Geology and Geochemistry of the Pitch Uranium Mine Area, Saguache County, Colorado

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Geology and Geochemistry of the Pitch Uranium Mine Area, Saguache County, Colorado

By J. THOMAS NASH

Description and interpretation of the geology and geochemistry of a new type of uranium deposit that occurs chiefly in brecciated dolomite

U.S. GEOLOGICAL SURVEY BULLETIN 1797

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Geology and Geochemistry of the Pitch Uranium Mine Area, Saguache County, Colorado

By J. Thomas Nash

Abstract

Uranium ore in the Pitch mine, Saguache County, Colorado, occurs chiefly in brecciated Mississippian Leadville Dolomite along the Chester fault, and to a lesser extent in sandstone, siltstone, and carbonaceous shale of the Pennsylvanian Belden Formation and in Precambrian granitic rocks and schist. Uranium-mineralized zones are generally thicker, more consistent, and of higher grade in dolomite than in other hosts, and roughly 50 percent of the reserves are in dolomite. Strong physical control by dolomite is evident, as this is the only rock type that is pervasively brecciated within the fault slices that make up the footwall of the Chester upthrust fault. Other rocks tended either to remain unbroken or to undergo ductile deformation. Chemical controls on uranium deposition are subtle and appear chiefly to involve coprecipitation of iron sulfide (pyrite or marcasite) with pitchblende and coffinite, suggesting that sulfide ion may be the reductant.

Chemical analyses of 116 rock and ore samples demonstrate that ore-bearing dolomites are significantly enriched in Fe, K, S, Mo, Cu, and Ni. Some statistical tests suggest that rocks high in Si, Al, Ba, Sr, Pb, Zn, and V are also enriched with uranium. The strong association of uranium with sulfur, ferrous iron, and molybdenum is most important geochemically. Petrologic studies reveal only minor alteration of dolomite adjacent to pitchblende and coffinite. The dark carbonate rocks are not bleached, but minor amounts of very fine grained silica were precipitated along with pitchblende-coffinite-pyrite or marcasite. Rocks in near-surface and permeable fault zones were oxidized, the uranium was leached, and soft ocher-colored dolomite was formed. The rock chemistry and the association of pitchblende with marcasite and pyrite suggest a hypothesis: uranium was reduced and deposited by aqueous sulfide derived from metastable sulfur compounds such as thiosulfate or through biogenic reduction of sulfate.

The Little Indian deposit, 2 km north of the Pitch mine, is likewise localized along the footwall of the Chester upthrust, chiefly in fractured Ordovician Harding Quartzite. The mineralogy and chemistry of the Little Indian deposit contrast with the Pitch deposit: iron and uranium minerals are oxidized, and P, As, Ti, Mn, Sr, Ba, and Mo are enriched in ore. Most uranium in the Little Indian was deposited in response to reactions with anions such as phosphate, arsenate, or silicate, rather than with sulfur. Some uranium is associated with organic pellets, and pyrite was formerly present, suggesting that an older period of uranium enrichment by reduction could have been important.

The Leadville Dolomite is the most important host for uranium in the Pitch mine, but other units contain important uranium resources where fractured along the Chester fault. Brittle character is a prime requirement of favorable host rocks. Chemical properties of favorable host rocks are also important and seem to involve pre-ore sulfides and organic matter. The juxtaposition by faulting of blocks of brecciated Leadville Dolomite and organic, sulfide-rich shale and fine-grained sandstone of the Belden Formation, may have provided the required combination of structural permeability and source of reductant.

The Laramide age of the Chester fault is a maximum age for the uranium deposits. The most likely age is Oligocene, when volcanic rocks covered the fault zone, because alteration of volcanic rocks is the most likely source of uranium and silica that formed jasperoid bodies in the fault zone. Observed and interpreted features at the Pitch deposit suggest a model of formation that has wide application to the Western United States. Key factors are (1) a wide zone of brecciation, commonly produced by upthrusts in brittle rocks; (2) a reductant provided by reactive pre-ore sulfide minerals or organic material and sulfate-reducing bacteria; and (3) a viable source of uranium, such as altered volcanic rocks. Pitch-type deposits can be anticipated to potentially contain 2,000–30,000 tonnes U_3O_8 with mixed high and low grades.

INTRODUCTION

The Pitch uranium mine is located in the Sawatch Range in Saguache County, Colorado, about 60 km east of Gunnison (fig. 1). The Pitch mine (formerly known as the Pinnacle mine or Erie No. 28 claim) and several other uranium prospects were located in 1955. Development of the Pitch mine began in 1959 with the opening of two adits. The mine closed in 1962 when its contract with the U.S. Atomic Energy Commission expired. About 100,000 tons of ore averaging 0.50 percent U_3O_8 (1,000,000 lb U_3O_8) were mined, and another 100,000 lb U_3O_8 were recovered by solution mining (Ward, 1978). In 1972, Homestake Mining Company acquired the property and began to reevaluate the mine area for additional

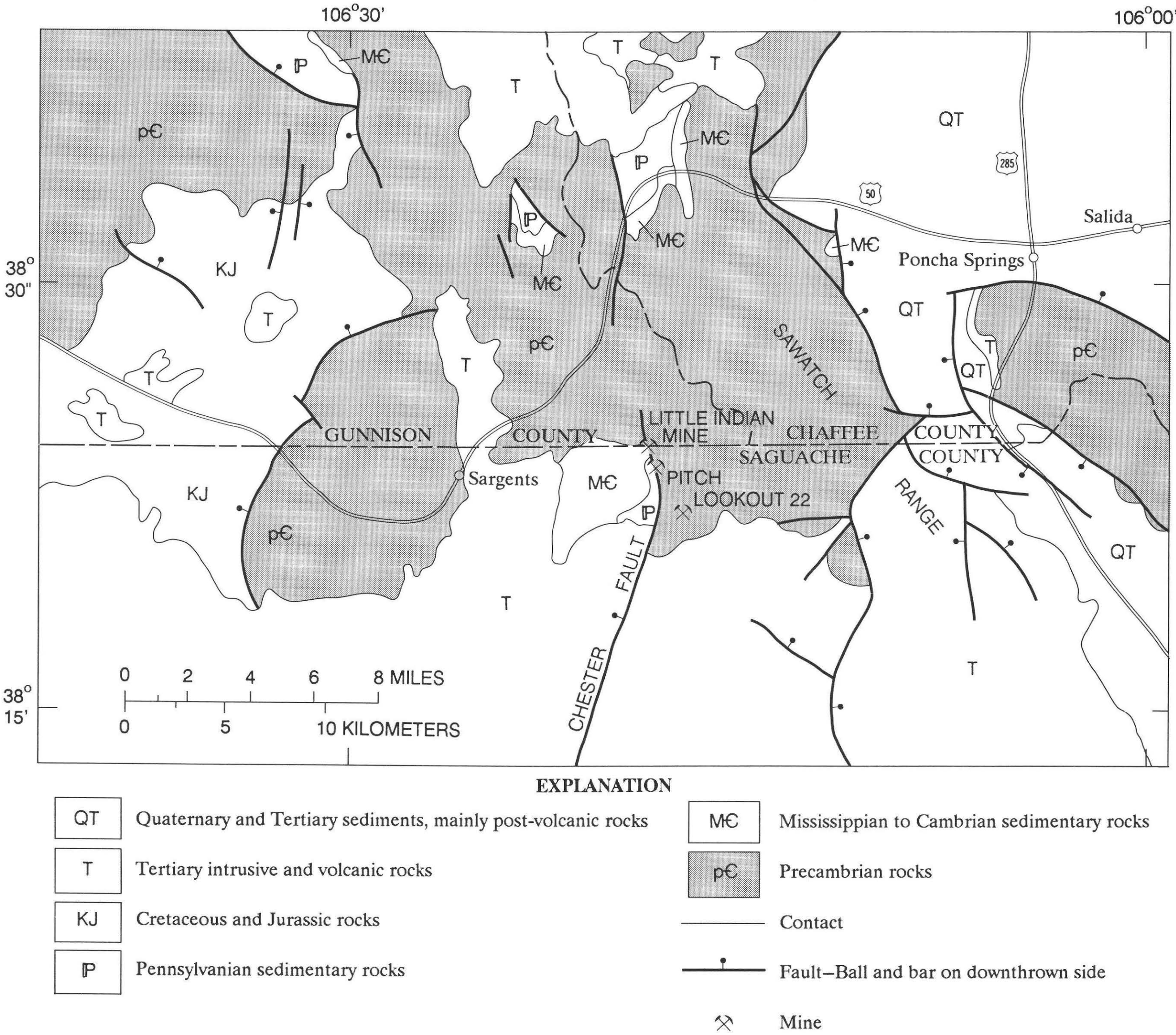

Figure 1. Generalized geologic map showing location of Pitch mine, Colorado (after Tweto and others, 1976).

reserves amenable to open-pit mining, because the previous history had demonstrated that fault offsets of ore and unstable wall rocks made underground mining costly.

In the period 1972–77, Homestake Mining Company documented a reserve that was minable by open-pit methods of 1.91 million tonnes of ore at an average grade of 0.17 percent U_3O_8 (3,245,000 kg U_3O_8) (Ward, 1978). Rather than seek high-grade "vein-type" ore, Homestake explored for more dispersed ore using vertical rotary drilling supplemented by about 10 percent angle and vertical core drilling. Success came in 1973 when the company recognized a "new type" of ore in brecciated dolomite of the Mississippian Leadville Dolomite. The dolomite was found to be complexly faulted between slices of sandstone, siltstone, and shale of the Pennsylvanian Belden Formation. Much of the ore mined from 1959 to 1961 also probably was in Leadville Dolomite, but was not recognized as such (J.M. Ward, Homestake Mining Co., oral commun., 1979). Homestake mined the deposit at a rate of about 600 tons per day from an open pit from 1979 to December 1983.

This study began in 1977 in conjunction with exploration and pre-mine development by Homestake Mining Company, and as a follow-up to geologic mapping by J.C. Olson (1983). A small test pit exposed part of the ore zone, but most of the study involved drill core and cuttings. About 9,000 m of drill core in 73 drill holes were logged, and more than 400 samples were taken; samples from roadcuts were taken as the best source of least altered rocks distant from ore. Major and minor elements were analyzed in 135 samples of core and outcropping rocks, about 150 thin and polished sections were studied on the microscope, and hundreds of samples were analyzed by X-ray diffraction. Thin sections were stained with alizarin red to impart a red stain to calcite, but X-ray diffraction proved most reliable for carbonate mineral identification. Some data included in a preliminary report (Nash, 1979) are not repeated here, but 36 new rock analyses are reported.

This study was made possible by the full cooperation of the Homestake Mining Company in providing base maps, access to the mine area, and samples of drill core. J. Mersch Ward, Homestake Mining Company, was a cordial host and provided much useful discussion. J.C. Olson, J.A. Campbell, N.S. Fishman, and A.R. Wallace offered helpful advice and comments on manuscripts.

URANIUM DEPOSITS

This report focuses on uranium deposits at the Pitch and Little Indian mines, both localized along the Chester fault. Uranium deposits occur in five rock types in the Marshall Pass area (Malan, 1959; Olson, 1983) and will be briefly reviewed here to orient the reader. The following discussions are arranged by decreasing age of host rocks; the ages of ores are not known.

Precambrian biotite schist.—Several prospects and small mines occur in the Harry Creek area (Lookout 22, Marshall Pass No. 5 prospects) about 2 km east of the Pitch mine. Uranium minerals probably include pitchblende and some hexavalent uranium minerals. Near these veinlike deposits are high-grade concentrations of uranium in alluvium (type 5 below).

Precambrian pegmatite.—Shears in Precambrian pegmatite in the Pitch mine area contain pitchblende, including the discovery outcrop for the Pitch mine (Ward, 1978).

Middle Ordovician Harding Quartzite.—Uranophane and other U^{+6} minerals fill fractures in the quartzite and generally are accompanied by limonite (Malan, 1959). A carbonaceous bed containing fish scales at the top of the Harding is radioactive. This bed guided prospectors to the Little Indian 36 deposit, where the Harding is fractured along the Chester fault 2 km north of the Pitch mine. Production from the Little Indian 36 mine from 1957 to 1959 was about 6,180 tonnes of ore with a grade of 0.48 percent U_3O_8 (29,550 kg U_3O_8) (Ward, 1978).

Lower Mississippian Leadville Dolomite and Lower and Middle Pennsylvanian Belden Formation.—Oxidized and reduced uranium minerals at the Pitch mine occur in dark-gray dolomite, sandstone, black shale, and coaly shale. Oxidation occurs to depths of about 100 m. In oxidized zones, disequilibrium is great and radioactivity is much in excess of chemical uranium content (Malan, 1959). Pyrite occurs in most unoxidized rocks, but many pyritic rocks have very low uranium content. Fractures, shears, and breccia zones host the uranium ores. Past production from the Pitch (Pinnacle) mine was about 500,000 kg U_3O_8 (Ward, 1978). Carbonaceous shales of the Belden are radioactive in many places, as at the mouth of Indian Creek, 6 km southwest of the Pitch mine. These radioactive shales apparently first attracted prospectors to the Marshall Pass area but no significant uranium concentrations have been found in Belden shales except at the Pitch mine.

Eocene(?) carbonaceous regolith.—Several unusual small, but high-grade, concentrations of uranium have been mined from "alluvium" (Gross, 1965) and carbonaceous regolith developed in Precambrian gneiss and schist and in places overlain by Tertiary volcanic flows (Malan, 1959). Mined localities were at the Lookout No. 22 claim, previously mentioned, and the Bonita claims east of the Continental Divide (about 11 km east of the Pitch mine). Pitchblende and a number of U^{+6} minerals have been identified from these deposits (Malan, 1959; Gross, 1965). Most of the several hundred tonnes of high-grade ore (about 1,770 kg U_3O_8) produced from these deposits was from the pockets in alluvium and a lesser amount from veinlike deposits within Precambrian host rocks (type 1) (Malan, 1959; Ward, 1978).

GEOLOGY

Stratigraphy

Rocks ranging in age from Early Proterozoic(?) to Oligocene(?) are exposed in the Pitch mine area. All units except the Oligocene(?) volcanic rocks contain uranium deposits, but the Leadville Dolomite is the most important host rock. The following description of rock units is primarily from Olson (1983).

Early Proterozoic(?) rocks.—The chief Early Proterozoic(?) rock type in the area is medium-grained red biotite granite. It is weakly foliated and generally friable from weathering. Quartz-muscovite-orthoclase pegmatites cut the granite in many places. Mica schist and hornblende gneiss occur as pendants in the granite. Granite and schist exposed in drill core are friable and soft. Deep road cuts in the granite along U.S. 50 about 6 km to the north expose no fresh granite.

Sawatch Quartzite (Upper Cambrian) and Manitou Dolomite (Ordovician).—Cambrian and Ordovician sedimentary rocks unconformably overlie the Precambrian basement. The oldest unit, the Upper Cambrian Sawatch Quartzite, is a clean, vitreous, medium-grained quartzite less than 1 m thick. It occurs in a small area just north of the Little Indian mine. The oldest of four similar appearing dolomite units is the Lower Ordovician

Manitou Dolomite. This 75- to 90-m thick unit of generally massive bedded dolomite was deposited unconformably on Precambrian rocks or conformably on the Sawatch Quartzite. The color is light gray when weathered and somewhat pink on freshly broken surfaces. Chert lenses and nodules a few centimeters long are common along bedding planes.

Harding Quartzite (Middle Ordovician).—The Harding Quartzite is a distinctive marker horizon in the Paleozoic section dominated by dolomitic rocks. The lower part consists of about 9 m of indurated medium- and fine-grained quartzite that forms well-exposed ledges. The upper 2–3 m are black shale and limonitic sandstone with distinctive fish scales, asphaltic pellets, and fossil trash; this unit is regionally radioactive. The Harding contains scattered low-grade uranium deposits at the Apache No. 4 prospect on Indian Creek, about 3 km west of the Pitch mine, and at the larger Little Indian deposit (Little Indian 36) 2 km north of the Pitch mine (fig. 1).

Fremont Dolomite (Upper Ordovician).—The Fremont Dolomite conformably overlies the Harding. The Fremont is about 55 m thick, chiefly massive-bedded medium-gray dolomite with lesser amounts of pale-gray limestone. Fossils are more common than in the other carbonate units. Fremont carbonates yield a distinctive fetid or petroliferous odor when freshly broken. Fractured Fremont Dolomite contains some hexavalent uranium minerals in the Little Indian deposit.

Chaffee Group (Upper Devonian and Lower Mississippian(?).—Unconformably overlying the Fremont is the Upper Devonian and Lower Mississippian(?) Chaffee Group, consisting of a lower red to gray-green shale and coarse-grained sandstone unit, the Parting Quartzite, and an upper unit, the Dyer Dolomite. The Parting is poorly exposed and only 3–6 m thick, but the green glauconitic fragments from it are a good marker. The Dyer Dolomite, about 50 m thick, consists of thin-bedded shaley limestone and dolomite and some massive dolomite. The pale-yellow to tan color on weathered surfaces is distinctive. The Dyer and overlying Lower Mississippian Leadville Dolomite are a regressive-transgressive marine sequence in western Colorado and, to the north, are separated by the Gilman Sandstone (Campbell, 1970). There is no sandstone equivalent to the Gilman in the Pitch mine area, which makes it difficult to locate the contact of the dolomites. On the basis of drilling patterns north of the Pitch mine, the Dyer appears to contain uranium deposits in the footwall of the Chester fault.

Leadville Dolomite (Lower Mississippian).—The Leadville Dolomite is about 130 m thick in the area, depending upon amount of pre-Belden erosion. The Leadville generally is dark-colored massive-bedded dolomite, although a few zones of pale-gray limestone are known. Some outcrops appear sandy, but under the microscope, quartz sand grains are rarely seen. Much of the Leadville is very fine grained dolomicrite that breaks with conchoidal surfaces, and some is crystalline with dolomite rhombs 100–200 μm (micrometers) in size. Centimeter-scale pods of black chert and intrabed slumps and faults are associated with the crystalline dolomite zones in some places. Calcite and chalcedony veinlets are common and often can be used to distinguish the Leadville from other dolomites. The upper surface of the Leadville is gently eroded and cut by caverns filled with iron oxides. The ferruginous material, probably karst filling, has the appearance of a gossan and was thoroughly, but unsuccessfully, prospected years ago. The limonitic filling is faintly radioactive. Leadville Dolomite is the most important host rock in the district in the newly developed Pitch mine, and because of this, it was investigated in detail in this study.

Some relations in the area suggest the possibility that the Leadville was deposited unconformably on Precambrian rocks of the ancient Sawatch uplift (DeVoto, 1980). Some drill-core intercepts and a series of backhoe trenches at the south end of the mineralized zone expose Leadville Dolomite resting on hematitic clay-altered Precambrian granite. The red clay zone is about 1–2 m thick and is sheared. The hematitic material resembles a regolith. There are no terrigenous clastic beds near this possible depositional contact, and thin sections of dolomite reveal it to be normal dolomicrite with less than 1 percent clastic quartz. Also, the Leadville section does not thin significantly toward the hypothetical uplift. On a regional scale, a large paleoslope would be required to permit both Leadville Dolomite and Sawatch Quartzite to have been deposited on the Precambrian. The Sawatch depositional contact is 2 km north of the Pitch mine and about 250 m lower in the section. The localities showing Leadville on regolith are interpreted to be fault contacts, even though the faults are not obvious in core. Maxiumum thickness of Leadville Dolomite in the mine is about 17 m, only a small fraction of the total Leadville section known in the area (about 130 m). It is not possible to establish the stratigraphic position of the Leadville in the mine because the formation is highly deformed, and the outlying Leadville displays no obvious internal units useful for correlation.

Belden Formation (Lower and Middle Pennsylvanian).—Unconformably overlying the Leadville is the Belden Formation, about 400 m of diverse lithologies including arkose, sandstone, shale, coal, and limestone of apparent fluvial-deltaic-marine origins. Facies changes are rapid, and surface outcrops suggest different compositions than do drill core because abundant soft clay-rich units are very poorly exposed. A lower unit is readily recognized by basal white kaolinitic sandstone and arkose, coal beds, and black to green-gray mudstone. The lower unit is about 90 m thick west of the Pitch mine.

The middle unit is characterized by pale-gray limestone and dark-red shale. The limestone forms discontinuous outcrops, but the poorly exposed shale is more abundant in drill cores. The middle unit is about 130 m thick. The upper unit is characterized by drab green-brown sandstone beds and gray shale. About 200 m of the upper unit is exposed near the Pitch mine; the top is not exposed.

Quartz Latite Tuff (Oligocene?).—The youngest rocks in the immediate Pitch mine area are poorly exposed remnants of sandy tuff less than 20 m thick that are part of an Oligocene(?) quartz latite ash-flow tuff unit. A few kilometers south and west of the mine are exposures of younger volcanic units that presumably once overlay the quartz latite unit in a volcanic trough coincident with the Chester fault (Olson, 1983). These younger units are Oligocene(?) volcanic breccia and conglomerate and overlying Oligocene (34 m.y. old) Rowley Andesite flows. Reconstructions by Olson (1983) indicate the base of the Tertiary volcanic section was about 100 m above the pre-mining surface of the Pitch mine. About 6 km south of the mine, more than 300 m of Oligocene andesitic volcanic rocks of the San Juan volcanic field cover Paleozoic rocks.

Structural Geology

The major structural feature in the Pitch mine area is the Chester fault, which dips east at about 70° and strikes nearly due north. The fault placed Precambrian rocks above and west of Paleozoic rocks (figs. 2 and 3). The term upthrust seems best for this fault because there is evidence that the fault surface is steep at depth and flattens upward (Nash, 1980). Net reverse displacement along numerous fault strands is more than 600 m. It is important to remember that the Chester fault is a zone of faults, not a single surface. The zone of faults is about 100 m wide in the mine area (fig. 2); it then splits into major east and west strands to the north. Within the fault zone, coherent, but highly broken, blocks of individual formations are bound by faults. Fault planes and shear zones could be recognized when core was logged, but it was generally not possible to determine the exact magnitude of displacement. Relations shown on figures 3 and 4 are highly generalized. Some drill holes intersected dolomite and Precambrian rocks several times before bottoming in dolomite, indicating complex up-and-down relative movement on the individual fault surfaces. East-trending normal faults offset the Chester fault (fig. 2). Paleozoic rocks west of the Chester fault are folded into a south-plunging syncline whose east limb is probably overturned under the fault zone (figs. 3 and 4). Tops of beds could not be identified to prove overturning. Farther west, Paleozoic rocks have a low dip and are gently warped into broad folds. Structure in the area is well illustrated by cross sections in Olson (1983).

Faulting in the Chester fault is of Laramide age. Cretaceous rocks about 20 km to the west are displaced by similar faults, and upthrusts elsewhere in the Rocky Mountains displace Cretaceous rocks. The Chester fault does not cut Oligocene volcanic rocks south of the Pitch mine (Olson, 1983); but at Marshall Creek, 3 km south of the mine, the volcanic rocks are displaced and rotated at the fault, probably reflecting some younger renewed movement along the fault.

Uranium deposits at the Pitch and Little Indian mines are structually controlled by the Chester fault. The selectivity for quartzite and dolomite is unusual among uranium deposits. A review of the literature (Nash, 1980) indicated that the physical situation could be explained by structural observations at other upthrusts and by behavior in experimental deformation. Although not well exposed, the geometry of faults in the Chester fault zone is similar to that observed elsewhere in other Rocky Mountain Laramide uplifts (Stearns, 1978). Figure 5 shows several features of interest.

In most places the Chester fault dips 60°–70° to the east. Good exposures near the old townsite of Chester, 3 km south of the mine (fig. 5, no. 1) show the fault dips 60° east, and drilling in the Pitch mine indicates dips of 60°–70° east. The highest level of the Chester fault is exposed on the ridge north of the Pitch mine (fig. 5, no. 2). The geometry of the fault trace in this area suggests more gentle dip, possibly 45° or less.

Paleozoic sedimentary rocks in the footwall of the fault zone are folded into a probable overturned syncline (fig. 5, no. 3) a style of deformation observed near many upthrusts (Berg, 1962).

South of the mine (fig. 5, no. 4) a thrust slice of Precambrian rocks extends west of the main upthrust block. Although this thrust may be younger than the upthrust, it might represent a flat split from the main upthrust zone.

Several features may reflect either compression or post-upthrust relaxation. The east-trending faults (fig. 5, no. 5) have mostly normal displacement and create a series of blocks with relatively small rotation. North-trending faults in the footwall block (fig. 5, no. 6) have apparent normal displacement and may represent subsidence faults as described by Wise (1963). Some of the offsets within the Chester fault zone also might reflect late-stage subsidence upon relaxation. Faults in Precambrian rocks of the uplift block (fig. 5, no. 7) may have been produced during arching of the upthrust block. However, no "keystone graben" (Wise, 1963) can be discerned.

The Chester fault displays many of the features described in other uplifts (Berg, 1962; Wise, 1963) recently explained as products of forced folding and faulting (Stearns, 1978). Geologic features (Stearns, 1978) and laboratory experiments (Friedman and others, 1976)

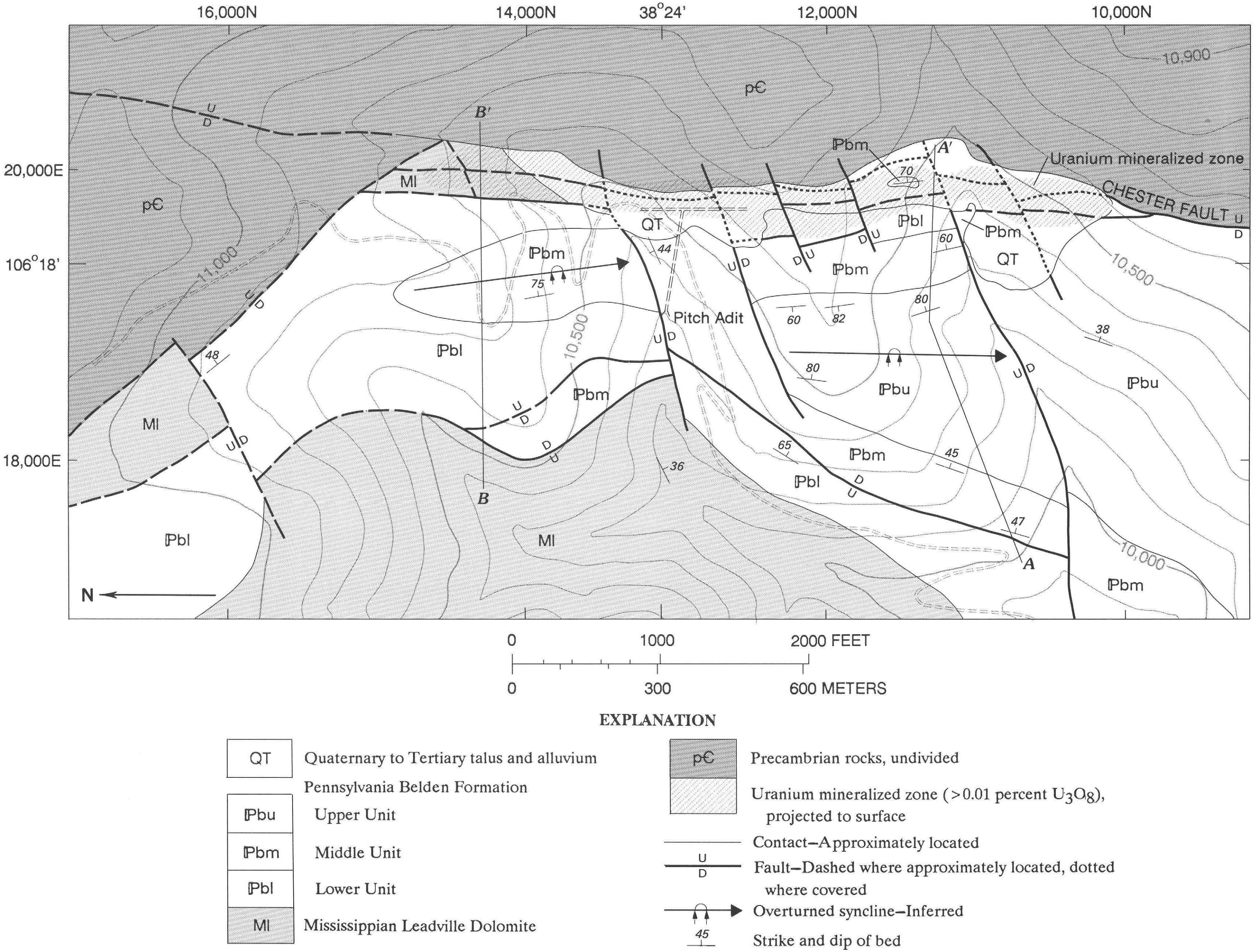

Figure 2. Preliminary geologic map of the Pitch mine area. Cross section *A–A'* is shown on figure 3 and cross section *B–B'* on figure 4. Geology in places adapted from mapping by Olson (1983) and J.M. Ward, Homestake Mining Co. (unpub. data, 1972–1977). Grid is mine coordinate system used by Homestake Mining Co.

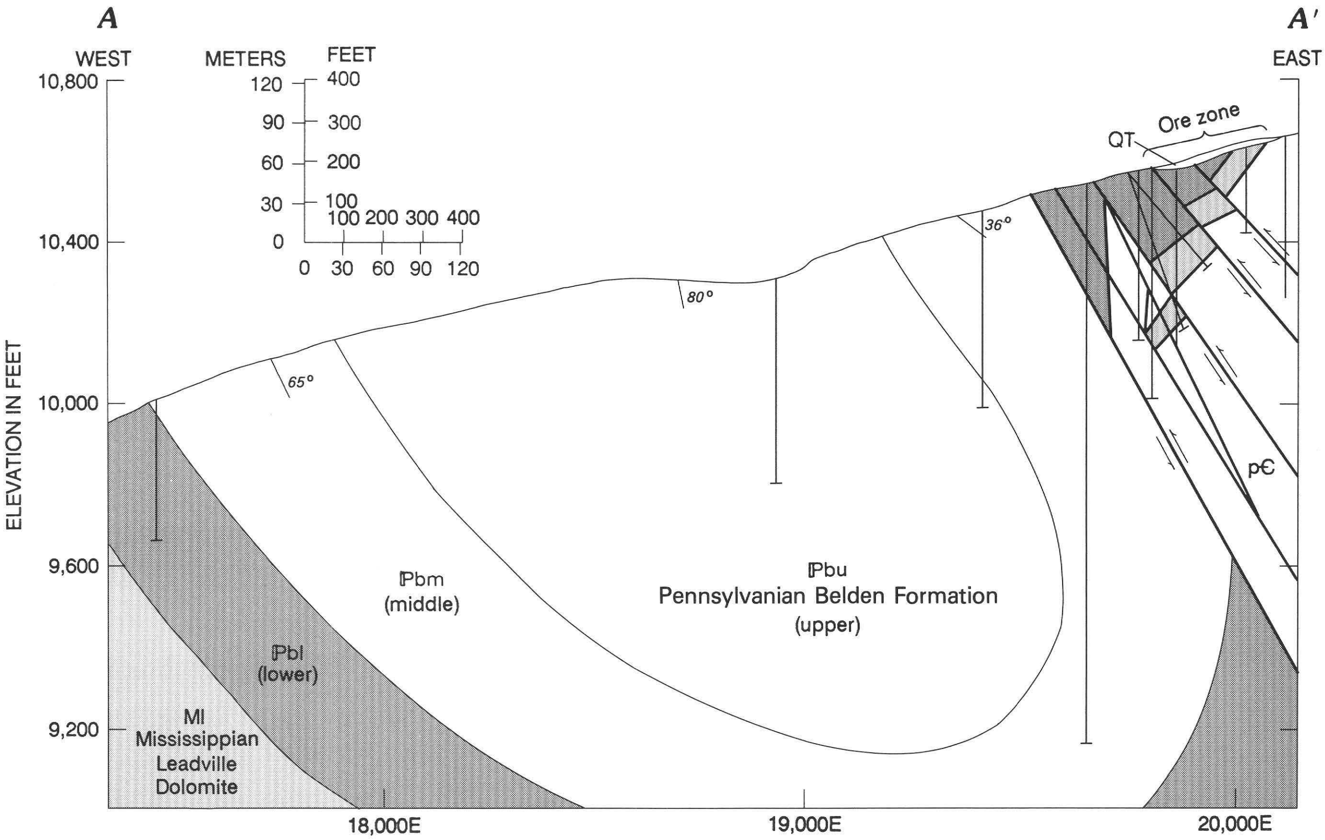

Figure 3. Schematic cross section *A–A′* of the Pitch mine area. Line of section is shown on figure 2. Structure in Chester fault zone is known from drilling to be much more complex than shown. Overturned synclinal structure is inferred from sparse surface outcrops showing bedding attitudes. Symbols are same as in figure 2.

indicate the importance of pressure, ductility, stratigraphic layering, and degree of attachment to the basement. The basement is a massive ram that induces or "forces" folding, faulting, or both, in overlying sedimentary rocks. The situation at the Pitch mine is one of "attached, brittle sections" (Stearns, 1978) in which there are many local faults and fractures because the attached brittle rocks cannot slip along the uplifting Precambrian block. For uranium and other ore deposits, the importance is the large volume of brecciated rocks favorable for ore deposition (Nash, 1980).

PETROLOGY AND GEOCHEMISTRY OF THE PITCH MINE

Petrology of Host Rocks

Petrographic studies were undertaken to describe host rock lithologies and alteration effects. A topic of particular interest was the mineralogy and textures of dolomites produced by diagenesis as compared with later alteration effects related to ore formation. In addition, petrographic data were used to help determine the stratigraphic identity of carbonate rocks in isolated fault blocks within the Chester fault. As the study evolved, it became evident that attributes such as content of fossils and clastic quartz could reliably differentiate carbonate units. Although Precambrian rocks contain some ore, they were not studied in detail because hand-lens observations suggested there would be little alteration to observe in thin sections. The following sections describe and contrast lithologies in the Leadville and Belden Formations.

Carbonates of the Leadville Dolomite generally contain more than 90 percent dolomite with minor quartz, clay, and calcite. Texture of dolomites from the Leadville is distinctive (fig. 6*A*), but not unique in this area. About one third of the samples contain microcrystalline dolomite with intergrown grains less than 10 μm in diameter. Dolomite in other samples has grain sizes ranging up to about 200 μm, generally as well-formed rhombohedra. The coarser grained dolomites show no spatial relation to uranium deposits or to faults. The recrystallization probably occurred in early diagenesis. Many of the coarsely crystalline dolomites are in zones with bedded chert lenses and intraformational slump and fold features, both of which suggest movement of diagenetic pore fluids

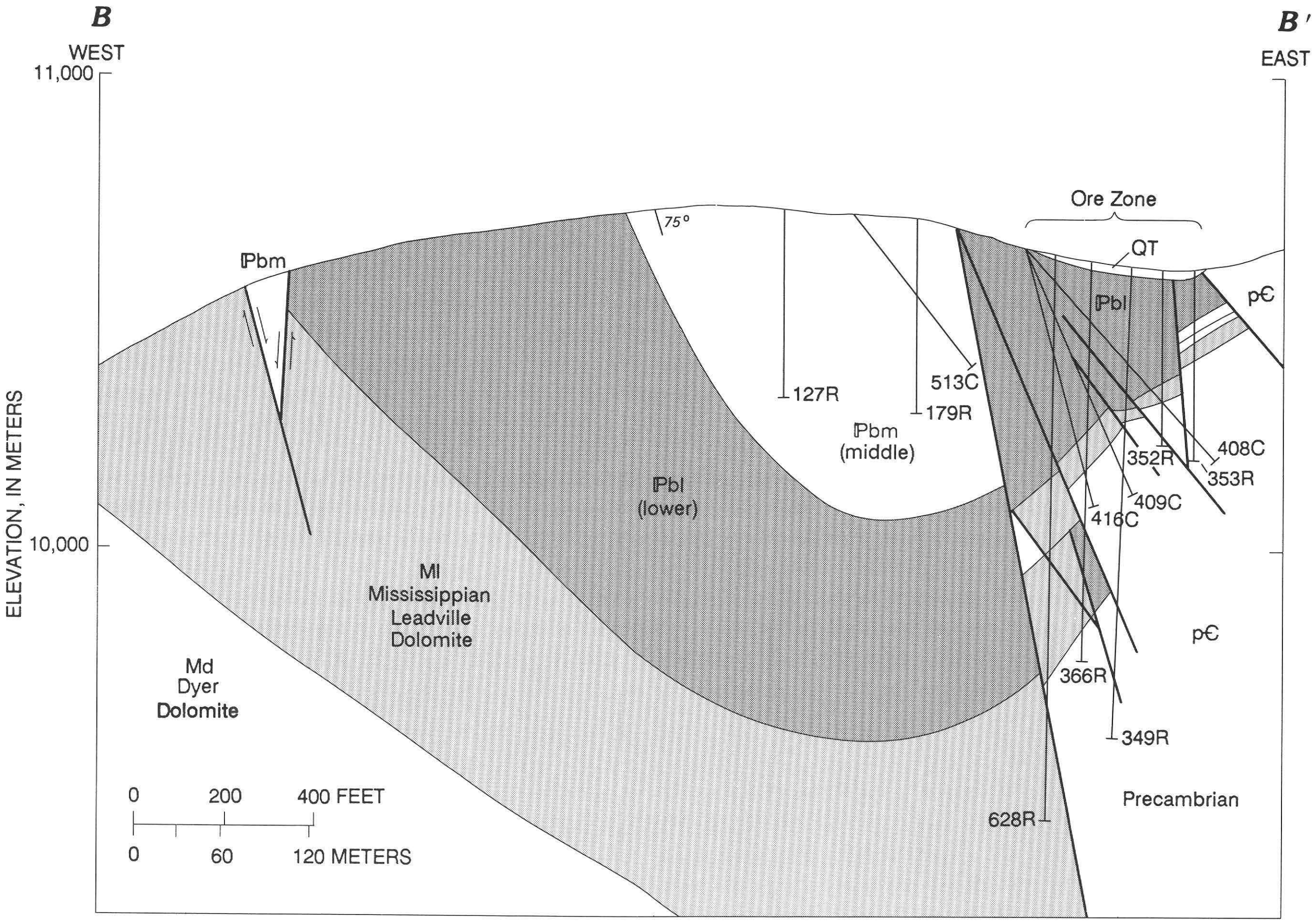

Figure 4. Cross section *B–B′* of the Pitch mine area. Line of section is shown on figure 2. Structure in ore zone is schematic; bedding in lower Belden units is near vertical in this zone. Symbols are same as on figure 2.

during lithification. Other evidence that this is a recrystallization process is the similar composition of the fine- and coarse-grained dolomites; both are devoid of clastic terrigenous and fossil detritus. Dolomite in the underlying Manitou, Fremont, and Dyer Dolomites generally is crystalline with rhombs about 100 μm wide that resemble the crystalline dolomite of the Leadville. Carbonate "mud" in the Belden Formation is extremely fine grained, similar to the Leadville dolomicrites, but it is calcite and generally supports fossils and quartz grains.

Two samples (nos. 37 and 38, table 1) from the Leadville collected about 1 km west of the mine are notably different from the typical carbonates described above. These samples show well-defined bedding and crossbedding, show calcite composition, and contain 30–40 percent fossils supported in very fine grained calcite mud (fig. 6*B*). They are classified as fossiliferous biomicrite (Folk, 1962) or packstone (Dunham, 1962). The locality 1 km west of the mine appears to be in the middle to upper part of the Leadville. The significance of these textures is that they testify to moderate current or wave energy that was sufficient to move particles but not great enough to winnow out the fine-grained carbonate mud.

Carbonate rocks in the Belden Formation are compositionally and texturally more diverse than those in the Leadville (fig. 6*C*). It is clear in outcrop, as well as under the microscope, that in the Belden a continuum exists from essentially pure carbonate rocks through terrigenous rocks. Of 29 Belden samples that contain more than 50 percent carbonate minerals, 60 percent contain more than 10 percent clastic quartz grains of sand or silt size, 28 percent contain fossils, 18 percent are bioturbated, and 12 percent contain intraclasts. Most Belden carbonates are composed of calcite only, but 15 percent contain dolomite in excess of calcite. Sparry calcite in the rock matrix or in fractures is common in Belden carbonates, but rare in the Leadville. Many of the Belden carbonates have grain-supported texture dominated by clasts of coarse-grained quartz or fossils with mud infilling, a texture not observed in the Leadville. Most Belden carbonates are classified as sandy micrite and biomicrite (Folk, 1962) or sandy wackestone and packstone (Dunham, 1962). Limestone in the Belden contains few

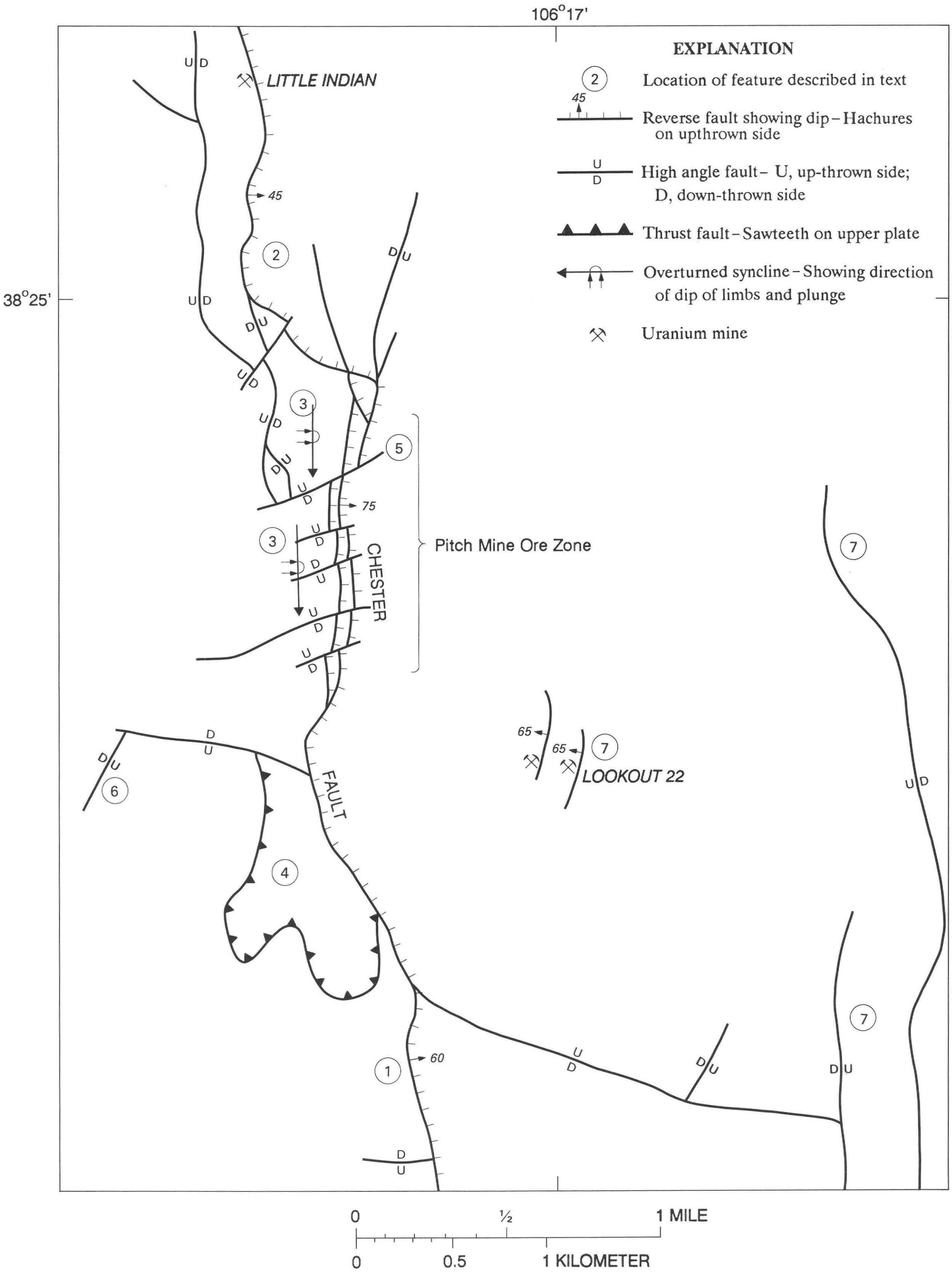

Figure 5. Simplified map of structural features in Pitch mine area (modified from Olson, 1983; Nash, 1979).

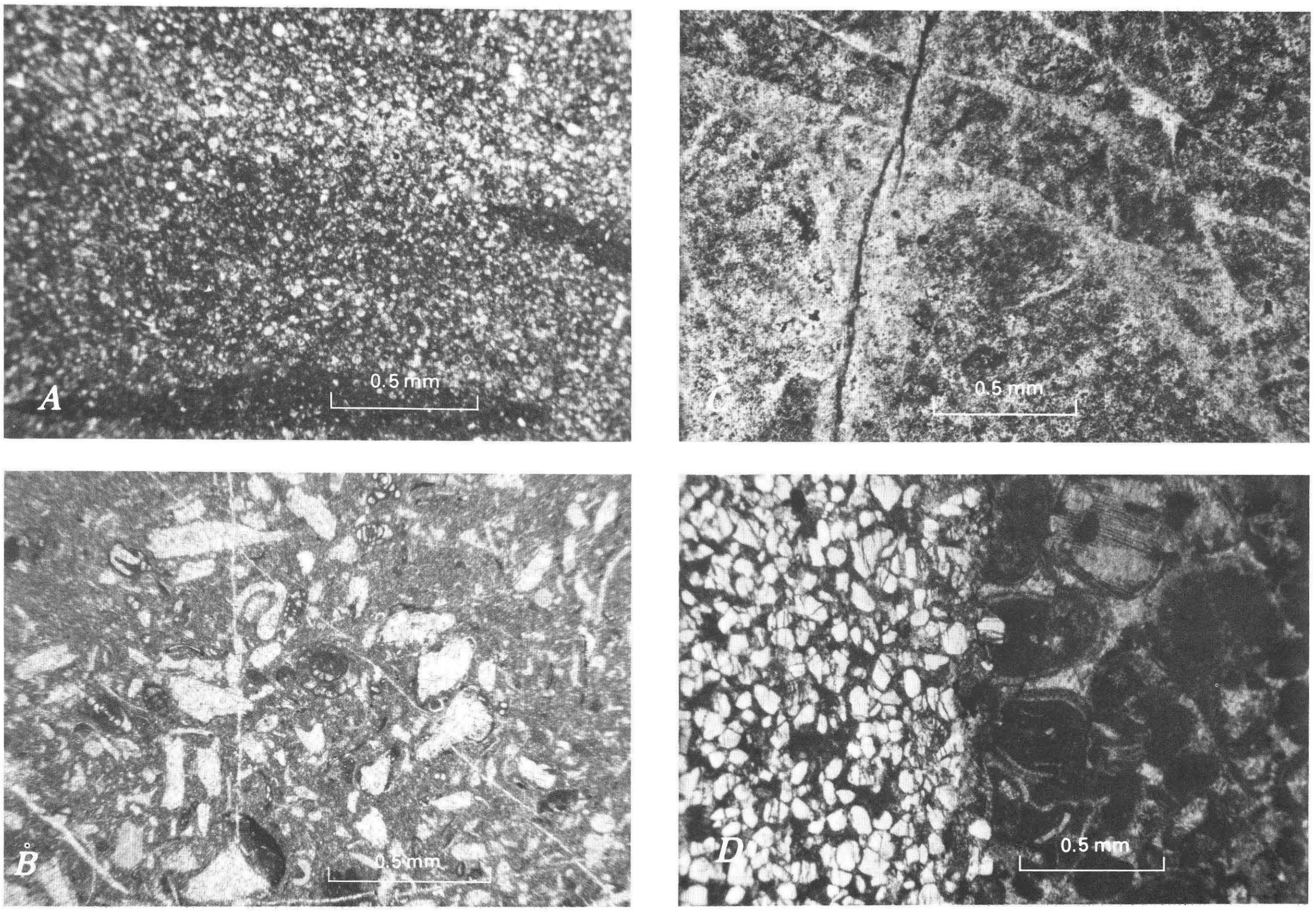

Figure 6. Photomicrographs of rocks from the Pitch mine. Photos taken in plane polarized light. *A*, Faintly laminated Leadville Dolomite (sample 298–377) with grains slightly recrystallized to about 30 μm average size; many dolomites have finer grain size and are not photogenic. *B*, Fossiliferous limestone unit (sample P38) in Leadville Dolomite; unit has atypical composition and is crossbedded in outcrop. *C*, Jasperoid alteration (sample P25) of Leadville Dolomite with typical veining and variable fine grain size; dark material is iron oxides and organic matter. *D*, Contact of clay-rich, very fine grained sandstone and oolitic limestone (sample P29) in middle unit of Belden Formation.

open fractures; it tends to make long pieces when cored and is rarely mineralized.

Terrigenous clastic strata are conspicuously absent from the Leadville Dolomite in the Pitch mine area. Microscopic examination of dolomites that appeared "sandy" in the field or drill core, and had been reported as such in the literature, did not reveal clastic quartz. A few samples contained about 2–5 percent silt-size quartz, and a few rare grains of sand-sized quartz were seen. Several samples taken at the Leadville-Precambrian contact, where I thought clastic material might be more abundant, did not contain more than 1 percent clastic quartz or any feldspar. Partly from this petrographic evidence and partly from an interpretation that the red clay at the top of the Precambrian is fault gouge not paleosol, these contacts were later judged to be fault contacts. A fair amount of aluminum, equivalent to about 4 percent clay, is present in the Leadville, but clay was not evident in thin sections. Only traces of clay minerals have been found in whole-rock X-ray diffraction tests of Leadville dolomites. The apparent absence of significant clastic quartz, and the presence of aluminum (clay), are consistent with other evidence for sedimentation in water that was quiet or protected from a clastic source by distance or a barrier.

Clastic rocks are abundant in the Belden Formation, in contrast to the Leadville. The basal unit of the Belden commonly is a medium to very coarse grained (0.3- to 2-mm) quartzose sandstone with variable amounts of potassium-feldspar, muscovite, plagioclase, and rock fragments. These sandstones and arkoses are white, from kaolinite matrix, and often contain about 1–4 percent pyrite as coarse euhedral crystals. The sandstones seem to be fluvial channel deposits. Curiously, these pyritic sandstones rarely contain uranium of importance by volume or grade even when in fault contact with uranium-rich dolomite breccia. More abundant in the Belden are 3- to 10-m-thick massive, soft, very fine grained sandstone and siltstone with abundant green or tan clay matrix and variable amounts of calcite cement. Two types of quartz grains are present: most are angular 50- to 100-μm grains, and some are about 300 μm in diameter and well rounded. The matrix is variable proportions of sericite, kaolinite, chlorite, and calcite. Pyrite, in amounts from 1 to 5 percent, is present as very fine to coarse grains in the matrix. These clay-rich fine-grained sandstones and siltstones are essentially unlithified; they are soft and plastic when cored. The plastic behavior does not allow fractures to remain open, which may explain why these sediments are the least likely to contain ore. The rare fine-grained sandstones that are mineralized contain low-grade, disseminated uranium.

Two types of chert are present as replacements of Leadville Dolomite; none has been seen in Belden Formation carbonate. One type is early diagenetic and occurs as discontinuous pods along bedding planes, as described by Banks (1970). The other, which I believe to be Tertiary in age, occurs in or near the Chester fault zone in zones tens of meters wide. The latter type of chert, more aptly termed jasperoid (Lovering, 1972), generally is brecciated (fig. 6*D*). Under the microscope, breccia textures are evident, but chalcedonic quartz is similar in fragments and matrix; the chalcedony seems to have cemented a preexisting carbonate breccia. These rocks are more than 90 percent SiO_2 and are composed of chalcedonic quartz with grains less than 15 μm in diameter. The chalcedony is speckled with opaque particles of iron oxide and possibly carbonaceous matter. Irregular veinlets or gradational swaths of more coarsely crystalline quartz (50 μm to 1 mm in size) cut the chalcedonic chert. Mineral and fluid inclusions are abundant in the quartz, but none are multiphase fluid inclusions; thus none could be used for thermometry.

Petrology of Altered Rocks and Ores

Three types of alteration have occurred in the Leadville Dolomite: (1) oxidation, in places accompanied by leaching of carbonate minerals; (2) subtle silicification by addition of thin films of silica along fractures; and (3) pervasive silicification to produce jasperoid. The first two alterations are parts of ore processes, and the last is not directly related to ore but may reflect processes operating in source rocks.

Oxidation has occurred to depths of more than 100 m along faults, and some breccia zones are pervasively oxidized to depths of about 60 m. Two extreme cases of a continuum are most easily described. Extreme oxidation and acid alteration at shallow levels have created porous, cellular rocks in which carbonate is removed, and the rock is a lacelike silica boxwork with limonite encrustation. Samples 3 and 612–15 are good examples (table 1). The altered rock is essentially a gossan. It tends to be highly radioactive but is deficient in chemical uranium. This type of disequilibrium indicates leaching of uranium in the past million years or localization of radium by sulfate (Phair and Levine, 1954). The other example is massive or brecciated dolomite having an ocher color imparted by hydrous iron oxides. The ocher dolomite is slightly softer than the unoxidized equivalent, but X-ray diffraction and petrographic studies show essentially no change in major minerals. Pyrite was destroyed and replaced in situ by iron oxides having cubic form, and iron oxides permeated grains and cracks to produce a strong coloring effect. Chemical analyses (table 1) indicate many of these rocks have gained several percent of iron relative to unoxidized equivalent dolomites. Uranium content of most ocher dolomites is only 50–200 ppm, but it probably was higher before oxidation. This oxidative alteration was produced by sulfuric acid generated by oxidation of sulfide minerals. The acid had a destructive effect on previously reduced ore zones. In some places, the leached uranium apparently was redeposited recently in zones that have chemical uranium in excess of radioactivity (Malan, 1959); one such environment of young uranium enrichment is peat bogs adjacent to the deposit (J.M. Ward, oral commun., 1980).

Subtle silicification of dolomite is best observed on newly exposed rocks in the Pitch open pit. Very thin films of quartz, sufficiently crystalline to sparkle in sunlight, coat breccia fragments in the ore zone. This alteration, possibly obscured by mud and dust, was not detected during drill-core logging and is not visible in most thin sections. Many samples of ore contain more than 10 percent SiO_2 (see analyses for samples 298–341, 713–102, 782–471 on table 1), an enrichment relative to barren equivalents. This alteration seems to be related to ore in zones of pitchblende and sulfide minerals, but the outer limits are not known.

Pervasively silicified Leadville Dolomite occurs at many locations between the Pitch and Little Indian mines. Some is preserved as residual boulders more than 3 m in diameter, and other examples form craggy outcrops along the Chester fault zone. This rock is best termed jasperoid; it is dark-gray to reddish-black, very fine grained, massive chalcedonic quartz containing streaks and patches of red iron oxides. Vuggy crystals are absent, and carbonate minerals are rare. SiO_2 content is generally more than 90 percent. In a few places a replacement interface with dolomite was observed, but in most places a replacement of dolomite is inferred from nearby outcrops of unaltered dolomite. The jasperoid is mildly radioactive in some outcrops.

The jasperoid commonly has a breccia texture of uncertain origin. The breccia was recemented into a strong rock that breaks across the breccia fragments. Individual fragments tend to have slightly different colors, and the matrix tends to be darker from higher content of iron oxides. The problem is whether this is a brecciated jasperoid or a jasperized breccia. I have not been able to determine if the jasperoid grades out into brecciated dolomite because outcrops are lacking at key places. I believe the rock was formed by silicification of a brecciated dolomite because the breccia is healed and because it is confined to the Chester fault zone and subsidiary faults. This silicification possibly is related to alteration of Oligocene(?) tuffs that formerly overlay the altered dolomite.

Uranium minerals in ores are inconspicuous despite grades in excess of 1 percent. Primary ores are dark gray to black, but they do not look much different from other dark dolomite breccias. Uranium, chiefly as pitchblende, and iron sulfides fill the matrix of breccias (fig. 7*A–D*). Macroscopic and microscopic studies reveal no alteration selvage in dolomite next to uranium minerals. The matrix is a dark mixture of comminuted dolomite, some fine silica, pitchblende, pyrite, and marcasite (fig. 7*B*). Detailed probing with a shielded geiger counter and radiographs (fig. 8) indicate that the great majority of uranium occurs in breccia matrix; unbroken dolomite contains sparse uranium minerals.

Within the 100-m-wide zone of faulting along the Chester upthrust (fig. 2) are fault-bound blocks of dolomite roughly 5–20 m wide and deep that carry the majority of the ore. Drill core penetrating these blocks displays uniform brecciation to centimeter-size fragments, and the uranium grade tends to be high (>0.2 percent U_3O_8) and relatively uniform throughout the dolomite breccia. Some sheared and brecciated zones contain tectonically mixed millimeter- to centimeter-size fragments of Precambrian, Leadville, and Belden rocks; these zones often are rich in clay gouge and tend to have lower

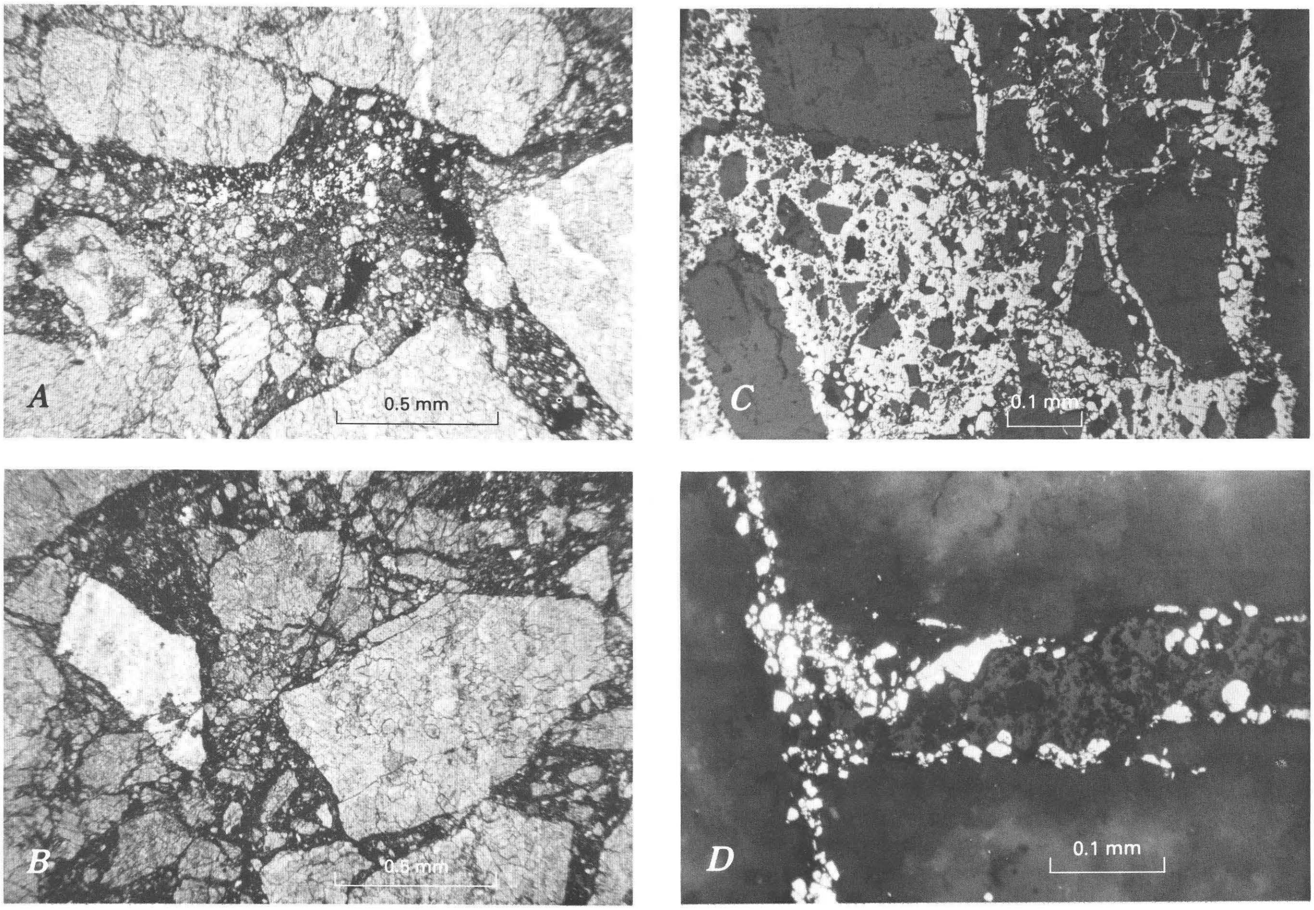

Figure 7. Photomicrographs of ores from the Pitch mine. *A*, Brecciated Leadville Dolomite (sample 298–345) characteristic of high-grade ores; opaque matrix is rich in sulfide and uranium minerals; transmitted light. *B*, Brecciated Leadville Dolomite (sample 298–345), main ore zone; angular fragment in upper center is chert, opaque matrix is ore; transmitted light. *C*, Ore-bearing brecciated dolomite (sample 298–327); pyrite and marcasite (white) and pitchblende (not shown in this field of view) are abundant in matrix; reflected light in oil immersion. *D*, Pitchblende-sulfide veinlet in brecciated dolomite (sample 298–327); pyrite and marcasite are white, pitchblende is gray; reflected light in oil immersion.

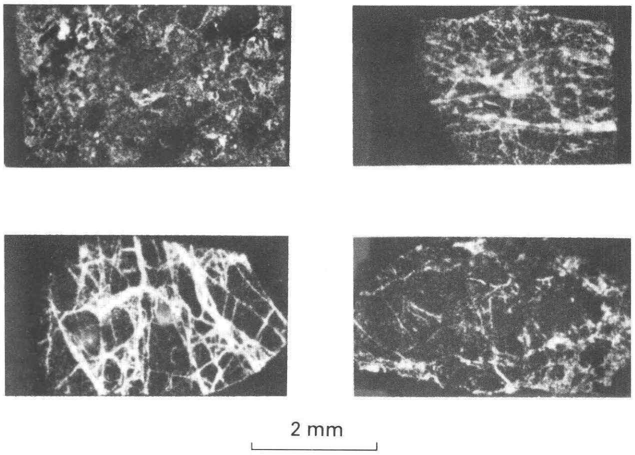

Figure 8. Radiographs showing distribution of uranium (white) in fractured dolomite from the Pitch mine.

of Precambrian, Leadville, and Belden rocks; these zones often are rich in clay gouge and tend to have lower uranium content than the monolithic dolomite breccias. Belden shales, especially those rich in carbonaceous material, are sheared and plastically deformed along fault strands; such zones tend to contain lower grade uranium (roughly 0.1 percent U_3O_8).

Earlier studies (Malan, 1959) described most ore as occurring in ''limestone and lignitic shale'' of a lagoonal facies of the Belden Formation. A stockpile of lignitic shale ore dumped below the old Pitch adit has been sampled by many visitors, but it is not typical of the ''new'' high-grade ore in brecciated dolomite. Carbonaceous black shales and black siltstones generally contain less than 0.05 percent U_3O_8.

Microscopic study of dolomite breccia ore revealed a relatively simple assemblage of pitchblende, coffinite, pyrite, marcasite, and minor quartz. Veinlets of pitchblende and coffinite more than 1 mm wide were rarely seen. These minerals filled the breccia matrix (fig. 7*C*, 7*D*) with very little additional gangue other than comminuted dolomite. About half of the black uranium minerals had low reflectivity under oil immersion reflected light, and some had red internal reflections; these observations suggested that the mineral is coffinite, but its abundance and age relative to pitchblende could not be determined with confidence. FeS_2 is both isotropic (pyrite) and anisotropic (marcasite). With high magnification and oil immersion reflected light, the marcasite is creamy yellow relative to pyrite and tends to form rectangular grains. In most samples, marcasite equaled pyrite in abundance. Marcasite of similar habit is abundant at the Midnite mine, Washington (Ludwig and others, 1981) and in many sandstone-type uranium deposits (Goldhaber and Reynolds, 1979).

Dolomites in the ore zone and in breccias along the Chester fault zone showed no recrystallization effects that can be related to ore or fracturing. Many are dolomicrites with grain size less than 10 μm, and dolomite in the matrix is also typically finely crystalline (less than 16 μm) and generally finer than the dolomite in the breccia fragments. Texture of dolomite is uniform within fragments, but differs between fragments in the same thin section, indicating that there has been no post-fault recrystallization. Even the edges of dolomite breccia fragments show no bleaching or recrystallization adjacent to pitchblende matrix-filling. As mentioned before, the greatest observed variation in dolomite texture is distant from the ore zone in zones of bedded chert and slumping that are interpreted to be effects of early diagenesis not related to ore.

The matrix of many breccias contains fine-grained dark material, some of which is fragments of Belden black shale in polylithic breccias, but most is simply a fine-grained mixture of dolomite, pitchblende and coffinite, and iron sulfides (fig. 7*C*). Organic carbon analyses (table 1) indicate contents in the range of 0.1–0.7 percent, which suggests that part of the dark color may be from organic material, but iron sulfides and uranium minerals are thought to be the predominant source of the color.

Geochemistry of Host Rocks

Chemical analyses of host rocks for major and minor elements were made to describe their compositions and the effects of alteration, to provide evidence for conditions of ore formation, and to determine elements useful as exploration guides. Chemical data for 116 samples of unaltered, altered, and ore-bearing rock from the Pitch mine area are in tables 1 and 2; sample locations are shown on figure 9. Unaltered rocks are here defined as those showing no recrystallization, mineral alteration, or abnormal radioactivity. They were selected from unweathered road cuts to minimize effects of ore processes and surface leaching. Altered rocks carry megascopic evidence of recrystallization or mineral alteration, and ore-bearing rocks are defined as having more than 1000 cps (counts per second) radioactivity in the field or more than 500 ppm (parts per million) uranium. Major element contents tend to confirm mineralogical observations, although the content of silica is more variable than anticipated. Minor element trends are subtle and were evaluated by statistical analyses, which were used to highlight and simplify the multielement data for geochemical interpretations. Discussion will focus on subsets of data based on lithology or ore type to reduce compositional variance and make interpretation more specific.

Correlation analysis (Davis, 1973) is useful for highlighting relations among variables. Several such analyses were made. The most effective was a test on

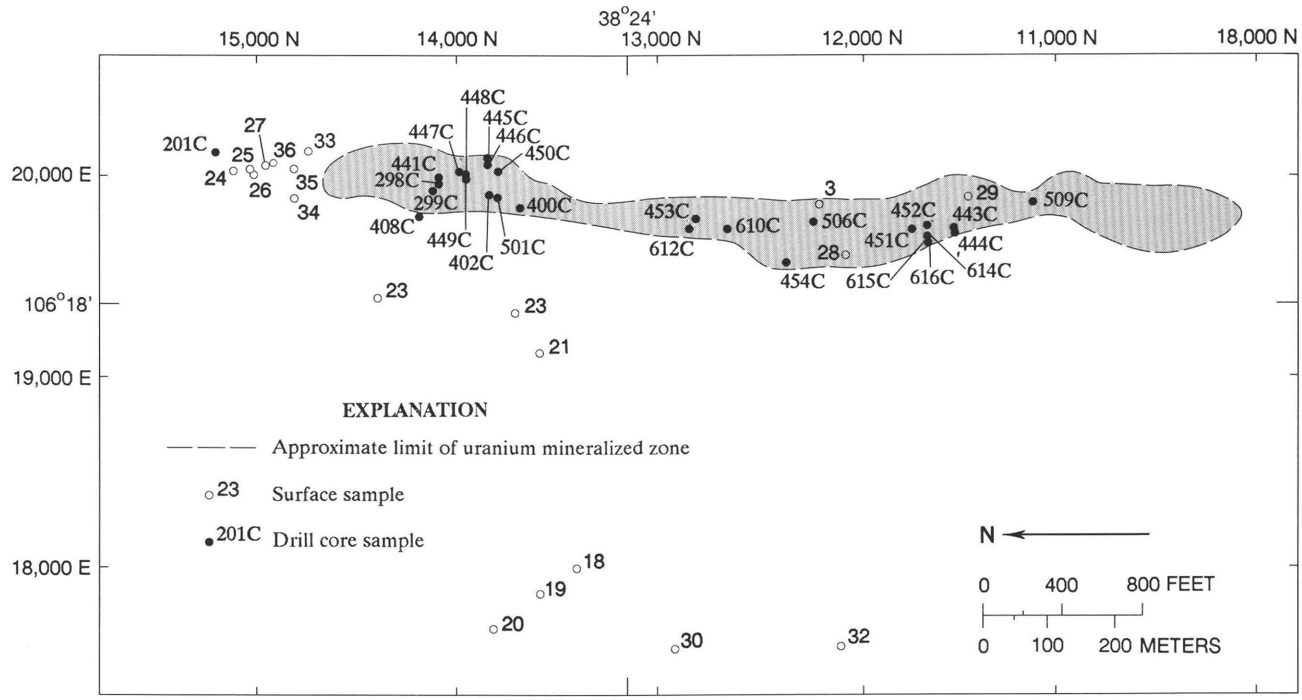

Figure 9. Map showing location of analyzed samples and drill holes.

33 variables describing 73 samples of Leadville Dolomite and alteration products. Log transformation of the data minimized the effects of lognormally distributed elements like uranium and produced higher correlation coefficients. Correlation coefficients for uranium are shown in table 3. Correlation coefficients that are significant at the 95 percent level of confidence are shown with an asterisk; the minimum value for significance depends on the number of samples and ranges from $r=0.225$ for $N=73$ to $r=0.381$ for $N=27$ (Dixon and Massey, 1957).

Uranium correlates significantly (95 percent confidence level) with Al, Fe_2O_3, FeO, K, H_2O^+, Mn, S, Cl, Ba, Sr, Pb, Zn, Mg, Cu, Ni, and Zr[1]. The very high correlations of uranium with S, FeO, Pb, and Mo are particularly worthy of note, as is the low correlation ($r=.12$) of U with organic carbon. Correlation analysis also shows high mutual correlations of Mg, Ca, FeO, Ba, Sr, and CO_2, presumably as carbonate minerals; chlorine correlates with this group, which possibly is evidence for dolomitization in high salinity fluids. Correlation analysis directs attention to a group of associated elements that may occur as clay minerals and (or) adsorbed constituents: Al, Fe_2O_3, K, Ti, P (rather than with calcium as apatite), F, Ba, Pb, Zn, Mo, U, Cr, Cu, Ni, V, and Zr. Many of the chalcophile elements (such as Pb, Zn, and Mo) are associated with both sulfur and Fe-Al oxides rather than being chiefly associated with sulfur in sulfide minerals.

The important relations of uranium with possible reductants sulfur and organic carbon are perhaps best seen on scatterplots (figs. 10 and 11). The plot of uranium versus organic carbon in 116 samples from the Pitch deposit (fig. 10) shows near random scatter, confirming the very low correlation coefficient. Sulfur and uranium, however, show a strong linear trend (fig. 11) that confirms the high correlation coefficient. A plot of molybdenum versus sulfur shows a similar linear trend. These plots, combined with petrographic observations, are conclusive evidence for a strong uranium association with sulfide minerals.

R-mode analysis of the Leadville geochemical data computed element groups similar to those just discussed. Factor analysis (Davis, 1973) in the R mode searches for relations between variables. For a simple model, three factors can be used that carry 64 percent of the compositional information, as follows: factor 1—Ti, K, F, Al, V, Cr, Sr, P, Zr, H_2O^+, and Na (elements in clay minerals or adsorbed on mineral surfaces); factor 2—Mg, Ca, CO_2, Cl (the carbonate mineral group; Si has negative loading on this factor); factor 3—U, S, Cu, Mo, Pb, Ba, Fe_2O_3, Fe0, Ni, and Mn (chiefly sulfur-related elements (chalcophile) or elements localized by reduction).

[1]Chemical references will be to element symbol rather than the oxide reported in data tables; for iron in two oxidation states, FeO or Fe_2O_3 will be specified if a specific valence is important.

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado

[Leaders (--), not determined; %, weight percent; Ctotal, total carbon; Corgan, organic carbon; Carbnt, carbonate; ppm, parts per million; XR, X-ray diffraction. Chemical analyses: major elements, including F and S—single solution technique (Shapiro, 1975) by H. Smith; minor elements—atomic absorption spectrometry for Ba, Sr, Ag, Pb, Zn, and Hg, specific-ion electrode for Cl, and spectrophotometry for Mo by E. Campbell; total carbon—combustion thermal conductivity by V.E. Shaw; carbonate carbon determined gasometrically by P.H. Briggs; organic carbon determined by difference; U—delayed neutron analysis by H.T. Millard, C. McFee, and C. Bliss; other minor elements—six-step emission spectrography by J.C. Hamilton and E. Silk. Mineralogy: semiquantitative estimates of dolomite (dolom XR), calcite (calcit XR), quartz (quartz XR), clay (clay XR), and iron oxide (hema XR) content made by X-ray diffraction by J.T. Nash; clays observed were kaolinite and sericite (10Å mica); iron oxides observed were hematite and goethite; precision and accuracy about ±1 part in 10]

Sample	SiO2 %	Al2O3 %	Fe2O3 %	FeO %	MgO %	CaO %	Na2O %	K2O %	H2O+ %	H2O- %	TiO2 %	P2O5 %
3	63.00	13.70	9.10	.04	.44	.46	.07	1.50	5.10	5.50	.27	.09
7	.60	.33	.59	.08	21.00	30.20	.31	.61	.10	.24	.01	.02
18	21.90	1.80	.36	.12	16.00	23.90	.04	.68	.43	.27	.19	.05
19	6.60	.82	.23	.08	17.80	31.30	.03	.36	.41	.25	.04	.02
20	17.30	1.50	.26	.08	16.10	26.70	.01	.47	.61	.14	.14	.04
21	5.90	1.00	.35	.20	.88	49.40	.08	.21	.66	.24	.08	.10
22	2.90	.33	.05	.16	.66	53.00	.07	.04	.47	.15	.01	.10
23	9.00	.53	.49	.16	.45	49.50	.05	.05	.56	.11	.03	.15
24	8.60	.03	.20	.16	18.70	29.50	.04	.01	.30	.06	.02	.02
25	96.90	.33	.18	.01	.18	.24	.06	.03	.47	.09	.0	.02
26	97.70	.53	.21	.20	.07	.15	.02	.05	.60	.10	.02	.03
27	61.00	.03	.06	.12	8.30	11.90	.01	.02	.24	.11	.0	.02
28	17.60	1.80	.46	.12	.76	43.50	.05	.43	.87	.33	.11	.20
29	2.90	.33	.07	.12	.44	53.00	.0	.15	.24	.08	.0	.01
30	.20	.03	.18	.40	19.40	32.40	.02	.01	.21	.07	.0	.01
31	.20	.03	.11	.44	20.80	30.50	.01	.03	.28	.09	.0	.02
32	22.80	2.50	.94	.12	10.20	28.60	.06	.70	1.00	.27	.11	.04
33	13.70	.13	.21	.40	17.80	26.70	.04	.06	.35	.05	.0	.02
34	97.00	.13	.14	.12	.29	.31	.0	.02	.32	.04	.0	.02
35	27.50	.23	.21	.24	14.70	22.20	.08	.05	.30	.11	.0	.03
36	9.80	.23	.08	.16	18.80	28.00	.06	.01	.30	.07	.0	.01
37	2.50	.13	.16	.08	.60	53.10	.01	.09	.30	.06	.0	.02
38	17.00	.63	.20	.08	.47	44.70	.05	.21	.33	.13	.03	.03
39	32.60	7.80	46.40	.08	.27	.61	.0	.61	9.10	2.20	.17	.20
40	4.50	1.00	.87	.08	17.60	30.60	.09	.25	.52	.10	.04	.02
41	.90	.03	.28	.04	20.60	31.00	.01	.04	.22	.20	.01	.02
43	1.40	.13	.05	.04	.97	52.40	.05	.05	.24	.16	.02	.01
44	97.00	.23	.80	.08	.10	.43	.0	.05	.53	.05	.01	.03
45	6.40	.13	.02	.12	19.00	29.70	.0	.01	.30	.16	.0	.01
201-69	13.60	3.80	.74	1.70	2.10	39.50	.04	.72	1.20	.39	.17	.20
298-313	.63	.34	.48	.36	20.60	29.60	.0	.04	.28	.06	.01	.0
298-327	.43	.13	4.50	1.30	18.60	27.20	.01	.02	.51	.27	.02	.02
298-334	2.40	.14	2.60	.48	19.50	27.50	.0	.0	.33	.10	.01	.01
298-341	48.00	.90	6.30	1.40	7.20	11.40	.0	.09	.59	.51	.01	.04
299-323	3.60	.60	.61	.24	19.80	29.40	.08	.10	.64	.12	.03	.02
299-334	9.40	1.60	1.10	.52	16.10	27.60	.02	.29	.73	.36	.07	.04
299-351	3.90	.74	1.20	.28	18.70	29.30	.0	.13	.68	.26	.03	.04
299-377	27.80	4.40	.99	.36	13.50	19.90	.07	1.20	1.10	.29	.29	.07
400-174	7.70	.93	2.00	.32	18.00	27.70	.03	.22	.28	.16	.04	.02
402-128	40.90	3.70	1.10	.60	10.30	17.20	.04	.88	.78	.36	.27	.09
408-368	21.50	2.90	1.50	.28	14.80	23.40	.07	.81	.85	.27	.15	.04
441-109	8.00	1.50	4.70	.04	17.00	27.60	.0	.41	1.00	.78	.07	.12
441-179	28.60	4.30	2.90	.16	12.10	20.00	.10	1.30	1.60	.65	.24	.09
441-204	35.30	4.10	2.20	.04	10.10	19.20	.06	.95	1.60	.68	.22	.12
441-209	39.70	3.60	1.50	.08	9.90	17.60	.05	1.10	.26	.44	.25	.10

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	MnO %	CO2 %	F %	S %	Ctotal %	Corgan %	Carbnt %	Cl ppm	Ba ppm	Sr ppm	Pb ppm	Zn ppm
3	.15	.13	.06	.03	.44	.44	.0	45	120	160	5.0	140
7	.10	47.10	.02	.02	12.71	.0	12.71	200	80	20	1.3	18
18	.06	34.40	.07	.06	10.24	.11	10.13	140	20	66	1.9	5
19	.03	43.10	.06	.07	11.63	.0	11.63	250	80	130	.8	5
20	.05	37.80	.07	.06	12.15	.19	11.96	75	20	130	2.1	5
21	.07	40.90	.03	.04	11.38	.31	11.09	25	160	350	5.8	58
22	.06	42.80	.02	.03	11.65	.17	11.48	25	180	500	1.0	56
23	.07	39.90	.03	.02	10.95	.20	10.75	25	80	330	2.2	20
24	.11	43.50	.02	.02	11.79	.09	11.70	140	80	20	2.0	32
25	.04	.0	.0	.02	.29	.29	.0	25	20	10	4.9	22
26	.04	.05	.0	.03	.44	.37	.07	25	20	10	15.0	22
27	.07	18.10	.0	.02	5.26	.33	4.93	120	40	10	5.9	22
28	.04	34.40	.07	.05	9.80	.47	9.33	25	170	325	9.5	10
29	.04	42.00	.01	.03	11.81	.12	11.69	25	160	300	1.4	5
30	.14	46.90	.02	.02	12.70	.01	12.69	25	20	20	2.3	30
31	.06	48.20	.01	.02	12.79	.04	12.75	85	100	10	2.6	5
32	.03	31.30	.07	.13	9.45	.79	8.66	55	100	110	11.0	5
33	.21	40.00	.01	.03	11.04	.0	11.04	25	72	20	2.4	22
34	.03	.08	.0	.02	.23	.23	.0	25	20	10	19.0	5
35	.15	33.50	.01	.02	9.33	.0	9.33	180	40	20	5.7	40
36	.08	41.70	.02	.02	11.82	.02	11.80	140	20	20	3.6	34
37	.02	41.40	.02	.07	11.72	.17	11.55	140	260	210	1.9	5
38	.02	34.70	.02	.04	9.81	.15	9.66	25	120	310	1.5	5
39	.08	.24	.06	.04	.51	.46	.05	25	20	10	7.3	350
40	.03	45.50	.05	.04	12.31	.23	12.08	160	120	56	3.6	14
41	.01	46.80	.03	.02	13.16	.09	13.07	180	40	10	3.8	34
43	.03	43.00	.01	.05	12.10	.32	11.78	70	140	130	1.4	12
44	.04	.06	.0	.02	.20	.13	.07	25	20	10	63.0	135
45	.02	45.20	.01	.02	12.37	.07	12.30	200	60	10	1.1	5
201-69	.14	35.70	.03	.14	10.12	.31	9.81	55	180	360	5.0	38
298-313	.18	46.80	.01	.12	12.99	.0	12.99	380	43	28	5.0	5
298-327	.19	41.10	.01	4.30	11.26	.03	11.23	390	280	31	25.0	5
298-334	.17	45.10	.01	1.90	12.33	.0	12.33	310	61	31	33.0	26
298-341	.09	16.00	.01	6.30	4.97	.72	4.25	160	320	21	120.0	140
299-323	.07	44.60	.02	.31	12.62	.41	12.21	480	83	57	25.0	2,600
299-334	.06	40.90	.02	1.10	10.99	.02	10.97	64	330	83	65.0	17
299-351	.05	43.20	.02	1.00	12.18	.19	11.99	100	110	180	73.0	5
299-377	.02	29.20	.08	.45	8.16	.11	8.05	160	140	190	5.0	35
400-174	.04	41.70	.02	1.50	11.63	.28	11.35	68	76	110	80.0	34
402-128	.03	23.10	.03	.49	6.73	.15	6.58	68	100	180	5.0	78
408-368	.03	33.80	.03	.64	9.62	.43	9.19	68	33	110	5.0	29
441-109	.10	39.90	.02	.04	11.07	.01	11.06	73	170	230	57.0	48
441-179	.12	27.80	.06	.04	7.86	.22	7.64	150	150	180	5.0	44
441-204	.15	25.50	.03	.04	7.37	.06	7.31	53	220	300	25.0	140
441-209	.05	25.90	.06	.06	6.80	.29	6.51	63	110	180	5.0	44

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	Mo ppm	Hg ppm	U ppm	Cr(s)ppm	Cu(s)ppm	Ni(s)ppm	Sr(s)ppm	V(s)ppm	Zr(s)ppm
3	3.30	2.600	778.00	--	--	--	--	--	--
7	.10	.005	.18	--	--	--	--	--	--
18	1.10	.005	1.86	14.0	.8	4.5	140.0	12.0	130.0
19	.70	.005	.41	--	--	--	--	--	--
20	3.10	.005	.72	13.0	.8	5.6	220.0	10.0	37.0
21	.20	.010	3.43	--	--	--	--	--	--
22	.10	.005	4.10	7.5	.8	2.0	1,200.0	8.5	35.0
23	.10	.005	3.60	--	--	--	--	--	--
24	.20	.015	3.92	3.7	.8	3.3	20.0	5.2	6.2
25	2.20	.065	1.05	--	--	--	--	--	--
26	14.00	1.150	14.20	18.0	3.4	1.9	5.6	2.8	9.9
27	2.50	.230	4.31	--	--	--	--	--	--
28	.40	.005	3.00	28.0	1.7	11.0	830.0	16.0	190.0
29	.10	.005	1.56	--	--	--	--	--	--
30	.50	.010	.89	.5	.8	3.4	25.0	8.0	6.8
31	.20	.012	1.74	--	--	--	--	--	--
32	1.50	.005	1.47	16.0	4.8	14.0	240.0	32.0	32.0
33	8.40	.076	3.99	--	--	--	--	--	--
34	4.10	.510	5.11	4.4	3.0	.8	1.1	.5	2.3
35	1.40	.180	2.32	--	--	--	--	--	--
36	3.00	.180	6.79	3.8	.8	4.3	21.0	3.8	5.9
37	.10	.005	2.65	--	--	--	--	--	--
38	.10	.005	2.42	15.0	.8	2.1	690.0	11.0	180.0
39	.80	.005	11.10	--	--	--	--	--	--
40	1.40	.005	2.16	13.0	2.1	4.9	130.0	13.0	18.0
41	.10	.005	.18	--	--	--	--	--	--
43	.10	.005	4.13	1.2	.8	.8	340.0	4.2	6.0
44	.50	.005	13.30	--	--	--	--	--	--
45	.10	.005	.76	3.3	.8	3.3	18.0	1.7	2.3
201-69	.50	.005	19.80	50.0	1.5	3.0	300.0	15.0	50.0
298-313	1.60	.005	1,160.00	--	--	--	--	--	--
298-327	4.50	.020	31,300.00	3.0	1.5	3.0	7.0	4.0	15.0
298-334	20.00	.100	4,160.00	5.0	1.0	15.0	7.0	5.0	10.0
298-341	88.00	.150	33,500.00	--	--	--	--	--	--
299-323	18.00	.039	1,960.00	--	--	--	--	--	--
299-334	73.00	.005	7,720.00	30.0	5.0	15.0	70.0	15.0	70.0
299-351	48.00	.005	4,300.00	--	--	--	--	--	--
299-377	3.40	.005	56.10	20.0	7.0	10.0	150.0	15.0	50.0
400-174	19.00	.560	739.00	--	--	--	--	--	--
402-128	15.00	.023	149.00	20.0	7.0	10.0	150.0	20.0	200.0
408-368	11.00	.005	151.00	--	--	--	--	--	--
441-109	.80	.120	35.70	20.0	3.0	20.0	300.0	15.0	30.0
441-179	.60	.005	38.50	--	--	--	--	--	--
441-204	1.00	.015	26.50	15.0	15.0	20.0	200.0	10.0	70.0
441-209	.40	.005	33.90	--	--	--	--	--	--

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	Dolom XR	CalcitXR	QuartzXR	Clay XR	Hema XR	Stratig	Elev Ft	North Ft	East Ft
3	.0	.0	10.0	.0	0	6	10,650	12,360	19,82
7	10.0	.0	.0	.0	0	3	9,040	9,000	5,00
18	6.0	.5	4.0	.0	0	6	10,360	13,410	18,02
19	7.0	1.0	2.0	.0	0	6	10,340	13,450	17,90
20	7.0	1.0	2.0	.0	0	6	10,320	13,650	17,72
21	8.0	.0	2.0	.0	0	7	10,480	13,610	19,14
22	1.0	8.0	1.0	.0	0	7	10,540	13,660	19,34
23	.5	8.0	2.0	.0	0	7	10,775	14,400	19,39
24	9.0	.0	1.0	.0	0	6	10,820	15,140	20,05
25	.5	.0	10.0	.0	0	6	10,800	15,050	20,04
26	.0	.0	10.0	.0	0	6	10,800	15,040	20,04
27	5.0	.0	5.0	.0	0	6	10,780	14,960	20,07
28	.0	7.0	3.0	.0	0	7	10,625	12,060	19,61
29	.0	6.0	4.0	.0	0	7	10,510	11,420	19,87
30	7.0	3.0	.0	.0	0	6	10,175	12,950	17,63
31	10.0	.0	.0	.0	0	6	9,975	11,620	17,13
32	6.0	.0	4.0	.0	0	6	10,160	12,120	17,65
33	7.0	.0	3.0	.0	0	6	10,725	14,750	20,14
34	1.0	.0	9.0	.0	0	6	10,760	14,820	19,89
35	1.0	.0	9.0	.0	0	6	10,760	14,830	20,03
36	6.0	.0	4.0	.0	0	6	10,775	14,920	20,09
37	.5	10.0	.5	.0	0	6	10,880	15,000	16,00
38	.5	10.0	.5	.0	0	6	10,780	14,600	16,20
39	.0	.5	8.0	.0	1	6	10,800	14,600	16,20
40	7.0	2.0	1.0	.0	0	6	11,130	16,600	17,00
41	9.0	.0	1.0	.0	0	6	11,120	16,700	16,80
43	.5	10.0	.5	.0	0	6	10,950	19,000	17,80
44	.0	.5	10.0	.0	0	6	10,900	16,500	18,30
45	6.0	3.0	1.0	.0	0	6	10,240	8,800	15,20
201-69	2.0	6.0	2.0	.0	0	7	10,749	15,200	20,13
298-313	10.0	.0	.5	.0	0	6	10,271	14,090	19,97
298-327	9.0	.0	.0	1.0	0	6	10,257	14,090	19,97
298-334	9.0	.0	1.0	.0	0	6	10,250	14,090	19,97
298-341	5.0	.0	4.0	1.0	0	6	10,242	14,090	19,97
299-323	9.0	.0	1.0	.0	0	6	10,270	14,120	19,93
299-334	8.0	1.0	1.0	.0	0	6	10,259	14,120	19,93
299-351	9.0	.0	1.0	.0	0	6	10,242	14,120	19,93
299-377	5.0	.0	4.0	1.0	0	6	10,216	14,120	19,93
400-174	8.0	.0	2.0	.0	0	7	10,374	13,690	19,96
402-128	5.0	.0	5.0	.0	0	6	10,428	13,850	19,99
408-368	6.0	.0	4.0	.5	0	6	10,355	14,200	20,05
441-109	9.0	.0	1.0	.0	0	7	10,494	14,080	20,03
441-179	7.0	.5	3.0	.5	0	7	10,436	14,080	20,07
441-204	6.0	.0	4.0	.0	0	7	10,416	14,080	20,09
441-209	5.0	1.0	4.0	.5	0	7	10,412	14,080	20,09

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	SiO2 %	Al2O3 %	Fe2O3 %	FeO %	MgO %	CaO %	Na2O %	K2O %	H2O+ %	H2O- %	TiO2 %	P2O5 %
441-219	23.00	2.00	1.60	.08	14.80	23.10	.02	.46	1.70	.37	.08	.04
441-223	92.20	.54	1.90	.04	.69	2.00	.01	.13	.31	.37	.02	.06
441-229	7.20	.63	2.10	.36	18.40	28.50	.03	.14	.50	.29	.05	.02
441-230	8.20	.84	.73	.88	18.40	27.40	.02	.21	.24	.12	.03	.02
441-32	29.70	5.10	1.90	.08	11.60	20.00	.05	1.50	1.60	.50	.29	.06
441-57	50.80	6.30	2.50	.20	7.10	11.40	.03	1.30	1.80	.49	.35	.11
442-84	17.40	1.10	4.70	.0	.35	41.00	.0	.05	.57	.76	.07	.13
443-301	10.40	1.30	.58	.24	18.10	27.50	.02	.42	1.00	.21	.06	.02
444-215	51.50	5.70	.90	.44	1.40	20.00	.03	1.60	.44	.56	.45	.09
445-28	4.30	.74	4.90	.0	13.20	34.60	.01	.18	.81	.54	.02	.0
446-40	18.90	2.30	1.30	.08	15.70	24.20	.02	.50	.16	.32	.14	.04
446-65	4.80	.53	2.90	.12	18.00	30.00	.01	.20	.48	.48	.03	.03
447-131	8.70	.73	2.50	.0	17.10	27.70	.03	.19	.51	.34	.05	.03
447-98	9.20	1.50	6.40	.0	16.50	25.20	.02	.34	1.60	.67	.05	.06
448-121	7.20	.43	.44	.16	18.40	29.90	.06	.18	.36	.20	.05	.01
448-65	23.80	3.30	2.60	.04	14.50	20.20	.03	.96	1.20	.55	.18	.09
449-201	76.00	1.30	1.10	.12	4.30	6.40	.01	.25	1.00	.26	.07	.05
449-33	75.60	7.40	1.60	.08	2.20	4.30	.03	1.60	1.90	.62	.53	.11
449-51	31.60	2.60	1.10	.16	12.40	21.60	.03	.73	.92	.23	.20	.07
449-87	7.30	1.00	.90	.08	19.20	28.20	.01	.33	1.10	.13	.05	.02
450-166	10.90	1.20	2.30	.04	16.80	28.00	.0	.23	.82	.38	.06	.04
451-247	6.70	.94	.44	.96	18.80	28.30	.0	.19	.38	.09	.03	.01
452-249	8.90	1.20	.50	.84	18.30	27.50	.0	.32	.46	.15	.05	.01
452-265	1.10	.34	.24	.44	20.60	29.40	.0	.11	.33	.01	.02	.01
452-339	68.50	6.50	.87	.88	3.70	6.50	.04	1.20	1.80	.50	.49	.10
453-113	4.60	.83	.39	.16	7.30	43.50	.01	.23	.50	.19	.05	.02
453-94	12.90	1.20	3.10	.08	2.90	42.40	.0	.53	.90	.40	.09	.04
453-97	12.50	1.70	.56	.12	13.40	32.10	.01	.54	.38	.21	.08	.03
454-90	13.50	1.20	1.10	.12	17.40	25.30	.01	.50	.93	.17	.08	.04
501-196	8.20	.53	.46	1.20	3.00	45.80	.07	.18	.27	.06	.03	.01
506-168	2.00	.53	.88	.60	19.20	30.70	.04	.13	.39	.11	.03	.01
509-200	40.70	1.90	.20	.08	.63	30.30	.04	.60	.46	.15	.24	.03
509-206	36.00	1.90	.33	.16	.40	34.00	.03	.64	.52	.14	.14	.04
610-152	22.30	1.10	.24	.08	.64	41.90	.02	.38	.45	.15	.08	.03
610-181	3.40	.33	.37	.76	18.50	30.20	.04	.11	.27	.10	.04	.01
610-228	58.60	11.60	2.60	.24	1.40	8.70	.21	3.40	2.50	.89	.69	.10
610-229	16.50	.82	.12	.24	.53	44.50	.02	.29	.38	.14	.09	.02
610-254	59.70	13.70	.76	4.10	1.20	4.50	.16	3.10	4.80	.64	.78	.19
610-51	8.00	1.60	.34	2.50	2.40	44.20	.28	.35	.75	.24	.08	.20
612-118	10.50	1.30	1.40	.16	9.70	37.40	.0	.39	.35	.12	.05	.04
612-128	15.30	1.80	1.20	.12	8.10	36.00	.07	.51	.65	.04	.09	.06
612-15	37.30	11.30	33.90	.24	.61	1.90	.06	1.20	7.90	3.60	.25	.16
612-160	15.60	.63	.44	.12	13.50	30.50	.01	.25	.30	.13	.03	.03
612-36	5.90	1.10	.63	.12	17.50	30.00	.07	.26	.34	.01	.04	.02
614-159	6.10	.83	.38	.20	17.00	31.60	.01	.32	.57	.03	.06	.03

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	MnO %	CO2 %	F %	S %	Ctotal %	Corgan %	Carbnt %	Cl ppm	Ba ppm	Sr ppm	Pb ppm	Zn ppm
441-219	.12	32.70	.02	.03	9.69	.31	9.38	100	160	77	25.0	610
441-223	.02	1.20	.01	.03	.44	.02	.42	120	250	65	160.0	1,000
441-229	.13	42.80	.01	.05	12.07	.09	11.98	150	120	65	41.0	850
441-230	.12	42.10	.03	.16	11.90	.45	11.45	130	76	49	20.0	710
441-32	.05	26.50	.06	.08	7.68	.25	7.43	75	160	130	5.0	92
441-57	.03	15.70	.03	1.70	5.00	.73	4.27	25	97	180	5.0	48
442-84	.16	32.80	.04	.04	9.11	.03	9.08	25	2,100	420	5.0	47
443-301	.06	40.20	.05	.34	11.42	.25	11.17	90	67	50	25.0	79
444-215	.03	15.80	.09	.21	4.80	.30	4.50	46	140	250	5.0	20
445-28	.31	41.60	.02	.03	11.66	.05	11.61	80	300	63	5.0	300
446-40	.03	35.10	.07	.08	9.92	.01	9.91	93	61	150	5.0	68
446-65	.08	43.20	.02	.12	12.39	.54	11.85	78	300	57	220.0	340
447-131	.13	41.50	.04	.05	11.59	.17	11.42	93	110	61	71.0	230
447-98	.07	37.80	.04	.06	10.81	.46	10.35	63	170	76	39.0	99
448-121	.07	42.80	.03	.04	12.21	.34	11.87	550	60	80	14.0	40
448-65	.03	31.50	.05	.02	9.09	.54	8.55	110	270	220	69.0	74
449-201	.14	8.70	.02	.03	2.72	.41	2.31	100	360	90	22.0	120
449-33	.03	3.60	.06	.03	1.21	.16	1.05	25	160	270	5.0	10
449-51	.02	29.30	.07	.10	8.44	.40	8.04	130	110	130	10.0	5
449-87	.01	42.90	.03	.05	12.01	.06	11.95	110	110	75	13.0	250
450-166	.06	40.40	.03	.06	11.28	.0	11.28	130	140	90	42.0	49
451-247	.15	43.80	.02	.06	12.20	.20	12.00	130	110	80	5.0	40
452-249	.19	42.40	.03	.07	12.32	.20	11.52	190	80	75	5.0	5
452-265	.05	47.40	.02	.06	12.55	.01	12.54	240	70	43	18.0	12
452-339	.0	7.90	.07	.37	2.50	.34	2.16	160	110	250	5.0	12
453-113	.12	41.40	.02	.20	11.91	.39	11.52	85	70	390	14.0	310
453-94	.14	35.60	.03	.02	9.70	.02	9.68	25	160	50	12.0	160
453-97	.02	39.50	.03	.06	11.14	.01	11.13	68	110	120	10.0	12
454-90	.04	39.20	.04	.03	11.18	.49	10.69	110	70	170	16.0	24
501-196	.08	39.60	.02	.15	11.02	.0	11.02	170	70	260	5.0	5
506-168	.25	45.60	.02	.06	12.79	.46	12.33	240	920	120	10.0	280
509-200	.05	24.70	.02	.04	6.79	.13	6.66	48	90	210	10.0	5
509-206	.01	26.30	.02	.22	7.71	.69	7.02	38	160	260	10.0	5
610-152	.10	32.80	.02	.03	9.51	.54	8.97	78	110	420	22.0	5
610-181	.12	45.50	.01	.06	12.40	.05	12.35	56	60	75	200.0	41
610-228	.04	6.40	.21	1.20	2.04	.26	1.78	25	300	350	5.0	29
610-229	.19	35.50	.02	.07	9.93	.02	9.91	47	120	310	10.0	36
610-254	.12	6.30	.10	.05	2.15	.25	1.90	41	450	130	85.0	110
610-51	.07	39.10	.03	.06	10.92	.06	10.86	110	90	310	5.0	37
612-118	.05	39.10	.04	.21	10.95	.0	10.95	130	90	210	14.0	14
612-128	.08	36.20	.02	.03	9.88	.18	9.70	68	100	400	17.0	57
612-15	.08	.01	.05	.01	.49	.28	.21	45	140	230	10.0	540
612-160	.04	37.80	.03	.03	11.06	.52	10.54	62	45	100	5.0	5
612-36	.03	44.10	.02	.03	12.48	.28	12.20	135	35	65	5.0	10
614-159	.05	42.10	.03	.12	12.46	.70	11.76	230	60	120	10.0	89

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	Mo ppm	Hg ppm	U ppm	Cr(s)ppm	Cu(s)ppm	Ni(s)ppm	Sr(s)ppm	V(s)ppm	Zr(s)ppm
441-219	.40	.010	50.70	10.0	7.0	20.0	70.0	15.0	30.0
441-223	.60	.110	62.60	--	--	--	--	--	--
441-229	.40	.058	61.80	15.0	3.0	30.0	30.0	7.0	20.0
441-230	3.40	.010	256.00	--	--	--	--	--	--
441-32	.80	.030	38.80	30.0	1.5	20.0	200.0	30.0	70.0
441-57	3.70	.005	107.00	--	--	--	--	--	--
442-84	.05	.065	38.80	20.0	7.0	7.0	500.0	15.0	15.0
443-301	7.80	.090	109.00	7.0	7.0	10.0	20.0	10.0	10.0
444-215	1.40	.005	141.00	--	--	--	--	--	--
445-28	9.40	.005	107.00	7.0	15.0	50.0	70.0	20.0	20.0
446-40	1.00	.005	12.50	15.0	7.0	20.0	70.0	15.0	50.0
446-65	1.80	.016	125.00	--	--	--	--	--	--
447-131	1.60	.010	97.80	5.0	7.0	20.0	50.0	7.0	20.0
447-98	7.40	.085	50.20	--	--	--	--	--	--
448-121	.05	.053	49.50	--	--	--	--	--	--
448-65	4.90	.045	49.90	--	--	--	--	--	--
449-201	1.50	.018	116.00	--	--	--	--	--	--
449-33	.80	.023	34.30	30.0	1.5	7.0	200.0	20.0	300.0
449-51	1.80	.005	20.80	--	--	--	--	--	--
449-87	1.40	.005	102.00	15.0	1.0	3.0	20.0	7.0	10.0
450-166	1.80	.160	109.00	10.0	3.0	20.0	50.0	15.0	30.0
451-247	1.00	.070	26.50	--	--	--	--	--	--
452-249	.70	.560	56.20	--	--	--	--	--	--
452-265	5.60	.560	113.00	3.0	3.0	3.0	7.0	7.0	10.0
452-339	1.00	2.500	24.60	--	--	--	--	--	--
453-113	14.00	.005	1,190.00	--	--	--	--	--	--
453-94	1.60	.060	53.60	15.0	3.0	30.0	50.0	15.0	70.0
453-97	1.40	.005	19.00	15.0	3.0	7.0	70.0	10.0	30.0
454-90	1.00	.093	37.90	--	--	--	--	--	--
501-196	.80	.005	64.40	7.0	1.5	3.0	200.0	5.0	10.0
506-168	1.60	.210	24.20	--	--	--	--	--	--
509-200	.80	.005	63.40	70.0	5.0	2.0	150.0	15.0	200.0
509-206	.70	.005	19.40	--	--	--	--	--	--
610-152	.70	.005	55.20	--	--	--	--	--	--
610-181	1.80	.075	103.00	3.0	1.0	10.0	30.0	10.0	7.0
610-228	2.10	.039	395.00	--	--	--	--	--	--
610-229	.80	.005	248.00	15.0	1.5	3.0	200.0	15.0	50.0
610-254	1.30	.042	228.00	3.0	50.0	7.0	150.0	30.0	150.0
610-51	.80	.005	111.00	30.0	1.5	7.0	500.0	15.0	20.0
612-118	1.60	.005	121.00	15.0	3.0	5.0	100.0	15.0	20.0
612-128	1.30	.039	59.20	20.0	5.0	15.0	500.0	20.0	50.0
612-15	14.00	.005	241.00	--	--	--	--	--	--
612-160	.50	.005	26.80	--	--	--	--	--	--
612-36	.05	.042	11.70	--	--	--	--	--	--
614-159	1.60	.005	33.00	--	--	--	--	--	--

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	Dolom XR	CalcitXR	QuartzXR	Clay XR	Hema XR	Stratig	Elev Ft	North Ft	East Ft
441-219	6.0	.0	4.0	.0	0	7	10,404	14,080	20,10
441-223	.0	.0	10.0	.0	0	7	10,400	14,080	20,10
441-229	8.0	.5	2.0	.0	0	7	10,395	14,080	20,10
441-230	7.0	1.0	2.0	.0	0	7	10,394	14,080	20,10
441-32	5.0	2.0	3.0	.0	0	7	10,557	14,080	19,99
441-57	5.0	.0	4.0	1.0	0	7	10,536	14,080	20,00
442-84	.5	5.0	4.0	1.0	0	7	10,522	11,813	19,59
443-301	7.0	.0	3.0	.0	0	6	10,283	11,520	19,93
444-215	5.0	.0	4.0	1.0	0	7	10,317	11,520	19,83
445-28	6.0	4.0	.5	.0	0	6	10,524	13,870	20,08
446-40	6.0	4.0	.0	.5	0	6	10,506	13,869	20,07
446-65	8.0	1.0	1.0	.0	0	6	10,483	13,869	20,08
447-131	6.0	2.0	2.0	.0	0	6	10,473	14,000	20,12
447-98	7.0	.0	3.0	.0	0	6	10,497	14,000	20,10
448-121	7.0	1.0	2.0	.0	0	6	10,474	13,978	20,07
448-65	6.0	.0	4.0	.0	0	6	10,514	13,978	20,03
449-201	6.0	.0	4.0	.0	0	7	10,378	13,978	20,07
449-33	2.0	1.0	6.0	1.0	0	6	10,530	13,978	20,00
449-51	4.0	3.0	3.0	.0	0	6	10,514	13,978	20,00
449-87	9.0	.0	1.0	.0	0	6	10,481	13,978	20,02
450-166	8.0	1.0	1.0	.0	0	6	10,416	13,800	20,04
451-247	7.0	.0	3.0	.5	0	6	10,323	11,740	19,75
452-249	8.0	.0	2.0	.0	0	6	10,283	11,650	19,75
452-265	10.0	.0	.5	2.0	0	6	10,267	11,650	19,75
452-339	3.0	.0	5.0	2.0	0	6	10,193	11,650	19,75
453-113	4.0	.0	5.0	1.0	0	7	10,486	12,802	19,81
453-94	3.0	5.0	2.0	.0	0	7	10,505	12,802	19,81
453-97	4.0	.0	4.0	2.0	0	7	10,502	12,802	19,81
454-90	7.0	.0	3.0	.0	0	6	10,565	12,377	19,59
501-196	.5	8.0	2.0	.0	0	7	10,353	13,810	19,99
506-168	10.0	.5	.5	.0	0	6	10,552	12,210	19,81
509-200	6.0	.0	4.0	.0	0	7	10,279	11,120	20,02
509-206	5.0	.0	5.0	.0	0	7	10,274	11,120	20,02
610-152	.5	6.0	4.0	.0	0	7	10,470	12,680	19,82
610-181	9.0	.0	1.0	.0	0	7	10,445	12,680	19,84
610-228	.0	1.0	5.0	2.0	0	7	10,405	12,680	19,86
610-229	.0	6.0	4.0	.0	0	7	10,404	12,680	19,86
610-254	.0	.0	5.0	3.0	0	9	10,382	12,680	19,87
610-51	3.0	6.0	1.0	.5	0	7	10,558	12,680	19,77
612-118	4.0	4.0	2.0	.0	0	7	10,470	12,870	19,81
612-128	4.0	3.0	3.0	.0	0	7	10,462	12,870	19,82
612-15	.0	.0	5.0	1.0	4	6	10,589	12,680	19,75
612-160	4.0	3.0	2.0	1.0	0	6	10,437	12,870	19,84
612-36	9.0	.5	1.0	.0	0	6	10,532	12,870	19,76
614-159	6.0	3.0	1.0	.0	0	7	10,416	11,660	19,84

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	SiO2 %	Al2O3 %	Fe2O3 %	FeO %	MgO %	CaO %	Na2O %	K2O %	H2O+ %	H2O- %	TiO2 %	P2O5 %
614-186	8.10	.63	.33	.20	17.60	29.50	.0	.26	.33	.07	.03	.02
614-209	4.60	.53	.25	.16	18.00	30.60	.0	.23	.98	.02	.04	.01
614-219	19.40	4.20	1.40	.24	14.40	23.60	.05	1.30	1.40	.42	.22	.04
614-225	9.20	.93	.48	.16	18.10	27.40	.04	.39	.77	.11	.06	.03
614-263	63.50	4.40	.65	.56	2.40	12.80	.10	1.30	1.40	.24	.35	.06
614-84	8.30	3.40	4.00	.44	.88	42.40	.03	.32	1.50	.24	.18	.63
615-261	8.90	.73	.21	.20	18.70	27.20	.01	.32	.35	.04	.05	.02
615-270	16.20	1.90	.56	.32	16.60	24.50	.02	.63	.68	.17	.15	.04
615-297	13.30	.23	.43	.16	17.30	26.70	.01	.15	.40	.06	.03	.02
615-308	12.70	2.50	1.10	.48	16.40	24.80	.04	.84	1.20	.29	.15	.05
616-231	9.20	4.90	3.80	.36	.81	41.50	.04	.40	2.60	.15	.21	.46
713-102	42.70	5.40	1.20	1.20	8.40	14.70	.14	1.60	1.60	.44	.19	.05
766-137	11.90	1.50	1.30	.60	16.90	27.60	.02	.38	.51	.22	.02	.03
766-165	13.80	1.90	.48	.60	17.20	25.90	.08	.50	.68	.19	.11	.02
766-183	4.40	1.20	.61	.88	17.80	29.60	.01	.10	.40	.18	.03	.01
766-190	24.90	1.60	2.30	1.60	12.30	22.60	.08	.26	.78	.52	.07	.03
766-199	9.30	1.30	1.30	.88	17.10	25.80	.01	.21	.41	.25	.05	.02
766-218	5.50	.59	1.40	2.50	16.00	28.60	.03	.07	.45	.29	.01	.02
766-220	48.60	8.30	1.90	1.60	5.90	10.10	.09	1.60	4.50	.37	.40	.09
769-130	12.70	2.00	.81	.68	16.80	26.50	.16	.57	.55	.20	.08	.03
769-218	43.10	3.50	.95	.72	9.90	15.70	.02	.91	.99	.30	.20	.07
782-047	55.10	7.10	4.10	.84	5.10	7.40	.04	1.60	2.70	1.40	.41	.07
782-336	62.70	1.00	4.10	.64	5.80	8.60	--	.11	.69	.44	.02	.03
782-355	6.90	.65	7.90	.62	15.90	24.50	--	--	.47	.50	.02	.04
786-133	27.20	.98	1.40	.12	13.30	23.80	.03	.08	.55	.33	.03	.05
786-138	10.30	1.10	.61	.79	17.40	26.60	--	.16	.50	.31	.07	.03

If additional factors are added, they carry elements with low communalities that make small groups, such as Hg with organic carbon, and Zn and Pb with Fe_2O_3.

Factor analysis in the Q-mode (Davis, 1973) was performed to search for relations between samples and groups of samples with similar character. Several data sets were run using different variables, including and excluding non-Leadville samples. The results are fundamentally similar and will be presented only for the Leadville subset of log-transformed data for 33 variables in 73 samples, as in the correlation analysis. Factor 1 carries 86 percent of the variance, factor 2 carries 3.8 percent, factor 3 carries 2.0 percent, and factor 4 carries 1.5 percent; other factors have eigenvalues of less than 1 and carry less than 1 percent of the compositional information. In the 3-factor varimax model, factor 1 is headed by sample 298–327 and contains 48 dolomite samples; uranium content does not seem to be important in defining this group. Factor 2 carries 15 samples and is headed by sample 26 (jasperoid) and sample 3 (gossan), which have negative loading. Factor 3 carries 10 samples, headed by sample 38 (limestone). In the 4-factor model, factors 1 and 3 are essentially the same as those in the 3-factor model, but factor 2 is broken up into two new factors, one headed by samples 612–15 and 3 (gossan type) and a new factor 4 headed by samples 34 and 26 (jasperoids). Q-mode analysis of the complete data set for 135 samples from all formations was not very informative. Although clay-rich Belden rocks were effectively carried on an "aluminum" factor, other rock types were classified according to chemistry, not stratigraphy or alteration. Dolomite samples from the Manitou, Fremont, and Dyer were grouped logically with Leadville dolomites, and Harding Quartzite samples were lumped with jasperoids. Correspondence analysis produced more graphic results than factor analysis and will be presented in more detail.

Correspondence analysis (David and others, 1977) is a variation on factor analysis in which R-mode and Q-mode results are computed simultaneously. Factor 3 highlights uranium and associated elements. Factor 3 carries 77 percent of the information on uranium, 90 percent of the information on sulfur, 90 percent on molybdenum, 53 percent on lead, and 31 percent on ferrous iron. Factor 1 carries the "carbonate" elements; factor

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	MnO %	CO2 %	F %	S %	Ctotal %	Corgan %	Carbnt %	Cl ppm	Ba ppm	Sr ppm	Pb ppm	Zn ppm
614-186	.03	43.20	.03	.10	11.75	.02	11.73	160	55	70	5.0	5
614-209	.03	43.90	.02	.17	12.66	.76	11.90	450	60	50	5.0	5
614-219	.05	33.50	.05	1.00	9.52	.29	9.23	190	120	150	42.0	36
614-225	.04	41.20	.03	.28	11.42	.0	11.42	65	60	53	12.0	66
614-263	.02	11.60	.04	.21	3.47	.40	3.07	25	130	130	5.0	5
614-84	.07	33.30	.10	3.10	10.24	.11	9.13	52	95	550	20.0	50
615-261	.02	42.40	.03	.08	12.21	.62	11.59	210	60	55	12.0	5
615-270	.05	39.10	.04	.36	10.37	.06	10.31	140	60	110	5.0	13
615-297	.06	41.60	.02	.22	11.46	.88	10.58	530	80	55	16.0	60
615-308	.14	39.40	.08	.72	10.51	.17	10.34	130	70	220	50.0	220
616-231	.08	31.50	.07	3.00	12.85	4.20	8.65	120	150	620	14.0	110
713-102	.03	20.30	.11	1.22	7.36	1.87	5.49	280	400	180	--	--
766-137	.03	40.10	.05	.74	11.30	.16	11.14	290	110	57	--	--
766-165	.08	38.70	.06	.30	10.90	.18	10.72	340	62	100	--	--
766-183	.08	44.30	.03	.74	11.55	.10	11.44	240	79	64	--	--
766-190	.21	31.40	.03	.29	12.18	.13	12.05	250	260	83	--	--
766-199	.10	40.90	.04	1.73	9.01	.47	8.54	230	63	71	--	--
766-218	.25	41.50	.02	.71	11.82	.03	11.79	130	150	68	--	--
766-220	.09	13.30	.06	1.04	3.91	.30	3.61	89	240	270	--	--
769-130	.07	39.60	.06	.43	11.13	.15	10.98	290	63	62	--	--
769-218	.09	22.10	.07	.47	6.65	.52	6.13	220	270	230	--	--
782-047	.07	9.20	.20	3.29	3.06	.52	2.54	240	58	260	--	--
782-336	.05	12.70	.01	3.65	3.92	.56	3.36	210	32	41	--	--
782-355	.12	36.60	.01	7.92	10.18	.19	9.99	410	110	36	--	--
786-133	.15	32.40	.02	.13	8.84	.69	8.15	320	720	51	--	--
786-138	.15	41.40	.03	.40	11.03	.03	11.00	330	190	38	--	--

2 carries chiefly Fe_2O_3, H_2O^+, and P. Factor 4 carries chiefly Al, Na, K, Ti, and F, elements probably associated with clay minerals.

Correspondence Q-mode analysis highlights relations between samples. In this analysis the same factors (vectors) are used as in the R-mode. Factor 1 carries dolomites; factor 2 carries hematite-rich gossan-type samples; and factor 3 carries samples rich in S, FeO, and U.

Plots of correspondence factor scores yield additional useful information (figs. 12, 13, 14). It is clear on figures 12 and 13 that R-mode scores plot close to the Q-mode scores, as they should by this technique. The plot of factor 1 versus factor 2 (fig. 12) breaks out three groups: (1) jasperoid-Si, (2) gossan-Fe_2O_3, and (3) carbonates-Ca-Mg. An interesting trend on figure 12 is the spread of sample points between the carbonate cluster and the gossan-cluster; these samples are oxidized ocher dolomites. The plot of factor 2 versus factor 3 (fig. 13) highlights the U-S-Fe0-Mo group of variables and samples rich in those elements. Again, there is a spread of ocher dolomite samples along the gossan-vector. Correspondence analysis classified the oxidized dolomites as having properties intermediate between unaltered dolomites and thoroughly altered gossan samples, in good agreement with results of petrographic studies.

A plot of factor 3 scores versus uranium content (fig. 14) shows a good linear trend for higher grade samples, which also contain more than about 1 percent sulfur. An interesting feature of figure 14 is the cluster of samples in the lower left-hand corner; the deviation of these samples from the linear trend suggests the interpretation that they have lost not only uranium but also other elements (S, FeO, Mo, Pb) that are in factor 3.

The classification of Leadville samples into four groups by factor and correspondence analysis is considered valid because these groups are the same as identified through the logging of core, the mapping of surface exposures, and petrographic study. Another test of the validity of the classification of samples is by t-tests of difference between groups (Natrella, 1963). Subsets were created according to Q-mode groupings and lithologic criteria. These tests examined groups, not individual samples. The t-test, comparing data for six samples of jasperoid from outcrops with nine normal unmineralized

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	Mo ppm	Hg ppm	U ppm	Cr(s)ppm	Cu(s)ppm	Ni(s)ppm	Sr(s)ppm	V(s)ppm	Zr(s)ppm
614-186	.80	.160	29.20	7.0	2.0	3.0	30.0	7.0	7.0
614-209	2.10	.005	135.00	--	--	--	--	--	--
614-219	5.30	.110	984.00	20.0	7.0	15.0	70.0	30.0	20.0
614-225	2.90	.005	785.00	7.0	3.0	3.0	15.0	7.0	7.0
614-263	.80	.020	125.00	--	--	--	--	--	--
614-84	12.00	.240	9.78	20.0	3.0	15.0	500.0	15.0	20.0
615-261	1.30	.005	38.40	--	--	--	--	--	--
615-270	1.10	.090	106.00	15.0	3.0	3.0	50.0	15.0	50.0
615-297	2.10	1.000	1,300.00	--	--	--	--	--	--
615-308	6.40	.140	330.00	15.0	10.0	20.0	100.0	15.0	20.0
616-231	8.10	.160	40.40	--	--	--	--	--	--
713-102	--	--	3,580.00	--	--	--	--	--	--
766-137	--	--	6,260.00	15.0	5.0	20.0	70.0	20.0	70.0
766-165	--	--	717.00	--	--	--	--	--	--
766-183	--	--	3,410.00	--	--	--	--	--	--
766-190	--	--	7,570.00	7.0	5.0	10.0	50.0	10.0	70.0
766-199	--	--	21,600.00	--	--	--	--	--	--
766-218	--	--	14,300.00	7.0	3.0	10.0	20.0	15.0	50.0
766-220	--	--	24,300.00	--	--	--	--	--	--
769-130	--	--	1,090.00	50.0	3.0	20.0	50.0	30.0	20.0
769-218	--	--	3,110.00	--	--	--	--	--	--
782-047	--	--	10,600.00	70.0	70.0	300.0	300.0	70.0	100.0
782-336	--	--	9,080.00	--	--	--	--	--	--
782-355	--	--	17,300.00	3.0	5.0	100.0	7.0	7.0	30.0
786-133	--	--	1,120.00	--	--	--	--	--	--
786-138	--	--	16,800.00	15.0	7.0	20.0	30.0	10.0	100.0

Leadville dolomites from outcrops, shows that Si is significantly enriched in jasperoid (at a 99 percent level of confidence) and that Mg, Ca, and Ba are significantly depleted. Contents of other elements are not significantly different between these two groups. Comparing the surface jasperoid samples with a group of 10 subsurface samples of silicified dolomite shows that the subsurface samples (ore-bearing) are significantly enriched in Al, Fe_2O_3, FeO, S, Ba, Sr, Cr, Ni, V, and U. Some of these differences may be due to leaching of the surface samples, although the surface samples were selected because they were unweathered and the least altered I could locate.

Comparison of ocher dolomites with unaltered dolomites reveals some important differences. For this t-test, data for 11 samples of ocher dolomite were compared with the data for 9 unaltered dolomites. Ocher dolomites are enriched in the following elements (level of significance in parentheses): Si (0.99), Al (0.99), Fe_2O_3 (0.99), K (0.99), Ba (0.95), Sr (0.99), Pb (0.95), Zn (0.99), Cu (0.99), Ni (0.99), V (0.99), and U (0.99). The enriched elements are those of the ore suite, which suggests that the ocher dolomites were mineralized previously, even if they are not now ore because of loss of uranium. The gossan-type samples number 3 and 612–15 are enriched in Fe_2O_3, Zn, Mo, Hg, and U relative to the ocher dolomite subset; this set was not analyzed by t-test because the two samples of gossan may not be representative geologically.

Ores of different grades contain variable concentrations of minor elements in addition to uranium. Three subsets were defined by uranium contents: (1) high grade, with U greater than 5,000 ppm (N=12); (2) medium grade, U from 500 to 5,000 ppm (N=26); and (3) low grade, U less than 500 ppm (N=37). The t-test shows that the high-grade set is tested as significantly enriched in FeO, K, and S relative to the medium grade; data are insufficient for some elements such as Mo and Cu for them to be significantly different even though they are enriched in three samples of high-grade ore. The medium-grade set is significantly enriched in FeO, K, S, Mo, Cu, and Ni relative to the low-grade set.

When the geochemical and statistical results are summarized, several statistical tests confirm the association of many elements with uranium. The most important

Table 1. Petrochemical data for host rocks, Pitch mine area, Colorado—Continued

Sample	Dolom XR	CalcitXR	QuartzXR	Clay XR	Hema XR	Stratig	Elev Ft	North Ft	East Ft
614-186	5.0	3.0	2.0	.0	0	7	10,396	11,660	19,86
614-209	7.0	2.0	1.0	.0	0	6	10,379	11,660	19,88
614-219	6.0	.0	4.0	.5	0	6	10,372	11,660	19,88
614-225	7.0	.0	3.0	.0	0	6	10,367	11,660	19,89
614-263	2.0	4.0	4.0	.0	0	6	10,340	11,660	19,91
614-84	6.0	.0	2.0	2.0	0	7	10,470	11,660	19,79
615-261	6.0	.0	4.0	.0	0	7	10,306	11,660	19,87
615-270	7.0	.0	3.0	.5	0	7	10,298	11,660	19,87
615-297	7.0	1.0	2.0	.0	0	6	10,274	11,660	19,88
615-308	8.0	.0	2.0	.5	0	6	10,265	11,660	19,89
616-231	6.0	.0	3.0	1.0	0	7	10,312	11,660	19,81
713-102	6.0	.0	4.0	.0	0	--	--	--	-
766-137	8.0	.0	2.0	.0	0	--	--	--	-
766-165	9.0	.0	1.0	.0	0	--	--	--	-
766-183	9.0	.0	1.0	.0	0	--	--	--	-
766-190	7.0	.0	3.0	.0	0	--	--	--	-
766-199	9.0	.0	1.0	.0	0	--	--	--	-
766-218	9.0	1.0	1.0	.0	0	--	--	--	-
766-220	5.0	.0	5.0	.0	0	--	--	--	-
769-130	8.0	.0	2.0	.0	0	--	--	--	-
769-218	5.0	.0	5.0	.0	0	--	--	--	-
782-047	4.0	.0	6.0	.0	0	--	--	--	-
782-336	5.0	.0	5.0	.0	0	--	--	--	-
782-355	8.0	1.0	1.0	.0	0	--	--	--	-
786-133	5.0	2.0	3.0	.0	0	--	--	--	-
786-138	8.0	.0	2.0	.0	0	--	--	--	-

[1]Stratigraphy: 1, Manitou Dolomite; 2, Harding Quartzite; 3, Fremont Dolomite; 4, Parting Quartzite; 5, Dyer Dolomite; 6, Leadville Dolomite; 7, Belden Formation.

[2]Location: coordinates are those used by Homestake Mining Co. For core samples, locations are computed for depth in hole and inclination, but drift of hole is not included. For surface samples, mine grid was extrapolated.

associations statistically and geologically seem to be S, FeO, Mo, K, Ca, and Ni. Silica and aluminum are enriched according to some tests, which is consistent with the deposition of small, but important, amounts of quartz and clay with uranium minerals.

GEOCHEMISTRY OF THE LITTLE INDIAN DEPOSIT

The Little Indian deposit, located 1 km north of the Pitch mine, was discovered in 1955 and brought into production in 1957. The mine was in production for two years and yielded 6,180 tonnes of ore grading 0.48 percent U_3O_8 (29,500 kg U_3O_8) (Ward, 1978). The mine workings totaled about 275 m generally along the strike of the Harding Quartzite (fig. 15).

Most uranium at the Little Indian deposit occurs in sandstones of the Harding Quartzite (fig. 16*A*). The quartzite zone in the lower part of the Harding is typically barren. Some uranium also occurs in dolomites of the Fremont Dolomite and Manitou Dolomite (fig. 16*B*), stratigraphically above and below, respectively, the Harding. My observations of rocks in the Little Indian area and in three drill cores were limited and possibly not representative. I was impressed by the following uranium associations: (1) Only hexavalent uranium minerals were observed in core and identified in the laboratory. (2) Uranium always occurs in association with iron oxides of brown ("limonite") to red ("hematite") color. Some pyrite was observed under the microscope; it occupies the matrix of poorly sorted sandstone, is highly altered to iron oxides, and is older than the hexavalent uranium minerals. (3) Uranium and iron oxide minerals occupy gash fractures in sandstone and dolomite and are disseminated in the matrix of coarser, poorly sorted sandstone (fig. 16*A*). Other than the oxidation of pyrite, previously mentioned and possibly related to ore, there

Table 2. Statistical summary of chemical data, Pitch mine area, Colorado
[XR, X-ray diffraction]

Constituent	Minimum	Maximum	Geometric mean	Geometric deviation	Valid value
		Major elements, in weight percent			
SiO_2	0.20	97.7	12.26	3.58	116
Al_2O_3	.03	13.7	1.03	3.78	116
Fe_2O_3	.02	46.4	.80	3.64	116
FeO	.00	4.1	.23	3.00	116
MgO	.07	21.0	6.18	4.39	116
CaO	.15	53.1	19.47	3.07	116
Na_2O	.00	.31	.033	2.35	113
K_2O	.00	3.40	.25	3.67	115
H_2O^+	.10	9.10	.64	2.22	116
H_2O^-	.01	5.50	.36	.64	116
TiO_2	.00	.78	.069	2.96	116
P_2O_5	.00	.63	.037	2.42	116
MnO	.00	.31	.062	2.11	116
CO_2	.00	48.2	22.70	4.52	116
F	.00	.21	.030	1.99	116
S	.01	7.92	.12	4.86	116
C (organic)	.00	4.20	.18	3.38	116
C (carbonate)	.00	13.07	7.32	2.79	116
		Minor elements, in parts per million			
Cl	8.91	550.	29.8	17.4	116
Ba	20.	2100.	101.4	2.28	116
Sr	10.	620.	92.0	2.84	116
Pb	0.	220.	9.67	3.42	101
Zn	5.	2600.	33.2	4.50	101
Mo	0.5	88.	1.38	4.91	101
Hg	0.05	2.6	.022	5.58	101
U	0.18	33500.	75.3	16.7	116
Cr	.5	70.	11.0	2.60	57
Cu	.8	70.	3.02	2.72	57
Ni	.8	300.	8.18	3.03	57
V	.5	70.	10.9	2.17	57
Zr	2.3	300.	28.1	3.11	57
		Mineralogy, in parts per ten			
Dolomite XR	0.	100	49	22	116
Calcite XR	0.	100	22	26	116
Quartz XR	0.	100	24	22	116
Clay XR	0.	30	2	6	116
Hematite XR	0.	40	0.3	4	116

are few signs of reaction next to uranium minerals. The disseminated uranium probably in part replaces small amounts of clay minerals in the matrix. (4) Small amounts of organic trash and epigenic hydrocarbon in veinlets are present but are only slightly radioactive.

The Little Indian deposit is structually controlled by the zone of fracturing below the Chester fault zone. The major upthrust surface, the contact between Precambrian granite and sedimentary rocks, was not the locus of uranium deposition. The setting (fig. 15) is similar to that in the Pitch mine, but I have insufficient information to document details. Paleozoic sedimentary rocks strike west to northwest and dip about 30° south. The north-striking Chester fault displaces Precambrian rocks upward and westward over the Paleozoic section. The Paleozoic rocks appear to continue with relatively minor change in attitude under the upthrust, judging from my sparse drill hole observations. The rocks intersected in drill core below the upthrust plane are fractured, but not thoroughly brecciated as at the Pitch deposit. The sedimentary rocks do not seem to be complexly sliced into fault blocks as in the Pitch area, but core from drill hole

Table 3. Correlation of elements with uranium in Leadville Dolomite

[Computed for 73 samples; *, coefficient significant at 95 percent level of confidence]

Variable	Correlation
Si	.10
Al	.41*
Fe_2O_3	.56*
FeO	.68*
Mg	.20
Ca	.07
Na	.08
K	.32*
H_2O^+	.33
Ti	- .02
P	.22
Mn	.39
CO_2	.04
F	.00
S	.82
C (organic)	.12
C (carbonate)	.02
Cl	.45*
Ba	.43*
Sr	.28*
Pb	.67*
Zn	.31*
Mo	.64*
Hg	.21
Cr	.26
Cu	.51*
Ni	.55*
V	.30
Zr	.33*
Dolomite XR	.34*
Calcite XR	- .22*
Quartz XR	- .03

775 indicates that about one third of the Harding section was removed by faulting.

Uranium minerals identified in this study and by Malan (1959) include uranophane $[Ca(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O]$, autunite $[Ca(UO_2)_2(PO_4)_2 \cdot nH_2O]$, kasolite $[Pb(UO_2)_2(SiO_3)_2(OH)_2]$, and probable novacekite $[Mg(UO_2)_2(AsO_4)_2 \cdot 9H_2O]$. Uranium is hexavalent in all of these minerals. No quadrivalent uranium minerals have been observed. Most of the uranium minerals observed in thin sections are honey-yellow, slightly pleochroic, moderately birefringent, with platelike form, all characteristics of autunite. A yellow mineral with an X-ray diffraction pattern close to that of novacekite drew attention to a possible role of arsenate ion. However, subsequent chemical analyses showed only moderate arsenic contents with arsenic consistently lower than uranium, indicating the arsenate could have been only partially responsible for localizing uranium.

Chemical data for 19 elements in 19 samples taken from three drill cores are in table 4, and data for 38

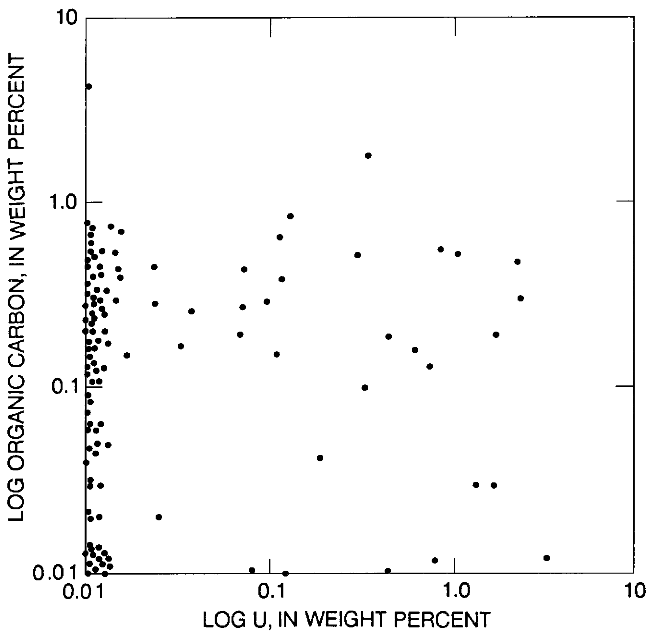

Figure 10. Plot of uranium versus organic carbon in samples from the Pitch mine.

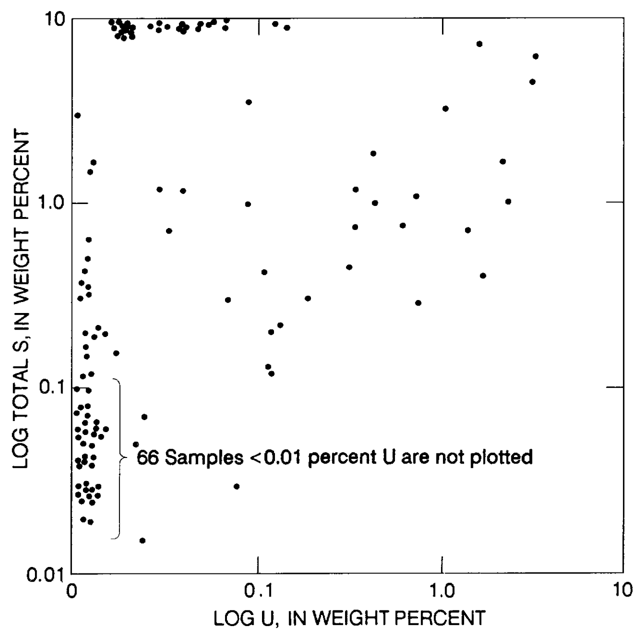

Figure 11. Plot of uranium versus total sulfur in samples from the Pitch mine.

elements are summarized in table 5. Fourteen of the samples were analyzed by X-ray fluorescence (XRF), which may yield somewhat different data than the wet-chemical methods employed on 121 other samples; for this reason and the fact that this is a small suite of grab samples that may not be representative, no statistical significance is given to these data, although the data are considered to be reliable. Correlation analysis on the data

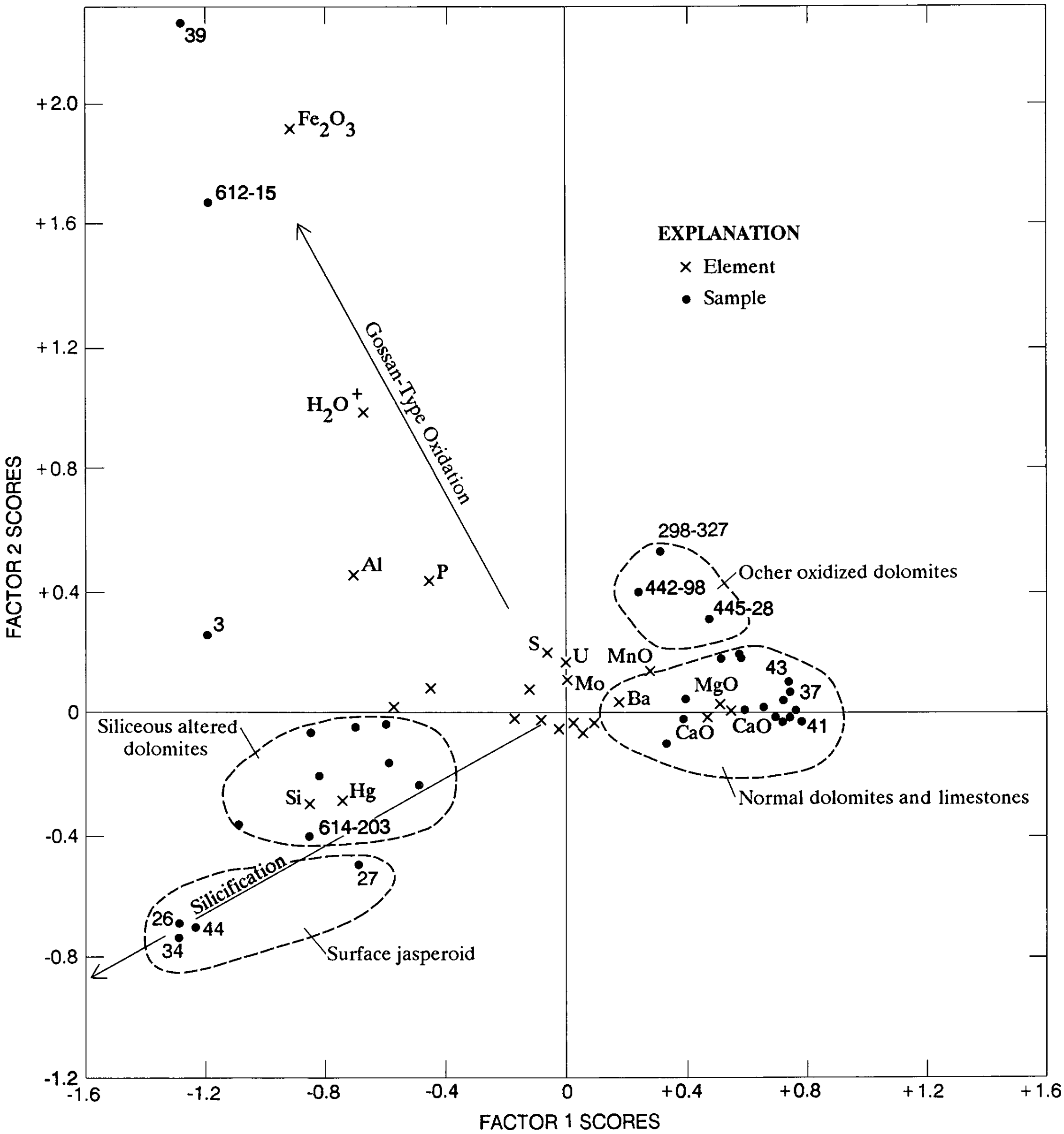

Figure 12. Plot of correspondence-analysis factor scores for factor 1 and factor 2.

from 19 samples indicates that six elements correlate strongly with uranium: Ti, Mn, Ni, Sr, Ba, and Mo. For this sample suite sulfur and uranium are independent ($r=0.008$). Computed correlations of phosphorous and arsenic with uranium are negative; however, in some samples phosphorous and arsenic are enriched with uranium.

A comparison of the average composition of 12 Harding Quartzite samples with data for the Pitch mine suite indicates that contents of Mg, Ca, Fe, S, Mn, and Sr are lower in the quartzites and that Si, Al, P, Ba, and Pb are higher. Mean contents of P, S, Ba, Mn, Pb, and Sr are lower in seven samples of carbonate rocks from the Little Indian deposit as compared with carbonates in the Pitch mine. Contents of Fe, P, and Sr are higher in quartzite samples than in carbonates from the Little Indian.

The predominant mineralogic and chemical feature of the Little Indian mineral deposit is oxidation, in contrast to the Pitch mine, which has predominantly reduced minerals and associated elements. Elements enriched in the Little Indian deposit are logically explained by transport and deposition under oxidizing conditions; the anions phosphate, arsenate, and silicate are important in localizing metals and uranium.

Oxidation at the Little Indian extends to more than 130 m below the present land surface. The oxidation

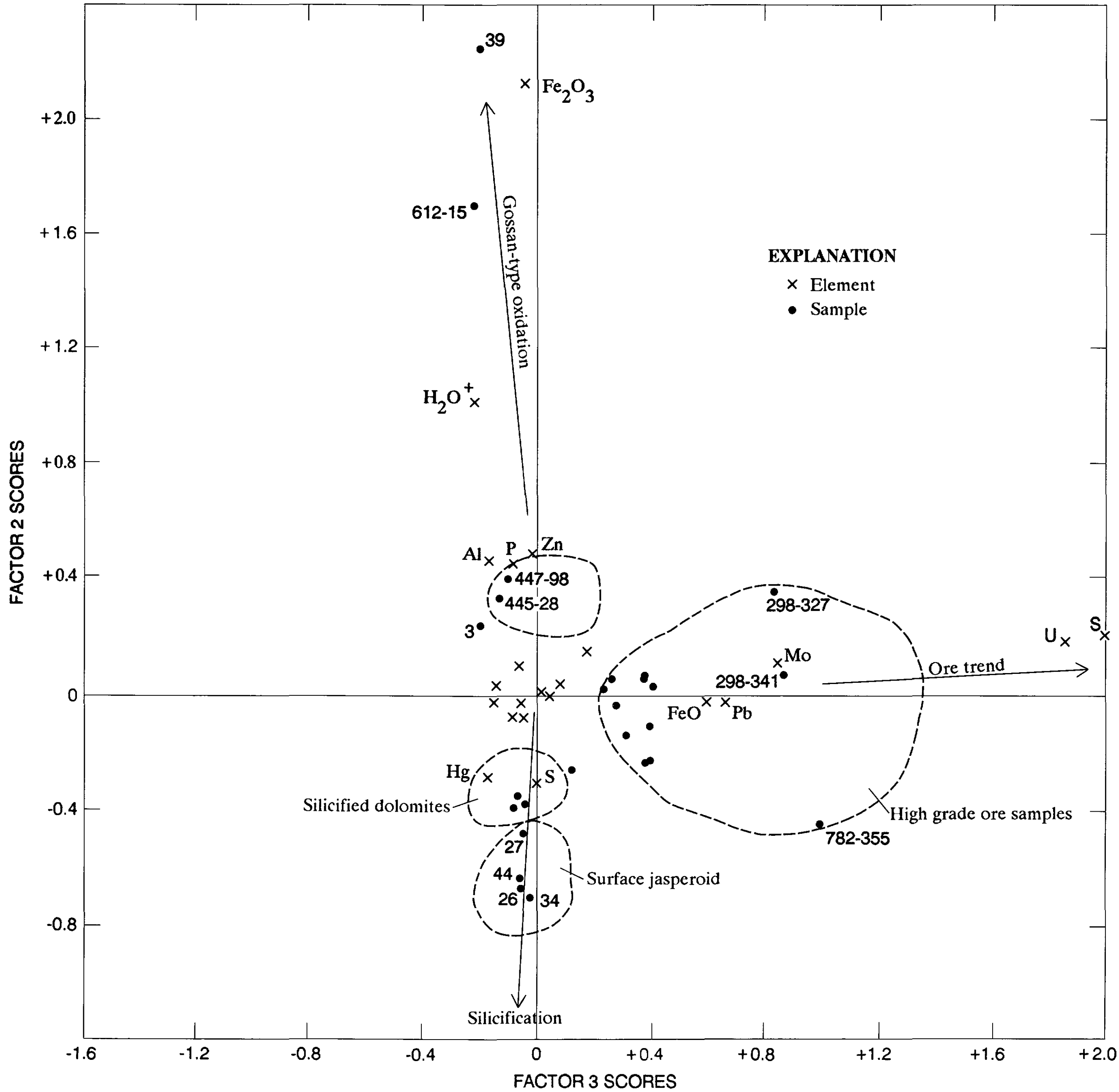

Figure 13. Plot of correspondence-analysis factor scores for factor 2 and factor 3.

extends a few meters below the uranium minerals. This is not difficult to explain, however, if one considers the presence of the Chester fault zone and the ground-water outlet in Agate Creek 1 km to the north at an elevation about 100 m below the zone of oxidation and uranium enrichment. Tertiary ground-water regimes are more difficult to interpret, but the distribution of volcanic rocks suggests that the valley of Marshall Creek was a paleovalley and would have been below the Little Indian in the Oligocene. Oxidation seems to be most pervasive in the vicinity of sandstone-carbonate rock contacts. This may reflect structural and lithologic control of ground-water flow. The regional radioactivity of a bed in the Harding that contains fish scales, hydrocarbon pellets, and pyrite (now hematite) suggests there may have been an older zone of reduced uranium, possibly produced by early diagenetic processes. This uranium might have been remobilized and redeposited to form the Little Indian deposit, or there could have been other sources in granitic or volcanic rocks.

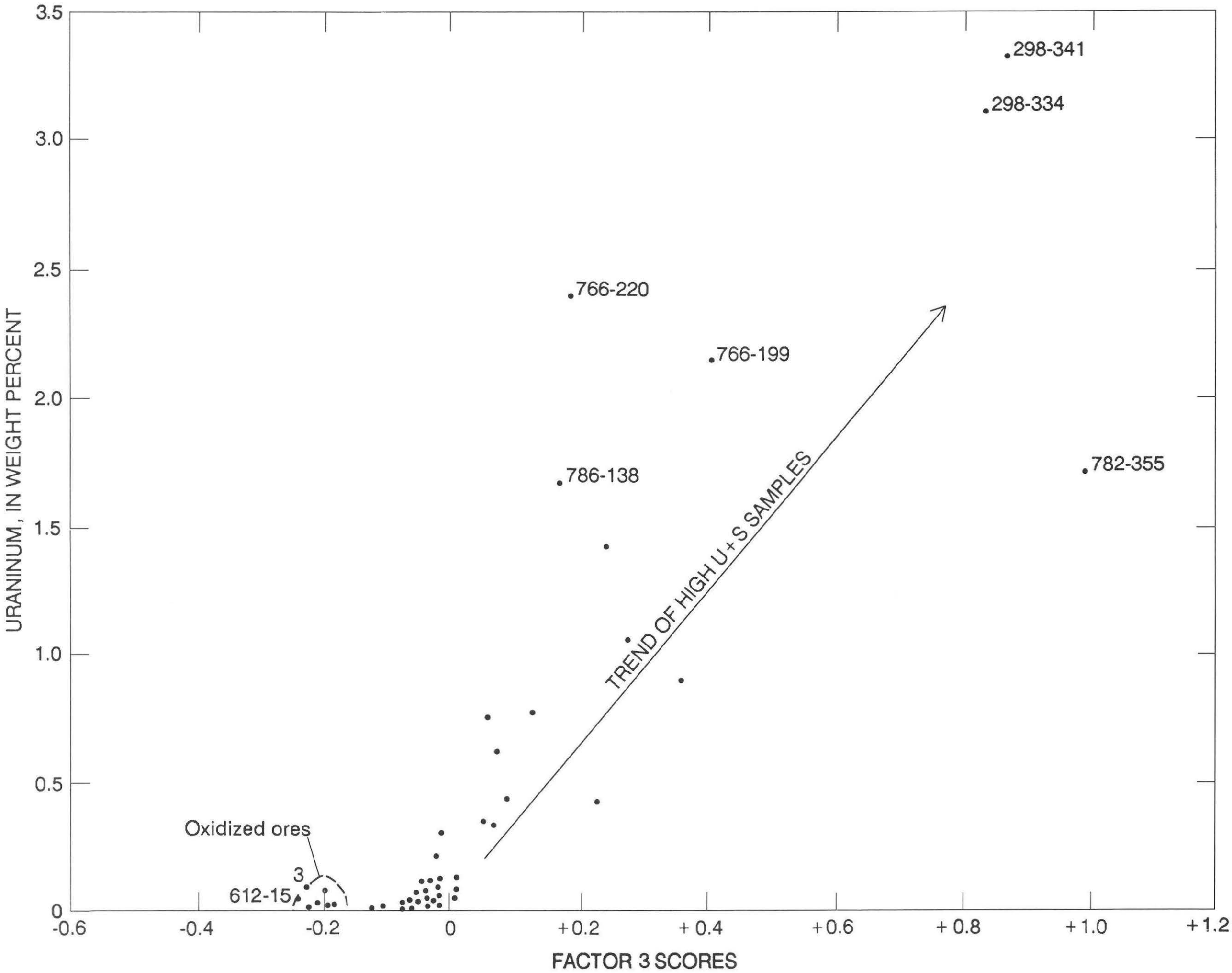

Figure 14. Plot of uranium content versus correspondence-analysis score for factor 3.

INTERPRETATION AND DISCUSSION

Structural Control of Ore

The most important factor in producing the uranium deposits is the Chester fault. The Pitch orebody is within the zone of multiple fault strands, and the richest ore zones are in thoroughly brecciated Leadville Dolomite. The brittle character of the dolomite is an important contributing factor. The Little Indian deposit is also along the Chester fault where brittle quartzites are fractured. Drilling in the area between these two ore deposits reveals additional uraniferous zones in brecciated rocks along the Chester fault zone.

More specifically, the structural mechanism is forced faulting of brittle rocks above a rigid basement block in an upthrust (Stearns, 1978; Nash, 1980). In theory, experiment, and nature, brittle rocks (such as dolomite) develop abundant fractures and breccia when they occur immediately above upthrust basement blocks. At the Pitch mine, as in experiments (Friedman and others, 1976), maximum fracturing occurs where brittle beds intersect the reverse fault plane at angles near 70°. At lower angles of intersection, deformation is less intense, probably due to deflection of shears onto bedding planes. Exploration for zones of maximum brittle deformation should focus on brittle beds and changes in dip where beds are folded next to the fault zone. Concave-downward curvature of the fault surface should be anticipated.

Possible Role of Karst

Karst is well known in the Leadville Dolomite in central Colorado. Iron-stained karst in the Pitch mine area has been prospected for metals (many have been excavated or blasted) and are shown as prospect pits on the

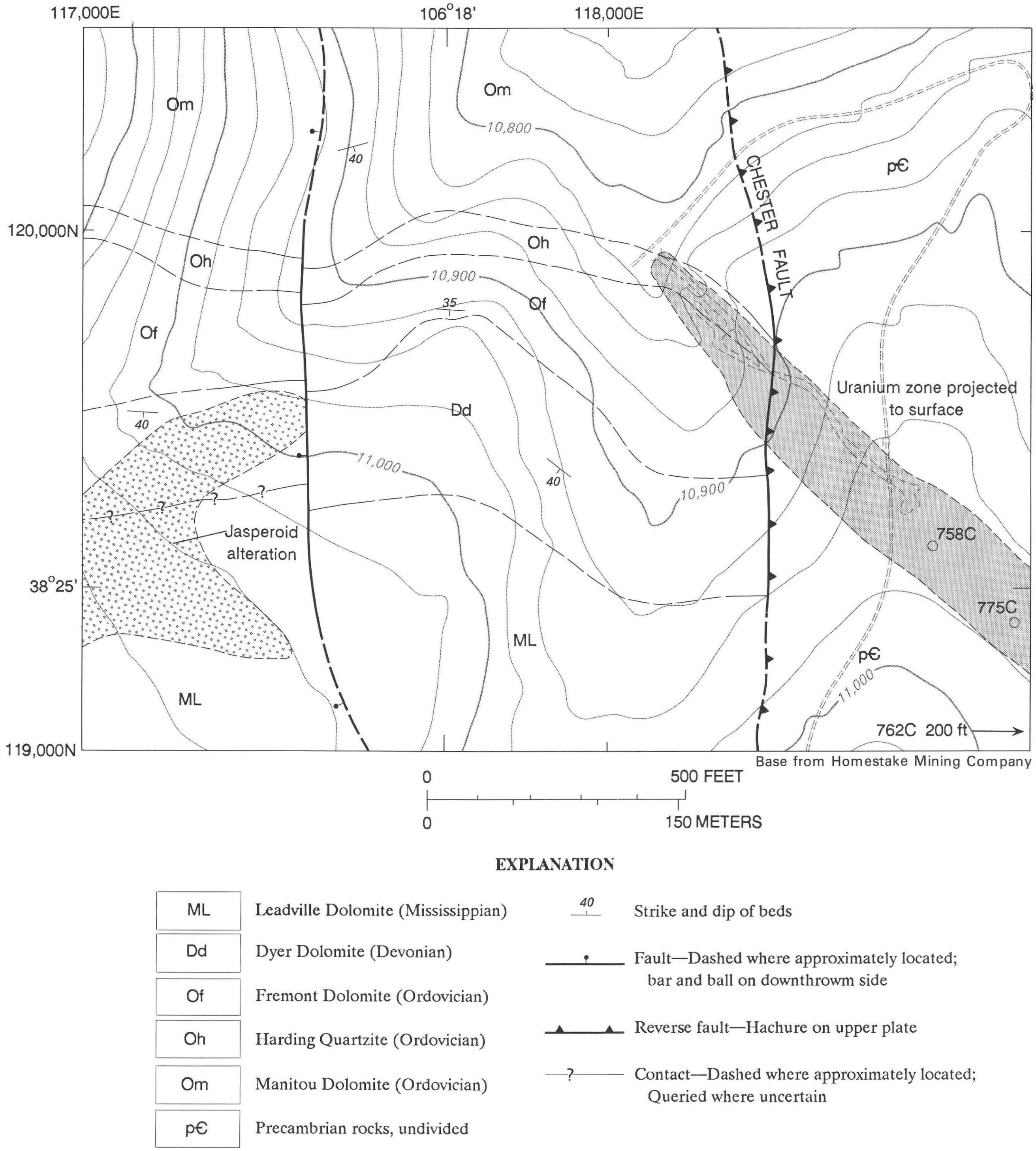

Figure 15. Generalized geologic map of the Little Indian deposit area.

topographic map of the area. Recently Dupree and Maslyn (1979) proposed that uranium at the Pitch mine "largely occurs in the black organic-rich matrix material of carbonate breccias". They added that "these breccias have previously been described as Pennsylvanian Belden Formation fault breccias. The carbonate breccias formed by surface karst weathering, as washed-in cave and sinkhole fill, and by sinkhole collapse." My observations, particularly in the ore zone, do not agree with those interpretations. The carbonate rock breccias are classic tectonic breccias very clearly related to the complex faulting along the Chester fault. The breccia and uranium grade

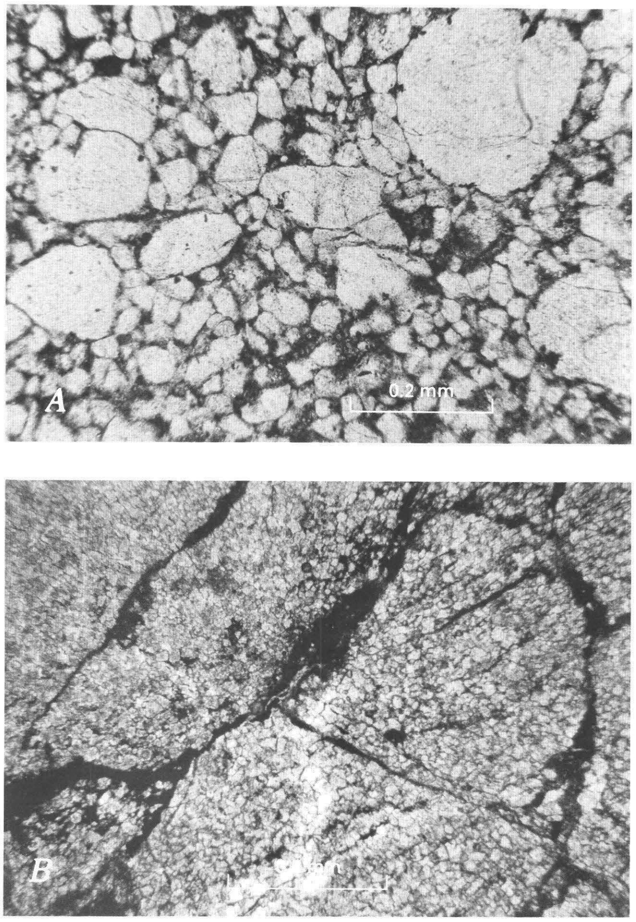

Figure 16. Photomicrographs of ores from the Little Indian deposit. Photos taken in plane polarized light. *A*, Sandstone unit (sample 775–374) having clay-rich matrix and organic material (black) within Harding Quartzite. Note bimodal grain size of quartz grains. *B*, Autunite in fractured Manitou Dolomite (sample 762–494).

die out below and to the west of the faults. After inspecting numerous cores, new open pit exposures, and thin sections, I found no evidence for the "organic-rich matrix" or "washed in clayey sinkhole fill," postulated by Dupree and Mastyn (1979). Chemical analyses did not indicate abundant organic carbon or aluminum in uranium-bearing breccias. Close inspection and microscopic examination revealed black portions of some core as fragments of black shale of the Belden; their presence is consistent with tectonic mixing of breccia in a complex fault zone. Karst features that I have observed outside the mine are characterized by iron oxide fillings, not black clays; and they are only slightly radioactive.

Importance of Leadville Dolomite

The fact that most of the reserves at the Pitch mine occur in the Leadville Dolomite raises a question: Why is the Leadville Dolomite important? This question is underscored by two other facts: (1) most of the high-grade ore at the Pitch mine is in dolomite, and (2) no other significant uranium deposit in the United States occurs in dolomite. I cannot definitively answer the question, but offer the following speculation.

The Leadville Dolomite is a favored host because of its brittle character and structural position, as described earlier. The uniformity of the dolomite, with no shale interbeds, and very fine grain size may have made the Leadville section especially susceptible to the pervasive fracturing and brecciation needed to prepare ground for an economic volume of uranium minerals.

The Leadville Dolomite is clearly not the only brittle host rock. The Little Indian deposit occurs in the Harding Quartzite and partly in dolomites of the Fremont Dolomite and Manitou Dolomite, where these rocks are fractured. Judging from the drill pattern between the Pitch and Little Indian deposits, I infer that other uranium zones occur in Paleozoic dolomites along the Chester fault, but I do not have specific information to evaluate the importance of that resource relative to uranium in the Leadville. Precambrian granitic rocks also host veins of uranium where fractured. My conclusion from these general observations is that several types of rocks can host uranium if they fail by brittle fracture.

Fractured rock alone obviously does not make an ore deposit; chemical factors also must be conducive to ore deposition. The chemical data show a strong association between sulfur, iron, and uranium in the Pitch deposit. The Leadville Dolomite may have been enriched in iron and sulfur as FeS_2 during diagenesis. The role of tidal-flat sedimentation and diagenesis of dolomicrite in causing iron and sulfur enrichment were discussed elsewhere (Nash, 1979), and no specific conclusions could be made because of the paucity of literature on these topics. I favor the concept that FeS_2 and also organic carbon were enriched in the Leadville during tidal-flat sedimentation and early diagenesis. This FeS_2 and organic carbon then would have been available to play a direct or indirect role in chemically localizing uranium in the Leadville after it was fractured and uranium was introduced.

Uranium Transport and Deposition

Chemical and petrologic data both indicate a close association of uranium with ferrous iron and sulfur. Other elements such as lead and molybdenum, enriched with uranium, are presumed to have been localized by sulfur. The lack of wallrock alteration adjacent to pitchblende in dolomite suggests that the transporting fluids were roughly in equilibrium with dolomite and that the solutions were not very acidic. The transport of silica could have occurred if conditions were more alkaline than

Table 4. Analytical data for host rocks and ores, Little Indian deposit, Colorado

[Leaders (--), not determined; L, less than value shown in parentheses; N, not detected. Chemical analyses same as for table 1, except first 14 samples were analyzed by X-ray fluorescence for major elements by J.E. Taggart. Total iron reported as Fe_2O_3]

Major elements in weight percent

	Sample No.	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	TiO_2	P_2O_5	S	Stratigraphy[1]
1	758-353	2.0	.5	.10	11.6	33.0	.07	L(.05)	L(1.0)	.10	1
2	758-359	88.0	3.0	2.7	.30	1.1	1.0	.20	L(1.0)	.05	2
3	758-361	82.0	5.4	3.5	.50	1.2	1.7	.30	1.0	.07	2
4	758-367	96.0	2.0	1.4	.30	.50	.20	L(.05)	1.0	.09	2
5	758-377	90.0	2.0	1.6	.30	1.3	.30	.09	2.0	.10	2
6	762-428	97.0	1.0	.06	.10	L(.10)	.30	.08	L(1.0)	.07	2
7	762-514	5.3	.80	.30	5.0	33.0	.20	L(.05)	L(1.0)	.10	3
8	726-469	14.0	.80	1.5	8.3	24.0	.20	L(.05)	L(1.0)	.10	1
9	775-360	1.0	L(.05)	.30	5.0	35.0	.03	L(.05)	L(1.0)	.10	3
10	775-371	90.0	2.0	1.0	.10	1.8	.20	.09	2.0	.30	2
11	775-374	83.0	4.0	3.2	.30	2.0	1.0	.30	2.0	.30	2
12	775-381	94.0	3.0	.30	.30	.50	.98	.20	L(1.0)	.06	2
13	775-409	97.0	2.0	.62	.10	.20	.20	L(.05)	L(1.0)	.06	2
14	775-431	2.0	.60	.30	8.3	35.0	.10	L(.05)	L(1.0)	.10	1
15	758-349	2.0	.03	.17	20.7	30.3	.14	.02	.01	.02	3
16	758-352	2.2	.43	.22	20.6	29.6	.25	.03	.01	.02	3
17	758-357	84.3	4.5	2.7	.63	3.0	1.4	.29	.90	.04	2
18	758-361	83.9	4.7	2.9	.87	2.0	1.5	.33	.64	.04	2
19	758-363	95.0	1.4	.67	.41	1.5	.42	.12	.12	.02	2

Minor elements in parts per million

	Sample No.	As	Ba	Cr	Cu	Mn	Ni	Pb	Sr	U	V
1	758-353	L(2.0)	2.0	2.0	5.0	150.0	N	20.0	10.0	13.7	5.0
2	758-359	108.0	70.	15.0	50.0	70.0	30.0	100.0	30.0	219.0	70.0
3	758-361	237.0	100.0	30.0	50.0	30.0	10.0	200.0	150.0	5330.0	100.0
4	785-367	25.0	70.0	1.0	30.0	10.0	5.0	70.0	50.0	81.4	N
5	758-377	62.0	50.0	2.0	50.0	3.0	5.0	700.0	30.0	52.4	L
6	762-428	8.0	20.0	3.0	15.0	5.0	5.0	30.0	100.0	10.8	L
7	762-514	L(2.0)	5.0	2.0	3.0	150.0	5.0	10.0	5.0	11.5	N
8	762-469	308.0	100.0	3.0	7.0	500.0	200.0	300.0	30.0	73700.0	N
9	775-360	2.0	2.0	2.0	5.0	300.0	5.0	20.0	7.0	107.0	7.0
10	775-371	12.0	30.0	3.0	100.0	20.0	5.0	100.0	150.0	216.0	L
11	775-374	52.0	100.0	10.0	100.0	20.0	50.0	200.0	300.0	104.0	20.0
12	775-381	2.0	15.0	15.0	10.0	7.0	5.0	10.0	50.0	8.39	30.0
13	775-409	35.0	70.0	5.0	7.0	50.0	20.0	30.0	10.0	13700.0	30.0
14	775-431	L(2.0)	5.0	3.0	3.0	300.0	L	N	7.0	15.7	N
15	758-349	--	15.0	--	--	400.0	--	--	40.0	89.4	--
16	758-352	--	35.0	--	--	300.0	--	--	55.0	18.3	--
17	758-357	--	80.0	15.0	30.0	80.0	7.0	--	130.0	346.0	70.0
18	758-361	--	90.0	20.0	30.0	80.0	7.0	--	120.0	4800.0	70.0
19	758-363	--	30.0	3.0	10.0	N	2.0	--	87.0	807.0	10.0

[1]Stratigraphy: 1, Manitou Dolomite; 2, Harding Quartzite; 3, Fremont Dolomite.

Table 5. Statistical summary of chemical data, Little Indian deposit, Colorado

Element	Minimum	Maximum	Geometric mean	Geometric deviation	Valid values
Major elements, in weight percent					
SiO_2	1.00	97.9	58.35	42.9	19
Al_2O_3	.03	5.40	2.12	1.63	18
Fe_2O_3	.06	3.50	1.24	1.19	19
FeO	.04	1.60	.096	.061	5
MgO	.41	20.7	8.64	10.9	5
CaO	.20	35.0	13.05	15.3	18
Na_2O	.00	.12	.046	.045	5
K_2O	.07	1.70	.56	.54	18
H_2O^+	.36	2.10	1.14	.81	5
H_2O^-	.05	.60	.28	.21	5
TiO_2	.02	.33	.17	.11	12
P_2O_5	.01	2.00	.97	.81	10
MnO	.00	.05	.022	.022	5
CO_2	.02	47.0	18.6	25.5	5
F	.02	.40	.15	.17	5
S	.02	.30	.092	.079	19
Minor elements, in parts per million					
Ag(s)	2.	10.	5.5	3.31	4
B(s)	20.	150.	58.9	43.1	9
Ba(s)	2.	100.	45.6	38.8	14
Be(s)	1.5	3.	2.20	.76	5
Co(s)	5.	100.	32.5	45.2	4
Cr(s)	1.	30.	78.8	8.31	17
Cu(s)	3.	100.	29.7	31.4	17
Mn(s)	3.	500.	115.4	151.4	14
Ni(s)	2.	200.	24.1	50.3	15
Pb(s)	10.	700.	137.7	191.7	13
V(s)	5.	100.	41.2	33.5	10
Zr(s)	100.	500.	253.8	124.9	13
As	2.0	308.	77.4	102.7	11
Cl	25.	365.	161.	186.2	5
Ba	15.	90.	50.0	32.9	5
Hg	.10	.39	.026	.011	5
Mo	.5	4.5	2.02	1.95	5
Pb	5.	130.	69.4	60.9	5
Sr	35.	150.	72.0	47.0	5
Zn	5.	220.	79.0	87.9	5
U	8.39	73700.	5243.0	16913.	19

pH 9, and deposition could have occurred upon neutralization by carbonate rocks. However, deposition of silica more commonly occurs in response to cooling (Holland and Malinin, 1979). The transport of silica is quite unlike the transport of uranium because the anionic complexes that carry uranium are not effective for silica. The association of uranium with FeS_2, in particular with marcasite, yields the greatest amount of information on conditions of uranium transport and deposition.

Research by Goldhaber and Reynolds has documented the important role of marcasite in roll-type uranium deposits (Goldhaber and others, 1978; Goldhaber and Reynolds, 1979; Reynolds and Goldhaber, 1983). Marcasite also is closely associated with pitchblende in the hardrock deposit at the Midnite mine, Washington (Ludwig and others, 1981). Experimental, isotopic, and paragenetic data on marcasite strongly support the hypothesis of formation from metastable sulfur oxyanions such as thiosulfate (Granger and Warren, 1969; Goldhaber and Reynolds, 1979). An important property of these sulfur oxyanions is that they spontaneously break down into sulfide and sulfate ions; sulfide ion so generated is an excellent reductant and also would be present to form FeS_2. Mechanisms described by Granger and Warren and by Goldhaber and Reynolds seem appropriate for the Pitch mine. First, pre-ore sulfides in the Leadville Dolomite and in the Belden Formation were oxidized, possibly by uranium bearing solutions, in the near-surface environment. Oxidation of pre-ore pyrite created thiosulfate or similar ions that moved down the hydraulic gradient of the Chester fault zone where they disproportionated and caused reduction of uranyl ions. Additional reduction could have been caused by bacterial sulfate ions. Sulfur isotope analyses of marcasite could place constraints on the sulfur cycle and substantiate which reduction mechanism was active. (See Reynolds and others, 1982, for details.)

The low uranium content of most pyritic Belden sandstones is not easily explained. Low permeability caused by high clay content may explain why some localities are barren. Other localities adjacent to faults and ore-grade dolomite breccia are especially puzzling. One possible explanation is that the pyrite in these sandstones was nonreactive under reducing conditions, thus did not provide sulfur oxyanions capable of reducing uranium. Partial oxidation of pyrite creates reactive sulfur species capable of reducing uranium (Granger and Warren, 1969).

Resource Implications

The Pitch deposit, as understood from drilling and mining over the past ten years, constitutes a "new" type of deposit with the potential to carry significant resources in other areas. A somewhat similar deposit occurs at Copper Mountain, WY. (Yellich and others, 1978), and exploration possibilities along Laramide upthrusts of Colorado have been reviewed by Nash (1980). For regional-scale exploration and resource assessment, the key factors are presence of a major structure, such as an upthrust; brittle rocks; a potential source of uranium, such as altered tuffaceous rocks; and a reductant, generally not known from surface exposures.

A grade and tonnage model based on one deposit is not reliable, but for this deposit, structural control is so strong that good estimates can be extrapolated from structural information. The following comments are based on the announced reserve of 3,245,000 kg U_3O_8 at an average grade of 0.17 percent U_3O_8 (Ward, 1978), my logging of drill core, and my observations on drilling patterns in the Pitch mine area. The geometry of the deposit is shown on figure 2. More generally, without regard to economic factors, the resource zone along the Chester fault zone is roughly 100 m wide, 200 or more meters deep, and at least 3 km long. Important parts of the Pitch deposit (brecciated dolomite) contain more than 0.2 percent U_3O_8, but there are also large volumes of slightly brecciated rock (granite, siltstone, sandstone, carbonaceous shale) with grades in the range 0.02–0.10 percent. Extensive development drilling of the Copper Mountain deposit also indicates major amounts of low-grade (<0.05 percent U_3O_8) mineralization. It is thus known that this type of deposit contains both high grade and low grade zones of uranium which can only be evaluated by careful drilling. The Pitch and Copper Mountain deposits are assumed to be relatively large examples of their type. Judging from the volume of favorably prepared rocks at the Pitch deposits and the known large size of other upthrust zones, a rough estimate of potential resources in one of these deposits is in the 10,000 to 30,000 tonnes U_3O_8 range, only part of which would ever be economic to recover, if found.

SUMMARY: GENETIC MODEL

Information presented in this paper is consistent with, but does not prove, a near-surface genesis for the Pitch uranium deposit in the Oligocene(?), shortly after volcanism. The following discussion and speculation are directed to the Pitch deposit, but may be pertinent to the Little Indian deposit also. Preparation for ore emplacement included sedimentation and diagenesis of brittle rocks, some containing diagenetic pyrite, and brecciation in the Laramide along the Chester fault. The uranium deposits are conclusively post-Chester fault as the structural permeability along that fault zone is a key ore control. A post-volcanic Oligocene(?) age is postulated for the following model.

Uranium Source

Quartz latite welded tuff of Oligocene(?) age containing pumice and glass was deposited above the Chester fault. This unit, and other volcanics, were probably several hundred meters thick; thin relicts are exposed between the Pitch and Little Indian mines (Olson, 1983). These tuffs would have been highly reactive shortly after deposition and would have undergone reactions similar to those described by Zielinski (1981). This alteration of volcanic rocks is believed to have been the source of silica to form the jasperoid along the Chester fault in brecciated carbonate rocks below the volcanic pile. Volcanic rocks within 10 km of the Pitch mine are more radioactive today than other rocks, such as Precambrian granite; and freshest samples contain an average of 10.5 ppm uranium and 35.2 ppm thorium (two freshest samples). This most radioactive volcanic unit is the Rowley Andesite; it is not exposed along the Chester fault but is stratigraphically younger than the quartz latite tuff. The quartz latite is more silicic than the Rowley Andesite[2], thus it quite possibly contained more uranium, particularly before alteration.

[2]Chemical analysis (J. T. Nash, unpub. data, 1980) of two samples of Rowley Andesite shows an average of 64.6 percent SiO_2, 4.1 percent Na_2O, and 5.3 percent K_2O which suggest the unit sampled is a high-potassium dacite.

Paleohydrology

In the Oligocene(?), the Pitch mine area was beneath a volcanic trough and about 600 m above the Marshall Creek paleovalley (Olson, 1983). Some lakes probably existed at times and were filled by tuffaceous rocks. Ground water in the Pitch mine probably flowed southward along the Chester fault toward Marshall Creek, beneath a cover of volcanic rocks. Volcanism in the area would probably have heated the ground water, possibly to 50–75 °C. At a depth of a few hundred meters, in a permeable fault zone, the ground water probably would have been oxygenated or partially oxygenated. Conditions would have been excellent for uranium transport.

Uranium Deposition

Laterally or downward moving fluids carrying uranium, molybdenum, silicon and possibly sulfur oxyanions (Reynolds and others, 1982) deposited uranium and silica when they encountered structurally prepared traps that promoted reducing conditions. Reduction could have been caused by sulfate-reducing bacteria or by disproportionation of sulfur oxyanions in the fluid that transported uranium. Silica is not responsive to reduction, but possibly it precipitated in response to cooling (Holland and Malinen, 1979). There are no criteria to define temperature, but presumably it was below 100 °C at the postulated shallow level.

The essential ingredients are postulated as upthrust faulting and brecciation, brittle rocks containing pyrite, and a volcanic source containing leachable uranium. Details of the ore-forming process need refining, but the proposed, largely empirical model can expedite uranium exploration.

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