clearly existed in these areas; whether valuable metals also were present and were deposited in one place or another cannot be determined without much more detailed investigation than was done in this study. [Resource potential--High for alunite and kaolinite; Moderate or Unknown for metallic resources]

The Pine Grove district (Locality C2) in the west-central Wah Wah Mountains was discovered in the early 1870's, but early mining activity was very minor. Chief production took place during intermittent activity between 1911 and 1945, when an estimated 2,600 tonnes of ore containing 3 kg Au, 500 kg Ag, 1,300 kg Cu, 112,000 kg Pb, and 127,000 kg Zn was produced from small replacement ore bodies in carbonate strata. Jones and Dunham (1946) estimate that reserves of about 60,000 tonnes of similar-grade ore remain unmined. In 1977, Phelps-Dodge Mining Co. announced the discovery of a large, deeply buried stockwork molybdenum-tungsten deposit; this deposit has since been extensively explored by Getty Minerals Corp. Stream-sediment samples from the Pine Grove vicinity showed weak anomalies in Ag, Pb, and Cu, but no other indications of proximity to a major ore deposit (Miller and others, 1980; unpub. data).

The Wah Wah Mountains near the Pine Grove district consist of a homocline of upper Precambrian and Cambrian strata that is cut by both low-angle thrust faults and younger high-angle normal faults. The mineralized area is localized by an intrusive igneous center consisting of two contiguous small stocks of quartz latite or quartz monzonite that were intruded about 24 Ma (Abbott and others, 1983). Keith (1983) has correlated one of the intrusions with the oldest Blawn ash-flow tuff sheet in adjacent parts of the Wah Wah Mountains. The igneous rocks are in part moderately to strongly argillized, silicified, sericitized, and pyritized, and locally contain disseminated ore and gangue minerals. The ore bodies mined in the past were in fault-bounded blocks of limestone and shale that were partly replaced by calcite, quartz, galena, sphalerite, and pyrite, with less abundant tetrahedrite, chalcopyrite, ankerite, and rhodochrosite. All ores mined were partly oxidized. The deeply buried molybdenum-tungsten ore body is apparently a typical stockwork "porphyry-type" deposit associated with an altered hypabyssal intrusion. On the basis of the first four drill holes, it was estimated that the deposit contains nearly 100 million tonnes of ore averaging 0.29-0.38 percent MoS_2 (World Mining, 1978, p. 78). The top of the deposit is reported to lie at depths of 900-2,000 m below the surface (Abbott and others, 1983). Many holes have subsequently been drilled to define the ore body more completely, but the results have not been made public. The resource estimates based on early data probably have been revised significantly as the result of this subsequent drilling, so that the early figures should be used only to indicate that a major discovery has been made at a considerable depth below the surface. Without access to the more recent results, it would be idle to speculate here on the mineral endowment of the district. [Resource potential--High]

A number of scattered mineralized or possibly mineralized areas have been identified throughout the southern Wah Wah Mountains within an area known to have at least some igneous centers related to the Blawn Formation. Arsenic and barium are strongly anomalous and lead and copper weakly anomalous in stream-sediment samples collected throughout the area (Miller and others, 1980; unpub. data). Hydrothermal activity in several of these areas is known to have taken place during the Blawn igneous episode, and that at the others is postulated to have taken place at about the same time. In the Staats mine area (Locality C3), a rhyolite intrusion about 2 km long and 0.5 km wide cuts Paleozoic quartzite and dolomite. The brecciated wallrock around the plug contains lenses of uranium-bearing fluorite from which about 4,500 tonnes of metallurgical fluorspar (Thurston and others, 1954, p. 17) and 1,700 tonnes of uranium ore (also fluorspar) have been shipped. The principal primary ore minerals are fluorite and uraninite; small quantities of cassiterite also have been reported (Lindsey and Osmondson, 1978). The rhyolite plug was intruded about 20 Ma (op. cit., 1978). An approximately coeval rhyolite dome in the Blawn Formation capping a nearby hill at The Tetons contains anomalous quantities of Be, Ga, Li, Mo, Nb, and Sn (M. G. Best, written commun., 1983; Lindsey and Osmondson, 1978). [Resource potential--High]

A pile of rhyolite lava flows as much as 400 m thick with associated possible shallow intrusions makes up the upper part of the Blawn Formation on the east flank of the Wah Wah Mountains about 10 km east of the Staats mine (Locality C4) (Abbott and others, 1983). One of these flows is weakly altered and contains sparse gem-quality red beryl crystals that have been mined and used in jewelry.

Four large areas of alunitized and kaolinitized tuffaceous rocks occur within an area about 6 km across on and near the lower eastern slopes of Blawn Mountain (Locality C5). All the principal alunite-kaolinite deposits formed in welded tuff in the Lund Tuff and Wah Wah Springs Formation of the Needles Range Group, or in an overlying lapilli tuff forming the lower part of the Blawn Formation (Abbott and others, 1983). Samples of alunite from one of the deposits have been dated by K-Ar methods as 22.5-20 Ma (H. H. Mehnert, unpub. data, 1982-1983), indicating that alteration took place during the Blawn period of igneous activity. The strongly altered rocks are closely limited to a specific stratigraphic interval just above and below the unconformity between the Needles Range Group and Blawn Formation where large irregular masses of the host rocks have been pervasively replaced.

As reported by the U.S. Bureau of Land Mangement (1977), the most fully evaluated deposit (their Area C) is estimated to contain about 150 million tonnes of alunitic rock averaging 14.45 percent Al_2O_3. Two other areas (their areas A and B) appear to be of similar magnitude; their Area D is about the same size but is dominantly kaolinite (Whelan, 1965; U.S. Bureau of Land Mangement, 1977). Other less explored areas of alunitic and kaolinitic rocks occur in the same general area. A major resource for alunite clearly exists in these altered areas and it may become economically viable should technology be developed to extract the contained alumina, potash, and sulfate.

The source of the sulfur for the Blawn Mountain alunite appears to have been magmatic ($\delta^{34}S$ = +1.45 ^{o}/oo, R. O. Rye, written commun., 1982). Whether this magmatic sulfur was supplied separately to each altered area through a local hydrothermal system and was oxidized at the favored stratigraphic interval, or whether it pervaded the favored stratigraphic interval from a central source (or sources) and was locally oxidized is not now known. The answer to this question is critical in evaluating the potential for mineral resources at depth. If the altered areas had local sources for their magmatic sulfur, each major altered area would have the potential for zoned hydrothermal metal deposits at the intrusive, skarn, replacement, and vein levels below. If the sulfur moved laterally along zones of enhanced permeability, favorable source intrusions and associated deep mineral deposits could be located some distance from the areas where the solutions were ultimately oxidized and alunite formed. [Resource potential--High for allunite; High to Moderate for metalliferous deposits]

The Blue Mountains-Jockey Spring area (Locality C6) is an ill-defined area about 20 km long northeastward and 15 km across in the southern Wah Wah Mountains, south and southeast of the Staats mine and the highly altered areas east of Blawn Mountain. This area is characterized by three structural domes with thrust-faulted Paleozoic and Mesozoic sedimentary rocks in their cores, surrounded by Tertiary volcanic rocks. The principal exposed mineral occurrences include numerous small iron and manganese bodies, uranium prospects, and a small mine that produced some native sulfur and mercury. Most mineral occurrences are in sedimentary rocks but some also occur in the Blawn Formation.

The principal iron (and manganese) prospects in the Blue Mountains-Jockey Spring area are the Blawn Wash, Emma, and Iron Duke mines in the western Blue Mountains (Bullock, 1970, p. 12-13). These workings expose small bodies of manganiferous limonite, geothite, and earthy hematite along fractures in Cambrian carbonate strata; the resource potential of these deposits as sources of iron ore is considered negligible. The Katie (Cima) mercury and sulfur mine 5 km south-southwest of Jockey Spring (Locality C7) was operated for a few years following World War II, when a small quantity of native sulfur and cinnabar was mined from argillized and silicified tuff in the Blawn Formation. This deposit may have formed later in Miocene time when hydrothermal activity related to the Steamboat Mountain Formation affected several nearby areas to the southwest. This possibility will be considered in more detail in later sections of this report. Cambrian carbonate beds adjacent to the ore body have been converted to iron-stained jasperoid; this material should be checked for possible precious-metal content.

The main potential for undiscovered mineral resources in the Blue Mountains-Jockey Spring area would seem to be at depth within the domed areas. These domes appear to have been uplifted by vertical forces, probably by magmatic pressure from hidden intrusions. If, as seems likely, these intrusions were emplaced during the Blawn igneous episode, they probably are rhyolitic in composition and could have been the source for concentrations of Sn, W, Mo, Be, or other lithophile elements in the upper parts of the intrusions or in adjacent wallrocks. The most favorable area to test this possibility appears to be about half a kilometer northwest of Blue Peak in the Blue Mountains, where Mesozoic rocks have been in part converted to hornfels, including calc-silicate minerals, probably by an underlying intrusive body. Too many unsubstantiated assumptions are involved in this interpretation to permit the resource potential to be evaluated with confidence. [Resource potential--Moderate]

Fluorspar was discovered in the Indian Peak area (Locality C8) in the southern Needle (Indian Peak) Range in 1936 (Everett and Wilson, 1951). The principal mining activity took place largely during World War II (1940-45), when a total of about 20,000 tonnes of ore containing 25-50 percent CaF_2 was mined from several properties. No production has been recorded since 1945, although there has been sporadic exploration activity. The fluorspar-producing area is entirely within the resurgent core of the 30-29 Ma Indian Peak caldera (Grant and Best, 1979). The intracaldera facies of the Wah Wah Springs Formation of the Needles Range Group, and a quartz monzonite stock emplaced late in the caldera cycle are the chief host rocks. Mineralization was significantly later than development of the caldera, however, and seems to have been associated with fluorite-bearing rhyolite dikes of probable Blawn Formation age. Both the dikes and the vein zones that locally contain fluorspar are localized along faults that cut not only the resurgent caldera core, but other late Oligocene and early Miocene volcanic units that accumulated within the caldera area.

The fluorspar-bearing deposits occur along well-defined zones of fissured and brecciated rock cemented by quartz, lamellar calcite, and spotty concentrations of fluorite (Thurston, 1954). Shoots that contain more than 25 percent fluorite constitute the main ore bodies; some of these are as much as 3.5 m wide, 65 m long, and 80 m in vertical extent. The largest producing properties were the Cougar Spar and Holt-Blue Bell mines, but other smaller deposits also were mined.

There appears to be a moderate to good possibility that other fluorspar deposits of the type already mined occur along the known vein zones. It seems much less likely that other vein zones not yet prospected will be found. The exposed veins are similar in many respects to fluorspar deposits that form in very shallow environments, as at Northgate, Colo. (Steven, 1960). The deeper levels of such hydrothermal systems may be the repositories of other mineral deposits, although this has yet to be proven. One of the authors (TAS) has faced this question several times, and has come to contradictory conclusions. At Northgate, Colo., Steven (1960) suggested that sulfide-bearing ore deposits could well exist at depth, but in the western San Juan Mountains, Colo. (Steven and others, 1977), he cited evidence that crystallization of shallow rhyolite intrusions resulted in loss of fluorine from levels of about 1,000 ppm in marginal vitrophyres, to only a few hundred ppm in the devitrified (crystallized) interiors. By comparable losses, crystallization of even a moderate-sized pluton at depth could easily have supplied sufficient fluorine to account for the fluorspar in the Indian Peak area without necessarily forming any associated sulfide-bearing ore deposits nearby. The very minor pyrite associated with the fluorspar-bearing veins probably indicates a low sulfur content in the mineralizing solutions. [Resource potential--High to Moderate for fluorspar]

MINERALIZED AREAS ASSOCIATED WITH THE MOUNT BELKNAP VOLCANICS

The Mount Belknap Volcanics was erupted from two source areas in the northern Tushar Mountains and Antelope Range (eastern part of Area D) between 21 and 14 Ma (Steven and others, 1979; Cunningham and Steven, 1979a). Hydrothermal activity took place many times and in many different places in association with Mount Belknap igneous centers (Steven and others, 1978), and the two most productive parts of this area (the uranium mines in the Central Mining Area and the base- and precious-metal-producing Deertrail mine) have exploited ores deposited during this interval. Many environments have been identified that seemingly have good possibilities for containing important undiscovered mineral resources. Callaghan (1973) has given an almost encyclopedic description of individual mine workings in this area.

Igneous activity in the eastern source area began about 21 Ma near the eastern margin of the southern Antelope Range where a group of silicic volcanic domes was erupted. The activity migrated progressively southwestward with time until 16 Ma, emplacing small hypabyssal intrusions, local lava flows, and one small ash-flow tuff sheet whose eruption caused the small Red Hills caldera to subside (Steven and others, 1979; Cunningham and Steven, 1979a; Steven and others, in press). At 14 Ma, local rhyolite lava flows were erupted in the eastern part of the source area, and small intrusions were emplaced more widely, including a postulated intrusion at the southwest end of the source area (Cunningham and Steven, 1979c; Cunningham, Rye, and others, 1984) that may be economically important.

Significant mineralization took place in the eastern part of the source area about 19 Ma (Cunnningham and others, 1982) when the uranium-bearing veins in the Central Mining Area (Locality D1) (Kerr and others, 1957) were deposited. Between 1949 and 1967, these veins supplied 175,000 tonnes of uranium ore averaging 0.20 percent U_3O_8 (Callaghan, 1973, p. 48). Molybdenum is associated with the uranium, and is increasingly abundant downward. Cunningham and Steven (1979b) and Steven and others (1981) have related the uranium-molybdenum deposits to a hidden intrusion postulated to underlie the mineralized area, and have suggested that this intrusion may also contain a porphyry-type disseminated molybdenum deposit.

Low-grade uranium values reportedly were encountered in extensive exploration drilling by industry in a several-kilometer-wide belt east of the main uranium-producing Central Mining Area. It is not known whether this peripheral mineralized material formed by leakage of uranium from the mineralized center to the west (Steven and others, 1981, p. 117), or whether it was deposited in the upper part of a separate hydrothermal system. [Resource potential--High]

A major composite hydrothermal system developed in the Tushar Mountains at the southwest end of the eastern source area about 14 Ma (Cunningham and Steven, 1979c; Cunningham, Rye, and others, 1984). Two adjacent and approximately coevel centers located at Alunite Ridge and at the top of Deertrail Mountain (both indicated by Locality D2) are marked by intensely altered rocks: at Alunite Ridge major alunite veins as much as 20 m thick filled open fissures in a structural dome cut by radial fractures, and on Deertrail Mountain highly kaolinitized rock marks the focus of another radial fracture pattern. These areas have been interpreted to have formed by acid-sulfate alteration above hidden stocks. At the levels now exposed, the strongly altered cores of these systems are markedly low in trace and ore elements, probably because these elements were especially soluble in the low-pH solutions responsible for the alteration. Precious and base metals are concentrated in an annular ring surrounding the barren cores. Quartz veins containing gold, silver, and minor base metals cut propylitized volcanic rocks and some of the underlying quartzite in part of this annular ring, and the Deertrail mine exploits a manto in carbonate strata along the east side of the ring. The Deertrail mine has produced about 250,000 tonnes or ore containing about 4,545 kg gold, 61,462 kg silver, 8.7 million kg lead, 11.2 kg zinc, and 580,000 kg copper.

Cunningham and Steven (1979c) and Cunningham, Rye, and others (1984) have suggested that the igneous cupolas underlying Alunite Ridge and Deertrail Mountain have an excellent chance for hosting porphyry-type disseminated copper and molybdenum deposits. It is likely also that metal-bearing skarn deposits exist marginal to the postulated intrusions, as well as replacement deposits (comparable to the Deertrail manto), and vein deposits (like those exposed in nearby volcanic rocks) in the surrounding wallrocks. [Resource potential--High]

The western source area of the Mount Belknap Volcanics was violently active about 19 Ma, when the Joe Lott Tuff Member was erupted and the Mount Belknap caldera (Locality D3) subsided. Several environments favorable for the formation of mineral resources existed during and following caldera development (Steven and others, 1981, p. 117). The caldera was filled by interlayered densely welded ash-flow tuff and thick lava flows, and the fill was locally cut by small intrusions above the southern ring fracture zone. The fill was pervasively bleached and altered shortly after it accumulated, and small areas near some of the intrusions were extensively argillized and pyritized by local hydrothermal activity. Weak to strong geochemical anomalies in many elements, particularly Sn, Be, Th, Zn, Bi, W, and Mo were detected in samples of stream sediment, rocks, and water collected in and near the Mount Belknap caldera (Miller and others, 1980; unpub. data; Tucker, Miller, and McHugh, 1980; Tucker, Miller, and Motooka, 1981, 1982; Miller and others, 1984a, 1984b, 1984c).

Uranium and molybdenum anomalies in stream-sediment and rock samples were detected near some of the intrusions, and have been interpreted to indicate high potential for porphyry-type mineral deposits near the tops of the exposed or nearby hidden intrusive bodies (Steven and others, 1981, p. 116; Tucker, Miller, and Motooka, 1981, 1982). The pervasively altered caldera fill shows evidence of remobilization of uranium and other elements, and although irregularly moved from one place to another, the uranium content seems to have increased from an average of about 13 ppm for glassy rocks from the Mount Belknap Volcanics in general to about 16.4 ppm in the caldera fill (Steven and others, 1981, p. 113, 117). It is uncertain whether this increase is the result of differential solution and redeposition of uranium in the fill, or of an addition of epigenetic uranium from the magma chamber underlying the caldera. There is a definite tendency for the remobilized uranium to be selectively deposited in more permeable parts of the caldera fill, both in talus-mudflow breccia at the margins of intracaldera lava flows, or in tongues of talus-landslide breccia extending from the caldera walls into the fill. Beryllium also is irregularly anomalous in the caldera fill (Tucker and others, 1982), but the precise sources of the anomalies have not been determined. In view of the evidence for movement of several of the metallic constituents in the dispersed hydrothermal system that altered the caldera fill, a definite possibility exists that some of the bodies of rock containing redeposited elements, particularly uranium, may be large enough and of high enough grade to constitute mineral resources. [Resource potential--High]

Combined geologic, geochemical, geophysical, and geochronologic data (Cunningham and others, 1984) indicate that an area along Indian Creek (Locality D4) between the west margin of the Mount Belknap caldera and Beaver basin may be underlain by a mineralized intrusive body that was emplaced about 16 Ma. Surface evidence for mineralization is most clearcut at the Mystery-Sniffer mine, which has produced small quantities of uranium (Osterstock and Gilkey, 1956; Wyant and Stugard, 1951). McHugh and others (1980) detected anomalous concentrations of Li, Be, F, Mo, U, As, and Mn in water from the mine area. Farther west, rhyolite dikes containing fluorite and uranium have been dated by K-Ar methods as about 16 Ma. The area containing these dikes is also marked by a strong aeromagnetic low, and remote-sensing techniques have determined that this same area has been pervaded by potassium- and uranium-bearing solutions which increased the contents of these elements by a small but definite amount throughout the area of the magnetic anomaly. The buried 16 Ma pluton interpreted to underlie this area could well have zonally arranged mineral deposits associated with it, and constitutes a definite target for additional study and perhaps exploration. [Resource potential--High]

MIOCENE MINERAL DEPOSITS IN THE MINERAL MOUNTAINS

Most of the composite Mineral Mountains batholith (western part of Area D) consists of granite and quartz monzonite plutons as large as 6 by 10 km across (Sibbett and Nielson, 1980) that were emplaced in early Miocene time (Aleinikoff and others, in press), approximately concurrent with eruption of the Mount Belknap Volcanics in the Tushar Mountains to the east. The contacts of some of these early Miocene intrusions with Paleozoic carbonate strata are marked by skarn zones that locally contain the tungsten mineral scheelite.

Scheelite was discovered in the central part of the Richfield quadrangle in 1940, and was widely prospected for and locally mined during World War II (Hobbs, 1945). Most prospects in the Mineral Mountains are located along a 5- to 6-km segment of the contact zone between granitic intrusive rocks and Mississippian Redwall Limestone along the southeastern flank of the mountains (Locality D5). Anomalous beryllium has been detected in these same skarn zones (Miller and others, 1980; unpub. data), and one mine (the Miller mine) has produced a small quantity of beryllium from beryl and helvite in pegmatite dikes cutting the contact zone (Earll, 1957, p. 97). As described by Hobbs (1945), the chief mines and prospects in this area, the Strategic Metals (Blue Star) mine, Beaver Tungsten (Beaver View) mine, Daily Metal mines, and Contact Claim, explore garnetiferous skarn zones in the carbonate strata adjacent to or near the intrusive contact. Scheelite is sparsely disseminated through some of the skarn, and locally forms higher grade pockets a few tonnes to several tens of tonnes in size that contain as much as several percent WO_3. The tungsten content generally is much lower and varies widely; the ore bodies are small and erratically distributed, and most of the skarn is effectively barren. Total production from this area has been about 1,000 tonnes of ore containing between 0.5 and 1.0 percent WO_3. In all likelihood, other bodies of mineralized rock of the type already discovered occur in the contact metamorphosed zones, but these are too small, low grade, and erratically distributed to constitute resources.

Another tungsten occurrence at the Two Rs mine (Locality D6) is located on the west slope of the Mineral Mountains, about 8 km due west of the tungsten-bearing skarns at the Beaver Tungsten mine discussed above. This prospect explores a scheelite-bearing epidote-garnet skarn along the contact between granite and Permian and Pennsylvanian Pakoon and Callville Limestones, undivided. About 65 tonnes of tungsten ore averaging about 0.58 percent WO_3 was produced, but virtually no additional ore was blocked out. [Resource potential--Moderate]

MINERALIZED AREAS ASSOCIATED WITH THE STEAMBOAT MOUNTAIN FORMATION

An area in the southern Wah Wah Mountains and southern Needle (Indian Peak) Range (Area E), about 25 km long northeast-southwest and 15 km across within the Richfield quadrangle and extending southward and westward into adjacent areas, contains large areas of middle Miocene rhyolite that have been called the Steamboat Mountain Formation (Best and Davis, 1981). Several K-Ar age determinations indicate an age of 13-12 Ma. Hydrothermally altered rocks are prominent at several places within this area, and weak to strong geochemical anomalies in many elements have been detected in stream-sediment samples (Miller and others, 1980; unpub. data).

Areas of hydrothermally altered rocks associated or possibly associated with the Steamboat Mountain Formation occur in the southern Needle (Indian Peak) Range and Wah Wah Mountains in an area extending 5-7 km outward east, south, and west from the alluvial fill at the south end of Pine Valley. These areas extend from the area of the Katie (Cima) mine discussed under mineral resources associated with the Blawn Formation, southward to the vicinity of Mountain Spring Peak (Locality E1), westward to the Bible Spring fault zone (Locality E2), and then northward to Typhoid Spring (Locality E3). The altered areas range from small patches a few meters in diameter, to large areas as much as 7 km across. Some of the altered areas are closely localized along the northeast-trending Bible Spring fault zone (Best and Davis, 1981), or along its trend northeastward where it projects directly toward the Katie (Cima) sulfur-mercury deposit; other altered areas are more randomly scattered or are associated with local igneous centers of Steamboat Mountain age.

Whereas many of the altered areas clearly involve Steamboat Mountain Formation and are thus middle Miocene or younger in age, some of the mineralized rock along the Bible Spring fault zone may be older. Movement on the fault zone began in early Miocene and continued intermittently for an indefinite period thereafter (M. G. Best, written commun., 1983). Some of the early faults are overlapped by unbroken rhyolite of Steamboat Mountain, whereas other faults cut the younger rocks. Altered rocks along the zone are in part offset by some of the faults. The sulfur-mercury deposit at the Katie (Cima) mine has been interpreted to be of Blawn age, and some of the other areas of mineralized rocks may be of that age as well.

The Bible Springs fault zone and its projected extensions seems especially favorable for the occurrence of mineral resources. Reconnaissance geochemical sampling of stream sediments within this area disclosed weak to strong anomalies in As, Ba, Be, Bi, Mo, Sn, and Zn (Miller and others, 1980; unpub. data). A follow-up investigation of bedrock geochemistry of a 160-km^2 area in the southwestern Wah Wah Mountains (Locality E4) (Tucker, Miller, Motooka, and Huber, 1981) outlined several areas particularly enriched in one or more of the elements Li, F, Y, Be, Nb, Rb, Mo, Bi, and Pb. Some of these local anomalies coincide with areas of altered rocks, and some do not. Tucker, Miller, Motooka, and Huber (1981) concluded that the anomalies had their source in hidden highly differentiated felsic intrusions, some of which may contain porphyry-type molybdenum deposits. We concur in this conclusion, and extrapolate it to the other altered areas associated with the Steamboat Mountain Formation as well. Not only does the porphyry environment seem likely to contain mineralized rock in certain favorable locations, but the surrounding wall rocks also are possible hosts to skarn, replacement, or vein-type deposits. Lithophile elements such as Mo, U, Be, W, and Sn, as well as the more common base metals Pb and Zn, are expected constituents in such postulated mineral deposits. Present exposures are near the top of the original volcanic accumulation, so potential ore deposits may be relatively deep. Detailed geological, geochemical, and geophysical studies of this whole area would seem worthwhile to locate possible targets for exploration. [Resource potential--High]

MINERALIZED AREAS ASSOCIATED WITH THE RHYOLITE OF GILLIES HILL

Silicic igneous rocks were emplaced widely over east-central Richfield quadrangle (Area F) in middle Miocene time, 10-7 Ma (Evans and Steven, 1982; Rowley and others, 1978). Remnants range from large volcanic domes at the north end of Beaver basin (rhyolite of Gillies Hill), to porphyritic and aphyric dikes and plugs cutting the batholithic core of the Mineral Mountains, to scattered small volcanic centers on the west side of the Mineral Mountains and in the northern part of the Black Mountains. Hydrothermal activity related to this period of igneous activity has been recognized only along the fault marking the western margin of the Tushar Mountains, where samples of alunite from two localities have been dated as about 9 Ma (Steven and others, 1979; Cunningham, Steven, and others, 1984).

As detailed by Cunningham, Steven, and others (1984), the Sheep Rock alunite deposit (Locality F1), located about 16 km northeast of Beaver, forms the core of a zoned hydrothermal system that has the Sheep Rock and the Sunday gold mines in its periphery. The Sheep Rock alunite deposit formed by near-surface oxidation of H_2S to sulfuric acid, which converted a local mass of Mount Baldy Rhyolite Member of the Mount Belknap Volcanics to alunite and kaolinite. The Sheep Rock gold deposit consists of quartz-calcite veins containing shoots of manganese oxides, native gold, pyrite, and possibly argentite, cerargyrite, ruby silver, and tellurium (tellurides?) (Butler and others, 1920). Sulfur isotope data (R. O. Rye, oral commun., 1981) indicates that the sulfur in the alunite probably had a magmatic source.

Combined geological, geophysical, and remote-sensing data (Cunningham, Steven, and others, 1984) suggest that the Sheep Rock area probably is underlain by a 9 Ma (silicic?) intrusion which supplied sulfur and other materials to an overlying hydrothermal system. Potassium, uranium, and thorium pervaded the overlying rocks; reduced sulfur was introduced along fractures to be oxidized near the surface to sulfuric acid at the center of the system, and gold and other metals were deposited in veins in peripheral parts of the system. The potential for ore deposits in the buried porphyry, skarn, and replacement environments is not known, but the zonal arrangement of near-surface deposits suggests that deeper zones are well worth considering as exploration targets. The silicic composition of nearby coeval volcanic rocks suggests that any deep ore deposits associated with the postulated intrusion may contain one or more of such lithophile elements as Mo, Sn, Nb, Be, and U. [Resource potential--High]

MINERALIZED AREAS ASSOCIATED WITH SILICIC ROCKS IN KINGSTON CANYON

As noted by Rowley and others (1981), a 5.4-Ma rhyolite volcanic center at Phonolite Hill in Kingston Canyon in the southeast part of the Richfield quadrangle (Area G) is accompanied by locally altered wallrocks (Locality G1). These altered rocks have been prospected for uranium and thorium, but no ore bodies have been found. Only barium is anomalous in stream sediments collected in this area (Miller and others, 1980; unpub. data). Because of the small size of the altered areas and their low contents of metallic trace elements, only a low potential for the occurrence of mineral resources can be postulated. [Resource potential--Low]

MINERALIZED AREAS ASSOCIATED WITH PLIOCENE AND YOUNGER SILICIC ROCKS

Silicic volcanic rocks of Pliocene and early Pleistocene age (3-2 Ma) crop out in the Coyote Hills and Twin Peaks area at the south end of the Black Rock desert (Area H), and of Pleistocene age (1-0.5 Ma) in the central Mineral Mountains (Area I). A few anomalous metal values were obtained from scattered stream samples (Miller and others, 1980; unpub. data), and the source of one anomaly is a limonite-cemented flow-margin breccia at South Twin Peak. However, no well-defined areas showing evidence of significant mineralization were identified. The resource potential for epigenetic deposits associated with igneous activity thus seems low. The silicic rocks in the Mineral Mountains have been interpreted (Lipman and others, 1978) to be surface expressions of the magmatism responsible for the Roosevelt geothermal area on the west side of the Mineral Mountains, but this resource is not being considered in this report.

Of historical interest, rhyolite obsidian from the Pleistocene flows in the Mineral Mountains was the first mineral resource in the Richfield quadrangle to have been produced and used for technological purposes. The material is of excellent implement quality, and was extensively used by aboriginal inhabitants of this region (Lipman and others, 1978). Whether this resource again becomes important in the local economy depends largely on whether human wisdom achieves parity with technical skill in the field of nuclear science.

MINERALIZED AREAS NEAR COVE FORT AND SULPHURDALE

Modern solfataras and thermal springs are active in the Cove Fort-Sulphurdale area (Area J) in the east-central part of the Richfield quadrangle, just east of a Pleistocene (0.5 Ma) basaltic andesite shield volcano (Clark, 1977; Moore and Samberg, 1979; Steven and Morris, 1983b). It is not known whether the thermal activity is related to the nearby mafic volcano, or to a hidden igneous body underlying the thermal area itself. The center of the active hydrothermal area is near the intersection of a major east-trending fault of early Miocene age, and the main north-trending basin-range fault along the west flank of the Tushar Mountains (Cunningham and others, 1983).

The solfataras are manifested by areas of highly altered rock in which H_2S and SO_2 are presently being exhaled and native sulfur is being deposited. Sulfur is being produced from an open-pit mine at Sulphurdale (Locality J1), and several presently inactive pits east, northeast, and north of Cove Fort (Locality J2) have produced sulfur in the past. Judging from the size of the altered areas, probably as much sulfur remains in this general area as has been mined in the past.

One of the pits along a northeast-trending basin-range fault 2.5 km north of Cove Fort (Locality J3) contains significant quantities of fluorite, and some attempts have been made to produce this commodity. According to Callaghan (1973, p. 125), about 4,000 tonnes of fluorspar have been produced from this mine. The fluorite is highly broken and is in part recemented by native sulfur, so fluorite deposition clearly preceded modern sulfur deposition. It is not known whether the fluorite formed early during the present mineralizing episode, or whether it is significantly older and was related to either the 9-Ma rhyolite of Gillies Hill to the south, or to the 3- to 2-Ma rhyolites in the Coyote Hills and Twin Peaks areas to the northwest.

Present exposures of fluorite in the pit and adjacent areas are limited, and do not suggest that a major resource is present.

The roots of the Cove Fort-Sulphurdale hydrothermal system are potential repositories of mineral resources. It is difficult to assess this possibility without knowledge of the source of the heat that powers the system and supplies at least some materials to it. From a resource point of view, however, any deep mineral concentrations occurring here probably are unavailable for use because of heat and noxious gases, including live steam.

The thermal area and its associated solfataras are included in what has been classified as the Cove Fort KGRA (known geothermal resource area), and has been tested as a possible source of geothermal power. Early drilling encountered anomalous heat flow toward the periphery of the thermal area (Moore and Samberg, 1979), and more recent (1983) drilling has discovered steam at Sulphurdale. Geothermal resources are not within the scope of this report, and will not be discussed further. [Resource potential--High to Moderate]

URANIUM IN BASIN FILLS

Steven and others (1981) presented evidence that several billion pounds of uranium was freed from Mount Belknap Volcanics source rocks by post-depositional diagenesis and solution. Much of this mobilized uranium entered the hydrologic regime and was transported to concurrently developing nearby basins (specific locations are prefixed K on pls. 1 and 2). The same reasoning can be applied to other late Cenozoic rhyolite accumulations within the Richfield quadrangle. The ultimate sumps were the major alluviated structural troughs now marked by the Escalante and Sevier Deserts. As discussed in the section on playa deposits, uranium content in the fill in at least some of these deeper basins may have been so diluted by water and sediments from barren terrains that the uranium was dispersed rather than concentrated. The water supplied to interim sumps nearer the uranium-bearing source rocks, however, may have had higher concentrations of uranium, which could have been precipitated by local reducing conditions within the complex basin fills.

Steven and others (1981) called attention to several late Cenozoic basin-fill deposits that seem to have some possibility for containing secondarily deposited uranium. The fill in the Big John caldera (Locality K1) consists of a blanket of conglomerate and sandstone underlying devitrified and zeolitized Joe Lott Tuff Member of the Mount Belknap Volcanics. These stream deposits are exposed in two areas; rocks on the upstream side of the drainage basin are strongly oxidized, whereas rocks on the downstream side are unaltered. The covered area between possibly may be the site of an oxidation-reduction front with associated roll-front uranium deposits.

The middle Miocene Sevier River Formation is another potential host for secondarily deposited uranium in the eastern part of the Richfield quadrangle (Steven and others, 1981, p. 119-120). The formation in this vicinity was deposited in broad basins that show virtually no relation to the present distribution of horsts and grabens that constitute the High Plateaus. Rowley and others (1981) have shown that the present topography here formed largely during a period of intense faulting in late Miocene time between 8 and 5 Ma. Thus, the configuration of the basins, and the directions of flow of possible uranium-bearing surface and ground waters derived from the Mount Belknap Volcanics sources during Sevier River sedimentation undoubtedly were significantly different from those now in existence. Much more data than are now available will be required to locate possible sites of uranium concentration within the basin fills deposited during these complexly changing structural and sedimentary environments.

Beaver basin (Locality K2) is a late Cenozoic structural basin filled by a complex sequence of stream and lake sediments (Machette, 1982). Downfaulting and sedimentation began in the late Miocene sometime before 9 Ma when the rhyolite of Gillies Hill was erupted at the north end of the basin (Evans and Steven, 1982), and alunite formed in local solfataras at two places along the eastern boundary fault of the basin (Steven and others, 1979; Cunningham, Steven, and others, 1984). Subsequently the basin has subsided repeatedly, and has been the site of repeated deposition of fluviatile and lacustrine sediments (Machette, 1982). The basin was drained for at least part of late Miocene time, but at other times it was closed and periodically contained lakes of varying size. The present outlet via Minersville Canyon was established in Pleistocene time. Uranium-bearing source rocks were exposed in the Tushar Mountains to the east (Mount Belknap Volcanics), in low hills to the north (rhyolite of Gillies Hill), and in the Mineral Mountains to the west (Mineral Mountains composite batholith) (Miller and others, 1979) all during subsidence and alluviation of the Beaver basin, and should have supplied uranium to the water that pervaded the complex alluvial and lacustrine fill of the basin. Highly anomalous concentrations of radon and helium have been detected at places in the basin (Steven and others, 1981; Reimer, 1979; McHugh and Miller, 1982), and geochemical samples of well waters (Miller and others, 1980; Miller, Wanty, and McHugh, 1984) strongly suggest the presence of uranium concentrations nearby. Preliminary drilling programs were conducted by several companies in the early 1980's, but none of the results has been made public. The potential is considered high for the occurrence of resources of uranium within the alluvial fill of Beaver basin. [Resource potential--High]

Possible environments favorable for uranium deposition may also exist in basins adjacent to accumulations of Blawn Formation and Steamboat Mountain Formation in the southwestern part of the Richfield quadrangle. Miller and McHugh (1981a) and Miller, Wanty, and McHugh (1984), using well water samples, have identified areas possibly proximal to uranium deposition in the Escalante Desert of Milford (Localities K3). Other areas in the Escalante Desert or in the southern Hamblin, Pine, and Wah Wah Valleys may also be favorable, although presently available data are much to sketchy to locate them. [Resource potential--High near localities K3; Unknown elsewhere]

UNCLASSIFIED MINERAL DEPOSITS

Mineralized areas that cannot now be classified confidently with respect to geologic association are scattered widely throughout the Richfield quadrangle (specific locations are prefixed L on pls. 1 and 2). These range from deposits that have produced small quantities of ore, to prospects and local mineral occurrences, and to scattered areas containing anomalous concentrations of different elements as detected during geochemical surveys connected with the present investigation.

The Gordon district in the southwestern Pavant Range (Locality L1) contains the Blue Bell mine, which produced slightly more than 500 tonnes of ore between 1925 and 1957. This ore averaged 0.35 g/tonne Ag, 0.1 percent Pb, and 10.3 percent Zn, contained in small pod-shaped ore bodies consisting of smithsonite, hemimorphite, and minor cerussite and anglesite in a gangue of ocher, iron-stained calcite, sanded dolomite, and minor barite. These bodies replace walls of Devonian Sevy and Simonson Dolomites along a low-angle fault in the plate above the Red Ridge thrust fault. Stream-sediment samples show weakly anomalous metal values over an area 10 km across including the Blue Bell mine (Miller and others, 1980; unpub. data). The mineralized rock at the Blue Bell mine is remote from known centers of igneous activity, and its geologic association is not known. [Resource potential--Unknown]

The Fullmer clay pit (Locality L2) along Mill Creek in the northern Tushar Mountains exploits a body of kaolinite formed by intense argillic alteration of the Joe Lott Tuff Member of the Mount Belknap Volcanics (Callaghan, 1973, p. 119-120). Alteration was localized along an east-trending nearly vertical fault of unknown age. The clay produced from this pit was shipped to Salt Lake City, Utah, where it was used to manufacture fire bricks. It is not known whether the isolated hydrothermal activity responsible for forming the kaolinite at the Fullmer pit took place late in the period of Mount Belknap magmatism, or during a younger and unrelated period. Projected kaolinite resources are limited to the area developed by the existing pits where the valuable clay remaining is restricted to the shallow depth to which intense argillic alteration extended. Lacking knowledge on the geologic association of the altered area, it is difficult to judge the potential at depth for contrasting types of mineral resources. [Resource potential--Unknown]

The Jarloose district (Locality L3) in the northern Black Mountains 2.5-7 km southeast of Minersville, Utah, has a few minor prospect pits and small mine workings scattered over an area of about 10 km^2 (Erickson and Dasch, 1968). Patchily argillized rocks occur in the northwestern part of the district. The prospects and altered rocks seem to be localized around an intrusive andesite plug that may mark the core of a local volcano in the Mount Dutton Formation. Some spotty occurrences of gold in minor quartz-calcite veins were detected in connection with this investigation (P. D. Rowley, unpub. data), but no other evidence for significant related mineralization was recognized. [Resource potential--Low]

Another extensive area 8 km long east-west and as much as 2 km across in the northwestern part of the Black Mountains (Locality L4) is characterized by irregularly bleached and altered rocks (Erickson and Dasch, 1963; Rowley, 1978). The more intensely argillized rocks were converted in part to alunite and kaolinite, and some rocks have been thoroughly silicified. Hematite, limonite, and pyrite are the only metallic minerals reported from the altered areas. The geochemical survey connected with this investigation found only anomalous barium in the area of altered rocks. [Resource potential--Low]

The laccolithic intrusive center near Spry in the southeasternmost part of the Richfield quadrangle (Anderson and Rowley, 1975) (Locality L5) contains minor patches of altered and mineralized rock. Doelling (1975) describes many widespread small veins containing manganese oxides, but none is large enough or rich enough to have supported production. Altered rocks along a northeast-trending fault near the northwest margin of the intrusions contains visible cinnabar, but none of the samples taken by Doelling contained more than a percent of mercury. One sample contained 2 oz per ton of silver. Fluorite was reported from a few mine dumps near the Spry intrusions. None of the widespread mineral occurrences described by Doelling (1975) suggested proximity to larger or more high-grade deposits, and the chance that such exist is not considered good. [Resource potential--Low]

A few minor prospects are scattered throughout the Cricket Mountains (no locality shown on pls. 1 and 2) (Doelling and Tooker, 1983); most occur along minor fissure zones or in limestone or dolomite beds adjacent to shale units. The mineralized rock generally consists of iron-stained calcite and dolomite with scattered concentrations of partly oxidized galena. The largest prospects are at the Galena mine and Rock Hammer mine, but neither has produced more than a few tonnes of ore. The virtual absence of intrusive rocks or hydrothermally altered zones associated with the mineralized occurrences suggests only a poor likelihood that significant undiscovered resources exist in the Cricket Mountains. [Resource potential--Low]

The stream-sediment geochemical survey made as part of this investigation (Miller and others, 1980; unpub. data) disclosed widely scattered anomalous concentrations of many metallic elements throughout the bedrock areas in the northwest part of the Richfield quadrangle (no locality shown). The anomalies seem associated with limonitic fracture coatings, particularly within cherty layers in carbonate strata. The different anomalous elements (As, Th, Zn, Bi, W, Cu) are not coextensive. Field checking showed that many of the anomalous samples were taken short distances downstream from brecciated (but not strongly altered) strata along late Cenozoic faults. Many of these fault zones were sampled, but none showed metal concentrations comparable with those in the associated anomalous stream-sediment samples. At the present time, we do not know the sources of the anomalous values obtained from stream-sediment samples in this broad area, and thus are unable to assess their significance with respect to mineral resource potential [Resource potential--Unknown]

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