Geology and Uranium Deposits of the Cochetopa and Marshall Pass Districts, Saguache and Gunnison Counties, Colorado

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Geology and Uranium Deposits of the Cochetopa and Marshall Pass Districts, Saguache and Gunnison Counties, Colorado

By JERRY C. OLSON

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A study of regional geologic history of two districts in which uranium deposits are related to fault zones, early Tertiary erosion surfaces, and volcanic rocks

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Metric unit		Inch-pound equivalent
millimeter (mm)	=	0.04 inch (in.)
centimeter (cm)	=	0.39 inch (in.)
meter (m)	=	3.28 feet (ft)
kilometer (km)	=	0.62 mile (mi)
kilometer^2 (km^2)	=	0.39 mile^2 (mi^2)
metric ton	=	1.10 short ton
metric ton	=	2205.07 pounds (lb)

GEOLOGY AND URANIUM DEPOSITS OF THE COCHETOPA AND MARSHALL PASS DISTRICTS, SAGUACHE AND GUNNISON COUNTIES, COLORADO

By JERRY C. OLSON

ABSTRACT

The Cochetopa and Marshall Pass uranium districts are in Saguache and Gunnison Counties, south-central Colorado. Geologic mapping of both districts has shown that their structural history and geologic relationships have a bearing on the distribution and origin of their uranium deposits. In both districts, the principal uranium deposits are situated at the intersection of major faults with Tertiary erosion surfaces. These surfaces were buried by early Tertiary siliceous tuffs—a likely source of the uranium. That uranium deposits are related to such unconformities in various parts of the world has been suggested by many other authors. The purpose of this study is to understand the geology of the two districts and to define a genetic model for uranium deposits that may be useful in the discovery and evaluation of uranium deposits in these and other similar geologic settings.

The Cochetopa and Marshall Pass uranium districts produced nearly 1,200 metric tons of uranium oxide from 1956 to 1963. Several workings at the Los Ochos mine in the Cochetopa district, and the Pitch mine in the Marshall Pass district, accounted for about 97 percent of this production, but numerous other occurrences of uranium are known in the two districts. As a result of exploration of the Pitch deposit in the 1970's, a large open-pit mining operation began in 1978.

Proterozoic rocks in both districts comprise metavolcanic, metasedimentary, and igneous units. Granitic rocks, predominantly quartz monzonitic in composition, occupy large areas. In the northwestern part of the Cochetopa district, metavolcanic and related metasedimentary rocks are of low grade (lower amphibolite facies). In the Marshall Pass district, layered metamorphic rocks are predominantly metasedimentary and are of higher (sillimanite subfacies) grade than the Cochetopa rocks.

Paleozoic sedimentary rocks in the Marshall Pass district range from Late Cambrian to Pennsylvanian in age and are 700 m thick. The Paleozoic rocks include, from oldest to youngest, the Sawatch Quartzite, Manitou Dolomite, Harding Quartzite, Fremont Dolomite, Parting Formation and Dyer Dolomite of the Chaffee Group, Leadville Dolomite, and Belden Formation. In the Cochetopa district, Paleozoic rocks are absent.

Mesozoic sedimentary rocks overlie the Precambrian rocks in the Cochetopa district and comprise the Junction Creek Sandstone, Morrison Formation, Dakota Sandstone, and Mancos Shale. In the Marshall Pass district, Mesozoic rocks are absent and were presumably removed by pre-Tertiary erosion.

Tertiary volcanic rocks were deposited on an irregular surface of unconformity; they blanketed both districts but have been eroded away from much of the area. They include silicic ash flows as well as andesitic lava flows and breccias. In the Marshall Pass district, a 20- to 200-m thickness of waterlaid tuff of early Tertiary age indicates the former presence of a lake over much of the district.

In the Cochetopa district, faults have a predominantly east-west trend, and the major Los Ochos fault shows displacement during Laramide time. In the Marshall Pass district, the Chester fault is a major north-trending reverse fault along which Proterozoic rocks have been thrust westward over Paleozoic and Proterozoic rocks. Displacement on the Chester fault was almost entirely of Laramide age.

Both faults and old erosion surfaces or unconformities are important in the origin of uranium deposits because of their influence on the movement and localization of ore-forming solutions. In the Cochetopa district, all the known uranium occurrences crop out within 100 m of the inferred position of the unconformity surface beneath the Tertiary volcanic rocks. Much of the district was part of the drainage of an ancestral Cochetopa Creek. The principal uranium deposit, at the Los Ochos mine, is localized along the Los Ochos fault and is near the bottom of the paleovalley where the paleovalley crosses the fault. This suggests that both the fault and the erosion surface in the paleovalley were factors in localizing the uranium deposits.

In the Marshall Pass district, the principal uranium deposits are probably at only a shallow depth beneath the prevolcanics erosion surface as restored. The principal uranium deposits, such as those at the Pitch mine, are in veins in several Paleozoic and Precambrian rock units and are localized chiefly along the Chester fault. Low-grade mineral occurrences are common in a 1- to 2-m-thick zone near the top of the Harding Quartzite. The principal controls for the location of uranium deposits in the Marshall Pass district are the permeable channelways that uranium-bearing solutions followed, either along fault zones or, in the case of the Harding Quartzite deposits, a permeable layer in the sandstone.

Siliceous ash-flow tuff (in both districts) and waterlaid tuff of Oligocene(?) age (in the Marshall Pass district) overlie the uranium deposits and are the most likely sources from which uranium was leached to form the deposits. The ore of both districts is characterized by a simple chemical composition, containing only small amounts of copper and other metals. The simple composition and near-surface formation of the uranium deposits are evidence that supergene processes were involved in depositing the uranium.

The genetic model suggested for uranium deposits in these two districts may be applied to further exploration for uranium here and elsewhere. Areas would be considered favorable where silicic volcanics, especially tuffs, overlie, or formerly covered, older rocks that are cut by prominent fault zones. Permeable zones such as brecciated fault zones or porous sedimentary beds, which may have channeled uraniferous waters, are favorable potential sites for deposition of uranium carried in solutions moving downward or laterally.

INTRODUCTION

The Cochetopa and Marshall Pass uranium districts are in Saguache and Gunnison Counties, south-central Colorado (fig. 1). Both districts have been mapped and studied to determine structural history and geologic relationships bearing on the distribution and origin of their uranium deposits. One of the purposes of this study is to develop a genetic model for uranium deposits in the Cochetopa and Marshall Pass districts that may aid in the discovery and evaluation of uranium deposits in this and other similar geologic settings.

The field work for this report consists of the geologic mapping of five 7½-minute quadrangles in the Cochetopa district in 1966–1974 (Olson 1976a, b; Olson and Steven 1976a, b; and Olson and others, 1975) and of one and one-quarter 7½-minute quadrangles in the Marshall Pass district in 1975–1978 (Olson, 1979, 1983). Contributing to the regional geologic knowledge was the earlier mapping, by the author and D. C. Hedlund, of six 7½-minute quadrangles that extend westward from the Cochetopa district and encompass the Powderhorn district (Olson and Hedlund, 1973; Hedlund and Olson, 1973, 1974, 1975; Olson, 1974; and Hedlund, 1974). Discussions with J. T. Nash of the Pitch mine (Nash, 1981) and with J. Mersch Ward and other geologists of the Homestake Mining Company have added to the author's understanding of the Pitch mine.

In this report, my primary system of measurement is the metric system. However, the inch-pound system is used when other sources are cited that originally reported measurements in the inch-pound system. Altitudes that are shown in feet on a topographic map are given in feet only. A conversion table follows the table of contents.

PREVIOUS WORK

Discovery and early development of uranium deposits in the Cochetopa district were described by Thornburg (1955). Malan and Ranspot (1959) studied the Cochetopa district and have discussed the mineralogy, structure, and other features of the uranium deposits in some detail.

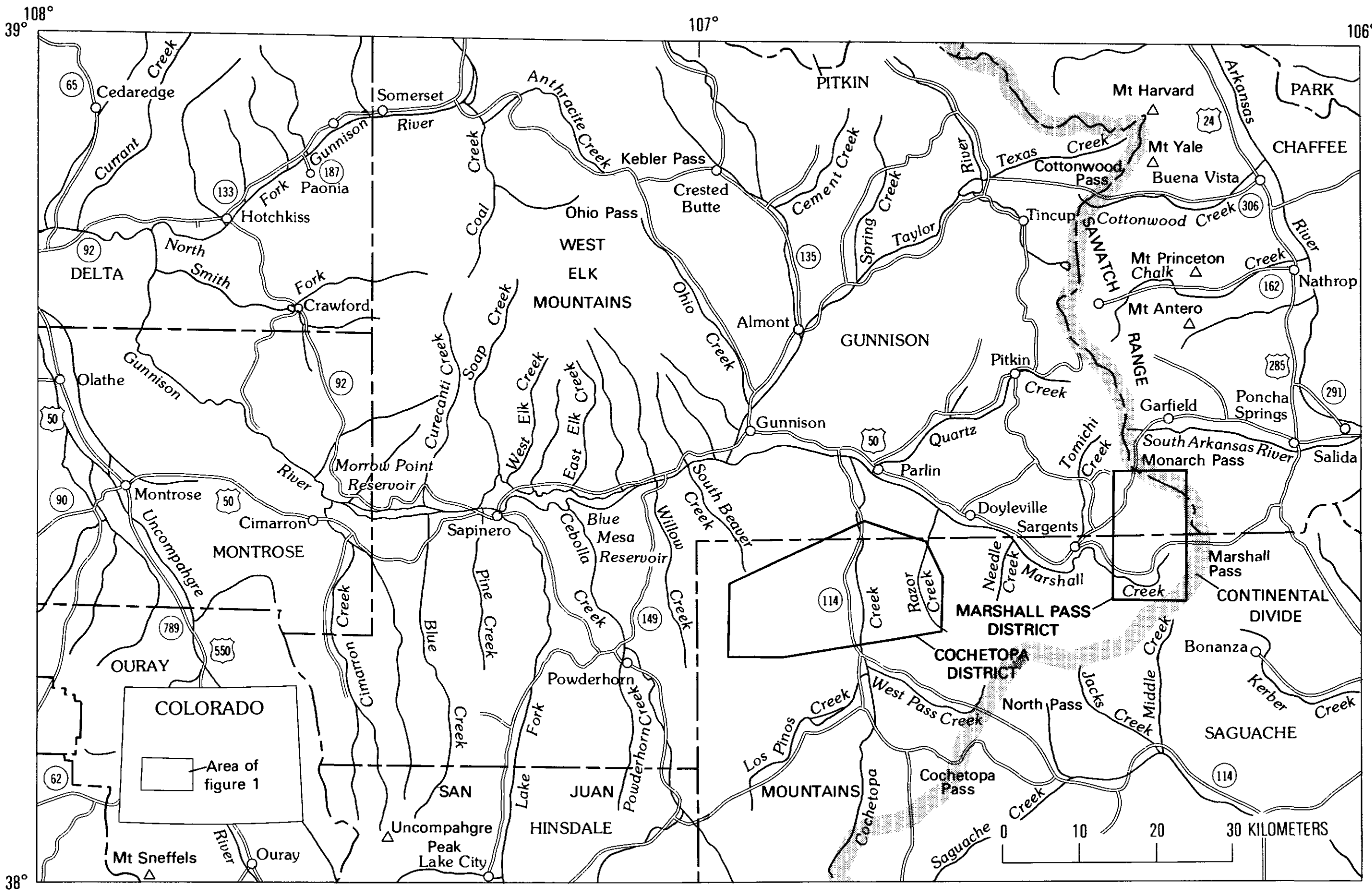


FIGURE 1.—Location of Cochetopa and Marshall Pass districts, Saguache and Gunnison Counties, western Colorado.

TABLE 1.—*Uranium production of the Cochetopa and Marshall Pass districts, 1956-1963, by mine*

[Data from Nelson-Moore and others (1978), p. 175, 389-394]

Mine	Ore: Short tons	Ore: Grade (percent)	Uranium oxide (pounds)
Cochetopa district			
Los Ochos (T-1, East)	448,685	0.14	1,253,513
Los Ochos (T-2)	37,565	.13	97,618
LaRue	7	.20	28
Total	486,257		1,351,159
Average grade		0.14	
Marshall Pass district			
Pitch (Pinnacle)	104,520	0.58	1,206,112
Little Indian No. 36	8,152	.44	71,762
Lookout No. 22	514	1.31	13,500
Lookout Nos. 24 and 33	63	.28	371
Marshall Pass No. 5	18	1.00	380
Bonita	163	.15	472
Total	113,430		1,292,597
Average grade		0.57	
Both districts			
Total	599,687		2,643,756
Average grade		0.22	

R. P. Fischer and N. L. Archbold studied the Los Ochos mine in 1958, when the underground workings were accessible. Notes, samples, and observations made by them have provided considerable information in the preparation of this report, although the responsibility for any conclusions therefrom rests with the present author.

Several studies of the Marshall Pass district in the 1950's provide general geologic information and mining data (Malan, 1959; Ranspot and Spengler, 1957; Ranspot, 1958; Baker and Scott, 1961; Baker, 1960; Dunn, 1957). Mineralogic studies were made by Gross (1965). Additional information bearing on the geology of this district was presented in the 1970's by Raines (1971) and Evans (1973); mining and exploratory activities were described by Marrs (1970) and Ward (1978).

URANIUM PRODUCTION

In the late 1950's and early 1960's, the Cochetopa and Marshall Pass districts yielded over 599,000 short tons of ore containing over 2,600,000 pounds of 0.22-percent uranium oxide according to Nelson-Moore and others (1978, p. 389-394). During the four peak years 1958-1961, the production of the two districts ranged from 212 to 266 short tons of uranium oxide per year, valued at $1,387,000 to nearly $2,000,000 per year (U.S. Bureau of Mines, 1956-1963). About 97 percent of the production (table 1) was from the Los Ochos and Pitch mines. The Los Ochos mine as used in this report comprises the main (T-1 or Thornburg), West drift, East (Kathy Jo), and T-2 mine workings (locations shown on fig. 3).

Exploration during the 1970's has shown reserves of 2.1 million short tons of ore containing 7.14 million lb of 0.17-percent uranium oxide at the Pitch mine, according to J. M. Ward (1978), of Homestake Mining Company. Open-pit mining of this ore was begun in 1978.

REGIONAL GEOLOGY

The generalized geology of the region including the Cochetopa and Marshall Pass districts is shown on figure 2. The oldest rocks in the region are interlayered, generally conformable metasedimentary and metavolcanic rocks of Early Proterozoic age, between 1.7 and 1.8 b.y. Proterozoic rocks are not differentiated on figure 2, but the principal groups are discussed in the following paragraphs and their distributions are shown on the numerous geologic quadrangle maps of the region.

In the Proterozoic rocks of the eastern half of the map area of figure 2, the metasedimentary rocks predominate; they are intruded by extensive batholithic granite and the grade of metamorphism reaches the sillimanite subfacies.

In the central and western parts of the map area of figure 2, the Proterozoic rocks include abundant bimodal volcanic and volcaniclastic rocks as well as metasedimentary rocks and granitic to quartz dioritic intrusive bodies. The grade of metamorphism is as low as greenschist facies locally in the central part of the map area, but increases westward through a widespread amphibolite facies, and reaches the sillimanite subfacies in the northwest corner of the map area. Where the grade of metamorphism is low, original textural and structural features such as pillows, amygdules, and graded bedding may be preserved and may aid in resolving the depositional origin and original stratigraphic succession of the rocks.

The Proterozoic layered rocks can be divided into four groups, from oldest to youngest:

The lowest, oldest group of rocks are metasedimentary and consist chiefly of siltstone, fine-grained sandstone, and graywacke that are metamorphosed to argillite, slate, phyllite, fine-grained schist, or to higher grade metamorphic rocks. In the Iris NW 7½-minute quadrangle, this group of rocks is as much as 2,000 m thick (Hedlund and Olson, 1974, cross section B-B′), although the total thickness is not known because its lower contact is obscured by a younger intrusive body.

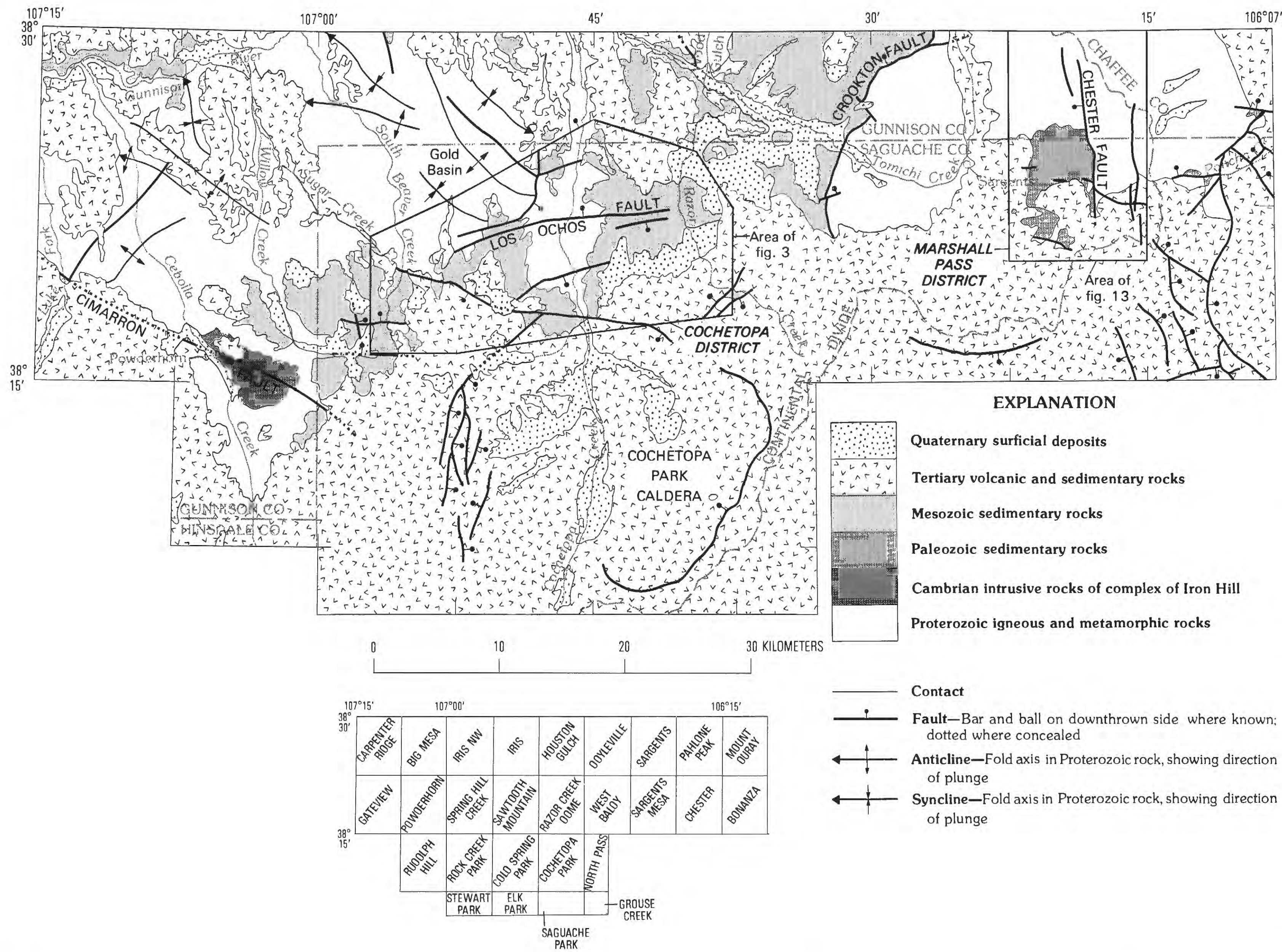


FIGURE 2.—Generalized geology of region including the Cochetopa and Marshall Pass districts, Colorado. (Geology modified from Tweto and others, 1976.)

The second group of rocks are predominantly rhyolitic to dacitic felsite and quartz porphyry, although basaltic flows and metasedimentary rocks are interlayered, particularly below the thickest mass of felsite. The felsitic volcanics and volcaniclastics are thickest, more than 1 km, in three areas: (1) in a tight southeastward-plunging syncline in the central part of the map area of the Iris 7½-minute quadrangle, (2) on the flanks of an anticlinal fold in the southwestern part of the map area of the Iris NW 7½-minute quadrangle, and (3) in the west-central part of the map area of the Powderhorn 7½-minute quadrangle (fig. 2). These three thick masses probably represent one or more centers of domical accumulation aligned in an east-northeast direction. Outward from these three areas, thinner layers of felsic rocks from 1 m to several hundred meters thick are intricately interlayered with metasedimentary rocks, basaltic flows, and pyroclastics.

The third group of rocks consist chiefly of tholeiitic flows and volcanic breccia (greenstone), ranging from chlorite-actinolite schist to hornblende schist and amphibolite. These rocks predominate in a belt as much as 5 km wide in the Gateview 7½-minute quadrangle, where they were named the Dubois Greenstone (Hunter, 1925, p. 28–36). Eastward, the greenstone belt is 2.3 km wide in the Powderhorn and Spring Hill Creek 7½-minute quadrangles (fig. 2) and reaches a thickness of 2 km at Cochetopa Creek (Olson, 1976a, cross section C–C′). This thickest mass of greenstone lies stratigraphically above the main body of felsitic volcanics described above, although thin basalt flows and breccias of similar tholeiitic composition are interlayered with other parts of the Proterozoic stratigraphic section. Purplish-gray quartzite (metachert) layers occur in many places between flows. The chert layers and the presence of pillow structures in the basalt flows indicate deposition of the basalt flows beneath the sea.

The fourth group of rocks, which overlie the tholeiitic basalt sequence, consist predominantly of metasedimentary rocks. These are generally fine grained and quartzose, most commonly a quartz-biotite schist, although feldspathic varieties occur locally in the lower part overlying thick volcanic rocks. In the northwestern corner of the map area of figure 2, these predominantly metasedimentary rocks are known as the Black Canyon Schist; there they exceed 3,000 m in thickness, are probably much thicker, and occur in a large northwest-plunging synclinorium.

The Proterozoic metavolcanic and intercalated metasedimentary rocks contain sulfide mineral deposits that have been mined in the "Gunnison gold belt," which extends from the Lake Fork of the Gunnison River eastward across the center of the map area of figure 2 as far as Cochetopa Creek, practically coextensive with the Dubois Greenstone and felsitic volcanic rocks. Pyrite is the most abundant sulfide, making up as much as 25 percent of quartz-sericite schist locally; galena, sphalerite, and chalcopyrite are present in places in amounts generally less than 0.5 percent. These volcanogenic mineral deposits occur both as concordant layers along bedding and as filling of discordant fractures.

Precambrian intrusive rocks ranging in composition from quartz diorite to granite occupy large areas of the exposed Precambrian basement in the map area of figure 2. The Precambrian intrusives can be divided into three principal types characterizing three east-northeast-trending belts. The first intrusive rock type, occurring in a belt along the southern and eastern margins of the map area, consists of extensive batholithic granite or quartz monzonite bodies, including the Powderhorn Granite, the quartz monzonite of Cochetopa Creek, the granite of Woods Gulch, and the gneissic quartz monzonites in the Sargents area, with only small areas of metamorphic rocks. The second intrusive rock type, occurring in a central east-northeast-trending belt dominated by metasedimentary and metavolcanic rocks, contains granitic to quartz dioritic intrusive bodies that generally conform to the foliation of enclosing rocks and are mostly interpreted to be syntectonic in origin. The third intrusive rock type, occurring mostly in a belt along the northwestern margin of the map area, consists mainly of small, irregular, discordant stocks and dikes of biotite granite and leucogranite in areas that are mainly migmatite and quartz-biotite schist.

Alkalic igneous rocks, massive niobium-bearing carbonatite, and associated veins containing thorium and rare earths were emplaced in Cambrian or Late Proterozoic time in the Powderhorn area at the west end of the map area of figure 2.

Paleozoic sedimentary strata ranging in age from Cambrian to Pennsylvanian are present in the eastern part of the map area of figure 2, including the Marshall Pass district. In this area, Sawatch Quartzite of Late Cambrian age or Manitou Dolomite of Early Ordovician age overlie Proterozoic rocks, and are in turn overlain, from oldest to youngest, by the Harding Quartzite of Middle Ordovician age, the Fremont Dolomite of Late Ordovician age, the Parting Formation and Dyer Dolomite of the Chaffee Group of Late Devonian and Early Mississippian(?) age, the Leadville Dolomite of Early Mississippian age, and the Belden Formation of Early to Middle Pennsylvanian age. The Paleozoic strata have a combined thickness of 700 m. In the central and western parts of the map area, however, Paleozoic strata are absent and probably were not deposited because at that time this area, part of the

Paleozoic Uncompahgre highland, was a positive area of non-deposition or erosion.

Mesozoic sedimentary rocks are absent from the eastern part of the map area of figure 2; however, they overlie the Proterozoic rocks in the western and central parts of the map area. The Proterozoic rocks are commonly overlain by the Junction Creek Sandstone of Middle Jurassic age, which is in turn overlain, from oldest to youngest, by the Morrison Formation of Late Jurassic age and the Burro Canyon(?) Formation, Dakota Sandstone, and Mancos Shale of Cretaceous age. The Mesozoic strata have a combined thickness of 500–700 m in the area studied.

Throughout the map area of figure 2, Oligocene volcanic rocks cover large areas, occurring as many scattered remnants of once widespread formations. The volcanics comprise about 300–450 m of silicic ash flows as well as andesitic lava flows and breccias 800 m or more in thickness.

The predominant trends of major faults in the region are northward or in a west-northwest direction. Faulting occurred in Precambrian time and was less active in early Paleozoic time, but important fault movements in late Paleozoic time can be demonstrated in the areas of Paleozoic rocks in the eastern part of the map area of figure 2. Considerable fault movement occurred in Late Cretaceous to early Tertiary time, and Tertiary faults that cut Oligocene volcanics are also evident.

In the pre-Oligocene fault pattern, at least three major persistent faults, with displacements of more than a hundred meters, dip steeply, strike about N. 30°–65° W., and are upthrown on the northeast side. These include the Cimarron fault near Powderhorn, a fault along Sugar Creek that may extend from the Gunnison River to Cochetopa Creek, and the Powerline Spring fault extending from the lower part of Razor Creek Valley, in the northeastern part of the map area of the Houston Gulch 7½-minute quadrangle, northwestward to Quartz Creek valley 2 km north of the Houston Gulch quadrangle. In the eastern part of the map area of figure 2, two major faults trend northward, the Crookton and Chester faults. Both are reverse faults that dip steeply eastward. Precambrian rocks on the hanging walls of the faults are thrust over Mesozoic rocks on the Crookton fault and over Paleozoic rocks on the Chester fault. Near the center of the map area, the Los Ochos fault zone strikes a little north of east and is nearly vertical.

COCHETOPA DISTRICT

The generalized geology of the Cochetopa district is shown on figure 3, and the various rock formations are described in the following section. Important elements in the geologic history of the district, such as faults, Tertiary paleotopography, and paleodrainage are also described, particularly the geologic features bearing on the source and localization of the uranium deposits.

GEOLOGIC SETTING

The Proterozoic rocks are metasedimentary and metavolcanic gneiss and schist, intruded by igneous rocks ranging from granodiorite to quartz monzonite and granite in composition. No Paleozoic sedimentary rocks are found in the Cochetopa district, and the Mesozoic rocks were deposited unconformably on the Precambrian. The sequential geologic history of the Mesozoic and Cenozoic Eras may be summarized as follows: development of a smooth, planar erosion surface in Jurassic time; deposition, on this surface, of the Junction Creek Sandstone and Morrison Formation of Jurassic age, followed by deposition of the Burro Canyon(?) Formation, Dakota Sandstone, and Mancos Shale of Cretaceous age; Laramide tilting and faulting; erosion to form a terrain of moderate relief; and deposition, on this surface, of lava flows and volcanic breccia of intermediate composition and subsequent deposition of silicic ash-flow tuff, all of Oligocene age. The Oligocene volcanics covered virtually the entire district, but they were removed from much of the area by subsequent erosion and canyon cutting by Cochetopa Creek (a superimposed stream), its tributaries, and other nearby creeks.

PROTEROZOIC ROCKS

Proterozoic metamorphic rocks occur in the northwest half of the Cochetopa district (fig. 3). The stratigraphic sequence includes felsic and basaltic metavolcanic rocks as much as 2 km thick, which are overlain and underlain by metasedimentary rocks. None of these rock types are differentiated on figure 3, but they have been mapped in detail by Olson (1976a, b), Olson and Steven (1976a, b), and Olson and others (1975). The original volcanic rocks were deposited in large part under water; this is indicated by pillow structures in flows and by local quartzite (metachert) beds as much as 45 m thick. In part the metavolcanic rocks are felsitic, consisting of flows and pyroclastic rocks such as ash-flow tuff and breccia of rhyolitic to rhyodacitic composition. They also include tuffaceous sediments and abundant intermediate to mafic flows, pillow lavas, and pyroclastic rocks. The metavolcanic rocks are generally correlative with the Dubois Greenstone (Olson and Hedlund, 1973) in the Powderhorn district to the west.

The metavolcanic rocks are underlain by predominantly metasedimentary rocks at least 2 km thick, consisting of metamorphosed graywacke, siltstone, fine-grained sandstone, and rare conglomeratic beds, with interlayered basaltic to andesitic sills and flows. Metasedimentary rocks also overlie the metavolcanic rocks and are at least several kilometers thick. They consist chiefly of fine-grained rocks such as siltstone, mudstone, or fine-grained sandstone that have been metamorphosed to argillite, slate, quartz-biotite schist, and locally quartzofeldspathic schist. Less common are layers of amphibolite and hornblende schist that are predominantly of igneous origin but may be in part of sedimentary origin.

The metavolcanic and metasedimentary rocks are intruded by Proterozoic igneous rocks. These intrusive rocks include a hornblende-biotite granodiorite, the quartz diorite to quartz monzonite of Gold Basin, the quartz monzonite of Cochetopa Creek and associated pegmatites, and a small stock of biotite syenite.

The hornblende-biotite granodiorite is gray, medium grained, and commonly foliated, and forms a body 1 km wide and at least 4.5 km long, in an east-west direction, that crosses Cochetopa Creek.

The quartz diorite to quartz monzonite of Gold Basin is a light-pinkish-gray, medium-grained rock that occurs in a syntectonic stock 11 km long and 3.5 km wide. The composition of the rock varies but typically is about 65 percent sodic oligoclase, 2–5 percent microcline, 27 percent quartz, 7 percent biotite, and minor muscovite, epidote, hornblende, garnet, chlorite, apatite, and iron oxides. This rock forms a stock in the core of an anticlinal fold in the older metasedimentary rocks in the Iris and Iris NW 7½-minute quadrangles.

The quartz monzonite of Cochetopa Creek is a pink to salmon, medium- to coarse-grained, weakly gneissic rock that occupies an exposed area of 6×8 km in the southern part of the district. Associated with this rock type are locally sheared and foliated pegmatite dikes commonly 10–20 m thick, composed chiefly of coarse pink feldspar and white quartz.

The biotite syenite is a gray gneissic rock composed of alkali feldspar and fine-grained biotite aggregates, with minor quartz, apatite, epidote, and opaque minerals. It is present in only one small body 500 m long just west of Bead Creek.

MESOZOIC ROCKS

Mesozoic rocks in the Cochetopa district lie unconformably on Proterozoic rocks. They include the Junction Creek Sandstone of Middle Jurassic age, the Morrison Formation of Late Jurassic age, and these Cretaceous units: the Burro Canyon(?) Formation and Dakota Sandstone (undivided) and the Mancos Shale. The Junction Creek Sandstone and the overlying Morrison Formation are shown as one unit (Jmj) on figure 3, and the Cretaceous rocks are also shown as an undifferentiated unit (Kmdb). Throughout most of the region, these strata have a nearly flat to gentle northeast dip. Steep dips are rare and are generally found only near a major fault zone.

The Junction Creek Sandstone in the Cochetopa district is a fine- to medium-grained, locally crossbedded, white to light-yellowish-gray eolian quartzose sandstone ranging in thickness from near 0 to 90 m. The sandstone is silica cemented and quartzitic in some areas.

The Junction Creek is at the base of the Jurassic section in the Gunnison region and was considered part of the Morrison Formation by some early workers (for example, Larsen and Cross, 1956, p. 51–52). The use of the Junction Creek Sandstone nomenclature and the relation of this unit to the Morrison Formation and Entrada Sandstone are well shown on the geologic map of the Black Canyon region (Hansen, 1971), and are also discussed by Hansen (1965, p. 47–50). According to these reports, the Entrada Sandstone was not deposited east of approximately the eastern boundary of the Black Canyon of the Gunnison National Monument. The sandstone unit shown as Junction Creek on Hansen's map extends from the east edge of the map area of the Sapinero 7½-minute quadrangle onto the Carpenter Ridge 7½-minute quadrangle (Hedlund and Olson, 1973), from which it has been traced eastward through the intervening quadrangles as far as the Razor Creek Dome 7½-minute quadrangle (Olson and Steven, 1976b).

The Morrison Formation consists of variegated reddish-brown to greenish-gray mudstone, siltstone, and a few thin beds of sandstone and limestone as much as 1 m thick. In the Iris 7½-minute quadrangle, the formation has a maximum thickness of 140 m, but elsewhere in the Cochetopa district it is commonly about 80–90 m thick. The Morrison is generally conformable with the underlying Junction Creek Sandstone, but is overlain unconformably by the Burro Canyon(?) Formation and Dakota Sandstone.

The Dakota Sandstone of Late Cretaceous age ranges from 30 to 100 m in thickness. It consists of light-gray to light-brown, moderately to well cemented to quartzitic, medium- to coarse-grained, commonly crossbedded quartzose sandstone, containing sporadic gray chert pebbles. Thin coaly carbonaceous beds are locally present. Several thin siltstone and platy sandstone layers occur in the upper part. The lower part of the unit, which contains sporadic lenses of chert-pebble conglomerate, may be in part correlative with the Burro Canyon Formation.

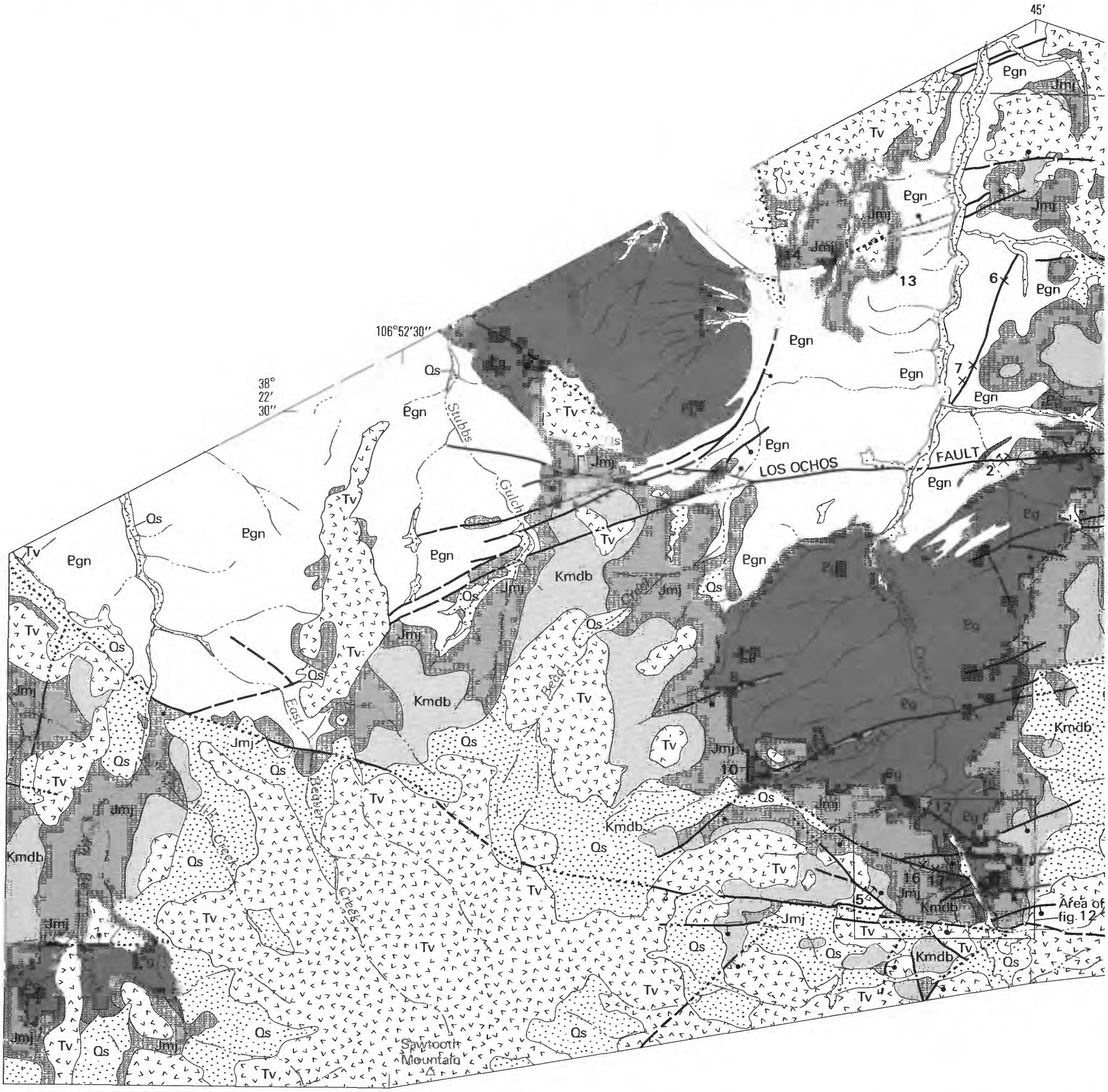
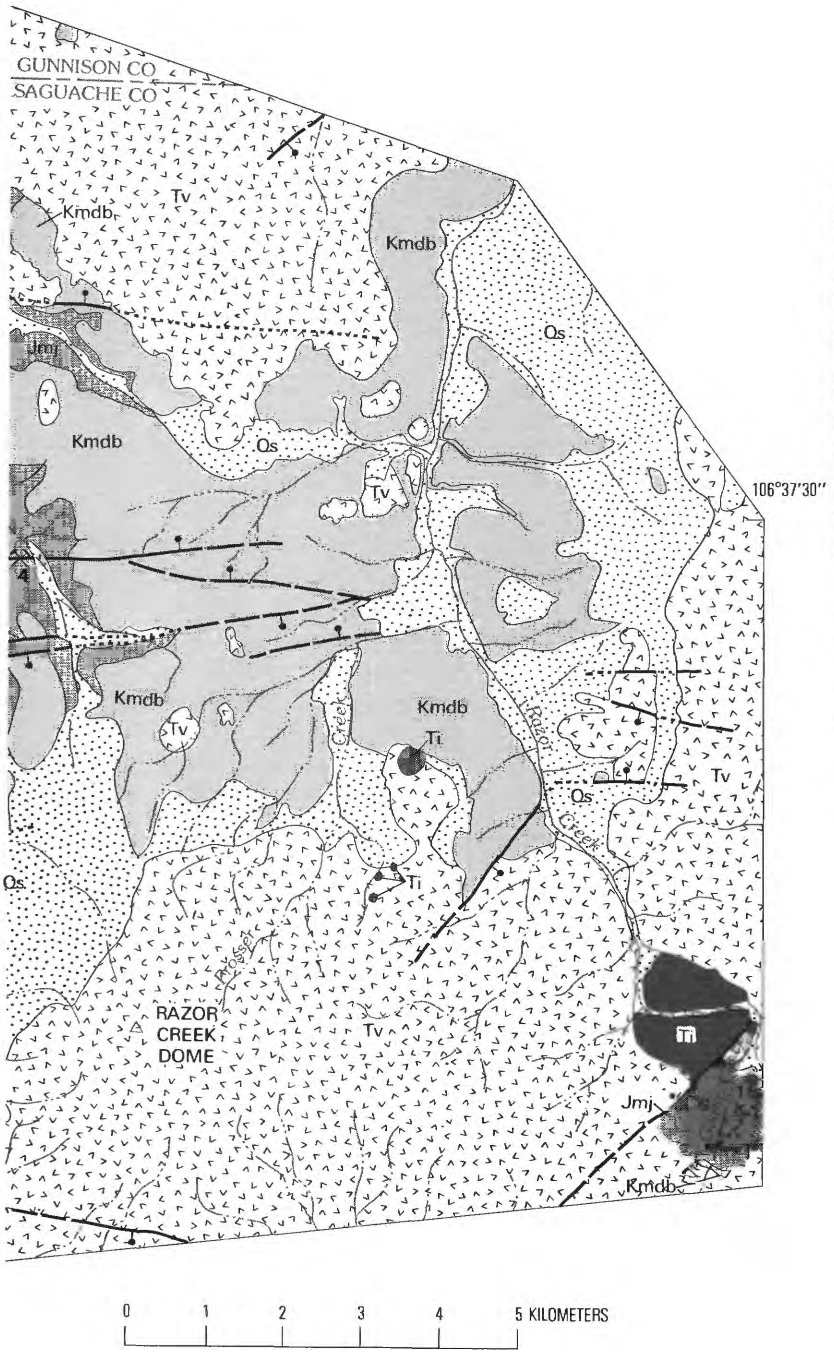


FIGURE 3 (above and facing page).—Generalized geology of the Cochetopa district, Saguache and Gunnison Counties, Colorado. (Geology generalized from Olson, 1976a, b; Olson and Steven, 1976a, b; Olson and others, 1975.)



EXPLANATION

Qs	Surficial deposits	Holocene and Pleistocene	QUATERNARY
Ti	Intrusive rhyolite and quartz latite porphyry	Oligocene	TERTIARY
Tv	Volcanic rocks	Oligocene	TERTIARY
Kmdb	Mancos Shale, Dakota Sandstone, and Burro Canyon(?) Formation	Upper and Lower Cretaceous	CRETACEOUS AND JURASSIC
Jmj	Morrison Formation and Junction Creek Sandstone	Upper and Middle Jurassic	CRETACEOUS AND JURASSIC
Pɢ	Granodiorite, granite, and quartz monzonite		PROTEROZOIC
Pgn	Gneiss and schist		PROTEROZOIC

Contact

Fault—Bar and ball on downthrown side where known; dashed where inferred; dotted where concealed

Vertical fault

Mine

Prospect

Mines and prospects

1. Los Ochos (T-1, Thornburg)
2. Los Ochos (West drift)
3. Los Ochos (East, Kathy Jo)
4. Los Ochos (T-2)
5. LaRue
6. Belle Lode
7. Do Dah
8,9. Milbob
10. Name unknown
11. Moultry and Hicks
12. M. and W.
13. Post
14. Name unknown
15. Anna (Lucky Friday)
16. Mercury
17. Elisha (Bet)

The Dakota Sandstone is overlain conformably by the Late Cretaceous Mancos Shale, a sequence of soft, drab dark-gray-brown silty shale with scattered lenses of friable gray sandstone and sparse calcareous concretions. The maximum exposed thickness of an incomplete section is about 400 m, but the upper part has been removed by erosion. The Mancos Shale is characterized by slumping and hummocky landslide topography.

TERTIARY VOLCANIC ROCKS

The Tertiary volcanic rocks have been divided into two main groups: (1) intermediate-composition lava flows, volcanic breccias, and related gravel deposits, which were deposited prior to the deposition of (2) an assemblage consisting predominantly of silicic welded to nonwelded ash-flow tuffs (Olson and others, 1968).

The Tertiary volcanic stratigraphy is illustrated in table 2, which shows the correlation of Tertiary volcanic rocks in the five 7½-minute quadrangles in which the Cochetopa district lies. The rocks are described more fully on the geologic quadrangle maps of the Iris (Olson, 1976a), Houston Gulch (Olson, 1976b), Razor Creek Dome (Olson and Steven, 1976b), Sawtooth Mountain (Olson and Steven, 1976a), and Spring Hill Creek (Olson and others, 1975) 7½-minute quadrangles.

The intermediate-composition lava flows consist of aphanitic to finely porphyritic rhyodacite and quartz latite, and the intermediate-composition volcanic breccias consist of grayish-brown to red tuff breccia and flow breccia. These flows and breccias are at least 700 m thick on Sawtooth Mountain and Razor Creek Dome, which were probably the local volcanic centers from which the flows and breccias spread over most of the district. At the base of the flows and breccias, light-colored, intermediate-composition, unconsolidated to moderately welded tuff occurs locally and is as thick as 5–10 m in the Houston Gulch quadrangle and 60 m in the Razor Creek Dome quadrangle. The flows and breccias are considered generally equivalent to the Conejos, Lake Fork, and San Juan Formations and other intermediate-composition rocks of Oligocene age. These flows and breccias have been dated at 34.7–31.1 m.y. (Steven and Lipman, 1976, p. 4) elsewhere in the San Juan Mountains volcanic field.

Gravel deposits accumulated to thicknesses of as much as 90 m above the intermediate-composition lava flows and volcanic breccias. The gravels are composed mostly of subrounded cobbles and boulders of Tertiary volcanic rocks—chiefly brown quartz latite or rhyodacite—and lesser amounts of granite and other Precambrian rocks, Mesozoic quartzitic sandstone, and rarely of welded tuff older than the Fish Canyon Tuff. The proportion of pre-Tertiary rocks in the gravels increases northward, away from the source of the volcanic components. The gravels covered an extensive pediment-like surface of low relief. Thinner gravel deposits are also found locally between units in other parts of the Tertiary volcanics section.

The intermediate-composition lava flows, volcanic breccias, and related gravels are overlain by an assemblage of predominantly silicic welded to nonwelded ash-flow tuffs, some units of which have been correlated with ash flows to the west (Olson and others, 1968) and to the south in the San Juan Mountains (Steven and Lipman, 1976). The oldest of the tuffs would be between 27.8 and 28.4 m.y. old if correlated with the Blue Mesa Tuff, which lies mainly west and south of the district; its age would exceed 27.8 m.y. if correlated with the Bonanza Tuff, which is distributed around the Bonanza caldera about 50 km east of the district. The other units are between 28.4 m.y. and 26.4 m.y. in age, the youngest being the Cochetopa Park Tuff.

The oldest of the welded tuffs appears to be older than the Sapinero Mesa Tuff and occurs in a small area in the Houston Gulch 7½-minute quadrangle. This tuff is crystal poor, containing 3–10 percent phenocrysts, mostly of clear sanidine and plagioclase, and minor biotite. The 60-m-thick, densely welded part of the tuff is underlain by about 60 m of nonwelded tuff containing pumice blocks and lapilli, and a thin zone of similar nonwelded tuff overlies the densely welded tuff. The age and appearance of the oldest tuff suggest a possible correlation with the Blue Mesa Tuff or, more likely, the Bonanza Tuff whose source lies about 50 km to the east.

The densely welded Sapinero Mesa Tuff extends into the district from its source to the southwest and occurs in several erosional remnants about 25–100 m or more thick. The Sapinero Mesa Tuff contains 5–12 percent phenocrysts and is generally characterized by a red color and a local, thick, black vitrophyre near its base.

The Fish Canyon Tuff, the most voluminous ash-flow sheet in the San Juan Mountains, occurs in the Cochetopa district in thicknesses of about 75–130 m. It is a crystal-rich tuff that is unconsolidated to densely welded and has a platy structure in some places.

In the Iris and Houston Gulch 7½-minute quadrangles, nonwelded and welded tuffs younger than the Fish Canyon Tuff have been called the tuff of Cochetopa Creek. The lower part, about 60–90 m thick, is predominantly soft, white, nonwelded to lightly welded, and locally zeolitic. The upper part, about 60–100 m thick, is moderately to densely welded and has a vitrophyre as much as 5 m thick at its base. Possible correlations of the lower part with the Rat Creek Tuff and of the upper part with the Nelson Mountain Tuff have been

TABLE 2.—*Correlation of Tertiary volcanic rocks in the Cochetopa district*

[Blank box indicates stratigraphic unit is not present. See figure 2 for locations of the five 7½-minute quadrangles]

<table>
<tr><th></th><th></th><th></th><th>Iris quadrangle</th><th>Houston Gulch quadrangle</th><th>Spring Hill Creek quadrangle</th><th>Sawtooth Mountain quadrangle</th><th>Razor Creek Dome quadrangle</th></tr>
<tr><td rowspan="11">OLIGOCENE</td><td rowspan="6">28.4–26.4 m.y</td><td rowspan="7">Predominantly silicic, welded to nonwelded ash-flow tuffs</td><td></td><td></td><td></td><td>Cochetopa Park Tuff (upper member), caldera-fill sediments, base not exposed</td><td>Cochetopa Park Tuff (upper member), caldera-fill sediments, at least 200 m thick, base not exposed</td></tr>
<tr><td>Tuff of Cochetopa Creek, welded, 100 m thick</td><td>Tuff of Cochetopa Creek, welded, 60 m thick</td><td rowspan="2">Cochetopa Park and Nelson Mountain Tuffs, 60+ m thick</td><td rowspan="2">Cochetopa Park (lower member) and Nelson Mountain Tuffs, about 100 m thick; includes 60-m-thick, nonwelded basal tuff</td><td rowspan="2">Cochetopa Park (lower member) and Nelson Mountain Tuffs, in erosional remnants</td></tr>
<tr><td>Tuff of Cochetopa Creek, nonwelded to lightly welded, 60 m thick</td><td>Tuff of Cochetopa Creek, nonwelded to lightly welded, 90 m thick</td></tr>
<tr><td rowspan="2">Fish Canyon Tuff, welded (except at top and bottom), 115 m thick</td><td>Fish Canyon Tuff, welded, 100 m thick</td><td rowspan="2">Fish Canyon Tuff, welded, 75 m thick</td><td rowspan="2"></td><td rowspan="2">Fish Canyon Tuff, welded, 40+ m thick</td></tr>
<tr><td>Fish Canyon Tuff, nonwelded, 30 m thick</td></tr>
<tr><td>Tuff of pre-Fish Canyon age, 55 m thick; probably correlative with Sapinero Mesa Tuff or Bonanza Tuff</td><td>Sapinero Mesa Tuff(?), 25 m thick</td><td>Sapinero Mesa Tuff, 100 m or more thick</td><td>Sapinero Mesa Tuff, 80 m thick</td><td rowspan="2"></td></tr>
<tr><td>28.4–27.8 m.y.</td><td></td><td>Tuff of pre-Sapinero Mesa age, from top to bottom: nonwelded, thin; welded, 60 m thick; nonwelded, 60 m thick</td><td></td><td></td></tr>
<tr><td rowspan="4">34.7–31.1 m.y.</td><td rowspan="4">Intermediate-composition lava flows, volcanic breccias, and related gravels</td><td>Gravels, 90 m thick</td><td>Gravels, 60 m thick</td><td></td><td>Gravels, 15 m thick</td><td>Gravels, 15 m thick</td></tr>
<tr><td rowspan="3">Intermediate-composition lava flows and volcanic breccias, 75 m thick</td><td>Intermediate-composition lava flows, 150 m thick</td><td rowspan="3">Intermediate-composition lava flows and volcanic breccias, 500 m thick</td><td rowspan="3">Intermediate-composition lava flows and volcanic breccias, 700 m thick</td><td>Intermediate-composition lava flows and volcanic breccias, 700 m thick</td></tr>
<tr><td>Intermediate-composition volcanic breccias, 200 m thick</td><td rowspan="2">Intermediate-composition moderately welded to nonwelded tuff, 60 m thick</td></tr>
<tr><td>Intermediate-composition unconsolidated tuff, 5–10 m thick</td></tr>
</table>

suggested (Olson, 1976a, b) because of lithologic similarity and stratigraphic position. Steven and Lipman (1976, p. 25), however, considered that the Rat Creek and Nelson Mountain Tuffs did not extend this far northeast of their source calderas, and that in the Iris and Houston Gulch 7½-minute quadrangles these tuffs (derived from the Cochetopa Park caldera) constitute a separate unit younger than the Rat Creek and Nelson Mountain Tuffs. The tuff of Cochetopa Creek is therefore correlated with the Cochetopa Park Tuff in this report.

The Cochetopa Park Tuff was at first named the Cochetopa Park Member of the Nelson Mountain Tuff (Steven and others, 1974), but it was elevated to formation status and the correlation with the Nelson Mountain Tuff was withdrawn by Steven and Lipman (1976, p. 25). The Cochetopa Park Tuff was divided into an upper member and a lower member in mapping of the Sawtooth Mountain and Razor Creek Dome 7½-minute quadrangles (Olson and Steven, 1976a, b). The lower member was found to be at least partly correlative with the upper or welded part of the tuff of Cochetopa Creek, which is about 40–50 m thick, and to have had a probable source in the Cochetopa Park caldera. The upper member of the Cochetopa Park Tuff consists of sandy and silty stream sediments and beds of airfall and ash-flow tuff that were deposited within the Cochetopa Park caldera. The upper member is more than 200 m thick, but the base is not well exposed.

FAULTS

Structural movements in the Cochetopa district since the deposition of Upper Jurassic sediments have been chiefly near-vertical adjustments along steeply dipping faults, as evidenced by the steep dips found locally on Mesozoic beds near faults. Generally, throughout the district, numerous faults cut pre-Tertiary rocks, but few cut Tertiary rocks, and many faults have a predominantly east-west trend. The Los Ochos fault, for example, cuts all the Mesozoic and Precambrian rocks within the district. In addition to the main Los Ochos fault, two or more subparallel faults occur within 50 m of the main fault to the north. Within this zone, the Mesozoic rocks are closely jointed and broken by many fractures that commonly strike northeast to east. At the Los Ochos mine, the faults do not appear to displace the Tertiary intermediate-composition lava flows and breccias; however, some renewed Tertiary movement is suggested by the fact that sandstone beds in the Junction Creek and Dakota Sandstones, which were silicified probably in Tertiary time, are brecciated in and near the faults.

A series of east-west-trending faults in the south-central part of the map area of figure 3 are downthrown to the south, in step-like fashion. These faults adjoin the northern margin of the Cochetopa Park caldera, which extends southward from the southernmost fault and is about 20 km in diameter, and they appear to have formed in conjunction with subsidence of the caldera.

PALEOTOPOGRAPHY AND PALEODRAINAGE

The generalized topography and drainage in Oligocene time for an area including the Cochetopa district have been approximated, by contouring the inferred base of the Oligocene volcanics, in order to bring out features of the structural history and possible relations of this surface to uranium deposits. Figure 4 shows 200-ft contours drawn on the base of the Oligocene volcanic rocks over a region of 1,500 km^2 south of lat 38°30′ N., from Doyleville on the east to the Powderhorn district on the west. The contours indicate that the relief of the area in pre-Oligocene time was probably a little less rugged than that of today. It was considerably more rugged, however, than that on which the Jurassic sediments were deposited; the latter was a smooth peneplain. The contours delineate a composite erosion surface that was not completely exposed at any one time over the entire area because the volcanic units that overlie the surface in different places are not all of the same age. Thus, parts of the surface were covered while other parts were still being eroded. Age determinations made elsewhere in the San Juan region on volcanic rocks correlative with those overlying the composite erosion surface indicate an age range of 34 to 26 m.y. for the time of burial of the surface.

Drainage seems to have been generally northwestward prior to the deposition of the Oligocene volcanics. This drainage trend probably extended for a considerable distance northwestward of the map area of figure 4, as the volcanic pile of the West Elk Mountains did not yet exist. There was probably also a major valley along the Cimarron fault in the vicinity of the 8,000-ft contour shown northwest of Powderhorn (fig. 4).

Figure 5 shows 100-ft contours drawn on the base of the Oligocene volcanics for only the Cochetopa district (Olson, 1976a, b; Olson and others, 1975; and Olson and Steven, 1976a, b). Contours indicate the valley of an ancestral Cochetopa Creek and its tributary drainage pattern. Fault movements of Laramide age, such as those of the Los Ochos fault, predated and did not displace the erosion surface, but toward the south the buried erosion surface was disrupted by many post-volcanics faults and the paleodrainage features were obscured by the Cochetopa Park caldera.

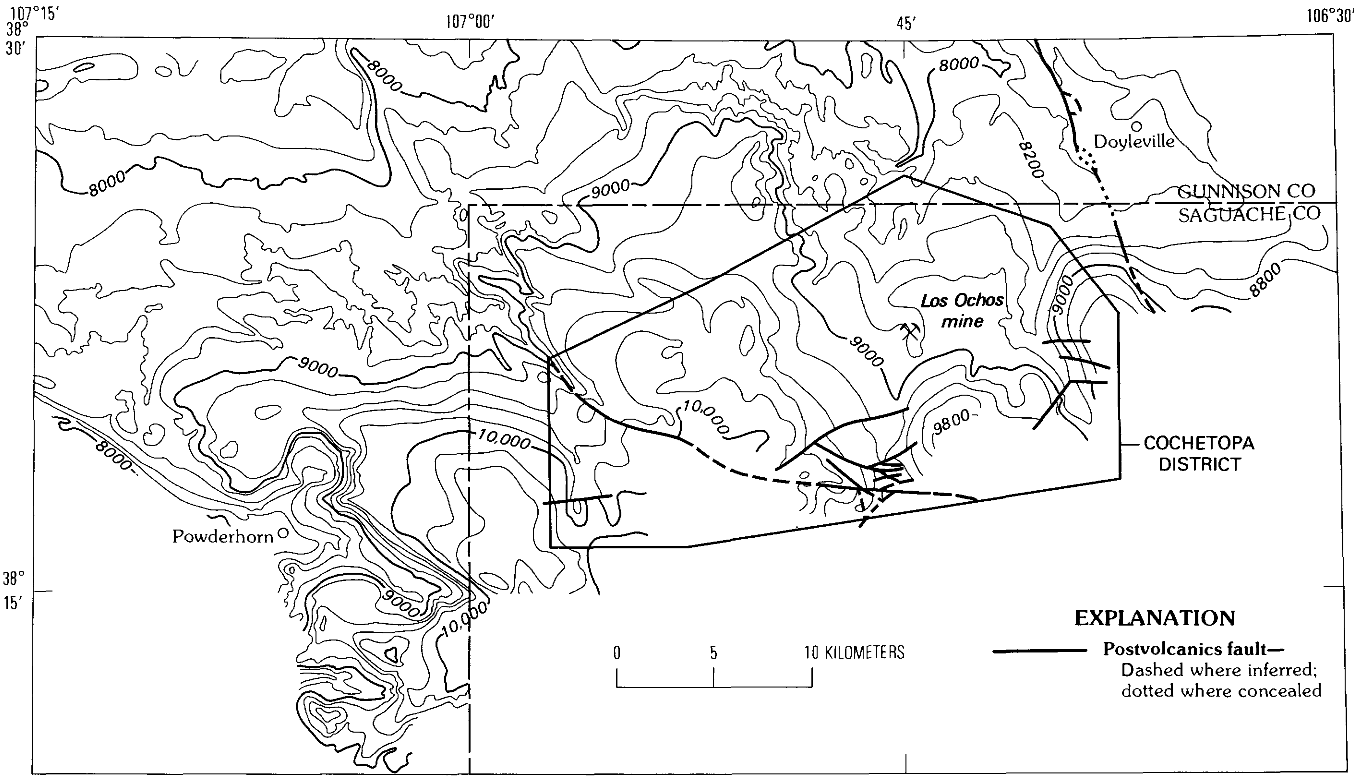


FIGURE 4.—Paleotopographic contours on base of Oligocene volcanic rocks in parts of Gunnison and Saguache Counties, Colorado. Contour interval, 200 ft.

Two geologic sections (figs. 6 and 7) illustrate paleotopographic and paleodrainage features as well as bedrock geology. Figure 6 is a longitudinal section that shows the ancestral Cochetopa valley floor (restored) and geologic features along its course, projected to a north-south plane. The section also shows the projected profile of the bottom of modern Cochetopa Creek (fig. 8), which is incised about 150 m below the ancestral valley and about 2 km west of it. The ancestral Cochetopa valley floor has largely been eroded away, as is shown by the present topography along the north-south section.

In figure 7, the nearly vertical Los Ochos fault is taken as the plane of the section, which shows the geology of the north wall of the fault. The unconformity at the base of the Mesozoic rocks dips at a low angle northeastward, and the restored surface at the base of the Oligocene has an even lower angle of slope northeastward in this area. Figure 7 also shows the restored profile of the ancestral valley of Cochetopa Creek, as well as the modern canyon (fig. 8).

URANIUM AND OTHER MINERAL DEPOSITS

Uranium, thorium, and mercury deposits have been found in the Cochetopa district and their locations are shown on figure 3. These deposits characteristically are along faults, and faults have been the main guide to exploration in the Cochetopa district where mineral deposits are not exposed. All the uranium occurrences shown on the map (fig. 3) crop out within 100 m vertically of the prevolcanics erosion surface as restored. The occurrences are mostly in the Mesozoic and Precambrian rocks below the erosion surface, but in several places the tuff above it is mineralized. Most of these deposits have been prospected, but little uranium has been produced except at the Los Ochos mine. In the following two sections, the uranium deposits are mostly discussed first, followed by the thorium deposits and the one known mercury deposit.

LOS OCHOS MINE

The Los Ochos mine is 2.2 km east of Cochetopa Creek in Saguache County and 6.25 km south of the Gunnison County line (fig. 3). The uranium deposit was discovered at the surface, from its radioactivity and secondary uranium minerals, by one of a group of eight prospectors (Los Ochos) in 1954 (Thornburg, 1955, p. 56). The claims were leased by Vance and Garth Thornburg, who later, with others, formed the Gunnison

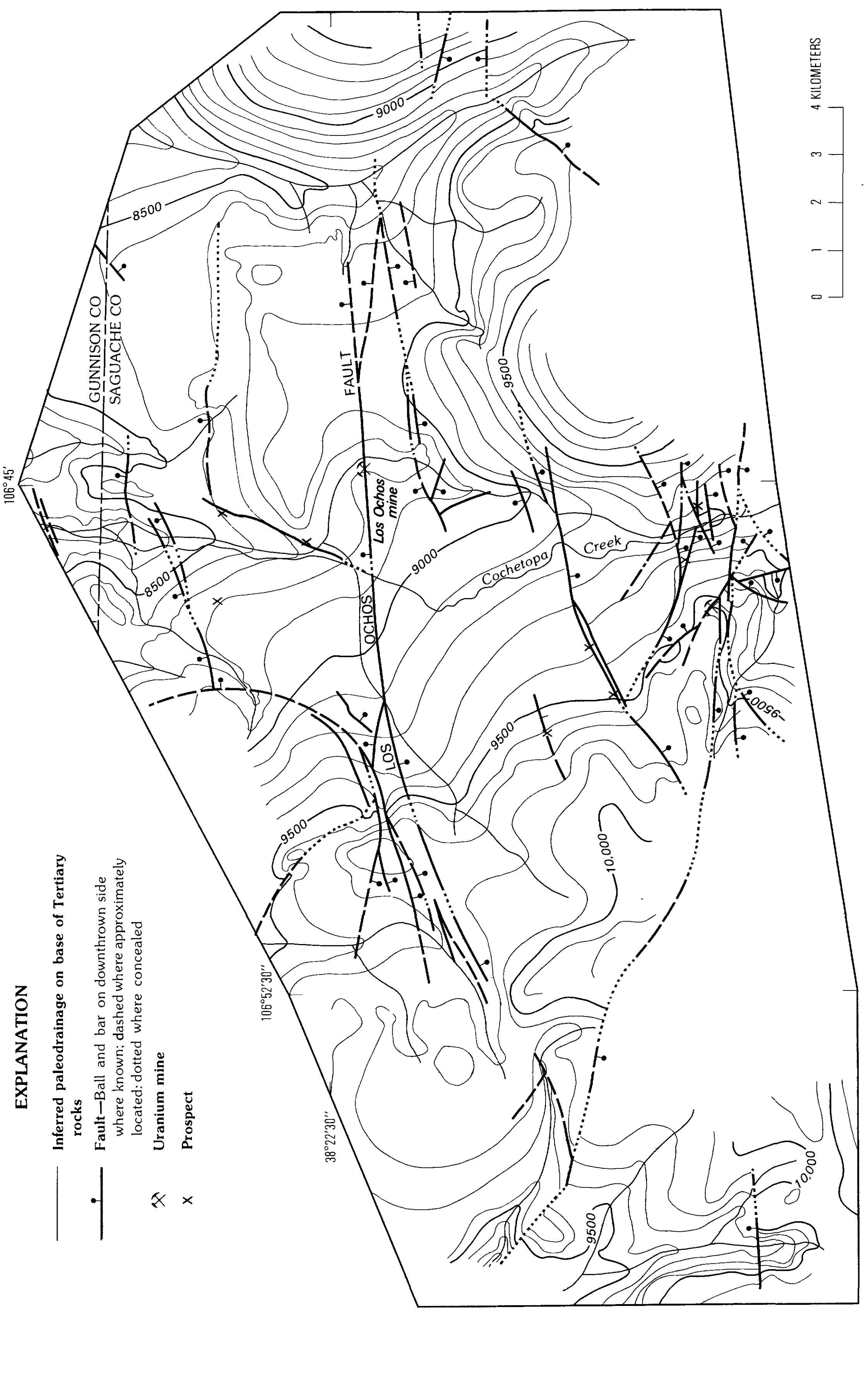


FIGURE 5.—Paleotopographic contours and inferred paleodrainage on base of Oligocene volcanic rocks in the Cochetopa district, Saguache and Gunnison Counties, Colorado. Contour interval, 100 ft.

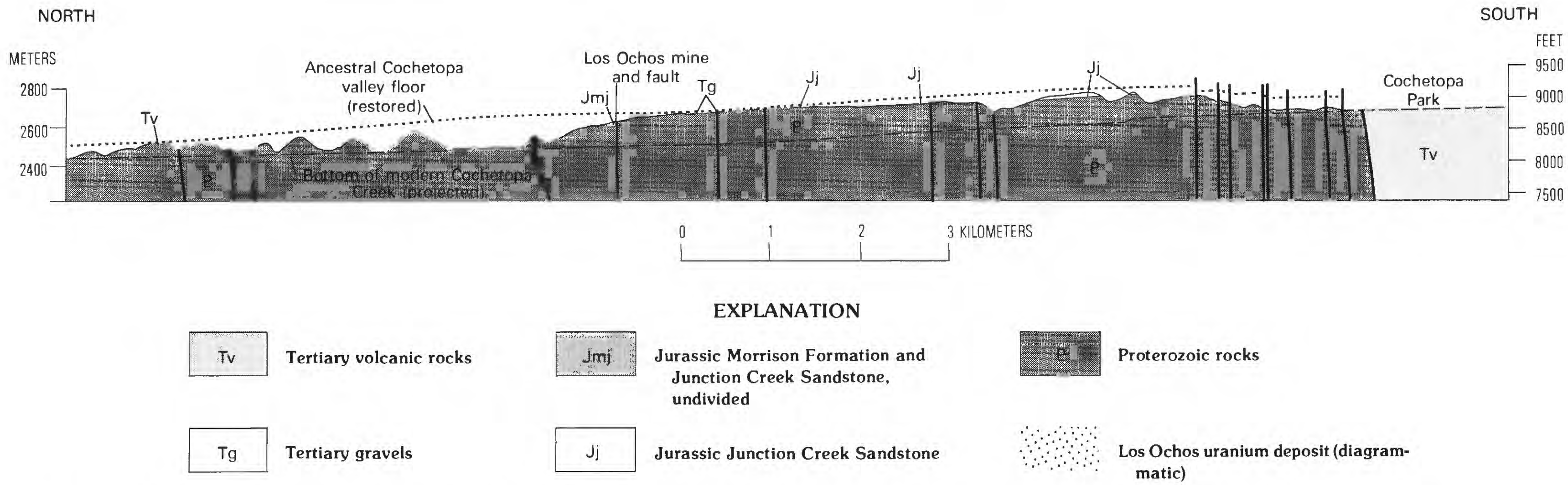


FIGURE 6.—North-south section along bottom of ancestral Cochetopa valley, showing projection of modern Cochetopa Creek. Vertical exaggeration x2.

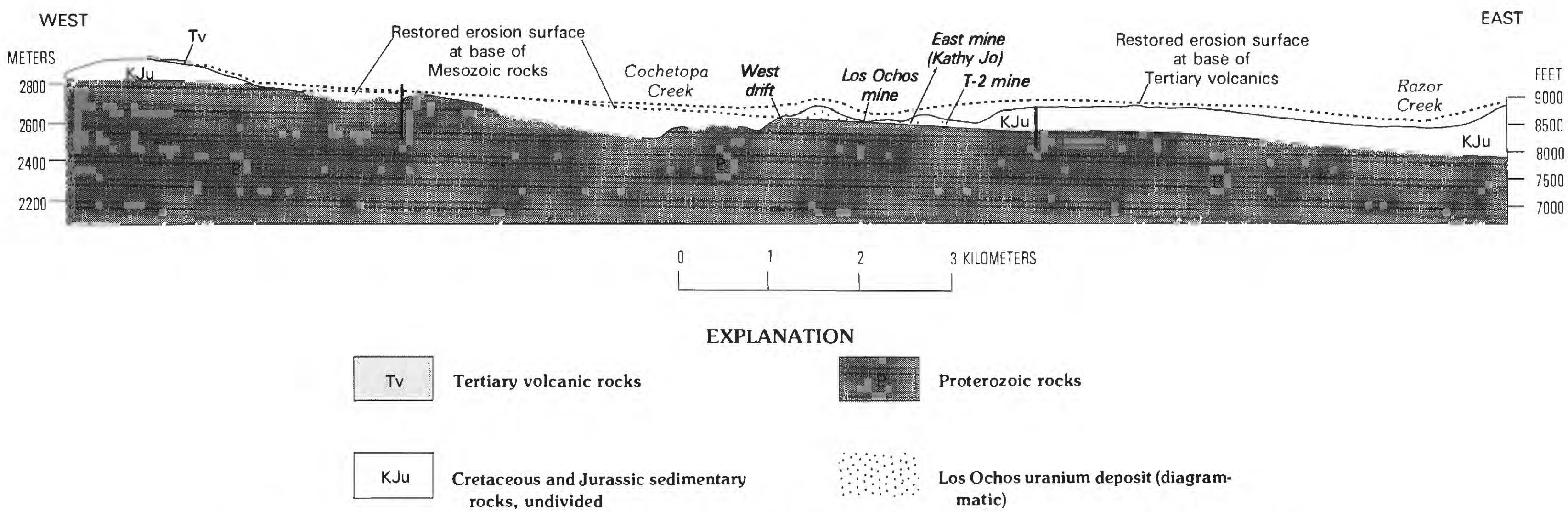


FIGURE 7.—West-east section along Los Ochos fault, showing geology of north wall of fault. Vertical exaggeration x2.

FIGURE 8.—View to south of 180-m-deep canyon of Cochetopa Creek, just south of Los Ochos mine. Rim of canyon is just below approximate position of prevolcanics erosion surface, which sloped gently to east. Cochetopa Dome, in Cochetopa Park, rises in background.

Mining Company, which produced uranium from October 1954 to 1962 (table 1). A concentrator with nominal capacity of 200 short tons per day was constructed and operated in Gunnison. The mine shut down in 1962, the mill shortly after, and no production has been reported since that time. A small amount of exploration drilling has been done by Homestake Wyoming Partners (later Homestake Mining Company), who acquired an interest in the property in 1974. The Los Ochos mine, as termed in this report, comprises the main (also known as the T-1 or Thornburg mine), West drift, East (also known as the Kathy Jo of the Gunnison Mining Company), and T-2 mine workings (locations (nos. 1-4, respectively) shown on fig. 3).

The uranium-mineralized area extends over a length of 1,800 m along the Los Ochos fault. The main drifts and stopes in the mineralized rocks are at an altitude of 8,600-8,820 ft beneath the east side of a small hill that rises to 8,930 ft. Here, the main workings consist of two inclines (one 410 ft long), a main haulageway 1,200 ft long, and interconnecting drifts and stopes (fig. 9) that extend westward from the adit on the east side of the hill. The Los Ochos fault also was explored on the west side of the hill, where the West drift yielded a small amount of uranium. East of the main workings, the East and T-2 mine workings were developed. The East mine is an incline reported to be 190 ft long in 1955, from which there is 265 ft of drifting, a 22 ft raise, and a 20 ft winze. Its workings are reported to extend a total length of 900 ft and width of 50-250 ft on the north side of the Los Ochos fault (Nelson-Moore and others, 1978); the average depth to ore was 70 ft. The T-2 mine, which is the easternmost part of the Los Ochos mine, consists of an incline and stopes. Uranium was produced (table 1) from the T-2 workings from 1959 to 1962. In all, a total of more than 2,500 ft of drifting and 6,200 ft of core drilling is reported to have been done in the Los Ochos mine workings prior to 1971 (Nelson-Moore and others, 1978).

The main workings and the West drift provide good exposures of the Los Ochos fault (figs. 10 and 11). The fault strikes from N. 72° E. to nearly east-west and is nearly vertical. The south wall of the fault is composed of Precambrian rock, namely the quartz monzonite of Cochetopa Creek, which has inclusions or pendants of schist. On the north wall, which has been downthrown about 35-50 m, a sequence of Mesozoic rocks comprising the Junction Creek Sandstone, Morrison Formation, and Dakota Sandstone unconformably overlies Precambrian rock.

The Los Ochos orebodies mined in the main workings and in the three other workings previously described resemble irregular pipes and are in brecciated, silicified sandstone and mudstone of the Junction Creek and Morrison Formations, except for one that is reported to have extended into altered Precambrian schist (Malan and Ranspot, 1959, p. 19). The richest uranium concentrations have been found in and near the fault, where permeability is greatest. They tend to occur where the rocks are highly fractured, mostly in mudstone and sandstone, within 60 m of the fault contact with the Precambrian footwall. Weakly mineralized rock occurs as much as 150 m from the fault, apparently in favorable permeable beds in the sediments. The boundaries of the ore deposits, therefore, are locally sharp against Precambrian rock but may be irregularly gradational in the sedimentary rocks.

Five orebodies in the main workings are reported by Malan and Ranspot (1959, p. 7), who described the largest of these, referred to as Nos. 1 and 2. A typical orebody is reported to be about 40×40 ft in plan and 200 ft in vertical dimension. The first ore shoot explored (No. 1) was nearly vertical, over 80 ft long, and 10-20 ft wide (Thornburg, 1955, p. 56), raking about 80° E. Orebody No. 2 is about 380 ft west of No. 1, in the Morrison Formation and Junction Creek Sandstone adjoining the fault zone on the north side. Orebody No. 2 is reported to have been about 130×40 ft and to have extended from the main haulage level up about 90 ft in a raise. The East mine was in a small orebody, in brecciated Junction Creek Sandstone just north of the fault,

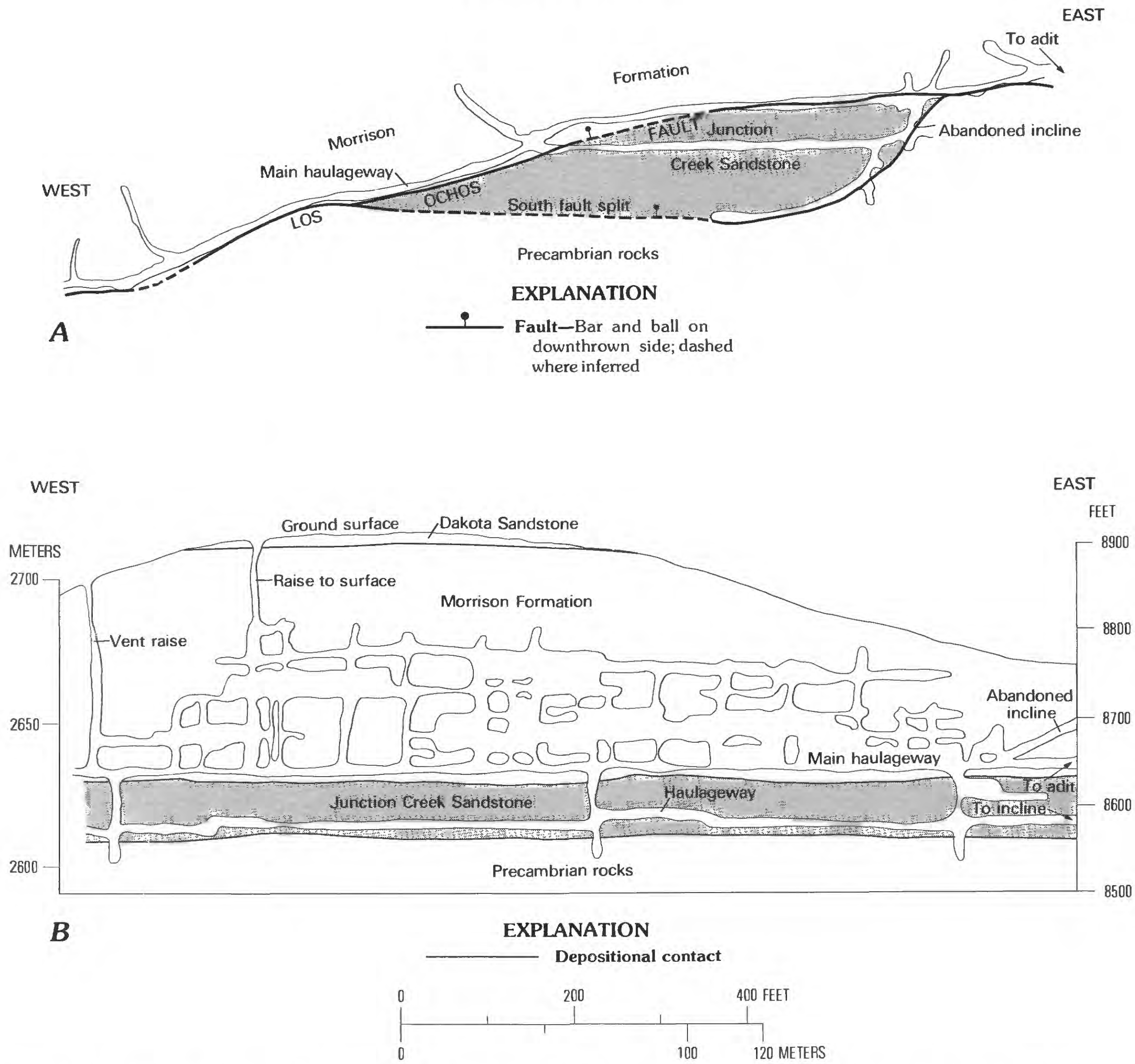


FIGURE 9.—Main Los Ochos mine. *A*, Plan of main level, and *B*, Longitudinal projection along plane of Los Ochos fault. Datum is approximate. (Modified from U.S. Atomic Energy Commission, 1959.)

of generally similar shape to that of orebodies in the main workings.

The uranium ore at the Los Ochos mine contains only a few ore minerals, consisting of uraninite (pitchblende), secondary uranium minerals, marcasite, chalcedony, barite, clay minerals, quartz, jordisite, and ilsemannite. Secondary uranium minerals reported from the deposit include autunite, uranophane, metazeunerite, torbernite, johannite, uranopilite, and zippeite. A little asphaltite is present. Chalcocite and alunite have been reported.

The uranium oxide content of typical uranium ore at the Los Ochos mine is about 0.14 percent. Here, the common occurrence of uranium is as sooty, black, fine-grained pitchblende in veinlets with marcasite and clay minerals. In places, the pitchblende forms a coating on marcasite. Two generations of marcasite are reported by Malan and Ranspot (1959, p. 8); it occurs as fine disseminations, veinlets, and small concretionary and reniform structures. Chalcedony forms veinlets in the sedimentary rocks. Barite occurs as amber, yellow, or honey-yellow, tabular crystals, which appear older than pitchblende and younger than some marcasite. Malan and Ranspot gave the following paragenesis for the deposition of ore and gangue minerals: (1) silicification of the host rocks; (2) fracturing and brecciation of the

FIGURE 10.—Photograph of Los Ochos fault, portal of West drift, Los Ochos mine.

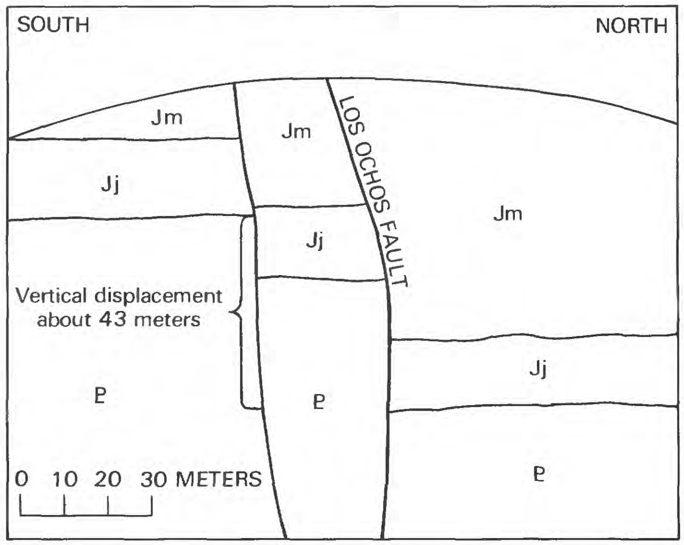


FIGURE 11.—Generalized cross section of Los Ochos fault, Los Ochos mine. Jm, Jurassic Morrison Formation; Jj, Jurassic Junction Creek Sandstone; Ꝑ, Proterozoic rocks.

host rocks; (3) deposition of marcasite and clay minerals; (4) renewed fracturing of ore and nearby rocks; (5) deposition of marcasite; (6) deposition of pitchblende; (7) filling of fractures by kaolinite. Secondary uranium minerals commonly show relationships indicating they formed later than most events in this sequence.

Marcasite is reported to occur mainly in joints and to extend farther east along the fault zone than pitchblende. Marcasite is considered a favorable guide to ore, but marcasite commonly also occurs without pitchblende. R. P. Fischer and N. L. Archbold (written commun., 1958) found no clear relationship between the abundances of marcasite and uranium minerals. The prevalence of marcasite as the iron sulfide in the deposit suggests precipitation under conditions of lower pH and lower temperatures than for pyrite. Much marcasite in other areas is considered to be of supergene origin, thus providing some evidence for supergene mineral deposition at the Los Ochos mine.

The radiometric and chemical uranium oxide determinations are generally in equilibrium, or slightly in favor of chemical uranium oxide, in samples from surface outcrops at the main and East workings of the Los Ochos mine, and at the LaRue mine. However, samples from underground at the Los Ochos main and East workings are out of equilibrium in favor of chemical uranium oxide by 10–50 percent, the majority in the 20–30 percent range (Malan and Ranspot, 1959, p. 16). Several samples taken in 1974 were analyzed by C. M. Bunker and C. A. Bush by gamma-ray spectrometry to determine Ra_eU, thorium, and potassium at different low grades, with the results shown in table 3. The thorium content of the samples is lower than the average crustal abundance of thorium and probably represents the approximate thorium content of the host sediments of the Junction Creek Sandstone. The potassium content, which varies among different samples, reflects the varying amounts of clay minerals and feldspar. These minerals tend to be sparser in the samples with greater uranium content.

Wall rocks of the deposit are intensely altered in a zone as much as 300 m thick along the Los Ochos fault. Feldspars originally present in Mesozoic sedimentary and Precambrian rocks are altered to clay minerals, of which kaolinite, montmorillonite, and illite were identified by X-ray methods (Malan and Ranspot, 1959, p. 11). White clay minerals also occur as thin films and as joint fillings as much as 2 cm thick. Chlorite and sericite occur as alteration minerals in the Precambrian rocks. The white clay veinlets that fill joints and fractures appear to be among the youngest of the gangue minerals.

Among the conspicuous alteration effects are silicification of the Junction Creek Sandstone, Morrison Formation, and Dakota Sandstone, and bleaching of the variegated mudstones of the Morrison Formation to a gray or pale-green color. Silicification of the sedimentary rocks mostly preceded the deposition of ore (Malan and Ranspot, 1959, p. 8); silicified rock is conspicuous in the ore zone although not restricted to it. Brecciation of silicified rock provided channelways for uraniferous ore-forming solutions. Silicification is of two types. One is associated with ore deposition, as shown by veinlets of chalcedony in vein material. But the other

TABLE 3.—*Ra_eU, thorium, and potassium contents of samples from the Los Ochos mine*

[ND, not determined. Gamma-ray spectrometric analyses by C. M. Bunker and C. A. Bush, U.S. Geological Survey]

Sample No.	Location	Ra_eU (ppm)	Thorium (ppm)	Potassium (percent)
Z1703	Face at portal of West drift.	143.71	<5	0.94
Z1704		329.16	5–9	2.88
Z1705		81.54	5–8	2.75
Z1706		13.20	6.92	4.25
Z1700	Ore pile from main incline.	542	ND	ND
Z1701		380	ND	.5
Z1702	Rim of dump, main incline.	125	7	1.1

silicification is a regional feature that appears to have formed where sandstone beds such as those in the Junction Creek or the Dakota were immediately beneath siliceous volcanic rocks that were deposited in Oligocene time. Both types of silicification are found at the Los Ochos mine, but the fact that silicification is intense near the uranium deposits indicates that much of it at the Los Ochos is associated with ore deposition.

The mudstone is bleached within and near the margins of the uranium deposit. Within the orebodies, some unbleached brownish-red mudstone remains as cores of slabs, blocks, or chips between fractures in the highly shattered fault zone. The bleaching along joints and fractures, which presumably indicates the extent of solutions in the rocks, is generally greatest near the main faults, and diminishes with distance away from the main fractures. Bleached rock is found chiefly along fractures and partly in certain permeable beds. The uranium deposits, the sulfide minerals, and the white clay occur in the bleached rocks rather than in the unbleached brownish-red mudstone (R. P. Fischer and N. L. Archbold, written commun., 1958).

A thorium vein occurs on the Los Ochos property at a point 500 m east of the main workings. This vein is considered of probable Cambrian age, like the Powderhorn thorium deposits, and thus is not related to the uranium mineralization. The thorium vein is a purplish-red to yellow-brown, 50-cm-thick, limonitic shear zone in granite containing inclusions of schist. The shear zone strikes N. 65° E., dips 75°–80° N., and is traceable for about 100 m in the bulldozed pit. The radioactivity of the vein is commonly about four times background level of the granite, but locally reaches about 10 times background level.

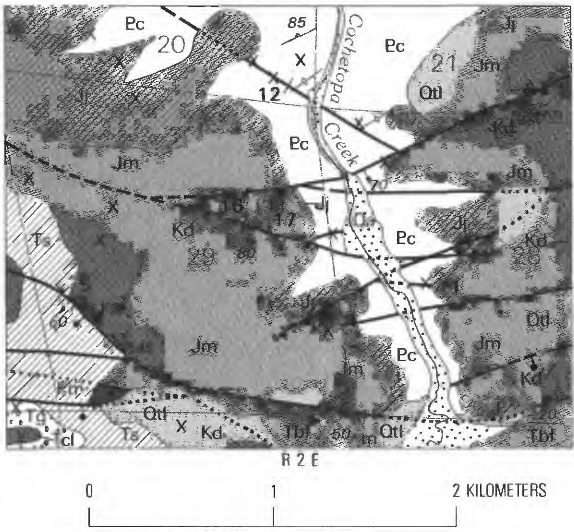
OTHER MINES AND PROSPECTS

The locations of the following mines and prospects are all shown on figure 3; in addition, the locations of five of the mines and prospects (nos. 5, 11, 12, 16, and 17) are shown at a larger scale on figure 12.

The LaRue mine (fig. 12, no. 5) is 1.75 km west of Cochetopa Creek and is at an altitude of 9,540 ft. A normal fault at the LaRue mine trends N. 63° W. and dips 60° SW. Along the fault, the hanging wall of Oligocene welded tuff (Sapinero Mesa Tuff) has been downthrown about 60 m. Twenty eight pounds of uranium oxide (table 1) and 16 lb of vanadium oxide were mined from a silicified zone in Dakota Sandstone in the footwall of the fault. Malan and Ranspot (1959, p. 15) reported that of five vertical drill holes, three bottomed in altered rhyolitic tuff in the hanging wall of the fault, whereas the other two penetrated similar tuff but bottomed in silicified, fractured, weakly mineralized sandstone and mudstone of the Morrison(?) Formation. Uranophane, autunite, and a little torbernite occur at the LaRue, coating sand grains and filling fractures and pore spaces. An ore sample analyzed by gamma-ray spectrometry contained 1,890 ppm uranium, but the thorium and potassium contents were too low to be determined. A minor amount of uraniferous asphaltite is also present. The oxidized uranium minerals may be the surface expression of primary mineralization.

Low-grade uranium deposits are found in prospect pits on the Belle Lode claim (fig. 3, no. 6), in secs. 28 and 33, T. 48 N., R. 2 E. Here, a broad, steeply dipping shear zone is at least 3.3 km long in Proterozoic fine-grained schist (metasiltstone). The shear zone is a red-brown band, owing to abundant fine disseminated hematite, trending N. 28° E. across a broad bench east of Cochetopa Creek. The shear zone, which is exposed in several pits and in trenches 90 m and 50 m long, locally contains thin quartz-carbonate-barite veins. Malachite and azurite are abundant in the veins, chalcocite and tenorite have been identified, and pitchblende has been reported. A sample of the vein material and altered wall rock analyzed by gamma-ray spectrometry contained 113 ppm Ra_eU, 9.5 percent potassium, and only 10 ppm thorium. The radioactivity of the vein material is about 5–10 times the background radiation of the red-stained schist and is highest in breccia cemented by vein material.

Thin uranium-bearing veins have been exposed by several bulldozer pits about 330 m south of the Belle Lode claim, in the same shear zone. A maximum radioactivity of about five times background was found on the margin of a 15-cm-thick, light-colored vein. Here, the shear zone, which is red stained over a width of about 100 m, strikes about N. 30° E. and dips steeply. Much of the radioactivity of the red-stained material is slightly higher than normal background of the schist, suggesting that small quantities of uranium may be disseminated in this part of the shear zone.



EXPLANATION

Qa	Alluvium	Holocene	QUATERNARY
Qtl	Landslide, talus, or colluvium	Holocene	QUATERNARY
Tcl	Cochetopa Park Tuff (lower member)	Oligocene	TERTIARY
Tg	Gravel deposits	Oligocene	TERTIARY
Ts	Sapinero Mesa Tuff	Oligocene	TERTIARY
Tbf	Breccias and flows of intermediate and rhyolitic composition	Oligocene	TERTIARY
Km	Mancos Shale	Late Cretaceous	CRETACEOUS
Kd	Dakota Sandstone	Late Cretaceous	CRETACEOUS
Jm	Morrison Formation	Late Jurassic	JURASSIC
Jj	Junction Creek Sandstone	Middle Jurassic	JURASSIC
Pc	Quartz monzonite of Cochetopa Creek		PROTEROZOIC

Contact

Fault—Showing dip. Bar and ball on downthrown side where known; dashed where inferred; dotted where concealed

Vertical fault

Strike and dip of bedding

Strike and dip of foliation

Inclined

Vertical

Mine

Prospect

FIGURE 12.—Geology of an area near Cochetopa Creek, showing location of some prospect pits. Numbered pits as follows: 5, LaRue (uranium); 11, Moultry and Hicks (thorium); 12, M. and W. (thorium); 16, Mercury (mercury); 17, Elisha (uranium). (Geology from Olson and Steven, 1976a.)

Some uranium is found in several weakly mineralized zones on the Do Dah claim (fig. 3, no. 7), about 1,600 m southwest of the Belle Lode claim. Here, considerable prospecting by bulldozer exposed a shear zone more than 6 m wide, which strikes N. 45° E. and dips 55° SE. Greatest radioactivity is in a 30-cm-thick, dark-red vein, about 20 m below the unconformable contact of the Junction Creek Sandstone with the Proterozoic schist. A sample of the dark-red vein material and adjacent altered wall rock, analyzed by gamma-ray spectrometry, contained less than 10 ppm thorium, 328 ppm Ra_eU, and 8.5 percent potassium.

A silicified fault in NW¼ sec. 30, T. 48 N., R. 2 E., between Proterozoic metatuff and Jurassic Junction Creek Sandstone, was prospected for uranium by test pits (fig. 3, no. 14) and a drill hole, but no production has been reported.

Uranium is found in six bulldozer pits on part of the Milbob group of claims (fig. 3, no. 8). Here, a steeply dipping fault striking N. 70° E., exposed in a row of pits, separates a thin erosional remnant of Junction Creek Sandstone from adjacent quartz monzonite. Parts of the sandstone near the fault show some anomalous radioactivity (0.1–0.15 mR (milliroentgen) per hour), and this has been tested by several drill holes a few feet deep into the Precambrian quartz monzonite. Samples taken by Goodknight (1981, p. 187) contained as much as 0.035 percent uranium oxide. Other prospect pits (fig. 3, no. 9) of the Milbob group are about 2 km to the southeast on a fault of similar east-northeast trend. Samples of Junction Creek Sandstone from these prospect pits contained as much as 0.056 percent uranium oxide (Goodknight, 1981, p. 187).

Anomalous radioactivity in quartz monzonite adjacent to a vertical fault has been explored by a pit (fig. 3, no. 10) and a shallow drill hole through Morrison Formation into quartz monzonite. The fault, which strikes N. 17° W., has quartz monzonite on the east or upthrown side and Morrison Formation on the downthrown side. Radioactivity near fractures is three to four times background of other quartz monzonite nearby, whereas the Morrison Formation is locally about one and a half times background.

Uranium is reported to occur on the Post claim group (fig. 3, no. 13) in silicified Junction Creek Sandstone heavily impregnated with limonite and hematite. A sample of the sandstone contained 0.021 percent uranium oxide and concentrations of arsenic and molybdenum as well (Goodknight, 1981, p. 186).

Some uranium is reported to have been found, and numerous claims staked, in the vicinity of Razor Creek and Lions Head in the southeastern part of the map area of the Houston Gulch 7½-minute quadrangle in secs. 17, 19, 20, 22, 28, 29, 30, 31, 32, 33, and 34, T. 48 N., R. 3 E. (Nelson-Moore and others, 1978). This area, which is in the northeast corner of the map area of figure 3, consists predominantly of Cretaceous rocks overlain by Tertiary volcanics. No detailed information on the presence or character of uranium deposits in this area has been reported.

Anomalous radioactivity occurs in a small pit west of Kreuger Ranch, just north of the border of figure 3, at a point 2 km north of the Gunnison–Saguache County line and 0.55 km west of Cochetopa Creek. This pit is in welded tuff near the base of the Oligocene volcanics section and near a channel cut into the ancestral erosion surface. Radioactivity at the pit is about two and a half times background of nearby Proterozoic tuff. Yellow stains occur on fractures at the pit, but they are not anomalously radioactive. The anomaly is thought to be due to a small amount of uranium, but a uranium-bearing mineral has not been identified.

Uranium was drilled for about 1957 on the Surefire Mining claims, on the east side of Houston Gulch, 4 km southeast of Parlin and 12.75 km N. 21° E. of the Los Ochos mine. The claims are outside the map area of figure 3, extending from sec. 25, T. 49 N., R. 3 E., into secs. 30 and 31 (Nelson-Moore and others, 1978). Fractures in Morrison Formation sandstone on the Surefire claims are reported to contain autunite in places; float samples are reported to contain 1–2 percent uranium oxide.

The radioactivity in the previously described deposits is primarily due to uranium and its daughter products, but thorium is the preponderant radioactive element in several deposits in the district. One low-grade thorium vein occurs near the Los Ochos mine, mentioned in the preceding, and others are on the Moultry and Hicks claim, the M. and W. claims, and the Anna claim, described in the following paragraphs.

Anomalous radioactivity is found along a shear zone on the Moultry and Hicks claim (fig. 12, no. 11), on the east side of the canyon of Cochetopa Creek. This shear zone is 1.5 m wide, dips 85° N. to vertical, and trends east-west. It cuts gneissic, porphyritic quartz monzonite of Cochetopa Creek. A gouge zone along the shear zone in a prospect pit is silicified and limonitic, and has a radioactivity three to eight times background of the quartz monzonite. A sample analyzed by gamma-ray spectrometry contained 35.5 ppm Ra_eU, 103 ppm thorium, and 11.6 percent potassium. The overlying Junction Creek Sandstone of Jurassic age, although somewhat brecciated and iron stained on a projection of the shear zone, is not anomalously radioactive, suggesting a pre-Junction Creek age for the thorium mineralization. Uranium occurs locally in Junction Creek Sandstone along a fault in a prospect pit 300 m N. 45° E. of locality 11 (fig. 12), in NW¼ sec. 28, T. 47 N., R. 2 E. Goodknight (1981, p. 187) reported that a sample from this occurrence contained 0.097 percent uranium oxide (mainly in uraninite and brannerite) and high amounts of molybdenum and lead. Other shear zones occur nearby along the canyonsides, but most show little or no anomalous radioactivity.

On the M. and W. group of claims (fig. 12, no. 12), a series of roadcuts and four trenches have been excavated over a distance of 150 m, trending N. 60° W., up the north side of a steep ravine west of Cochetopa Creek. The country rock in the area is gneissic, hematite-stained quartz monzonite of Cochetopa Creek, which is overlain on the rim of the ravine by Junction Creek Sandstone. A vertical shear zone striking N. 60° W. cuts the quartz monzonite. The shear zone is mostly 0.5–0.8 m thick. At its west end, just below the unconformable Junction Creek Sandstone contact, the shear zone and associated minerals widen to about 3 m. The minerals in the shear zone are hematite, limonite, quartz, and minor fluorite. The thorium-bearing mineral has not been identified but is presumably thorite. Two samples of the vein were analyzed by gamma-ray spectrometry. One sample about 40 m east of the lower contact of the Junction Creek Sandstone contained 62.5 ppm thorium and 11.5 ppm uranium. Another sample nearly 100 m east of the first, near the ravine, contained 59.6 ppm thorium and 26.4 ppm uranium.

Radioactivity due chiefly to thorium was found on the Anna (Lucky Friday) claim (fig. 3, no. 15) in a mineralized shear zone in Proterozoic quartz monzonite of Cochetopa Creek. The shear zone strikes N. 35°–65° E. and dips 70° SE., as exposed in a 3-m-deep shaft and two bulldozer pits 20 and 25 m long. Another shear zone 60 m south of these workings is exposed in the road and is probably a separate mineralized fracture. The latter is only 5 m from the contact of quartz monzonite and the Fish Canyon Tuff of Oligocene age. The shear zone that was excavated is marked by gouge, altered wall rocks, and abundant limonite, hematite, and manganese oxide in closely spaced fractures, and by radioactivity as high as 0.4 mR per hour or 27 times the background of 0.015 mR per hour. Bastnaesite was identified by J. W. Adams as a minor constituent of carbonate-quartz-barite veinlets that also occur in the same shear zone. One selected bastnaesite-rich sample contained 0.7 percent thorium, according to semiquantitative six-step spectrographic analysis by A. T. Myers.

In the Cochetopa district, the thorium-bearing veins are confined to the Precambrian rocks and are thus apparently unrelated to the uranium deposits. Some of them contain small but anomalous amounts of uranium, however, such as the samples containing 35.5 and 26.4 ppm uranium previously mentioned. Inasmuch as typical thorium-bearing veins in the Powderhorn district have a low uranium content, exceeding 10 ppm in only 3 of 74 samples (Olson and Hedlund, 1981, p. 32), it is postulated that the small amounts of uranium in the Cochetopa samples may have been deposited in much older veins from ground water in Tertiary time. The two veins sampled at locality nos. 11 and 12 (fig. 3) were only 40–75 m below the ancestral Cochetopa Creek valley as shown on figure 5. Hence the presence of uranium-bearing ground waters may be inferred, and the preexisting mineralized shear zones may have provided channelways for solutions and sulfide minerals to promote deposition of uranium.

Cinnabar was discovered at the Mercury mine (fig. 12, no. 16) in 1941 by A. T. Smith. The Mercury mine is 1 km N. 60° E. of the LaRue mine, at an altitude of 9,350 ft. Smith staked 15 or 20 claims on which he built a temporary retort, dug many small pits, and later leased the property to Colorado Mercury Mines, Inc. (Tweto and Yates, 1945). It was explored by a shaft 100 ft deep, a drift from the bottom (reported to be about 50 ft long), and several test pits. A small adit in the fault at the Mercury mine explores a northwest-trending fracture that is mineralized by fluorite, quartz, and reportedly gold (Tweto and Yates, 1945).

Country rocks at the Mercury mine include the Dakota Sandstone, Morrison Formation, Junction Creek Sandstone, and the Proterozoic quartz monzonite of Cochetopa Creek. These units are cut by a fault, which is exposed in the mine workings, that strikes N. 60° W. and dips steeply south. In pits on the north side of the fault, the beds of the Morrison Formation dip 45°–80° NE., in contrast to the gentle dip characteristic of Mesozoic rocks in the region. The steep dips are no doubt associated with the faulting. The Dakota Sandstone, which caps a small hill west of the mine, is on the south or downthrown side of the fault. The shaft was sunk from approximately the base of the Dakota through the underlying mudstone and sandstone of the Morrison Formation and apparently into Junction Creek Sandstone adjacent to the fault.

Although numerous pits have been dug near the Mercury mine and a small amount of core drilling has been done, cinnabar is known only in the immediate vicinity of the shaft. Cinnabar apparently was found chiefly near the surface, and the lower underground workings found little. The area surrounding the mine is one of generally poor exposures, composed of Morrison Formation on which blocks of sandstone, quartzite, and a little limestone are scattered. This rubbly surface approximates the ancestral erosion surface on which the Oligocene volcanics were deposited, as shown by a few small patches of rhyolite that remain where they originally filled small depressions in the erosion surface. The Mesozoic rocks near the fault contain abundant hematite films and stains, particularly in brecciated sandstone beds. The vein material associated with cinnabar consists mostly of brown, red, yellow, and gray jasperoid, with minor quartz, marcasite, fluorite, and manganese oxide.

The Mercury mine was examined by Ogden Tweto and R. G. Yates, in 1944, and their report (Tweto and Yates, 1945) has provided much of the following information on the cinnabar deposit.

The cinnabar occurs in the deposit in several ways—as films on surfaces of the jasper breccia, as cavity fillings in the breccia, as streaky disseminations in partly jasperoidized sandstone and limestone, and as films or thin veinlets, generally less than 3 mm thick, in sheeted and brecciated quartzite. Locally, cinnabar has penetrated into quartzite for as much as 2 cm from a joint face, and it occurs as almost microscopic shells around the individual quartz grains. Cinnabar commonly occurs as a film on occasional quartz and limestone fragments in the clay-rubble mantle in places where the bedrock also contains cinnabar.

A little cinnabar was found by Tweto and Yates (1945) in two prospect pits, 10–15 ft long, which are in a strongly sheeted quartzite zone about 100 ft wide. In these pits, closely spaced fractures strike about N. 40° W. and dip steeply southwest. Of the hundreds of sheeting planes cut by each pit, only two or three in each pit are marked by cinnabar, and these cinnabar films are 30–120 cm apart. The cinnabar mostly is a paper-thin film, but locally it is 3 mm thick. The maximum width of a cinnabar-bearing film in any one sheeting plane is only about 2.5 cm.

Uranium has not been found in association with cinnabar, but it has been found about 120 m S. 75° E. of the Mercury mine on the Elisha (also known as the Bet) claims (fig. 12, no. 17), near the same fault as adjoins the cinnabar occurrence. Here, two bulldozer pits about 30 m long are in a rhyolite having conspicuous biotite phenocrysts. The rhyolite occurs in patches too small to be outlined on figure 12. The pits expose angular, silicified, fine-grained Dakota Sandstone blocks, some of which contain a little uranophane and marcasite(?), in a matrix of the rhyolite.

The occurrence of cinnabar and uranium in the Mercury mine area appears to be related to both the fault and the erosion surface buried by the Oligocene volcanics. The fault movement at the Mercury mine is interpreted to have taken place largely before the deposition of the Oligocene volcanics. At the time of Oligocene volcanism, a fault-line scarp may have existed from which the surface sloped away southward. Broken blocks of Dakota Sandstone, eroded from the fault-line scarp, may have moved southeastward down the slope. The irregular debris-mantled slope was then buried in Oligocene time by rhyolite and later volcanics, and can be seen under the remnants of pockets of the rhyolite. The known uranium occurrence on the Elisha claim is probably in a pocket or depression in the irregular surface at the base of the volcanics and is also near the fault. The cinnabar, jasperoid, fluorspar, marcasite, and hematite at the Mercury mine are also concentrated near the erosion surface at the base of the volcanics, particularly near the fault.

The Cochetopa district contains numerous mineral deposits other than the uranium, mercury, and thorium occurrences previously discussed. Many small mines were developed in the years from about 1870 to 1910 in the northern part of the district in what has been termed the Gunnison gold belt. These deposits of gold, silver, copper, lead, and zinc are volcanogenic and were formed in Proterozoic time in association with volcanism largely or entirely beneath the sea. The Proterozoic volcanogenic deposits are of considerable geologic and economic interest but they do not contain uranium and therefore will not be discussed further in this report. It is conceivable, however, that uraniferous ground waters circulating in Cenozoic time may have deposited uranium locally in Proterozoic sulfide veins, although no examples of this are known in the district at this time.

SOURCE AND LOCALIZATION OF THE URANIUM DEPOSITS

In the Cochetopa district, both the Oligocene erosion surface and faults were factors in localizing sites of uranium mineralization. The probable source of the uranium, chiefly Oligocene volcanic rocks, and the means of transportation, localization, and deposition of uranium are discussed in the following paragraphs.

Oligocene silicic ash-flow tuffs, which are generally younger than the intermediate-composition flows and breccias, are the most likely source of the uranium in the deposits. The tuffs were leached by ground water, and much of this leaching probably occurred shortly after the tuffs were deposited. Another potential source is the Proterozoic quartz monzonite of Cochetopa Creek, widespread in the area southeast of the deposits, from which uranium could be leached by oxidation, weathering, and erosional processes, or by hydrothermal alteration during Tertiary volcanism. Evidence of extensive hydrothermal alteration has not been observed, however. A geologic setting that is broadly comparable to the Cochetopa district, that of the Tallahassee Creek district 120 km to the east, has recently been investigated (Dickinson and Hills, 1982; Hills and Dickinson, 1982). These authors concluded that the source of uranium in the Tallahassee Creek district deposits was both leaching of Oligocene volcanic rocks and erosion of Precambrian granite. In the Cochetopa district, however, surficial alteration of the quartz monzonite is discounted as a uranium source, inasmuch as the deposits are thought to have formed when the quartz monzonite was blanketed by Tertiary volcanic rocks.

The ore deposits at the Los Ochos mine, as well as several other uranium occurrences, are localized near the bottom of the Cochetopa Creek paleovalley that was buried by Oligocene volcanic rocks. Where the ancestral Cochetopa Creek crossed the Los Ochos fault, its valley floor is interpreted to have been probably only about 40 m (fig. 5) above the present day surface. A trap for ore deposition may have been formed at that point by the fault and the small block of Mesozoic rocks on the fault's north side. Such a trap could have been effective in causing ore deposition from hypogene fluids moving up the fault or, more likely, from supergene fluids moving laterally above the erosion surface. If these deposits are hypogene, the ore-forming fluids might also be expected to rise at other places along the fault zone; hence, the position of the ore at the paleovalley floor may be more than fortuitous and suggests that the paleodrainage was a factor in ore deposition. Uranium was probably leached from the overlying volcanic rocks in Oligocene or later time by downward-percolating ground water. The dissolved uranium was later precipitated at topographically low points in the basement surface under locally favorable conditions.

The ore localization at the Los Ochos and other mines is also clearly related to the physical conditions in the rocks, the fracturing and brecciation having provided permeability for mineralizing solutions. Bleaching of wall rocks along fractures also suggests that fractures were an important control. The prevalence of bleached rocks in and near the Los Ochos ore deposits indicates that solutions permeated fractures near the ore deposits but did not appreciably affect distant areas more than a few hundred meters laterally along the fault zone.

Both prevolcanics and postvolcanics faults and their wall rocks have been mineralized, the Los Ochos mine being on a prevolcanics fault. Evidence of the age of uranium mineralization is shown by the localization of uranium minerals in the fault cutting the Sapinero Mesa Tuff at the LaRue mine. This postvolcanics fault is one of a set of normal faults that mark the northern boundary of the down-dropped Cochetopa Park caldera. The ore minerals at the LaRue mine are secondary uranium minerals, and exploration thus far has not ascertained whether primary uranium oxide occurs nearby. The mineralized faults indicate, however, that uranium-bearing waters migrated through the rocks following volcanism, less than 28 m.y. ago, the age of the Sapinero Mesa Tuff. Thus at the time of mineralization, the Cochetopa Creek paleovalley, which encompassed much of the Cochetopa district, was covered with volcanic rocks.

The surface of the Oligocene volcanics was constantly subject to erosion. When the terrain was blanketed by welded tuffs, a new Cochetopa Creek valley became incised in its present position about 2 km west of the ancestral valley (fig. 5). It is noteworthy that if the modern canyon (fig. 8) of Cochetopa Creek had been recut along the ancestral channel (fig. 5), the Los Ochos uranium deposits would have been eroded away as the canyon deepened.

A supergene origin of uranium in the Cochetopa deposits is clearly compatible with the position of the deposits close to the ancestral erosion surface. Several other lines of evidence also permit this interpretation. For example, the cryptocrystalline silica that has permeated fractures and intergranular spaces in sediments in the Los Ochos fault is likely derived from ground water that percolated downward through overlying siliceous tuffs, dissolving silica from the tuffs to be precipitated in favorable structures and particularly in sandstone beds. The composition of the uranium ore also suggests deposition from supergene ground-water solutions. Only a few minerals make up the uranium ore, and marcasite as the principal sulfide mineral is most often found in surface and near-surface deposits formed at low temperature and from acid solutions. The suite of trace elements is sparse and the dominant extrinsic elements are lead, molybdenum, cobalt, and, to a lesser extent, nickel, according to 18 spectrographic analyses reported by Malan and Ranspot (1959, p. 10–14). If the uranium had been derived from juvenile residual fluids from magmatic crystallization, however, a greater number of minerals and a different, more complex suite of trace elements might be expected.

The mineral paragenesis at the Los Ochos mine shows that, in general, the sulfide minerals, mainly marcasite, preceded barite, and the uraninite (pitchblende) was generally formed after both marcasite and barite. The uraninite was commonly deposited around grains of marcasite and in permeable rocks nearby. The sulfide mineral (marcasite) was deposited earlier from supergene or hydrothermal solutions along the fault. Later barium- and uranium-bearing, oxidizing, alkaline ground waters deposited the sulfate and oxide minerals upon entering the reducing environment of the fault. Whether the mineralization was in two or more separate, distinct phases, or was one continuous process depositing consecutively marcasite, barite, and uraninite is uncertain. The fact that marcasite is reported to be distributed more widely along the fault than the uranium minerals suggests that the later phases of mineralization were channeled into a narrower zone, presumably closer to the ancestral Cochetopa Creek.

MARSHALL PASS DISTRICT

The Marshall Pass district is an area of 182 km^2 near the Continental Divide, about 40 km east of the Cochetopa district (fig. 2). The salient geologic features of the district are shown on figure 13, which is generalized from a more detailed published map (Olson, 1983). In the following section, the rocks and other geologic features are discussed. The structural history and the influence of paleotopography and paleodrainage on uranium deposition are brought out by structure contours drawn on the base of the Harding Quartzite and on the base of the Tertiary volcanics. Inferences regarding the source and localization of uranium deposits will also be discussed as possible guides in exploration.

GEOLOGIC SETTING

The Marshall Pass district is underlain by rocks ranging in age from Proterozoic to Tertiary (fig. 14). Proterozoic gneiss, schist, and gneissic quartz monzonite occupy large areas. An unconformity separates the Proterozoic rocks from the overlying thin discontinuous layer of Sawatch Quartzite of Late Cambrian age. Manitou Dolomite (Early Ordovician) overlies the Sawatch Quartzite, or the Proterozoic in areas where the Sawatch is absent. The succession of strata above the Manitou includes the Harding Quartzite (Middle Ordovician), Fremont Dolomite (Late Ordovician), Parting Formation and Dyer Dolomite of the Chaffee Group (Late Devonian and Early Mississippian?), Leadville Dolomite (Early Mississippian), and the lower, middle, and upper members of the Belden Formation (Early and Middle Pennsylvanian).

Mesozoic rocks are absent from the Marshall Pass district. Tertiary volcanic and minor sedimentary rocks, mostly or entirely of Oligocene age, overlie the Paleozoic and Proterozoic rocks. The Tertiary volcanics were deposited unconformably on the pre-Tertiary erosion surface and probably covered the entire district in Oligocene time.

Two major faults dominate the structure of the district. On the north-trending Chester reverse fault, Proterozoic igneous and metamorphic rocks were thrust westward over Paleozoic and Proterozoic rocks, folding the Paleozoic strata into a tight syncline. On another major fault, which crosses Tank Seven Creek, Proterozoic granite was thrust northward over the Belden Formation and older Paleozoic rocks. Both faults were covered by Tertiary volcanic rocks, which show some local fracturing but little or no displacement by the faults.

PROTEROZOIC ROCKS

Proterozoic rocks occupy about 60 percent of the Marshall Pass district (fig. 13), and include the following principal types, from oldest to youngest: mica gneiss and schist (31 percent of the area of Proterozoic rocks), hornblende gneiss and schist (7 percent), gneissic hornblende diorite (2.4 percent), three kinds of gneissic quartz monzonite (47 percent), and gneissic pegmatitic granite and pegmatite (12 percent).

The mica gneiss and schist are interlayered with thin beds of calc-silicate rocks, biotite-epidote quartzite, blue-gray quartzite, coarse silvery muscovite schist, and spotted schists. Migmatite occurs in varying amounts in different areas, ranging from incipient growth of feldspar crystals to pegmatitic streaks and layers. Fibrous sillimanite is present in some of the micaceous rocks; thus, the grade of metamorphism is the sillimanite subfacies of the amphibolite facies. This grade is higher than that of the Cochetopa district, which is lower amphibolite to greenschist facies.

The hornblende gneiss and schist are fine- to coarse-grained rocks composed of plagioclase, gray- to blue-green amphibole, chlorite, quartz, epidote, garnet, and sphene. The hornblendic units are interlayered with various mica gneisses and probably represent both sedimentary and volcanic origins. Hornblende schist of probable sedimentary origin is layered and has a high quartz content that varies in different layers. Hornblende schist or gneiss that may be of volcanic origin is less common but is represented by a few layers that contain round white spots resembling amygdules or spherulites, curved fractures, and textural variations that resemble poorly defined pillow structures.

The age and stratigraphic position of the mica gneiss and schist and the hornblende gneiss and schist of the Marshall Pass district in relation to those of the layered metamorphic rocks of the Cochetopa district are not known. The metamorphic rocks of the two districts differ in stratigraphic sequence, proportions of rock types, and metamorphic grade. The thick masses of metabasalt and felsite of the Cochetopa district have no equivalents in the Marshall Pass district.

Intrusive rocks of Early Proterozoic age in the Marshall Pass district have been divided into six mappable units (Olson, 1983). The oldest of these is probably the gneissic hornblende diorite (Xd) that occurs in two small areas near the Chester fault and the fault's inferred northward extension. The diorite is older than and is cut by a few pegmatite and granite dikes.

The other five mappable Precambrian intrusive rock types are grouped into one undifferentiated unit (Xg) on figures 13 and 14. Their age relations have been shown on a more detailed map of the district (Olson, 1983). Of the five, the two oldest units are porphyritic gneissic quartz monzonites characterized by numerous subparallel, tabular or rectangular phenocrysts of microcline 1–2 cm long. Of these two, a darker, biotite-rich gneissic quartz monzonite can be distinguished from a leucocratic, biotite-poor variety. The third rock type intrudes the gneissic quartz monzonite and is a medium-grained, light-gray to red, slightly gneissic quartz monzonite. It occurs as a batholithic body and as small dikes, and is locally pegmatitic.

The remaining two Precambrian intrusive rock types are gneissic pegmatitic granite and pegmatite. White to pink, gneissic pegmatitic granite is cut by pegmatite and rare aplite dikes. Most pegmatite dikes are less than 50 m thick but some reach 100 m. One dike was mined for feldspar. Near Harry Creek, the pegmatites contain magnetite commonly in crystals as large as 7 cm in diameter.

Generally speaking, the gneissic pegmatitic granite and pegmatite are closely associated with the mica gneiss and schist, the oldest Precambrian unit, forming small bodies and apophyses in the older rocks and enclosing numerous xenoliths of schist and gneiss. The several types of gneissic quartz monzonites, on the other hand, commonly occur as larger batholithic bodies, less intimately associated with the metamorphic rocks, although they also occur locally as small dikes in the metamorphic rocks.

The age of the Precambrian igneous rocks of the district has not been established with certainty, but the rocks are mostly gneissic quartz monzonites generally similar to other rocks of 1.7 b.y. age, as dated elsewhere in south-central Colorado. (For discussion see Tweto, 1977, p. D12.) Because ages near 1.4 b.y. have also been obtained for some igneous bodies outside the district but in the general region, such an age cannot be excluded.

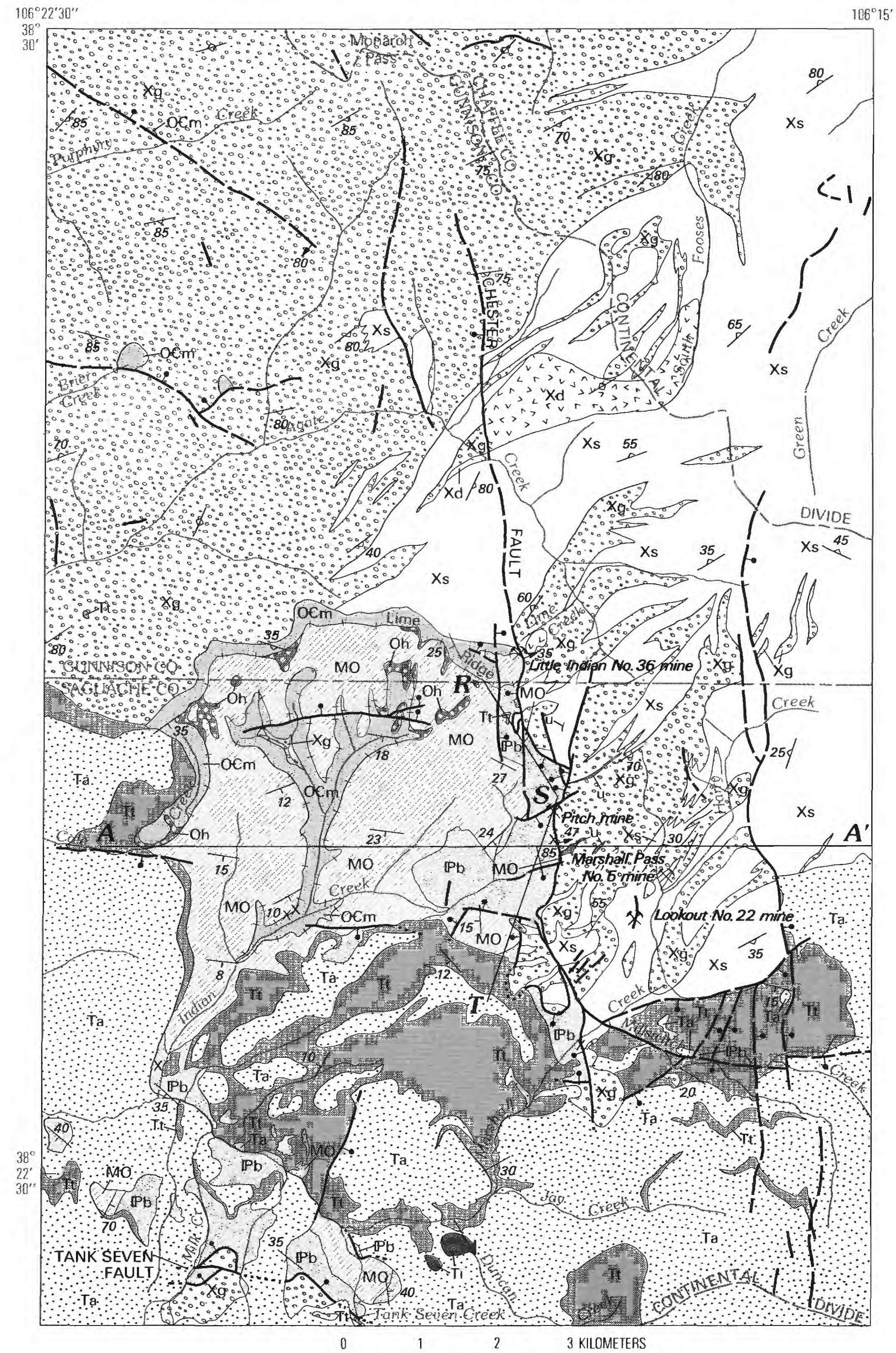
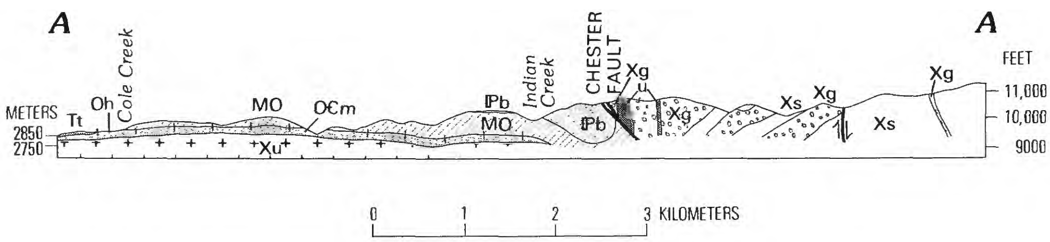


FIGURE 13 (above and facing page).—Generalized geology and cross section of the Marshall Pass district. Opposed arrows in cross section *A-A'* show relative movement across fault. Cross section *R-S-T* is shown in figure 20.



EXPLANATION

Ti	Rhyolite plug	Oligocene	TERTIARY
Ta	Rawley Andesite		
Tt	Waterlaid tuff, welded ash-flow tuff, other generally siliceous volcanic rocks, and gravels, undifferentiated		
IPb	Belden Formation	Middle and Lower Pennsylvanian	PENNSYLVANIAN
MO	Leadville Dolomite (Lower Mississippian), Chaffee Group (Lower Mississippian? and Upper Devonian), and Fremont Dolomite (Upper Ordovician)		MISSISSIPPIAN, DEVONIAN, ORDOVICIAN, AND CAMBRIAN
Oh	Harding Quartzite (Middle Ordovician)		
O€m	Manitou Dolomite (Lower Ordovician) and Sawatch Quartzite (Upper Cambrian)		
u	Ultramafic dike rocks	Age uncertain	
Xg	Pegmatitic granite and gneissic quartz monzonite	Early Proterozoic	PROTEROZOIC
Xd	Gneissic hornblende diorite		
Xs	Mica gneiss and schist; migmatite, locally sillimanitic; hornblende gneiss and schist		
Xu	Crystalline rocks, undivided		

Contact

80 — **Fault**—Showing dip. Bar and ball on downthrown side where known; dashed where inferred; dotted where concealed

30 — **Strike and dip of bedding**

Strike and dip of foliation

75 — **Inclined**

Vertical

X **Prospect pit**

Uranium mine

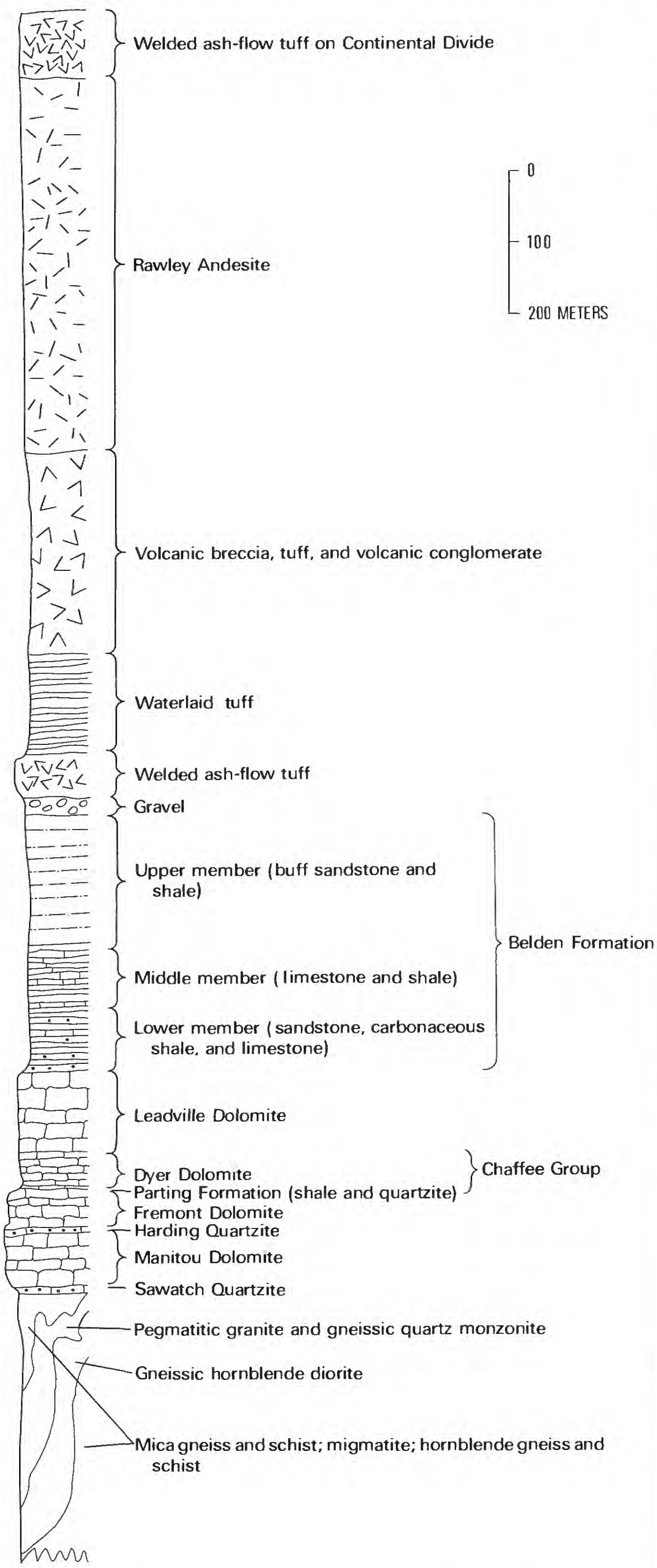


FIGURE 14.—Columnar stratigraphic section, Marshall Pass district.

Ultramafic rocks of uncertain age cut the pegmatitic granite and older rocks in at least six dikes 1–100 m thick near the Chester reverse fault. These dark-green, schistose to massive, ultramafic dike rocks (peridotite) are composed of chlorite, colorless to palest green amphibole, pyroxene, and olivine and its alteration products—serpentine, magnetite, biotite, and minor plagioclase. The fact that these dikes are localized in the hanging-wall block within 800 m of the fault suggests possible intrusion into fractures related to deep faulting.

PALEOZOIC ROCKS

Paleozoic sedimentary rocks cover an area of about 24 km^2 in the Marshall Pass district (fig. 13). These units have a total thickness of 700 m and range in age from Late Cambrian to Pennsylvanian (figs. 13 and 14).

The Sawatch Quartzite of Late Cambrian age was deposited unconformably on the Proterozoic rocks after a long period of erosion. It is a white, vitreous, medium-grained quartzite composed largely of rounded quartz grains 0.1–0.7 mm in diameter. The quartzite is about 5 m thick near the head of Brier Creek in the northwestern part of the district. The southernmost known exposure of Sawatch Quartzite, about 1 m thick, is on Lime Ridge (fig. 13). Here it occurs at the base of the Manitou Dolomite and extends for a distance of 1 km west of the Chester fault.

Sawatch Quartzite also occurs as sandstone dikes in Precambrian quartz monzonite. These are interpreted to have formed as sand filled open fractures in the underlying quartz monzonite at the time of Sawatch deposition. The two known dikes trend northwest in the northwest corner of the district and are less than 6 m thick (Olson, 1983). The two dikes are 500 m west and 3,400 m S. 41° W. of Monarch Pass. Thin sections show that rounded quartz grains, some with quartz overgrowths, make up more than 95 percent of the sandstone dikes, with only a small percentage of microcline, plagioclase, muscovite, and interstitial calcite.

The Manitou Dolomite of Early Ordovician age is a bluish-gray to light-gray dolomite, commonly having a pink cast on a fresh surface. It is 75–90 m thick and, although thin bedded in the lower part, is mostly massive and cliff forming. It is well exposed and forms bold cliffs in the canyon of Indian Creek and on Lime Ridge. A characteristic feature of the Manitou is the presence of nodules and lenses of chert along bedding planes, especially in the formation's lower half. The Manitou Dolomite was deposited unconformably on Precambrian crystalline rocks or on thin, discontinuous beds of Sawatch Quartzite.

The Harding Quartzite of Middle Ordovician age was deposited unconformably on the Manitou Dolomite. The Harding is 10–12 m thick, consists of quartzite and minor black shale, and is a distinctive marker bed among the predominantly carbonate rocks of the Paleozoic section. The lower two thirds of the Harding is a white, medium- to fine-grained, silica-cemented quartzite. The upper third of the formation is mostly a medium- to coarse-grained, fossiliferous, limonitic quartzite. Black carbonaceous shale in a layer 5–15 cm thick is common at the top.

The Harding Quartzite is widely distributed in central Colorado. Stratigraphic variations in the region have been described by Sweet (1961, p. 17–19), and can be briefly summarized here. The formation has a maximum thickness of 55 m at a point 4 km north of Cotopaxi, and it thins in every direction from that point. The Harding along the Front Range and Wet Mountains is divisible into three rather persistent members: a lower thin-bedded sandstone member, conglomeratic at the base; a middle shale member; and an upper thin-bedded to massive sandstone member that includes a distinctive red siltstone or shaly siltstone either near or well above its base. West of the Front Range, there is usually no subdividing shale member, and the Harding is thick-bedded quartzitic sandstone that contains soft limonitic casts of fish plates. Shale is negligible in the formation near, west, and south of Salida, but the shale content increases markedly north and east of Salida. The regional distribution of Harding Quartzite is illustrated on figure 19 and its uranium occurrences are discussed further in the "Uranium in the Harding Quartzite" section of this part of the report.

The Fremont Dolomite of Late Ordovician age conformably overlies the Harding Quartzite and is about 55 m thick. It consists of bluish-gray, commonly mottled, massive, crystalline dolomite and limestone. The Fremont is the most fossiliferous formation in the district, and it commonly has a fetid odor when broken. Chert blebs are present locally but are much less abundant than in the Manitou Dolomite. The resistant, massive lower part of the Fremont commonly forms prominent cliffs; the upper 15 m is less resistant, thin-bedded, shaly to sandy dolomite.

The Chaffee Group of Late Devonian and Early Mississippian(?) age in the study area consists of two formations—the Parting Formation and the Dyer Dolomite. The Parting Formation, deposited unconformably on the Fremont Dolomite, is 3-6 m thick and consists mostly of red, green, and gray mudstone or shale. Coarse-grained, locally conglomeratic quartzite beds as much as 2 m thick are common, and shaly limestone is also present. The Dyer Dolomite, which lies conformably on the Parting Formation, is 45–50 m thick. The lower part is a white to creamy-gray or light-tan, thin-bedded, commonly sandy dolomite and limestone. The upper part consists of locally fossiliferous, thin-bedded sandy dolomite and contains a few massive, cream-colored dolomite layers. The Dyer Dolomite characteristically weathers to small brownish-yellow fragments that have a smooth surface, and this weathering feature helps distinguish it from other formations. The Dyer Dolomite is generally considered to be of Late Devonian age but possibly includes some Early Mississippian(?) strata.

The Leadville Dolomite of Early Mississippian age generally lies conformably on the Dyer Dolomite. The Leadville consists of massive, blue-gray to brownish-gray dolomite and subordinate but abundant limestone; calcite veinlets are plentiful. The thickness is about 100–130 m and varies owing to unequal erosion during post-Leadville, pre-Belden time. Near its base it is commonly a thin-bedded, blue-gray sandy limestone in a thickness of 25–30 m. A grayish-brown dolomite with white flecks of dolomite, termed "salt-and-pepper" dolomite, was noted several places in a 20-m-thick zone near the middle of the Leadville. Massive, thin-bedded dolomite and limestone are common in the upper part. Near the top, thin quartz veins, minor chert bodies, karst features, a brecciated appearance, and minor replacement of limestone by limonite and hematite locally give evidence of pre-Belden weathering and erosion at the unconformity surface. Gray dolomite breccia is common in the Leadville in a large fault-bounded area 2 km south-southwest of the Pitch mine, where the breccia probably formed largely by structural movements.

Some small replacement iron deposits of impure limonite occur beneath the unconformity at the top of the Leadville. These bodies are as much as 3 m thick and 60 m in exposed length, and they have been prospected for iron ore early in the history of the district. A sample of the better grade limonite taken by the U.S. Bureau of Mines in 1957 (Harrer and Tesch, 1959) assayed 42.6 percent iron, 0.07 percent phosphorous, 0.43 percent sulfur, 20.8 percent silica, and 0.1 percent manganese, and lost 14.3 percent on ignition.

The Belden Formation of Early and Middle Pennsylvanian age lies unconformably on an irregular surface of Leadville Dolomite in most of the district. In the southern part of the district, the Belden in a few places appears to overlie the Precambrian rocks. Ward (1978) reported that units of the Belden Formation rest directly on Precambrian rocks at the Pitch mine. Contacts between the two are poorly exposed in these structurally complex areas, but the author believes that most or all of these contacts are faults inasmuch as some fault contacts are exposed locally and the map pattern of formations is better interpreted as due to faulting.

The Belden has been divided into three members (Olson, 1983), which are combined on the generalized geologic map (fig. 13). The lower member ranges from 40 to 100 m thick and is composed chiefly of red, yellow, or brown fine-grained sandstone and shale. Layers of black shale or mudstone, containing coaly carbonaceous material, are 1–3 m thick. Lenticular, white, gray, or reddish-brown, arkosic or quartzose, micaceous, gritty, coarse-grained sandstone, quartzite, and conglomeratic sandstone occur mostly near the base and in the lower part of the unit. The conglomeratic sandstone consists of pebbles and cobbles of quartz, Precambrian rocks, and lesser amounts of limestone enclosed, in various proportions, in a sandy matrix of subrounded to subangular quartz grains commonly 0.2–1 mm in diameter and of sparse interstitial iron oxides and clay minerals. A few thin, medium-gray, fine, granular, detrital limestone beds, from several cm to 30 m thick, occur near the top of the lower member.

The heterogeneous lower member of the Belden is interpreted to have been formed from detritus eroded from the rising Uncompahgre highland and to have been deposited chiefly in fluvial, deltaic, and coastal-plain environments. The lithology is generally similar to that of the Kerber Formation to the southeast of the district, as described by Burbank (1932, p. 13), with which it may be at least partly correlative. The number of limestone beds in the lower member increases as it grades upward into the middle member.

The middle member of the Belden Formation is 30–120 m thick and is composed of layers of partly fossiliferous, blue-gray limestone, a few centimeters to as much as 30 m thick, interbedded with gray to purplish-red shale, siltstone, and fine-grained sandstone. Exposures are generally poor, but the abundant limestone fragments in sandy or silty soil help to distinguish this unit from units above and below. In drill holes near the Pitch mine, the shale and fine sandstone are generally more abundant than the limestone, although the limestone is more conspicuous on the surface owing to its greater resistance to weathering. The beds of limestone and fine-grained clastic sediments indicate a marine environment of deposition, and the middle member was probably deposited in a northwest-trending arm of the sea off the northeast side of the Uncompahgre highland.

The upper member of the Belden Formation is composed chiefly of buff- or drab-colored, medium- to coarse-grained sandstone, interbedded siltstone and gray shale, and minor conglomeratic sandstone. The contact with the middle member is gradational and is distinguished mainly by the absence of limestone beds and the presence of coarser detritus in the upper member. Although the top of the upper member has been removed by erosion, its remaining thickness is 200 m or more. It is interpreted to have formed chiefly by shallow-water, near-shore marine deposition of medium- and fine-grained clastic sediments in a northwest-trending trough just off the northeast edge of the Uncompahgre highland, from which the clastics were eroded, and by coarser grained, fluvial clastic deposition. The upper member of the Belden is generally similar in lithology to and probably at least partly correlative with the Gothic Formation of Langenheim (1952, p. 561–563) and Bartleson (1972) and with the Minturn Formation described to the east of the district by DeVoto (1972).

TERTIARY VOLCANIC AND INTRUSIVE ROCKS

Tertiary volcanic rocks cover an area of about 49.1 km^2 in the area of the Marshall Pass district shown on fig. 13; Tertiary intrusive rocks comprise only two small plugs and several thin dikes. The Tertiary volcanic rocks are divided into two units on the generalized geologic map (fig. 13), but they have been subdivided and described more completely on a detailed map of the district (Olson, 1983). On figure 13, the Rawley Andesite, a thick mass of andesitic flows, is shown as one unit (Ta), and the remainder of the undifferentiated volcanic rock section is shown as the second unit (Tt). These undifferentiated volcanics consist chiefly of silicic tuffs, tuffaceous sediments, and gravels.

The Tertiary volcanic rocks in the district have not been dated radiometrically, but stratigraphic relations with units that have been dated in nearby areas suggest an Oligocene age for at least the upper part of the Tertiary volcanics.

The Rawley Andesite of Oligocene age is a sequence of dark-grayish-brown, mostly porphyritic andesite flows, as much as 550 m thick in the southern part of the district. The andesite contains phenocrysts of plagioclase, augite, biotite, magnetite, and sparse hornblende and olivine or its alteration products, in a dark-gray, pilotaxitic, aphanitic or glassy groundmass. The formation includes lesser amounts of dark quartz latite, somewhat lighter in color than andesite, and dark olivine-bearing basalt. Typical in the andesite are lath-shaped plagioclase phenocrysts 0.1–3 mm in diameter.

The Rawley Andesite was named for a locality in the Bonanza district (Burbank, 1932, p. 16–21) to the southeast. The Bonanza volcanic center is the probable source of Rawley Andesite flows in the Marshall Pass district. Rawley Andesite flows on the northeast side of the Bonanza volcanic center were dated by R. E. Van Alstine and R. F. Marvin (Lipman and others, 1970, p. 2336–2337) at 34.2 and 33.4 m.y. in age. These K-Ar dates have been recalculated by R. F. Marvin (oral commun., 1980) using new decay constants as 35.0 and 33.4 m.y., respectively.

The undifferentiated units of the Tertiary volcanics section are heterogeneous, but are predominantly siliceous, and they include a variety of types described briefly in the following paragraphs in order of generally decreasing age.

Gravel deposits, locally consolidated into conglomerate, are 0–60 m thick and are found generally at the base of the Tertiary volcanics section. They also occur locally between flows in other parts of the section. The gravels contain rounded boulders as much as several meters in diameter composed largely of Precambrian and Paleozoic rocks, less commonly of Tertiary volcanic rocks. The composition of some boulders indicates they were transported from sources as distant as several kilometers.

Densely welded ash-flow tuffs occur above the gravels and at the base of the Tertiary volcanics section, and are also interlayered with andesitic flows, waterlaid tuff, and other Tertiary units. These oldest tuffs comprise two or more ash flows whose combined thickness is at least 60 m, separated by thin gravel deposits. The ash-flow tuff typically is a quartz latite and contains 10–30 percent phenocrysts of biotite, plagioclase, and quartz in a felsitic red-brown to light-gray matrix. Fragments of white pumice, as large as 2 cm but commonly 1–4 mm in diameter, make up as much as half of some tuffs. A eutaxitic structure is caused by gray to black, partly glassy, lenticular, collapsed pumice fragments. Spherulitic texture is common. Sparse inclusions of older rocks, including Precambrian rocks, andesite, other volcanics, and waterlaid tuff, make up several percent of some units.

Above these lower silicic ash-flow tuffs is a thickness of 20–200 m of white to light-brown, fine-grained, thin-bedded waterlaid tuff. The tuff is commonly soft and easily eroded, but in places it is hard, brittle, and platy. Fine biotite grains are commonly present, and there is a minor mixture of sand grains or other nontuffaceous detritus. A few rare yellow-brown sandstone units, not mapped separately, are as much as 10–15 m thick. The extent of the lake in which the waterlaid tuff was deposited is discussed further in the "Paleotopography and paleodrainage" section of this part of the report.

The source of the welded tuffs and waterlaid tuff in the lower part of the Tertiary volcanics section has not been established. They may be from the Bonanza volcanic center, but they may well have been from the Mount Aetna volcanic center, 10 km north of Monarch Pass, which was active at about that time.

Purplish- to reddish-brown or cream-colored tuff breccia, flow breccia, lapilli tuff, and volcanic conglomerate are common in the Tertiary volcanics section. They are most abundant in the area between Millswitch and Marshall Creeks and around their confluence, where they underlie Rawley Andesite and overlie the waterlaid tuff. They are composed of clasts of locally derived Precambrian rocks, andesite, quartz latite, pumice, and sparse Paleozoic limestone in a matrix of volcanic ash, with detrital sand grains in places. A crude, coarse layering is present locally in these fragmental rocks. The tuffaceous matrix commonly contains 10–45 percent phenocrysts of feldspar and biotite; pumice fragments are as much as 1 cm in diameter. Quartz latite clasts also contain plagioclase, sanidine, and biotite phenocrysts in a pale-red felsitic or glassy matrix. Precambrian rock fragments, typically about 5–8 cm in diameter although many exceed 1 m, were apparently shed from an uplifted block to the northwest and were deposited on the slopes of a subsiding basin.

The youngest of the Tertiary extrusive rocks are several white, cream-colored, to grayish-brown welded ash-flow tuffs of probable quartz latitic composition on the Continental Divide near the head of Duncan Creek (fig. 13). These tuffs range from crystal poor (10–15 percent phenocrysts) to crystal rich (30–40 percent). Phenocrysts are of biotite, clear rectangular feldspar in grains as much as 1×2 mm, quartz, and a few small crystals of magnetite and hornblende. Eutaxitic structure is shown by collapsed pumice fragments and shards. Inclusions of darker andesite or quartz latite flows make up several percent of some tuff layers. Cavities are locally present in the vapor-phase alteration zone. The tuffs in this erosional remnant are about 80–90 m thick, and they are probably correlative with the Bonanza Tuff of the Bonanza district to the southeast, having their source in the Bonanza volcanic center.

Intrusive rocks of Tertiary age are of two types. Quartz porphyry dikes near Porphyry Creek, near the northwest corner of the map area, are not shown on figure 13 and are only about 1 m to a few meters thick. The porphyry consists of sparse small phenocrysts of quartz and feldspar as much as 2 mm in diameter set in a white to purplish-gray felsitic matrix with a flow structure. Zircons from a thicker body of similar porphyry about 2.4 km west of the west edge of the map area of figure 13 have been assigned a fission-track age of 34.4±3.3 m.y. by Naeser and Cunningham (1976).

The second type of Tertiary intrusive rock is a fine-grained to felsitic rhyolite that forms two small plugs cutting Rawley Andesite south of Marshall Creek, near the mouth of Duncan Creek (fig. 13). These plugs have a steeply dipping, platy, planar flow structure. Perlitic obsidian occurs in a thin zone near the contact. The larger rhyolite plug, 275×450 m in area, is on both sides of Duncan Creek, and the smaller plug, 150×225 m in area, is about 200 m southwest of the larger plug.

Quaternary deposits not shown on figure 13 include glacial till or morainal deposits, rock glacier, talus or landslide deposits, colluvium, and alluvium.

FAULTS

Several major faults are prominent features in the structural framework of the district. The Chester fault is a complex zone of reverse faulting 60 to more than 100 m wide; the displacement exceeds 430 m. The fault trends northward and dips eastward from about 20° to near vertical. Gentler dips are found near the Little Indian No. 36 mine north of Lime Ridge (fig. 13), whereas steeper dips occur from the Pitch mine southward. The Chester fault zone, named from a former station on the Denver and Rio Grande Western Railroad on Marshall Creek, is the contact between Precambrian and Paleozoic rocks for about 6 km. To the south of this 6-km interval, the fault is buried by Oligocene volcanic rocks. To the north of this interval, its position is less certain because of poor exposures and the absence of Paleozoic rocks. Several smaller faults in the Monarch Pass area are flanked by Precambrian rocks on both sides and may be associated in origin with the Chester fault movement.

Most of the displacement on the Chester fault probably occurred in Laramide time. The fault displaces Pennsylvanian sedimentary rocks, which are highly deformed and brecciated in the fault zone. It does not appreciably offset any Tertiary volcanic rocks, but steep dips occur in a few places in Tertiary waterlaid tuff near the Chester fault, indicating some movement after deposition of the volcanics. Furthermore, structure contours drawn on the pre-Tertiary erosion surface show that the Precambrian rocks of the hanging-wall block locally formed a north-trending ridge and fault-line scarp prior to the deposition of Tertiary volcanic rocks; such a topographic expression is compatible with the inferred Laramide age of faulting.

The Chester fault zone is highly complex in detail, and even the abundant drill-core data near the Pitch mine have not produced a clear-cut picture of the structure of all the blocks within the zone. Beneath the hanging-wall block of Precambrian rocks, the bedding of the sedimentary rocks dips steeply and in places is overturned to nearly parallel the typical 45°–90° dip of the main fault. Within the footwall block, the soft, incompetent shale of the Belden Formation deformed easily; subparallel fractures distributed the displacement over a zone 100 m wide and brought various rock types into juxtaposition. Some relationships seem best explained by slabs or blocks of Precambrian rock being broken from the sole of the hanging wall and driven or forced into incompetent deformed sediments of the footwall.

On a larger scale, figure 13 shows several large fault-bounded blocks adjoining the main Chester fault plane on the west. These include a large block 500 m wide of Leadville Dolomite and Belden Formation south of Indian Creek, a block of Precambrian rock 500 m wide adjoining it to the southeast, a block of Precambrian granite at the southernmost exposure of the Chester fault east of Marshall Creek, two small wedges about 100 m across of Leadville Dolomite 0.5 and 1 km north of the Pitch mine, and a wedge of Precambrian schist 100 m wide just south of Lime Ridge. All of these blocks are bounded by faults and appear to have been thrust westward, in front of the main Precambrian block and over the adjoining younger rocks, by reverse faults related to the main Chester reverse fault.

Another reverse fault forms the contact of Precambrian granite and Belden Formation on the slope west of Tank Seven Creek. It seems likely that this fault extends west-northwest, across areas where rocks and contacts are poorly exposed, at least as far as Milk Creek, beyond which it is buried by Rawley Andesite. To the east-southeast, the inferred fault zone is buried by Rawley Andesite and other volcanics, but it may be related to the Kerber Creek fault system exposed about 27 km to the southeast. Both fault systems involve thrusting of older rocks northward over younger rocks, and the faults are inferred to have been positioned near the northeast edge of the Uncompahgre highland at the time of deposition of Pennsylvanian clastic sediments.

A fault zone predating the deposition of volcanic rocks that is probably related to the Tank Seven fault is inferred from local structural complexity near the mouth of Tank Seven Creek. This fault zone probably extends northwestward in or near Marshall Creek valley, an interpretation that is perhaps strengthened by the configuration of structure contours drawn on the pre-Tertiary erosion surface, which show a northwest-trending ridge just north of Marshall Creek.

Several faults that cut the Tertiary volcanic rocks are inferred in the Millswitch Creek area, and two other faults cut the volcanics just west of the mouth of Tank Seven Creek and on Cole Creek (fig. 13). The area between Millswitch Creek and the upper part of Marshall Creek is believed to be an east-plunging trough filled with a thick section of Tertiary volcanics and gravel deposits. This trough-like depression was also occupied by the early Tertiary lake or lakes, as the waterlaid tuff is present to considerable thickness in the Millswitch Creek area. Faulting in this area indicates that subsidence has occurred since and perhaps during deposition of the volcanics, and the amount of subsidence increases toward the east. Coarse boulder gravels, containing boulders of pre-Tertiary rocks 2 m or more in diameter, were shed off the higher ground to the northwest. On the north side of Millswitch Creek, two large blocks of rock from the lower member of the Belden(?), each about 50–100 m in diameter, are surrounded by Tertiary volcanics. These blocks are probably allochthonous masses, shed off the nearby uplift, which moved down slope under gravity and became incorporated in the fragmental volcanics.

PALEOTOPOGRAPHY AND PALEODRAINAGE

To clarify the structural history of the Marshall Pass district and to show how the structure influenced the sites of uranium deposition in the "Source and localization of the uranium deposits" section of this part of the report, inferred structure contours have been drawn on the base of the Harding Quartzite (fig. 15) and on the base of the Tertiary volcanics and gravels (fig. 17). The control of these contours is good where based upon exposures of the contacts; in some areas, however, no exposures or subsurface information are available and inferences have been made. In one area near Millswitch Creek (lat 38°23′ N., long 106°16′ W.), near the east edge of the map area of figure 17, structure contours on the base of the Tertiary volcanics are not shown because of the scarcity of subsurface information, the considerable thickness of the Tertiary deposits, and the likelihood of numerous small faults in addition to those shown on figure 17.

The Harding Quartzite was chosen for contouring because it is a conspicuous thin marker bed that also contains anomalous amounts of uranium. The structure contours on the base of the Harding Quartzite (fig. 15) show that the Harding Quartzite has been tilted at an angle of about 7°–8° S. as a result of structural movements since its deposition, when it was nearly flat and nearly concordant with the other Paleozoic formations. Some tilting and folding of the Harding Quartzite occurred in Laramide time, when all Paleozoic rocks were greatly deformed in conjunction with movements on the Chester reverse fault. The structural shape, strike, and dip of the Harding Quartzite at the beginning of Tertiary time are approximated in figure 16, obtained by tilting the surface contoured on figure 15 about 7° N. 22°30′ E. This amount of tilting since deposition of the Tertiary rocks is described in the following discussion of figures 17 and 18. If this restoration (fig. 16) of the attitude of the Harding Quartzite prior to Tertiary volcanism is correct, the formation had a gentle dip averaging about 7° ESE. at that time. In the northern part of the map area of figure 16, structure contours indicate that the dip of the Harding at that time was about 12°–13° S.

At the time that the Tertiary tuffs were deposited, the Precambrian rocks on the east side of the Chester fault stood above the Paleozoic rocks to the west as a fault-line scarp. The structure contours on the base of the Tertiary volcanics and gravels (fig. 17) show that the pre-Tertiary erosion surface west of the Chester fault has a predominant dip of about 7° in a direction a little west of south. This angle of tilt is the approximate amount necessary, in reverse, to restore the surface to a more nearly flat surface that existed at the time the earliest Tertiary volcanics and gravels were deposited. This surface was nearly flat but there were slight depressions in parts of the map area.

The earliest Tertiary ash flows were followed by the deposition of waterlaid tuff, the bedding of which was nearly flat at the time of deposition. The inferred structure contours on figure 18 and the position of the outcrops of waterlaid tuff indicate the approximate position and outline of the depression that was occupied by a lake in Tertiary time. The lake occupied at least 30 km^2 in the district (fig. 18). Lacustrine deposits of early Tertiary age similar to the waterlaid tuff in the Marshall Pass district have also been noted by Dings and Robinson (1957, p. 33) and Raines (1971, p. 28) in the Tomichi Creek valley north of Sargents, indicating the presence of one large lake at least 20 km long or several smaller lakes.

The pre-Tertiary topographic expression of two possible buried northwest-trending faults is shown on figure 18. One of the possible buried faults is in the valley of Marshall Creek, less than 200 m south of the creek, and the other is a possible parallel fault about 1 km to the north. These linear features inferred in the pre-Tertiary topography are subparallel to the faults exposed and inferred in the area from the lower part of Tank Seven Creek to Milk Creek and thus may be subparallel faults in the same zone. Much of the area of the linear features is covered by Tertiary volcanic rocks or is poorly exposed and the contours are largely inferred, hence this suggestion is quite hypothetical. The possibility that other northwest-trending faults might parallel the one exposed west of Tank Seven Creek is of interest because of the similarity of these structural features to the Kerber Creek fault zone 27 km to the east-southeast, which is discussed in the "Faults" section of this part of the report.

URANIUM DEPOSITS

Most of the mineral exploration in the Marshall Pass district has been for uranium, although minor workings have been excavated for iron near the unconformity at the Leadville-Belden contact and for feldspar in two

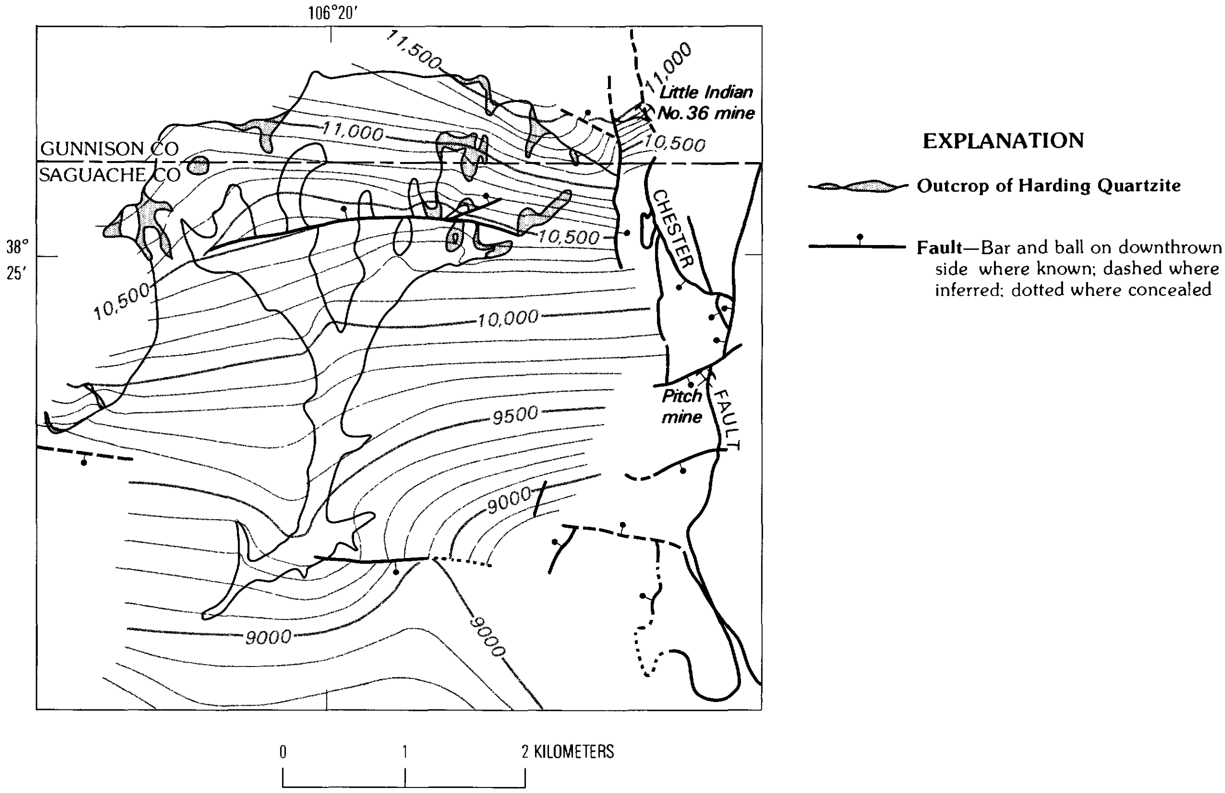


FIGURE 15.—Inferred structure contours on base of Harding Quartzite, Marshall Pass district. Contour interval, 100 ft.

Precambrian pegmatites. Uranium was discovered in carbonaceous shale of the Belden Formation near the mouth of Indian Creek in the spring of 1955, followed by discoveries in the Harding Quartzite northwest of Indian Creek, in the Harding at the Little Indian No. 36 mine, and then in shear zones in Precambrian rocks in the Harry Creek area, 2 km southeast of the Pitch mine.

PITCH MINE

Drilling and exploration of the large deposit at the Pitch (formerly known also as the Pinnacle) mine were started in 1956 (Baker and Scott, 1961), and it was mined by small underground workings from 1958 until 1962. During this time, five main stope areas were developed, representing about 1.3 million ft^3 (Marrs, 1970), which were entered from the main haulageway, 1,500 ft long, and an earlier crosscut and drift, 850 ft long.

Uranium was recovered at the Pitch mine by the process of underground leaching from 1968 to 1972 by the Pinnacle Exploration Company. The processing and recovery of uranium in the leaching operation have been described by Marrs (1970). Mine effluents were recycled through the mine workings and were treated in an ion exchange plant on the property.

Later exploration at the Pitch Mine, from 1972 to 1978, established a reported reserve of 2.1 million short tons of ore at an average grade of 0.17 percent uranium oxide (Ward, 1978). Open-pit mining of the deposit by Homestake Mining Company began about November 1978. The pre-1978 production of the Pitch mine and other deposits in the district is shown in table 1.

Uranium deposits at the Pitch mine are found in beds of the Belden Formation and Leadville Dolomite where they are steeply upturned and brecciated in the footwall of the Chester reverse fault. Uranium minerals reported from the Pitch mine are uraninite, sabugalite, metatorbernite (Ward, 1978), and uranium carbonate minerals such as rutherfordine (Marrs, 1970). The ore is characterized by a high lime content. Pyrite and marcasite are sparsely distributed in the Pitch mine ore, and traces of copper-bearing sulfide are present. The ore is generally simple in composition, containing only small amounts of copper and other metals. On the fault at Chester, 3 km south of the Pitch mine, a prospect drift was run along a silicified fault breccia zone containing malachite and azurite stain and a little pyrite, but no anomalous amounts of uranium were found.

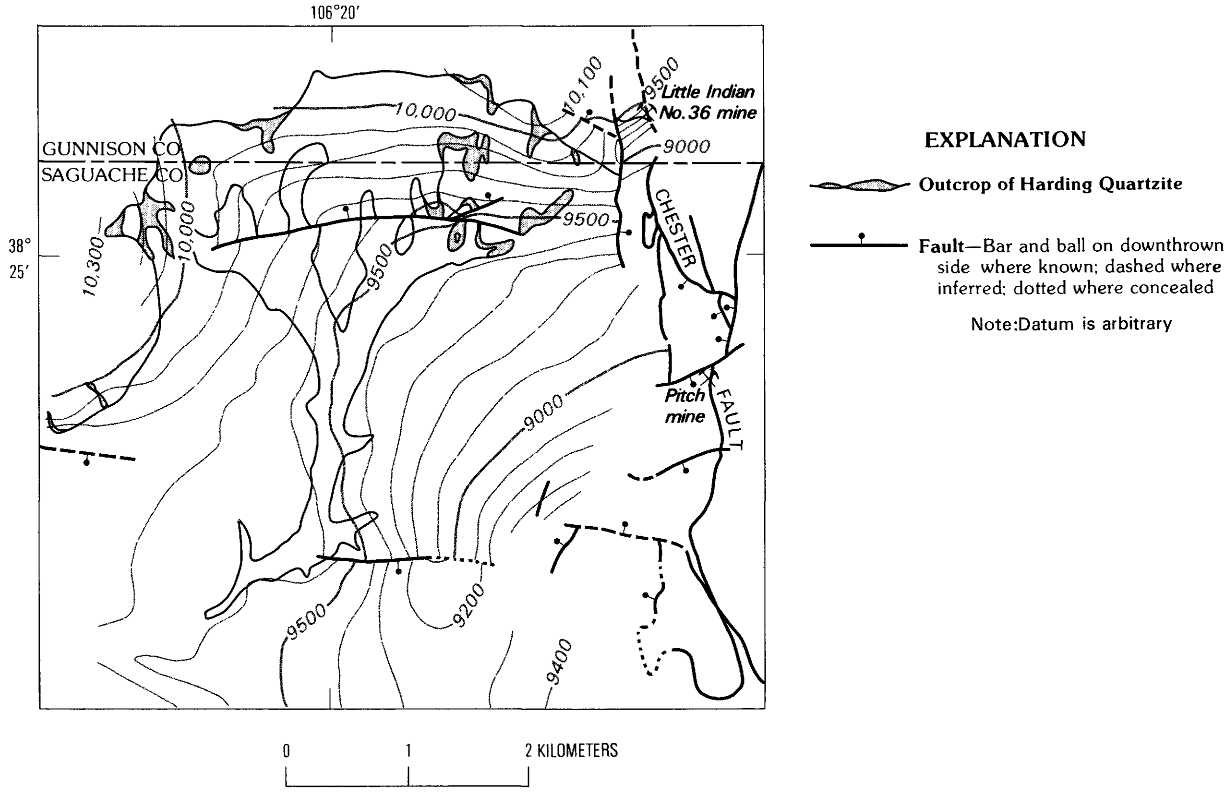


FIGURE 16.—Inferred structure contours on base of Harding Quartzite, if present surface is tilted 7° toward N. 22°30′ E. Contour interval, 100 ft.

The Pitch mine ore is irregularly distributed over a strike length of at least 1.5 km. Its occurrence is related mainly to permeability and to physical openings created by fault movements, shearing, and brecciation. A multitude of displacements occurred over a zone more than 100 m wide in the Paleozoic rocks beneath the hanging-wall block of Precambrian rock. Cross faults, striking a little north of east, cut the Chester fault and may have affected the flow of solutions in places. Blocks and wedges of massive Precambrian rocks and dolomite, their long dimensions generally parallel to the Chester fault, alternate with incompetent shale and sandstone masses in the fault zone. The more competent rocks were brecciated, and the varying permeability created channels to guide ore-forming solutions. Uranium ore is found in association with intensely brecciated limestone or dolomite slabs and along contacts between these rocks and Precambrian muscovite schist and granite. Baker and Scott (1961, p. 489) described lenses containing 2,000–60,000 short tons of ore that occurred in or adjacent to limestone wedges. Finely disseminated pitchblende in the Pitch mine deposit is also found in sandstone in the Belden Formation. This ore is commonly found in the general vicinity of coaly carbonaceous shale layers in the Belden, although the carbonaceous material, itself, generally does not contain uranium concentrations.

URANIUM IN PRECAMBRIAN ROCKS

Numerous uranium occurrences are known in the Precambrian rocks of the Marshall Pass district and nearby areas, but production has been small. Deposits in Precambrian rocks are found at the Lookout No. 22 and Marshall Pass No. 5 mines in the Harry Creek area, and at the Bonita mine in a nearby area east of the district. Deposits at the Lookout, Marshall Pass, and nearby claims are in mineralized sheared and brecciated zones in Precambrian coarse-grained granite containing inclusions of biotite gneiss and schist. The shear zones prospected in the Harry Creek area strike predominantly northeast and dip steeply, and the wall rocks are altered and hematitic.

At the Lookout No. 22 mine, on the steep west side of the canyon of Harry Creek, 514 short tons of ore were produced from colluvium overlying a shear zone between Precambrian coarse granite and schist. The

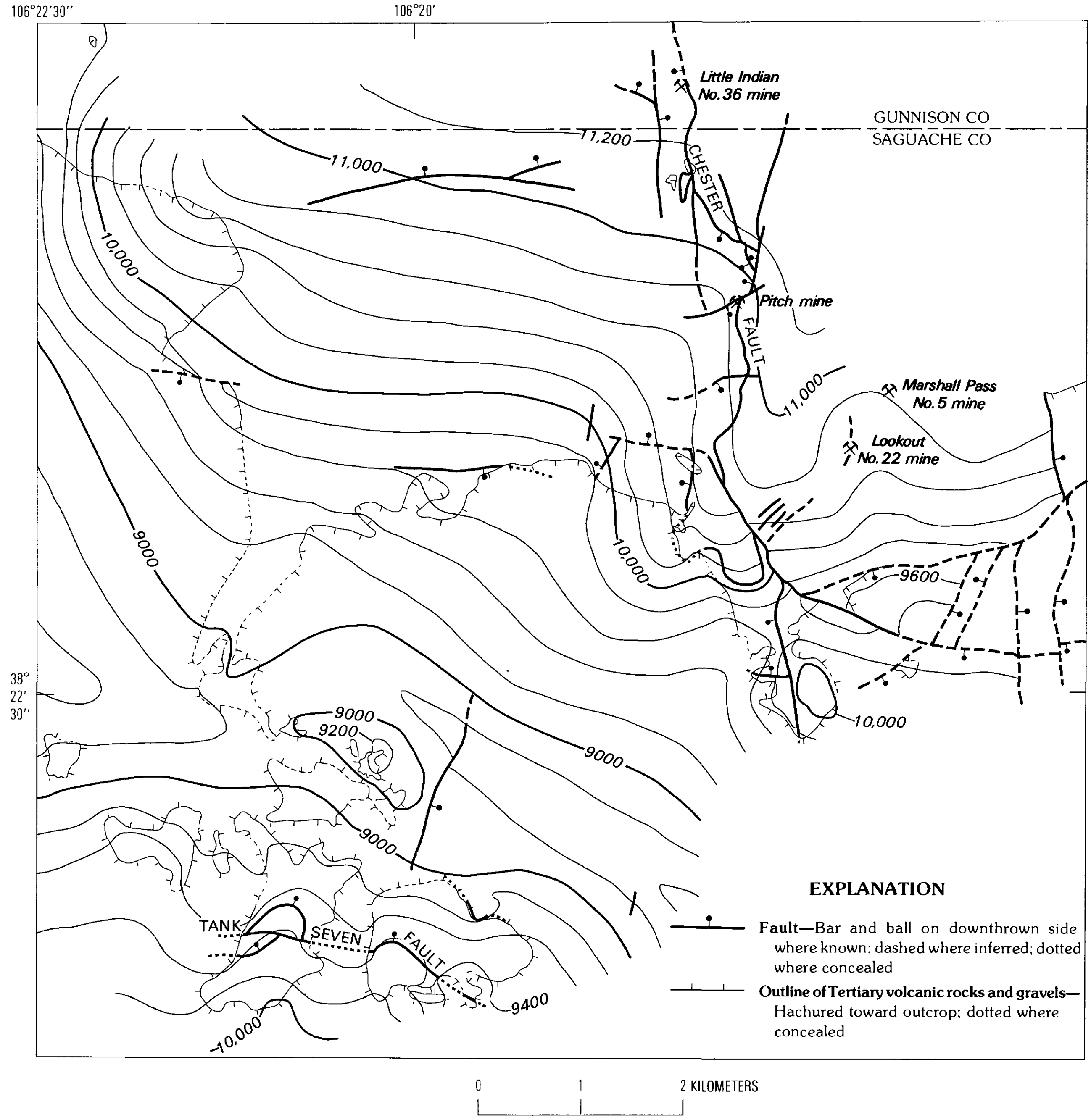


FIGURE 17.—Inferred structure contours on base of Tertiary volcanics and gravels, Marshall Pass district. Contour interval, 200 ft.

uranium minerals and sulfide minerals replace the schist. Radioactive minerals (Gross, 1965) include uraninite, schoepite, epiianthinite, becquerelite, soddyite, boltwoodite, uranophane, zeunerite, metazeunerite, and a hydrated autunite. Other minerals present are tetrahedrite, chalcopyrite, sphalerite, chalcocite, covellite, galena, pyrite, and marcasite. Uraninite is reported to occur in banded and colloform masses showing fractures and microfaults that have been rehealed by later uraninite. According to Gross (1965), secondary uranium minerals and sulfides cut the uraninite and occur interstitially between banded masses.

The Lookout No. 22 mine has also been described by Malan (1959, p. 15), who reported that a vein about 1 m thick that strikes N. 20° W. and dips 70° SW. underlies the uraniferous colluvium. The walls are coated with adularia, and wall rocks are silicified for about a meter

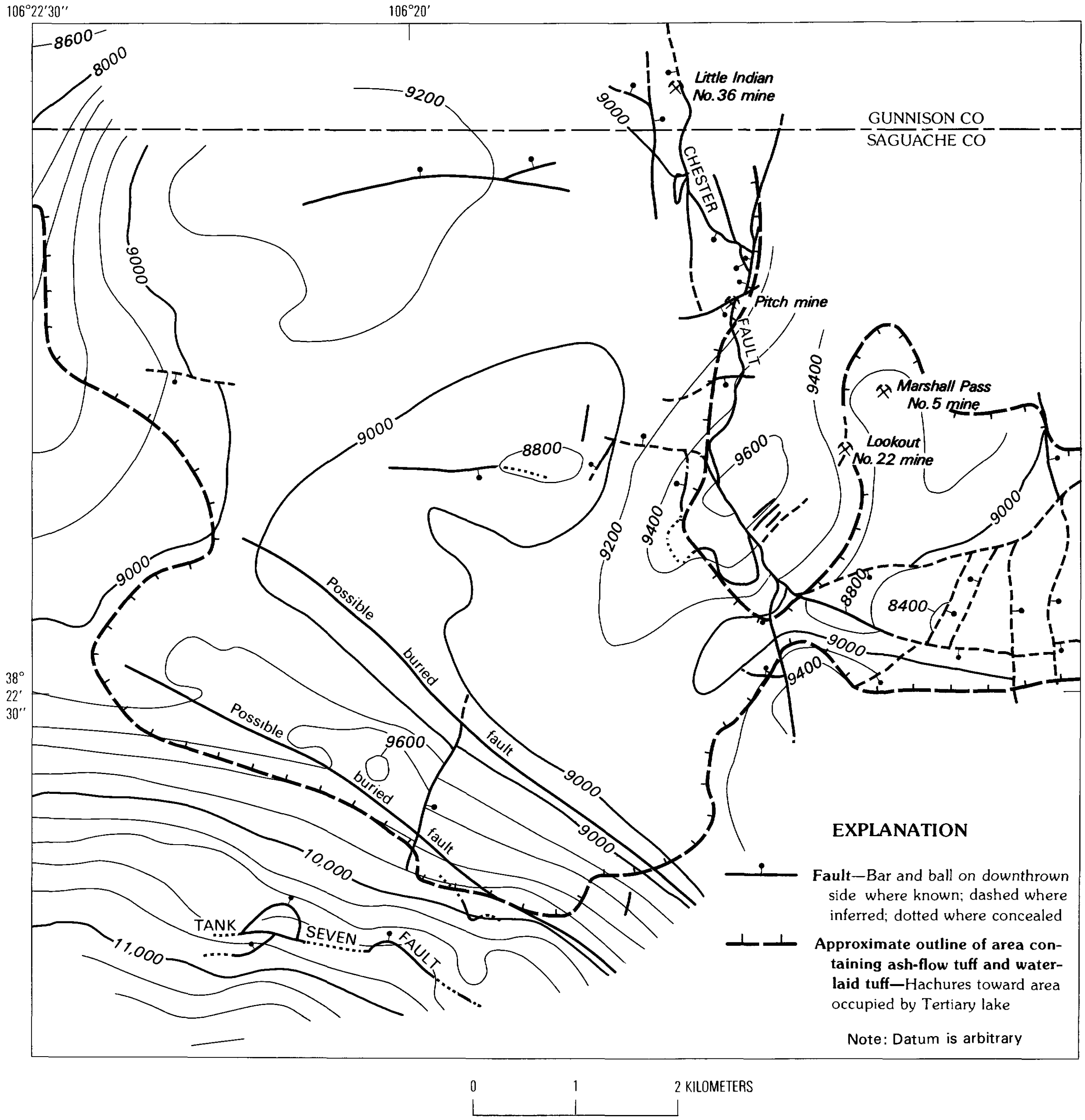


FIGURE 18.—Inferred structure contours on base of Tertiary volcanics and gravels, if present surface is tilted 7° toward N. 22°30′ E. Contour interval, 200 ft.

outward from the vein. Breccia fragments of wall rock were cemented by silica, followed by further brecciation and introduction of silica into veinlets. Unoriented quartz crystals line the walls of the veinlets and grade from fine to coarse inward from the walls. Five other nearby prospect pits show epigenetic concentrations of uranium minerals in this type of geologic setting, and silicification preceded the uranium mineralization in these occurrences as well as that of the Lookout No. 22 mine.

The Marshall Pass No. 5 mine is on a steep south-facing slope in a tributary drainage west of Harry Creek. The mica schist country rock at the mine is intruded by dikes generally less than 1 m thick of pegmatite, granite gneiss, and aplitic granite. Pyrite and hematite fill narrow fractures in the various rocks, and quartz of at least two generations occurs as veinlets and cement between breccia fragments of the country rock. According to Malan (1959, p. 15–16), uranium ore was found as float in the colluvium, but no in situ ore was visible at the time of Malan's examination. Uranium minerals reported in the ore include pitchblende and its alteration products, in which becquerelite has been identified by X-ray diffraction as one of the major components. The pitchblende is associated with chalcocite, covellite, galena, and secondary hematite and (or) goethite.

The Bonita mine is on Poncha Creek about 0.8 km below the confluence of Starvation Creek and Poncha Creek, 12.3 km east of the Pitch mine, in sec. 23, T. 48 N., R. 7 E. Although outside the main Marshall Pass district, the Bonita deposit is described here because of its comparable geologic setting and proximity to deposits in the district. The workings consist of a drift running N. 80° W. from a portal immediately above the meadow in the bottom of Poncha Creek valley. The drifting was begun in the fall of 1954, and a small amount of ore was produced (table 1) from 1955 to 1958 (Nelson-Moore and others, 1978, p. 389). Underground workings are reported to total about 375 ft in length. In 1974, a bulldozer cut was dug in an outcrop of dark volcanic flow rock west of the portal of the drift.

The drift portal at the Bonita mine is in a small outcrop of Precambrian gneissic granite. The granite is overlain by Tertiary volcanic rocks consisting mostly of dark dacitic or andesitic flows and breccias, which blanket the area for several kilometers surrounding the claims and generally dip 20° S. to 20° SW. Near the base of the Tertiary volcanics, a light-colored porphyritic volcanic unit about 30 m thick occurs on the slope above the portal and in an outcrop on the south side of Poncha Creek. This rhyolite porphyry contains about 40 percent feldspar phenocrysts in a very fine grained matrix. According to Malan (1959, p. 16–18), the Precambrian gneissic granite and associated pegmatite and schist are directly overlain by a mineralized, arkosic, carbonaceous regolith. In this zone, which is as much as 0.6 m thick, uraninite occurs in, and is essentially restricted to, discontinuous seams of carbonaceous material. Rocks near the mineralized zone are commonly altered to sericite, clay minerals, and hematite. Autunite occurs in the oxidized zone. The carbonaceous material is thought to have collected in a small, restricted drainage basin prior to deposition of the 30-m thickness of light-colored volcanics. The rhyolite porphyry layer is overlain by a carbonaceous shale bed 0.5–1 m thick dipping 25° SW. Where exposed underground, the shale is highly argillized and iron stained. Pollen and spores in the shale have dated it as Eocene (Malan, 1959, p. 16). A great thickness of andesitic volcanics overlies the shale.

Several faults occur in the Bonita mine area. One vertical fault, striking about N. 80° W., cuts granite at the portal. A prominent brecciated, silicified shear zone cuts Precambrian granite about 100 m west of the mine workings, striking N. 45° W. and dipping 70° NE. Another fault 120 m east of the mine portal strikes N. 10° W. between Tertiary basalt porphyry and Precambrian granite gneiss. At least two small northwest-trending faults were encountered in the mine workings.

URANIUM IN THE HARDING QUARTZITE

The Harding Quartzite is the host rock for several uranium deposits in the Marshall Pass district and in several localities to the southeast in the western part of the map area of the Pueblo 1°×2° quadrangle. Figure 19 shows the area of outcrop of lower Paleozoic sedimentary rocks in the region encompassing the Marshall Pass district and the western part of the Pueblo 1°×2° quadrangle. The Harding Quartzite is one of several Paleozoic units shown on figure 19.

In the Marshall Pass district, a limonitic zone 1–2 m thick about 2–3 m below the top of the Harding Quartzite is commonly uraniferous. This zone is characterized by carbonaceous material, fish scales and other fossil remains, and asphaltic pellets. Individual beds in the mineralized zone are mostly 5–20 cm thick and are chiefly sandstone (quartzite) with a few 5–10 cm shale beds. Four samples were collected from this zone north of Indian Creek in the area 700–1,000 m east of Bulls Creek. The four samples ranged from 19 to 250 ppm Ra_eU, 2 to 31.6 ppm thorium, and 0.56 to 2.3 percent potassium.

The uranium content of the 1- to 2-m-thick mineralized zone near the top of the Harding Quartzite ranges from 100 to 300 ppm in many places in the Marshall Pass district. In this zone the uranium is associated with pyrite, hematite, and goethite. Locally, the uranium content exceeds 300 ppm. For example, at the Little Indian No. 36 mine, which was worked from June 1957 to November 1958, the ore contained an average of 0.44 percent uranium oxide. This ore occurred in Harding Quartzite beds that are steep, nearly vertical, or overturned adjacent to the Chester reverse fault. Uranium minerals reported from the Harding Quartzite at this locality include uranophane, uraninite, autunite, and boltwoodite.

Uranium deposits in the Harding Quartzite are found at several places in the western part of the map area of the Pueblo 1°×2° quadrangle (fig. 19). Three deposits that will be discussed in the following paragraphs are the Noland Gulch, Rainbow's End, and Beginner's Luck prospects.

On the north side of Noland Gulch (fig. 19), in SW¼ sec. 32, T. 46 N., R. 9 E., the Harding Quartzite dips

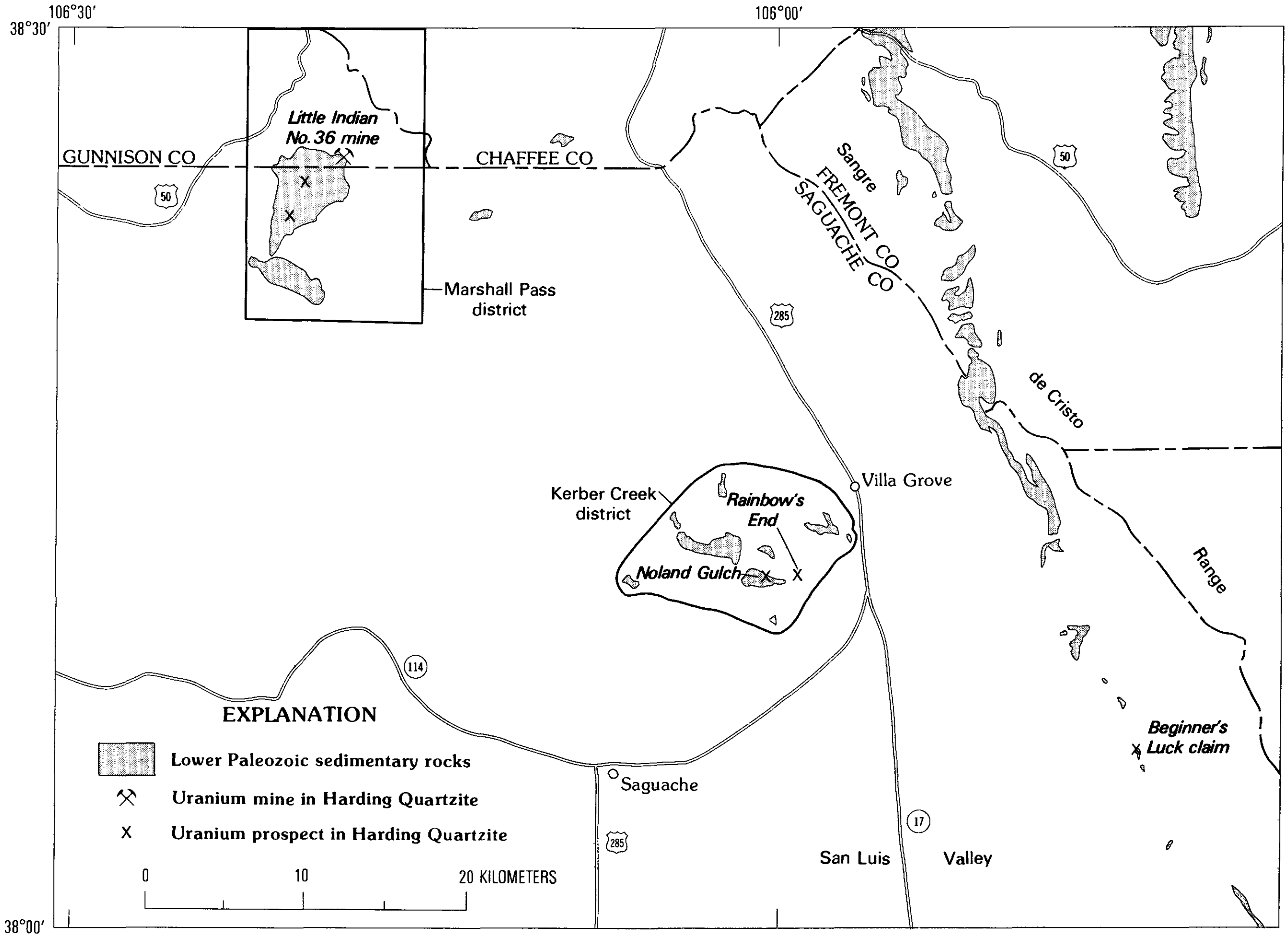


FIGURE 19.—Map of region encompassing the Marshall Pass district and the western part of the Pueblo 1°x2° quadrangle, showing localities prospected for uranium in Harding Quartzite and outcrop areas of lower Paleozoic sedimentary rocks. (Geology from Scott and others, 1978, and Tweto and others, 1976.)

50° SW. and is at least 13 m thick, where exposed in a prospect drift 0.8 km north of Noland Spring. The top 2 m is composed of greenish-gray quartzite, below which is 0.6 m of green and pink, fine-grained sandstone. The main zone prospected, 1.2 m thick, is a rusty brown layer 2.4–3.6 m below the top of the formation. This zone is underlain by 0.3 m of green shale, below which is at least 10 m of gray, white, and brown quartzite. The 1.2-m-thick mineralized zone shows the highest radioactivity with a scintillation counter, as much as 10 times background of nearby dolomite, whereas the 0.6-m-thick sandstone above and the 0.3-m-thick green shale below are four to five times background, respectively. The quartzite above and below the radioactive zone generally has less than twice background radioactivity.

The Rainbow's End prospects (fig. 19) have been described by Nelson-Moore and others (1978, p. 393). There has been no production from these prospects, but a few small pits have been dug in the S½NE¼ sec. 33, T. 46 N., R. 9 E. No uranium minerals are visible, but radioactivity as high as 0.18 mR per hour (background 0.02–0.09 mR per hour) is reported to be associated with limonite staining and carbonaceous matter, in the form of fish scales and asphaltic pellets, in a 1.4-m-thick carbonaceous bed in the upper part of the Harding Quartzite. An unidentified copper mineral is present in places.

On the Beginner's Luck claim, 9 short tons of ore were mined from the Harding Quartzite in 1955 at a grade of 0.15 percent uranium oxide and 0.09 percent vanadium oxide, yielding 26 lb of uranium oxide and 16 lb of vanadium oxide (Nelson-Moore and others, 1978, p. 388). The deposit is reported to be in the NE¼ sec. 33, T. 45 N., R. 11 E., extending into sec. 3, T. 44 N., R. 11 E. The host rock is compact, gray Harding

Quartzite that weathers to a dark-gray to buff color. Uranium is reported to occur in small discontinuous fractures, 1-5 ft long and several inches in maximum thickness, trending N. 41° W. and dipping 56° SW. in the quartzite. Uranium minerals include autunite; uraninite and coffinite have been reported.

SOURCE AND LOCALIZATION OF THE URANIUM DEPOSITS

A model for the origin of the Marshall Pass uranium deposits involves (1) a source of uranium, consisting predominantly of a thick accumulation of siliceous tuffs, (2) solution and transportation of dissolved uranium by ground waters percolating downward and laterally through permeable tuffs, (3) concentration of uraniferous waters by a paleohydrologic system that included the Tertiary lake and channeling of uraniferous waters into certain zones, and (4) a means of precipitating the uranium, probably a reducing environment with carbonaceous materials.

The most likely source rocks for the uranium in the deposits are the overlying light-colored siliceous tuffs. Study of structure contours on the pre-Tertiary erosion surface (fig. 17) indicates that the known uranium deposits were formed only a short vertical distance below the surface on which the ash-flow tuffs and waterlaid tuff were deposited. The structure contours, together with the extent of waterlaid tuff exposures, indicate a minimum extent of the Tertiary lake basin outlined on figure 18. Leaching of tuff in the watershed of this lake basin could have supplied ample uranium to form the deposits, which was probably carried in solution in ground waters percolating through zones of greatest permeability.

Other potential sources might be considered for supplying the uranium in the Marshall Pass deposits. For example, weathering and erosion of the Proterozoic granitic and metamorphic rocks in and near the district might have supplied some uranium, but the contribution from these Proterozoic rocks is thought to have been very small in comparison to the tuffs that were favorably situated above the deposits. Likewise, there is no evidence that the uranium was deposited from ascending hydrothermal fluids from a magmatic source; the only known Tertiary intrusive rocks in the district are the two small rhyolite plugs near the mouth of Duncan Creek and the thin quartz porphyry dikes near Porphyry Creek in the northwest corner of the area.

The formation of uranium deposits in the Marshall Pass district was controlled by faults, a sedimentary layer in the Harding Quartzite, and proximity to the erosion surface on which the Tertiary volcanics were deposited. The Pitch and Little Indian No. 36 mines are on the Chester fault zone, and deposits in Precambrian rocks in the Harry Creek area are also on faults that served to localize the ore-forming solutions.

The surface of unconformity beneath the volcanics was probably an important factor in the movement of surface and ground water. Proximity of the ore deposits to the prevolcanics surface is demonstrated by remnants of welded tuff atop Lime Ridge, together with larger patches of the same rock to the south near Marshall Creek. Before being partly eroded away, the surface beneath the volcanics was probably about 30-150 m above the present ground surface (fig. 20) at the Pitch mine, and probably within at most a few hundred meters at other deposits.

The Tertiary lake that covered at least 30 km^2 in the district may have been a factor in ore genesis, as siliceous waterlaid tuff as much as 200 m thick accumulated in the lake basin. At the time the lake existed, the position of the Chester fault near the Pitch mine was marked by an inferred fault-line scarp near the east shoreline. The uranium-mineralized faults in the Harry Creek area are also inferred to have been just beneath the prevolcanics unconformity and within the inferred outline of the Tertiary lake. Later, some postvolcanism faulting occurred and the tuff beds were folded and tilted to a variable southerly dip averaging about 8°. These structural movements modified the hydrologic regime and may have enhanced the conditions for water movement along faults and other aquifers.

Localization of uranium in a sandstone layer is illustrated by the deposits in the Harding Quartzite, which also show a probable relationship to paleotopographic features of the prevolcanics surface. In most of the district the uraniferous layer in the Harding was a few to a few hundred meters beneath the early Tertiary lake and the tuffs deposited in and around it. The uranium content, which is 100-300 ppm at many places in the Harding, may have been leached from tuffs in the lake basin and deposited in favorable locations beneath the paleotopographic surface. Uranium-bearing ground waters apparently migrated selectively in the thin Harding sandstone layer because of its greater permeability than the surrounding dolomites and limestones. The richest uranium concentration in the Harding, averaging 0.44 percent, is the Little Indian No. 36 deposit, at a point where the Chester fault cuts steeply dipping Harding Quartzite; the uranium concentration here is attributed chiefly to the effect of fracturing along the fault.

Whereas physical factors involved in localizing the uranium are evident, the chemical factors in precipitating the uranium minerals are less obvious. The

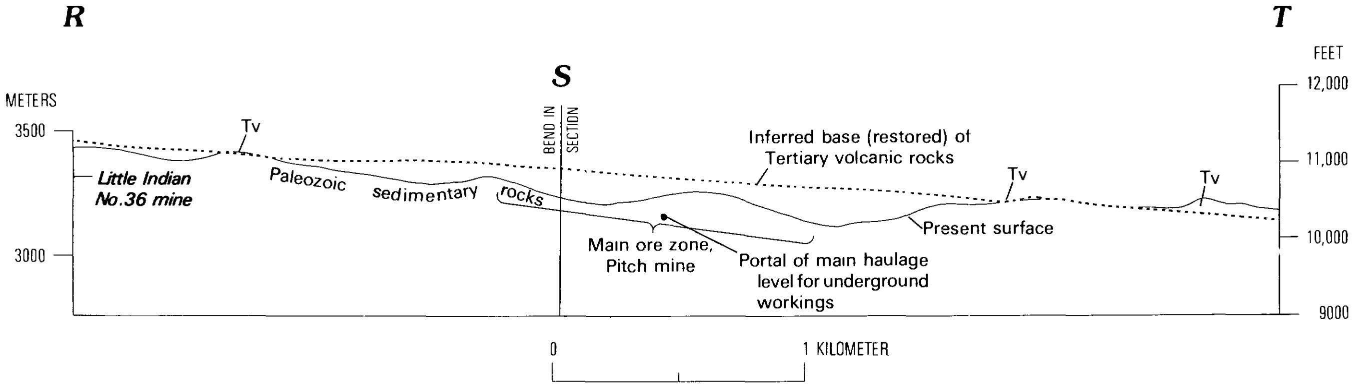


FIGURE 20.—Projection showing three exposures of Tertiary volcanic rocks (Tv) in relation to the Pitch mine. Line of projection *R-S-T* shown on figure 13.

carbonaceous material commonly associated with uranium ore probably aided in precipitating the uranium minerals. In the Harding Quartzite, the uranium-bearing zone, 1–2 m thick, contains carbonaceous material, fish scales and other fossil remains, and asphaltic pellets. These organic remains provided reducing conditions to cause precipitation of uranium carried in subsurface waters. In the large fault-controlled deposits at the Pitch mine, the Belden Formation contains abundant coaly carbonaceous material in the vicinity of ore in many places in the fault zone, a favorable reducing environment for uranium precipitation. The carbonaceous material itself contains very little uranium, however. The dolomite commonly associated with ore has anomalous iron and sulfur (0.35 percent) contents (Nash, 1981, p. 197), which, along with the coaly carbonaceous material, may have contributed to a favorable reducing environment for ore deposition.

The uranium deposit at the Bonita mine, 10 km east of the Marshall Pass district, is a nearby example of uranium concentrated by similar processes to those described in the genetic model for the Marshall Pass district. The layer of light-colored siliceous volcanics that overlies the erosion surface on Precambrian granite gneiss, at the base of the Tertiary volcanics section, is a potential source rock from which uranium may have been leached by ground waters. The uranium at the Bonita mine was concentrated just beneath the volcanics in the regolith zone, as much as 0.6 m thick, which contains carbonaceous material that presumably provided reducing conditions to precipitate the uranium.

APPLICATION OF GENETIC MODEL TO URANIUM EXPLORATION

Exploration for uranium in the Cochetopa and Marshall Pass districts and in comparable areas might be aided by consideration of the genetic model proposed for uranium deposits in these districts.

Uranium deposits in the Cochetopa district illustrate the genetic model in having (1) abundant siliceous tuff nearby to provide a potential source of uranium through leaching, (2) a paleohydrologic system through which supergene uraniferous ground waters could migrate downward and laterally and be localized in channelways such as the buried Cochetopa paleovalley, (3) the Los Ochos and other faults as permeable zones to further channel and trap the uraniferous ground waters, and (4) localized reducing conditions, as indicated by sulfur-bearing minerals and asphaltite in small amounts, to promote the precipitation of uranium.

Likely places to search for uranium, having the favorable criteria as indicated by the genetic model, exist in unexamined parts of the Cochetopa district. In the western part of the Cochetopa district, for example, the drainage basins of South Beaver Creek and Sugar Creek contain fault zones in older rocks overlain by remnants of volcanic rocks that include siliceous tuffs. Somewhat similar relationships can be found in the area of lower Razor Creek near its confluence with Tomichi Creek.

A similar genetic model applies to the Marshall Pass district, although details of the geologic setting are different: (1) Large volumes of siliceous tuff had been deposited in the low parts of the Tertiary lake basin by ash flows and by erosion and redeposition of similar tuffaceous material from nearby areas. (2) The uranium was probably leached from the tuff and carried by downward- and laterally-moving ground waters. (3) The Chester and other faults, such as those in the Harry Creek area, along with sandstone beds in the Harding, provided permeable zones for the movement and localization of uraniferous water. (4) Uranium may have been precipitated under reducing conditions in the presence of carbonaceous material as found locally in the Belden Formation and Harding Quartzite.

Fault zones in the Marshall Pass district, particularly where covered by younger tuffaceous rocks, are probably the most favorable sites for undiscovered uranium occurrences, and some faults are no doubt buried by younger rocks. Inasmuch as the Tertiary lake and its tuffaceous sediments are inferred to have extended northwestward to Tomichi Creek and thence northward in Tomichi Creek valley 10–13 km from Sargents, as far north as Deadman Gulch, a possibility exists for uranium deposits to occur near the pre-Tertiary erosion surface in this area. Although fault zones comparable to the Chester fault are not known in this area, several faults have been mapped beneath the Tertiary rocks (Raines, 1971), and several cut the Tertiary rocks in the Tomichi Creek valley north of Sargents.

The genetic model outlined above can be applied to uranium deposits in the Harding Quartzite. The most important factors in causing uranium mineralization in the Harding are its permeability, which permitted access to uranium-bearing ground waters, and its content of organic material, which provided reducing conditions necessary to precipitate the uranium. According to this epigenetic interpretation of origin, the most likely places to find uranium deposits in the formation are places where a source for uranium can be postulated to provide uranium to the ground-water system. In the Marshall Pass occurrences, and probably the Kerber Creek also, the areas where Harding was overlain by siliceous, tuffaceous volcanics may offer the best potential for uranium. The mineralized zone in the Harding Quartzite lay beneath the Tertiary lake, and in much of the area had a gentle southeasterly dip (fig. 16) toward the Chester fault. One might presume that the more uraniferous parts of the Harding were nearer the erosion surface at this time, but this is difficult to determine because of sparse data on which the position of the surface is inferred.

Known occurrences indicate that uranium deposits in the Harding are likely to be less than 2 m thick and low grade (200–300 ppm). The high-grade deposit at the Little Indian No. 36 mine is localized in a particularly favorable structural position in the Chester fault zone. Unless such structural controls are found, the potential of the Harding Quartzite for large tonnages of high-grade ore is not great, although small, low-grade occurrences may be common in some areas.

In other parts of the world, vein-type uranium deposits have also been found in older rocks below unconformities, in situations comparable to those of the Cochetopa and Marshall Pass districts, or in rocks immediately above unconformities. The hypothesis that such deposits may be formed by supergene processes has been subscribed to by many workers in Canada, Australia, Spain, France, Japan, and other parts of the world. The source of the uranium is commonly ascribed to leaching of siliceous volcanic rocks in the section above the unconformity or to leaching of granitic rocks in adjacent areas near the unconformity. As in our model, faulting is commonly an important ore control, and in some districts the shape of the buried topography may have been a factor in ore control.

Outside of the Cochetopa and Marshall Pass districts, there are several areas in the United States, particularly the Western States, where the elements of this genetic model may be applicable. Some similarities may be found, for example, in the Stanley Basin, Idaho, where uranium deposits are localized near the unconformity beneath the lower Tertiary Challis Volcanics. In the Tallahassee Creek area, Colorado, uranium deposits are found in the lower part of the Tertiary section of volcanic rocks and gravels, and some deposits extend into underlying Precambrian rocks. Other areas of Colorado that may contain uranium deposits similar in origin to those described in this report are South, Middle, and North Parks, and some Front Range areas including Kenosha Pass. Elsewhere in the West, similarities in geologic relationships and probably in genesis are shown in the Copper Mountain district, Wyoming; the Northwest uranium deposit and nearby areas in northeastern Washington; the Sonora Pass district, California; and several small uranium districts in the Basin and Range region, for example the Olancha, Calif., and Hallelujah Junction, Calif.-Nev., districts. Several districts have been cited by Nash (1980) as examples of structural control of ore deposition along major thrust faults.

Many other districts could no doubt be added, but the few examples listed serve to illustrate types of districts in which faults and ancient erosion surfaces may be important guides to uranium deposits, which may occur both above and immediately below the erosion surface, particularly where suitable source rocks such as overlying siliceous tuffs are present. Thus the delineation and study of ancient erosion surfaces and drainage systems may be useful, in conjunction with studies of structural features such as faults, as guides in exploration for deposits in similar geologic settings.

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