Alteration and Mineralization in the Eastern Part of the Soldier Mountains, Camas County, Idaho

By Reed S. Lewis

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Metric Conversion Factors

Multiply	By	To obtain
Miles	1.609	Kilometers
Feet	0.3048	Meters
Inches	2.54	Centimeters
Tons	1.016	Metric tons
Short tons	0.907	Metric tons
Troy ounces	31.103	Grams
Ounces	28.35	Grams

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By Reed S. Lewis

Abstract

The eastern part of the Soldier Mountains in Camas County, south-central Idaho, is underlain principally by plutonic rocks of Cretaceous and Eocene age that locally have undergone propylitic, potassic, and muscovite-quartz alteration. Muscovite-quartz alteration is Cretaceous in age and is localized along joints and fractures, some of which are filled with quartz. Associated veins have yielded minor amounts of gold. Potassic alteration is probably both Cretaceous and Eocene in age but is weakly developed and limited in extent. Propylitic alteration is Eocene in age and is pronounced around biotite granite plutons. Despite a clear association between plutons of biotite granite and widespread propylitic alteration, mineralization associated with these rocks was minimal. Mineralized areas within more mafic Eocene plutons are characterized by veins and (or) stockworks(?) enriched in copper, molybdenum, and silver, but these areas are restricted in size and have not been productive.

Introduction

This report describes hydrothermal alteration and related mineralization in the eastern part of the Soldier Mountains of Camas County, Idaho (fig. 1). Reconnaissance of the area in a two-day period during the summer of 1984 revealed a complex series of plutonic rocks overlain in places by younger volcanic rocks. The plutonic rocks are locally altered, as indicated by pink zones adjacent to fractures in otherwise gray granodiorite. The alteration was thought at the time to be potassic and to have potential for associated porphyry-type mineral deposits. Criss (1981) and Criss and Taylor (1983) have shown that feldspar in plutonic rocks in the study area was depleted in ^{18}O, a depletion that they attributed to exchange with heated meteoric waters. Their reconnaissance study indicated that epizonal Eocene plutons, unmapped at that time, were probably responsible for circulation of the meteoric water and resultant feldspar alteration. Because of the complex intrusive relations and the associated alteration, it was clear that the area was well suited for a detailed investigation of hydrothermal alteration and mineralization within a granitic terrane.

This research originated as part of a Ph.D. study at Oregon State University (Lewis, 1990). Geologic mapping and sampling were conducted during the summers of 1985 and 1986, in conjunction with the Hailey CUSMAP (Conterminous United States Mineral Assessment Program) project undertaken by the U.S. Geological Survey. Mapping was followed by detailed petrographic study of samples of the plutons and their altered equivalents, chemical analysis of whole-rock samples, and determination of $^{18}O/^{16}O$ ratios of constituent minerals.

Previous geologic mapping in the study area was reconnaissance in nature. Piper (1924) studied ground water on Camas Prairie and distinguished between plutonic and volcanic rocks north of Fairfield. As part of a study of the geology and ore deposits of the Little Smoky and Willow Creek mining districts, which are mostly east and north of the study area, Ross (1930)

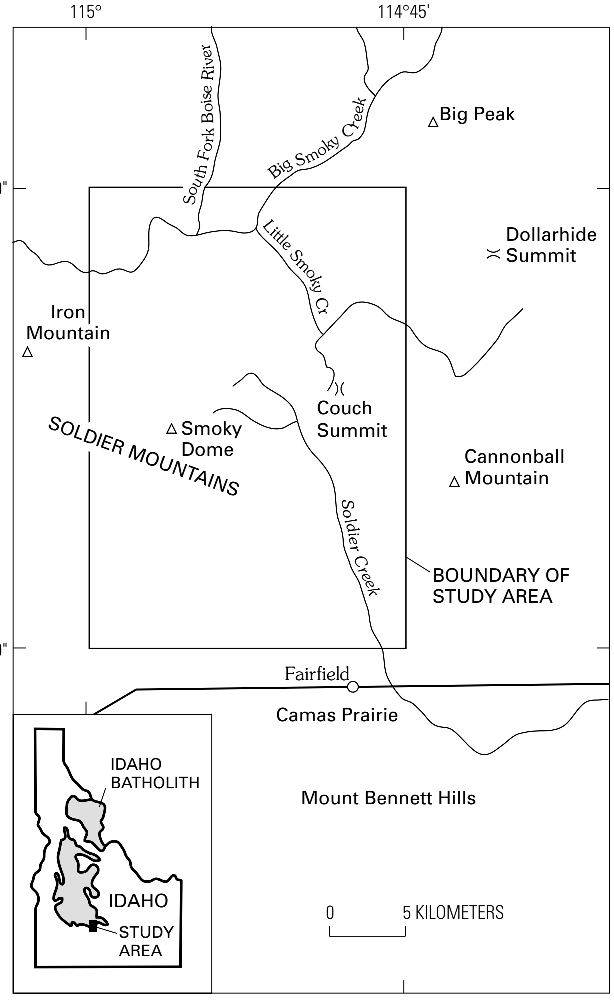

Figure 1. Index map showing the location of the Soldier Mountains study area, Camas County, south-central Idaho.

constructed a geologic sketch map that includes the eastern part of the study area. More recently, Cluer and Cluer (1986) investigated the formation of Camas Prairie, which they concluded was a late Cenozoic rift (graben) developed as a result of downwarping of the Snake River Plain. Gehlen (1983) and Darling (1987, 1988) mapped the Dollarhide Mountain 7.5-minute quadrangle, which adjoins the study area to the northeast, and Bennett (in press) mapped the quadrangles to the west. The studies by Darling and Bennett were part of the Hailey CUSMAP project, and results of their mapping are included on the geologic map of Worl and others (1991).

Lithology

The eastern part of the Soldier Mountains is underlain principally by plutonic rocks of Cretaceous and Eocene age (fig. 2). Reliable radiometric ages for the Cretaceous plutonic rocks have yet to be obtained. Samples dated by the $^{40}Ar/^{39}Ar$ method indicate partial to total argon loss during Eocene time (Lewis, 1990; L.W. Snee , unpub. data, 1992). Correlation with similar rocks elsewhere in the batholith (Lewis and others, 1987; L.W. Snee, unpub. data, 1992) indicates that an age of 95–75 Ma is likely.

The Cretaceous plutonic rocks, which are part of the Idaho batholith, can be divided into three phases: (1) potassium-rich hornblende-biotite granodiorite (fig. 2, unit Kgdk); (2) hornblende-biotite tonalite (fig. 2, unit Kt); and (3) biotite granodiorite (fig. 2, unit Kgd). The hornblende-biotite granodiorite contains large books of biotite and belongs to a potassic suite of plutons that is more widely exposed east of the study area (Lewis, 1989; Worl and others, 1991). The hornblende-biotite tonalite and biotite granodiorite contain small “shreddy” biotite books and belong to a sodic suite of plutons mostly north and west of the study area (Lewis, 1989; Schmidt, 1962, Worl and others, 1991).

Four phases of Eocene plutonic rocks are present in the eastern part of the Soldier Mountains. All are epizonal and are associated with dike swarms. The earliest three units are the most mafic; they range from gabbro to granite in composition and are collectively referred to as the quartz monzodiorite suite (fig. 2, unit Tqmd). Regional distribution of the three units is shown by Worl and others (1991, units Tqm, Tfgd, Tgb). This intrusive activity probably began about 48 or 47 Ma, based on $^{40}Ar/^{39}Ar$ age spectra of biotite and potassium feldspar (Lewis, 1990; L.W. Snee, unpub. data, 1992). The youngest phase is biotite granite (fig. 2, unit Tg), the plutons of which are referred to as the biotite granite suite or pink granite suite. Contacts between the biotite granite and the older Eocene plutonic rocks are sharp, and dikes of biotite granite locally crosscut the older Eocene rocks. Both suites are present throughout central Idaho and are the intrusive equivalents of the Challis Volcanic Group (Bennett and Knowles, 1985). More detailed descriptions of the plutonic rocks in the Soldier Mountains and the surrounding region are given in Lewis (1990, 1991), Lewis and Kiilsgaard (1991), and Kiilsgaard and others (in press).

The Challis Volcanic Group in the eastern part of the Soldier Mountains is characterized by lava flows of rhyodacite, dacite, and andesite. Overlying these flows is a series of Miocene volcanic rocks including rhyolite tuff that correlates with rhyolite tuff of the Gwin Spring Formation, peralkaline rhyolite tuff of Cannonball Mountain, and a series of porphyritic olivine basalt flows (Lewis, 1990).

Structure

Two types of structures are prominent in the eastern part of the Soldier Mountains: faults and swarms of dikes that follow zones of structural weakness. The distribution of major faults is shown in figure 2. Most faults dip steeply and were recognized by topographic expression, changes of rock type, or zones of cataclasis. The only low-angle fault that could be traced any distance is present in the extreme northeastern corner of the study area, but the sense of motion along this structure is unknown. Numerous other low-angle structures probably are present but were not recognized with certainty because of poor exposures and lack of marker units.

The Worswick Creek fault system is probably one of the oldest high-angle structures in the area. It consists of a series of northeast-trending faults characterized by easily eroded zones of sheared rock. Some of these faults may continue southwest of the Couch Summit fault, but none could be traced because of poor exposures. The northeast trend of the Worswick Creek fault system parallels the predominant trend of Eocene dikes in the area, and a majority of the dikes were intruded along or near this zone of weakness. Thus, the fault system probably was present during Eocene time. The northeast trend is the same as that of the much larger Trans-Challis fault system to the north, along which Eocene intrusive activity was also localized (Kiilsgaard and Lewis, 1985; Kiilsgaard and others, 1986). The two systems are probably contemporaneous. Direction of displacement along the Worswick Creek fault system is unknown, but there is no topographic break that would indicate recent dip-slip motion. Although rocks along the fault zone are sheared and brecciated, hydrothermal alteration is minimal.

Intense propylitic alteration is localized along some of the faults in the study area. This alteration is characterized by epidote veinlets, the replacement of biotite by chlorite, and the replacement of oligoclase and andesine by albite. Here and elsewhere in the region this type of alteration is spatially associated with Eocene plutons (Criss and Taylor, 1983; Lewis, 1990). Thus, faults that localize propylitic alteration were probably present in the Eocene. Examples include the east-trending fault 2.5 km southwest of the U.S. Forest Service Big Smoky Guard Station, the Couch Summit fault, and the northwest-trending fault 2.5 km east of the guard station (fig. 2).

West-northwest- to north-northwest-trending faults such as the Couch Summit and Soldier Mountains faults are characterized by topographic breaks and probably have had dip-slip motion in the past several hundred thousand years. Some or all of these faults may still be active. Their west-northwest to north-northwest trends parallel basin and range structures in the region, and all are interpreted as steep normal faults. Hydrothermal alteration along these faults is variable. In some cases juxtaposed rocks are sheared but not visibly altered. Rocks along the Couch Summit fault are propylitized across a width of

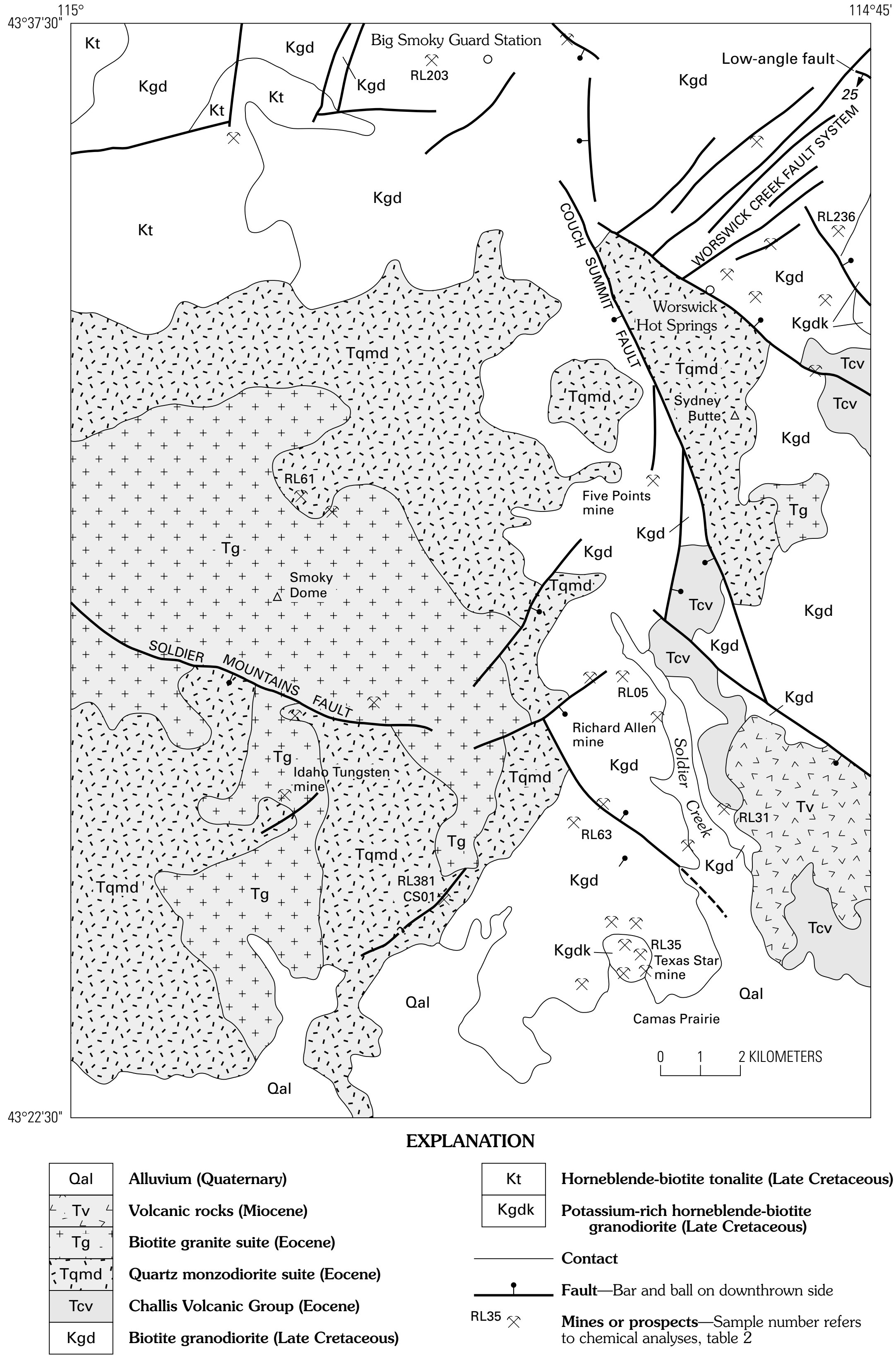

Figure 2. Simplified geologic map of the eastern part of the Soldier Mountains, Idaho. Modified from Lewis (1991).

roughly 300 m. Because of the spatial relationship between propylitic alteration and Eocene plutonic rocks, this type of alteration is thought to be Eocene in age. Thus, the Couch Summit fault has probably been the site of recurrent movement during the past 50 m.y. Most of the other steep normal faults are probably younger, but age of initial movement is difficult to establish.

The Soldier Mountains fault is the southernmost part of a structure 80 km long that extends as far north as the South Fork of the Payette River, east of Lowman, Idaho. The northern part of the fault, recognized by Anderson (1934), is termed the Deer Park fault. Net vertical displacement on the Soldier Mountains fault, based on topographic relief, is roughly 700 m (2300 ft). Vertical displacement on the order of 500 m (1600 ft) is likely along the southern end of the Couch Summit fault.

The low-angle fault in the northeastern corner of the study area dips about 25°. It continues northeast into the Dollarhide Mountain quadrangle, where it forms a resistant ridge of propylitized (chlorite- and epidote-rich) Cretaceous biotite granodiorite. The map by Darling (1987) of the Dollarhide Mountain quadrangle shows this feature as a hydrothermally altered zone in the biotite granodiorite, not as a fault. The origin of this structure is uncertain, but it is probably a low-angle extensional fault of Eocene age. Propylitic alteration, such as in this fault zone, is commonly associated with Eocene plutonism elsewhere in the region (Criss and Taylor, 1983). Darling (1987) mapped a hornblende quartz monzonite of suspected Eocene age below the altered and sheared biotite granodiorite and inferred an Eocene age for alteration in this part of the Dollarhide Mountain quadrangle.

Low-angle shear zones were also noted during underground mapping of the Richard Allen mine west of Soldier Creek. Alteration along these shear zones is characterized by coarsely crystalline secondary muscovite rather than by a propylitic (chlorite-epidote) assemblage. Similar alteration elsewhere in the study area has been radiometrically dated as Cretaceous (approximately 70 Ma) (Lewis, 1990). Because of poor exposure, none of these muscovite-bearing shear zones is recognizable at the surface.

Hydrothermal Alteration

Cretaceous and Eocene plutonic rocks in the eastern part of the Soldier Mountains area have undergone muscovite-quartz, potassic, and propylitic alteration (table 1). The muscovite-quartz alteration is equivalent to quartz-sericite (or phyllic) alteration. A fourth type of alteration involves the widespread formation of turbid potassium feldspar in the Eocene plutonic rocks. This turbidization is particularly pronounced in the biotite granite. The only hydrothermally altered volcanic rocks are those of the Challis Volcanic Group, which are characteristically propylitized. Because the focus of this study was alteration in plutonic rocks, the following discussion is restricted to these rock types.

Muscovite-Quartz Alteration

Muscovite-quartz alteration is most pronounced in the northeastern part of the area, particularly east of the Worswick Creek fault system. It is localized along joints and fractures and is restricted to rocks of the Cretaceous batholith. Granitic rock adjacent to gold-bearing quartz veins in the area has also undergone muscovite-quartz alteration. Muscovite-quartz alteration differs from the weak sericitization that affects propylitized

Table 1. Characteristics of alteration types in the eastern part of the Soldier Mountains, Idaho.

	Muscovite-quartz	Potassic	Propylitic	"Turbidization"
Distribution	Localized along fractures in Cretaceous granodiorite; local quartz-vein association	Locally present adjacent to veins, dikes, and Eocene granodiorite of quartz monzodiorite suite	Common along fractures and locally pervasive in Cretaceous and Eocene units; common in vicinity of Eocene biotite granite	Pervasive in Eocene biotite granite and to a lesser extent in quartz monzodiorite suite
Mineralogy	Coarse muscovite, quartz, and pyrite ± albite ± calcite	± potassium feldspar ± biotite (new minerals or recrystallized preexisting minerals)	Epidote, chlorite, albite, and sericite ± magnetite ± hematite(?) ± potassium feldspar ± leucoxene ± calcite ± quartz ± fluorite	Hematite(?) imparts pink color, but turbidity is probably result of open spaces in feldspar
Age	Cretaceous	Cretaceous and (or) Eocene	Eocene	Eocene

rocks of all ages in the study area in that the secondary mica is coarsely crystalline, typically 1–4 mm across. The mica has replaced plagioclase, potassium feldspar, and biotite. In addition to muscovite, primary quartz and fine-grained, secondary quartz are abundant. Secondary pale-pink albite is generally the only feldspar and, unlike albite in the propylitized rocks, it is not turbid. Euhedral secondary pyrite is common and protrudes into small cavities in altered rocks. Calcite is present locally. Much of the weakly altered Cretaceous granodiorite contains populations of both coarse- and fine-grained secondary muscovite replacing plagioclase feldspar. The coarse-grained muscovite is probably indicative of weak muscovite-quartz alteration, and later propylitic alteration formed the fine-grained mica.

Muscovite-quartz alteration in the Soldier Mountains area is characterized isotopically by relatively heavy muscovite ($\delta^{18}O$ of 7.7–8.0 per mil) and by quartz that has a higher $\delta^{18}O$ value (11.6 per mil) than its original value near 10.2 per mil (Lewis, 1990). The relatively high $\delta^{18}O$ values are the result of interaction either with magmatic fluids or with meteoric waters in which $\delta^{18}O$ values have been greatly increased as a result of low water to rock ratios. A $\delta_{qtz\text{-}musc}$ value of 3.9 per mil from one sample indicates an alteration temperature of about 425°C (Lewis, 1990) using the fractionation data of Bottinga and Javoy (1973). Assuming that 425°C is the correct temperature, the water in equilibrium with the quartz and muscovite had a $\delta^{18}O$ value of about 7 per mil. Altered rocks were depleted in sodium and iron, and enriched in calcium and potassium (Lewis, 1990).

Coarse secondary muscovite is common around quartz veins throughout the southeastern part of the Idaho batholith. The fact that it is absent in Eocene plutonic rocks suggests that muscovite-quartz alteration is Cretaceous in age. A sample of this coarse muscovite from the study area was dated by the $^{40}Ar/^{39}Ar$ method and yielded a stepwise release plateau of 70.3$\pm$0.4 Ma (Lewis, 1990). This result confirms the Cretaceous age of muscovite-quartz alteration in the study area and implies that similar alteration in the region may also be of this age.

Potassic Alteration

Potassic alteration of Cretaceous granodiorite was recognized at three localities in the study area, and only as a result of petrographic study. Although other areas are undoubtedly affected, potassic alteration probably is areally limited and weakly developed. Temperatures of alteration are high (>400°C) because biotite and potassium feldspar are stable phases.

The most pronounced potassic alteration is at the Texas Star mine north of Camas Prairie (fig. 2). Here, potassium-rich hornblende-biotite granodiorite is crosscut by widely spaced quartz veins, adjacent to which fine-grained secondary potassium feldspar has formed as subgrains (0.1 mm across) along grain boundaries. A second area of potassic alteration is about 250 m northeast of the Couch Summit fault, 1 km from its southern end. Biotite granodiorite at this locality contains both finely crystalline biotite that has replaced more coarsely crystalline primary biotite, and subgrains of potassium feldspar along grain boundaries. Alteration is fracture controlled and not extensive. Small dikes of fine-grained biotite granite and dacite in this area may have been the source of heat and (or) potassium-rich fluids. The third locality affected by potassic alteration is on the ridge at the head of Bowns Creek, 8 km southwest of Big Smoky Guard Station. Here, Cretaceous biotite granodiorite collected about 75 m from the contact with Eocene granodiorite of the quartz monzodiorite suite contains patches of secondary potassium feldspar partly replacing plagioclase feldspar and fine-grained biotite that has replaced coarser primary biotite. Geochemical data indicate that alteration at this locality involved high-temperature recrystallization of existing minerals but without significant addition of potassium to the rock (Lewis, 1990). Despite the lack of measurable potassium enrichment, the term “potassic alteration” is applied because the potassium-bearing minerals biotite and potassium feldspar were stable.

Oxygen-isotope ratios of feldspar from the Bowns Creek locality probably were not affected by potassic alteration. The altered Cretaceous granodiorite has $\delta^{18}O$ values of 8.6 per mil for potassium feldspar and 8.5 per mil for plagioclase feldspar, similar to typical unaltered values of 8.0–9.0 per mil (Lewis, 1990). The lack of a shift in $\delta^{18}O$ values and the proximity of the Eocene pluton indicate that the water involved in this recrystallization process was likely at high temperature and of magmatic origin. Assuming a temperature of 500°C, and using the fractionation data of O’Neil and Taylor (1967), the composition of the water in equilibrium with feldspar of 8.5 per mil would be about 6 per mil.

The age of the alteration at these three localities is not well constrained. Alteration and associated mineralization at the Texas Star mine may be Cretaceous in age because Eocene plutonic rocks are some distance away; however, the possibility of a buried Eocene pluton cannot be discounted. Alteration at the other two localities is most likely Eocene in age, especially at the Bowns Creek locality, because the altered rock is about 75 m from a contact with an Eocene stock.

Propylitic Alteration

Propylitic alteration is by far the most prevalent alteration type in the eastern part of the Soldier Mountains. It is characterized by the replacement of biotite by chlorite and the replacement of oligoclase and andesine by albite. Epidote is also common and typically forms 1–2-mm-thick veinlets spaced a few centimeters to decimeters apart. The hydrothermally altered areas are only part of an areally more extensive altered region recognized by Taylor and Margaritz (1976, 1978) and Criss and Taylor (1983) that was defined on the basis of lowered $\delta^{18}O$ values of feldspar (as much as -8 per mil) and lowered δD values of biotites (as much as -180 per mil). These investigators demonstrated that the propylitic alteration was related to large-scale circulation of heated meteoric waters around epizonal Eocene plutons.

Although Cretaceous biotite granodiorite unit (fig. 2, unit Kgd) is propylitized in many areas, the most widely altered rocks in the study area are those of the Eocene quartz monzodiorite suite (unit Tqmd). Eocene biotite granite (unit Tg) is propylitized only locally. Important alteration controls are proximity to Eocene intrusive rocks (particularly biotite granite), as well as to faults, epidote veinlets, and joint surfaces. The altered areas are typically restricted to within a few centimeters of the veinlets and joint surfaces, but in some cases the alteration is pervasive over several hundred square meters. Prophylitic alteration implies relatively low temperatures (160°C–325°C), based on measurements in active geothermal systems (McDowell and Elders, 1980) and on fluid inclusion studies (Kerrich and Kamineni, 1988). Propylitized areas are not known to be mineralized.

A characteristic feature of the propylitic alteration is albitization of plagioclase feldspar. The albite, which is generally pink and turbid, was initially mistaken for potassium feldspar; however, X-ray diffraction analysis indicated a composition of almost pure anorthite. Locally, the albitized plagioclase feldspar was itself partly replaced by potassium feldspar, although secondary potassium feldspar is generally confined to veinlets. Minor epidote, in addition to albite and sericite, has replaced the plagioclase feldspar.

Secondary albite has been reported elsewhere in the region. Reid (1963) described albite in altered zones of Cretaceous granodiorite several hundred yards wide adjacent to the biotite granite in the Sawtooth Range, 40 km north of the study area. In addition, clay, sericite, chlorite, and epidote were reported. Albite and epidote that postdate silicification and sericitization along quartz veins were noted by Allen (1952) in the Volcano mining district, 30 km southwest of the study area. The veins reportedly crosscut early Tertiary granophyric dikes.

Potassium feldspar appears to be less affected by the propylitic alteration than plagioclase feldspar. At a few localities, turbid altered potassium feldspar is present. Epidote and, more rarely, chlorite also formed as secondary minerals after potassium feldspar.

Biotite in the propylitized rocks has been replaced by chlorite and by lesser amounts of epidote, sphene, sericite, and leucoxene. As recognized by Criss (1981), chloritization of biotite was widespread in the southern lobe of the batholith. Primary magnetite was mostly unaffected by the propylitic alteration, except in some of the most strongly propylitized samples where it was replaced by hematite. Secondary magnetite is common in epidote veinlets. Hornblende was replaced by chlorite and epidote but was less affected by hydrothermal alteration than biotite. Sphene was altered to leucoxene and, in strongly propylitized rocks, to epidote, as was allanite.

Epidote veinlets, typically 2 mm or less wide, are another common feature of the propylitized rocks. Most veinlets are entirely filled, but some contain central cavities into which euhedral epidote has grown. Plagioclase feldspar has been preferentially albitized adjacent to these veinlets. Magnetite and potassium feldspar are subordinate minerals in the epidote veinlets. Sericite, albite, chlorite, quartz, and fluorite are also in the epidote veinlets but in negligible abundance. The presence of secondary magnetite within veinlets may in part explain the variability in magnetic susceptibility of altered rocks in the southern part of the Idaho batholith that has been documented by Criss and Champion (1984). Potassium feldspar in the veinlets is typically anhedral and has poorly developed grid twins. Rarely, it forms euhedral rhombs, characteristic of adularia. Calcite is present locally and is more common in rocks that do not contain appreciable epidote.

Unaltered feldspar in the biotite granodiorite unit (fig. 2, unit Kgd) has $\delta^{18}O$ values of 8.0 to 9.0 per mil (Lewis, 1990). Propylitized rocks contain oligoclase that ranges from 8.4 per mil to -1.4 per mil and albitized plagioclase feldspar that ranges from -2.0 to -4.7 per mil; potassium feldspar values are as low as -3.5 per mil (Lewis, 1990). Criss analyzed feldspars in the study area that have $\delta^{18}O$ values as low as -5.8 per mil. These data all indicate that the feldspars have exchanged with low - $\delta^{18}O$ fluids (meteoric water) during propylitic alteration. Water in equilibrium with the albitic feldspar would be about -10 per mil, using fractionation data of O'Neil and Taylor (1967) and assuming a temperature of 250°C. Criss and Taylor (1983) estimated a $\delta^{18}O$ value of -15 per mil for meteoric water in the Atlanta lobe during Eocene time but thought that $\delta^{18}O$ values for those waters had been shifted to about -9 to -3 by interaction with wallrock. The -10 per mil value based on albite-water equilibrium is considered a rough approximation of the composition of some of the isotopically least shifted hydrothermal waters in the study area during Eocene time. This low $\delta^{18}O$ value is in contrast to the relatively high $\delta^{18}O$ values of water (about 7 per mil) calculated for the muscovite-quartz alteration. The major- and trace-element compositions of most propylitized samples are similar to those of unaltered samples; however, in strongly propylitized rocks sodium and hydrogen were added and calcium was depleted (Lewis, 1990).

Turbidization of Eocene Feldspar

A characteristic feature of Eocene biotite granite (fig. 2, unit Tg) is the presence of turbid potassium feldspar. The process that clouds the feldspar is here referred to as turbidization. Except for local phenocrysts that have gray cores, all potassium feldspar in Eocene granite is pink and turbid; the gray cores of phenocrysts are less turbid than the pink rims. Potassium feldspar in rocks of the Eocene quartz monzodiorite suite (unit Tqmd) is either gray or pink. Plagioclase feldspar in all of the Eocene rocks is white and less turbid than potassium feldspar. Cretaceous granodiorite (units Kgd, Kgdk) contains gray to pale-pink potassium feldspar that is less turbid than potassium feldspar in Eocene rocks.

The turbidity and pink color of the potassium feldspar in the Eocene rocks, particularly biotite granite, is a pervasive feature not related to large-scale faults or joint surfaces. Martin and LaLonde (1979) suggested that turbidity in potassium feldspar results not from mineral inclusions but from open spaces produced by reconstitution of a feldspar in the presence of water. Microfractures in turbid areas of the feldspar suggest that alteration (turbidization) was enhanced in more permeable areas of the crystals and that fluids were an important part of that process. The gray cores of phenocrysts are interpreted as relict, unaltered areas. The less turbid (and more gray) potassium feldspar in Cretaceous granodiorite apparently did not undergo fluid interaction to the same extent as did the Eocene plutons. The higher level of emplacement of the Eocene plutons relative to their Cretaceous counterparts may have facilitated both increased porosity and greater availability of meteoric waters, thus promoting turbidization. The pink color of the feldspar presumably is the result of crystals of hematite. Guthrie and

Veblen (1988) reported oxides of iron line minute (<5μm) open spaces in turbid alkali feldspars. The inferred presence of hematite is an indication that the fluids were oxidizing.

Mineralization

The study area includes parts of the Soldier, Rosetta, Big Smoky, Little Smoky, and Skeleton Creek mining districts. Small mines and prospects are present (fig. 2), but none have had significant production. The principal interest has been in gold, but minor amounts of lead and silver have also been produced.

Mines and prospects in the eastern part of the Soldier Mountains were visited, and the mineralization at these localities was related to specific geologic features such as rock type and structure. In this way, structures and rock units favorable for exploration were identified. Sixteen mineralized rock-chip samples were analyzed to characterize the metal types present, and 188 stream-sediment samples were collected to identify metal-enriched areas that may not have been previously identified. Rock-chip analyses are listed in table 2 and results of the stream-sediment sampling are given in Lewis (1990, 1991).

Texas Star (D. Marie) Mine

The Texas Star mine is at the northern edge of Camas Prairie in the southeastern part of the study area (fig. 2). The underground workings were not extensive and are now inaccessible. According to R.E. Gibbons of Fairfield, Idaho (written commun., 1985), the property was located in 1891 by E.M. and H.S. Hego as the Texas Star. Ross (1930) reported that in 1892 1.75 tons of ore shipped from the Texas Star yielded 1.53 ounces of gold, 49.5 ounces of silver, and 1,651 pounds of lead. Continued work in 1893 produced 17.19 tons of ore yielding 75.2 ounces of gold, 132.3 ounces of silver, and 6,000 pounds of lead. According to R.E. Gibbons, a ten-stamp mill was subsequently installed on the property, and underground work indicated that oxidized ore extended to a depth of 10–20 m (30–60 ft). The oxidized zones of all known veins are reported to have been worked out, but records of the production from the mill, which was eventually removed, are not available. Subsequent work on the property is well summarized by R.E. Gibbons:

> "The ground stood idle for many years although the late Jack Wallace, a lifetime prospector of the local Soldier Mountain area, claimed, worked, and lived on the property for over twenty-five years, until his death in the late forties, apparently without success as his efforts didn't alter the landscape greatly, nor did he die a rich man."

The Texas Star mine and a number of prospect pits present west and north of the mine are in potassium-rich hornblende-biotite granodiorite (fig. 2, unit Kgdk), part of the potassic suite of the Idaho batholith (Lewis, 1989). The granodiorite is both texturally and mineralogically similar to the Hailey granodiorite unit of Schmidt (1962), which is exposed in the Hailey gold belt area to the east (unit Kgdk of Worl and others, 1991). The contact with the biotite granodiorite unit (unit Kgd) is poorly known but is thought to be immediately east of the Texas Star mine. Dump samples indicate that veins of quartz containing pyrite, galena, and magnetite crosscut the granodiorite. Molybdenite is sparingly present along quartz-free fractures. Alteration minerals include sericite, chlorite, calcite, and secondary potassium feldspar. A composite sample of granodiorite and molybdenite veinlets (table 2, sample RL36) contained 200 ppm Mo, and a composite sample of vein quartz containing visible sulfide minerals (table 2, RL333) contained 49 ppm Ag, 15 ppm Au, and 3.9 percent Pb. A composite sample of vein quartz and sulfide minerals from a prospect pit north of the Texas Star (table 2, sample RL35) contained 200 ppm Ag, 2.7 ppm Au, and 2.0 percent Pb. Complete analyses and sample descriptions are given in table 2.

Exposures of potassium-rich hornblende-biotite granodiorite (unit Kgdk) west and north of the Texas Star mine contain an unusually large number of prospects (fig. 2). The characteristics of these prospects are similar to those of the mine.

Richard Allen Mine

The Richard Allen mine is north of the Texas Star mine on the west side of Soldier Creek (fig. 2). The property was developed with several adits and prospects pits, but only the uppermost adit was accessible at the time of this study. According to the State Mine Inspector's report for the year 1939 (Cambell, 1940), total development is on the order of 600 m (2,000 ft). The amount of production from the Richard Allen mine is unknown, but it is unlikely that it was substantial.

Bedrock at the Richard Allen mine is biotite granodiorite (fig. 2, unit Kgd) of the sodic suite of the Idaho batholith. The granodiorite is crosscut by dikes and sills of dacite that are probably Eocene in age. Exposures of quartz veins or other mineralized rock are not evident.

A geologic map of the uppermost adit at the Richard Allen mine is shown on figure 3. Both the granodiorite and dacite in the adit are highly sheared and altered to clayey gouge, secondary muscovite, and chlorite. Most of the shears are subhorizontal and the shearing is pervasive; discrete faults are lacking. Because the shearing involves the dacite sills and dikes, at least some of the movement is likely Eocene or younger in age. Three composite chip samples were collected along the length of the upper adit (samples RL151, RL152, and RL153; fig. 3, table 2); all three contained less than 0.05 ppm Au.

Five Points (Perseverance) Mine

The Five Points mine is north of the Richard Allen mine and southwest of Sydney Butte (fig. 2). All of the workings are presently inaccessible. According to Ross (1930), the mine was developed by four tunnels having a total length of about 300 m (1,000 ft). As of 1930, development had been carried on intermittently for several years. Recorded production from the Five Points mine is less than 1,000 tons of ore that yielded between 100 and 500 ounces of gold and between 1,000 and 5,000 ounces of silver (Mitchell and others, 1991).

Table 2. Mineralized samples from the eastern part of the Soldier Mountains, Idaho.

[Sample localities are shown on figure 2. Detailed locations are given in Lewis (1991). In parts per million. Methods of determination: Atomic-absorption spectroscopy and inductively coupled plasma spectroscopy for Ag, Au, Cu, Mo, Pb, Zn, As, Cd, Bi, and Sb; six-step semiquantitative emission spectroscopy for B, Ba, Be, Co, Cr, La, Nb, Ni, Sc, Sr, V, Y, and Zr. Analysts: J. Motooka, C. Taylor, R.J. Fairfield, L.S. Laudon, F.W. Tippitt, B. Bailey, O. Erlich, B. Roushey, and P.L. Hagemon]

	RL05	RL31	RL35	RL36	RL61	RL63	RL87	RL151	RL152	RL153	RL163	RL203	RL236	RL333	RL381	CS01
Ag	3.0	29	200	0.55	35	37	1.0	0.15	0.17	0.09	37	0.9	<0.05	49	340	1,000
As	20	<10	100	<10	<10	10	260	<10	<1.0	<1.0	100	<1.0	100	120	50	<200
Au	0.80	2.4	2.7	0.05	0.05	<0.05	0.05	<0.05	<0.05	<0.05	3.3	<0.05	<0.05	15	0.05	<10
B	20	10	10	<10	10	10	10	10	10	10	10	15	15	10	<10	<10
Ba	1,000	70	50	700	500	1,000	500	1,500	700	700	50	500	70	30	300	2,000
Be	1	2	1.5	1	1	1	3	<1	<1	<1	1	<1	1	<1	<1	2
Bi	<1	28	590	1	340	120	<1	<1	<1	<1	15	<1	<1	6.8	390	>1,000
Cd	0.6	0.7	1.3	<0.1	0.4	2.9	<0.1	0.1	<0.05	<0.05	30	0.90	0.06	19	4.4	<20
Co	<5	<5	<5	10	15	<5	<5	7	<5	<5	5	<5	<5	<5	10	50
Cr	<10	<10	10	50	20	<10	<10	70	<10	<10	<10	<10	<10	<10	50	100
Cu	50	80	450	70	5,000	20,000	50	5	9.6	4.2	1,500	130	2.5	1,400	11,000	10,000
Hg	0.02	0.08	0.10	0.02	0.02	0.02	0.22	0.18	0.12	0.18	0.02	0.04	0.10	0.2	--	--
La	50	<20	<20	100	<20	50	20	70	50	70	<20	50	50	<20	50	<50
Mo	<0.5	12	20	200	3.0	5.0	67	0.5	0.18	<0.15	15	0.32	4.5	<0.15	480	1500
Nb	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ni	5	5	<5	15	10	<5	5	15	<5	<5	<5	<5	<5	<5	30	70
Pb	440	1,500	20,000	45	110	180	10	10	9.9	16	2,000	94	10	39,000	1,800	5,000
Sb	<2	<2	18	<2	<2	<2	16	<2	<1.2	<1.2	<2	<1.2	<1.2	<1.2	<1.2	<100
Sc	<5	<5	<5	7	<5	<5	<5	10	<5	<5	<5	<5	<5	5	<5	10
Sr	200	<100	<100	500	100	500	<100	1,000	500	300	<100	200	<100	<100	100	300
V	20	10	30	70	30	20	30	70	10	<10	15	15	15	10	20	70
Y	<10	<10	<10	10	<10	15	<10	15	10	10	<10	<10	<10	<10	<10	15
Zn	140	290	250	70	110	150	10	40	26	32	10,000	260	47	1,600	1,400	2,000
Zr	70	20	70	50	70	100	100	100	70	70	20	50	100	30	70	300

Description of mineralized samples

RL05 Chip sample across silicified zone 1 m wide from prospect pit in biotite granodiorite northwest of Richard Allen mine.
RL31 Composite sample of high-graded vein quartz from prospect pit in biotite granodiorite southeast of Richard Allen mine.
RL35 Composite sample of high-graded vein quartz from prospect pit in coarse-grained hornblende-biotite granodiorite north of Texas Star mine.
RL36 Composite sample of high-graded coarse-grained hornblende-biotite granodiorite and sparse molybdenite veinlets from the mine dump at the Texas Star mine.
RL61 Chip sample across quartz vein 0.5 m wide from prospect pit in biotite-hornblende granodiorite north of Smoky Dome.
RL63 Composite sample of copper-stained biotite granodiorite and quartz veins 1-3 cm wide from prospect pit southwest of the Richard Allen mine.
RL87 Composite sample of high-graded vein quartz from the dump at the Idaho Tungsten mine.
RL151 Chip sample along 21 m (70 ft) of dacite dike in the upper adit of the Richard Allen mine.
RL152 Chip sample along 14 m (47 ft) of biotite granodiorite in the upper adit of the Richard Allen mine.
RL153 Chip sample along 12 m (40 ft) of biotite granodiorite in the upper adit of the Richard Allen mine.
RL163 Composite sample of high-graded vein quartz from the dump at the Five Points mine.
RL203 Chip sample across silicified zone and fault gouge 1 m wide above small caved adit in biotite granodiorite west of Big Smoky Guard Station.
RL236 Chip sample across quartz vein 2 m wide from outcrop in biotite granodiorite northeast of Worswick Hot Springs.
RL333 Composite sample of high-graded vein quartz from the dump at the Texas Star mine.
RL381 Composite sample of high-graded vein quartz and biotite-hornblende granodiorite from prospect pit northwest of Texas Star mine.
CS01 Composite sample of high-graded vein quartz and biotite-hornblende granodiorite from prospect pit northwest of Texas Star mine.

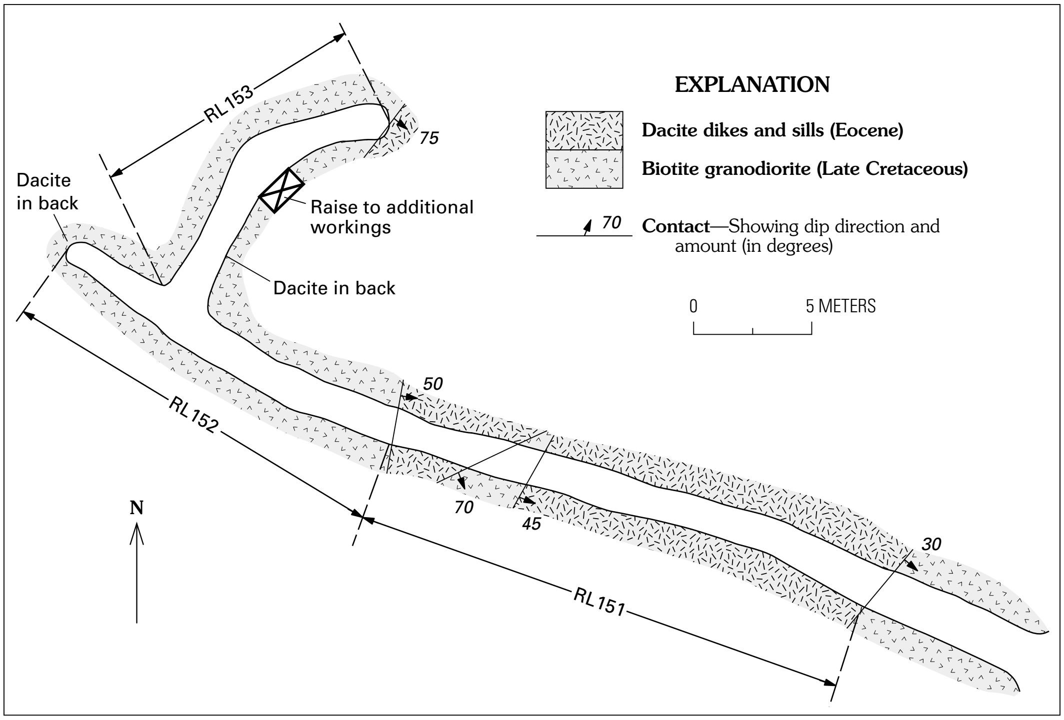

Figure 3. Map of the uppermost adit of the Richard Allen mine. Location of mine shown on figure 2. Analyses for samples RL151, RL152, and RL153 are shown in table 2.

Bedrock at the mine is Cretaceous biotite granodiorite (fig. 2, unit Kgd) of the sodic suite of the Idaho batholith. A steeply dipping quartz vein at the mine that strikes north-south probably was emplaced along the southern end of a fault that continues to the north along Five Points Creek. The vein is as wide as 1 m and can be traced about 60 m (200 ft) up the slope above the mine where it abruptly ends, possibly as a result of displacement along a low-angle fault. Dump samples of granodiorite are altered to clay gouge, sericite, and chlorite. Galena and pyrite are present in dump samples of vein quartz. A composite sample of sulfide- and oxide-rich dump material (table 2, sample RL163) contained 3.3 ppm Au, 37 ppm Ag, 0.2 percent Pb, and 1.0 percent Zn.

Idaho Tungsten Mine (Soldier Mountain Deposit)

The Idaho Tungsten mine is between Rough Creek and the East Fork of Corral Creek about 5 km (3 mi) south of Smoky Dome (fig. 2). The mine is hosted by Eocene biotite granite (unit Tg). Mineralized rock is confined to narrow, chalcedonic quartz veins that contain sparse amounts of tungsten. Tungsten minerals were not recognized during this investigation, but, according to Shannon (1926), ferberite is present in three narrow parallel veins 1–0 cm wide and about 50 cm apart. Cook (1956) reported that one of the veins strikes about N. 55° E. and dips 50° N. and is within one of a set of fractures of similar attitude that cuts the granite in this area. This vein was explored with an adit, about 60 m (200 ft) long, that is now caved. Production was limited to about 6.6 tons of hand-sorted ore averaging about 4.4 percent WO_3 (Cook, 1956). A sample of vein material collected from the dump (table 2, sample RL87) contained less than 50 ppm W.

Unnamed Mines and Prospects in Cretaceous Intrusive Rocks

Several prospects pits and small caved adits are present within the biotite granodiorite unit (unit Kgd) of the sodic suite (fig. 2). Those northeast of Worswick Hot Springs have been referred to as the Rosetta claim group (Umpleby, 1915). Deposits hosted in the biotite granodiorite are characterized by veins of quartz containing minor amounts of sulfide minerals and gold. The granodiorite adjacent to the veins has undergone muscovite-quartz alteration. Chip samples were taken across four of these veins (table 2, fig. 2, samples RL05, RL31, RL203, and RL236); two contained detectable amounts of gold (0.80 and 2.4 ppm) and two contained <0.05 ppm Au.

Copper mineralized rock is not common in the biotite granodiorite, but one prospect pit about 3.5 km (2 mi) southwest of the Richard Allen mine contains small amounts of malachite and azurite. The copper minerals coat fractures and have replaced potassium feldspar. Sparse veinlets of quartz crosscut the granodiorite; they are 1–3 cm wide and contain iron-oxide minerals and epidote. The feldspar and biotite have been locally replaced by secondary albite, sericite, and chlorite. This mineralization may be related to the intrusion of Eocene granodiorite of the quartz monzonite suite (fig. 2, unit Tqmd), which is exposed 1 km to the west. A composite sample rich in quartz and secondary copper minerals (sample RL63, table 2) contained 37 ppm Ag, 5 ppm Mo, and 2.0 percent Cu.

Unnamed Mines and Prospects in Eocene Intrusive Rocks

Mineralization is less common in rocks of Eocene age than in rocks of Cretaceous age. A small prospect pit has exposed a quartz vein within the quartz monzodiorite suite (unit Tqmd) about 3 km (2 mi) north of Smoky Dome (fig. 2). Malachite coats fractures in the vein, which is 0.5 m wide and trends east-west. A chip sample taken across the vein (sample RL61, table 2) contained 0.05 ppm Au, 35 ppm Ag, and 0.5 percent Cu. A small prospect pit 700 m to the southeast exposes a quartz vein 12 cm wide that is also stained with malachite.

One of the more promising prospects in the area is between McMahan Creek and the West Fork of Threemile Creek, roughly midway between the Idaho Tungsten mine and the Texas Star mine (fig. 2). A small prospect pit has exposed malachite-stained biotite-hornblende granodiorite of the quartz monzodiorite suite that is crosscut by numerous veinlets of quartz that are suggestive of a stockwork deposit. Chlorite, epidote, and iron-oxide minerals are abundant. Two collections of composite samples of the veined granodiorite were analyzed (samples RL381 and CS01, table 2) and contained high concentrations of silver (340 and 1000 ppm), copper (1.1 and 1.0 percent), and molybdenum (480 and 1500 ppm). This prospect may to be along a northeast-trending fault, but exposures in the area are poor and the existence of a fault is uncertain.

Mineralization and Lithology

Mineralization in the eastern part of the Soldier Mountains is confined to plutonic rocks of Cretaceous and Eocene age (fig. 2). Volcanic rocks of Eocene and Miocene age exposed in the eastern part of the area are unmineralized. The spatial relationship between mineralization and Cretaceous and Eocene plutons, and the lack of mineralization in Miocene rocks, indicates that mineralization in the eastern part of the Soldier Mountains is Eocene and older.

The one radiometric date on an alteration mineral is Cretaceous ($^{40}Ar/^{39}Ar$ date of 70.3$\pm$0.4 Ma on secondary muscovite), and gold-bearing quartz veins that have quartz-muscovite alteration selvages are probably of similar age.

Copper-silver and tungsten mineralization in the Eocene plutons can be no older than Eocene. The lack of documented post-Eocene intrusive activity suggests that the mineralization is related to the latest stages of Eocene plutonism.

Most of the mines and prospects are in Cretaceous intrusive rocks, and the greatest density of mines and prospects is within the small exposure of potassium-rich hornblende-biotite granodiorite unit at the northern edge of Camas Prairie. This granodiorite unit belongs to the potassic suite of the Idaho batholith, which characteristically contains a greater number of mines and prospects than does the sodic suite. This greater tendency toward mineralization is evident in plutons of the potassic suite exposed to the east in the area of the Hailey gold belt (Lewis, 1989).

Mineralization and Structure

As a result of poor exposures, the relationship between mineralization and structure in the southern part of the area has not been well established. Most of the veins in this area are not obviously related to large through-going faults; instead, they probably were emplaced along small shears and joints within the granitic rocks; strike lengths of these structures are on the order of a few tens of meters. The faults recognized in the southern part of the area are relatively young and either offset Eocene and Miocene volcanic rocks or show topographic expression (for example, the Soldier Mountains fault, fig. 2). Because these faults offset Miocene rocks, it is likely that latest motion on these structures postdated mineralization in the area.

Mineralization in the northern part of the area is more clearly related to larger structures. The Five Points mine is on the southern end of a north-trending fault (fig. 2), the trace of which is marked by sheared biotite granodiorite along Five Points Creek. The Worswick Creek fault system is a pronounced set of northeast-trending faults in the northeastern part of the area (fig. 2). Scattered prospects, collectively referred to as the Rosetta claim group, are in the area of this fault system. The northeast trend of the Worswick Creek fault system is parallel to that of the Trans-Challis fault system to the north, which hosts several gold-bearing deposits (Kiilsgaard and others, 1986).

Conclusions

The eastern part of the Soldier Mountains in Camas County, south-central Idaho, is underlain principally by plutonic rocks of Cretaceous and Eocene age. Eocene volcanic rocks, correlative with the Challis Volcanic Group, and Miocene volcanic rocks, in part correlative with the Idavada Volcanics, are locally preserved. Numerous steeply dipping faults are present; those that trend northeast probably are the oldest and localized the emplacement of Eocene dike swarms. North-northwest- to west-northwest-trending faults exhibit topographic expression and are interpreted as basin and range structures; however, some of these faults may have been the site of recurrent movement since Cretaceous time.

Plutonic rocks in the eastern part of the Soldier Mountains have undergone propylitic, potassic, and muscovite-quartz alteration. In addition, feldspar in the biotite granite has been turbidized. A schematic diagram summarizing the effects of this alteration is shown on figure 4. Muscovite-quartz alteration is Cretaceous in age ($^{40}Ar/^{39}Ar$ plateau of 70.3$\pm$0.4 on muscovite) and is localized along joints and fractures, some of which are filled with vein quartz. This alteration type involved relatively high $\delta^{18}O$ fluids (about 7 per mil) of either magmatic, or strongly shifted meteoric origin.

Following a period of uplift, hydrothermal activity resumed in Eocene time, concurrent with intrusion of epizonal plutons. Weak potassic alteration occurred locally, but propylitization was the predominant and widespread alteration type. Propylitic alteration around the youngest plutons (biotite

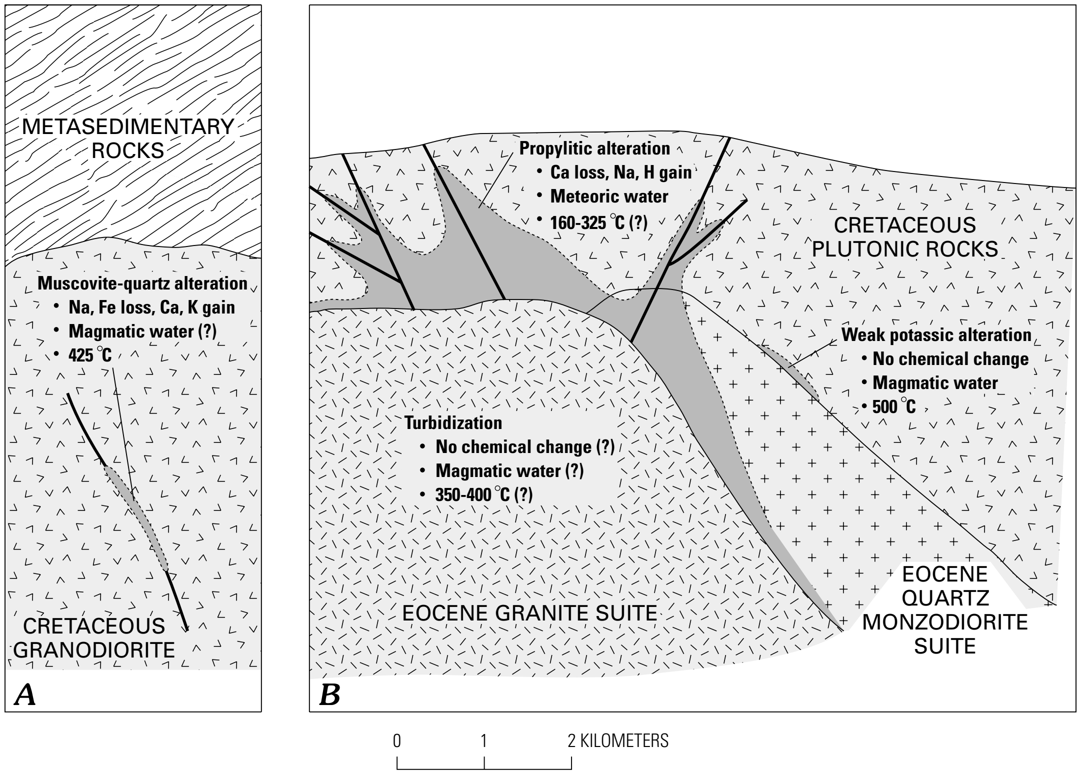

Figure 4. Schematic cross sections illustrating characteristics of hydrothermal alteration types of Cretaceous (*A*) and Eocene (*B*) age in the Soldier Mountains study area, Idaho. Erosion has removed most of the metasedimentary rocks shown on the left, although roof pendants, too small to show on figure 2, are still preserved (see Lewis, 1991).

granite) was particularly strong, and both Eocene and Cretaceous plutonic rocks were affected. Faults and joint surfaces served as conduits for fluid circulation. Concurrent(?) movement of heated oxygenated fluids within the cooling plutons of biotite granite caused turbidization of potassium feldspar, imparting an overall pink color to these rocks. Unaltered feldspar has $\delta^{18}O$ values of 8.0-9.0 per mil, but in propylitized rocks $\delta^{18}O$ values for feldspar as low as -5.8 per mil indicate exchange with heated meteoric water.

Potassic alteration is probably both Cretaceous and Eocene in age but is limited in areal extent and is weakly developed. Potassic alteration adjacent to Eocene granodiorite of the quartz monzodiorite suite resulted in recrystallization of existing minerals but did not cause a shift in the oxygen isotope ratios of feldspar. The water involved in this process was probably magmatic in origin ($\delta^{18}O$ about 6 per mil). Little, if any, change took place in major-element compositions of these recrystallized rocks.

Rock type and, to a lesser extent, structure have influenced the development of mineralized areas in the eastern part of the Soldier Mountains. Most mines and prospects are hosted by granodiorite of the Late Cretaceous Idaho batholith. Although the highest density of prospects is within potassium-rich hornblende-biotite granodiorite of the potassic suite, most mineralized areas are in the more widespread biotite granodiorite of the sodic suite.

Mineralized rock within biotite granodiorite of the sodic suite is characterized by gold-bearing quartz veins that contain minor amounts of pyrite, galena, and sphalerite. Quartz-muscovite alteration is common along side these veins. This mineralization is probably Late Cretaceous in age and related to the final stages of emplacement and cooling of the Idaho batholith.

Mineralized rock within granodiorite of the potassic suite is similar to that of the sodic suite; however, in addition to gold and galena, molybdenite is present, and host rocks have locally undergone potassic alteration. Similar to the sodic suite, this mineralization is probably Late Cretaceous in age.

Despite a clear association between Eocene biotite granite plutons and widespread propylitic alteration, mineralized rock in the Eocene biotite granite suite is limited to a small number of quartz veins and minor amounts of tungsten. None of the veins in the older rocks surrounding the biotite granite is known to be related to the intrusion of these plutons. Mineralized areas within rocks of the quartz monzodiorite suite are characterized by veins or stockworks(?) rich in copper, molybdenum, and silver. Although these mineralized areas are geochemically similar to porphyry copper deposits, they are not extensive, nor are they associated with widespread hydrothermal alteration, as is the case for the porphyry-type deposits.

The mineral potential of the eastern part of the Soldier Mountains is moderate to low relative to other areas in central Idaho; however, additional discoveries of vein-type gold deposits within the plutonic rocks of Cretaceous age are possible. The rocks of the potassic suite are more favorable than those of the sodic suite, but they are not extensively exposed. Favorable structures for mineralization include the north trending fault north of the Five Points mine and the series of northeast-trending faults of the Worswick Creek fault system. Plutonic rocks of the Eocene biotite granite suite are not likely to contain substantial mineralized rock, but the possibility exists for porphyry-type copper-molybdenum-silver deposits is in rocks of the quartz monzodiorite suite. None of the known areas of mineralized rock is of the size or intensity, however, that is characteristic of major porphyry systems.

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