GEOLOGY OF DOLOMITE-HOSTED URANIUM DEPOSITS AT THE PITCH MINE, SAGUACHE COUNTY, COLORADO

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SUMMARY

Newly documented uranium ore in the Pitch mine occurs chiefly in brecciated Mississippian Leadville Dolomite along the Chester upthrust zone, 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 new 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 reverse-fault zone. Other rocks tended to either remain unbroken or undergo ductile deformation. Chemical controls on uranium deposition are subtle and appear chiefly to involve coprecipitation of FeS_2 as pyrite and marcasite, suggesting that sulfide ion may be the reductant.

Leadville Dolomite in the area is about 130 m thick and is predominantly nonfossiliferous dolomicrite. In the Pitch mine, Leadville Dolomite is bound by faults and maximum known thickness is about 17 m. Mud texture, paucity of fossils and other allochems, thin laminations, and probable algal mat structures suggest sedimentation in a tidal-flat (possibly supratidal) environment. Preservation of mud texture and lack of replacement features indicate that dolomitization was an early, prelithification process, as in modern tidal flats, and produced a chemically and texturally uniform rock over tens of meters vertically with relatively few limestone beds surviving. Carbonate rocks of the Belden Formation, in contrast to those of the Leadville, contain calcite in great excess of dolomite, more than 5 percent silt-size quartz and clay, and abundant fossils and oolites. Belden limestones (sandy micrite and sandy wackestone) probably were deposited in an intertidal or subtidal environment. Not much uranium ore occurs in these rocks. Chemical aspects, such as the iron, sulfur, and organic carbon contents, are similar to those of Leadville dolomites, and hence seem favorable, but limestones in the Belden generally are only mildly fractured.

The content of most minor elements in ore-bearing dolomites is normal for rocks of this composition, but iron, sulfur, molybdenum, and lead are enriched in ore. One surface expression of ore in dolomite is ocher, leached, porous gossan that is characterized by residual silica and limonite and by high radioactivity but low uranium content.

INTRODUCTION

An important recent economic development on the Western Slope was the reopening of the Pitch mine as an open-pit uranium mine in 1979. The Pitch mine is in the Sawatch Range in Saguache County, Colorado, about 60 km east of Gunnison (fig. 1). The Pitch deposit (formerly known as the Pinnacle) and several other uranium prospects were located in 1955. Mining began in 1959 with the opening of two underground adits, and ceased in 1962 when the contract with U.S. Atomic Energy Commission expired. About 100,000 tons of ore averaging 0.50 percent U_3O_8 (1,000,000 lbs or 454,000 kg U_3O_8) was mined, and another 100,000 lbs (45,400 kg) U_3O_8 was recovered by solution mining (Ward, 1978). In 1972, Homestake Mining Company acquired the property and began to reevaluate the mine area for additional reserves amenable to open-pit mining, because the previous history had demonstrated that fault offsets of ore and unstable wallrocks made underground mining costly.

In the period 1972 to 1977, Homestake Mining Company documented a reserve minable by open-pit methods of 2.1 million tons of ore at an average grade of 0.17 percent U_3O_8 (7,140,000 lbs or 3,245,000 kg U_3O_8) (Ward, 1978). Rather than seek high-grade "vein-type" ore, Homestake explored for more dispersed ore. 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 in 1959–61 also was probably in Leadville Dolomite, but was not recognized as such (J. M. Ward, Homestake Mining Co., oral communication, 1979). Homestake is mining the deposit at a rate of about 600 tons per day from an open pit that ultimately will be about 1,500 m long and have an average depth of 120 m.

GEOLOGIC SETTING

Rocks ranging in age from Precambrian to Oligocene(?) are known in the Pitch mine area (Table 1). Precambrian rocks are chiefly pegmatitic granite, hornblende-biotite schist, hornblende gneiss, and pegmatite. A hematitic regolith was developed on the Precambrian rocks prior to the Cambrian. Above the Precambrian was deposited about 600 m of Paleozoic rocks. The lower half is

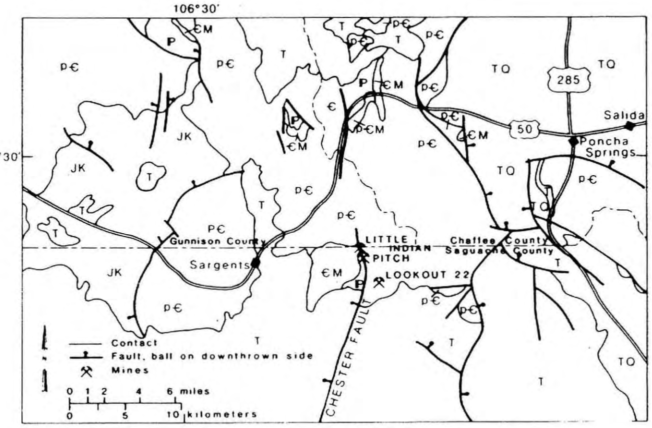


Figure 1. Generalized geologic map and location of Pitch Mine, Colorado (after Tweto and others, 1976). Note that more detailed mapping (Olson, 1979) does not show the Chester fault cutting Tertiary volcanics. Abbreviations: TQ, Tertiary and Quaternary sediments, mainly post-volcanic; T, Tertiary intrusive and volcanic rocks; JK, Jurassic–Cretaceous rocks; ℙ, Pennsylvanian sedimentary rocks; ЄM, Cambrian to Mississippian sedimentary rocks; pЄ, Precambrian rocks.

Table 1. Simplified stratigraphic column in the Pitch Mine area (Modified from Olson, 1979)

Oligocene(?) QUARTZ-LATITE FLOWS: light-colored felsic flows, 0–20 m thick

–unconformity–

Pennsylvanian BELDEN FORMATION: contains three units: upper green and brown sandstone and gray shale (200 m or more thick); middle blue-gray limestone with red shale and fine sandstone (30–60 m thick); and lower white sandstone and black shale (40–90 m thick)

–unconformity–

Mississippian LEADVILLE DOLOMITE: dark blue-gray to brownish-gray dolomite and minor limestone; contains calcite and chalcedony veinlets and local black chert zones; about 130 m thick

Devonian DYER DOLOMITE: tan to light-gray dolomite; about 50 m thick

Devonian PARTING QUARTZITE: varicolored shale and quartzite; about 5 m thick

–unconformity–

Ordovician FREMONT DOLOMITE: blue-gray limestone and dolomite; about 55 m thick

Ordovician HARDING QUARTZITE: white quartzite, commonly with limonitic stain, and some black shale; about 10 m thick

–unconformity–

Ordovician MANITOU DOLOMITE: light-pinkish-gray dolomite, 75–90 m thick

Cambrian SAWATCH QUARTZITE: vitreous quartzite less than 1 m thick

–unconformity–

Precambrian granitic and metamorphic rocks

predominantly dolomite, but it contains three units of quartzite that are useful stratigraphic markers between the similar-appearing dolomites. The Mississippian Leadville Dolomite is the darkest dolomite in the area, and generally is massive with faint laminations. The top of the Leadville Dolomite is locally limonitic, the result of a karst that was developed prior to deposition of the Pennsylvanian Belden Formation. The Belden Formation comprises diverse rock types, including coarse kaolinitic sandstone; green, clay-rich, fine sandstone; black and red shale; and gray and black limestone and minor dolomite. Abrupt facies changes are common over lateral distances of 300 m. A few erosional remnants of Oligocene(?) quartz latite flows are preserved topographically above and a kilometer north of the Pitch mine. About 6 km south of the mine, more than 300 m of Tertiary andesitic volcanics of the San Juan volcanic field cover Paleozoic rocks.

The major structural feature in the mine area is the Chester fault zone, which dips east at about 70°, strikes nearly due north, and places Precambrian rocks above and west of Paleozoic rocks (figs. 2 and 3). Net reverse movement along numerous faults is more than 600 m. The fault zone is about 100 m wide in the mine area (fig. 2). Paleozoic rocks immediately west of the Chester fault are folded into a south-plunging syncline whose east limb is probably overturned under the fault zone (fig. 3). Farther west, the Paleozoic rocks have a low dip and are gently warped in broad folds. East-trending faults cut the Chester fault zone and form rotated blocks. The faulting in the Chester fault zone is of Laramide age; Cretaceous rocks about 20 km to the west are displaced by similar reverse faults, and Oligocene(?) volcanic rocks show small displacement, probably from reactivation along the Chester fault. Younger north-trending faults displace volcanic rocks southeast of the mine (Olson, 1979).

URANIUM DEPOSITS

Uranium anomalies, occurrences, and deposits are known in five geologic settings in the Marshall Pass district. The following are arranged by decreasing age of host, but the ages of mineralization are not known.

(1) Precambrian biotite schist—several vein-type 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. Mineralization is probably pitchblende and some hexavalent uranium minerals. Near these vein-like deposits are high-grade concentrations of uranium in alluvium (type 5 below). The deposits are probably related, and the high concentrations mined probably reflect supergene processes (Malan, 1959; Gross, 1965).

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

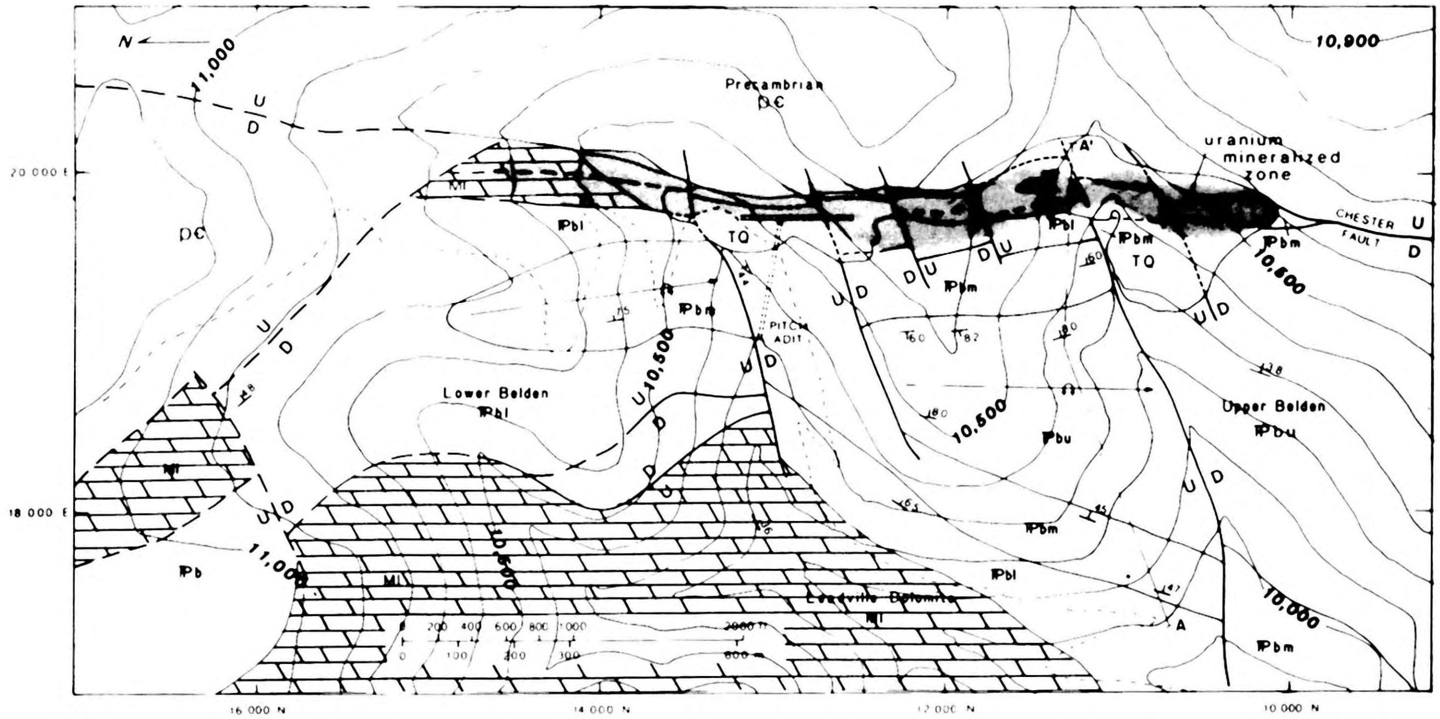
(3) Ordovician Harding Quartzite—uranophane and other U^{+6} minerals fill fractures in the quartzite and generally are accompanied by limonite (Malan, 1959). A bed containing carbonaceous trash, organic pellets, and fish scales near the top of the Harding is radioactive. This bed guided prospectors to the Little Indian 36 deposit, where the Harding is fractured in the Chester fault zone 2 km north of the Pitch mine. Production from the Little Indian 36 mine from 1957 to 1959 was about 6,800 tons ore averaging of 0.48 percent U_3O_8 (65,000 lbs or 29,500 kg U_3O_8) (Ward, 1978).

(4) Mississippian Leadville Dolomite and Pennsylvanian Belden Formation—at the Pitch mine, oxidized and reduced uranium minerals 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 uranium content. Pyrite occurs in most unoxidized rocks, but many pyritic rocks have very low uranium content. Fractures, shears, and breccia zones carry the uranium ores. Past production from the Pitch (Pinnacle) mine was about 1,100,000 lbs (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.

(5) 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 tons of high-grade ore (about 3,900 lbs or 1,800 kg U_3O_8) produced from these deposits was from the pockets in alluvium, and a lesser amount from vein-like deposits within Precambrian host rocks (type 1, above) (Malan, 1959; Ward, 1978).

The ages and genetic relations of these various types of uranium



EXPLANATION

TQ:	Tertiary to Quaternary talus and alluvium	36	Strike and dip of beds
IPbu:	Pennsylvanian Belden Formation, upper unit		Fault, dashed where approximately located, dotted where covered
IPbm:	Pennsylvanian Belden Formation, middle unit		Contact, approximately located
IPbl:	Pennsylvanian Belden Formation, lower unit		Overturned syncline, inferred
Ml:	Mississippian Leadville Dolomite		Uranium mineralized zone (> 0.01 percent U_3O_8), projected to surface
p€:	Precambrian rocks, undivided		

Figure 2. Geologic map of the Pitch Mine area. Cross section A-A' is shown on Figure 3. Geology in places adapted from mapping by Olson (1979) and J. M. Ward, Homestake Mining Co. (unpub. data, 1972–1977). Base generalized from 1:2,400 map of Homestake Mining Co. Grid is mine coordinate system used by Homestake Mining Co.

deposits are unresolved problems. Most observers suspect that the deposits share some fundamental geologic features, such as a common source.

PETROLOGY OF CARBONATE HOST ROCKS

Approximately 350 m of carbonate rocks in five formations occur in the mine area. Many of the carbonate rocks are lithologically similar to each other, especially the pinkish-tan-weathering dolomites of the Manitou, Fremont, and Dyer Dolomites. Dolomites and limestones of the Belden and Leadville Formations generally are darker than the underlying carbonates.

Dolomite is the predominant rock of the Leadville in the mine area, although limestone occurs in a few places. Typical dolomites are medium gray to black, often with brownish or reddish-brown tones, and tend to be a bit lighter and bluish on weathered surfaces. Bedding ranges from medium to massive, commonly with faint laminations (mm scale). Carbonaceous shale and sand layers are rare and are thin where present. Most Leadville dolomites are fetid when broken.

Brecciation of several types is common in the Leadville Dolomite. In a few places, the brecciation is associated with curved surfaces and bounded by undeformed beds, suggesting intraformational slumping. Some breccia at the top of the Leadville contains iron oxides and seems to reflect karst development. A large area of breccia 2 km south of the Pitch mine contains angular and subangular fragments but little sparry carbonate cement. This breccia, which probably formed in pre-Belden time, contains small amounts of iron oxides and does not seem to be related to karst.

Leadville Dolomite in the Chester fault zone at the mine is interpreted to be bound by faults (fig. 2). In some localities, the dolomite lies on a hematitic regolith of Precambrian rocks, which suggests a possible depositional contact, but other relations suggest that these are fault contacts. Maximum 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 has not been possible to establish the stratigraphic position of the Leadville in the mine because it is highly deformed, and the outlying Leadville displays no obvious internal units useful for correlation.

Chert is common in the Leadville as veinlets, stringers, and concretionary nodules. The chert is generally black. In some well-exposed localities bed-like chert is faulted and cut by a breccia of recrystallized dolomite. Much of the chert is probably early diagenetic (Banks, 1970) although the occurrence of several cherty or "jasper" zones that crop out over an area of more than a thousand square meters adjacent to (under) the Chester fault zone suggests that some chert may be structurally controlled and of Tertiary age.

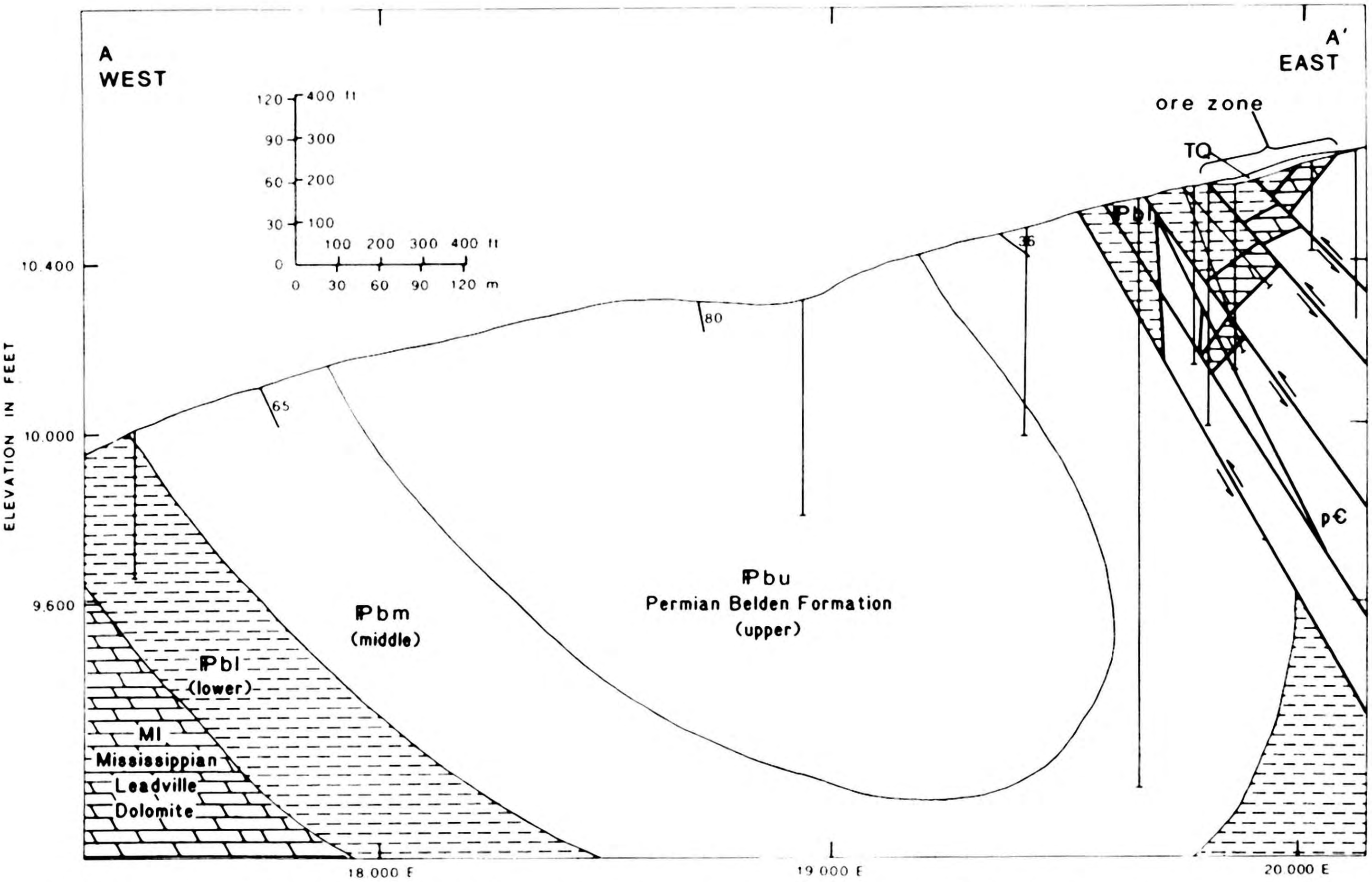


Figure 3. Schematic cross section A-A' of the Pitch Mine area. Line of section is shown on the geologic map (fig. 2). Structure in the Chester fault zone is known from drilling to be much more complex than shown. The overturned synclinal structure is inferred from sparse surface outcrops showing bedding attitudes. Symbols are same as on Figure 2.

Carbonate rocks in the Belden Formation generally are limestone, with rare dolomite, and have thick to massive bedding. Color is light gray or bluish gray in outcrop, and medium gray to black or brownish black on fresh surfaces or core. Terrigenous material is generally abundant in Belden carbonates; black or red shale laminae or enclosing beds are much more common than in the Leadville. White or pink calcite veinlets are common in the Belden carbonates, but chert and intraformational breccia have not been observed.

Petrographic studies (Nash, 1979) show that the Leadville Dolomite consistently contains more than 95 percent dolomite and rarely contains more than traces of terrigenous quartz and clay. However, chemical analyses and normative mineral calculations indicate more quartz and clay than are visible in thin sections. Pyrite is, or was, present in essentially all dolomites in amounts ranging from about 0.2 to 16 percent. Twenty percent of the dolomites display faint lamination, 7 percent contain intraclasts, 8 percent contain burrows or evidence of bioturbation, 3 percent contain sparse fossils (a few brachiopods), and 2 percent contain pellets. Sand grains are generally round and are probably windblown. Possible mudcracks are present in 5 percent of the dolomites, and possible "birdseye" textures (openings filled by sparry carbonate) are present in 3 percent. No gypsum, anhydrite, or halite were observed in thin sections or X-ray diffraction patterns, nor were any casts or pseudomorphs after these evaporite minerals detected.

Based on composition and texture, all the Leadville dolomites are classified as dolomicrites (Folk, 1959, 1962) or dolomite mudstone (Dunham, 1962). The dolomites formed from dolomite mud or dolomitized lime mud. The general absence of terrigenous grains or carbonate clasts testifies to a probable lack of strong currents or wave action, meaning that the environments were probably protected from the source by a barrier or by distance.

Samples from the Leadville collected about 1 km west of the mine are notably different from the typical carbonates described above. These samples show good bedding and crossbedding, are composed entirely of calcite, and contain 30 to 40 percent fossils (ostracods, gastropods, foraminifera, and brachiopods) and oolites supported in very fine calcite mud. 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.

Carbonate rocks in the Belden Formation are compositionally and texturally more diverse than in the Leadville. In the Belden a continuum exists between essentially pure carbonate rocks and terrigenous rocks. Here we will consider only those samples containing more than 50 percent carbonate minerals. Of the 29 samples that meet this criterion, 60 percent contain 10 to 50 percent quartz sand and silt grains, 28 percent are fossiliferous, 18 percent are bioturbated, and 12 percent contain intraclasts. Most of the Belden carbonates contain calcite and little or no dolomite; 15 percent had dolomite in excess of calcite. Based on these compositional and textural data, most Belden carbonates are classified as sandy micrite (Folk, 1962) or sandy wackestone (Dunham, 1962). In a few samples, sparry calcite cements clasts; these rocks contained little mud and are classified as grainstone (Dunham, 1962).

Chert nodules and stringers in the Leadville are replacements of carbonate rock and are very finely crystalline chalcedonic quartz. Grain size typically is less than 15 microns. Specks of iron oxides and carbonaceous matter occur between chalcedony crystallites. Irregular veinlets or swaths of more coarsely crystalline quartz (50 microns to 1 mm size) cut or grade from the aphanitic chert. Textures of chalcedony and quartz in the broad, silicified "jasper" zones are similar to that in chert nodules.

The most important host for ore in the Pitch deposit is dark-gray dolomite of the Leadville. In the ore zone, this dolomite has a consistent composition. Calcite is a minor constituent, except in some near-surface-oxidized ocher dolomites that underwent some dedolomitization. Silica content is the major variable and is chiefly chert, which probably is older than the ore. Fragments of chert are seen in breccia; hence that chert is pre-fault.

Carbonate breccias are extensive in the Chester fault crush zone. It is common to observe in drill core 5 to 10 m of uniformly and thoroughly brecciated dolomite. Such zones typically contain uniform and high ore grades, indicating that dark dolomite breccia is a favorable host, presumably for both physical and chemical reasons. The breccias generally are not well cemented, and fragments and matrix are not notably recrystallized. Extensive cementation of breccia by silica or sparry carbonate has not been recognized. Many breccias are a mixture of lithologies that must have originated in different formations. The mixing of breccia fragments is consistent with the extremely complex interfaulting of slivers of Precambrian, Leadville, and Belden rocks.

Dolomite in the ore zone, and in breccias along the Chester fault zone, shows remarkably little recrystallization. Many are essentially unrecrystallized (grain size less than 4 microns), and dolomite matrix between the breccia fragments typically is very finely crystalline (less than 16 microns). Crustified overgrowths have not been observed, even in fault breccia. Recrystallization of these carbonate rocks seems to be normal coalescive neomorphism, typical of diagenesis (Folk, 1965). Hence, most recrystallization probably occurred in the Paleozoic, long before the area was deformed and probably long before uranium was emplaced.

Pyrite occurs in all Paleozoic rocks in the ore zone. It is most conspicuous as coarse crystals in white Belden sandstones, but pyrite is also present as small crystals in siltstone, carbonaceous shale, and coal, and in dolomite and limestone of the Belden and Leadville. Pyrite in carbonate rocks occurs in three habits: (1) along silty bedding planes; (2) dispersed as tiny crystals, generally less than 50 microns in size, throughout the rock; and (3) along fractures and in breccia matrix. Fine dispersed pyrite probably accounts for as much as about 0.5 weight percent sulfur found in chemical analyses (Nash, 1979).

The distribution of uranium minerals in carbonate rocks is complex. Veinlets of pitchblende and coffinite a few millimeters wide are rarely seen. Much of the uranium is not in recognizable minerals in drill core or under the microscope in incident light. Many core samples containing 2 to 5 weight percent U_3O_8 have no visible uranium minerals. Most of the uranium is carried in the matrix of breccia and along numerous tiny cracks as very fine grained films of pitchblende or coffinite. Pyrite and marcasite generally are in the same openings.

Carbonate rocks in the Chester fault zone are oxidized to depths of more than 100 m along faults and can be pervasively oxidized in the upper 60 m of some breccia zones. In the most severe instances, near-surface carbonate rocks are oxidized and leached to a porous, friable, ocher rock composed of quartz and iron oxides with only traces of calcite. More common is an intermediate product—ocher dolomite that may have some voids and that has more quartz and calcite than normal. Under the microscope, the ocher dolomites seem to be only slightly modified, with the exception that original disseminated pyrite is oxidized to iron oxides and cracks are covered with a thin film of iron oxide. Hence, there seem to be two end-member situations: (1) dolomite that has been thoroughly leached and oxidized to form gossan, and (2) barely altered dolomite in which the only major change is oxidation of pyrite and transport of some iron to produce a strong color effect. Ocher dolomite of both types generally contains about 50 to 200 ppm uranium, but probably contained much more prior to oxidation. Most of this oxidation and uranium leaching must be relatively recent, because the oxidized rocks are badly out of radioactive equilibrium. Some reduced zones contain uranium in excess of daughter products, suggesting redeposition of recently leached uranium. Presumably the cause of the leaching is sulfuric acid generated by oxidizing pyrite. Radium is precipitated by sulfate, a factor contributing to the disequilibrium problem (Phair and Levine, 1954).

GEOCHEMISTRY OF CARBONATE ROCKS

Chemical analyses of 99 samples of carbonate rocks are reported by Nash (1979) and summarized in Table 2. Some general comments can be made.

Aluminum

Mean aluminum content of Leadville and Belden carbonates is 1.79 and 2.17 percent Al_2O_3, respectively, which is equivalent to 4.4 and 5 percent normative clay (Table 2). The clay in the Leadville samples generally is not evident in thin sections, possibly because of the contrasting optics of dolomite and very fine clay. The aluminum content of these carbonates is much higher than reported by Weber (1964) for primary dolomites or by Till (1970) for lagoonal carbonate sediment. However, the amount of normative clay, calculated from aluminum, is less than Roehl (1967) reported for supratidal dolomite. Till (1970) demonstrated that aluminum content correlates strongly with carbonate mud content in Holocene sediments and suggested that an environmental factor, probably quietness of water, controls the concentration of clay minerals and carbonate mud.

Iron

Total iron content of the Leadville Dolomite (2.84 percent Fe_2O_3; 1.99 percent Fe) appears to be abnormally high, approximately seven times the 0.40 percent Fe_2O_3 reported by Weber (1964). Belden carbonates contain about four times the amount of iron that Weber reports. Statistical tests on ore zone samples indicate that iron and normative FeS_2 correlate strongly with uranium, confirming the mineralogical associations seen under the microscope. Iron appears to be a key chemical component, but its behavior in sedimentation and diagenesis can not be specified well.

Organic carbon

Organic carbon content of Leadville Dolomite (mean 0.24 percent) is not as high as anticipated for these dark-gray rocks. This value matches the average reported by Gehman (1962) for his survey of carbonate rocks. Apparently the Leadville and Belden carbonates do not contain abnormal amounts of organic carbon, al-

Table 2. Statistical summary of petrochemical data for Leadville Dolomite and Belden Formation

Variable	Leadville Dolomite Average	Standard deviation	Minimum value	Maximum value	Belden Formation Average	Standard deviation	Minimum value	Maximum value	Mean Reference value[1]
SiO_2 (%)	22.67	26.93	0.20	97.70	21.37	20.57	2.90	92.20	--
Al_2O_3 (%)	1.79	2.65	0.03	13.70	2.17	2.21	0.33	11.60	0.34 (W)
Fe_2O_3 (%)	2.54	7.28	0.02	46.40	1.37	1.30	0.05	4.70	0.40 (W)
FeO (%)	0.27	0.30	0.00	1.40	0.33	0.48	0.00	2.50	--
MgO (%)	13.28	7.06	0.07	20.80	7.43	6.98	0.35	18.70	--
CaO (%)	23.92	11.64	0.15	53.10	31.98	12.82	2.00	53.00	--
Na_2O (%)	0.030	0.03	0.00	0.10	0.04	0.05	0.00	0.28	0.053 (W)
K_2O (%)	0.38	0.42	0.00	1.60	0.55	0.61	0.04	3.40	0.79 (W)
H_2O^+ (%)	0.98	1.56	0.16	9.10	0.80	0.61	0.24	2.60	--
H_2O^- (%)	0.39	0.84	0.01	5.50	0.28	0.22	0.03	0.89	--
TiO_2 (%)	0.088	0.11	0.00	0.53	0.13	0.13	0.00	0.69	0.034 (W)
P_2O_5 (%)	0.038	0.03	0.00	0.20	0.093	0.11	0.01	0.63	--
MnO (%)	0.074	0.06	0.00	0.31	0.078	0.05	0.01	0.19	0.032 (W)
CO_2 (%)	33.15	15.26	0.00	48.20	33.02	10.76	1.20	45.50	--
F (%)	0.032	0.02	0.00	0.08	0.038	0.03	0.01	0.21	0.032 (G)
S (%)	0.36	0.99	0.01	6.30	0.34	0.73	0.02	3.10	--
C total (%)	9.37	4.13	0.20	13.16	9.42	2.98	0.44	12.85	--
C organic (%)	0.25	0.22	0.00	0.88	0.34	0.66	0.00	4.20	0.24 (Ge)
Carbonate (%)	9.11	4.17	0.00	13.07	9.07	2.96	0.42	12.35	--
Cl (ppm)	143.6	125.7	25.0	550	82.5	53.8	25.0	230	207. (W)
Ba (ppm)	116.8	131.7	20.0	920	182.8	317.9	55.0	2100	86. (W)
Sr (ppm)	91.9	75.4	10.0	310	240.5	147.9	49.0	620	174. (W)
Pb (ppm)	20.9	34.9	0.8	220	22.7	39.9	1.0	200	68. (W)
Zn (ppm)	112.6	341.0	5.0	2600	127.7	236.4	5.0	1000	1100. (W)
Mo (ppm)	6.94	15.5	0.05	88.0	2.28	4.0	0.05	19.0	1.1 (G)
Hg (ppm)	0.187	0.49	0.005	2.6	0.050	0.099	0.005	0.56	0.07 (G)
U (ppm)	1506.8	5874.4	0.18	33500	116.4	217.9	1.56	1190	2.1 (G)
Dolomite XR[2]	5.8	3.1	0.0	10	4.3	2.8	0.00	9.0	
Calcite XR[3]	1.18	2.32	0.0	10	2.3	2.8	0.00	8.0	
Quartz XR	3.0	2.8	0.0	10	3.1	1.6	1.0	10.0	
Clay XR	0.2	0.46	0.0	2	0.3	0.6	0.00	0.0	
Hematite XR	0.08	0.5	0.0	4	0.0	0.0	0.0	0.0	
Dolomite NM	63.8	33.0	0.5	99.0	37.6	33.3	2.0	92.0	
Calcite NM	9.8	19.7	0.0	95.0	38.9	34.5	0.5	95.0	
Quartz NM	19.5	26.3	0.5	98.0	16.9	19.2	2.0	91.0	
Clay NM	4.4	7.6	0.0	39.0	5.02	5.5	1.0	31.0	
Hematite NM	1.8	6.8	0.0	44.0	0.58	0.8	0.0	3.2	
Pyrite NM	0.8	2.40	0.0	16.0	0.8	1.9	0.0	8.0	

[1]Reference values from Graf (1960), (G); Gehman (1962), (Ge); and Weber (1964), (W).

[2]Abundance determined by X-ray diffraction, in parts per ten.

[3]Normative minerals calculated from chemical analyses.

though the literature data base does not appear broad enough to be a reliable comparison. Preliminary correlation and R-mode factor analyses indicate that uranium is essentially independent of organic carbon content.

Sulfur and normative pyrite

Sulfur content of these rocks, about 0.35 percent for both Leadville and Belden samples, may be abnormal. However, I have been unable to locate any chemical data on sulfur content of carbonate rocks elsewhere. Normative pyrite and total S correlate extremely highly with uranium. Sulfur and iron in these rocks seem important in the formation of the uranium deposits.

Minor elements

Minor elements Ba, Ag, Cr, Cu, Hg, Mo, Pb, Sr, V, and Zn were investigated for use as possible pathfinder elements for uranium (Nash, 1979). Minor-element concentrations in the Leadville and the Belden appear to be at or below normal levels, compared to those in carbonate rocks elsewhere (Weber, 1964; Graf, 1960). Mo is the only minor element enriched in either formation: it has a mean concentration of about 6.7 ppm in Leadville samples, and it ranges as high as 88 ppm in a high-grade ore sample. Mo correlates strongly with U in statistical tests on ore sample subsets but does not form a halo beyond uranium ore.

INTERPRETATION

Sedimentation and diagenesis of Leadville Dolomite

The texture and the mineralogy of the dolomicrites and of their neomorphosed equivalents are consistent with numerous reports of ancient and Holocene dolomite termed "primary" or "early" dolomite. These rocks are generally believed to form from carbonate mud that accumulated in relatively quiet water, such as lagoons, or in beach areas beyond the reach of normal wave action (supratidal zone). Many features associated with supratidal environments are observed in the Leadville dolomite, particularly the thin laminae and the lack of fossils. Other features need comments. Algal stromatolites are either poorly developed or absent in the Leadville of this area. Nothing resembling stromatolite heads has been observed, but possibly the relatively common thin laminae are flat-laminated stromatolites or algal mats such as are present in some supratidal zones (Campbell, 1970; Gebelein and Hoffman, 1973; J. A. Campbell, oral communication, 1979). Although neomorphism could have obscured stromatolite structures, the apparent absence of stromatolites seems to be a problem if the Leadville was supratidal. Desiccation cracks and "birds-eye" textures are rare if present at all, and no evaporite minerals have been confirmed or inferred.

Sedimentation of the finely laminated carbonate muds of the Leadville appears to have occurred in a tidal-flat or supratidal environment, based on comparisons with modern (e.g., Shinn and others, 1969) and ancient (Laporte, 1967; Roehl, 1967) examples. The same interpretation has been made for the Leadville and Dyer carbonates to the north (Conley, 1972; Nadeau, 1972; Campbell, 1970). Dolomitization probably started soon after the mud was deposited. This interpretation is based chiefly on the lack of replacement textures and preservation of micrite textures. The dolomite is texturally and chemically uniform over tens of meters vertically, and few limestone beds exist. The observed uniformity is not readily explained by any of the numerous dolomitization hypotheses in the recent literature.

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 best ore zones are in thoroughly brecciated Leadville Dolomite. The brittle character of the dolomite is an important accessory factor. The Little Indian deposit likewise is along the Chester fault where brittle quartzites are broken and turned on end. Drilling in the intervening area between these two ore deposits reveals additional uraniferous zones in brecciated rocks along the Chester fault.

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. To explore for zones of maximum brittle deformation one must focus on brittle beds, changes in dip where beds are folded next to the fault zone, and anticipate concave-downward curvature of the fault surface.

Chemical control of ore

The chemistry of ore deposition in dolomite is not well understood, but there probably was some wallrock involvement. Organic carbon was suspected at first, but chemical analyses reveal relatively low and uniform organic carbon content and no correlation with uranium content. Iron and sulfur contents are anomalous, and FeS_2 as pyrite and marcasite occurs in most uraniferous breccia and veins. The presence of a large proportion of FeS_2 as marcasite may be an indication of formation from metastable sulfur compounds as in some sandstone-type uranium deposits (Goldhaber and Reynolds, 1979; Granger and Warren, 1969). A sulfur species, such as sulfite or thiosulfate, might be the reductant responsible for precipitating uranium and keeping it within the carbonate breccia.

Possible role of karst

Karst is well known in the Leadville Dolomite in central Colorado. Iron-stained karst localities in the Pitch mine area have been prospected for metals and are shown on the 7½-minute topographic map of the area. Recently, Dupree and Maslyn (1979) have proposed that uranium at the Pitch mine "largely occurs in the black organic-rich matrix material of carbonate breccias" that formed by sinkhole collapse and fill. My observations, particularly in the ore zone, do not agree with those interpretations. The carbonate breccias are classic tectonic breccias and are clearly related to faulting in the Chester fault zone. The breccia, and uranium grade, die out below and to the west of the faults. By inspection of numerous cores, new open-pit exposures, and thin sections I find no evidence for "organic-rich matrix" or washed-in clayey sinkhole fill. Chemical analyses do not indicate presence of unusual amounts of organic carbon or aluminum in uranium-bearing breccias. On close inspection and microscopic examination, black portions of some core are 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 of the mine are characterized by iron oxide fillings, not black clays, and are only slightly radioactive.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the cooperation of Homestake Mining Company. This project obviously would not have been possible without their permission to examine surface and mine exposures, and to log and sample drill core and cuttings. Homestake also provided important base maps and geologic information. J. Mersch Ward, District Geologist, was a gracious host and offered stimulating discussion. Jerry C. Olson and John A. Campbell, both of the U.S. Geological Survey, offered helpful advice on regional geology and carbonate petrology.

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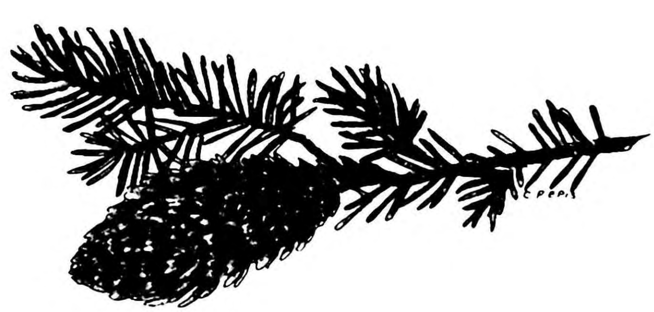

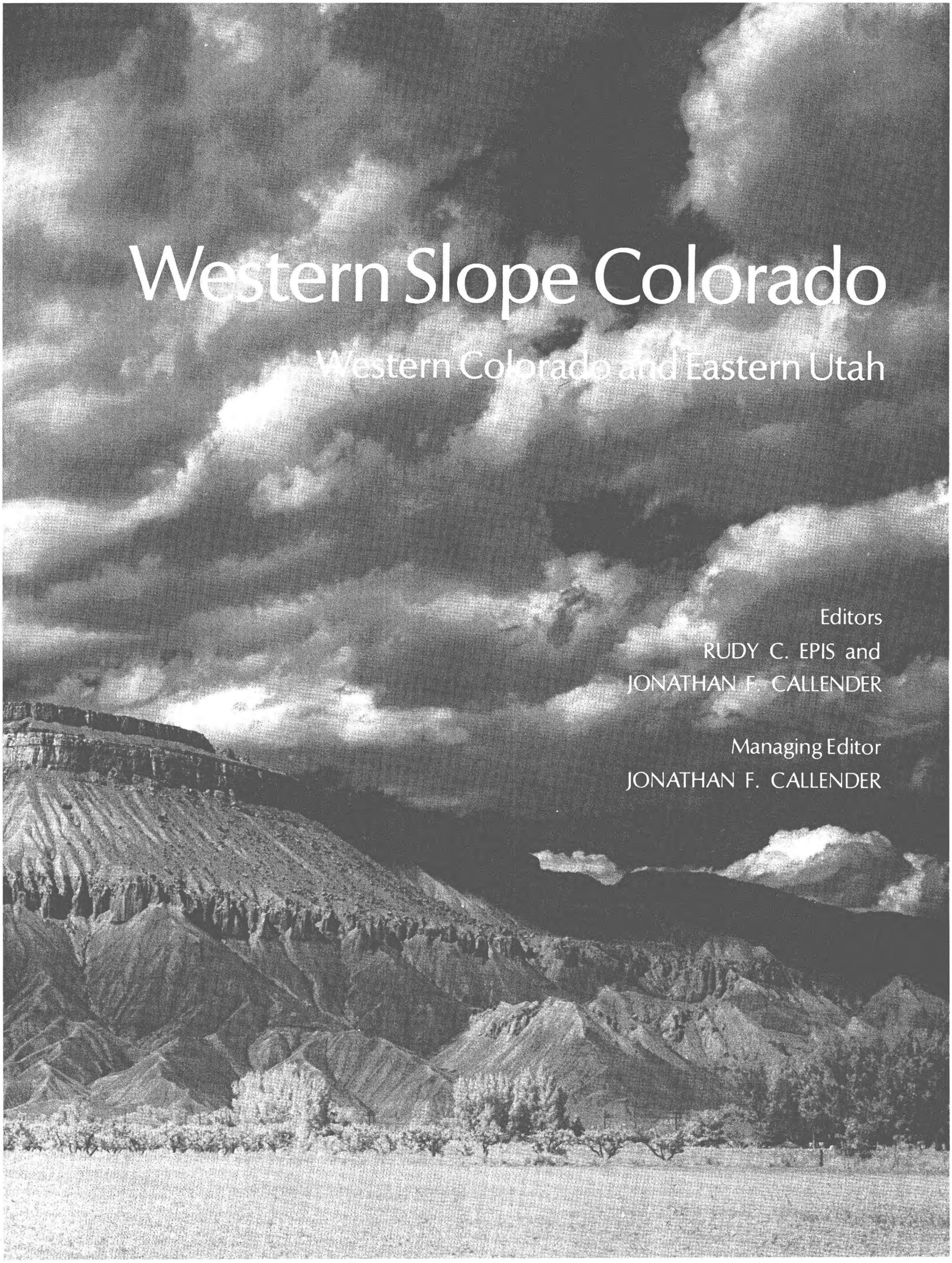

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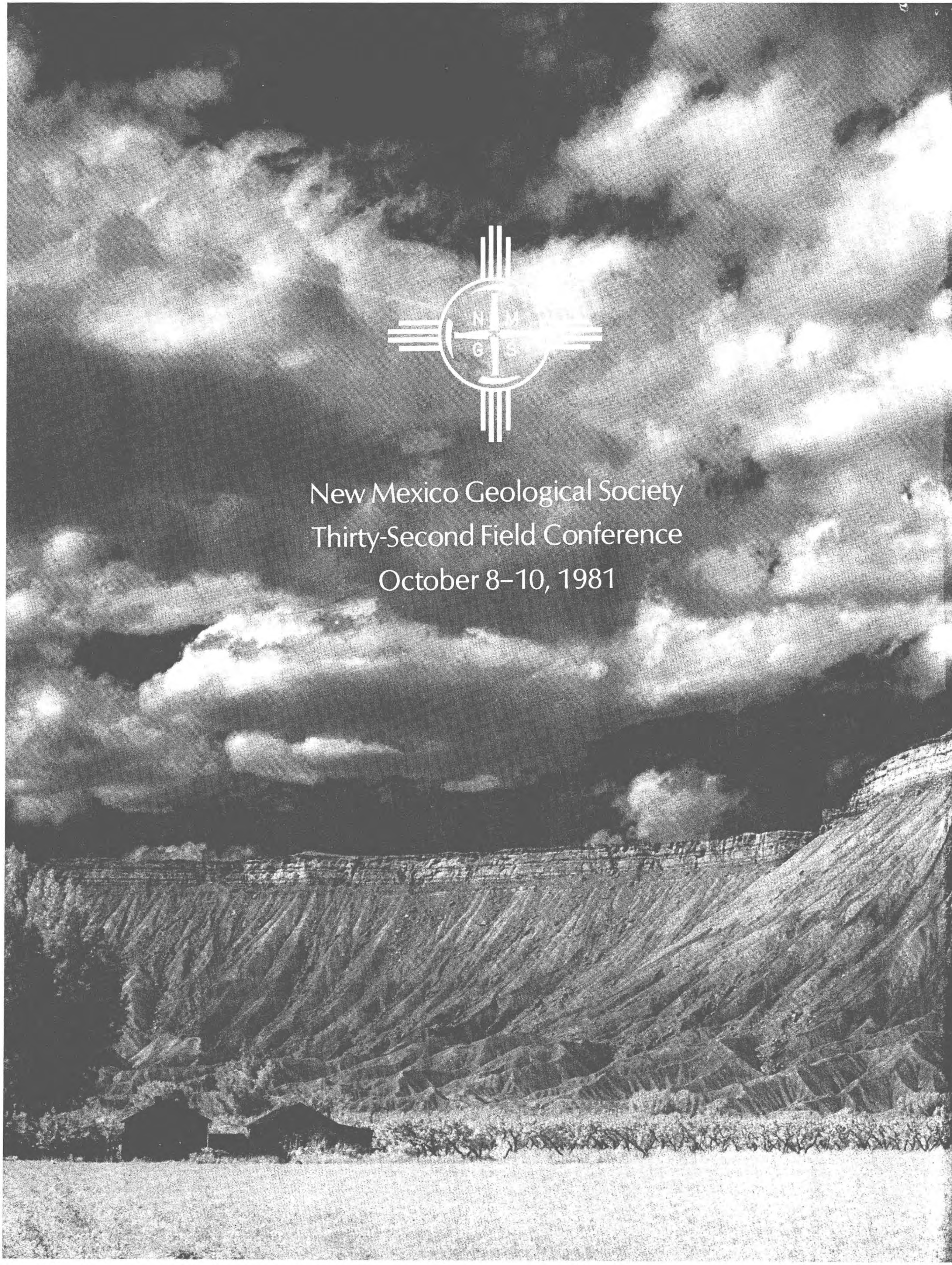

New Mexico Geological Society
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