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Alteration and Vein Mineralization, Ladwig uranium mine, Jefferson County, Colorado

by

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ABSTRACT

Uranium ore at the Ladwig mine, Jefferson County, Colo., occurs in steeply dipping, northwest-striking faults and related fractures with a carbonate-adularia assemblage that forms in altered wallrocks and fills veins. The faults occur between large intrusive pegmatites and garnetiferous gneisses of Precambrian age, and were reactivated as the result of the early Paleocene uplift of the Front Range foothills.

Mineralization in the deposit includes both wallrock alteration and vein filling. Alteration was intense but local, and chiefly involved the carbonatization of mafic minerals in the wallrocks. Felsic minerals in the wallrocks are relatively unaltered. The veins are filled with an adularia-pitchblende-carbonate assemblage with minor related sulfides and coffinite. Many of the iron-bearing carbonates in both the alteration and vein assemblages have been altered to hematite.

The mineralization and alteration are believed to have formed in response to initially high amounts of CO_2 and the subsequent release of dissolved CO_2 by boiling or effervescence. Uranium, carried in a dicarbonate complex, was precipitated directly as pitchblende when the CO_2 was released. The expulsion of H^+ during boiling created a net oxidizing environment which oxidized the iron-bearing carbonates. Late stage calcite and sulfides were deposited in existing voids in the veins.

INTRODUCTION

The eastern foothills of the Colorado Front Range contain several vein-type uranium deposits, including the nation's largest vein-type deposit at the

Schwartzwalder mine. As part of a broader study to define the genesis of the foothills deposits, and to compare them with other vein-type uranium occurrences in the nearby Colorado Mineral Belt, the Ladwig mine, located 6.5 km south of the Schwartzwalder mine, was studied to define some of the characteristics of the deposits. This report describes the results of a field and petrologic study of the deposit.

Interest in vein-type uranium deposits is acute, especially in light of the recent discoveries of large vein deposits in northern Saskatchewan, Canada (see Hoeve and Sibbald, 1978). Similar deposits occur in the Colorado Front Range, but their genesis has not been satisfactorily defined. It is hoped that by establishing some genetic framework for these deposits that known deposits can be adequately evaluated, and that favorable areas for exploration can be defined.

Location and Previous Work

The uranium deposits occur in a zone, called here the Foothills Belt, that is located within 8 km of the range front west of Denver, and extends for 80 km along the range front (fig. 1). The Ladwig mine is 6.5 km northwest of Golden, Colo., in Jefferson County, at a surface elevation of 2260 m.

Most previous investigations have concentrated on the Schwartzwalder mine, which has been in production for more than 20 years. Other reports have considered the Ralston Buttes district (Sheridan and others, 1967), of which the Ladwig mine is a part, or hard-rock uranium deposits in the Front Range, including the Ladwig mine (Sims and Sheridan, 1964). The only report dealing specifically with the Ladwig mine was on a geochemical prospecting survey by Ferris and Bennett (1977). The surface geology of the area at and around the mine has been mapped at 1" = 60 feet by Sheridan and others (1967). The geology of the Ralston Buttes Quadrangle, in which the mine is located, was mapped at 1:24,000 scale and described by Sheridan and others (1967).

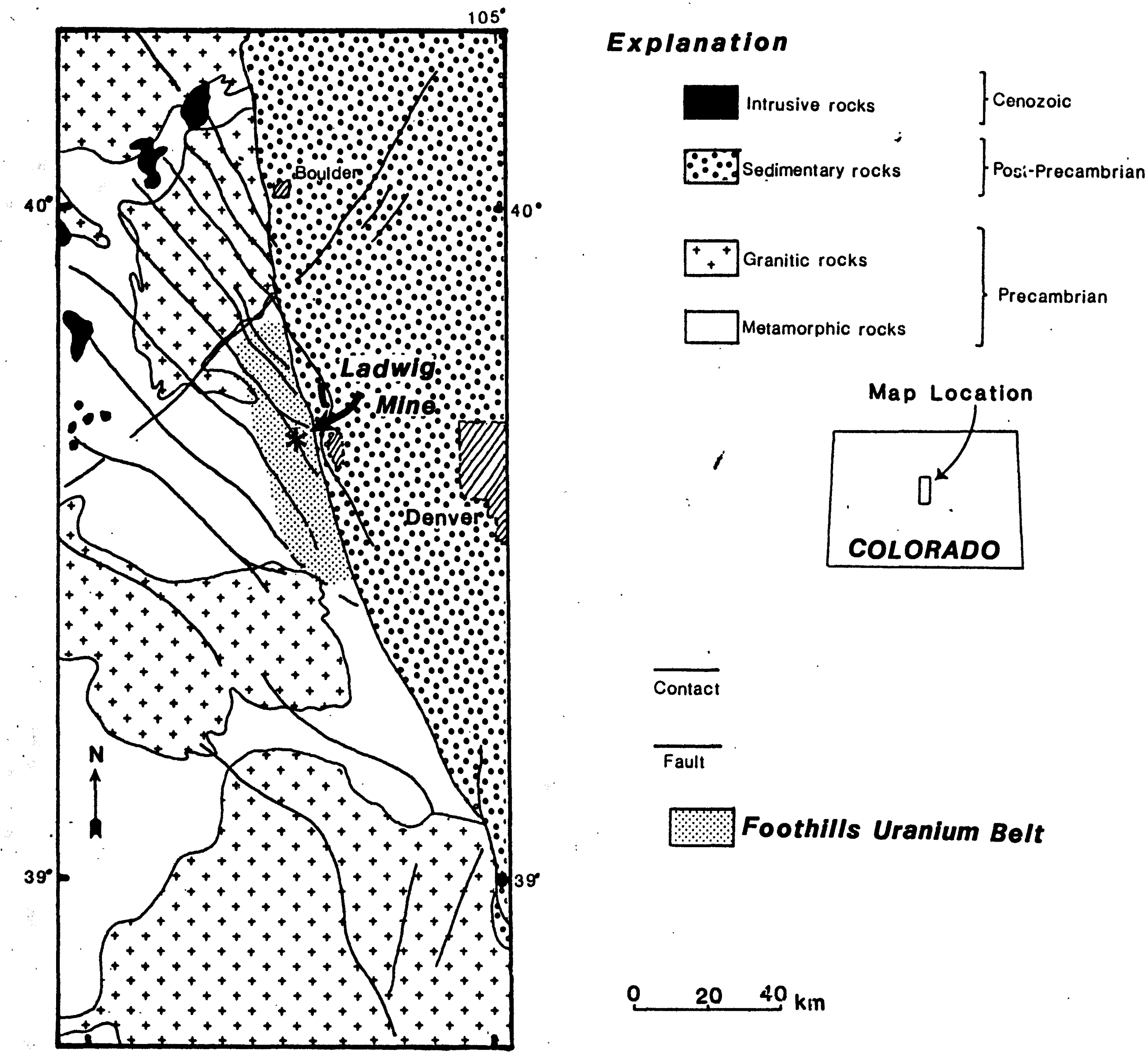


Figure 1. Generalized geologic map of Foothills region, Colorado Front Range, showing location of Ladwig Mine (from DeVoto and Paschis, 1979).

Current Studies and Methods

Field work for this study, begun in August 1978, included underground and minor surface mapping. Approximately eighty samples of wallrocks and vein material were examined optically with reflected and transmitted light. X-ray diffraction aided identification of alteration products. Drill core from surface and underground diamond drilling was examined with special emphasis on structure and vertical changes in mineralogy.

Geologists at Energy Fuels Nuclear, Inc., currently exploring at the mine, were extremely helpful and generous during this project. Brad Watts and Allen Reid of that firm provided invaluable information and discussions. Mike Malone of the USGS prepared the thin and polished sections, whose exceptional quality aided the study immensely. Reviews of the manuscript by J. Thomas Nash of the U.S. Geological Survey and C. S. Ferris of Reserve Oil and Minerals Corporation were greatly appreciated. I am indebted to Dr. Samuel B. Romberger of the Colorado School of Mines for the use of his unpublished information regarding uranium transport and deposition.

REGIONAL GEOLOGIC SETTING

The Foothills Belt is part of a structural block comprising Precambrian igneous, metasedimentary, and metavolcanic rocks (fig. 1). It is flanked to the east by Paleozoic and younger continental and marine sediments more than 3.3 km thick which lie unconformably on the Precambrian basement complex. Paleocene dikes intrude both crystalline and sedimentary rocks, and related flows are interbedded with nearby early Cenozoic units. The Colorado Mineral Belt, a northeast-trending zone of Late Cretaceous and Tertiary intrusives and ore deposits, intersects the Front Range foothills geomorphic region 32 km north of the Ladwig mine.

Precambrian metasedimentary and metavolcanic rocks in the Front Range formed as a result of several periods of Precambrian plastic deformation, regional metamorphism to amphibolite grade, and cataclasis (Sheridan and others, 1967). The metamorphic rocks were intruded by three batholiths during Precambrian time. Vertical uplift of the Front Range crystalline block during Pennsylvanian and Late Cretaceous times caused orogenic sedimentation in flanking basins. Nonorogenic continental to marine sedimentation occurred from Cambrian to Cretaceous time.

Precambrian deformation created a prominent northwest-trending series of fractures which were modified by movement during the Pennsylvanian and the Laramide orogeny. Most of the present features of the faults, including brecciation, offset of sediments in the flanking basins, and mineralization, are products of Laramide movement (Tweto and Sims, 1963). Movement along the faults during that time carried the northeast side up and to the southeast; vertical offset on individual faults was as much as 1500 m (Wells, 1967).

Uplift of the foothills region took place after the 65 m.y. uplift of the Front Range core, as orogenic sediments derived from the core uplift were deformed by the foothills uplift (Tweto, 1975). Shoshonite dikes which invaded Cretaceous sediments 61.9 m.y. ago were deformed along with the enclosing sediments (Hoblitt and Larson, 1975). The Foothills Belt uranium deposits occur along the faults, the modern features of which developed during foothills uplift. Although there may have been Precambrian uranium of unknown grade in the Precambrian structures, the present uranium deposits probably formed during or after the foothills uplift.

The northwest-trending faults, or breccia faults, are generally parallel, and occur from Colorado Springs on the south to Fort Collins on the north. Some breccia faults continue along strike for as much as 81 km. The Ladwig deposit occurs in the Hurricane Hill breccia fault, which is paralleled to the west by the Junction Ranch breccia fault and to the east by the Rogers breccia fault.

GEOLOGY OF THE LADWIG MINE

The geology at the Ladwig mine includes three major elements: steeply dipping Precambrian metasediments, large intrusive pegmatites, and breccia faults with subsidiary fractures (fig. 2). The faults, with the exception of one east-west fault, follow the contacts between the pegmatites and the east-striking metasediments. Ore mineralization is concentrated along the faults. Faulting is related to movement along the Hurricane Hill breccia fault zone.

Mine Workings

The Ladwig mine contains two separate sets of workings: the original workings on a hilltop and a more recent adit 245 m below the original workings (fig. 2). The original surface workings, developed in the 1950's and known as the Aubrey Ladwig lease, included a small open pit, a 23 m vertical shaft, and a 42 m crosscut (Sheridan and others, 1967); all were inaccessible for this study. In 1969, Reserve Oil and Minerals Corp. drove a 900 m adit westward from Cressman's Gulch at an elevation of 2073 m. The long adit, known as the Parker adit, extends beneath the original workings. Energy Fuels Nuclear, Inc., is currently involved in an exploration program at the mine.

In the Parker adit, five major veins have been intersected and designated by number (fig. 3). Veins 1 through 4 trend northwesterly and are vertical or steeply dipping. The 5 Vein trends N. 80° E. and is essentially vertical. No correlation between surface and underground veins has been established. The surface geochemical anomaly reported by Ferris and Bennett (1977) was subsequently shown to be related to the 4 Vein (C. S. Ferris, 1979, written commun.).

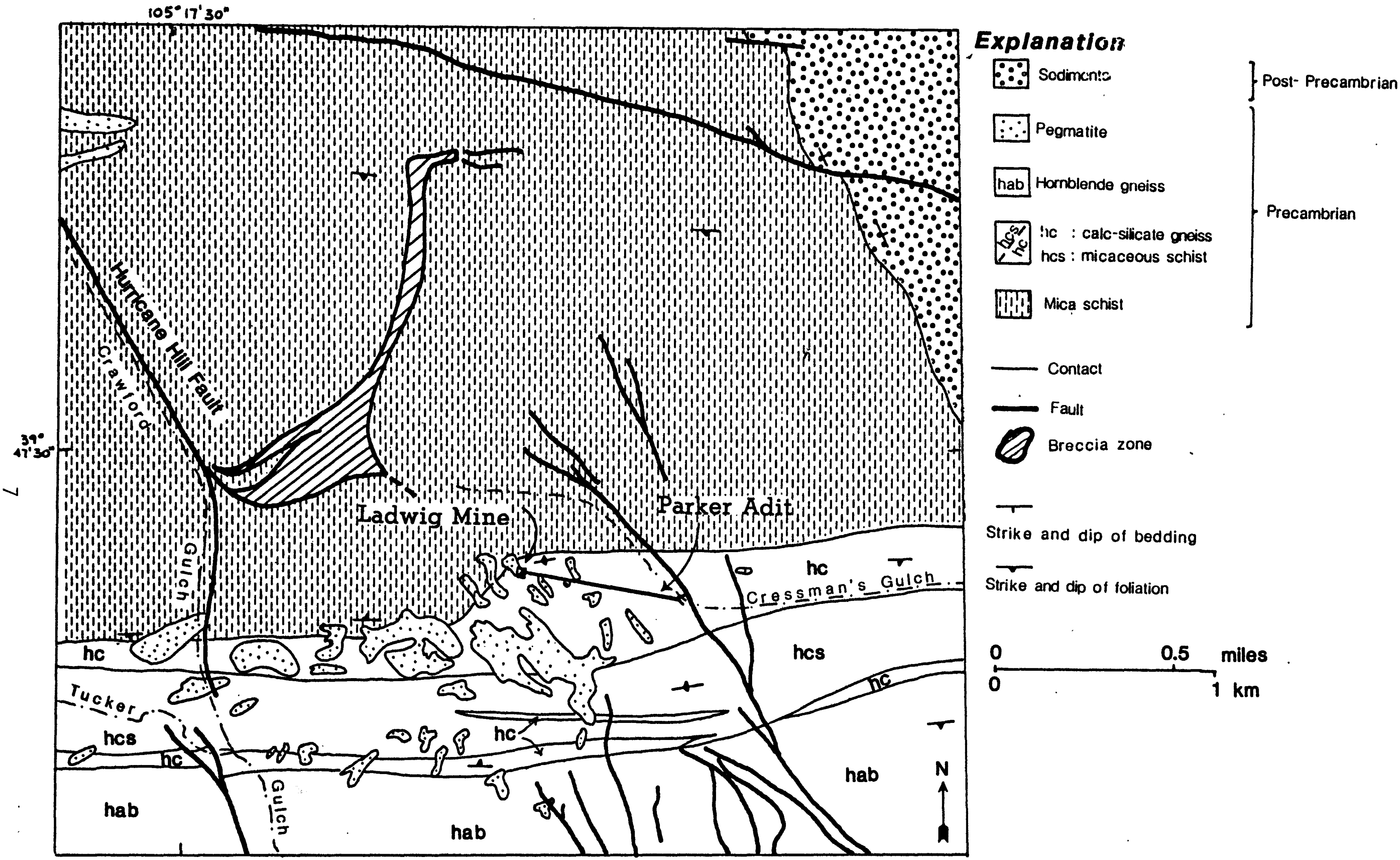


Figure 2. Geology in the vicinity of the Ladwig Mine, Colorado (from Sheridan and others, 1967).

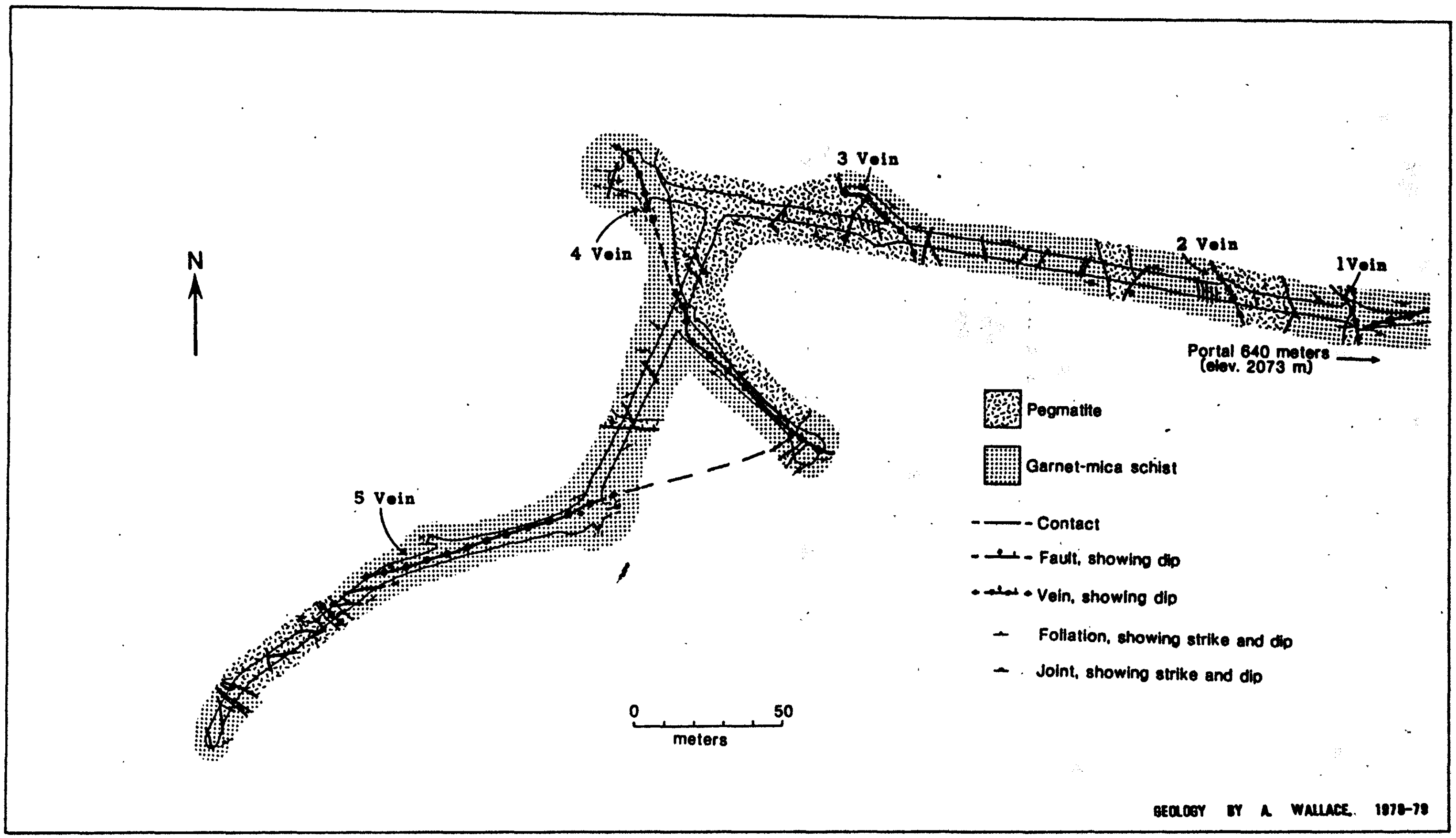


Figure 3. Geologic map of the western portion of the Parker Adit, Ladwig Mine.

Wallrocks

Wallrocks in the Ladwig mine include lower Proterozoic metasediments and middle Proterozoic(?) intrusive pegmatites (figs. 2 and 3). Metasediments dip steeply and strike to the east-northeast. The thick pegmatites cut the foliation of the metasediments, and appear to be large northwest-trending tabular bodies elongate along strike and dip.

Metasediments

The Ladwig mine is situated entirely in the transition zone between a major mica schist unit to the north and an interlayered calc-silicate gneiss unit to the south. The transition zone is dominated by a garnetiferous quartz-mica gneiss. The transition into the mica schist unit to the north is defined by the decrease in garnet. The transition into the calc-silicate gneiss to the south is defined by an increase in amphibole.

The garnetiferous gneiss has a heterogeneous lithology, but garnet is generally present and conspicuous. Eighty percent of the section is a garnetiferous quartz-mica gneiss. Quartz-biotite gneiss, mica schist, and quartzite layers constitute the other twenty percent of the section, reflecting some variability in the original sedimentary composition. All units are fine grained (1.0 mm).

Quartz, biotite, garnet, and feldspar are the major minerals in the transition zone, with subordinate muscovite, pyrite, and pyrrhotite generally present. Cordierite, sillimanite, zircon, and apatite are rare accessory minerals. Biotite and quartz are fine grained, and enclose poikiloblastic almandine garnets, which are as much as 2 mm in diameter. Biotite is pleochroic from beige to rusty brown. Quartz is anhedral, with minor undulatory extinction; grains in quartz layers show more undulations. The garnets are faintly pink, isotropic, and vary from unaltered euhedral crystals to masses replaced by quartz and biotite. Quartz, biotite, and magnetite are common inclusions in all garnets. The amount of garnet present varies from 10 to 70 percent; distinct thin (2-20 mm) layers with abundant garnet alternate with layers containing no garnet.

Microcline and plagioclase are most common in rocks containing relatively less garnet. All feldspars are unaltered, and are fine grained. Microcline shows good grid twinning, but plagioclase is often untwinned.

Pyrite and pyrrhotite are common in the metasediments, with pyrrhotite commonly altering to pyrite. Some thin rock layers contain as much as 50 percent iron sulfides, and conformable quartz-iron sulfide lenses are found in a few places. Magnetite is present only as a minor accessory mineral.

Muscovite occurs in some units, creating a two-mica gneiss with biotite. Muscovite has the same textures as biotite, and appears to be contemporaneous with the other minerals, including biotite. Sericite occurs in some rocks as an alteration product of staurolite.

Staurolite, cordierite, and sillimanite are rare accessory minerals. Sillimanite forms dense fibrous clots. Staurolite and cordierite occur as isolated porphyroblasts.

The calc-silicate gneiss unit was observed only in drill cores, as the unit is not present in the Parker adit workings. Thin hornblende-bearing layers become increasingly common in the garnetiferous gneiss towards the major calc-silicate gneiss, with pleochroic green hornblende included in the quartz-biotite-garnet assemblage. Biotite- and hornblende-rich layers are usually segregated, but garnet is present in both. The main calc-silicate gneiss unit is essentially free of garnet. Zoisite is present in trace amounts in or near hornblende-bearing rocks.

Foliation in all of the rock types is distinct, and is reflected both by mineral layering and by orientation of tabular crystals. Garnets are segregated into layers, but do not appear to have formed after foliation development.

The metasedimentary rocks in and around the Ladwig mine have been metamorphosed to medium to high grades, as indicated by the mineral assemblage (see Sheridan and others, 1967). The original sedimentary section was likely a transition from a pelitic lithology to the north to a more calcareous lithology to the south, with interbedded quartzose units.

Pegmatites

Large pegmatites cut the foliation of the metasedimentary rocks, as seen on the surface, in the Parker adit, and in drill core. Pegmatites are exposed in at least a third of the western part of the Parker adit (fig. 3). Contacts between the pegmatites and metasediments are sharp and of intrusive origin. There is no obvious petrographic change in the metasediments with proximity to the pegmatites, but some small fragments of gneissic material are enclosed by pegmatite along the contacts.

The mineralogy of the pegmatites in the Parker adit is simple, but complex as well as simple pegmatites were observed on the surface. The complex suite is similar to that found in the Parker adit, but contains abundant tourmaline with minor beryl. The occurrence of two pegmatite types possibly suggest two intrusive periods.

The dominant minerals in the very coarse grained (1-10 cm) pegmatites are quartz, microcline, plagioclase, and muscovite. Graphic and perthitic textures are common, and all feldspars are twinned. Tourmaline and garnet in the Parker adit pegmatites occur only as rare small grains in some samples. Most rocks contain only the four major minerals.

The pegmatites are texturally invariable. Foliation textures in the metasediments are not present in the pegmatites. None of the pegmatites are visibly zoned.

Structure

Structure in the Ladwig mine includes folded and foliated metasediments, faulting in the Hurricane Hill fault zone, and large bodies of intrusive pegmatites. The metasediments and pegmatites influenced Laramide movement along the fault zone, and the faults are of economic importance as they were the sites of uranium mineralization.

The metasediments in and around the mine are strongly foliated and mildly folded. Foliation trends N. 80° E. to N. 80° W., and dips are within 10° of vertical. Small isoclinal folds occur in the surface workings, and several open folds are present in the Parker adit.

The pegmatites cut the foliation of the metasediments, and show no evidence of post-intrusive foliation or folding. The pegmatites are as much as 61 m thick, and are elongate to the north and northwest. The vertical extent of individual pegmatites is unknown, but drilling records indicate that thick pegmatitic rock units are common from the surface to at least 550 m below the surface; pegmatites are common both at the surface and in the Parker adit. Localization of the Precambrian intrusives was probably controlled by the ancestral Hurricane Hill fault zone, which expands to 3 km in width in the mine area. However large pegmatites are not common except in the Ladwig mine area (Sheridan and others, 1967) (fig. 2).

The Ladwig mine is located in the Hurricane Hill breccia fault zone, which was reactivated during the Laramide orogeny (Sheridan and others, 1967). The zone is a narrow, well-defined breccia fault 5 km northwest of the mine, but diffuses into a wide zone of faulting in the area of the mine (fig. 2).

The zone, as seen in the Parker adit, is a series of parallel northwest-trending vertical faults which generally occur along or near the pegmatite-metasediment contacts. Some smaller faults in gneisses are not visibly related to a contact, and one fault, along which the 5 Vein occurs, strikes to the east-northeast.

Faults in proximity to the pegmatite-gneiss contacts were probably controlled by the pegmatites during Laramide movement. The interfaces between the thick rigid pegmatites and the less rigid gneisses were likely zones for movement. The relatively rigid pegmatites can be visualized as large bodies floating in a sea of gneiss. Movement of blocks bounding the wide fault zone caused the pegmatites to be pushed and jostled, creating movement along the interfaces with metasediments (see fig. 4). Minimal internal fracturing in the pegmatites, as compared to well-developed fault features in the metasediments, seems to support that mechanism.

Drag folding in the garnetiferous gneisses indicates right lateral movement along the faults, with the northeast side moving up. Changes in the direction of foliation in the gneisses due to horizontal drag range from 30° to 50°; rotation of small fold axes near the 4 Vein was at least 30°, indicating upward vertical drag on the southwest wall (fig. 3).

A mineralized northeast-trending fault was found in the Parker adit workings; it is designated as the 5 Vein (fig. 3). The fault is parallel to subparallel to the foliation of the gneisses. It appears that the northwest veins offset the 5 Vein, although exposures are poor. A northeast shear of the same orientation was noted in the Parker adit immediately east of the 1 Vein. An eastward projection of the 5 Vein would not be more than 15 m north of the northeast shear, so it is possible that the eastern shear is an uninterrupted continuation of the 5 Vein. This, however, is interpretive and

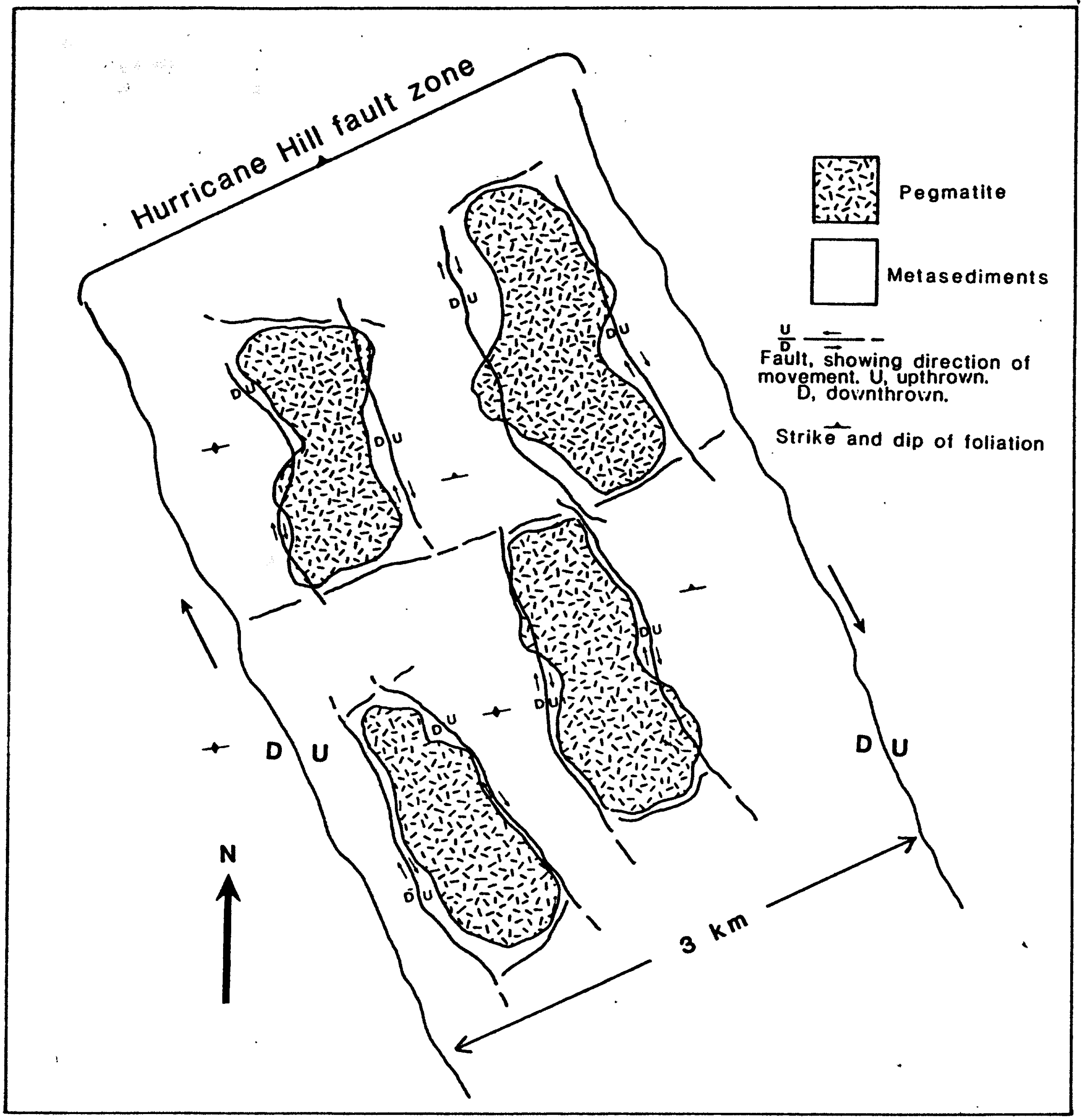


Figure 4. Diagrammatic sketch of the development of faults along pegmatite-metasediment contacts during Laramide movement along Hurricane Hill fault zone.

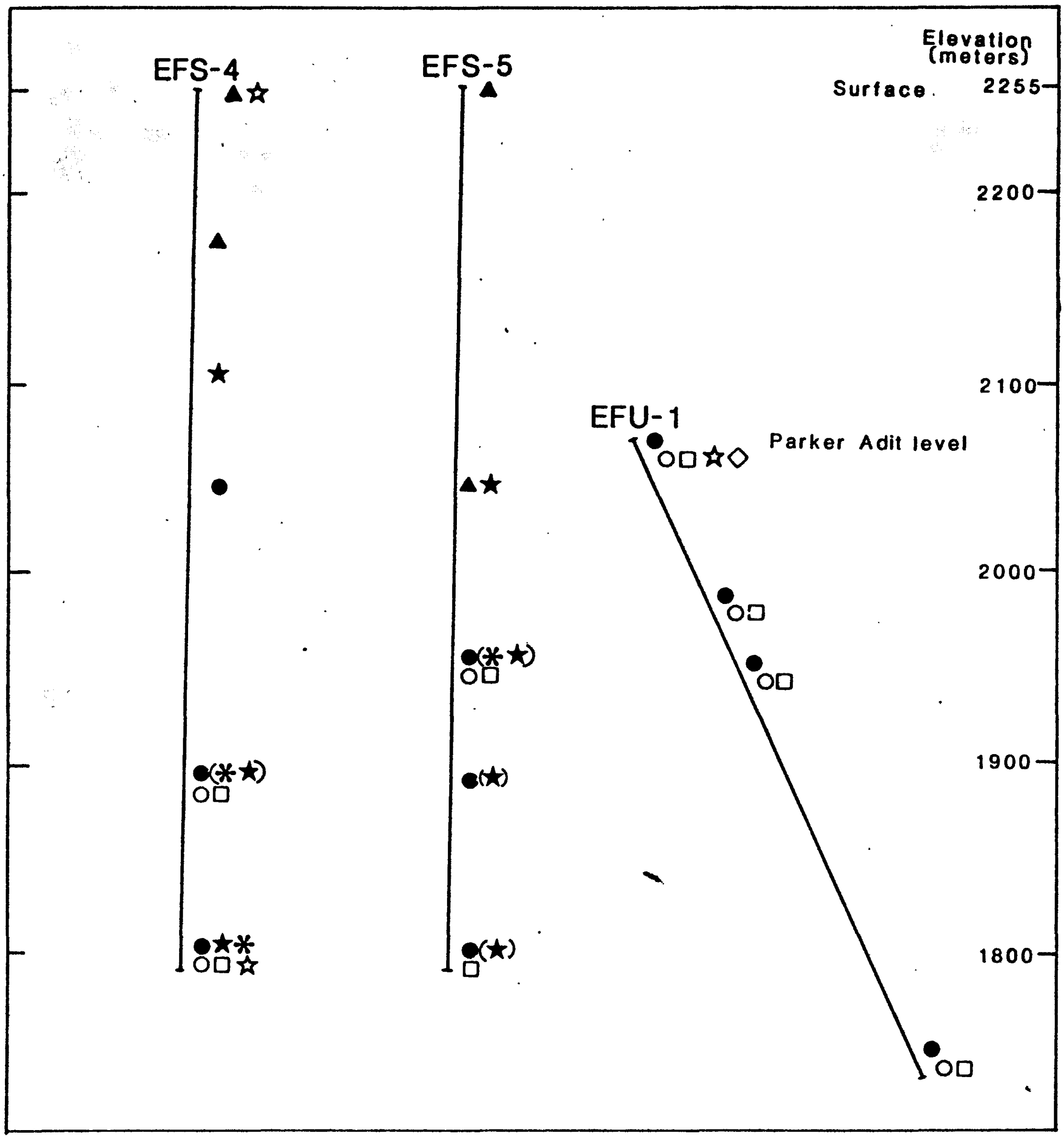
requires more evidence from future drilling. The formation of the northeast fault (5 Vein) was also likely related to pegmatite jostling.

Subsidiary fractures related to the larger faults are predominantly sets of smaller fractures dipping at moderate angles into the faults from the west. They strike 35°-40° more southwest than the faults, and dip 25°-35° NE. The abundance of these fractures increases from 1 in 30 cm to 1 in 3 cm towards the faults. Most are less than 2 mm wide with no mineralization, but fractures as much as 2.5 cm are mineralized. Movement, as indicated by cymoid loops and visible offset, varies from normal to reverse, but is never more than 1 m. The fractures closely resemble flats or horsetail fractures found in many vein type ore deposits (McKinstry, 1948).

The amount of brecciation along the major faults appears to be directly related to the host rock lithology and to fault orientation relative to foliation. Brittle rocks, such as pegmatites and garnet- and quartz-rich metasediments, fractured into breccia fragments with minimal interstitial gouge. More micaceous rocks formed gouge instead of fragments. Movement along faults parallel to foliation took place largely along foliation planes, so brecciation, except in unfoliated rocks, was minimal. Brecciation becomes more abundant as the angle between the foliation and fault plane increases.

VEIN MINERALIZATION

Alteration and ore mineralization is localized in and around the faults and related fractures of the Hurricane Hill fault zone. Both alteration and vein assemblages are dominated by carbonates, but adularia and uranium are also common in the veins. Carbonate alteration predominates below 150 m from the surface, but is absent above that level (fig. 5). Alteration is locally intense around the veins, but does not extend for more than 1 m away from the veins into the wallrocks. Alteration around nonvertical veins is



Key to symbols:

○ Carbonate	● Carbonate
□ Adularia	▲ Iron oxides (not related to carbonates)
☆ Fluorite	★ Chlorite
◇ Quartz	✱ Sericite

( ): minor amounts

Figure 5. Schematic section of the distribution of alteration and gangue minerals, based upon interval sampling from drill core and upon mine samples, Ladwig Mine, Colo.

more intense above the vein and largely absent below the veins (fig. 6). Vein minerals line and fill fractures and cavities in the open fractures.

Mineralogy

Carbonates

Carbonates are ubiquitous in both the vein and alteration assemblages, but textures and compositions are extremely variable. Compositions range from siderite ($FeCO_3$) and magnesiosiderite ($(Fe,Mg)CO_3$) through iron dolomite ($Ca(Fe,Mg)(CO_3)_2$) to pure calcite ($CaCO_3$). Vein carbonates are generally much more coarse grained than alteration carbonates.

Carbonate alteration is restricted to mafic minerals in the wallrocks, especially biotite and iron sulfides; hornblende is only locally replaced. The composition of the carbonates is largely determined by the cation composition of the replaced mineral: siderite replaces iron sulfides, magnesiosiderite replaces biotite, and iron dolomite replaces hornblende. The carbonates are granular and extremely fine grained, and could be identified only by their X-ray patterns. Some carbonates, especially those that replace pyrite, are bladed. Coarser and more calcic carbonates replace the primary alteration carbonates.

Iron dolomite and calcite are common in the veins, where they line cavities and fractures. Coarse calcite, with rhombs of as much as 2 cm, is extremely abundant in all fractures, and always fills any voids remaining after uranium mineralization. Iron dolomite is also common, but is finer grained than the calcite.

Adularia

Adularia is present in both alteration and vein assemblages. It is fine grained and poorly identifiable in the alteration assemblage, but staining and X-rays help to identify it. In the veins it lines cavities and fills thin

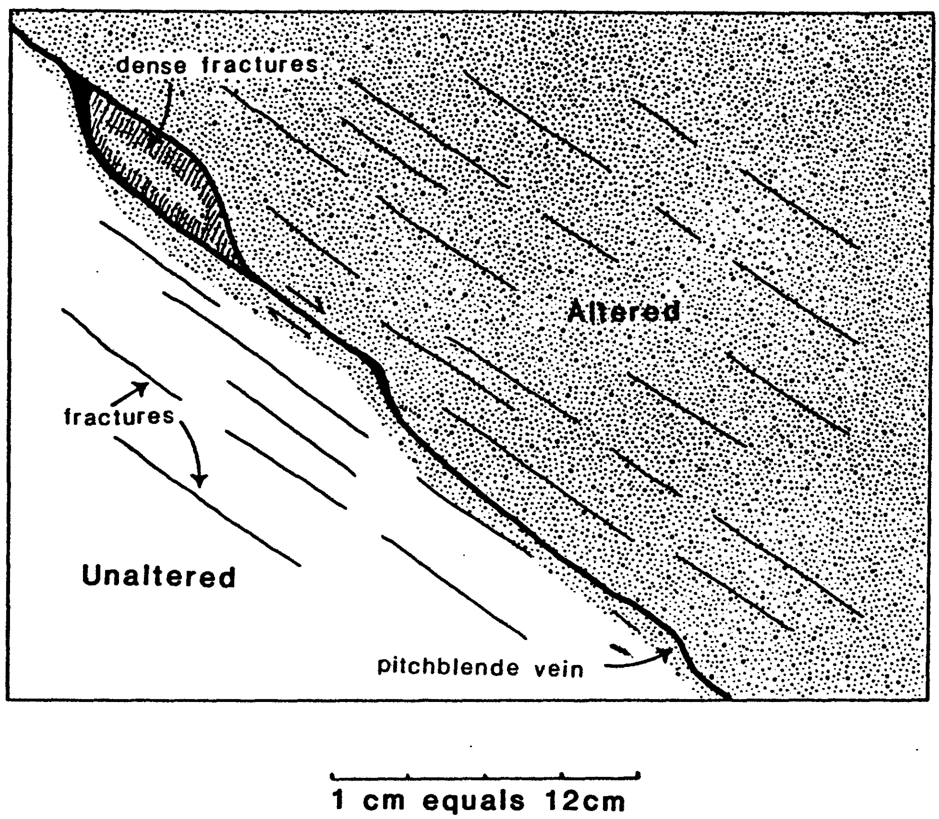


Figure 6. Detail of mineralized horsetail fracture south of 5 Vein. Note lack of alteration below vein.

fractures, and is commonly found with pitchblende and coffinite. Siderite-adularia alteration assemblages are commonly cut by fractures containing adularia. Vein adularia is coarser (as much as 2 mm), and forms diamond-shaped twinned crystals; X-rays indicate that it is triclinic.

Uranium Minerals

Pitchblende and coffinite are the only uranium minerals encountered in this study, although meta-autunite and other secondary uranium minerals were reported from the surface workings (Sheridan and others, 1967). Pitchblende is ubiquitous in the veins, and forms botryoidal coatings on breccia fragments; it is extremely fine grained. It also occurs in veins with adularia. Coffinite coexists with, and may have replaced, pitchblende. Like pitchblende, it is very fine grained, but can be distinguished from that mineral by its lower reflectivity. It occurs only with pitchblende.

Sulfides

Sulfides are present in both the alteration and vein assemblages, but are much more abundant in the veins. Pyrite replaces Precambrian pyrrhotite in the wallrocks, commonly with siderite. Pyrite, chalcocite, and chalcopyrite are intimately intergrown with pitchblende and coffinite, and are extremely fine grained (less than 0.1 mm). These sulfides, plus sphalerite, galena, and exsolved bornite and digenite also fill cavities and veins with calcite and adularia.

Hematite

Hematite is relatively common in the veins and wallrocks, and is the only alteration mineral found above the 150-m level of the mine (fig. 5). Hematite in the lower levels is extremely fine grained, and replaces the iron-bearing carbonates in both the veins and wallrocks. Hematite in the upper levels replaces biotite and hornblende.

Sericite and Chlorite

These two minerals are rare, and are generally found only in the wallrocks. Chlorite slightly replaces garnet and biotite; sericite replaces a few feldspar grains. Both minerals cannot be directly related to alteration or vein mineralization, and may be products of Precambrian regional metamorphism.

Quartz and Fluorite

Quartz was found in only one sample from the 4 Vein. The five grains are euhedral and fill a small vug adjacent to the vein. No other silica species were seen in the mine. Isolated grains of purple fluorite were found with calcite in a veinlet adjacent to the 3 Vein, and in drill core at the 457 m level.

Zeolite

Several small radiating clusters of zeolite (?) were seen in an adularia veinlet near the 4 Vein; the low birefringence, extremely low relief, and radiating habit indicate that the mineral is probably a zeolite.

Paragenesis

Mineralization in and around the veins can be divided into three stages: wallrock alteration, uranium-stage mineralization, and post-uranium mineralization. Wallrock alteration commenced prior to the uranium stage, but probably did not stop at the onset of that stage. The uranium and post-uranium stages are, obviously, sequential.

Three periods of fracturing and brecciation are visible in the veins. The earliest and most intense period preceded all vein and alteration mineralization; the net effect was to open the Hurricane Hill fracture system to the hydrothermal fluids. The second period of fracturing preceded the uranium stage, but followed the major stage of wallrock alteration. The third period occurred after the uranium stage sometime during the deposition of calcic carbonates and sulfides in the veins.

A paragenetic diagram of the alteration and vein mineralization is shown in figure 7.

Wallrock Alteration

Alteration is characterized by the pervasive replacement of mafic wall-rock minerals by iron- and magnesium-rich carbonates. Felsic minerals were not affected. Early iron-magnesium carbonate alteration was progressively succeeded by alteration involving more calcic carbonates; the later carbonates commonly replaced the earlier carbonates.

Alteration was limited largely to the metasediments, simply because the pegmatites do not contain many mafic minerals. The only such minerals were replaced by carbonates. No felsic minerals were replaced.

It is difficult to determine how much alteration took place during the two stages of vein mineralization. Veinlets of pitchblende and adularia cut areas of intense alteration, giving the impression that the bulk of the alteration preceded the uranium stage. The replacement of the earlier carbonates by the more calcic iron dolomites could have taken place during or even after uranium mineralization. As the general trend of carbonate composition is towards an increase in calcium with time, it would seem logical that the intermediate carbonates would form in the time period between non-calcic and calcic carbonates.

Adularia formed with siderite and magnesiosiderite in the wallrocks in patches containing no other minerals, indicating either complete alteration of some other mineral or open-space filling. The feldspar also formed after to the second period of fracturing, as vein-filling adularia cuts the carbonate-adularia areas, but there is no evidence that adularia actually replaced anything. Therefore, although adularia deposition was contemporaneous with some alteration, it is not necessarily an alteration product itself.

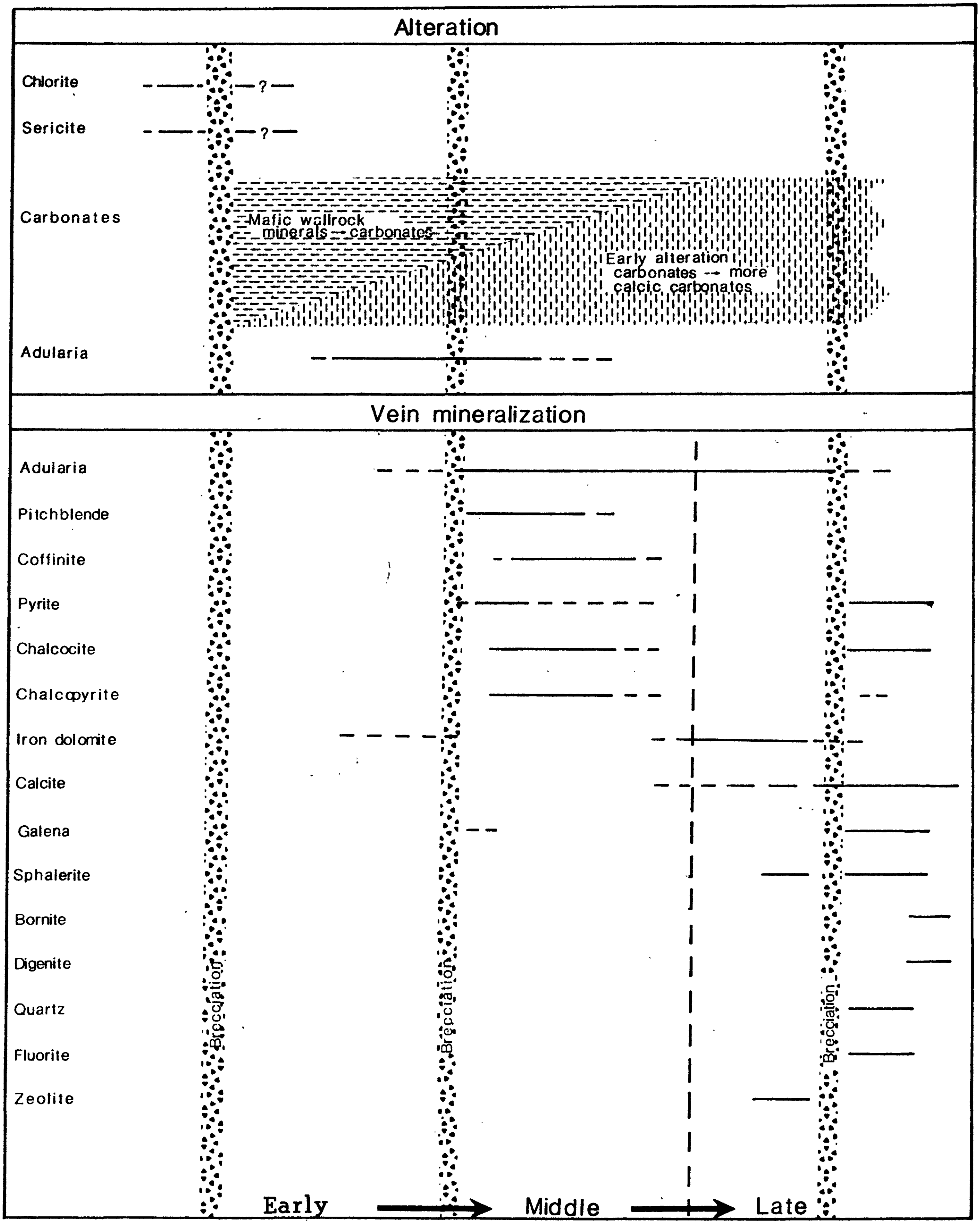


Figure 7. Paragenetic diagram of alteration and vein mineralization, Ladwig Mine.

Vein Mineralization

The second period of fracturing created openings into which adularia and uranium minerals were deposited. Adularia deposition in veins slightly preceded uranium mineralization, but uranium deposition began relatively soon afterwards. Adularia was deposited in small amounts during uranium precipitation. Both adularia and uranium minerals rim fragments of altered wallrock and line veins and fractures. Sulfide textures indicate that chalcocite and chacopyrite were deposited with and slightly after the uranium minerals; pyrite may even have begun to form before uranium was deposited.

The filling of the veins and fractures continued with the increased deposition of adularia and the precipitation of carbonates in the veins. The first carbonates to appear in the veins were more iron-rich, but the compositions of later vein carbonates were relatively more calcic, ending with pure calcite vein filling. All carbonates line cavities and vugs, and coat the uranium-adularia rims on rock fragments.

Sulfides formed with adularia and carbonate gangue as vein fillings following the uranium stage. Quartz and fluorite occur with calcite and sulfides in post-uranium veinlets and cavities. The zeolites occur with adularia in a veinlet that cuts uranium mineralization.

The third period of fracturing took place during the post-uranium stage of mineralization, and most of the pure calcite with related sulfides was deposited after the fracturing.

Geochemistry

Twenty-eight samples of vein material and altered and unaltered wallrocks were collected and analyzed by various quantitative and semiquantitative methods for 49 elements, including uranium, and for noncarbonate and carbonate carbon. Due to the extreme variability in the sampling technique (generally nonchannel, high-grade samples), uranium analyses cannot be extrapolated to estimate ore grade in the veins.

Ten samples were collected in a profile from unaltered pegmatitic and gneissic wallrocks into the 3 Vein in an attempt to detect chemical variations in and around the vein. Other samples were collected from the 2 and 4 Veins and adjacent wallrocks. The analyses from all three veins show definite increases in uranium and molybdenum in and immediately adjacent to the veins; figure 8 illustrates the variability. The results support the surface geochemical study of Ferris and Bennett (1977), which found a strong correlation between the two elements in soil samples at the Ladwig mine.

The results of the analyses for all of the other elements were inconclusive; little or no variation is shown. Because the veins occur at the interface between pegmatites and metasediments, the analyses generally reflect the lithologic change rather than any apparent vein-related variation. Although the sample population was admittedly small, it does not appear that any element besides molybdenum is consistently related to uranium in the veins.

DISCUSSION

Observations made during this study suggest that the alteration and vein mineralization at the Ladwig mine was the product of a deep boiling hot spring. Further studies of stable isotopes, radiometric age dating, and fluid inclusions (if any can be found) would provide more accurate estimations of the ore-forming environment.

Structural Setting

The uranium ores at the Ladwig mine were deposited in breccia faults and fractures that were reopened during the Laramide uplift of the Front Range foothills. Local and regional structural relationships indicate that the fault movement took place sometime after the intrusion of shoshonite dikes

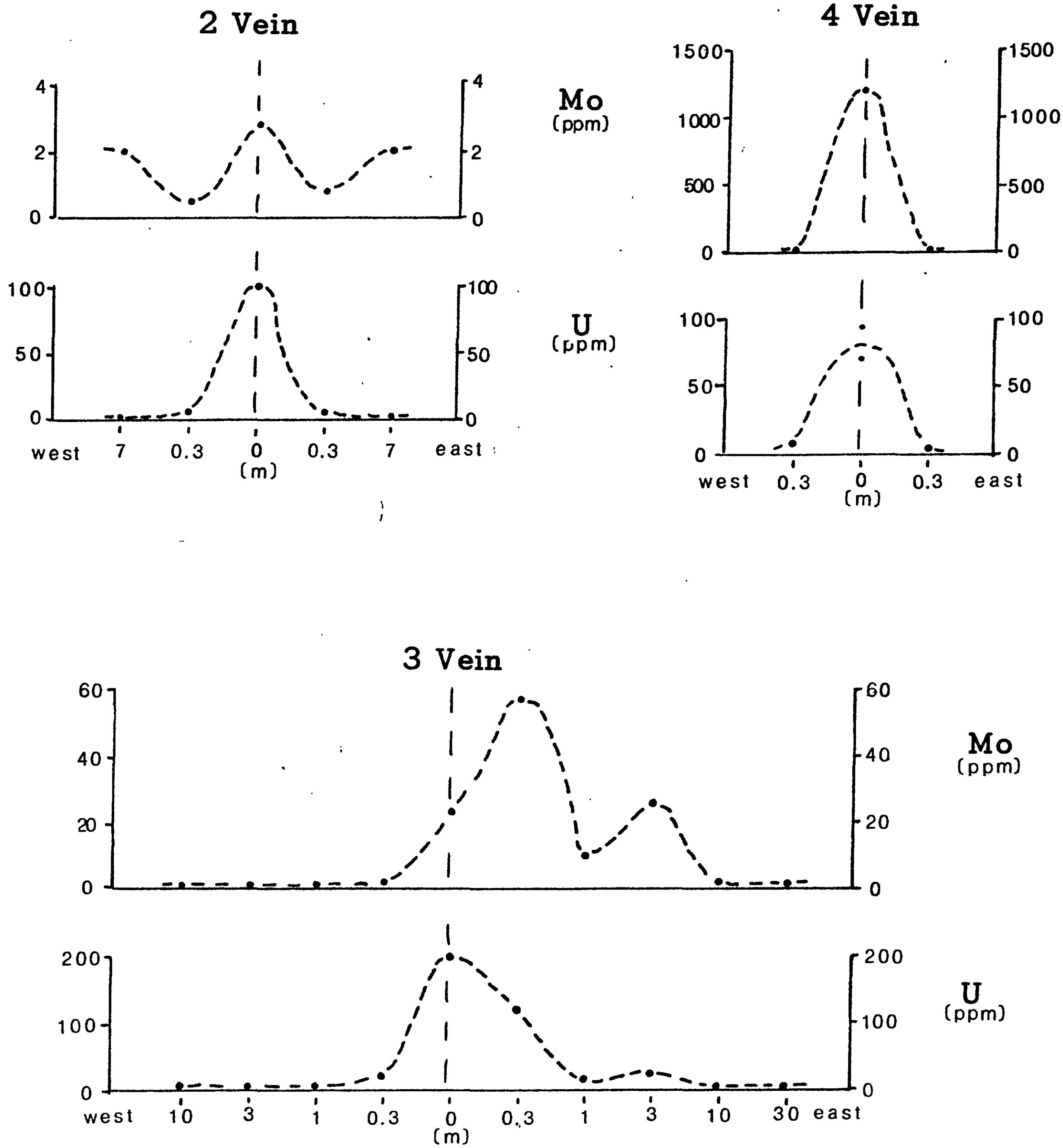


Figure 8. Variations inuranium (U) and molybdenum (Mo) with distance from 2, 3, and 4 veins, Ladwig Mine. Analyses by M. Coughlin, B. Vaughn, M. Schneider,, W. Stang: U. By P. Aruscavage, J. Budinsky, E. Campbell, J. Kane, R. Moore: Mo.

61.9 m.y. ago. Textures in the veins indicate that some movement occurred during mineralization, but that the bulk of the movement occurred prior to ore deposition. There is no evidence that a pre-Laramide uranium deposit in the faults was locally remobilized by Laramide tectonism. Uranium, as it now occurs, was transported to its present location after foothills uplift.

Ore mineralization took place in open faults and fractures. The development of the open spaces was controlled by the brittleness of the wallrock, and by the relative orientation of foliation with respect to the strike of the fault. Optimum brecciation, with minimal gouge, occurred where steep faults cut brittle pegmatites and garnetiferous gneisses. The relative rigidity of the large pegmatities controlled the development of faults along or near their contacts with the enclosing gneisses. The deep extent of the pegmatites, when coupled with the steep dips of the gneisses, created a deep set of open fractures and faults. As the pegmatites and brittle gneissic rocks are present only in a narrow zone in the major breccia fault system, adequate open spaces probably do not extend far along fault strike, a fault-wallrock relationship encountered in many foothills deposits (Sims and Sheridan, 1964). The net effect of faulting was to create a deep, but narrow, vein system of open fractures.

Alteration and Vein Mineralization

The mineralogy of all periods of mineral formation, including alteration, is generally similar to that of shallow hot-spring-type hydrothermal systems (Ellis, 1967). Carbonate in solution appears to have been a critical factor for mineralization, and for uranium transport and deposition; the behavior of carbonate conceivably controlled or influenced nearly all stages of mineralization.

The temperature of mineralizing fluids can only be estimated very approximately from the vein mineralogy. No adequate fluid inclusions were observed for temperature studies. Adularia, common in many deeper hot spring environments, forms at 185°-250°C at Wairakei, New Zealand (Ellis, 1967), and above 220°C at Ohaki-Broadlands, New Zealand (Browne and Ellis, 1970). The formation and stability of quartz, as compared to chalcedony or amorphous silica, might also suggest a temperature over 175°C (Fournier and Rowe, 1966), even at very low dissolved silica concentrations. The relative lack of zeolites might suggest greater depths (and resulting temperatures) in a hot spring system (Ellis, 1967), but might also be a reflection of abundant CO_2 in the system (Browne and Ellis, 1970), and thus is probably not a good temperature guide. Based upon the known temperatures for adularia deposition and quartz stability, an approximate temperature of near 200°-225°C might be reasonable for this discussion.

Early alteration of the wallrocks chiefly involved carbonatization, but may have started with minor sericite-chlorite alteration. Consideration of mineral equilibria suggests that the system was buffered to a neutral or slightly alkaline pH by the abundant carbonate. The formation of pyrite, instead of marcasite, with siderite from pyrrhotite requires a nonacidic environment (Kullerud, 1966), and adularia forms with siderite at 200°C above a pH of 6.2 (neutrality = 5.6) (S. B. Romberger, 1979, written commun.).

Alteration chiefly involved anion metasomatism, with the introduction of CO_2 and removal of SiO_2. Iron and magnesium from the altered minerals (biotite, pyrite, etc.) remained to form siderite and magnesiosiderite. Other cations ($K+$, Al^{+2}) and anions (S^{-2}) were removed. As the intense early alteration diminished, less iron and magnesium were released. Calcium from solution began to form in the carbonates, due to the increase in the

Ca/(Fe + Mg) ratio (Holland, 1967), and the iron-dolomite carbonates became progressively more common.

Adularia is a relatively rare hydrothermal mineral, and its formation requires fairly specific conditions. A major requirement is high K+/H+ (Hemley, 1959), and a neutral or slightly basic pH. Wallrock alteration involving hydrogen metasomatism is used frequently to explain an increase in pH in other systems, but evidence for such alteration is missing at the Ladwig mine. Another efficient way to increase alkalinity and pH is to release CO_2 in a reduced pressure environment, either by boiling or effervescence of CO_2. Meyer and Hemley (1967) suggest this process for ancient hot-spring environments, and Browne and Ellis (1970) describe it specifically for the Ohaki-Broadlands hydrothermal area.

Boiling and effervescence are pressure-temperature-related phenomena, and, in many hot-spring environments, are related to a pressure reduction. The general coincidence of adularia and the second period of brecciation might indicate that the open spaces created by brecciation reduced the confining pressure and induced boiling or effervescence. The lack of vertical mineral or alteration variation indicates that the boiling conditions persisted over a large vertical depth. Browne and Ellis (1970) found that the K-feldspar-quartz-calcite assemblage at Broadlands forms under non-equilibrium conditions from a relatively fast flow of water rising up a fissure. The mineralogy there is relatively constant over a large (500 m) vertical interval.

The continued precipitation of adularia, even after uranium deposition, indicates that the pH of the system did not drop below neutral conditions, nor did it become too basic. Sericite or zeolites would have formed, respectively, had the pH gone to either extreme (Hemley, 1959).

An abundance of CO_2 in the system can be inferred from several lines of evidence. The lack of epidote or Ca-zeolites in the mineral assemblage indicates a CO_2 concentration of 1.0 M or above (Browne and Ellis, 1970). At temperatures above 200°C, the stability field for siderite is drastically reduced, and exists only at CO_2 fugacites above 1.0 atm (Holland, 1965). The coprecipitation of adularia and siderite requires a PCO_2 of up to 10 atm (S. B. Romberger, 1979, written commun.). The preponderance of carbonate minerals in the vein and alteration assemblages attests to an abundance of CO_2 in the system.

It is not known if the solution actually boiled, with the expulsion of steam along with CO_2, or whether CO_2 simply unmixed from the hot solution and effervesced. Many modern hot springs expel steam and other gases as a result of boiling. It is conceivable that, with a large amount of dissolved CO_2, and with some reduction in pressure, CO_2 could have effervesced without concomitant boiling. Both boiling, with CO_2 loss, and effervescence, could have accounted for the surmised increase in pH and alkalinity in the Ladwig deposit.

The coprecipitation of adularia and pitchblende at 200°C occurs at a pH above 6 (S. B. Romberger, 1979, written commun.), indicating that the conditions during uranium precipitation were roughly the same as during the earlier adularia-siderite stage. These conditions are coincident with the stability field for the dicarbonate complex (Helgeson, 1969). Presuming an initially high PCO_2, uranium would have been carried in solution by a dicarbonate complex (Romberger, 1978).

The loss of CO_2 by boiling or effervescence appears to have controlled several processes. As mentioned earlier, the precipitation of adularia was likely controlled by CO_2 loss and the resultant rise in K^+/H^+. The loss of

CO_2 also would have destroyed the uranium-dicarbonate complexes, thereby releasing uranium dioxide. As the uranium-dicarbonate and pitchblende stability fields are coincident, it appears that pitchblende was deposited directly from solution by the reaction:

$$UO_2\ (CO_3)_2^{-2} + H_2O = UO_2 + 2HCO_3^- + 1/2\ O_2.$$

The precipitation of calcic carbonates, including dolomite, is a logical consequence of CO_2 loss, both because carbonates are less soluble at a lower PCO_2, and because available calcium and iron could combine with the released carbonate (Holland, 1967). Sulfide deposition could have been caused by several mechanisms, including a temperature drop related to heat loss during CO_2 and steam loss, and oversaturation due to water vaporization if boiling did occur. The post-uranium deposition of quartz suggests some cooling of the system.

All iron-bearing carbonates, including post-uranium iron dolomite, are replaced by hematite. Later carbonates, due to their lower iron contents, show correspondingly less hematite alteration than early, iron-rich carbonates. Dissociation of water, and the subsequent loss of H^+ in the above reaction, may have created a net oxidizing environment similar to that postulated by Czamanske and Wones (1973). The result would have been the oxidation of the iron carbonates.

It is possible that the late-stage formation of calcite and sulfides may have been related to the influx of a different fluid. Brecciation during the third period of fracturing broke existing, nearly isotropic sphalerites. The calcite-sulfide stage contains abundant pyrite that is unoxidized, and fresh, unbroken yellow sphalerite. As the assemblage fills vugs and cavities in the veins, and as it is clearly the youngest assemblage, it can only be said that it formed last and after brecciation. The freshness of the pyrite, however, may indicate that it formed after the oxidation of the iron carbonates.

The behavior of quartz in the system is interesting. As quartz deposition is highly dependent upon heat loss and dissolved silica concentrations, the stability of wallrock quartz and the general lack of vein quartz suggests that either heat loss was minimal, or that, despite heat loss, silica never became oversaturated in solution (Fournier and Rowe, 1966). The expulsion of CO_2 (and probably steam) withdrew heat, but vein adularia, deposited by effervescence or boiling, probably consumed a large amount of dissolved silica, preventing oversaturation. Only after adularia ceased to form did vein quartz precipitate. The formation of quartz, instead of chalcedony or amorphous silica, indicates that temperatures were probably above 125°C (Fournier and Rowe, 1966). The equilibration of quartz and dissolved silica prior to CO_2 release might be indicative of constant high temperatures at depth for a long period of time.

The fine-grained nature of all but the late-stage calcite-sulfide assemblage suggests that precipitation was rapid. This would be consistent with the observations of Browne and Ellis (1970) that precipitation of vein adularia is a rapid process from a fast flow of water.

CONCLUSIONS

The mineralogy and textures of the Ladwig ores suggest that they formed in a deep hot-spring environment, possibly as a result of CO_2 loss. A comparison of the ores with modern hydrothermal systems reveals many similarities between the two. It is unfortunate that suitable fluid inclusions were not found for temperature and fluid chemistry determinations, but reasonable approximations could be made nevertheless.

The depth to which mines like the Ladwig can extend is difficult to predict. Drilling at the Ladwig indicates that the system extends to a depth of over 500 m. DeVoto and Paschis (1979) report that current development in the nearby Schwartzwalder mine is approximately 900 m. Deep drill holes at Broadlands in New Zealand extend for more than 1000 m (Browne and Ellis, 1970). Clearly the Foothills Belt deposits may extend beyond their current limits.

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